Channel curvature and sediment supply controls on the morphology and surface grain sorting of meandering gravel-bed rivers: experimental insights

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Introduction

Straight and meandering gravel bed rivers develop bar-pool bed topography and distinct bed sorting patterns. Field and flume observations have shown that straight channels with alternate bars tend to display coarse bar tops and fine pools (e.g., Mosley and Tindale, 1985; Lisle and Madej, 1992), while curved channels develop point bars that are finer than adjacent coarse pools (e.g., Bluck, 1971; Bridge and Jarvis, 1976; Whiting and Dietrich, 1991, Clayton and Pitlick, 2007). This reversal of the dominant bed sorting pattern is clearly linked to channel curvature, but we still do not fully understand how the flow field and bed topography in curved channels influence mixed-grain-size sediment transport to produce these patterns.

This extended abstract focuses on two experiments (low discharge and high discharge) conducted in a 20-degree curved channel under differing hydraulic and sediment boundary conditions. These are two experiments in a series of curved channel experiments to be conducted which all aim to document and provide insight on the mechanisms controlling bed topography and sorting in meandering gravel-bed rivers.

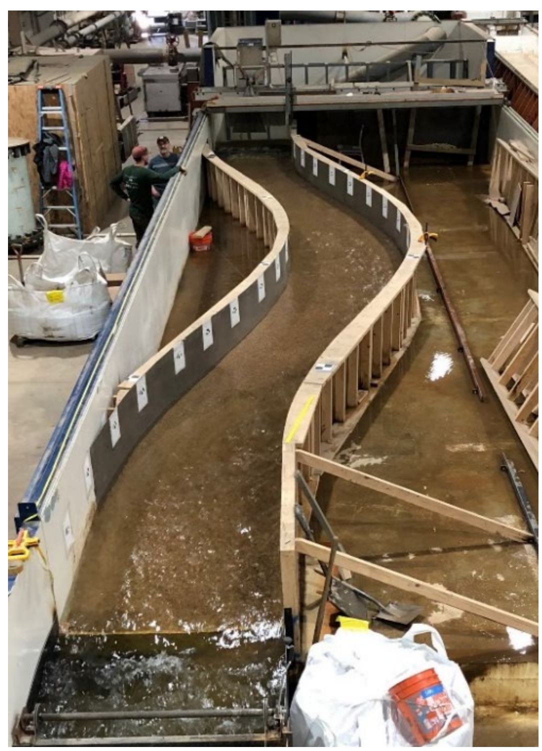

Figure 1. The channel where both experiments were conducted. Flow is from the top of the photo to the bottom. Sediment feeder is visible on scaffolding at upstream end.

Methodology

These experiments were conducted in a 16-ft wide basin at the Colorado State University hydraulics lab. A 1.35-meter-wide curved channel was constructed in this basin with a 20-degree crossing angle as shown in Figure 1. The curve was based on a sine generated trace defined by $\phi = \omega \sin\left(2\pi \frac{s}{m}\right)$ where ϕ is the angle the channel centerline makes with the horizontal down valley axes, ω is the angle the crossing angle of 20-degrees, s is the streamwise distance and m is the meander wavelength (Whiting and Dietrich, 1993). The downstream end had a metal tailbox with an adjustable tailgate to collect sediment transport out of the channel and control the downstream water surface elevation. The rate of sediment leaving the flume was determined by drying and weighing the sediment collected in this tailbox at the end of each timed run. A sediment auger-type feeder was placed above the channel at the upstream end and fed sediment at a constant rate for the entire experiment. The remaining hydraulic, geometric, and sediment related parameters for both experiments are shown in Table 1.

Table 1. Experimental parameters for both the low discharge and high discharge experiments.

