PATH OF GRAVEL MOVEMENT IN A COARSE STREAM CHANNEL

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INTRODUCTION

Little is known about the path of gravel transport within a mountain stream, and it is often assumed that gravel bedload generally follows the thalweg where flow is deepest and fastest. However, field studies have shown this not to be the case. Based on the forces of flow and gravity acting on bedload particles in a meander bend, Dietrich and Smith (1984), Parker and Andrews (1985) and Bridge (1992) concluded that coarse and fine bedload followed different paths. The coarse portion approaches a stream bend along the inside bank and crosses over to the outside bank near the bend apex. Measured bedload travel paths in sand-bedded meandering streams by Bridge and Jarvis (1976; 1982), Dietrich and Whiting (1989), Anthony and Harvey (1991) and Julien and Anthony (2002) also showed that the fine and coarse portion of bedload followed different paths. The coarse fraction, coarse sand and pea gravel, traveled laterally over the head of the point bar close to the inside bank, shifted towards the stream center at the bend apex and towards the thalweg in the outside bank at the bend exit. This path coincided approximately with the location of highest grain shear stress. We may reasonably ask whether gravel transport in coarse-bedded mountain streams with a meandering thalweg also follows a similar distinct and predictable path.

Knowing where within a stream cross-section most of the gravel travels not only furthers our general understanding of how gravel transport and stream morphology work together, but the ability to identify the location of maximum transport by simply looking at the local stream morphology would also be helpful for planning field measurements of gravel transport. Sampling could be focused at the locations of highest transport within a cross-section and thus increase the accuracy obtained from a specified number of samples. If wadeability was an issue, sampling could be focused at locations within a cross-section where most of the transport occurs in relatively shallow flow. In order to find out where within a stream most of the gravel bedload is transported we examined the lateral positions of gravel bedload measured in eight individual cross-sections in different gravel- and cobble-bed streams, as well as the gravel transport path over a point bar.

METHODS

Gravel bedload transport was measured at eight sites in six different streams that were classified as having plane-bed and step-pool morphology. Although not generally meandering, all streams had a meandering thalweg and gravel bars that were mostly submerged during low and moderate flows. Gravel transport was measured using bedload traps. Bedload traps consist of an aluminum frame 0.3 by 0.2 m in size that is fastened onto a ground plate that is anchored to the stream bottom. Bedload is collected in a 0.9-1.6 m long net with a 3.5 mm mesh width.

Sampling time was typically 1 hour, but was reduced when transport rates were high. Four to six bedload traps were typically installed across the stream spaced 1-2 m apart (Bunte et al. 2003, 2004, 2005) (Figure 1). Four to 9 samples of gravel bedload transport were collected almost every day over the snowmelt highflow season that typically lasted 4-7 weeks. This amounted to 21-163 samples per site with an average of 80. At one stream, Halfmoon Creek, near Leadville, CO, gravel bedload was measured with 6 bedload traps installed in two neighboring cross-sections. One spanned a riffle close to the pool exit, while the other was located about 8 m downstream and spanned a point bar-thalweg cross-section (Figure 1).

Figure 1 Bedload traps installed at two neighboring cross-sections at Halfmoon Creek.

Gravel transport rates were computed for each trap per cross-section individually and then assigned to the portion of stream width represented by each trap. Summing across the stream yielded the cross-sectionally averaged transport rate. The proportion of total transport passing through individual stream sections during a highflow season can be computed for each measuring site.

Although none of the streams were classified as meandering, all of the measuring sites were situated within reaches that had a meandering thalweg. In some cross-sections, the thalweg was near one of the banks, in others the thalweg was near the center of the stream. Assuming an idealized reach with a meandering thalweg (see center part of Figure 2), the measured cross-sections from different streams can be longitudinally arranged over an idealized meandering reach such that the lateral location of the thalweg in the measured cross-sections matches the one in the idealized reach. Each individual cross-section then represents a specified location, i.e., some cross-sections represent the upstream part of a submerged point bar, some the downstream part, and some the riffle or crossing (Figure 2). For each of the cross-sections, the lateral position of maximum annual gravel bedload transport is known from the field measurements.

