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Criticality in the planform behavior of the Ganges River meanders

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ABSTRACT

The critical point of planform transition from straight to meandering in the wandering Ganges River is identifiable. Recent remote-sensing data indicate that four similar meanders cut off, or attempted to cut off, after ~31–35 yr, primarily due to channel aggradation. As main channels aggrade, sinuosity is maximized for broad channel widths and small radii of curvature and relaxes for bends of greater radii. Maximized form resistance occurs close to self-organized criticality and promotes cutoffs. Avulsions lead to main channel narrowing and prevent further bend tightening, relaxing the system by reducing sinuosity. Thus, the wandering river oscillates in space and time across the transition from a more ordered to a more chaotic state. Planform behavior is described by the Jerolmack-Mohrig mobility number and the Parker stability criterion, which well define meander behavior as they approach criticality and then relax via partial or completed avulsions. The results have significance for river engineering and river network and stratigraphic modeling. Such an approach could be of practical value when predicting the behaviors of other major wandering rivers.

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INTRODUCTION

Stølum (1996) showed that channel sinuosity oscillates across a predictable critical state mediated by local cutoff (avulsion) processes. Such an adjustment is a form of self-organized criticality (SOC; Bak, 1996); when the critical state is reached, meanders adjust to regain order before evolving further. Using the criticality concept, we show that the course of the wandering Ganges River, India (study area: 24.459317°N, 88.103924°E; Fig. 1), oscillates in space and time from a more ordered to a more chaotic state (Stølum, 1996), without change in the magnitude and frequency of external forcing. However, the SOC environment and time scale can be subject to local fixed controls (here bedrock pinch points) that condition SOC behavior (Camazine et al., 2001). The low-sinuosity river (ordered state) increases its sinuosity (chaotic state) until local bank instabilities, manifest as avulsions, lead to channel shortening to reach a low sinuosity value again. Meander regrowth follows. Thus, the critical state is defined as the planform pattern transition point.

Between Farakka Barrage (West Bengal, India) and Hardinge Bridge (Sara, Bangladesh), three meanders occur, with a further meander immediately upstream of the barrage (Fig. 1**[[The figure does not identify the barrage or bridge – label these in the figure?]]**). At any river kilometer, there is a low-gradient sandy main meandering channel or up to three additional lesser cutoff channels. Such rivers are termed “wandering” (Church, 1983). Floodplains and bars have no significant vegetation control. Today, the basal control point of the upstream bend is the Farakka Barrage, and at each of the other bends, translation is limited by geological pinch points (Hossain et al., 2013) that impose important control on meander evolution. Eleven maps (A.D. 1780–1967) reveal a persistent pattern of four meanders increasing in amplitude without downstream translation until cutoffs occur over decadal time scales that lead to periodic reduction in main channel length and sinuosity. In addition, 38 yr of remote sensing data (Landsat Multispectral Scanner, Thematic Mapper, Indian Remote Sensing Satellites Linear Imaging Self-Scanning [LISS] I and LISS III) (from 1972) were used to explore channel planform changes by identifying completed avulsions or partial avulsions (Fig. 1). Main channel widths and radii of curvature at meander apices were quantified for each of the four meanders through time.

SETTING

The annual peak flow on the Ganges River usually occurs within a 1.5 m stage range. Bankfull discharge is exceeded yearly, then the low natural levees are overtopped by shallow floodplain flow or are breached by small cutoffs that transect the major meander loops. These cutoffs scour the floodplains (Coleman, 1969), but the main channel does not realign. Rather, it takes several years for the main flow to adopt any enlarging cutoff channel (Fig. 1). Upstream of the Farakka Barrage the sediment load is 729×10^6 t yr^{-1} (Wasson, 2003) which, due to the barrage, reduces downstream to 300–500 $\times 10^6$ t yr^{-1} at Hardinge Bridge (Hossain et al., 2013). The barrage (constructed in 1975) was fully aggraded by 1995 (Fig. 2), and much sediment now passes by canal to the Bhagirathi-Hooghly River. Thus, the sediment load downstream of the barrage reduces by ~41%–68%.

Four similar meander bends were studied (Fig. 1): one upstream (R1) and three downstream (R2–R4) of the barrage. All bends developed simultaneously and cut off, or attempted to cut off, by chute development over similar time scales (31–35 yr). Thus, although the remote sensing time series is too short to develop a statistical assessment of cutoff frequency, there are four replicates of the cutoff phenomenon.

