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Complexity in a cellular model of river avulsion

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Abstract

We propose a new model of river avulsion that emphasizes simplicity, self-organization, and unprogrammed behavior rather than detailed simulation. The model runs on a fixed cellular grid and tracks two elevations in each cell, a high elevation representing the channel (levee) top and a low one representing the channel bottom. The channel aggrades in place until a superelevation threshold for avulsion is met. After an avulsion is triggered a new flow path is selected by steepest descent based on the low values of elevation. Flow path depends sensitively on floodplain topography, particularly the presence of former abandoned channels. Several behavioral characteristics emerge consistently from this simple model: (1) a tendency of the active flow to switch among a small number of channel paths, which we term the *active channel set*, over extended periods, leading to clustering and formation of multistory sand bodies in the resulting deposits; (2) a tendency for avulsed channels to return to their previous paths, so that new channel length tends to be generated in relatively short segments; and (3) avulsion-related sediment storage and release, leading to pulsed sediment output even for constant input. Each of these behaviors is consistent with observations from depositional river systems. A single-valued threshold produces a wide variety of avulsion sizes and styles. Larger "nodal" avulsions are rarer because pre-existing floodplain topography acts to steer flow back to the active channel. Channel stacking pattern is very sensitive to floodplain deposition. This work highlights the need to develop models of floodplain evolution at large time and space scales to complement the improving models of river channel evolution.

Keywords: Self-organized; Morphodynamics; Fluvial architecture; Nonlinear

1. Introduction

Since Leeder (1978) first recognized the fundamental connection between avulsion and the architecture of channel sand bodies, a great deal of research has been done to develop the connection in two and then three dimensions (Allen, 1979; Bridge and Leeder, 1979; Bridge and Mackey, 1993; Mackey and Bridge, 1995). Major developments along the way have included field tests (Behrensmeyer and Tauxe, 1982; Johnson et al., 1985; Kraus and Middleton, 1987; Maizels, 1990; Leeder et al., 1996), incorporation of avulsion–architecture into sequence stratigraphy (Shanley and McCabe, 1993), refinement of understanding avulsion mechanisms (Smith et al., 1989; Slingerland and Smith, 2004), and proposals of characteristic avulsion-related stratigraphic patterns (Bridge and Mackey, 1993; Mackey and Bridge, 1995).

The theme of much of this work has been the development of more complex and inclusive simulation models and a better understanding of the local mechanisms and triggering of avulsions. In our view, systems that are truly "complex" in the current sense of the term,

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i.e. having coupled dynamics over a wide range of scales and/or showing self-organized behavior, invite study using a variety of approaches, from simple models to highly detailed simulations.

In this paper we propose an approach that complements the line of simulation models, such as that of Mackey and Bridge (1995). We investigate complex dynamics in a set of minimalist models of river avulsion. "Minimal" means that we try to minimize the number of free parameters and overall model complexity, while maximizing richness of model behavior and spontaneous pattern formation. Our work has been guided by the following observations from case studies of modern avulsions and preserved sequences:

(1) Although stratigraphic models have typically portrayed avulsion as leading to creation of a new channel path, nearly all documented modern avulsions are into pre-existing, i.e. previously abandoned, channels (Aslan and Blum, 1999; Slingerland and Smith, 2004).
(2) Preserved channel sand bodies commonly show multi-storey stacking of individual channel units (Friend et al., 1979; Mohrig et al., 2000; Sheets et al., 2007) (i.e. they represent several, typically 2–5, individual channel depths stacked vertically).
(3) Whether single or multi-storey, preserved channel sand bodies typically have lenticular erosional bases cut into floodplain deposits.
(4) In contrast to the view that floodplains are featureless surfaces onto which sediment accumulates by passive vertical accretion, recent work has shown that floodplains are topographically complex and include frequent small channels that may strongly influence spatial patterns of sedimentation (Dietrich et al., 1999).
(5) Channels become susceptible to avulsion once they superelevate themselves, via differential deposition, to a condition in which the channel top is approximately one channel-depth above the surrounding floodplain (Mohrig et al., 2000; Jerolmack and Mohrig, 2007).

Points (1) and (2) are closely related in that reoccupation coupled with net deposition is a natural way to create multi-storey sand bodies. Point (3) requires that some fraction of avulsion events must involve creation of new, erosively based channels into floodplain deposits, implying permanent abandonment of an equivalent length of channel if total channel length is conserved on average. Point (4) together with the sensitivity of water flow to topography implies that floodplain topography, particularly the fate of abandoned channels, is likely to exert a strong influence on avulsion and channel architecture. Point (5) implies that avulsion may be characterized as a threshold phenomenon that allows slow storage and rapid release of sediment within the fluvial system. The importance of abandoned channels was recognized as far back as Allen (1979) who saw the channels as topographic repellers. Floodplain topography was also included in the work of Mackey and Bridge (1995) and Sun et al. (2002), who used white noise to simulate small-scale floodplain roughening. Adding noise is a reasonable way to simulate unresolvable random processes, but here we (mostly) avoid it: one of our chief aims is to investigate self-organized behavior. In that context, repeatedly injecting high-dimensional chaos into the model leads to an intertwining of the intrinsic stochastic behavior of the model and the programmed randomness of the noise that is hard to untangle.

2. Model development

At large time and space scales, the transport of fluvial sediments has been modeled as a linear diffusive process (Paola, 2000). Field and experimental evidence suggests, however, that large-scale sediment transport is highly intermittent, i.e., nonlinear (Paola and Foufoula-Georgiou, 2001; Kim et al., 2006). At the scale of fluvial basins we identify an emergent dynamic that results from the interaction of channels with their floodplains — the process threshold of river avulsion. Experience with other threshold phenomena (e.g., sandpiles, earthquakes, landslides and forest fires) suggests that such a threshold should dominate the large-scale transport dynamics, and that as a result the system may be insensitive to smaller-scale model details. We take advantage of these properties to create a model in which within-channel transport is treated as simply as possible, while the emergent large-scale process of avulsion is modeled explicitly.

The avulsion model we propose is a cellular model in the spirit of previous cellular models of landscapes (Chase, 1992; Howard, 1994) and braided rivers (Murray and Paola, 1994). The model domain is a fixed Cartesian grid of square cells. For convenience, we will refer to the model system as a river, but the scheme we propose and the results could apply equally to submarine channel systems. The cells are regarded as larger than the river channel belt (meandering or braided), so we do not attempt to model the inner workings of the channel(s). The channel belt is thus restricted to a width of less than one cell. The others are regarded as floodplain cells.

