

Single-thread channels as the result of localized erosion and deposition driven by vegetation

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ABSTRACT: A series of laboratory experiments demonstrated how riparian vegetation could transform a braided morphology to a single-thread channel. When the system is braided, new channels form in areas not currently occupied by flow. In addition, deposition occurs within channels causing the flow to split. Plants deter the flow from occupied areas and decrease the probability for erosion. This has the effect of localizing the flow and focusing erosion along the banks, where shear stress is highest. By strengthening the banks, plants prevent channel widening. This reduces the probability for deposition to occur in the middle of a channel and concentrates deposition along the outer bank as the channel migrates. We used a 1D cellular automata model to explore the role of bank erosion and deposition on channel dynamics. It was possible to produce different channel patterns by varying the parameter governing the probability of erosion and deposition.

1 BACKGROUND

1.1 *Channel patterns*

Natural alluvial rivers self-organize into distinct morphologies that can be considered as a continuum of patterns from incoherent (braided) to highly organized (meandering). Braided are characterized by multiple rapidly shifting channels that interact with each other and migrate unconstrained across a wide braidplain, evolving in way that is difficult to predict. The area of the braidplain that is occupied by flow at any given time can vary widely and change quickly with changes in discharge. So does the number of active channels. Meandering rivers are single-thread and sinuous and migrate laterally in a predictable manner which is driven by erosion of the outer bends and deposition along the inner banks. Most meandering rivers on Earth are flanked by vegetated floodplains which are inundated only when floods are large enough to spill over the channel's banks. Between these end-members are other commonly recognized morphologies such as anastomosing, island-braided, wandering (irregularly sinuous), etc.

Braided channels are the default pattern that develops when an unbounded water flow interacts with non-cohesive sediment (Murray and Paola, 1994; Paola, 2001). Experiments with sand and water confirm this to be the case: experimental self-formed channels

composed of sand-sized particles and larger lack a mechanism for stabilizing sinuous channels and eventually widen and subdivide to form braiding (e.g., Friedkin, 1945; Schumm et al, 1987). It is surprisingly difficult to produce dynamic, self-maintaining meandering stream channels at experimental scales, and it is far from obvious how the balance that sets up a coherent channel and sets its capacity emerges from a simple, chaotic braided channel that develops spontaneously.

One of the key challenges to achieving self-sustaining meandering is to prevent the channel from widening, which leads to bar formation and channel splitting (e.g., Ashmore, 1991b). Another key challenge is to discourage the flow from occupying and enlarging chute channels (the swale between the bar and the inner bank) which typically leads to the development of multiple channels.

Efforts to reproduce single-thread channels experimentally have been aimed at overcoming the tendency for these channels to widen and split by using a variety of sediment types and mixtures with higher cohesion (e.g., Jin and Schumm, 1986; Smith, 1998; Peakall et al, 2007), and by adding fine-grain or lightweight suspended sediment to fill in chute channels through deposition (Peakall et al 2007; Brauderick et al, 2007). The results of these studies highlight that increased bank stability is key to the development of meandering.

2 INTERACTIONS BETWEEN BRAIDING AND VEGETATION IN AN EXPERIMENTAL CHANNEL

2.1 Overview

A series of experiments at the St. Anthony Falls Laboratory demonstrated that riparian vegetation used to stabilize banks can cause a braided channel to self-organize to, and maintain, a single-thread channel (Figure 1, Tal and Paola, 2007; Tal and Paola *in press*). The initial condition for the experiments was steady-state braiding in noncohesive sand under uniform discharge. From here, an experiment consisted of repeated cycles of alternating a short duration high flow with a long duration low flow, with uniform dispersal of alfalfa seeds (*Medicago sativa*) over the bed at the end of each high flow period. Plants became established on freshly deposited bars and areas of braidplain that were unoccupied during low flow. The presence of the plants had the effect of progressively focusing the high flow so that a single dominant channel contained between well defined banks developed (Tal and Paola, 2007; Tal and Paola *in press*). All the areas outside of the main channel were completely covered with vegetation and functioned as a floodplain. The experimental channels reproduced a number of important characteristics of natural single-thread channels. These included a stable with maintained by a balance between cut-bank erosion and point-bar deposition, a cross-sectional area adjusted to just contain the bank-full flow, actively migrating bends, channel cutoffs, and avulsions (Tal and Paola, 2007; Tal and Paola *in press*).

