# SCIENTIFIC EXPERIMENT'S IMPLICATION ON CHANNEL MEANDER'S BEHAVIOR AND INSTABILITY

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***The Chutes occurred at Pachmarhi (Befall), because the area of maximum coarse sediments deposition is not located at the boundary.***

**Abstract:** *On Earth and other planetary surfaces, meandering rivers are very common, yet the conditions required to sustain meandering channels are invisible. As a result, 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 morpho dynamics and to test theories for wavelength and bend propagation. Here it is reported an experiment in which meandering with near-constant width was maintained during repeated cutoff and regeneration of meander bends. It is found that elevated bank strength (provided by carpet grass) 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.*

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*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. The results also suggest that sand supply may be an essential control in restoring self-maintaining, actively shifting gravel-bedded meanders.*

**Keywords: channel patterns / fluvial geomorphology / river meandering**

River meandering consequently are the lateral bank shifting which 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 (Parker, G. 1976). Channel planform classification based on field observations qualitatively suggests that meandering depends strongly on channel slope, grain size, bank strength, and sediment supply (Schumm, S.A. 1985; Church, M. 2006). Theoretical models of river meandering (Schumm SA 1985, Seminara G, 2005), 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 proved that channels with sand or gravel bed and banks will develop bars and planform curvature but will inevitably braid (Wolman, M.G. Brush, L.M. 1961; Eaton, B.C. Church, M. 2004) because the weak outer banks erosion is faster than bars can develop 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 (Bertoldi, W. Tubino, M. 2005). Experiments using clay and silt materials to strengthen the banks have produced sinuous channels, and under some conditions, channels with high sinuosity (Friedkin, J.F. 1945; Peakall, J. Ashworth, P.J. Best, J.L. 2007), 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 (Peakall, J. Ashworth, P.J. Best, J.L. 2007) or bank migration ceases once sinuosity develops (Smith, C.1998 ). Recently, carper grasses have been used to provide bank strength in experimental channels. Adding carpet grass to braided flume channels transformed them into dynamic channels with characteristics of both single-thread and island-bar morphology. The carpet grass 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.

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 to explore specifically how to make a scaled gravel-bed meandering river. It is focused on gravel-bed meanders because of their importance to aquatic habitat (Trush, W.J. McBain, S.M. Leopold, L.B. 2000) and stream restoration (Kondolf, G.M.2006) and because they can be more readily scaled to laboratory dimensions and hydraulic conditions.

It is reported that the successful experimental generation of a lateral migrating, bedload-dominated, meandering channel with repeated cutoffs. The main challenges were to create conditions that permit outer bank erosion and inner bank deposition (including up to the height of the nearby floodplain) at the similar 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. It is hypothesized that in addition to hydraulic conditions that support meandering (Parker, G.1976), 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). The experiment strongly supports the first two hypotheses, but surprisingly, meandering was maintained without variable peaks. The experiment also suggests that sand supply and deposition should be included in the design of gravel bed meandering rivers for restoration projects and included in numerical models of gravel bar growth in meandering rivers.

## Experimental Methods

A 40-cm-wide, 1.9-cm-deep channel in a 6.1-m-wide, 17-m-long flume set at a slope of 0.0046 is carved. The downstream 12 m of the flume were slightly steeper (0.0052) than the basin as a whole; this steeper reach was generally downstream of the first bend and the influence of the flume inlet. The dimensions slope, and discharge placed the channel well within the meandering regime defined by Parker, G. (1976). The flume was filled with sorted sand with median diameter of 0.8 mm (Table 1), and an initial bend was carved at the inlet to hasten the onset of meandering (Fig. 1). Carper grass is used to provide bank strength, which required reseeding the flume every 15–20 h of run time and waiting 7–10 days for the carpet grass to grow. The carpet grass was primarily used as a means to provide bank strength, but it also increased flow resistance along potential chute cutoffs, and thereby promoted fine sediment accretion along the inner bank.Under two hydrologic regimes, the flume was run for 136 h. For the first 71 h, it is repeated that a simple two-stage hydrograph consisting of 5.5 h of bankfull flow and a 1.5-h flood flow. The discharge consisted of a steady bankfull flow for the remaining 65 h (Fig. 2 and Table 2). Beside this during the first 30 h, it ran three short duration flood flows at much higher rates to test the effect of high flows on bank resistance, overbank sediment deposition, and persistence of channel form (Fig. 2). The channel was in flood stage for about 25% of the first 71 h of the experiment and 13% of the total run time. During the last 65 h, the discharge consisted of a steady bankfull flow.