Because they are on average at least one belt width from the active channel, we regard them as distal floodplain, i.e. beyond the influence of short-range depositional features like levees and crevasse splays. Limited available data suggest that rates of sedimentation in this zone do not decay strongly with distance (e.g. Fly River, Papua New Guinea: (Aalto et al., 2007)), so we do not include the usual exponential decay function of floodplain deposition rate with distance. On the other hand, we apply diffusive morphodynamics along the channel path (explained below), and a fixed threshold for avulsion. An active channel is abandoned in favor of a new path (avulses) once any point along the channel becomes superelevated to a specified height above the surrounding floodplain. The details of implementation of this are described below.

2.1. Model domain and boundary conditions

The model domain is square, with reflecting boundaries on the left and right sides and an absorbing downstream boundary. The input values for water and sediment discharge are specified at the beginning of a model run and used to compute the domain-averaged slope, channel width and channel depth using diffusion theory (Paola, 2000). The domain is then initialized with a downstream slope equal to the equilibrium value, and seeded with infinitesimal random noise. Cell size is set to be substantially larger than the predicted channel width. Because in-channel processes are not explicitly modeled, the set of occupied cells may be thought of as a channel belt, although we retain the term "channel" for simplicity. Within the channel belt, the channel pattern is not resolved; we assume the dynamics of braiding or meandering are played out on a substantially shorter time scale than the avulsion processes we are interested in. To enforce net deposition in the river system, the most downstream cell of the active channel rises at a specified constant rate, σ. This produces the equivalent of uniform subsidence over the model domain, or relative sea level rise at some location downstream of the model domain. This setup might correspond to deposition on a delta, where the shoreline is not explicitly modeled and is located some distance downstream from the modeled area. The time step is chosen to be smaller than that indicated by the Courant stability criterion, based on chosen cell size and diffusivity. A variety of grid and cell sizes, time steps, and transport parameters were used, however none strongly affected the outcome of numerical experiments. The primary sensitivity in this model is to the handling of floodplain deposition. Therefore, a suite of runs was performed using the same basic parameters (Table 1) while varying only floodplain deposition, as described below.

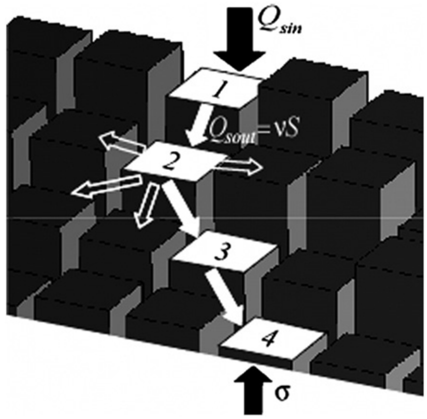

Fig. 1. Model setup. Cell 1 is the fixed inlet to the model domain and receives a constant sediment discharge, Q_{sin}. The channel (solid white arrows) is chosen following the path of steepest descent among downstream and next-door neighbor cells (hollow white arrows). Sediment is routed by linear diffusion where the flux out of each cell, Q_{sout}, is computed from a constant diffusion coefficient, ν and local slope, S. Cell 4 represents the bottom of the model domain which rises at a constant rate, σ. At each time step, elevation is adjusted using Eq. (1).

Table 1
Model parameters used for all numerical experiments, unless stated otherwise in the text

N	Δx [m]	Q_{sin} [m^3/s]	Q_{win} [m^3/s]	d [mm]	ν [m^3/s]	Δt [hr]	σ [m/yr]	B [m]	h [m]
39	105	0.01	20	0.3	9.7	17	0.5	22	1

N, Δx, Q_{sin}, Q_{win}, d, ν, Δt, σ, B and h are domain length, cell size, sediment discharge input, water discharge input, grain size, diffusivity, time step, subsidence rate, equilibrium channel width and equilibrium channel depth, respectively. Width and depth are computed using diffusion theory (Paola, 2000). Subsidence value is large to speed up rate of numerical runs. Floodplain deposition rate, ν_{fp}, varied among runs within a range of 1/4 to 1/2 of subsidence rate.

2.2. Channel initiation, transport, and avulsion

Water and sediment are introduced at a constant rate in a fixed cell location at the top center of the domain. The channel path is chosen as the path of steepest descent, where only the three downstream and two cross-stream cells are considered (i.e., no upstream flow is allowed; Fig. 1). The model tracks two elevations in each cell, a high elevation representing the channel top (nominally the levee top) and a low elevation representing the channel bottom. In floodplain cells that have never been visited by an active channel, these two elevations are equal. In active and abandoned channel cells, the high and low elevations are always separated by one channel depth: once a channel cell is identified, a uniform-depth channel is imposed by setting the low cell elevation to the high elevation minus the channel depth computed using input water and sediment discharges (Fig. 2). Channel-cell elevations are adjusted sequentially down the channel path by linear diffusion, maintaining the high-low elevation difference constant and equal to the flow depth. For each time step, for each active cell we find a set of elevation increments $\Delta\eta_{i,j}$:

$$\Delta\eta_{i,j} = \left(\frac{v\Delta t}{\Delta x^2}\right)\left[\frac{\eta_{i+1,j+n}(t)-\eta_{i,j}(t)}{\Delta x K} - \frac{\eta_{i,j}(t)-\eta_{i-1,j+m}(t)}{\Delta x K}\right] \tag{1}$$

where v is the diffusion coefficient, calculated using Eq. (2) below, Δx is the streamwise grid spacing, Δt the time step, n, m are index offsets for the steepest-descent path in the adjacent upstream $[i-1]$ and downstream $[i+1]$ rows; and $K=[\sqrt{2}, 1, \sqrt{2}]$ as $n, m = [-1,0,1]$. After all the increments are found, they are added to the low and high elevations in each cell, and the process is repeated.

