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Channelization of meandering river floodplains by headcutting

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ABSTRACT

Flows of water and sediment on Earth and other planets have a remarkable tendency to organize into channels across environments and scales. Channels are the primary conveyors of water, sediment, and nutrients through landscapes, and despite their prevalence, prediction of channel initiation and organization remains elusive. Models can predict channel initiation on steep hillslopes, but it is unclear how channelization arises on low-gradient floodplains. Here, we show that, in contrast to channelization on hillslopes, floodplains become channelized by headcutting at low specific discharges and moderate slopes (10^{-4} to 10^{-3} degrees). Using simplified numerical modeling of a floodplain with homogeneous soil, we show this difference arises because low specific discharge and moderate slopes maximize water drawdown at topographic discontinuities. Field data are consistent with model results and show that low specific discharges and moderate slopes are necessary, but not sufficient, conditions for channelization on floodplains in Indiana, Unites States. Our results imply that certain floodplains tend to self-channelize, and this increases the frequency of flooding and also enhances hydrological connectivity, which regulates biodiversity and nutrient processing.

INTRODUCTION

Floodplains are transformational engines that process, store, and release water, sediment, and nutrients that move through the landscape (Junk et al., 1989; Tockner and Stanford, 2002). Floodplain geomorphology modulates these functions, yet we know surprisingly little about what shapes floodplain surfaces. For instance, floodplain surfaces in a variety of settings often contain channel networks (Mertes et al., 1996; Trigg et al., 2012; Fagan and Nanson, 2004; Kupfer et al., 2015; Thayer and Ashmore, 2016; Rak et al., 2016; David et al., 2017). Despite the increasing awareness of floodplain channels, little is known about their origin or function (Fagan and Nanson, 2004; Trigg et al., 2012; David et al., 2017).

These floodplain channels are not simply vestiges of the main channel. Instead, these secondary channels are distinct from the main channel in planform and hydraulic geometry, are active at high river stages, span multiple meander wavelengths, and extend to the edges of the floodplain (Fig. 1A). Any model for floodplain development should account for initiation and emergence of secondary channels because they affect hydrologic connectivity (Covino, 2017), management strategies (Buijse et al., 2002; Lewin and Ashworth, 2014), and flooding hazards.

Most work on channel initiation has focused on steep hillslopes with gradients of 10^0 to 10^{-2} degrees. In those environments, channel initiation occurs above a given drainage area-slope threshold when overland flow, landsliding, or seepage erosion from groundwater (Montgomery and Dietrich, 1989; Dietrich and Dunne, 1993; Abrams et al., 2009) creates a step-like topographic discontinuity, or headcut. The headcut channelizes the landscape as it migrates upslope.

Herein, we show that migrating headcuts also channelize floodplains with gradients of 10^{-3} to 10^{-4} degrees. For instance, in floodplains, headcuts are commonly found extending up-valley off meander cutoffs (Fig. 1B) or main channel segments (Thayer and Ashmore, 2016). Geomorphic mapping and crosscutting relationships suggest these headcuts nucleate from channel segments and eventually connect to create a network (David et al., 2017). If headcutting channelizes low-gradient floodplains, then a reasonable null hypothesis is that headcuts should develop on steep floodplains with high specific discharges, as suggested by headcutting in steep-gradient landscapes (Montgomery and Dietrich, 1994).

CHANNELIZATION ON FLOODPLAINS

To investigate the factors that drive secondary channel formation on low-gradient floodplains, we collected empirical data from Indiana, Unites States. We divided all active floodplains in Indiana into 5-km-long bins and classified floodplains as channelized if they contained two or more channels outside the active channel belt (Fig. 1C; see the GSA Data Repository[1]). For each floodplain bin, we also calculated floodplain width (W) and slope (S) (David et al., 2017), and upstream drainage area (A). For all U.S. Geological Survey stream gages in Indiana with 20 yr of peak stream flow data and drainage area data (n = 97), we calculated the 5 yr flood discharge (Q_5) using a Weibull plotting position formula (Interagency Advisory Committee on Water Data, 1982). For these gages, we found a relation between Q_5 (m^3/s) and A (m^2) of the form $Q_5 = 0.000012 \times A^{0.8029}$ (see the Data Repository), which was used to determine Q_5 for all remaining floodplain bins. We chose the 5 yr flood discharge because it exerted the most geomorphic work (see the Data Repository). Additional tests showed our analyses did not depend on flood recurrence interval. The 5 yr specific discharge (discharge per unit width; m^2 s^{-1}) is given as $q_5 = \frac{Q_5}{W}$.