**The Ancient Meandering Rivers of Mars**

**Table 1:-**Experimental conditions

| **Parameter** | **Value** |
|---|---|
| Flume width | 6.7 m |
| Flume length | 17 m |
| Median coarse grain size | 0.8 mm |
| Median fine grain size | 0.3 mm |
| Initial channel width | 40 cm |
| Initial channel depth | 1.9 cm |
| Bankfull discharge | 1.8 l/s |
| Basin slope | 0.0046 |
| Froude number | 0.55 |
| Reynolds number | 4,500 |

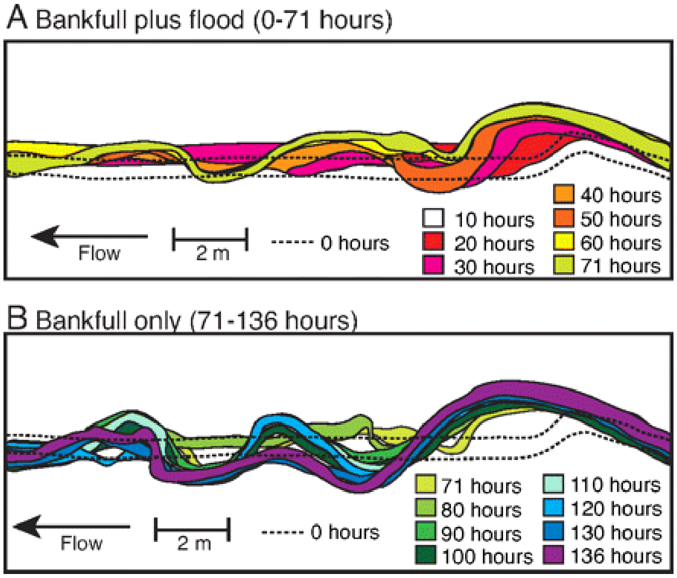


**Figure.1. The channel position through time. (*A*) explains the channel position during the first 71 h of the experiment when discharge included both a bankfull and flood flow, while (*B*) describes channel evolution from 71–136 h when the discharge was a steady bankfull flow. The original carved channel boundary is represented by the dashed lines, and the channel margin at 10 h is not visible beneath the boundary at 20 h, when the channel width was expanding. The short-lived cutoff at 29 h is not visible in this figure. Chutes have not been included in the figure for clarity, but the morphology of chutes is shown in Fig. 3.**

Although this flow was intended to be at bankfull stage, the channel shallowed, so that the discharge during the final 65 h was overbank with 2- to 5-mm-deep flows on the floodplain. As is typical of small experimental channels, the flow was in the hydraulically smooth rather than rough regime.

The sediment consists of a coarse (sand) and fine (lightweight plastic) sediment (Table 1) that were fed separately at the upstream end of the flume. The sand scales as gravel present in natural lowland gravel-bedded rivers. The unimodal fine sediment ranged between 0.25 and 0.42 mm in diameter and was not cohesive. The fine sediment scaled as sand in gravel-bedded streams, moving both as bedload and suspended load. The lightweight plastic was crucial for allowing this behavior by combining a low settling velocity (allowing for sediment to move in suspension), while reducing the critical stress relative to natural sediment with an equivalent settling velocity (e.g. silt). Because of excess Shields stress less than 2 for the majority of the bed sediment, the ratio of flow depth to median grain size less than 16, and the absence of depth-scaled bedforms (e.g. dunes and ripples), It is considered that this channel as representative of gravel bed streams passing fine sediment.