The formal basis for modeling time-averaged morphodynamic evolution of channelized flows using diffusion is reviewed in Paola (2000). The main assumptions are that the net effect of the discharge

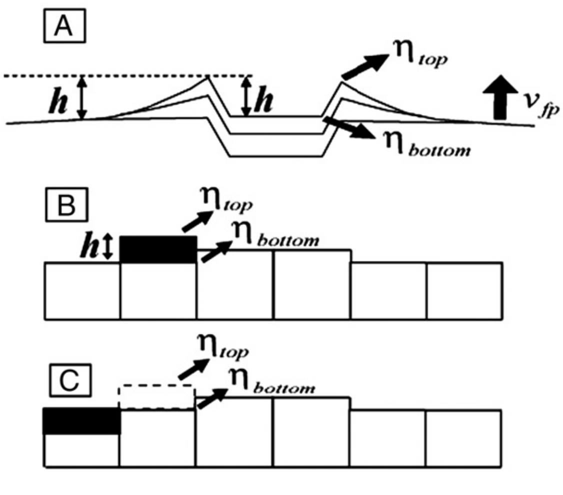

Fig. 2. Schematic of avulsion process. (A) A hypothetical cross-section of an aggrading channel. A channel is cut into the floodplain surface and aggrades in place until the levee top elevation (η_{top}) is one channel-depth, h, above the floodplain and it has reached the avulsion threshold. The floodplain aggrades at a slower velocity, v_{fp}. (B) The cellular representation of a channel (black square) that has reached the threshold for avulsion. The model does not explicitly treat the channel form, but only tracks the channel top and bottom elevations for a channel cell. (C) The channel avulses to the neighboring floodplain cell and excavates a new channel to depth h. The old channel location becomes floodplain, but retains its respective top and bottom elevations.

hydrograph can be represented via a repeated characteristic flood; that the channel adjusts itself to provide a constant dimensionless shear stress for that flood (Parker et al., 1998); and that the flow is quasi-uniform, i.e the shear stress is proportional to the depth-slope product. The diffusion coefficient, v, is given by:

$$v = \frac{8c_f^{1/2}Q_{\mathrm{win}}}{R}, \tag{2}$$

where $c_f = 0.01$ is a friction coefficient, $Q_{\mathrm{win}} = 20\mathrm{m}^3/\mathrm{s}$ is the input water discharge, and $R = 1.65$ is the relative specific density of quartz; $v = 9.7\mathrm{m}^3/\mathrm{s}$ for our chosen parameters (Table 1).

The river aggrades in place until a location along the channel has achieved a channel-top elevation equal to one channel depth above the floodplain. This criterion approximates the requisite condition for avulsion in many natural systems (Mohrig et al., 2000; Jerolmack and Mohrig, 2007). At each time step the levee (high) elevation of every cell in the active channel is compared to the low elevation of the five down- and cross-stream neighbors to check if any cell has exceeded this threshold for avulsion (Fig. 2). Once the avulsion threshold is met in a given row, a new channel path is determined from that point downstream following a new path of steepest descent. The steepest-descent path is determined from channel-bottom (low) elevations in each cell. If during the search a steepest-descent cell is found to lie in the current channel path, then the flow is considered to have rejoined the previous channel course and the search for a new path ends until the next instance of exceedance of the avulsion condition. For cells not part of the previous channel path, a new channel is instantaneously cut into the floodplain by setting the low (channel-bottom) cell elevation to the current high value minus the computed equilibrium depth, and all water and sediment are routed down the new path (Fig. 3). Floodplain sediments are considered to be deposited from a fine grained (washload) component in the active channel (see below). Sediment removed in the course of excavating the new channel is assumed to be fine-grained and, therefore, to travel as washload. Hence, it is transported out of the model domain without being exchanged with the channel bed, and it is not recorded in the sediment output of the model. The abandoned channel path now becomes part of the floodplain but retains the respective high-low elevation values (Fig. 2). Because the search for a new channel path uses the low elevation in each cell, the levees are open and re-occupation of an abandoned channel path is likely. If the steepest-path search of abandoned channels used the

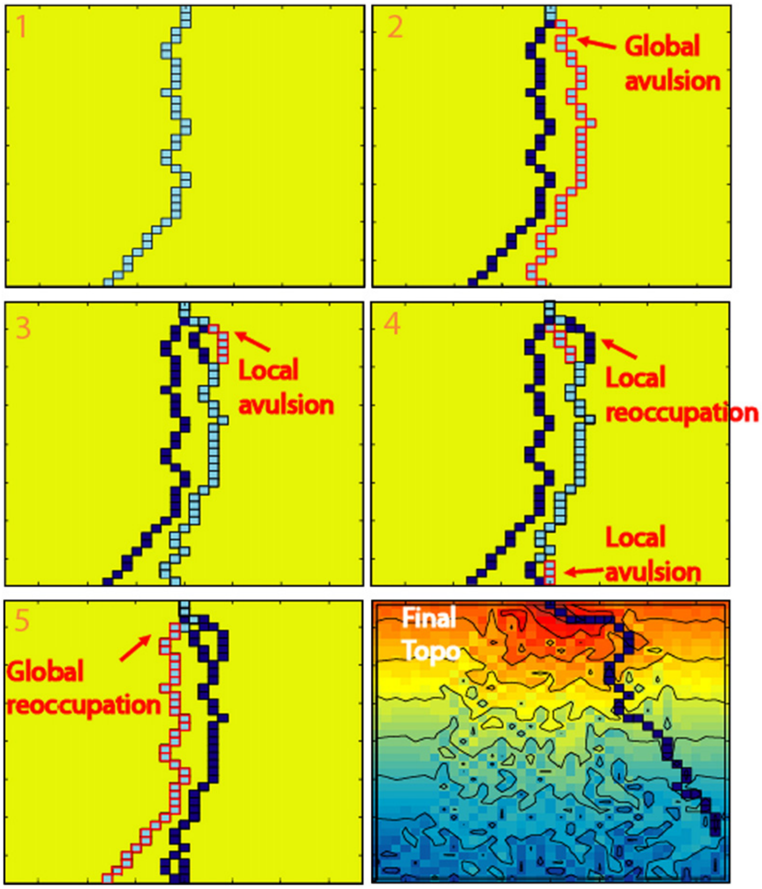

Fig. 3. Styles of avulsion. Active channel path is indicated by light blue cells, and red borders indicate cells involved in an avulsion. A large scale (global) avulsion (2) creates a new channel, then further (local) avulsions create smaller new channel segments (3–4) before a large avulsion returns flow to the previous channel path (5). Panel 6 shows the contoured relative topography at the end of a typical model run with uniform floodplain sedimentation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

elevation value of the levee rather than the bottom, channel reoccupation would be impossible.

2.3. Floodplain sedimentation

It is remarkable how little is known about how sedimentation on floodplains works, and in particular about how topography is erased and created by differential sedimentation and channel incision. The most commonly used general model for floodplain sedimentation is the sediment-diffusion model proposed by Pizzuto (1987). This elegant and useful scheme has been widely applied in architecture modeling [e.g. (Mackey and Bridge, 1995)]. It was not designed, however, to capture the processes of small-scale smoothing and roughening that are critical in setting floodplain topography. Alternatively, engineering simulation techniques developed for detailed modeling of specific, well characterized sites would be heavy-handed and excessively finicky if applied to generalized modeling of the long-term evolution of river systems — even if available computing power permitted it.

