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Hydrodynamic controls on alluvial ridge construction and avulsion likelihood in meandering river floodplains

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1 Hydrodynamic controls on alluvial ridge construction and
2 avulsion likelihood in meandering river floodplains

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10 **ABSTRACT**

11 Existing models of alluvial stratigraphy often neglect the hydrodynamic controls
12 on channel belt and floodplain sedimentation, and predict avulsion using topographic
13 metrics, such as channel belt super-elevation. This study provides a first demonstration of
14 the potential for simulating long-term river floodplain evolution (over >500 floods) using
15 a process-based hydrodynamic model. Simulations consider alluvial ridge construction
16 during the period leading up to an avulsion, and assess the controls on avulsion
17 likelihood. Results illustrate that the balance between within-channel and overbank
18 sedimentation exerts a key control on both super-elevation ratios and on the conveyance
19 of water and sediment to the floodplain. Rapid overbank sedimentation creates high
20 alluvial ridges with deep channels, leading to lower apparent super-elevation (the ratio of
21 ridge height to channel depth), and implying reduced avulsion likelihood. However,
22 channel deepening also drives a reduction in channel belt-floodplain connectivity, so that

23 conveyance of water to the distal floodplain is concentrated in a declining number of
24 channel breaches, which may favor avulsion. These results suggest that while super-
25 elevation ratios in excess of a threshold value may be a necessary condition for a
26 meandering river avulsion, avulsion likelihood may not be greatest where the super-
27 elevation ratio is maximised. Instead, optimal conditions for avulsion may depend on
28 channel-floodplain hydrodynamic connectivity, determined by the balance between
29 coarse (channel bed forming) and fine (floodplain constructing) sediment delivery. These
30 results highlight a need to rethink the representation of avulsion in existing models of
31 alluvial architecture.

32 **INTRODUCTION**

33 River avulsion involves the movement of alluvial channels, generally from areas
34 of high topography (alluvial ridges) to low points in the fluvial landscape (e.g., distal
35 flood basins). Such avulsions represent significant hazards with social and economic
36 consequences (Sinha, 2009). They also exert a key control on the evolution of river and
37 floodplain morphology (Slingerland and Smith, 2004) and the stratigraphic architecture
38 of sedimentary basins (Hajek et al., 2010). Multiple factors are known to influence
39 avulsion likelihood, including valley floor morphology, channel belt aggradation rate,
40 flood magnitude, floodplain vegetation and the grain size characteristics of the river
41 sediment load and valley deposits (Hajek and Wolinsky, 2012), yet avulsions remain
42 difficult to predict. Process-based numerical models have provided important insights
43 into aspects of avulsion mechanics, including the stability of bifurcation points in braided
44 river networks (Bolla Pittaluga et al., 2003), delta channel branches (Edmonds and
45 Slingerland, 2010) and crevasse splay sites where avulsions may occur (Slingerland and

46 Smith, 1998). However, models of long-term fluvial landscape evolution and alluvial
47 stratigraphy (Mackey and Bridge, 1995; Jerolmack and Paola, 2007; Karssenber and
48 Bridge, 2008) typically treat avulsion as a stochastic process, or predict avulsion using
49 simple topographic metrics (e.g., the ratio of the down-valley to cross-valley surface
50 gradients, or the channel belt super-elevation above the distal floodplain normalized by
51 the channel depth). Such models tend to neglect or simplify the role of hydrodynamics,
52 because solution of the governing equations describing fluid flow is computationally
53 expensive. Herein, we seek to investigate the hydrodynamic controls on floodplain
54 evolution and alluvial ridge construction in the period prior to an avulsion, and the
55 implications for the prediction of avulsion likelihood.