CONDITIONS FOR AVULSION

The avulsion condition largely is due to channel aggradation (Jerolmack and Mohrig, 2007) that forces overbank flows to occur more frequently. However, tightening bends deepen on their outer banks (Seminara, 2006), and increasing bend flow resistance causes both elevation in the outer bank flow level and increased bank erosion, which increases **[[Corre]]** channel width (Germanoski and Schumm, 1993). These conditions jointly are conducive to avulsion. Thus, the critical cutoff condition can be determined for each bend and depends on (1) channel geometry, (2) discharge, and (3) aggradation rate.

Channel Geometry

The radius of curvature (*r*) was determined for each of the main channel bends. The radii of curvature decreased through time, whereas the channel widths (*B*) often increased (Hossain et al., 2013). The inability of point bar progradation to match the rate of bend apex recession, such that *B* increases as bends tighten, has been noted elsewhere (Kasvi et al., 2015). The condition preceding a completed (or attempted) cutoff and a sudden decrease in sinuosity (*S*) occurred when the bend radius fell to between 5000 m and 2000 m. Thus, cutoff likelihood, in part, can be defined by the ratio *r*/*B* (Howard and Knutson, 1984). To cut off, the river must flow overbank and avulse by rapid erosion of the levee and floodplain surface. The minimum condition for overbank flow is bankfull discharge (van Dijk et al., 2014) plus super-elevated outer bank flow. For bankfull flow (Q_b ~56,633 m^3 s^{-1}; Coleman, 1969), for the channel width (~4000 m) immediately before cutoff occurs, and for the minimum radius of curvature (2000 m), the water surface super-elevation (Δy) is:

$$\Delta y = \frac{c\bar{U}^2\bar{B}}{rg}, \qquad (1)$$

where *c* is a coefficient (0.5) for subcritical flows, the bankfull bulk-flow velocity $\bar{U} = Q_\mathrm{b}/\bar{h}\ \bar{B}$, where $\bar{B}$ and $\bar{h}$ are average values of the channel width and depth (*h*) at bankfull, and g is acceleration due to gravity. Bankfull velocity is low (on the order of 1 m s^{-1}) such that inertia is small. Thus, super-elevation at the bankline is no more than ~50 mm above the channel center water surface. So, for these shallow overbank conditions, near-bankfull flows alone are not likely to induce cutoff (Howard, 2009). Rather, sustained outer-bank erosion, causing r/B to continue to decrease and further channel aggradation, is required to elevate water levels additionally. Alternatively, discharges much above bankfull are required.

Discharge

Rapid erosion of the outside bend will occur if discharge is adequate to entrain bank material for a sufficient time (Edmonds et al., 2009). Bendway flow resistance will reach a maximum as the radius of curvature reaches a minimum value. The straight channel shear stress (τ_T) due to skin friction (f) is:

$$\tau_T = \rho g R S_e = \rho f \bar{U}^2 , \qquad (2)$$

where ρ is the density of water, R is the hydraulic radius, and S_e is the energy slope. The hydraulic radius is ~16 m with a regional bankfull S_e of 5–6 × 10^{-5} (Coleman, 1969). These data provide an estimate of unit shear stress on the order of 10 N m^{-2}. Determining additional form resistance induced by bends is complex (e.g., Chang, 1983). However, for illustrative purposes, we utilize the method of Leopold et al. (1960) to estimate bend form shear stress ($\tau_B = \rho g \bar{h} S_\zeta$) using an energy dissipation term ($\bar{h} S_\zeta$):

$$\bar{h} S_\zeta = \frac{\bar{U}^2}{g}\left(\frac{B}{r} - 0.5\right) - h\left(1 + 1.5F^{0.66}\right) , \qquad (3)$$

where F is the near-bank Froude number for given local depth h. For the minimum values of r/B, the form-induced shear stress can be up to an order of magnitude larger than the skin shear stress. For greater r/B values, the form resistance declines. When

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avulsions were imminent, values of r/B are consistent for all four reaches ($\overline{1.29}$, standard deviation 0.72; n = 27) but smaller than those values (~3) reported by Begin (1986) and Howard and Knutson (1984) for the condition when bank retreat through erosion is maximized. Thus, the ability of the channel to develop significant form resistance and adjust through increasing sinuosity is maximized for small radii of curvature and decreases for bends of greater amplitude. However, increasing form resistance as bends tighten induces a backwater effect and super-elevation that is conducive to cutoff before r/B is maximized, preventing further bend tightening and relaxing the system by reducing sinuosity.

