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

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Supplementary Information:

DR1: Model Description

Simulations of floodplain evolution were carried out using a numerical model of flow, suspended sediment transport, overbank sedimentation and meander migration. The model solves the depth-averaged shallow water equations using an explicit finite volume approach, that employs an approximate Reinmann solver (Mingham and Causon, 1998). Suspended sediment transport is represented by solving an advection-diffusion equation for three grain size fractions (sand, silt and clay). The process equations and numerical methods used here are based on those adopted in an existing model of river morphodynamics (Nicholas et al., 2013). However, in order to simulate long-term floodplain evolution (e.g., over >500 floods) a number of steps are taken to increase model efficiency. First, the numerical schemes used here are first-order accurate in space. Second, processes within the river channel are modelled using one-dimensional schemes that represent the section-averaged channel depth, streamwise velocity and mean sediment concentrations at a series of cross-sections of constant width. The main advantage of using a one-dimensional approach in the channel is that it is not necessary to simulate processes at fine spatial resolutions, which would increase computational costs significantly. Floodplain processes are modelled in two-dimensions (i.e. using two-dimensional numerical schemes) on a regular grid representing the floodplain topography, with a spatial resolution equal to half the channel width. The one-dimensional and two-dimensional numerical schemes are coupled in order to allow water and sediment masses to be exchanged between the channel and floodplain. This is accomplished by defining the cells in the two-dimensional grid that are located within the channel (these cells lie within one half-channel width of the channel centreline). To allow the two-dimensional model to calculate fluxes of water and sediment between channel and floodplain cells it is necessary to define the values for the channel variables in the channel grid cells. This is accomplished by interpolating the values of the equivalent channel variables that have been calculated in the one-dimensional model. In the case of the flow velocities, the streamwise channel velocities in the one-dimensional model are transformed into velocity components in the x and y grid directions in the two-dimensional grid cells by assuming that the flow in the channel is aligned parallel to the local centreline orientation. Once the values of channel variables have been defined in the channel cells on the two-dimensional grid, the two-dimensional equations can be solved to update the values of all model variables in the floodplain cells. A final stage in each model time step involves using the calculated fluxes of water and sediment that have been conveyed between the channel and floodplain cells on the two-dimensional grid to update the one-dimensional model variables to account for gains and losses of water and sediment mass associated with channel-floodplain exchanges.

The model is applied to simulate flow, suspended sediment transport and overbank sedimentation in a sequence of floods. At the end of each flood, the migration of the river is simulated using the meander migration model of Howard and Knutson (1984). Following the application of the meander migration model, the revised channel centreline coordinates are used to determine if any of the grid cells have been converted from channel to floodplain or vice versa. Where floodplain cells have been converted into channel cells, the elevation of the cell is determined by interpolating between the bed elevations of the nearest channel cross-sections in the one-dimensional model. The volume of sediment eroded by bank migration is used to increment the sediment concentration (S) of the river, which is defined at the inlet to the model domain as a function of discharge (Q): $S = CQ^{1.5}$, where C is a constant that varies between simulations (see below).

Bed elevations in the channel are calculated by assuming that the channel has a constant streamwise slope that is defined by the initial mean slope of the floodplain and the channel sinuosity (i.e. as sinuosity increases the channel slope declines to maintain the same height drop between the reach inlet and outlet). Consequently, the model does not calculate bedload transport rates in the channel or use such rates to update channel bed elevations. Channel cross-section bed elevations are incremented after each flood by a defined rate of bed aggradation (A) that is constant for all locations. This approach is equivalent to that adopted in previous modelling studies (Van de Lageweg et al., 2016). It is adopted here to allow the investigation of floodplain evolution and alluvial ridge construction under a range of specified channel bed aggradation rates. The range of bed aggradation rates considered here (between 0 and 0.036 m flood^{-1}) was selected to produce channel bed aggradation amounts that vary between 0 and c. 2.5 times the initial channel depth, and hence to yield channel belt super-elevation ratios close to, and in excess of, the theoretical threshold for avulsion to occur (c.f. Mohrig et al., 2000; Hajek and Wolinsky, 2012). These aggradation rates can be compared with rates observed in modern channels (e.g., Skelly et al., 2003), rates reconstructed from Holocene floodplain deposits (e.g., Törnqvist, 1994) and rates used in alluvial architecture models (e.g., Mackey and Bridge, 1995), which extend across the range from <0.001 to >0.1 m year^{-1}. The assumption of spatially and temporally uniform aggradation represents an end-member scenario that is likely to be most applicable in the distal reaches of lowland rivers. It will be less applicable in upland rivers and alluvial fans, where aggradation may be localised and/or episodic (Davies and Korup, 2006) or where sharp discontinuities in fluvial sediment transport occur due to changes in channel morphology or valley gradient.