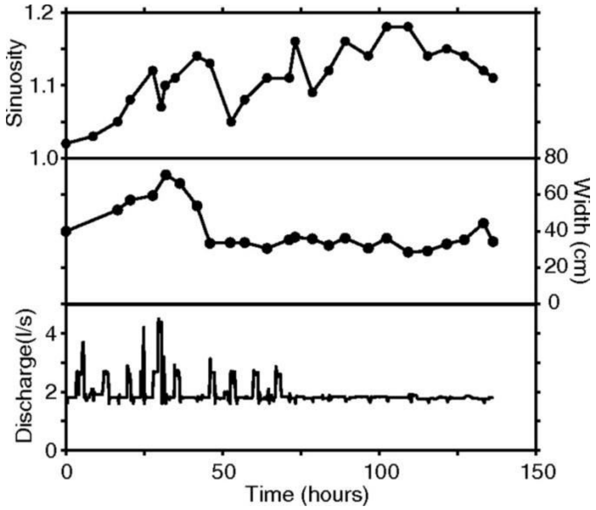


**Figure. 2. Discharge, channel width, and sinuosity alter with time. The channel width is the approximate of 10 measurements downstream of the upper 5 m, the straight reach dominated by the input conditions. The sinuosity is measured downstream of the first bend and does not consist the straight section immediately downstream of the inlet. Dips in the sinuosity are associated with cutoffs.**

The coarse feed was similar 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. It is varied that the fine sediment feed rate at the start of the experiment with a 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.

**Table 2:-** Comparison of conditions for the two runs

| **Variable discharge** | **Steady discharge** | |
|---|---|---|
| Duration | 0–71 h | 71–136 h |
| Bankfull discharge | 1.8 l/s | 1.8 l/s |
| Overbank discharge | 2.6 l/s | n/a |
| Plastic sediment specific gravity | 1.5 | 1.3 |
| Basin slope | 0.0046 | 0.0046 |

The fine feed comprised ≈82% of the total fed sediment, higher than portion of sand caught in bedload traps at gravel bed meandering rivers (Leopold, L.B. Emmett, W.W. 1997; Clayton, J.A. Pitlick, J.2007) 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, it 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. Two-types of commercially available lightweight plastic sediment as model sand is used. Both

**River Denwa meandering through gorges in the Pachmarhi, India. Denwa is a very old and prominent river in central part of India and the present meandering system dates almost certainly from the end of the Deccan Trap period**

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.

During the experiments, several calculations were made. Overhead photography was conducted at 5-min intervals during the experiment period to record the situation of the channel. Bed topography and water surface elevations were measured from a movable cart over 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 10s.

## Results Obtained

During the period of the 136-h experiment, the channel migrated both laterally and downstream, developing five bends and experiencing five distinct cutoff events. At the final stage of the experiment, the channel was entirely self-formed (Fig. 1). The wavelength stabilized at ≈14 channel widths, which is slightly higher than typically reported for meandering rivers (Knighton, D.1998). 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.

The width of the channel increased during the first 40 h of the experiment prior to stabilizing and remaining within ±12% of the resulting channel width for the balance of the experiment (Fig. 2). The primarily large increase in channel width corresponded to the high flow peaks, where bank erosion happened faster than point bars could accrete vertically to create floodplain deposits. For the balance 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 carpet grasses increase the strength of the banks relative to sand 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 grass roots 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 (Hooke, J.M. 2003) but similar to the lower Ganga River.