2.2 Experimental methods

Experiments were conducted in a 16 m × 2 m steel flume. The starting state for each experiment was

a fully developed, self-formed, steady-state braided channel. The system was designed with optimal conditions for braiding: cohesionless well sorted quartz sand ($D_{50} = 0.5$ mm) transported predominantly as bedload, with plenty of lateral space for the flow to reconfigure itself without significant constraint. A fully braided channel formed spontaneously after several hours. Once steady-state braiding had established, our strategy was to impose the essence of an annual cycle consisting of a mean flow during which the channel morphology remained relatively stable and transported very little sediment, and a relatively short annual flood that actively transported sediment and reworked the channel morphology. Each flood was followed by seeding intended to simulate annual establishment of vegetation on emergent river bars and banks by airborne seeds. We implemented this strategy by imposing a high flow (2.0×10^{-3} m³/s)—the same discharge used to establish the steady-state braiding—for one hour, then a protracted period of reduced discharge (4.0×10^{-4} m³/s). The low-flow period, constant for each experiment, was a variable parameter for the experimental series and ranged from 3 to 6 days. Sediment was fed at the upstream end at a constant rate during the high flow and was turned off during low flow. Vegetation was added as seeds that were dispersed manually over the entire bed at the end of each high flow with the low flow on. The volume of seeds necessary to cover an area of 2 m² at the desired seeding density (10000 seeds/m²) was measured and dispersed by hand as uniformly as possible. Seeds that landed on areas of the bed that were emergent at low flow established and colonized these surfaces while seeds that landed in the channels were either carried out of the system by the flow or redeposited further downstream. In each experiment the high-flow/low-flow-seeding cycle was repeated until we were certain that a new dynamic steady state had been established (17–31 times).

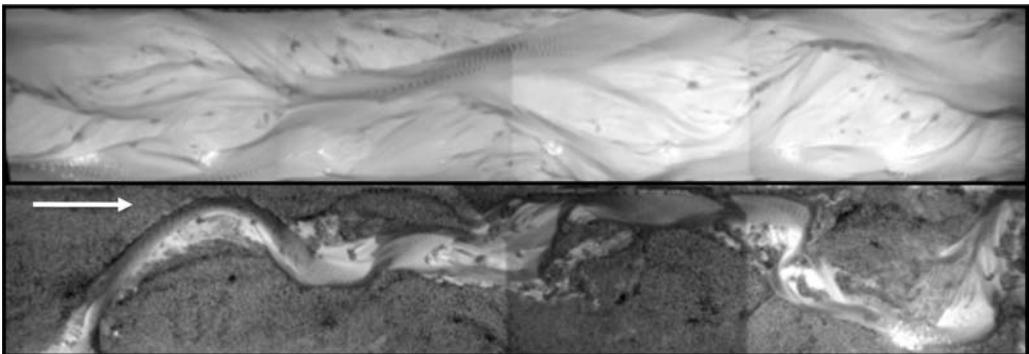


Figure 1. Transition from an unvegetated braided morphology to a dominant single-thread channel with a vegetated floodplain (Tal and Paola, 2007; Tal and Paola, *in press*). Arrow shows the direction of the flow. Study area is approximately 10 m long and 2 m wide.