		Experiment Version	
Category	Parameter	Low Discharge	High Discharge
Geometry	channel length	15.2 m	15.2 m
	channel width	1.35 m	1.35 m
	wavelength	12.2 m	12.2 m
	crossing angle (ω)	20°	20°
	slope	0.005 m/m	0.007 m/m
Hydraulics	width-to-depth ratio	20	15
	mean depth	0.07 m	0.09 m
	discharge	0.04 cms	0.10 cms
	mean boundary shear stress (τ)	3.36 Pa	5.45 Pa
Sediment	bed material	sub-angular gravel	sub-angular gravel
	D_{16}	1.8 mm	1.8 mm
	D_{50}	3.3 mm	3.3 mm
	D_{84}	5.0 mm	5.0 mm
	mean Shields stress (τ^*)	0.065	0.105
	excess shear ratio (τ^*/τ^*_c)	1.6	2.6
	upstream feed rate	59 kg/hr	230 kg/hr

Each experiment was run under steady discharge and steady feed conditions until the bed reached dynamic equilibrium. We determined that dynamic equilibrium had been reached when the rate of sediment leaving the flume equaled the rate being fed at the upstream end, and when the bed exhibited a steady slope with no substantial areas of aggradation or degradation. The rate of sediment leaving the flume was determined by weighing the dried sediment collected in the tailbox after each timed run. Both the low and high discharge experiment reached this condition after 25 hours of run time.

During the initial 25 hours of runtime, the flume was drained periodically to allow for topographic bed surveys. These surveys were accomplished through structure-from-motion photogrammetry (Morgan, 2017). For the high flow experiment, the resulting point clouds had approximately one-millimeter spatial resolution and overall registration accuracies of less than one-centimeter. The low flow experiment point clouds are of slightly lower quality due to a different photographing and processing procedure. A final topographic survey was conducted at the end of the measurement period described below. To better visualize the bed morphology, the detrended elevation is computed by removing the reach average slope from the original topographic model.

Once the bed reached equilibrium, we collected extensive measurements of relevant morphodynamic metrics. Measurements included detailed water surface profiles, velocity profiles, and bedload measurements. These measurements were collected at cross sections spaced about half a channel width apart (0.7 m). The water surface profiles and velocity data are not presented in this abstract. It is important to note, because the bed was at equilibrium, we can compute the cross-stream bedload transport rates from the downstream rates measured by the Helley-Smith bedload sampler (Dietrich and Smith, 1984; Nelson et al., 2010). Finally, a series of photos were taken near the bed to be photo sieved (Graham et al., 2005) to determine the surface grain size distribution. A roughness index (Wilson et al., 2007) was also computed from the point cloud and used as a proxy for the distribution of relative grain sizes.

Results and Discussion

Both experiments produced the characteristic bar-pool morphology of curved channels, with two pools and one fully formed bar (Figure 2). In both cases, one pool was located just downstream of the bend apex, as expected, and one was located upstream against the right bank just at the start of the curve. This upstream pool was an artifact of the single bend geometry, as the first initiation of the bend acted as a bend apex, forcing the formation of a pool. Without the full bend, a fully developed point bar was not able to form at the upstream end of the channel.