Bars were created by deposition of coarse sediment eroded from upstream banks and fine sediment fed from the upstream end of the flume. Very few of the coarse fed sediment were observed downstream of the first bar until after the first cutoff (Figs. 3 and 4). Prior to this time, deposition of fed sediment at the upstream-most bar caused erosion of the outer bank, which arranged sediment to downstream reaches. When it is 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. For connecting bars to the floodplain by filling the upstream end of chutes, Fine sediment was crucial. Chute channel development between the bars and the floodplain was controlled to rapid periods of migration at the start of the experiment and following cutoffs. 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 (Dietrich, W.E. Smith, J.D. 1984).

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.

Throughout the experiment, the sinuosity increased to a maximum value of 1.19 with dips during cutoff events, which controlled the sinuosity of the channel (Fig. 2). The water surface slope and bed slope ranged from 0.0044 to 0.0047 was observed 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 pre-cutoff 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 channel regenerated bars, and the abandoned channels were quickly plugged with fine sediment (Fig. 5).

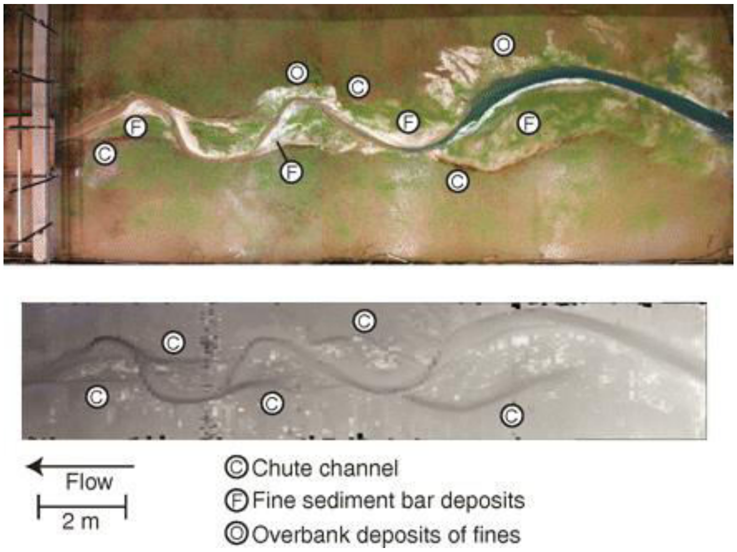


**Figure. 3. Overhead photograph and shaded topographic image 103 h after the start of the experiment. The topographic image does not cover the entire length and width of the flume. In the topographic image, darker areas are lower elevation. Labels denote chute channels, fine sediment deposits at the 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.**

