

Experimental evidence for the conditions necessary to sustain meandering in coarse-bedded rivers

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Meandering rivers are common on Earth and other planetary surfaces, yet the conditions necessary to maintain meandering channels are unclear. As a consequence, self-maintaining meandering channels with cutoffs have not been reproduced in the laboratory. Such experimental channels are needed to explore mechanisms controlling migration rate, sinuosity, floodplain formation, and planform morphodynamics and to test theories for wavelength and bend propagation. Here we report an experiment in which meandering with near-constant width was maintained during repeated cutoff and regeneration of meander bends. We found that elevated bank strength (provided by alfalfa sprouts) relative to the cohesionless bed material and the blocking of troughs (chutes) in the lee of point bars via suspended sediment deposition were the necessary ingredients to successful meandering. Varying flood discharge was not necessary. Scaling analysis shows that the experimental meander migration was fast compared to most natural channels. This high migration rate caused nearly all of the bedload sediment to exchange laterally, such that bar growth was primarily dependent on bank sediment supplied from upstream lateral migration. The high migration rate may have contributed to the relatively low sinuosity of 1.19, and this suggests that to obtain much higher sinuosity experiments at this scale may have to be conducted for several years. Although patience is required to evolve them, these experimental channels offer the opportunity to explore several fundamental issues about river morphodynamics. Our results also suggest that sand supply may be an essential control in restoring self-maintaining, actively shifting gravel-bedded meanders.

channel patterns | fluvial geomorphology | river meandering

River meandering—the lateral bank shifting that produces sinuous, single-thread channels—is inherent to coupled flow and sediment transport in gravel- and sand-bedded channels within a broad range of channel width-to-depth ratios (1). Channel planform classification based on field observations qualitatively suggests that meandering depends strongly on channel slope, grain size, bank strength, and sediment supply (2, 3). Theoretical models of river meandering (2–8), however, assume that the inner and outer banks migrate at the same rate during meandering no matter the bank strength and sediment supply. The processes by which inner bank deposition keeps pace with outer bank erosion are poorly known. This is a fundamental gap in our understanding of meandering rivers.

Laboratory experiments have demonstrated that channels with sand or gravel bed and banks will develop bars and planform curvature but will inevitably braid (9–11), because the weak outer banks erode faster than bars can grow and accrete to the inner bank. Braiding often develops due to flow diversion down chutes that form between the bar and the floodplain. Chutes occur because the area of maximum coarse sediment deposition is not located at the boundary between the bar and floodplain, but rather toward the center of the channel. These chutes are a locus for channel bifurcation and braiding (12). Experiments using clay and silt materials to strengthen the banks have produced sinuous channels, and under some conditions, chan-

nels with high sinuosity (13–16), but these experiments have not successfully created meandering channels with repeated cutoffs that both produce a floodplain and maintain their geometry. Instead, in such experiments, the channel simplifies to a single bend following cutoffs (16), or bank migration ceases once sinuosity develops (15). Recently, alfalfa sprouts have been used to provide bank strength in experimental channels (17–18). Adding alfalfa sprouts to braided flume channels transformed them into dynamic channels with characteristics of both single-thread and island-bar morphology. The alfalfa experiments replicate many processes observed in the field including avulsions and cutoffs, but meandering was intermittent and limited to a relatively small portion of the flume (18).

Although previous experiments were able to initiate channel meandering, they have not been able to maintain channel migration once sinuosity developed. The inability to generate self-maintaining laterally migrating channels with cutoffs in the laboratory prevents us from conducting scaled-experiments that would be valuable in problems ranging from developing practical guidelines for stream restoration, to channel response to climate change, and to understand the conditions necessary to support meandering channels observed on Mars and Titan. These practical and theoretical issues prompted us to explore specifically how to make a scaled gravel-bed meandering river. We focus on gravel-bed meanders because of their importance to aquatic habitat (19) and stream restoration (20), and because they can be more readily scaled to laboratory dimensions and hydraulic conditions.