56 **METHODS**

57 Floodplain evolution was simulated using a new numerical model of flow,
58 overbank sedimentation and meander migration. The simulations reported here do not
59 represent specific rivers, but provide insight into the general behavior of large
60 meandering sand-bed rivers, and the construction of floodplain topography in the period
61 between avulsions. Details of the modeling approach are provided in the Data Repository.
62 In summary, the model solves the depth-averaged shallow-water equations and an
63 advection-diffusion equation representing suspended sediment transport and overbank
64 deposition for three grain sizes (sand, silt and clay). These equations are solved in the
65 channel along a series of rectangular cross-sections (using a 1D numerical scheme) and
66 on a grid of cells representing the floodplain (using a 2D scheme). A sequence of floods
67 is simulated, each with the same hydrograph of 20 days duration, with peak and
68 minimum discharges of $15,000 \text{ m}^3\text{s}^{-1}$ and $2,500 \text{ m}^3\text{s}^{-1}$. After each flood, channel

69 migration is simulated using the meander migration model of Howard and Knutson
70 (1984), which includes neck cutoffs. Channel cross-section bed elevations are then
71 incremented by a defined rate of bed aggradation (A) that is constant for all locations (see
72 Data Repository). The channel is assumed herein to have a fixed width of 500m (equal to
73 twice the floodplain grid cell size of 250 m). The channel has a constant slope that is set
74 by the slope of the floodplain and the channel sinuosity (i.e., channel bed elevations are
75 not determined by sediment transport calculations). Channel depth is determined by the
76 difference between the channel bed elevation and the floodplain height in adjacent grid
77 cells. Initial conditions for each simulation are a planar floodplain with a constant
78 downstream gradient, and a straight channel with a constant depth. The total sediment
79 concentration (S) at the model inlet is defined as a function of discharge (Q) using a
80 sediment rating curve (Syvitski, et al., 2000): $S = C Q^{1.5}$, where C is constant during each
81 simulation, such that each flood has a constant sediment load. A set of 31 simulations,
82 each consisting of 580 floods, were carried out (see Data Repository) to investigate the
83 effects on floodplain and alluvial ridge construction of changes in bed aggradation rate
84 (A) and suspended sediment load (controlled by varying C , which is proportional to the
85 load and depends in nature on the controls on basin erosion rates, such as relief and
86 climate).

87 **RESULTS**

88 During all simulations, channel and floodplain evolution follows a similar
89 sequence (Fig. 1). The straight initial channel begins to meander and bend amplitude
90 increases until cutoff occurs. The channel belt widens and the number of abandoned
91 channel elements increases progressively. Near-channel sedimentation creates levees that

92 are breached by lateral erosion where bend migration is rapid (at bend apices). Levee
93 breaches promote formation of splay deposits and sediment transport away from river.
94 Low lying abandoned channels are also sites of preferential sedimentation, and provide
95 pathways for sediment conveyance to the distal floodplain.

96 Deposition within the channel belt drives construction of an alluvial ridge (Fig. 2).
97 Progressive growth of the ridge alters inundation patterns so that flow is increasingly
98 restricted to conveyance paths associated with levee breaches and with low-lying distal
99 flood basins (Fig. 1C). This tendency is also driven by an increase in channel depth
100 resulting from sedimentation near the channel, particularly when the rate of channel bed
101 aggradation is low. There is also a transition in sedimentation styles, from splay
102 dominated deposition in the early stages of simulations, to infilling of cutoff channels in
103 the later stages.

104 Overall, floodplain inundation declines over the course of simulations. However,
105 inundation extent fluctuates between flood events, and significant conveyance of water to
106 the floodplain continues to occur in the latter stages of most simulations (Fig. 1D).
107 Fluctuations in inundation are driven by autogenic mechanisms that control channel-
108 floodplain connectivity (e.g., bend migration, creation and infilling of levee breaches,
109 bend cutoff) rather than differences in flood magnitude, which does not vary. The
110 tendency for floodplain inundation to decline is weaker where channel bed aggradation
111 rates are high (Fig. 1E) and where floodplain sedimentation rates are low (due to low
112 suspended sediment loads, as in Fig. 1F), both of which lead to lower channel depths.