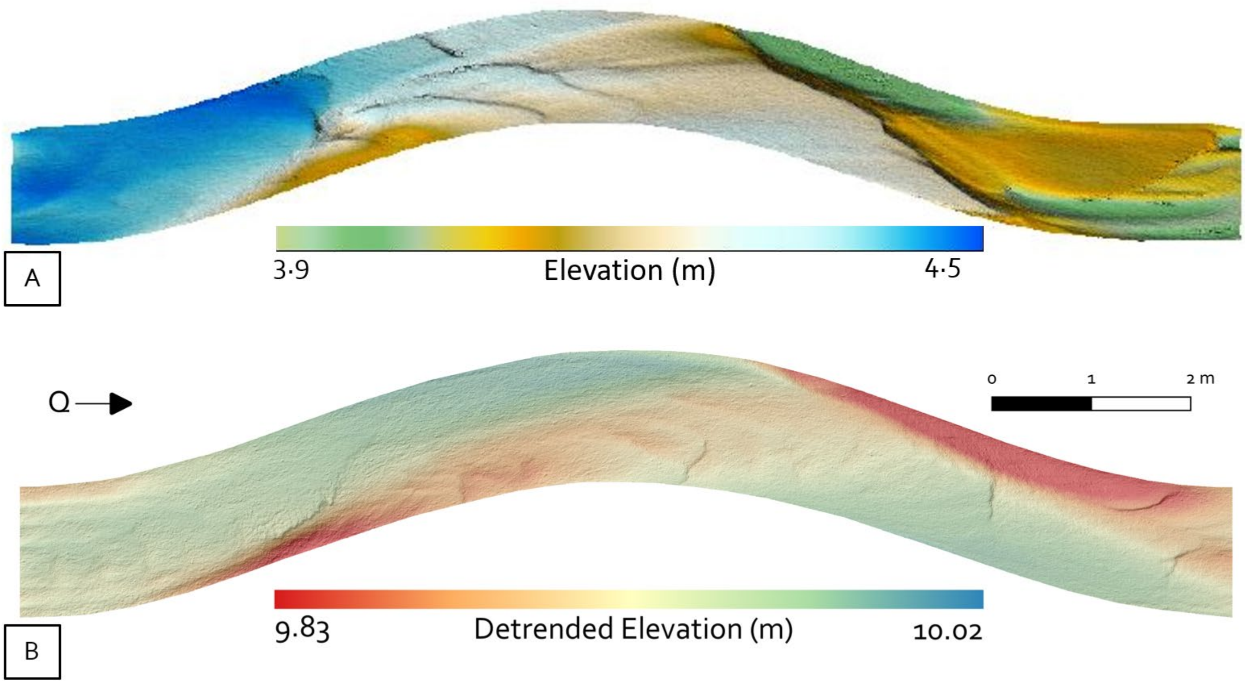

Figure 2. Equilibrium bed topography for the low flow (panel A) and high flow (panel B) experiments (panel A from Hanson (2016)).

Overall, the general morphology was very similar between the two experiments, despite having twice the discharge and nearly four times the sediment feed in the second design. This suggests that the formation of the bar pool morphology is primarily controlled by the channel geometry and is not a function of width-to-depth ratio (a function of discharge) or sediment supply. Morphologic differences between the two experiments include the fact that the bar top and the bottom of the pool are both located further downstream in the high flow experiment than they were in the low flow experiment. There are also minor differences in the amplitude of the bars relative to their adjacent pool. In the low flow experiment, there was a slightly larger elevation difference between the pool and adjacent bar (approximately 0.4 m). In the high flow experiment, the bar amplitude was slightly less (approximately 0.2 m). Therefore, while the general morphology is a function of channel geometry, the discharge and sediment supply appear to control the size and shape of the expected morphology.

In general, the expected sorting patterns observed in curved channels have been attributed to secondary flow paths (Parker and Andrews, 1985; Ikeda, 1989; Clayton and Pitlick, 2007). However, our understanding of this process is limited. One key question that has not previously been addressed is identifying the threshold degree of curvature necessary for the expected sorting pattern of coarse pools and fine bars to initiate. Surface grain size data from the low and high flow experiments (Figure 3) demonstrate the difference in the characteristic sorting pattern. The low flow surface grain sizes estimated from automatic photo sieving show very little coherent sorting throughout the bed (Figure 3A). Observations of the flume bed at 25 hours confirm the lack of any substantial sorting patterns (Hanson, 2016). Initial results from the high flow experiment (Figure 3B) suggest that the expected sorting pattern formed under high discharge, high sediment feed conditions. Figure 3B results show the roughness of a 2 mm DEM created from the high-resolution point cloud; coarse areas exhibit higher roughness than fine areas. Roughness is defined here as the largest inter-cell vertical difference of a central pixel and its adjacent pixels (Wilson et al., 2007). In the region of the pool, the DEM is rougher, indicating that the pool is coarser than the bar top. Observations of the bed at the end of the 25-hour high flow run support the presence of these sorting patterns. Relative roughness is used for the high flow experiment because automatic photo sieving has not been completed yet.