Here we report the successful experimental generation of a lateral migrating, bedload-dominated, meandering channel with repeated cutoffs. The key challenges were to create conditions that allowed outer bank erosion and inner bank deposition (including up to the height of the adjacent floodplain) at the same rate and that led to deposition in the bar-adjacent chute, such that the incipient meandering was not rapidly cutoff by flow diversion down the chute. We hypothesized that in addition to hydraulic conditions that support meandering (1), the necessary conditions to obtain successful experimental meandering were (i) bank strength greater than that due to deposited bedload (to slow outer bank erosion rate), (ii) the addition of suspended load (to both settle out in the chutes, reducing the tendency for a low sinuosity cutoff, and to become deposited on the bar top, raising the surface to floodplain level), and (iii) periodic overbank flow (to raise the depositional surface of the point bar and to disperse suspended sediment into nearby low areas). Our experiment strongly supports the first two hypotheses, but surprisingly, meandering was maintained without variable peaks. The exper-

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than 16, and the absence of depth-scaled bedforms (e.g., dunes and ripples), we consider this channel as representative of gravel bed streams passing fine sediment.

The coarse feed was identical to the sediment in the basin, but was painted blue. The coarse feed rate was periodically reduced to limit aggradation upstream of the first bend (see the *SI Text*). We varied the fine sediment feed rate at the beginning of the experiment with an averaged feed rate of 3.4 kg/h over the entire experiment. During the final 65 h, the fine feed rate was held constant at 3 kg/h. In these experiments, the lightweight sediment moved as both bedload and suspended load. The fine feed comprised $\approx 82\%$ of the total fed sediment, higher than portion of sand caught in bedload traps at gravel bed meandering rivers (21–23), which ranges from 20% to 70% of the bedload (depending on the river, the stage, and location within the bend). Because the fines travel as both suspended and bedload, we set the portion of the fine feed to be higher than bedload traps in the field, which do not trap sediment suspended in the water column. We used two types of commercially available lightweight plastic sediment as model sand. Both types of plastic ranged between 0.25–0.42 mm in diameter and were not cohesive. The lightweight plastic used for the first 71 h of the experiment had specific gravity of 1.5, and the plastic used for the remainder of the experiment had a specific gravity of 1.3. Additional details regarding the lightweight plastic sediment are provided in the *SI Text*.

Several measurements were made during the experiments. Overhead photographs were taken at 5-min intervals during the experiment to record the position of the channel. Bed topography and water surface elevations were measured from a movable cart above the flume. Water surface elevations were measured with a point gauge, and bed topography was measured using a laser sheet photographed by an oblique camera while the flume was dry. Velocity was measured using a dye tracer, and overhead photographs were taken every 10 s. Sediment discharge from the flume was not regularly monitored due to repeated equipment failure.

Results

During the course of the 136-h experiment, the channel migrated both laterally and downstream, developing five bends and experiencing five distinct cutoff events. At the end of the experiment, the channel was entirely self-formed (Fig. 1, *Movie S1*, and *SI Text*). The wavelength stabilized at ≈ 14 channel widths, which is somewhat higher than typically reported for meandering rivers (24). Alternate bars were not present before the development of curvature, despite conditions that should have favored alternate bar development. Bends grew through a combination of downstream and lateral translation, and on average the bends migrated about two channel widths laterally and about five channel widths downstream. Migration rates were fastest during initial bend development at the beginning of the experiment and immediately following cutoffs. These rapid periods of channel migration were associated with high rates of sediment deposition, which redirected flow and increase downstream bar migration rates (see *Movie S1* and *SI Text*).

The channel width increased during the first 40 h of the experiment before stabilizing and remaining within $\pm 12\%$ of the resulting channel width for the remainder of the experiment (Fig. 2). The initial large increase in channel width corresponded to the high flow peaks, where bank erosion occurred faster than point bars could accrete vertically to create floodplain deposits. For the remainder of experiment, the bar margin kept pace with bank erosion as the bar grew vertically to the elevation of the floodplain. The depth was more variable than the width, with local changes in depth due to changes in upstream bank erosion. At the conclusion of the experiments, the average depth was 1.3 cm.