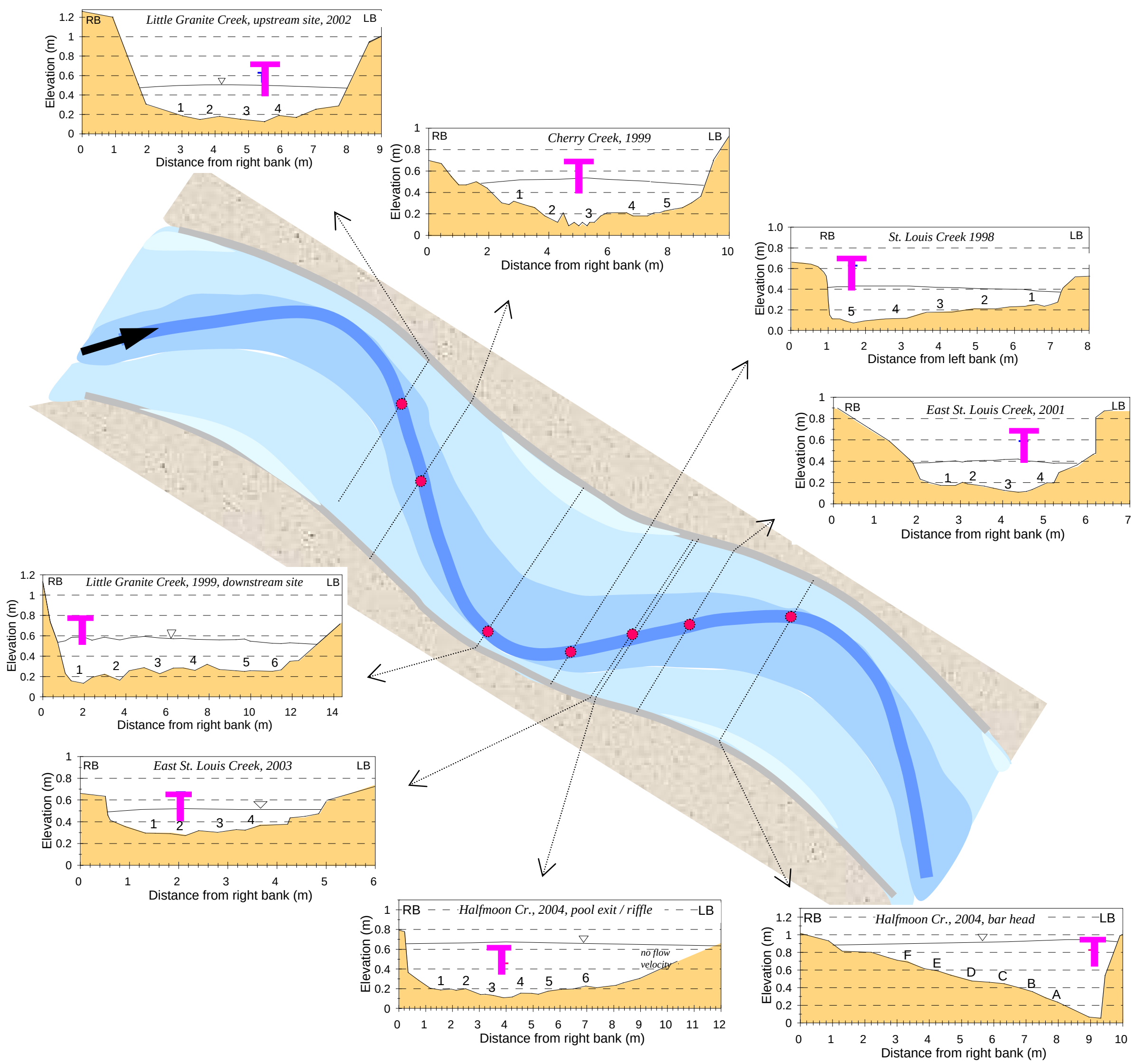

Figure 2 Longitudinal arrangement of measured cross-sections from different streams to represent locations within an idealized reach that has a meandering thalweg. The pink "T" indicates the thalweg. Darker blue colors indicate deeper flow. Numbers and letters in the cross-sections indicate bedload trap locations.

RESULTS

<u>Transport locations in eight cross-sections representing a meandering thalweg reach:</u> Results from our field studies showed that for cross-sections that extended from a bar on one bank to a thalweg on the other bank, most of the gravel traveled over the bar. At a pool exit, most gravel traveled through the thalweg, and at a riffle or crossing, transport was focused toward the side of the stream at which the next downstream bar appeared. Knowing the lateral position of major gravel transport for each of the 8 cross-sections that cover an idealized meandering thalweg reach, a picture of the downstream travel path can be developed. The combined results from the individual field studies strongly suggested that gravel transport in coarse-bedded streams with a meandering thalweg follows the path taken by the coarsest particles in sand-bedded streams indicated by the yellow stippled band in Figure 3: over the bankward side of the bar head, then diagonally across the bar and towards the pool near the bend apex.