As we will discuss further below, one of the most important results of the work presented here is that the predicted stratal patterns and channel stacking are very sensitive to how the floodplain topography, including abandoned channels, evolves. In our view, a real need exists for a model for floodplain morphodynamics that includes just enough dynamics to capture the main processes of topographic roughening and smoothing without requiring detailed knowledge of either channel or floodplain topography or detailed computation of the flow field. Development of such a model is beyond the scope of this paper, which is focused on avulsion and alluvial architecture. Here, as an initial exploration, we will investigate the behavior of a few simple but physically plausible general floodplain sedimentation models.

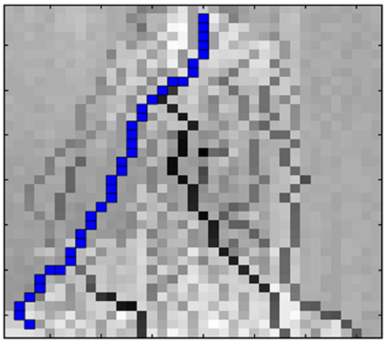

Fig. 4. Example of a floodplain dissected by abandoned channel paths, which are represented as points of lower relative elevation (darker). Blue cells show the currently active channel. This is a typical model run with uniform floodplain deposition. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Floodplain sedimentation is not essential to produce basic autogenic channel switching. Some form of floodplain deposition scheme, however, must be implemented to create and preserve stratigraphy, if only to provide a lithologic contrast to the channel deposits. Floodplain sediments are considered to be the fine-grained (washload) component of active channels, with an effectively unlimited supply from the channel. We do not, therefore, conserve mass of floodplain sediments but rather specify a floodplain deposition rate using rules outlined here. The simplest case is uniform floodplain deposition, which preserves the form of the floodplain through time. In this case deposition rate, v_{fp}, is specified as some constant fraction of the rate of subsidence. The next simplest approach we tried is depth-dependent deposition. In this case, the model domain is assumed to be flooded to an elevation equal to the top (levee) of the active channel (this is the highest possible value; most river floods reach a maximum level somewhat below this). Deposition, thus, occurs at a fixed background rate plus a rate that increases linearly with flood depth, i.e. inversely with floodplain elevation. This represents the increase in total charge of suspended material with water column height.

The scheme is implemented using the expression

$$\frac{\partial \eta_{i,j}}{\partial t} = \begin{cases} v_{\mathrm{fp}} + v_{\mathrm{fp}} \dfrac{(\eta_{i,\mathrm{top}} - \eta_{i,j})}{h}; \eta_{i,\mathrm{top}} \geq \eta_{i,j}, \\ 0; \eta_{i,\mathrm{top}} < \eta_{i,j} \end{cases} \tag{3}$$

where η, t and h denote elevation, time and mean channel depth, respectively. For each row, i, the elevation associated with the top of the channel is found ($\eta_{i,\mathrm{top}}$) and the depth below that elevation is computed for a given site on the floodplain (i,j) using its low elevation value to determine the local deposition rate. If a point on the floodplain is higher than the channel top for that row, then no sediment is deposited at that location. This scheme tends to smooth out elevation differences on the floodplain, preferentially erasing topographic lows such as channels.

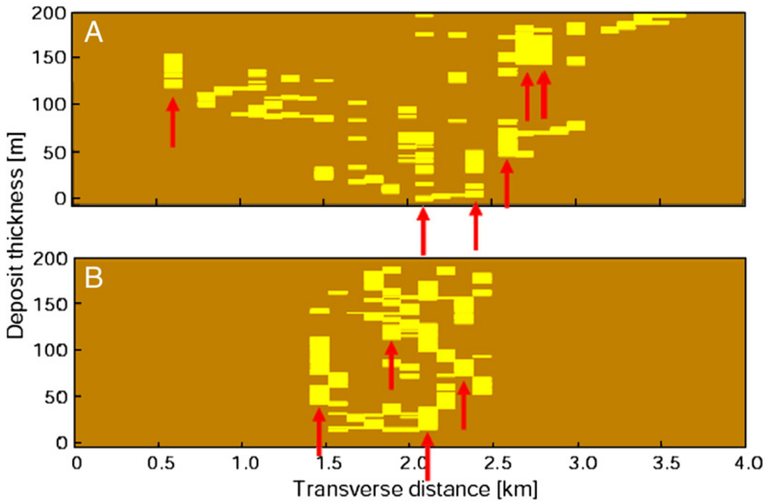

Fig. 5. Example stratigraphic vertical cross-sections for (A) uniform and (B) depth-dependent floodplain sedimentation. These are along-strike sections, taken approximately in the middle of the model domain and show channel stacking patterns. Channel deposits are represented by yellow boxes, and brown background represents floodplain deposition. Arrows indicate common channel locations due to flow reoccupation. Note channels are much less spatially dispersed in depth-dependent model run (B). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The last scheme tested was noisy floodplain sedimentation, in which the deposition rate in each cell is selected from a Gaussian distribution with a specified (positive) mean and variance. This scheme serves to roughen the floodplain topography in a manner not represented by the other two. However, the addition of noise here is undesirable in that it adds an imposed stochastic component that becomes inextricably mixed with the natural (self-organized) stochastic behavior of the model itself. Thus we look primarily at model behavior without added random noise.

3. Results

We focus on three emergent aspects of the model behavior that appear to be relatively insensitive to the details of how the model is formulated: (1) the tendency of the active flow to switch among a small group of channel paths rather than avulsing to random positions; (2) the tendency of the active flow, after avulsion, to find its way back to its previous channel; and (3) the tendency of threshold-dependent avulsion to produce variable sediment output associated with sediment storage and release. All model runs achieved a statistical steady state as determined by stationary distributions of avulsion times, avulsion lengths and sediment flux magnitudes as discussed below.

We reiterate that the least well constrained aspect of the model we propose is floodplain sedimentation. Thus, we have investigated uniform and depth-dependent models in some detail as described below. We discuss noisy model results and the sensitivity of the avulsion model to floodplain dynamics in the last part of this section.