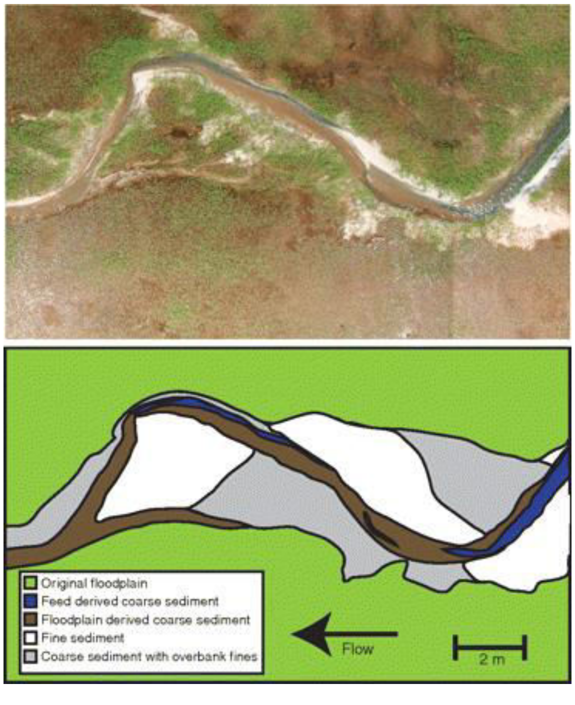
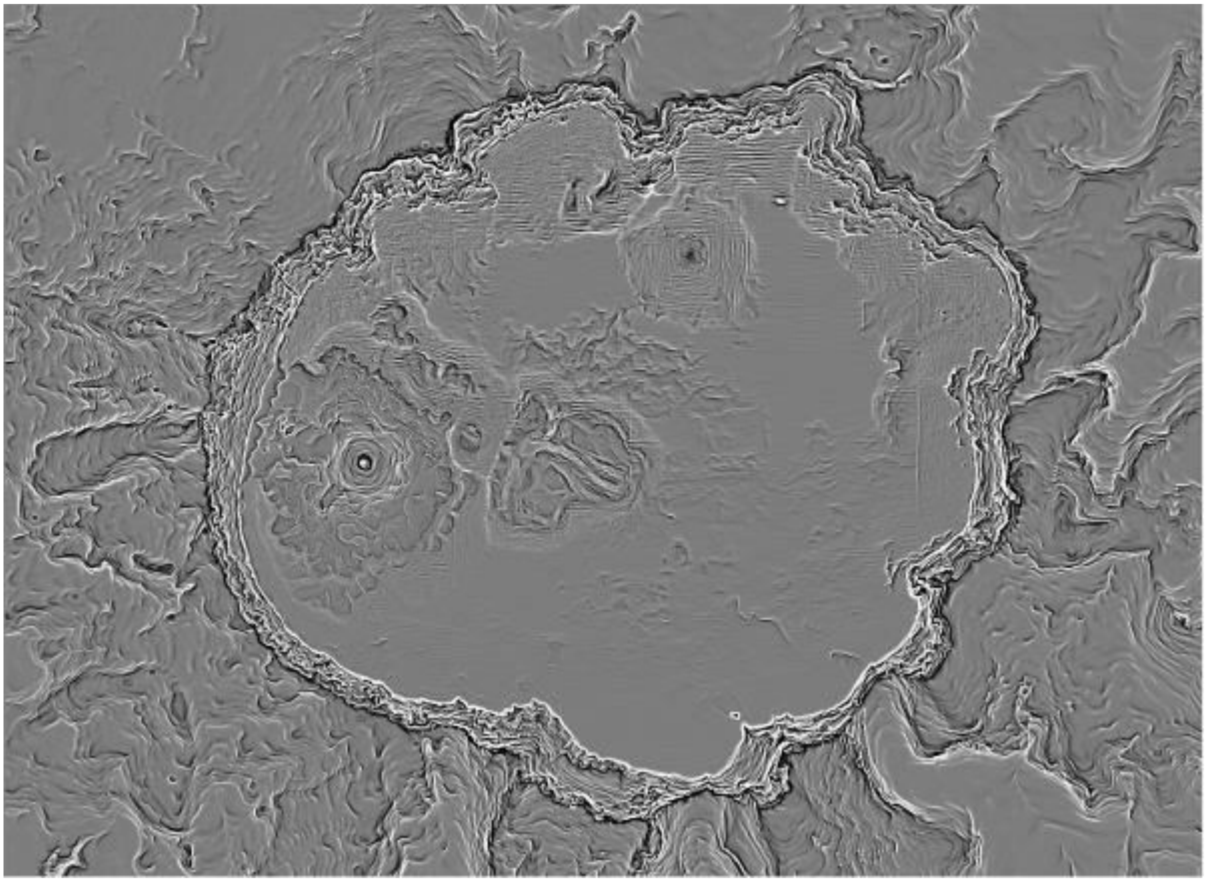


**Figure. 4.Sediment facies of second and third bars downstream from the flume inlet. Fine sediment facies are exhibited here where the most of the floodplain thickness was fine sediment. Deposition of organic matter from dead alfalfa creates some of the bar shown brown where it is initially fine sediment.**

**Figure. 5. Photograph of cutoff channel and fine sediment filling the first channel. Sediment colours are the one as Fig. 3. Fines comprised the downstream end of the bar seen in the photograph. This was the final cutoff of the experiments and was caused by headward erosion rather than bar migration into a chute.**