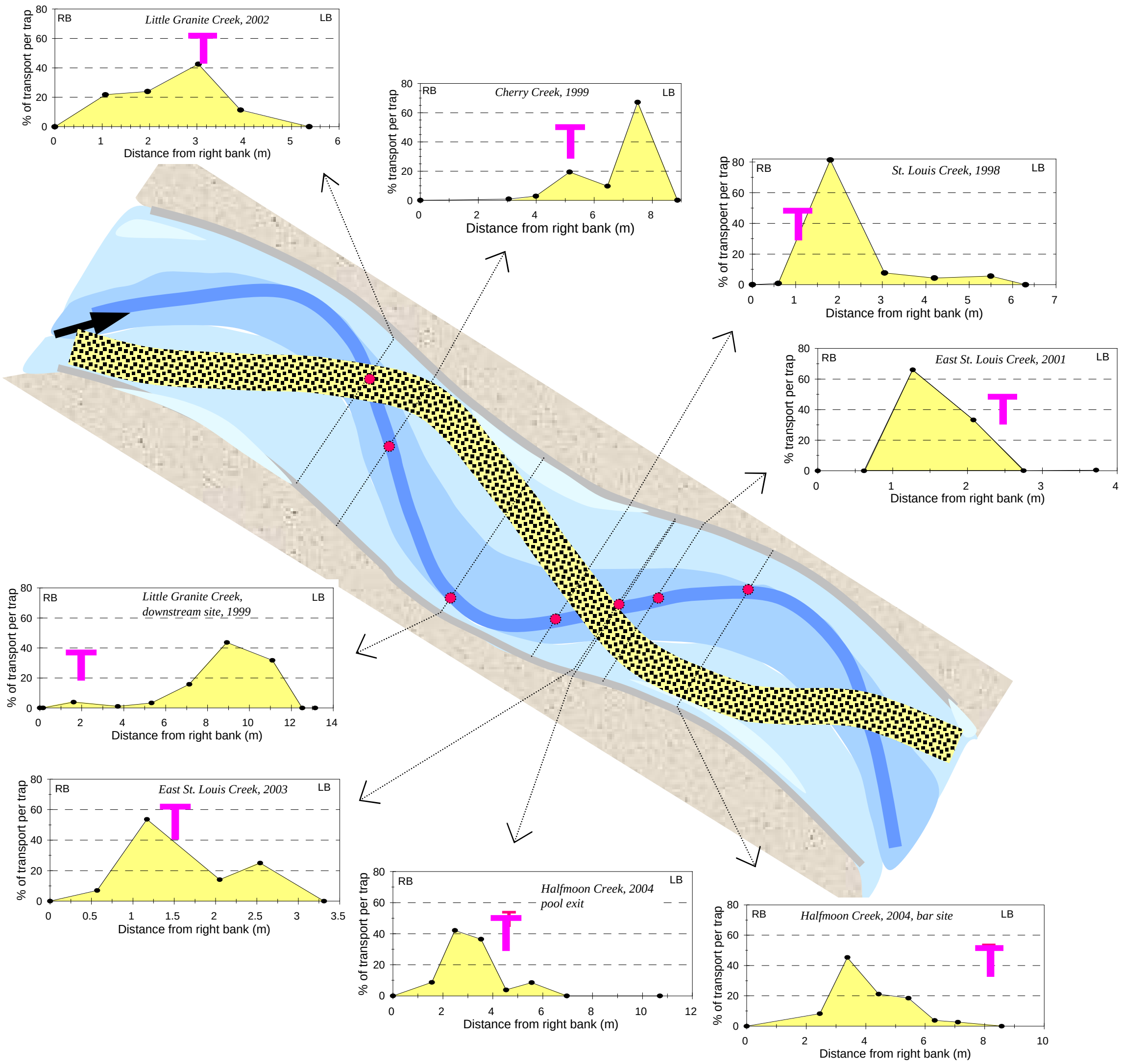

Figure 3 Lateral positions of maximum annual transport in eight cross-sections representing different locations within a meandering thalweg reach. The stippled yellow band indicates the travel path for gravel transport.