Remarkably, channelization on low-gradient floodplains occurs under different conditions than in steep-gradient landscapes. In steep landscapes, channels initiate when drainage area and slope increase (Montgomery and Dietrich, 1994), whereas our data show that channels in low-gradient landscapes initiate when specific discharges and slopes decrease (Fig. 1D). Notably, there are also many floodplains that do not channelize under lower specific discharges and slopes, and we present an explanation for

[1]GSA Data Repository item 2019004, detailed description of numerical model, empirical data collection methods, and Figures DR1–DR3, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

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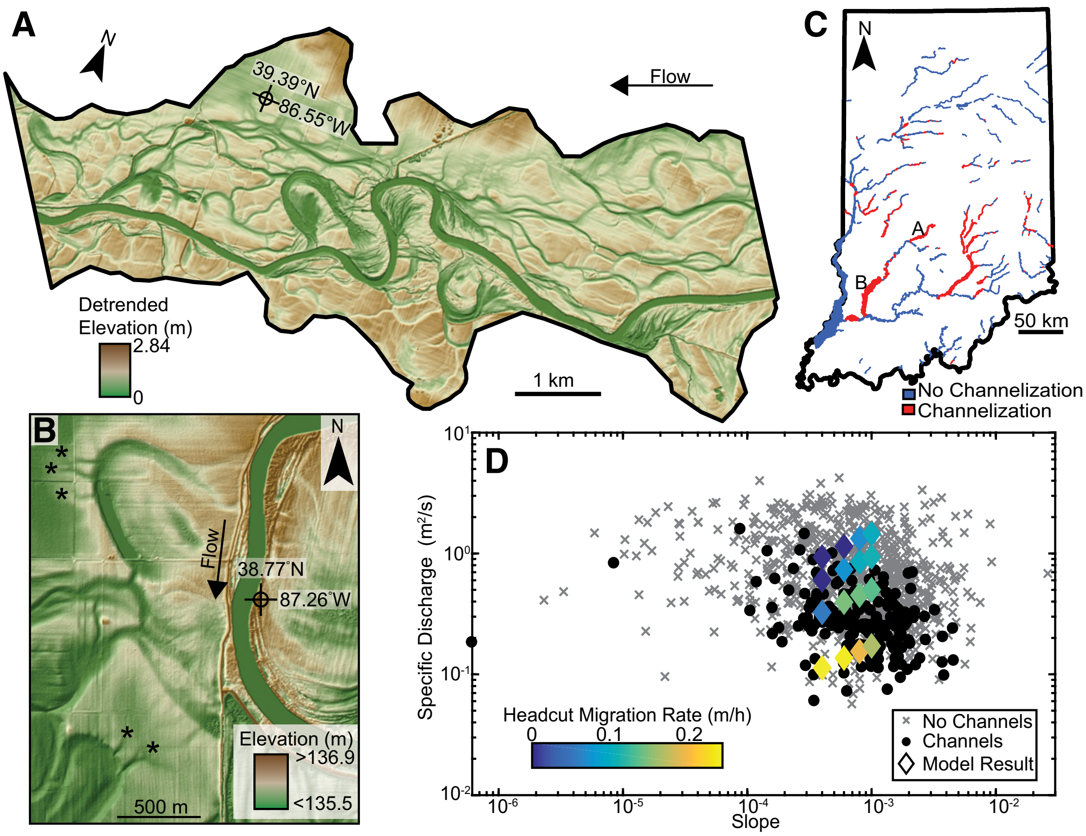

Figure 1. Floodplain channels in Indiana, United States. A: Hillshade digital elevation model (DEM) showing floodplain channels on West Fork White River, Martinsville, Indiana. B: Headcuts (marked by asterisks) extending off meander cutoffs on West Fork White River near Bicknell, Indiana. C: Map of Indiana showing floodplains with and without channels (modified from David et al., 2017). D: Floodplain channels occur on floodplains with lower specific discharges and moderate slopes. Colored diamonds show headcut migration rates based on numerical modeling experiments (see text for details).