The alfalfa sprouts increase the strength of the banks relative to sand without sprouts (25), and thereby decreased the rate of bank erosion, giving time for inner bank sediment accretion to keep pace with outer bank erosion. Banks eroded by the entrainment of grains along the margin rather than by large-scale bank failure. The sprouts both roughened the near-bank region and increased the stress required to move particles. Bank erosion was not a steady process and often occurred in pulses, as flow was redirected due to upstream bar migration and cutoffs. Peak erosion rates occurred when the minimum radius of curvature of a bend was one to three times the average channel width, lower than generally reported in the literature (26) but similar to the lower Mississippi River (27).

Bars were built by deposition of coarse sediment eroded from upstream banks and fine sediment fed from the upstream end of the flume. Little of the coarse fed sediment was observed downstream of the first bar until after the first cutoff (Figs. 3 and 4, *Movie S1*, and *SI Text*). Before this time, deposition of fed sediment at the upstream-most bar caused erosion of the outer bank, which provided sediment to downstream reaches. When we reduced the coarse feed rates to prevent aggradation at the upstream end of the flume, erosion of the bed upstream of the first bar sent sediment downstream.

Fine sediment was crucial for connecting bars to the floodplain by filling the upstream end of chutes. Chute channel development between the bars and the floodplain was limited to rapid periods of migration at the beginning of the experiment and following cutoffs (see *Movie S1* and *SI Text*). After their formation, the upstream end of chutes would at first be paths of weak inner bank flow that would carry in fine sediment. Here the sediment would settle, eventually blocking further inflow. Downstream of the bed apex, coarse sediment would shift outward by rolling down the bar front, while fine sediment would be carried inward with the secondary circulation (as described by Dietrich and Smith) (28). This fine sediment would tend to deposit on the downstream end of bars (Fig. 3, mark F, and Fig. 4, white facies) and settle in the downstream end of chutes, further blocking this pathway. The chutes for the two upstream-most bars were also sealed at their downstream end by deposition of fine sediment. The consequence of these processes, dominated by fine sedimentation, was that the chutes behind each bar were sealed at their upstream end and, at times, at the downstream end, and the water within them was not flowing. Hence, the chute did not enlarge as the experiment progressed (which would lead to cutoff or braiding). Fine sediment also was deposited overbank, forming levee-like features along the right margin of the channel (looking downstream) (Fig. 3, mark O). In natural meanders, such processes would contribute to bank strengthening through the deposition of sediment (silt and clay) that have high critical shear stress upon re-entrainment.

The sinuosity increased throughout the experiment to a maximum value of 1.19 with dips during cutoff events, which limited the sinuosity of the channel (Fig. 2). The water surface slope and bed slope ranged from 0.0044 to 0.0047 downstream of the first bend during the final 50 h of the experiment. The channel straightened via chute cutoffs five times during the 136-h experiment, or an average of one cutoff every 25 h (Figs. 1 and 2). Of the five cutoffs, four were caused by channel migration into an abandoned and isolated chute, and in two of these cutoffs, the channel switched back to its precutoff location within a few hours (Fig. 1). The fifth (and final) cutoff occurred when upstream bank erosion caused local aggradation increasing the flow depth over the floodplain deposits, even though the discharge was steady. The overbank flow became concentrated, where vegetation growth was weakest, and carved a small channel that eventually connected with the downstream chute and expanded into a cutoff. Following all of the cutoffs, the