2.3 Main results

These experiments, in which nothing was done to influence the resulting morphology, suggest that the evolution to a single-thread channel and a floodplain are directly related to effects of the plants. Vegetation had several critical roles in the formation and maintenance of a single-thread channel (Tal and Paola, *in press*). First, the plants slowed the rate of bank erosion through binding of the sediment by roots. By decreasing erosion rates, plants made it possible for deposition along the inner bank to match the rate of erosion along the outer bank (Figures 2 & 3). This enabled the channel to develop sinuosity and migrate laterally while suppressing channel splitting and the creation of new channel width. Second, vegetation reduced the rate of creation of new channels by discouraging the flow from reactivating chute channels. Third, vegetation

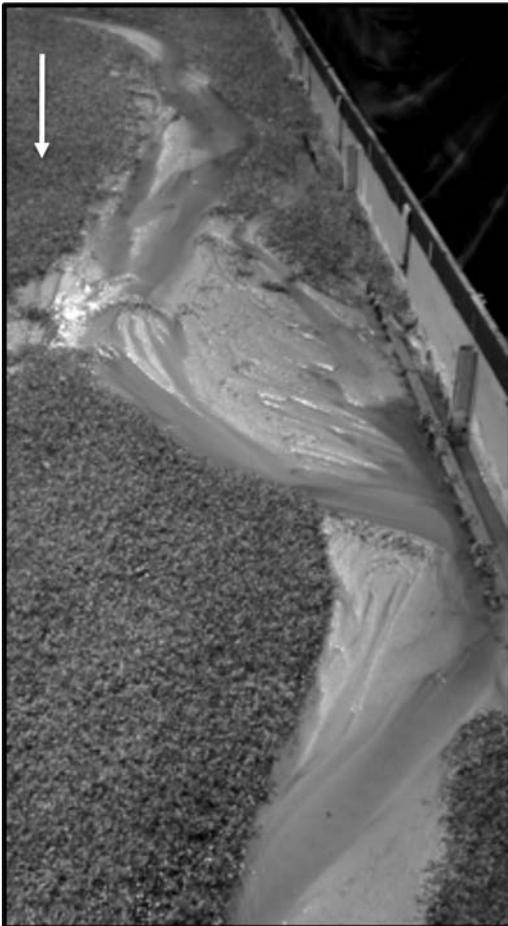


Figure 2. Reach of experimental channel (~6 m) at low flow showing freshly deposited point bars along the inner banks. Arrow shows the direction of the flow.

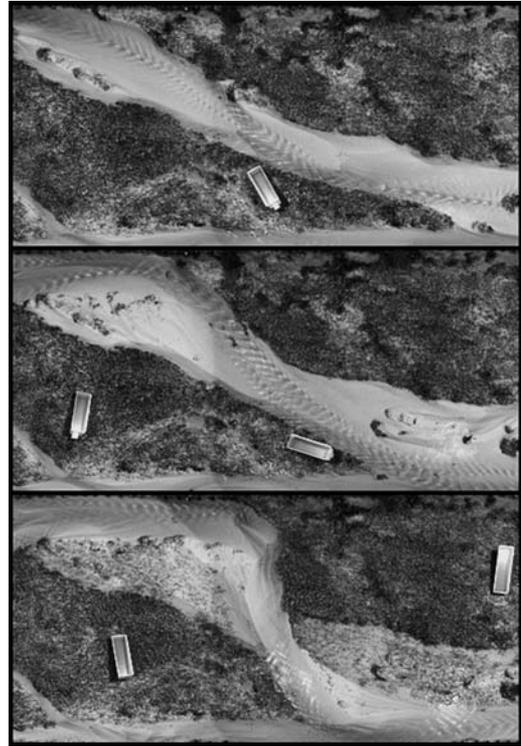


Figure 3. Reach of experimental channel (~3.5 m) showing bend migration and point-bar deposition (from Tal and Paola, *in press*).

discouraged cutoffs from occurring until significant super-elevation developed. This ensured that cutoffs resulted in wholesale diversion of the flow and discouraged the coexistence of multiple channels (Tal and Paola, *in press*).