113 All simulations are characterized by an alluvial ridge with a profile that is
114 concave in section (Fig. 2). Ridge height is influenced by the channel bed aggradation

115 rate and the suspended sediment load, which set the rate of overbank sedimentation.
116 Where the balance between bed aggradation and overbank sedimentation promotes an
117 increase in channel depth, and hence bankfull discharge capacity, ridge height is limited
118 by a decline in water and sediment delivery to the floodplain. Ridge height is also lower
119 for finer suspended sediment, for which deposition declines more slowly away from the
120 river, and for rapid channel migration, which reworks the alluvial ridge.

121 Avulsion likelihood can be related to the channel belt super-elevation ratio (β),
122 defined as the height of the alluvial ridge divided by the channel depth (Hajek and
123 Wolinsky, 2012). Figure 3A shows the relationships between β , the rate of channel bed
124 aggradation (A), and the river suspended sediment load (controlled by C). Higher rates of
125 channel bed aggradation promote greater values of β , which is consistent with existing
126 understanding (Hajek and Wolinsky, 2012). Higher suspended sediment loads increase
127 overbank sedimentation, creating higher alluvial ridges and deeper channels, the net
128 effect of which is to reduce the β . This implies that systems with higher alluvial ridges
129 and greater rates of floodplain aggradation may be less susceptible to avulsion, due to
130 increased channel depth and bankfull flow capacity, compared to systems in which the
131 channel belt aggrades more slowly. Clearly, the balance between in-channel and
132 overbank sedimentation exerts a key control on β .

133 Most simulations reported here use a suspended sediment load composed of 5%
134 sand, 75% silt and 20% clay. For simulations with a finer load (comprising 5% sand, 20%
135 silt and 75% clay), increased sediment conveyance away from the channel leads to lower
136 channel super-elevation values. For only one such simulation is $\beta > 1$, which is commonly
137 treated as a plausible threshold for avulsion (Jerolmack and Paola, 2007; Hajek and

138 Wolinsky, 2012). Simulations in which bank erodibility was adjusted to be either 50% (or
139 150%) of the default erodibility value, induced changes in rates of bank migration of
140 similar magnitude. However, the resulting changes in β were small (a 15% increase in β
141 for less erodible banks and a 6.5% reduction in β for weaker banks). This suggests that
142 the role of river migration in controlling the creation of flow breach points may be more
143 significant than its influence on channel super-elevation.

144 One limitation of theory that predicts avulsion likelihood based on topographic
145 indices is that it does not account for the hydrodynamic controls on channel-floodplain
146 connectivity. Herein, we calculate a simple metric of floodplain hydrodynamic
147 connectivity (α) that is equal to the mean depth of water on the floodplain after the flood
148 peak, divided by the fraction of the channel-floodplain interface that is inundated (the
149 location of this interface is illustrated in Fig. 1E). Figure 3b shows that in general, for a
150 given rate of channel bed aggradation, higher suspended sediment loads (controlled by C)
151 promote greater inter-flood variability in α and higher peak values of α as the alluvial
152 ridge develops. This inter-flood variability in α is a product of changes in channel-
153 floodplain connectivity driven by the autogenic mechanisms outlined above. Moreover,
154 this autogenic signal is stronger in systems with high suspended sediment loads that
155 promote rapid overbank sedimentation, deep channels and more localized bank
156 breaching. Figure 3c illustrates values of α_{95} , the 95th percentile of α values, calculated
157 over the final 200 floods of each simulation. Peak values of α_{95} occur where the channel
158 bed aggradation rate is lowest and the suspended sediment load is highest. Such
159 conditions maximise channel depth and the delivery of water to the floodplain through
160 localized bank breaches.