this later herein. These data suggest that the initiation and mechanics of headcuts on low-gradient floodplains do not obey the same drainage-area slope relationship as in steep-gradient landscapes. After all, on steep landscapes, headcutting is driven by plunging flow (Bennett and Alonso, 2005), seepage erosion (Dietrich and Dunne, 1993; Abrams et al., 2009), and mass wasting (Bull and Kirkby, 1997; Robinson et al., 2000), and these processes do not commonly occur on low-gradient, inundated floodplains (Bull and Kirkby, 1997). These processes could initiate headcuts at channel margins if the water surface drops far below the channel banks before floodwaters reenter. Even if this condition occurred on floodplains, we show later that headcut initiation models for steep slopes (Izumi and Parker, 2000) are inconsistent with our data in Figure 1D.

The result in Figure 1D is interesting, and it is not immediately clear why floodplains with lower specific discharges and slopes would be more effective at forming channels, especially because, provided all else is equal, lower specific discharges would produce less basal shear stress and lower erosion rates in a detachment-limited model for headcut erosion (Montgomery and Dietrich, 1994). To explore why lower specific discharges lead to floodplain channelization, we used numerical modeling experiments to simulate headcut development on low-gradient floodplains.

HEADCUT DYNAMICS ON FLOODPLAINS

We performed a series of numerical modeling experiments in Delft3D (https://oss.deltares.nl/web/delft3d/home/) to explore how surface water causes headcuts to initiate and evolve on floodplains, as observed in Figure 1B. Delft3D is a physics-based morphodynamic model that solves depth-averaged shallow-water equations (Lesser et al., 2004). We chose to employ a two-dimensional (2-D) model to allow multiple headcuts to develop across our modeling domain. Moreover, Delft3D can create self-formed channel networks on floodplains through incisional processes (Hajek and Edmonds, 2014).

Our model starts from a uniformly sloping floodplain with a trench that spans the width of the domain (Fig. 2A). The trench is a generic representation of any topographic discontinuity that might exist in a floodplain, such as part of a meander cutoff. The computational grid has square cells in the floodplain, each 225 m², and refines to rectangular grid cells of 75 m² at the trench (see Fig. DR1 in the Data Repository). The upstream boundary condition is a steady, uniform discharge carrying no sediment. Hence, our model assumes no discharge fluctuations from a time-varying hydrograph, no cross-valley flow, and no sediment delivered from the river to the floodplain. The downstream boundary condition is a fixed water level, set to maintain uniform flow depth over the floodplain. The simulation begins with a fully inundated floodplain at a depth equal to uniform flow, assuming the floodplain is fully inundated, and flow is dominantly down-valley. The initial surface has randomly distributed topographic

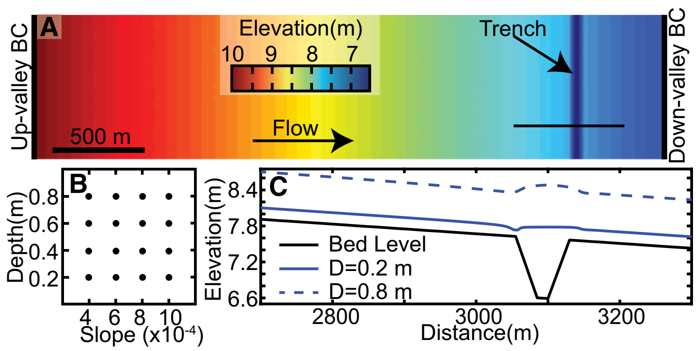

Figure 2. Numerical modeling experiments. A: Initial bed level in modeling domain. Solid black line is profile location of Figure 2C and Figures 3B–3D. Up-valley and down-valley boundary condition (BC) locations are shown with a black line along the domain edges. B: Parameter space explored for trench widths of 60, 75, and 90 m. C: Hydrodynamic results for slope $S = 8 \times 10^{-4}$ and trench width of 90 m along cross section in A. There is a prominent water surface drawdown at trench-floodplain interface for water depth D = 20 cm, whereas drawdown is suppressed for D = 80 cm.