A generic mechanism of width production in the braided state is the opportunistic creation of new channels. As existing flow paths become slightly less favorable, for example by bar deposition or increase in sinuosity, new ones are readily created in areas that are not currently occupied by flow. This effect is one that has made maintenance of experimental single-thread channels difficult (Tal and Paola, *in press*). Figure 4a shows the location of flow and dry riverbed in two images at 1-hour intervals during the unvegetated braided phase of one experiment. In an image created by differencing these two images, it's possible to see that the location of active channels at time one is decoupled from their location one hour later. Furthermore, the differenced image demonstrates the difficulty of predicting where new areas of flow will be located based on their previous location. In contrast, Figure 4b shows changes in the location of flow and dry river when the channel is single-thread. The changes

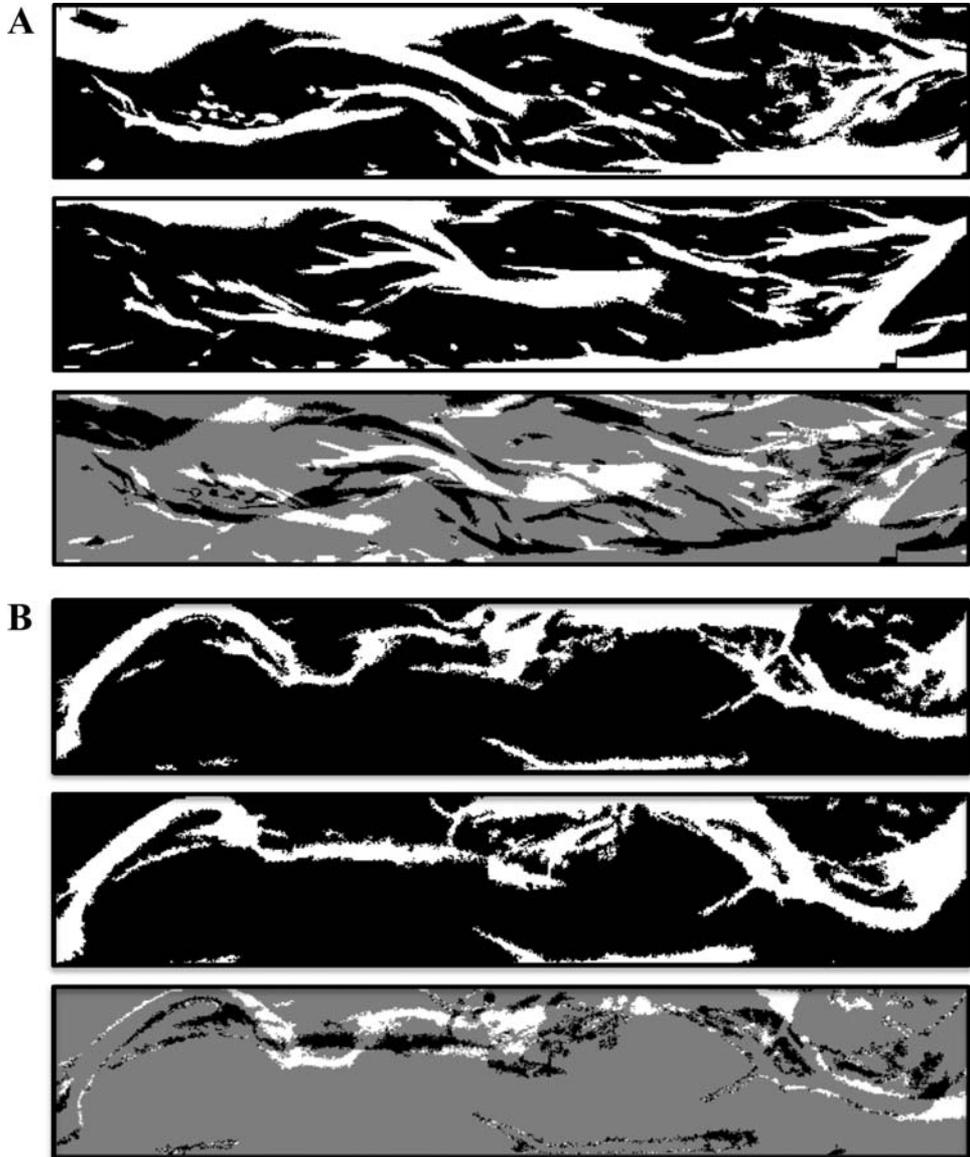


Figure 4. (A) The top two binary images were produced from photos taken one hour apart (t_1 -top, t_2 -middle) during the unvegetated braided phase of an experiment. White represents flow, black is (dry) bare sand. The last image in the sequence was created by subtracting t_1 from t_2 . Gray represents areas that did not change, white represents areas that were dry at t_1 and wet at t_2 , black areas were wet at t_1 and dry at t_2 . (B) The same sequence is shown for run B when the channel was single-thread with a well developed floodplain (from Tal and Paola, *in press*).

are highly localized in space—predominantly along the channel margin—and are more predictable because they are associated with lateral migration of the channel. The incoherent pattern of new flow paths in the braided state reflects the incoherent pattern of a braided channel, while the more orderly changes in