## Discussion

Even though it is expected that different discharge is required to promote the creation of floodplain via point bar growth, it is found that meandering was maintained during steady flows as well. This happened because, as the channel evolved, the designed bankfull flow became slightly over bank, which allowed overbank deposition during steady flow. Had the floodplain roughness been greater (through carpet grass density), the flow may have forced the steady flow to be entirely contained within the bankfull channel. 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 it continued with these high peaks, the channel likely would have braided. The 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 needs scaling time between the experiment and the field and also accounting for the number of days per year during which bank full flows or greater occurs. The mean values of bed grain size (40 mm), bank full width (43 m), and depth (1.5 m) of the gravel-bed meandering rivers analyzed by van den Berg ( Van den Berg, J.H.1995) 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 (Yalin, M.S.1971; Peakall, J. Ashworth, P. Best, J. 1996). Here it is used a Froude-scale approach common in laboratory experiments (Ashmore, P.E.1988; Parker, G. Toro-Escobar, C.M. Ramey, M. Beck, S. 2003). 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., λ0.5). If it is assumed that most channel migration occurs during bank full 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 (Micheli , E.R. Kirchner, J.W., 2002) 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 (Nanson, G.C. Hickin, E.J. 1986; Hooke, J.M. 2007) Hence, our rate is much faster than that typically found in natural channels. To reduce the migration, it could have grown carpet grass to a high density (bank strength is linearly related to carpet grass density). 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.



**Planform curvature (commonly called plan curvature) is perpendicular to the direction of the maximum slope. A positive value indicates the surface is sidewardly convex at that cell. A negative plan indicates the surface is sidewardly concave at that cell. A value of zero indicates the surface is linear Profile curvature relates to the convergence and divergence of flow across a surface.**

Investigating a meandering morphology and steady width under such fast migration rates requires an equally rapid bar growth rate. In this experiment, the fine sediment was critical to maintaining this rapid bar growth rate because fines deposited in regions where coarse sediment did not: At the upper elevation of the bars, the chute tops, and downstream of the bar apex. It is noted that in relatively sinuous gravel bed meanders with high migration rates, sand makes up the majority of the sediment accreted along the inner bank (Leopold, L.B. Wolman, M.G. 1960; Hooke, J.M. 1995). Without fine sediment deposition, the bars would not have grown to the elevation of the floodplain, and the chutes would be much larger.

There may have been sufficient time for bar growth to keep pace with bank erosion in the absence of fine sediment, if the migration rates were much slower, but several lines of evidence shows that this may not be the example. 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 Dietrich, W.E. Smith, J.D.1984) and the downstream end of the bars are therefore finer (Fisk, H.N. 1944; Clayton, J.A. Pitlick, J. 2008). 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.

Eventhough the migration rates in this experiment were high relative to natural rivers, the sinuosity was relatively low. The maximum sinuosity downstream of the first bend was 1.19, which is lower than most meandering gravel-bedded channels, in which sinuosities are often greater than 1.5 (Hooke, J.M. 2007; Hickin, E.J, Nanson, G.W. 1984). Inspite of 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 . As also observed by Friedkin (Friedkin, J.F. 1945), sinuosity was limited by the cutoff frequency. In this 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, it would be expected meandering channels in the field to have higher sinuosity where cutoffs are suppressed by rapid filling of chute channels during bar growth.

These results recommend that developing highly sinuous channels requires adequate time for fine sediment to completely infill low areas along the inner bank such that chutes are desirably 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 this experiment, it was paused 1 week for every 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

After increasing the bank strength relative to non-cohesive sediment and increasing deposition of fine sediment in troughs between point bars and the floodplain, it is created a self-sustaining meandering channel in a laboratory flume. The initial sedimentologic and hydraulic conditions were adequate for meandering as defined by Parker (Parker G, 1976). 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. The 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 define that bank strength and, necessarily, sand is required 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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