Aggradation

The aggradation rates for meander bends R2–R4 are unknown, but for R1, channel aggradation and subsequent attempted avulsion were induced by backwater sedimentation above the barrage. A linear and then asymptotic approach to constant zero aggradation is typical of impoundments (Wu et al., 2012) and provides a maximum aggradation rate, ~0.18 m yr^{-1}, to use as a scalar in R1 (Fig. 2A). Bend extension increases rapidly once one-third of the impoundment depth is filled (Fig. 2B). For R2–R4, the aggradation rate (V_a) is assumed to be proportional to the reduction in the sediment load (V_a = 300/729 × 0.18 m yr^{-1}) below the Farakka Barrage. As the system aggraded, channel sinuosity increased, and attempted avulsions and cutoffs developed (Figs. 2 and 3). As ~~channel aggradation rate,~~ T_A**[[Clarify how this differs from V_a]]**, mediates the ~~rate of lateral erosion,~~ T_C, the latter a key variable to define critical state (Stølum, 1998), consideration of T_A:T_C can define the critical state of the planform pattern transition if other factors are significantly subordinate.

PLANFORM SCALING MODEL

The model used to show the meander behavior is the Jerolmack and Mohrig (2007) approach to calculate the avulsion frequency (f_A) of a river. The avulsion frequency,

$$f_A = \frac{V_a N}{\bar{h}}, \quad (4)$$

is known approximately. Each reach avulsed, or tried to avulse, at a time scale of ~31–35 yr, so f_A can be set to 0.03 for active channels N = 1–4, with an average channel depth of $\bar{h}$ = 22 m. Jerolmack and Mohrig (2007) developed a channel mobility number (M) to discriminate single-channel versus multichannel form:

$$M = \frac{T_A}{T_C} = \frac{\bar{h}}{B}\frac{V_c}{V_a}, \quad (5)$$

where ~~T_C is the time to migrate one channel [illegible]th and~~ V_c is the bank erosion rate. M = T_A/T_C = 1 defines the critical planform pattern transition (Jerolmack and Mohrig, 2007). The general trend of M in Figure 3 shows the temporal trajectories of reach behavior. For $M >> 1$, a single, laterally mobile sinuous channel is expected. For $M \approx 1$, then transition is expected between a single channel and multiple channels. For $M << 1$, a multichannel avulsive system is expected. In accord with SOC, few, small avulsions release energy which suppresses the likelihood of large avulsions, whereas large avulsions increase the energy capacity of the network, which is a destabilization (Stølum, 1998). Accordingly, the network is attracted to $M \approx 1$. Such a simple model uses few parameters to elucidate emergent behavior without appeal to detailed process.

M is used here with the Parker (1976) channel stability criterion (ε),

$$\varepsilon = S_e \sqrt{g\bar{h}\bar{B}^4}/Q, \quad (6)$$

to define system trend through channel pattern phase space (Fig. 4), where Q is a formative discharge (bankfull value). A single-thread channel should dominate when

$\varepsilon \ll 1$, while a braided form should be common for $\varepsilon \geq 1$. Jerolmack and Mohrig (2007) argued that a plot of M versus ε discriminated between planforms representing rivers *at a single point in time* across spatial scales. In contrast, we use the M-ε phase space to explore meander bend evolutions *through time* as the channel morphology varies across the point of criticality due to hydraulic and morphological forcing. It is evident that meander R1 differs in its behavior in contrast to R2–R4, in that the Parker criterion for R1 lies between values of 0.6 and 1.5 while the other meanders exhibit values typically <0.4. The values of $M = 1$ and $\varepsilon < 0.4$ define four quadrant phase spaces for channel planform discrimination (Fig. 4).

DISCUSSION

A power-law avulsion distribution may characterize SOC behavior but, as with many studies (Hooke, 2007), our reach length is inadequate for this test. In addition, a time constant is imposed on the Ganges' SOC cutoff behavior by spatial pinch points, such that cycling occurs, similar to other guided SOC phenomena (Prokopenko et al., 2014).

So, we focused on the critical state: defining avulsion as an autogenic response of a channel when it cannot adjust further through gradual variation of sinuosity (Stølum, 1996). As M approaches 1, there is an increased propensity for channel alignment to reset by cutoff to regain low sinuosity.

In a flume, lacking bank-stabilizing vegetation, cutoffs occurred at a small value of $S \approx 1.2$, preventing the development of more sinuous channels (Braudrick et al., 2009). The Ganges River also is vegetation free and tends to avulse when S is ~1.3 (Fig. 3). However, the situation is not simple, as a new avulsion relaxes the system such that both cutoff and main channel can be simultaneously active. There is not usually a simple abandonment of the main channel in favor of the new channel (Fig.

1). These “soft avulsions” (Edmonds et al., 2011) divert some discharge and sediment from the main channel (Coleman, 1969), but much load continues down the main channel. The effects of cutoffs on main channel response are poorly known (Seminara, 2006). However, as main channel discharge declines, deposition occurs in the main channel below the avulsion point, reducing channel width (Sorrells and Royall, 2014); the main thalweg depth is less affected as long as the main channel discharge remains greater than the cutoff discharge. The relaxation in the system, due to the soft avulsion, results in the main meander r/B increasing as B adjusts more readily than r, which sustains potential for bank erosion downstream of the avulsion as flow is increasingly confined by channel narrowing through time (Coleman, 1969). Thus, soft avulsion may assist a channel in maintaining its meandering habit and so delay a catastrophic reduction in sinuosity. Notwithstanding the relaxation due to B, r also increased in three of the meanders, preventing or delaying avulsion (Fig. 3).