the single-thread state reflect the coherent nature of the channel and its migration kinematics. The effect of the vegetation is therefore to organize the flow so that it is conveyed in a single well-defined channel in which localized changes in wetted area reflect coherent migration of the channel as a whole.

Plants initially colonized braid-bars that were emergent during low flow. By adding cohesion to the sediment (roots) and increasing surface roughness (leaves and stems) vegetation deterred the flow from reoccupying areas which were colonized. Areas with established vegetation provided stable conditions which promoted new seedling establishment.

In addition, plants that survived the flood continued to grow while the density of vegetated areas increased with successive seedings, thereby enabling bars to evolve into islands. As this cycle continued, islands expanded and merged with other islands to form increasingly larger islands and eventually a floodplain (Tal and Paola, *in prep*). Figure 5 shows the results of transition matrices calculated for images captured at 5-minute intervals during all of the high flows of one experiment (Tal and Paola, *in prep*).

From the transition matrices, the probability for vegetated cells to become eroded versus the probability for these cells to remain dry was calculated

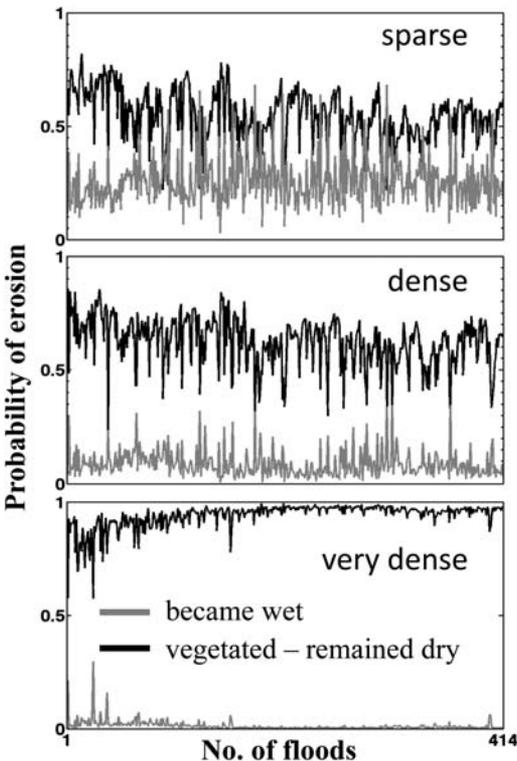


Figure 5. Probability for an area that was vegetated at t_1 to get eroded (become wet) at t_2 versus the probability that it will remain dry at t_2 . Probabilities were calculated for different stages of vegetation cover (increasing from top to bottom). Probabilities were calculated between images captured at 5-minute intervals during all of the high flows for one experiment.

for increasing intensities of vegetation cover. Younger sparsely vegetated areas had a higher probability of getting eroded than mature densely vegetated areas, which were more resistant.