3.1. Switching within a consistent group of channel paths

For an avulsion to occur, some location along the channel must have a bottom elevation that equals or exceeds the low elevation of a neighboring floodplain cell. The cells downstream of the avulsion node, however, often have bottom elevations that are lower than the floodplain. The presence of such remnant channel topography on the floodplain means that abandoned channels can continue to act as attractors for flow that has escaped the existing channel by meeting the avulsion criterion described above. In terms of planform behavior, this attractor property means that the flow tends to reoccupy former channels, leading to a pattern of switching within a set of existing channel paths as opposed to creation of an entire new channel pathway (Fig. 4). In this sense the model we propose captures one of the main features of documented avulsions in modern rivers — the tendency to reoccupy

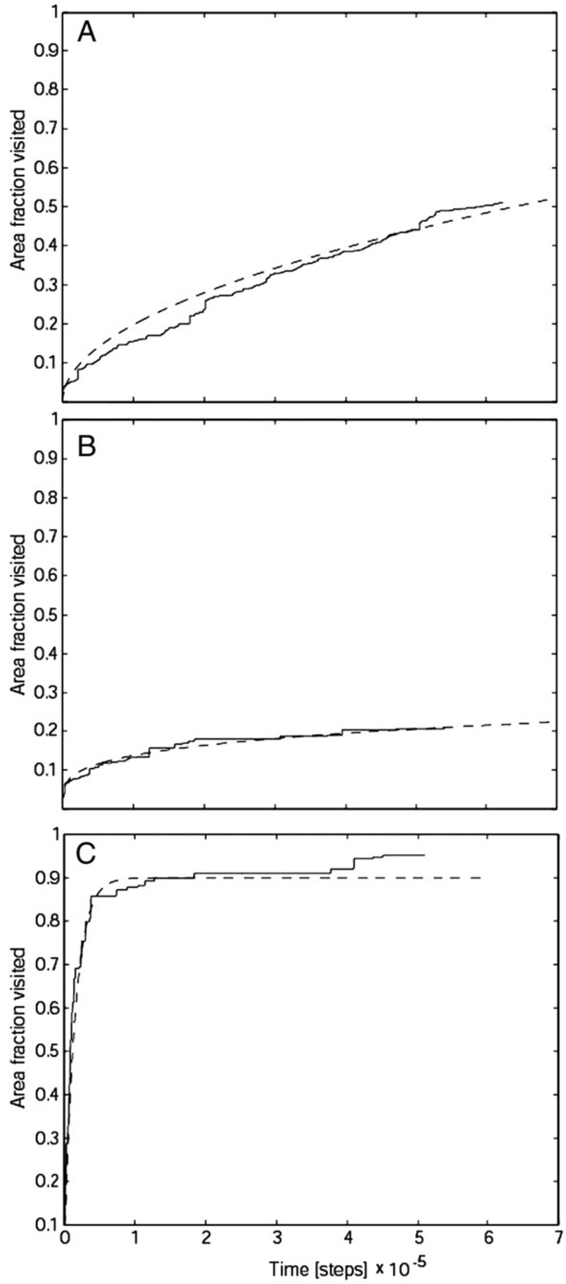

Fig. 6. Cumulative fraction of new channel area created in time for (A) uniform floodplain sedimentation, (B) depth-dependent floodplain sedimentation, and (C) model in which channels act as repellers. New fraction grows as approximately the square root of time for uniform floodplain deposition, as time to the one-fourth for depth-dependent floodplain sedimentation, and as $1-e^{-t}$ for the case of repelling channels; trends indicated by dashed lines.

formerly abandoned channels. We term the set of channels within which switching occurs the *active channel set*. Stratigraphically, the consequence of channels as attractors is the creation of multi-storey sand bodies (Fig. 5). Channel reoccupation means that avulsion paths are not selected randomly, and the result is that channel bodies in the subsurface are clustered, leaving areas outside the active channel set unvisited for long periods of time.

In the case of uniform floodplain deposition, all channels created by avulsion are preserved in the landscape. Under these conditions the active flow alternates among the same 3 or 4 channels for long periods of time (generally from 5 to 20 channel-depths of deposition). Eventually an avulsion may create a new path rather than return flow to an old one. Such an event sometimes leads to the creation of a new active channel set, while other times the new channel simply adds one more route to the existing active channel set. Depth-dependent floodplain sedimentation tends to erase abandoned-channel topography and, hence, reduce the number of active channel paths, while also making the rest of the floodplain smoother. The behavior is qualitatively similar, however, to the constant-rate case as long as old channels are not erased at a rate faster than avulsions can occur (Fig. 5). The smoothing of the floodplain makes the creation of new channels less frequent than uniform floodplain deposition, because active and recently abandoned channels have local steepness that is far greater than the planar floodplain. Also, since older channels are more completely erased than younger channels, the active channel set tends to consist of a smaller number of channels. Overall this scheme reduces the lateral dispersion of channels when compared to uniform deposition, and leads to more frequent reoccupation because the active channel set is reduced in number. If avulsion is slow compared to preferential filling of topographic lows such that all abandoned channels disappear rapidly and the floodplain is smooth, then the steepest-descent path remains fixed. Even if the threshold for avulsion is exceeded, no path will be steeper than the path of the active channel for this case. The result is a single channel stacked indefinitely high in the stratigraphic record.

3.2. Return of avulsed flow to the previous channel

Illustrations in textbooks tend to depict avulsion as a catastrophic switch in channel path over most of the length of the river system. In our model, avulsions with length scales comparable to the domain length nearly always involve switching between existing channel paths rather than creation of a new channel path. This distinction may seem subtle but it is extremely important, especially for the spatial continuity of avulsion-derived channel bodies in the subsurface. Creation of new channel path length is typically a short-range process, while spectacular long avulsions usually involve reoccupation of former channel courses that have not completely filled in. To illustrate the influence of previous channels as topographic attractors, we plot the fractional area of the model domain that has been visited by a channel against time (Fig. 6). If channel path selection were random, the fraction of unvisited area would decay like e^{-t} and, hence, the creation of new channel area would grow as $1-e^{-t}$. In the case where previous channel paths remain as topographic lows, however, the creation of new channel paths grows much more slowly than $1-e^{-t}$. This new area measure scales as $t^{1/2}$ for numerical experiments with uniform floodplain deposition. For depth-dependent deposition, the creation of new channel area is even slower (it scales as $t^{1/4}$) due to the strong attraction of a smaller number of channels. To verify that topographic attraction is the

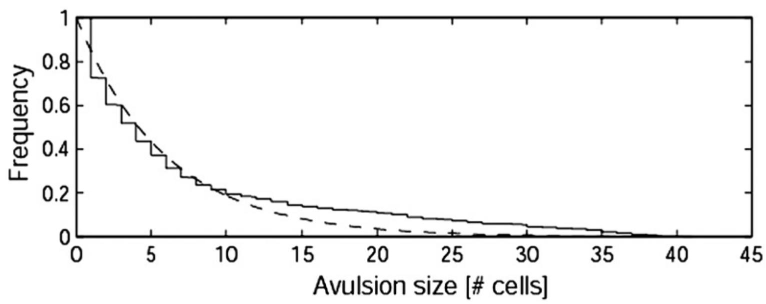

Fig. 7. Distribution of avulsion sizes shown as frequency–magnitude plot, where size is measured by the number of cells involved in each avulsion. Plot is for noisy floodplain sedimentation, but distribution is typical of all model runs. Dashed line shows an exponential function, which closely approximates the distribution. The tail of the distribution is poorly fit because of finite-size effects and flow reoccupation, which generate a mode of avulsion sizes with a value close to the domain size (N=39). This has been verified using a larger domain (N=99).

cause of the observed scaling, we performed additional numerical experiments in which abandoned channels were filled in to the levee top rather than left empty (i.e., we forced old channels to act as repellers). In this case, the filling of floodplain space by the active channel followed the $1 - e^{-t}$ growth expected for a random process (Fig. 6).