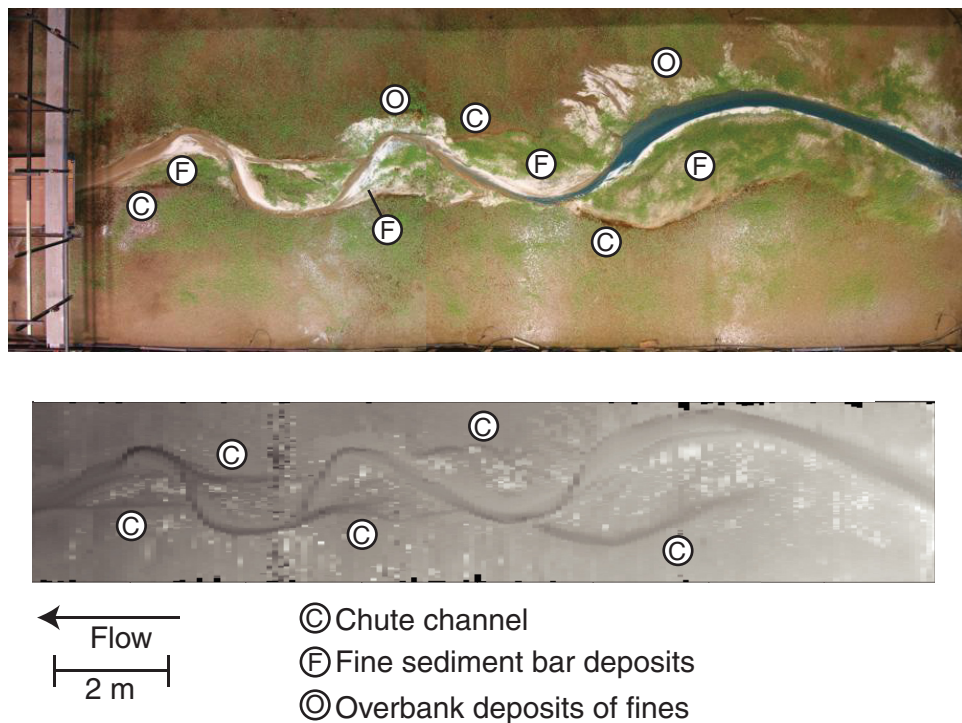


Fig. 3. Overhead photograph and shaded topographic image 103 h after the beginning of the experiment. The topographic image does not extend the length or entire width of the flume. In the topographic image, darker areas are lower elevation. Labels indicate chute channels, fine sediment deposits at the downstream end of bars, and areas of overbank deposition. In the photograph, the blue sediment is sand fed from upstream, the brown sediment is derived from the bed and banks of the channel, and the white sediment is fine sediment fed from upstream. The right bank was slightly lower than the left bank. A feature similar to a breakout channel formed during periods of aggradation at the upstream end of the flume on the lower elevation right bank.

channel regenerated bars, and the abandoned channels were quickly plugged with fine sediment (Fig. 5).

Discussion

Although we expected that variable discharge would be required to promote the creation of floodplain via point bar growth, we found that meandering was maintained during steady flows as well. This occurred because, as the channel evolved, our designed bankfull flow became slightly overbank, which allowed overbank deposition during steady flow. Had the floodplain roughness been greater (through higher alfalfa density), the flow may have forced the steady flow to be entirely contained within the bankfull channel as observed by (18). High peak flow tests during the first 40 h of the experiment caused the channel to widen progressively (Fig. 2), as the bars did not have sufficient time to accrete vertically to the floodplain elevation, and had we continued with these high peaks, the channel likely would have braided. Our results imply that limiting bank erosion rate to the rate at which bars can grow is crucial for maintaining a meandering morphology. They also suggest that erosion during rare high events may control whether a channel has a braided or meandering morphology.

Comparing the experimental migration rates to the field requires scaling time between the experiment and the field and also accounting for the number of days per year during which bankfull flows or greater occur (see *SI Text* for further discussion). The mean values of bed grain size (40 mm), bankfull width (43 m), and depth (1.5 m) of the gravel-bed meandering rivers analyzed by van den Berg (29) suggest the length scale factor (λ) for our flume to be between 1/50 and 1/100. Time scales differently than length in flume experiments, however, and the scaling procedure differs depending on the process of interest (30, 31). Here we use a Froude-scale approach common in

laboratory experiments (32, 33). For Froude-scaled flows, this implies that the time in the flume is about 0.1 to 0.14 to the field scale (i.e., $\lambda^{0.5}$). If we assume that most channel migration occurs during bankfull flows, which are typically equaled or exceeded 8 days per year (cf. 34, 35), then our 136-h experiment corresponds to 5–7 years of high flows. Excluding the rapid migration rates at the beginning of this experiment, the average basin-wide migration rate calculated following the procedure described in Micheli and Kirchner (36) ranged between 0.5 to 0.7 channel widths per year, depending on the scaling factor. Migration rates reported in the literature for natural channels are often reported for individual bends and range from less than 0.01 to a maximum 0.18 channel widths per year with a clustering of data around 0.01 to 0.02 channel widths per year (37, 38). Hence, our rate is much faster than that typically found in natural channels. To reduce the migration, we could have grown alfalfa to a high density (bank strength is linearly related to alfalfa density) (25). Decreasing our migration rates to typical field values would, however, require increasing the duration of experiments by about an order of magnitude, requiring several years to complete.