A set of 31 simulations were carried out to investigate the controls on floodplain and alluvial ridge construction. The model was run in each simulation for a maximum of 600 floods. However, the maximum number of floods completed varied between simulations because it was limited by the wall time of the High Performance Computing facility used to carry out the simulations. Results presented in this paper were limited to a total of 580 floods to ensure that the number of floods simulated was the same for all model runs. The simulations reported herein are not intended to represent specific rivers, but to provide insight into the general behaviour of large meandering sand-bed rivers, and the construction of floodplain topography in the period between avulsions. Consequently, the model parameters outlined below are not intended to represent a particular river, but to be broadly representative of large lowland meandering sand-bed rivers in general. The model domain was 48 km wide by 72 km long, with a grid resolution in the two-dimensional model of 250 m. Initial conditions for each simulation are a planar floodplain with a constant downstream gradient of 0.1 m km^{-1}, and a straight channel with a constant depth of 8 m. In all simulations, the river width was defined to be 500 m. All floods had a duration of 20 days, with peak and minimum discharges of 15,000 m^3s^{-1} and 2,500 m^3s^{-1}, respectively. The main parameters that were varied between simulations were the rate of channel bed aggradation (A) and the constant (C) in the sediment rating curve: $S = C\,Q^{1.5}$, where Q is the river discharge and S is the sediment concentration at the model inlet. The value of C was fixed during each simulation, but varied over a wide range of values between simulations in order to examine floodplain evolution for rivers with contrasting suspended sediment loads (sediment load scales linearly with C) and contrasting rates of overbank sedimentation and alluvial ridge construction. The value of the exponent in the rating curve was held fixed at 1.5. Values for this exponent in natural rivers typically vary between c. 0.5 and 2.5 (Syvitski et al., 2000; Gautier et al., 2010).

Most simulations reported herein used a suspended sediment load composed of 5% sand, 75% silt and 20% clay (termed below the *default* sediment load). A small number of simulations used a load comprising 5% sand, 20% silt and 75% clay (termed below a *fine* sediment load). In the meander migration model, rates of channel centreline migration are scaled by a dimensionless bank erodibility constant (E). In most simulations this parameter was assigned a value of 1. In a small number of simulations E was assigned a value or either 0.5 or 1.5. A full summary of the model parameter values used in the model simulations are included in the Table below. This table also lists values for the channel belt super-elevation ratio (β), which equals the height drop from the alluvial ridge to the distal floodplain divided by the mean channel depth at the end of the simulation (averaged over the final 20 floods); and α_{95}, which is the 95th percentile of the values of the hydrometric connectivity metric (α), calculated over the final 200 floods of each simulation. The parameter α is calculated for each flood, and is equal to the mean depth of water on the floodplain after the flood peak (after 60% of the hydrograph duration has passed), divided by the fraction of the boundary between the main channel and the floodplain that is inundated (this boundary is illustrated in Fig. 1E in the main paper). For further details on the simulations please contact the lead author.

DR2: Table of Model Parameters and Results

A (m flood^{-1})	C	E	Load	β	α_{95}
0	0.00003	1	Fine	0.167	2.23
0	0.00003	1	Default	0.249	2.16
0	0.0003	1	Default	0.546	1.92
0.004	0.0003	1	Default	0.675	1.97
0.008	0.0003	1	Default	0.826	1.97
0.012	0.0003	1	Default	0.998	1.98
0.018	0.0003	1	Default	1.306	1.96
0.026	0.0003	1	Default	1.838	1.79
0.031	0.0003	1	Default	2.343	1.58
0.036	0.0003	1	Default	3.099	1.52
0	0.003	1	Default	0.649	3.52
0.004	0.003	1	Default	0.734	3.30
0.008	0.003	1	Default	0.824	3.22
0.012	0.003	1	Default	0.919	3.09
0.018	0.003	1	Default	1.069	2.79
0.026	0.003	1	Default	1.283	2.47
0.036	0.003	1	Default	1.567	2.49
0.004	0.01	1	Default	0.695	8.96
0.012	0.01	1	Default	0.833	6.64
0.018	0.01	1	Default	0.940	5.19
0.026	0.01	1	Default	1.090	3.72
0.036	0.01	1	Default	1.289	2.80
0	0.003	1	Fine	0.462	3.42
0.008	0.003	1	Fine	0.574	2.42
0.018	0.003	1	Fine	0.735	2.07
0.036	0.003	1	Fine	1.080	2.00
0	0.0003	0.5	Default	0.630	1.76
0	0.0003	1.5	Default	0.502	2.13
0.012	0.0003	0.5	Default	1.148	1.88
0.012	0.0003	1.5	Default	0.948	2.37
0	0.0003	1	Fine	0.364	1.73

Table 1: Model parameter values and simulated values of the metrics β and α_{95}. All parameters are defined in the text above Table 1.

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