The distribution of avulsion length (as measured by the number of cells involved in each avulsion) is approximately exponential (Fig. 7) for all model runs. A mode of long avulsions occurs, however, with a value determined by the size of the domain. This is an artifact of the finite size of the model, and also because many of these large avulsions are reoccupations of old channels rather than creation of new ones. Although whole-system avulsions do occur, the majority of avulsions involve only small segments of channel length, because in most cases the channel finds its way back to its previous path somewhere downstream of the avulsion point, consistent with observations in modern rivers. Importantly, a single-value threshold for avulsion produces a wide range of avulsion sizes and styles (Fig. 3); "local" and "nodal" avulsions are not fundamentally different. Nodal avulsions are simply rarer.

3.3. Relation between avulsion and sediment storage and release

If avulsions can be thought of as the "earthquakes" of river systems, then in rivers, sediment plays the role that strain does in tectonics. Sediment tends to be deposited (stored) nonuniformly over the river system. Crossing the threshold for avulsion releases the stored sediment in the same way that exceeding a rock-strength criterion releases stored strain energy stored on a fault. In the river system the stored sediment is released rapidly to the outlet of the fluvial system ((Paola and Foufoula-Georgiou, 2001); Fig. 8) generating highly intermittent behavior. Based on results from sandpile and slider-block models (Turcotte, 1997), one might expect the frequency–magnitude distribution of flux events to follow a power law. One fundamental aspect of our model that differs from these others, however, is the strong influence exerted by the system history in terms of abandoned channels acting as attractors. It is therefore not too surprising that the distribution of sediment flux magnitudes produced by our avulsion model is not power law; nonetheless, there is a wide range in output flux for a constant input rate (Fig. 8) with a strong skew toward fluxes larger than the mean. As above, we verified that topographic attraction was the cause of deviations from expected behavior through comparison

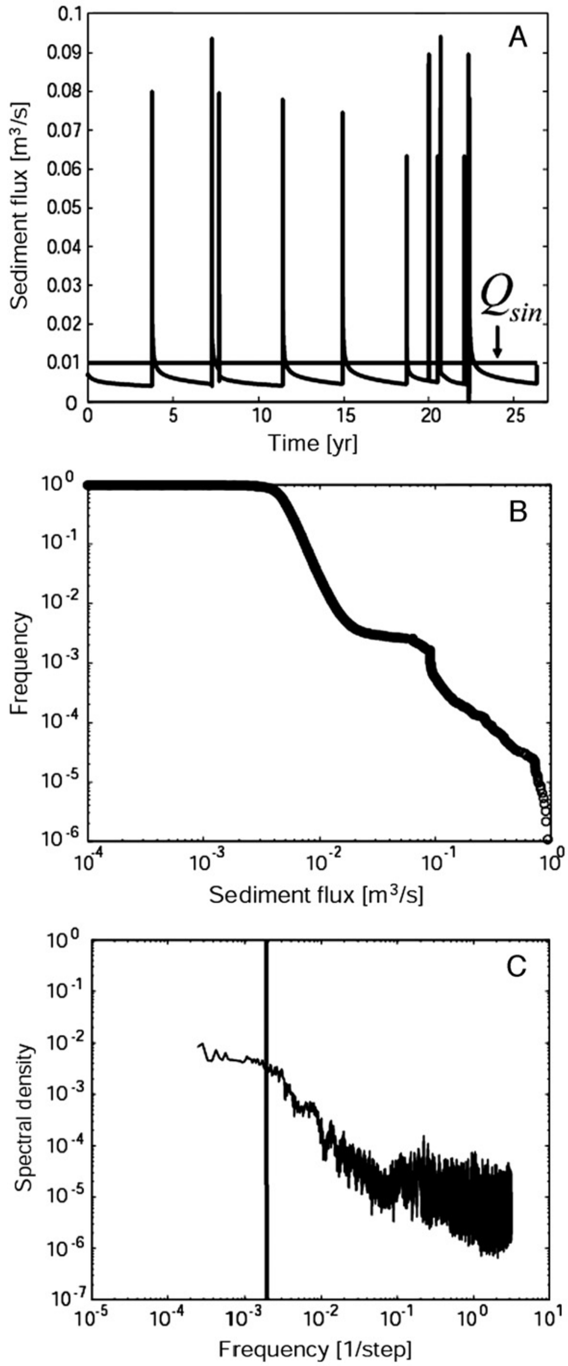

Fig. 8. Sediment flux output data for typical uniform floodplain deposition run. (A) Time series of output flux — horizontal line is constant input flux. (B) Frequency–magnitude plot of flux events. (C) Ensemble-averaged power spectra of flux time series. The characteristic avulsion time (Eq. (4)) is indicated by vertical line. At frequencies lower than this, a white noise spectra occurs. At higher frequencies (10^{-3} to10^{-1}) spectra indicate correlations with $1/f$ scaling.

with model runs in which abandoned channels were immediately filled in. In this case, we indeed find a power-law scaling relationship.

It is remarkable that an essentially deterministic model with one threshold can produce such varied dynamics. In our model an avulsion occurs once any point in the channel deposits to a height of one channel-depth above the floodplain. Because channel depth is constant and average deposition rate is fixed, we naively expect a characteristic avulsion time, T_{A} (Jerolmack and Mohrig, 2007),

$$T_{\mathrm{A}} = \frac{h}{\sigma - v_{\mathrm{fp}}}. \tag{4}$$

Does any signature of this time scale exist in the model output? The waiting times between avulsion events have an apparent power-law distribution, although the shape of the distribution appears to depend somewhat on the domain size (Fig. 9). In all model runs the computed characteristic avulsion time (Eq. (4)) corresponds approximately to the maximum avulsion time in the distribution (Fig. 9). In other words, one can compute the time scale of the largest avulsion from boundary conditions. This maximum avulsion time is analogous to the slope-clearing time scale in a running sandpile model (Hwa and Kardar, 1992). While no periodicity occurs in the model flux output, the characteristic avulsion time exerts a more subtle influence on system dynamics: at time scales smaller than T_{A} the output flux shows correlations across a wide temporal range, while above T_{A} the output flux is uncorrelated (Fig. 8) — behavior also seen in the running sandpile model (Hwa and Kardar, 1992). In this sense avulsion acts as a randomizing agent for landscape-scale sediment transport. The power-law distribution of waiting times implies that avulsion events are temporally correlated, which is different from the sandpile model and likely a result of history dependence in our model.