Areas of the riverbed that were colonized by plants were harder for the flow to erode compared to areas of the bed that were bare, causing the flow to become increasingly focused. The likelihood for an area covered with plants to become eroded decreased as vegetation cover increased. Eventually, erosion became concentrated along the edge of the channel where shear stress was highest and the vegetation cover reached steady-state. By preventing channel widening, bar formation (deposition) in the middle of channels decreased. Deposition was eventually focused along the inner bank in the form of pointbars helping drive lateral migration.

3 1D CELLULAR AUTOMATA

We use a 1D cellular automata model to explore the role of bank erosion and deposition on channel dynamics. Our goal is to use the model to test whether it is possible to reproduce a wide range of behaviors from a limited set of parameters that we think represent fundamental dynamics affecting the organization of natural rivers.

3.1 Model description

3.1.1 Finite number of states

The model consists of a 1D array which represents a cross-section of a river perpendicular to the direction of the flow. A cell i in this array has a logical value $\gamma(i)$ equal to either 0 representing dry riverbed or 1 representing flow. The total number of cells N represents the total active width of the riverbed. N_W is the number of flow cells, N_D is the number of dry cells ($N_D = N - N_W$). We consider a non-periodic boundary condition: the cell on either end of the array remains dry during all of the computations (i.e., $\gamma(1) = 0$, $\gamma(N) = 0$).

3.1.2 Transition between states

We consider erosion as the transition from dry to wet (0 to 1), and deposition as the transition from wet to dry (1 to 0).

Erosion is a function of the total shear stress σ_T exerted by the flow on the adjacent bank (dry cell). σ_T on each cell is a function of the shear stress exerted from the right (σ_R) and from the left (σ_L), which are determined by the number of consecutive wet cells adjacent to it from each direction respectively. We consider that there is no shear stress acting on the boundary of the system (i.e., $\sigma_L(1) = \sigma_R(N) = 0$). Stresses on all the other cells in succession (from $i = 2$ to

$i = N - 1$) are calculated as follows based on the present state of the system:

$$\sigma_R(N+1-i) = (\gamma(N+2-i))(\sigma_R(N+2-i) + 1)$$

$$\sigma_L(i) = (\gamma(i-1))(\sigma_L(i-1) + 1)$$

Then,

$$\sigma_T(i) = (1 - \gamma(i))(\sigma_L(i) + \sigma_R(i))$$

The erosion potential $\lambda_e(i)$ for each dry cell i is defined as

$$\lambda_e(i) = \begin{cases} \sigma_T & \text{if } \sigma_T \neq 0 \\ c & \text{if } \sigma_T = 0 \end{cases}$$

Pure bank erosion occurs when $c = 0$. As $c \rightarrow \infty$, erosion occurs everywhere randomly.

Using this potential, we define the probability for erosion as

$$p_e(i) = \frac{\lambda_e(i)}{\sum_n \lambda_e(i)}$$

A cell to be eroded is selected randomly from P_e .

The deposition potential $\lambda_d(i)$ for each flow cell i is a function of its location in the channel and is defined as

$$\lambda_d(i) = \delta(i) + (1 - \delta(i))d$$

with

$$\delta(i) = \begin{cases} 0 & \text{if not channel edge} \\ 1 & \text{if channel edge} \end{cases}$$

Pure bank deposition occurs when $d = 0$. Deposition occurs everywhere randomly when $d = 1$.

Using this rate, we define the probability for deposition as

$$p_d(i) = \frac{\lambda_d(i)}{\sum_N \lambda_d(i)}$$

A cell to be deposited is selected randomly from P_d .

3.2 Results

The results from several simulations are presented here. For all of the runs $N = 100$ and $N_w = 0.2 N$ selected randomly. Each run consisted of 2000 time-steps. At each time-step, one cell was eroded and one cell was deposited (i.e., total number of wet and dry cells remain constant).