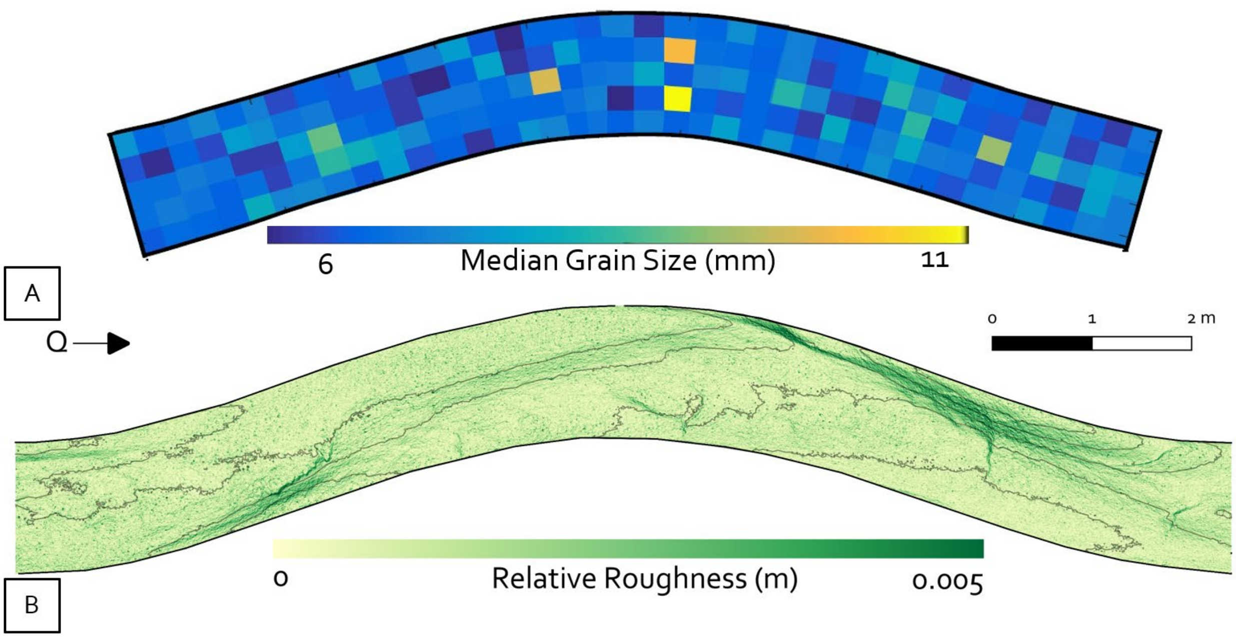

Figure 3. Median grain size determined via automatic photosieving for the low flow experiment (panel A) and relative roughness from a 2 mm raster for the high flow experiment (panel B).

These sorting results suggest that the formation of the characteristic curved channel sorting pattern is not solely a function of curvature, which remained constant between the two experiments. Rather, the expected sorting pattern requires not just a certain degree of curvature, but high enough sediment supply, and enough flow to transport the high sediment supply. Given the overall coarsening of the bed during the low flow experiment, we also speculate that the sediment supply was low enough to cause armoring of the bed, as the slope was not allowed to adjust.

Conclusions

Comparing bed morphology and surface sorting in two experiments with identical geometry but differing hydraulic and sediment conditions allows us to evaluate geomorphic and hydraulic controls on channel morphology and surface sorting. Although channel curvature determines the overall morphologic patterns (point bars and pools), the sediment supply and width-to-depth ratio control specific meandering channel morphology and sorting patterns. Furthermore, we conclude that sufficient sediment supply is necessary to develop characteristic sorting patterns, in addition to channel curvature.

We have also collected large bedload transport and velocity profile datasets for both the low and high flow experiments presented here. We expect that these data will provide insight into the hydrodynamic and morphodynamic processes in river bends that control bar-pool formation and characteristics. These experiments will represent the first near-field scale flume experiments in which detailed velocity measurements can be coupled with bedload transport data. With these data we hope to identify any coupling between size selective cross-stream sediment transport and secondary flow patterns.

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