3.4. Influence of floodplain deposition model

Up to this point we have discussed autogenic dynamics that are a robust result of the threshold avulsion model, regardless of floodplain deposition schemes. Variability in flux magnitudes and avulsion frequency, along with channel reoccupation and switching, occur over a wide swath of parameter space. One aspect of the model that is extremely sensitive to floodplain deposition, however, is the modeled stratigraphy. Once the avulsion threshold is met somewhere along a channel path, flow downstream of that cell is routed along the path of steepest descent. Avulsion paths are then very sensitive to floodplain topography. Because depth-dependent floodplain deposition smooths out floodplain roughness, the creation of a new channel is suppressed because the flow is strongly attracted back to its previous path. In our model runs this scheme tends to create unrealistic stacking patterns because channels stay in one place for long periods of time (Fig. 5). Alternatively, uniform floodplain deposition preserves all channels which also leads to excessive (although different) stacking of channel deposits due to the strong attraction of previous channel paths.

What would be required to produce more realistic channel stacking patterns is some way of slowly erasing old channel paths (via, for example, depth-dependent

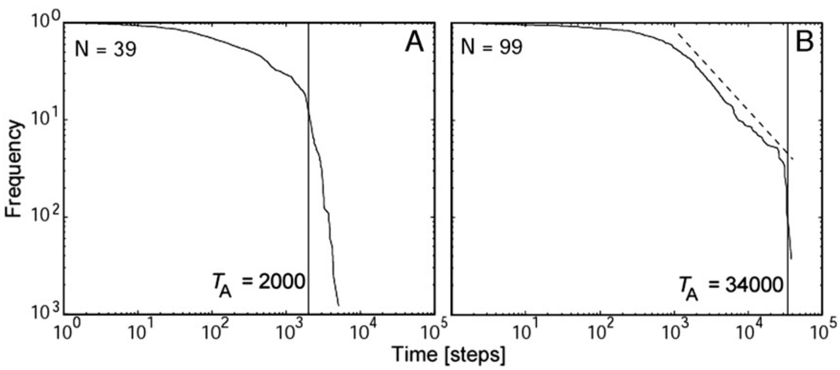

Fig. 9. Distribution of waiting times between avulsion events, shown as frequency–magnitude plot. (A) For smaller domain size (N=39) the distribution appears to be exponential, but (B) modeling a larger domain (N=99) demonstrates a power-law scaling (dashed line) in the distribution of waiting times. The exponential tail of both distributions is a cutoff due to finite-size effects. In all cases, however, the characteristic avulsion time computed from boundary conditions (Eq. (4); vertical line) predicts the maximum avulsion time well.

sedimentation) while creating potential new paths by floodplain roughening. Roughening processes are manifested by features such as tie channels on floodplains, but no general model for their development exists at present. Development of such a model requires fundamental new insights on the nature of floodplain evolution over long time and space scales, a task beyond the scope of this paper. To simulate floodplain roughening in a simplified way, we tried a random noise deposition model. While the addition of noise produced the desired stratigraphic effect in terms of diverting avulsions to new paths and erasing old channels, the model proved to be sensitive to the details of the noise. Because the focus here is on robust, detail-independent behavior, we did not develop the random noise approach further. We stress instead the main implication of the result: a major need in modeling alluvial architecture, even at this relatively broad-brush level, is a well founded model of floodplain roughening and fine-scale channelization.

4. Conclusions

Avulsion is an emergent, nonlinear threshold phenomenon at the landscape scale that creates storage and release events over wide temporal and spatial ranges. The qualitative behavior of the model we explore here is similar to other threshold-toppling models such as the sandpile, slider-block and forest fire models. The preservation of floodplain topography introduces a history dependence in our model, however, that is not present in the sandpile and slider-block models but is important in river and other channelized systems. The influence of antecedent topography on avulsion pathways leads to several patterns of behavior that are insensitive to the details of model implementation. First, flow alternates among a small number of channels – an *active channel set* – that are repeatedly abandoned and reoccupied. Second, this tendency to reoccupation leads in a natural way to spatial clustering and multi-storey stacking of channels in the stratigraphic record.

Importantly, a single-value threshold for avulsion produces a range of avulsion styles seen in nature. The majority of avulsions are small events in which the flow returns to the active channel at some point not far downstream of the avulsion site. Whole-system avulsions are rarer but do occur; however, they tend mainly to reoccupy an abandoned channel rather than create a new one. The mechanics of avulsion and channel reoccupation lead to preferred sites of channel deposition for long periods of time, and then abrupt shifts to new locations. This result suggests the potential for indications in the geologic record of periods of relative stasis followed by major depositional shifts caused by the inherent nonlinearity of sediment transport rather than changes in boundary conditions such as climate.

Although the avulsion threshold generates apparently stochastic dynamics, the behavior of the fluvial system is not entirely unpredictable. Rather, boundary conditions impose a maximum avulsion time and transport dynamics creates a wide range of events below that time. This characteristic avulsion time also exerts a more subtle influence on fluvial transport. Avulsion determines the “memory” of transport in the fluvial system, such that events separated by time scales larger than the maximum avulsion time are completely decoupled.

The sensitivity of stratal patterns to floodplain topography illuminates a major shortcoming of fluvial basin-filling models in general — lack of knowledge of floodplain deposition and erosion over large time and space scales. In our model the sole mechanism of floodplain roughening is the avulsion of the river and the creation of abandoned channels. In reality, floodplains are dissected with myriad smaller channels linking the river to wetlands, lakes and abandoned river paths. These channels may be erosional or depositional features. While it is not clear how such spillover channels form, they are clearly important for steering flood flows and serving as avulsion pathways. Rather than acting as a passive sink for overbank sediment, the fluvial floodplain provides a dynamic, time-varying boundary region for the channel. This paper highlights the need for further empirical and theoretical research on floodplain evolution and particularly on processes of small-scale roughening and smoothing. In addition to the potential of field and laboratory observations to shed light on this, the stratigraphic record itself may also provide a powerful tool for understanding overall patterns of floodplain sedimentation that would be difficult to discern with standard coring and dating methods.