The two controlling parameters of our model are c and d . We explored this parameter space according to the following combinations:

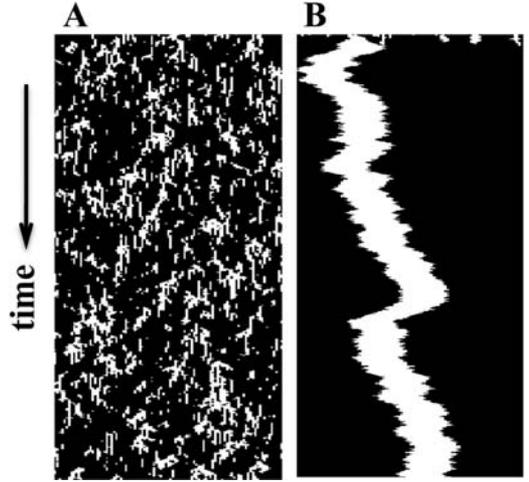


Figure 6. Evolution of a river cross-section through time: (A) braiding produced by random erosion ($c = 0.2$) and random deposition ($d = 1$), (B) single channel produced by bank erosion ($c = 0$) and bank deposition ($d = 0$).

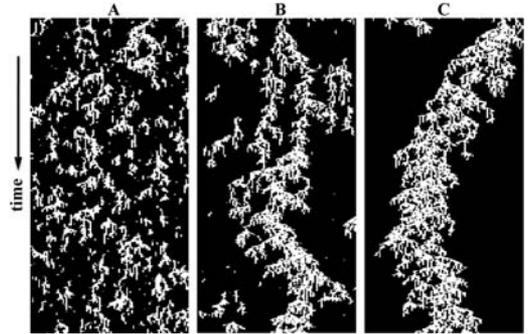


Figure 7. Evolution of a river cross-section through time for decreasing c values and $d = 1$: (A) $c = 0.1$, (B) $c = 0.01$, (C) $c = 0$. For decreasing values of c the channel belt becomes more clearly defined and global avulsions occur less frequently.

	$d \neq 0$	$d = 0$
$c = 0$	bank erosion random deposition	bank erosion bank deposition
$c \neq 0$	random erosion random deposition	random erosion bank deposition

Figure 6 shows the channel dynamics for two end member cases: (A) random erosion and deposition, (B) bank erosion and deposition. Random erosion and deposition maintained multiple channels across the entire width of the riverbed. No dominant flow path was established. Channels moved across the riverbed by lateral migration and global and local avulsions. In

the case of erosion and deposition along banks only, the randomly spaced flow cells at the start of the run rapidly converged to a single-thread channel which was maintained. The single thread channel migrated laterally but did not avulse, and developed sinuosity.

We explored several intermediate cases for different c values while keeping d constant (Figure 7). In doing so, we explored the effect of varying random erosion in order to simulate one of the key effects of vegetation on the riverbed. For decreasing values of c , the channel belt became more clearly defined and global avulsions occurred less frequently.

4 CONCLUSIONS

We have identified that a non-uniform probability of erosion on a riverbed has the effect of localizing the flow. In natural rivers, non-uniform erosion can be caused by the presence of riparian vegetation. By increasing bank stability and roughness, plants have the effect of deterring the flow from occupied areas and decreasing the probability for erosion of these areas. Vegetated area can continue to expand until the flow becomes focused into a single-thread channel that is strong enough to erode its banks and maintain a constant width.

Channel widening typically leads to deposition and the formation of mid-channel bars which cause the flow to split. By increasing bank stability and roughness, plants slow the rate of widening thereby reducing the probability for deposition to occur in the middle of the channel. Deposition becomes focused along the inner banks as erosion of the outer banks causes the channel to migrate laterally.

Preliminary results using a 1D cellular automata model to explore the role of bank erosion and deposition on channel dynamics demonstrate that changes in these parameters alone can produce a range of channel behaviors.

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