roughness of ±1 mm height. The composition of the floodplain substrate is a 0.5-m-thick layer of cohesive sediment at the surface to capture the role of pedogenesis on floodplains. Under the cohesive sediment, there is a uniform mixture of 70% cohesive sediment and 30% noncohesive 200 µm sediment. The critical shear stress (τ_c) for cohesive sediment erosion was set to 0.4 N/m^2 greater than the shear stress (τ) exerted on the floodplain. Hence, through all model runs, we controlled excess shear stress on the floodplain to explore how each parameter influenced the excess shear stress at the floodplain-trench interface by preventing erosion elsewhere in the domain. For a given trench width of 60, 75, or 90 m, we conducted runs varying floodplain slope (S) and water depth (D) across the parameter space in Figure 2B, resulting in 42 total runs. For more detail, see the supplementary material.

Our numerical model results indicate that the floodplain-trench interface creates a drawdown in the water surface profile (Fig. 2C), causing localized flow acceleration that increases the shear stress and initiates erosion at this location. We characterize this drawdown nondimensionally as a ratio between the uniform, upstream floodplain water depth unaffected by the trench (D) and the floodplain-trench interface water depth (d), where drawdown increases as D/d increases. Larger D/d leads to higher relative shear stress at the floodplain-trench interface (Fig. 3A).

Interestingly, we find that increasing D decreases D/d (Fig. 3B), and that D/d increases with increasing trench width (T_w) and floodplain slope (S) (Figs. 3C and 3D). In all model runs, the drawdown at the trench-floodplain interface initiates an erosional front, where multiple headcuts compete for discharge until a stable number of larger channels emerges, and these channels migrate upslope and channelize the floodplain (Fig. DR2).

Headcut migration rate increases with larger D/d (Fig. 4A). We measured average headcut migration rates by tracking the upstream extent, defined by 5 cm or more of erosion, of the fastest-migrating headcut. Headcut migration rates are insensitive to small changes in the erosion threshold. Our results also show headcut migration rate increases with decreasing S (Fig. 4A). Headcut migration rate is slower on steeper slopes because they develop multiple headcuts along the trench, producing more floodplain channels, each of which captures less discharge compared to shallower slopes with fewer headcuts (Fig. DR3).

Our theoretical results show that low specific discharges and low to moderate slopes (2×10^{-4} to 8×10^{-4} m m^{-1}) produce the fastest headcut migration rates. These mechanics differ from steep landscapes, where headcuts form as flow cascades over a vertical precipice (e.g., Izumi and Parker, 2000) and migration rate increases for higher specific discharges and slopes (Fig. 4B). However, in shallow-gradient landscapes, where the landscape is often fully inundated, the headcut initiates from drawdown in the water surface profile (Fig. 2B). The drawdown magnitude is maximized at low to moderate slopes and low specific discharges, which explains the data in Figure 1D. Moreover, when we plot our modeled headcut migration rate in Figure 1D, we find that channelized floodplains in Indiana generally have the hydrodynamic conditions that the modeling results suggest should create rapidly migrating headcuts. However, many floodplains in the channelized part of the parameter space do not have channels. This suggests that low specific discharges and moderate slopes are necessary, but not sufficient, conditions for channelizing floodplains. These floodplains may not channelize because they lack headcut initiation sites (e.g., oxbows) or have high sedimentation rates that offset headcut formation. Headcutting and channel formation are unlikely at high specific discharges because the drawdown decreases (Fig. 3B). These floodplains are either incapable of initiating headcuts, or if headcuts do form, they migrate slowly enough to be filled in by sediment.

IMPLICATIONS

Our results suggest that some meandering river floodplains should develop floodplain channels governed by the specific discharge and slope (Figs. 1D and 4B). The presence of floodplain channels changes flooding dynamics and enhances lateral surface-water connectivity between the channel and floodplain (Covino, 2017). In fact, these channelized floodplains in Indiana show exceptional connectivity, as secondary channels are filled with water over ~10 times per year (David et al., 2017). Such connectivity regulates biodiversity (Amoros and Bornette, 2002) and nutrient processing (Malard et al., 2002).