Transport path between the pool exit and the bar head: To confirm the gravel transport path along the inside bank between the pool exit and the head of a point bar, the lateral location of gravel transport was evaluated over two neighboring cross-sections in a pool-riffle section of a mountain gravel-bed stream (Halfmoon Creek). Integrated over the entire highflow season, most of the gravel was transported adjacent to the thalweg towards the inside bend in the pool exit/riffle cross-section. In the point bar cross-section, most gravel traveled over the shallow parts of the bar (compare the two lower right plots for Halfmoon Creek in Figures 2 and 3).

The lateral locations of gravel transport were not static over the highflow season but shifted laterally with the magnitude flow. At the lowest gravel transporting flows (14-27% of bankfull), most of the pea gravel in transport moved near the thalweg in the pool exit/riffle. At higher flows, gravel transport shifted towards the inside bank (Figure 4). At the bar head, most gravel transport occurred over the center of the bar at low flows and moved higher onto the bar as flows increased to 80% Q_{bkf}. The location of maximum transport rates were also the locations where the largest gravel particles were transported. Experiments with mobile tracer gravels confirmed the curved transport path along the inside bend. Gravel transport rates and the largest gravel bedload particle sizes had a secondary maximum closer to the thalweg, but transport rates there attained only 10% of the maximum rates. Almost no transport took place through the thalweg.

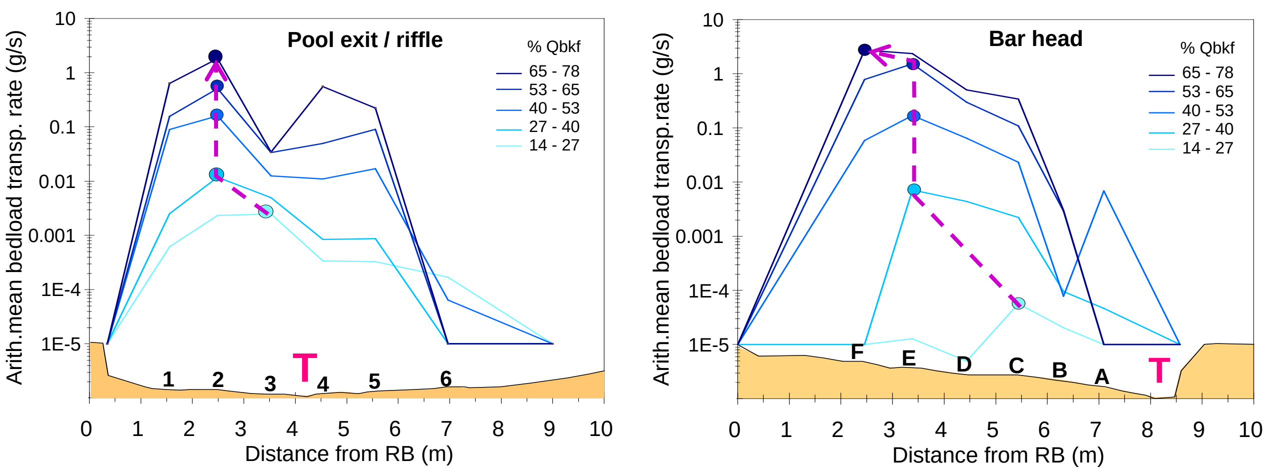

Figure 4 Lateral shift of gravel transport from near the center of the bankfull stream width at the lowest transporting flows towards the inside bank at the highest measured flows. Bold numbers and letters along the bottom of the plots indicate locations of bedload traps in the cross-section. The dashed arrows indicate the bankward shift in the locations of maximum transport with increasing flow.

Predictability of the lateral distribution of gravel transport rates from flow hydraulics and bed material size: Of several measured and computed parameters of flow hydraulics, the maximum mean flow velocity per vertical (v) measured in 0.6 of the water depth (d) coincided with the locations of maximum transport rates (Figure 5). By contrast, local water depth, discharge per unit width (q) and boundary shear stress (τ_o) were always largest at the thalweg and did not predict the lateral variation in gravel transport rates. Grain shear stress τ_g computed from $\rho_f \cdot [(v_d \cdot \kappa)/\ln(d/0.1\, D_{84})]^2$ (Dietrich and Whiting 1989) (where κ is a constant that is usually taken as 0.4, and D_{84} is the size for which 84% of the sediment is smaller) as well as dimensionless shear stress $\tau^*=\tau_o/(\rho_s-\rho_f)\cdot g\cdot D_{50}$ (with ρ_s = sediment density) which within a cross-section is a function of d/D_{50} both had their maxima in the thalweg, but secondary maxima were noticeable for the two parameters over the bar.