Maintaining a meandering morphology and steady width under such rapid migration rates requires an equally rapid bar growth rate. In our experiment, the fine sediment was critical to maintaining this rapid bar growth rate because fines deposited in areas where coarse sediment did not: At the upper elevation of the bars, the chute tops, and downstream of the bar apex. We note that in relatively sinuous gravel bed meanders with high migration rates, sand makes up the majority of the sediment accreted along the inner bank (39, 40). Without fine sediment deposition, the bars would not have grown to the elevation of the floodplain, and the chutes would be much larger.

If the migration rates were much slower, there may have been sufficient time for bar growth to keep pace with bank erosion in

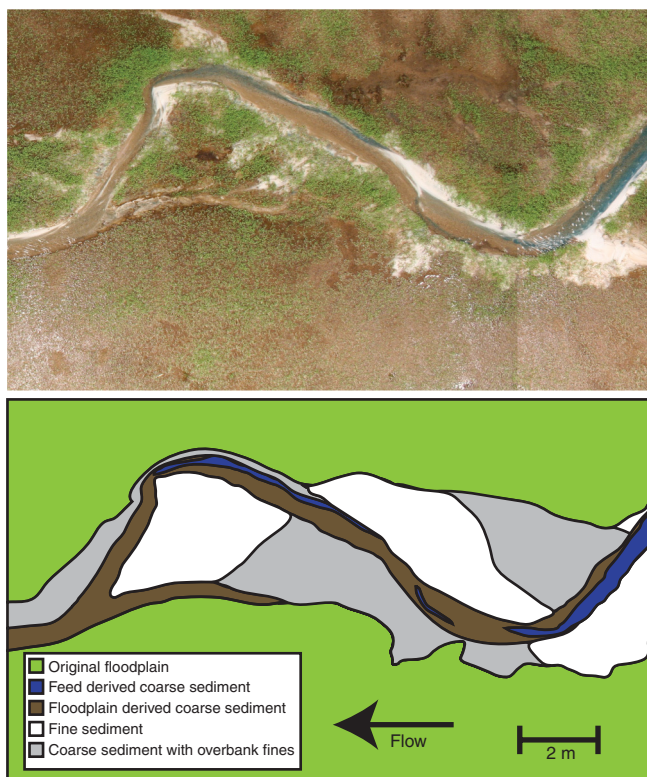


Fig. 4. Sediment facies in of second and third bars downstream from the flume inlet. Fine sediment facies are mapped where the majority of the floodplain thickness was fine sediment. Accumulation of organic matter from dead alfalfa makes some of the bar appear brown where it is primarily fine sediment.

the absence of fine sediment, but several lines of evidence indicate that this may not be the case. As discussed above, studies of coupled flow and sediment transport in meander bends show that bedload and suspended load follow separate paths, with bedload transported toward the outer bank downstream of the bar apex and suspended sediment transported toward the bar (28), and the downstream end of the bars are therefore finer (41–45). Even at flood discharge, bedload transport over the top of the bar tends to travel toward the outer bank. Hence, in the absence of suspended bed material, which can travel with the secondary currents to the inner bank and deposit (elevating the bar along the inner bank and closing the back bar chutes), there is no mechanism to attach the bar to the bank and to prevent chute cutoff at high flow. Dense vegetation can contribute to surface stabilization and retard chute cutoff, but without fine sediment to infill the chute, flow can reoccupy this path (and promote island bars). Vegetation growth on exposed bar surfaces also slows the flow, traps fine sediment, and induces vertical accretion. In exceptional cases of slowly migrating meanders with abundant vegetation, organic detritus may collect and consolidate to retard chute cutoff and maintain meandering. These experiments show that models of bar growth in meandering streams should include both coarse and fine sediment to allow bars to create floodplain deposits. The experiments also contradict the practice of limiting sand supply in many restoration projects in meandering rivers.