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References

Aalto, R., Lauer, J.W. and Dietrich, W.E., 2007. Spatial and temporal dynamics of sediment accumulation and exchange along Strickland River floodplains (PNG), over decadal-to centennial time scales. Journal of Geophysical Research Earth Surface, in review.

Allen, J.R.L., 1979. Studies in fluviatile sedimentation: an elementary geometrical model for the connectedness of avulsion-related channel sand bodies. Sedimentary Geology 24, 253–267.

Aslan, A., Blum, M.D., 1999. Contrasting styles of Holocene avulsion, Texas Gulf Coastal Plain, USA. In: Smith, N.D., Rogers, J. (Eds.), Fluvial Sedimentology VI. Blackwell Science, Oxford, England, pp. 193–209.

Behrensmeyer, A.K., Tauxe, L., 1982. Isochronous fluvial systems in Miocene deposits of northern Pakistan. Sedimentology 29, 331–352.

Bridge, J.S., Leeder, M.R., 1979. A simulation model of alluvial stratigraphy. Sedimentology 26, 617–644.

Bridge, J.S., Mackey, S.D., 1993. A revised alluvial stratigraphy model. In: Marzo, M., Puigdefabregas, C. (Eds.), Alluvial Sedimentation. Spec. Publs., International Association of Sedimentologists, pp. 319–336.

Chase, C.G., 1992. Fluvial landsculpting and the fractal dimension of topography. Geomorphology 5, 39–57.

Dietrich, W.E., Day, G., Parker, G., 1999. The Fly River, Papua New Guinea: inferences about river dynamics, floodplain sedimentation and fate of sediment. In: Miller, A.J., Gupta, A. (Eds.), Varieties of Fluvial Form. John Wiley and Sons, New York, pp. 345–376.

Friend, P.F., Slater, M.J., Williams, R.C., 1979. Vertical and lateral building of river sandstone bodies, Ebro Basin, Spain. Journal of Geological Society (London) 136, 39–46.

Howard, A.D., 1994. A detachment-limited model of drainage basin evolution. Water Resources Research 39 (7), 2261–2285.

Hwa, T., Kardar, M., 1992. Avalanches, hydrodynamics, and discharge events in models of sandpiles. Physical Review. A 45 (10), 7002–7023.

Jerolmack, D.J., Mohrig, D., 2007. Conditions for branching in depositional rivers. Geology 35 (5), 463–466.

Johnson, N.M., Stix, J., Tauxe, L., Cerveny, P.F., Tahirkheli, R.A.K., 1985. Paleomagnetic chronology, fluvial processes, and tectonic implications of the Siwalik deposits near Chinji Village, Pakistan. Journal of Geology 93, 27–40.

Kim, W., Paola, C., Swenson, J., Voller, V., 2006. Shoreline response to autogenic processes of sediment storage and release in the fluvial system. Journal of Geophysical Research Earth Surface 111 (F04013). doi:10.1029/2006JF000470.

Kraus, M.J., Middleton, L.T., 1987. Contrasting architecture of two alluvial suites in different structural settings. In: Ethridge, F.G., Flores, R.M., Harvey, M.D. (Eds.), Recent Developments in Fluvial Sedimentology. Special Publication, Society of Economic Paleontologists and Mineralogists, pp. 253–262.

Leeder, M.R., 1978. A quantitative stratigraphic model for alluvium, with special reference to channel deposit density and interconnectedness. In: Miall, A.D. (Ed.), Fluvial Sedimentology. Memoir, Canadian Society Petroleum Geologists, pp. 587–596.

Leeder, M.R., Mack, G.H., Peakall, J., Salyards, S.L., 1996. First quantitative test of alluvial stratigraphic models: southern Rio Grande rift, New Mexico. Geology 24 (1), 87–90.

Mackey, S.D., Bridge, J.S., 1995. Three-dimensional model of alluvial stratigraphy: theory and application. Journal of Sedimentary Research. B 65, 7–31.

Maizels, J., 1990. Long-term paleochannel evolution during episodic growth of an exhumed Plio-Pleistocene alluvial fan, Oman. In: Rachocki, A.H., Church, M. (Eds.), Alluvial Fans: A Field Approach. John Wiley & Sons, Chichester, pp. 271–304.

Mohrig, D.C., Heller, P.L., Paola, C., Lyons, W.J., 2000. Interpreting avulsion process from ancient alluvial sequences: Guadalope-Matarranya system (northern Spain) and Wasatch Formation, (western Colorado). Geological Society of America Bulletin 112 (12), 1787–1803.

Murray, A.B., Paola, C., 1994. A cellular model of braided rivers. Nature 371, 54–57.

Paola, C., 2000. Quantitative models of sedimentary basin filling. Sedimentology 47 (suppl. 1), 121–178.

Paola, C., Foufoula-Georgiou, E., 2001. Statistical geometry and dynamics of braided rivers. In: Mosley, M.P. (Ed.), Gravel-Bed Rivers V. New Zealand Hydrological Society, Wellington, NZ, pp. 47–71.

Parker, G., Paola, C., Whipple, K.X., Mohrig, D.C., 1998. Alluvial fans formed by channelized fluvial and sheet flow. I: theory. Journal of Hydraulic Engineering 124 (10), 985–995.

Pizzuto, J.E., 1987. Sediment diffusion during overbank flows. Sedimentology 34, 301–317.

Shanley, K.W., McCabe, P.J., 1993. Alluvial architecture in a sequence stratigraphic framework: a case history from the Upper Cretaceous of southern Utah, USA. In: Flint, S.S., Bryant, I.D. (Eds.), The Geological Modelling of Hydrocarbon Reservoirs and Outcrop Analogues. Special Publication, International Association of Sedimentologists, pp. 21–56.

Sheets, B.A., Paola, C., Kelberer, J.M., 2007. Creation and preservation of channel-form sand bodies in an experimental alluvial system. In: Nichols, G.J., Williams, E.A., Paola, C. (Eds.), Sedimentary processes, environments and basins — a tribute to Peter Friend. Special Publication, International Association of Sedimentologists. Blackwells.

Slingerland, R., Smith, N.D., 2004. River avulsions and their deposits. Annual Review of Earth and Planetary Sciences 32, 257–285.

Smith, N.D., Cross, T.A., Dufficy, J.P., Clough, S.R., 1989. Anatomy of an avulsion. Sedimentology 36 (1), 1–23.

Sun, T., Paola, C., Parker, G., Meakin, P., 2002. Fluvial fan deltas: linking channel processes with large-scale morphodynamics. Water Resources Research 38 (8), 1151. doi:10.1029/2001WR000284.

Turcotte, D.L., 1997. Fractals and Chaos in Geology and Geophysics. Cambridge University Press, Cambridge. 398 pp.