161 **DISCUSSION**

162 Existing models of alluvial stratigraphy often use topographic indices to predict
163 avulsion likelihood (Mackey and Bridge, 1995; Jerolmack and Paola, 2007; Karszenberg
164 and Bridge, 2008). Our results suggest that changes in channel depth are a key control on
165 water and sediment conveyance to the floodplain, hence metrics that do not incorporate
166 depth (e.g., slope ratios) may be less useful than metrics that do (e.g., super-elevation
167 ratios). Moreover, the usefulness of super-elevation ratios may depend upon how channel
168 depths are determined. For example, many models of alluvial stratigraphy estimate
169 channel depth using hydraulic geometry relations that are under-pinned by the concept of
170 river equilibrium or have no mechanistic basis (c.f. Paola, 2000). The applicability of
171 such relations in aggrading (i.e., non-equilibrium) channels is questionable. Channel
172 depth is more usefully conceptualised as a product of the difference between the rates of
173 river bed and floodplain aggradation, where the latter reflects the balance between
174 floodplain lowering due to channel migration (Lauer and Parker, 2008) and the rate of
175 overbank sedimentation. By adopting such an approach here, albeit with a simplified
176 representation of channel bed aggradation, we have shown that systems characterized by
177 high suspended sediment loads that build large alluvial ridges may be characterized by
178 deep channels and a lower than expected super-elevation ratio. This suggests that
179 approaches that rely on equilibrium channel theory, or which treat the channel belt as a
180 single unit that aggrades at a uniform rate, rather than resolving channel and floodplain
181 aggradation separately, may have limited utility for representing avulsion likelihood.

182 The existence of a positive correlation between channel super-elevation and
183 avulsion likelihood is a principle that is firmly established in alluvial sedimentology

184 (Hajek and Wolinsky, 2012). Our results show that growth of an alluvial ridge is
185 associated with changes in water and sediment conveyance to the floodplain that are
186 controlled by changes in channel depth, and by inter-flood variability in channel-
187 floodplain connectivity driven by autogenic mechanisms. We hypothesize that avulsion
188 likelihood will be maximised in systems where water conveyance to the floodplain is
189 concentrated (e.g., in a small number of breach points), rather than where floodwater is
190 transferred to the floodplain over a large fraction of the channel belt-floodplain interface,
191 because concentrated flow will be associated with greater erosion potential. Our results
192 suggest that the former condition is favored by high suspended sediment loads that build
193 deep channels and infill some levee breaches so that conveyance to the floodplain is
194 localized. However, these conditions do not yield the highest super-elevation ratios,
195 hence interpretation of such metrics as simple indicators of avulsion likelihood is
196 problematic.

197 We propose that, in low gradient meandering rivers such as those considered here,
198 conditions for avulsion are optimised where the balance of bedload and suspended load
199 favors two conditions: (1) sufficient channel bed aggradation to maintain water and
200 sediment delivery to the floodplain and thus create an alluvial ridge; (2) sufficient
201 suspended load to allow the construction of deep channels characterized by localized
202 channel-floodplain connectivity, and focused flow conveyance along potential avulsion
203 pathways. While super-elevation ratios in excess of a threshold value may be a necessary
204 condition for a meandering river avulsion, it is not certain that avulsion likelihood will be
205 greatest where the super-elevation ratio is maximised.

206 Our results do not consider situations in which the rate of channel bed aggradation
207 greatly exceeds the rate of overbank sedimentation, such that the channel is filled rapidly
208 and avulsions are frequent. Moreover, our assumption of spatially and temporally
209 uniform channel aggradation is more applicable in lowland rivers, and is not
210 representative of environments characterized by episodic and/or localized channel
211 aggradation (e.g., upland rivers and alluvial fans). Because our model simulations
212 prescribe the channel bed aggradation rate and assume that the channel width is fixed,
213 they likely under-estimate the potential for complex behavior resulting from changes in
214 the ratio of coarse to fine sediment supply. Despite that, these results demonstrate the
215 potential for investigating the controls on floodplain construction over periods of
216 centuries to millennia, using a model underpinned by a physics-based treatment of
217 hydrodynamics (i.e., the shallow water equations). These simulations highlight a need to
218 rethink existing conceptual models of avulsion likelihood and their implications for the
219 interpretation of the alluvial record. In the future, application of high resolution (channel-
220 resolving) 2D morphodynamic models can afford further insight into the controls on
221 avulsion (e.g., Hajek and Edmonds, 2014). More specifically, our results suggest that
222 such models may be particularly important tools for understanding how changes in the
223 ratio of coarse-to-fine sediment supply promote changes in channel morphology (e.g.,
224 cross-sectional form), local bed aggradation rates, and sediment exchanges with the
225 floodplain.