Meander R1, influenced by Farakka Barrage backwater, cycles from anastomosed-braided to a single-channel braided pattern (Fig. 4). This pattern differs from those of R2–R4, which cycle from avulsive-anastomosed to a sinuous single-channel pattern, as is typical of wandering rivers. Thus, the imposition of the barrage, with consequent accelerated upstream aggradation and reductions in slope and channel depth, but broadening of the channel, caused a shift from a wandering to a braided pattern, as indexed by the values of ε. Thus, our analysis indicates that rapid aggradation in a wandering river (R1) leads to braiding (*viz.* Carson, 1984, his wandering type II). Moreover, the wandering planform is sustainable through time, with three meanders (R2–R4) adjusting similarly through time from meandering to a straighter main channel planform by the development of bend cutoffs. So, the wandering habit is not necessarily indicative of a channel in short-term transition between single-channel meandering and braiding (Carson, 1984). To date, the reduction in sediment load downstream of the barrage has not changed the channel pattern, but a more stable meandering habit is predicted by Equation 5 (*viz.* Carson, 1984, his wandering type I) and has been observed recently (Hossain et al., 2013). Consequently, a considerable time lag can be associated with any transition. The similar trend in behavior among all four meanders through similar time scales is highly significant in that criticality develops naturally in the meandering system.

Clearly, the meanders are affected by the barrage. Nevertheless, the boundary conditions of a critical bend radius relative to channel apex width, the imposed discharge, and the aggradation rate drive the development of cutoffs as indexed by *M*, which reduces toward unity as the likelihood of cutoff becomes pronounced. This behavior develops independently of the presence of negligible bank-side vegetation. Thus, although vegetation can constrain planform, its presence is not a prerequisite to enable the wandering river planform to persist. By corollary, the behavior of other wandering rivers could be assessed in terms of cutoff criticality. Although channel behavior is explained by SOC, limitations remain; the detailed cutoff processes and how changes are transmitted beyond the cutoff locale require identification.

CONCLUSIONS

Low-sinuosity meanders on the Ganges River behaved similarly to each other ~~extending~~ over ~35 yr without downstream translation as sinuosity increased. Two meanders avulsed toward the end of the period, a third developed a soft avulsion, and the fourth was close to avulsion.

The critical bend radius-to-width ratio of $\overline{1.29}$ was associated with avulsion. The role of super-elevation was accounted for in the avulsion process, but was small.

Rather, as shown for a barrage-effected meander, sinuosity increased once the backwater developed fully and aggradation drove the avulsion process.

Self-organized criticality, with a mobility number (*M*) tracking meander development, showed that the critical transition is defined by $M \approx 1$ when avulsion was imminent (Fig. 4). Channel phase space (Fig. 4) defined by Parker's braiding criterion and *M* demonstrates that the meander upstream of the barrage adjusted from an anastomosed braided system to a single-thread braided channel. Downstream, the system follows a wandering river trajectory varying through time from a meandering to an avulsive-anastomosed planform and then returns to meandering after ~35 yr.

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FIGURE CAPTIONS

Figure 1. Development of Ganges River meanders R1–R4 in A.D. 1972–2011. Inset: Location map showing study area.

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Figure 2. A: Derivation of maximum channel aggradation rate, Ganges River, India. Triangles show years (*Y*) of aggradation; squares are years after Farakka Barrage was full. B: Sinuosity of the R1 meander over time. ~~“Full”~~**[[Explain the need for quotation marks (i.e., what is meant by “full”)]]** channel ~~aggradation~~ accelerates meander sinuosity.**[[In the figure, panel B, it is not clear what is meant by “Years of change in Base Level” – do you mean “Year” (singular, as in calendar year)? (Also, “Change” should be capitalized for consistency)]]**

Figure 3. Mobility number and sinuosity versus year for Ganges River meanders. Circles are mobility number (*M*) fitted with polynomial functions; squares are sinuosity of main channel; triangles are cutoff sinuosity. Black arrows are cutoff initiation dates; white arrow is date of cutoff failure (see Fig. 1).

Figure 4. Channel pattern phase space: AB—anastomosed-braided; BS—braided-single; AW—wandering; S—sinuous-single. Time trends, labeled with calendar years A.D., are shown for Ganges River meanders R1 and R4.