Although the migration rates in this experiment were high relative to natural rivers, the sinuosity was relatively low. Our maximum sinuosity downstream of the first bend was 1.19, which is considerably lower than most meandering gravel-bedded channels, where sinuosities are often greater than 1.5 (38, 46).



Fig. 5. Photograph of cutoff channel and fine sediment filling the former channel. Sediment colors are the same as Fig. 3. Fines also comprised the downstream end of the bar visible in the photograph. This was the final cutoff of the experiments and was caused by headward erosion rather than bar migration into a chute.

Despite the low sinuosity, the processes of bar growth, bank erosion, and cutoff were similar to gravel bed meanders in the field. These processes resulted in a channel with a width-depth ratio and a bend wavelength-to-width ratio within the range of natural channels (47). As also observed by Friedkin (13), sinuosity was limited by the cutoff frequency. In our case, the rapid migration (particularly downstream migration) increased the cutoff frequency by increasing the rate at which the channel migrated into open chutes. In addition, rapid migration during curvature development may limit chute filling because the main flow and high concentrations of sediment migrate away from the chutes. Filling the entire chute with sediment would decrease the cutoff frequency and consequently allow the sinuosity to increase, but this would require either much higher sediment concentrations or limiting migration rates to increase the time for fine sediment to deposit in the chute. Based on these experiments, we would expect meandering channels in the field to have higher sinuosity where cutoffs are suppressed by rapid filling of chute channels during bar growth.

Taken together, these results suggest that developing highly sinuous channels requires sufficient time for fine sediment to completely infill low areas along the inner bank such that chutes are essentially gone and cannot be exploited during chute cutoffs. This would reduce the frequency of chute cutoffs and allow the channel to develop a greater sinuosity. Experimentally, it may be difficult to achieve such high sinuosity channels through the method of bank strengthening with alfalfa sprouts, because growth of the sprouts imposes significant time delays in running experiments. In our experiments, we had to pause 1 week every for 15 to 20 h of runtime to reseed the alfalfa and allow it to grow. Making self-maintaining, high-sinuosity laboratory meanders will be the next experimental challenge.

Conclusions

By increasing the bank strength relative to noncohesive sediment and promoting deposition of fine sediment in troughs between point bars and the floodplain, we created a self-sustaining meandering channel in a laboratory flume. The initial sedimentologic and hydraulic conditions were sufficient for meandering as defined by Parker (1). The channel width stabilized after the first 40 h of the experiment, indicating that bank erosion and bar growth occurred at about the same rate, and there was little change in width as the channel migrated and cutoff. Chutes remained behind bars, and bars were connected to the floodplain

at their upstream end and were either open or closed off at their downstream end. Chute cutoffs occurred when the channel migrated into open chutes or following local aggradation and incision along preferential flow paths. Our migration rates were very fast relative to natural channels, which allowed chutes to remain behind bars and likely increased the cutoff frequency. Given such rapid migration rates, fine sediment was critical for attaching chutes to bars, elevating the deposition rate downstream of the bar apex and plugging cutoff channel. Sinuosity was low relative to meandering rivers in the field, likely because of the frequent cutoffs caused by partially open chutes. Slowing the migration rates to typical field values would likely increase the amount of fine sediment deposited in the chutes (and decrease chute cutoff frequency) but would increase the time required for the experiments significantly. Meandering was maintained with a steady, slightly over bank flow, and variable discharge was not necessary.

These experiments suggest that bank strength and, surprisingly, sand are necessary components of restoration projects for gravel bed meanders. The results provide data on entirely self-formed meandering channels that can be used to test theories of meandering that explicitly model inner bank sediment accretion, and thereby, predict channel width, rather than assume it is a fixed value. This should be a stepping stone toward a general mechanistic theory for channel width in river channels.

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