226 **SUMMARY**

227 This study provides a first demonstration of the potential for simulating alluvial
228 ridge construction and floodplain evolution using a process-based model under-pinned by

229 the shallow water equations. Simulations illustrate that hydrodynamic conditions that
230 likely promote avulsion (e.g., water delivery to the floodplain through a restricted number
231 of channel breach points) are not necessarily associated with conditions that maximize
232 established proxies for avulsion likelihood (e.g., channel belt super-elevation normalized
233 by channel depth). These results highlight a need to rethink the representation of avulsion
234 in models of alluvial architecture and sedimentary basin filling. Specifically, we
235 hypothesize that the ratio of coarse to fine sediment delivery to rivers exerts a key control
236 on avulsion frequency that is not accounted for well by existing models. Moreover, our
237 results suggest that improved representation of avulsion in models of alluvial architecture
238 necessitates the decoupling of channel bed and channel belt aggradation rates, and further
239 consideration of the morphodynamic conditions under which channel-floodplain
240 hydrodynamic connectivity is primed to optimise avulsion likelihood.

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290

291 **FIGURE CAPTIONS**

292

293 Figure 1. Spatial patterns of simulated deposit thickness for individual floods. Panels A to
294 D show deposits for four floods in a simulation for which $C = 0.003$ and $A = 0 \text{ m flood}^{-1}$.
295 Panels E and F show deposits for two other simulations with contrasting values of C and

296 *A*, but for the same flood shown in panel D. Flow is from left to right. Green indicates
297 areas with deposit thickness $<10^{-6}$ m. The main channel cells are shaded black. The
298 magenta dashed line in panel E denotes the channel-floodplain interface, used in the
299 calculation of the floodplain hydrodynamic connectivity metric (α).

300

301 Figure 2. Floodplain cross-sections at points located midway along the model domain.
302 Each panel shows results from a single simulation with different values of *A* and *C*.
303 Results are shown at four points in time, where *T* indicates the number of floods that have
304 been simulated.

305

306 Figure 3. A: Super-elevation ratio (β), which equals the height of the alluvial ridge
307 divided by the mean channel depth, plotted against the prescribed channel bed
308 aggradation rate (*A*). Each point represents the model results at the end of a single
309 simulation. The legend indicates the values of *C* used. (F) indicates a fine sediment load
310 with 5% sand, 20% silt and 75% clay. In all other simulations, the sediment load
311 comprises 5% sand, 75% silt and 20% clay. (L) indicates bank erodibility that is 50% of
312 the default value. (H) indicates bank erodibility that is 150% of the default value. Where
313 (L) or (H) is not specified, simulations use the default erodibility. B: Time series of the
314 parameter α , which is equal to the mean depth of floodwater on the floodplain 60% of the
315 way through the flood, divided by the fraction of the interface between the channel and
316 floodplain that is inundated (see dashed line in Fig 1E). Results are shown for three
317 simulations with contrasting values of *C* (*A* = 0.018 m flood⁻¹ in all cases). *C*: 95th
318 percentile of the values of the parameter α calculated over the final 200 floods in each

319 simulation, plotted against the prescribed channel bed aggradation rate (A). Symbols are
320 the same as those used in Figure 3A.

321

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