These results also have important implications for the morphodynamics of meandering rivers. We expect this headcutting process could create chute channels within the meander belt (e.g., Constantine et al., 2010). Additionally, headcuts may play a role in the initiation of avulsions that reroute the channel to new positions in the floodplain (Mohrig et al., 2000; Slingerland and Smith, 2004; Hajek and Edmonds, 2014). Our results show that the development and migration of headcuts on floodplains can create channelized pathways through which water can preferentially flow

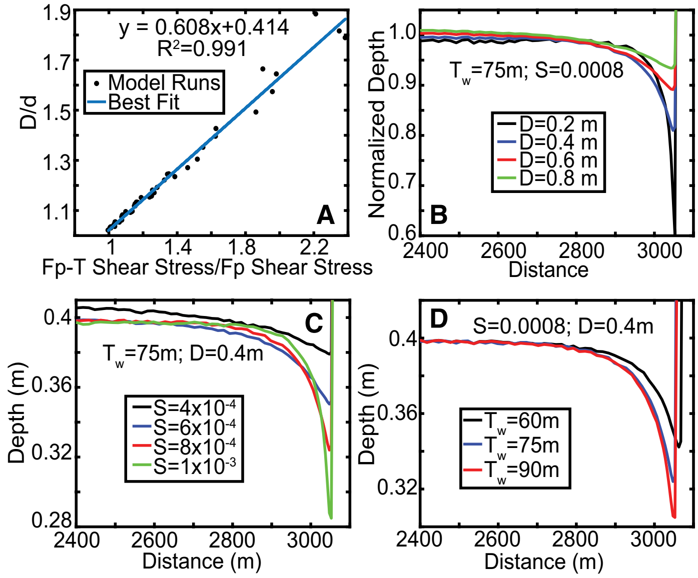

Figure 3. Dynamics of drawdown at floodplain-trench (Fp-T) interface. A: Shear stress at Fp-T interface normalized by upstream shear stress (Fp) increases linearly with drawdown (*D*/*d*, where *D* is floodplain water depth, and *d* is floodplain-trench interface water depth). B: Increasing floodplain water depth (*D*), for given slope (*S*) and trench width (*T*$_w$), decreases drawdown. C: Increasing floodplain slope (*S*), for a given water depth and trench width, increases drawdown. D: Increasing trench width, for a given water depth and slope, increases drawdown. Profile position in B–D is shown in Figure 2A.

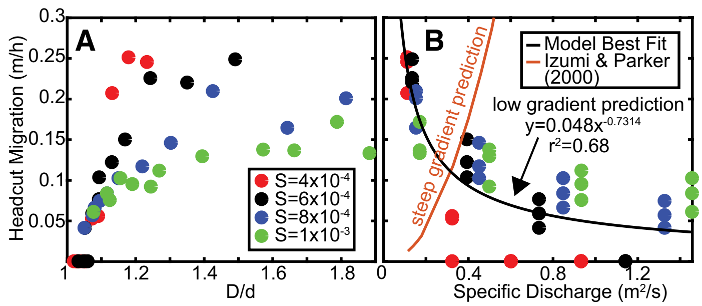

Figure 4. Controls on headcut migration rate. A: Headcut migration rate increases nonlinearly with *D*/*d* (where *D* is floodplain water depth, and *d* is floodplain-trench interface water depth), and lower slopes (*S*) have higher migration rates. B: Headcut migration rate nonlinearly decreases with increasing specific discharge. Black line shows fit for all model results, shown as dots colored by slope. Red line shows predicted migration rate based on analytical model of Izumi and Parker (2000).

(floodplain channels), and if these pathways enlarge through time, they could cause a river avulsion.

CONCLUSIONS

In this study, we explored the initiation and mechanics of headcuts developing off topographic lows in fully inundated floodplains using numerical modeling and field data. Field data from floodplains in Indiana and numerical modeling both suggest that headcutting on floodplains can create channelization at low specific discharges and moderate slopes. The headcutting is initiated by a drawdown in the water surface at the trench-floodplain (topographic discontinuity) interface. The headcuts then grow up-valley, causing floodplain channelization. This channelization process can create a vast network of floodplain channels that enhance connectivity and increase the frequency of flooding.

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