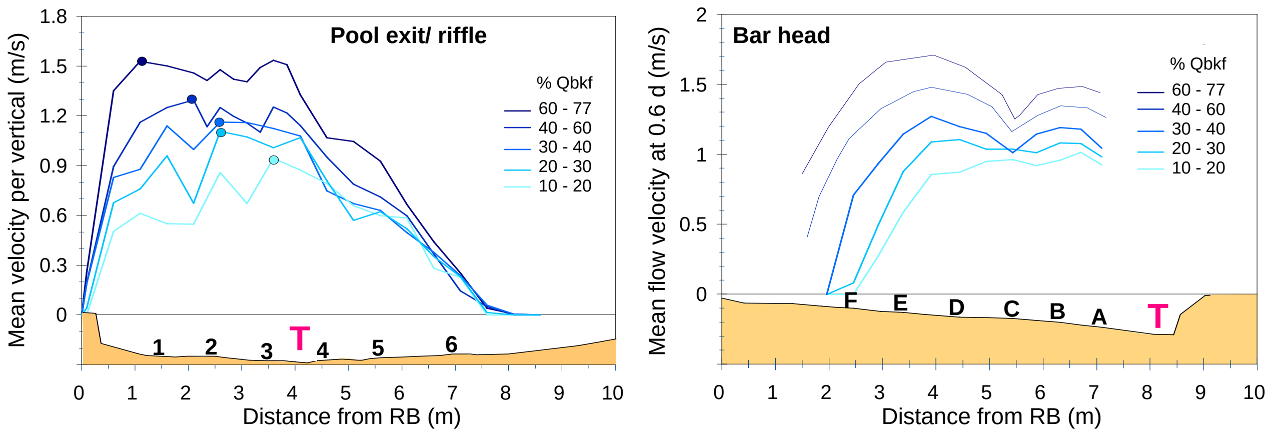

Figure 5 Lateral distribution of the mean vertical flow velocity in the pool exit/riffle (left) and the point bar-thalweg cross-section (right). Velocities at the point bar-thalweg cross-section for flows above 50% of bankfull are extrapolated and printed in dashed lines.

The bed material size and structure, by comparison, were good predictors of the bedload transport locations at Halfmoon Creek. At the bankward side of the bar, the local surface D_{50} bed-material particle size was 8 mm and increased to 46 mm in the thalweg. Besides a strong bankward fining trend, the bed on the bar was unarmored and easily erodible. The bed material in the thalweg was not only considerably coarser and devoid of surface fines but also strongly imbricated and thus quite erosion resistant. The surface bed material size in the pool exit/riffle cross-section did not show bankward fining except for a silty backwater deposit on the far bank.

Making use of the asymmetrical travel path for bedload sampling in deeper streams: Bedload transport in mountain streams is often collected using hand operated samplers such as a Helley-Smith-type sampler, bedload traps, basket-type samplers or non-recording pit traps (Ryan et al. 2005). These samplers are typically deployed in a straight reach with a symmetrical cross-section. All of these samplers require flows that are wadeable during sampler operation. Wadeability can be defined as the product of flow depth and mean vertical flow velocity in English units (Abt et al. 1989). Depending on a person's height and weight (as well as athletic skills and the slipperiness of the bed), values of 7-12 pose a limit to safe wading. At flows near bankfull or larger, even small streams often become difficult to wade, while wading may become next to impossible for many people in most cross-sections of larger streams.

Results from the study at Halfmoon Creek indicated that most gravel travels over the head of submerged point bars along the inside bend. This stream location – the upstream end of a sub-merged point bar – is generally likely to remain wadeable over much of the stream width when the riffle or crossing has become unwadeable at high flow. In our study, 90-95% of the cross-sectional gravel transport was collected within the 50% of the bankfull stream width at the inside bend during flows 40-80% of bankfull (Figure 6, left). This means that at the head of a point bar, the majority of all gravel bedload is transported within the wadeable portion of the stream (Figure 6, right).

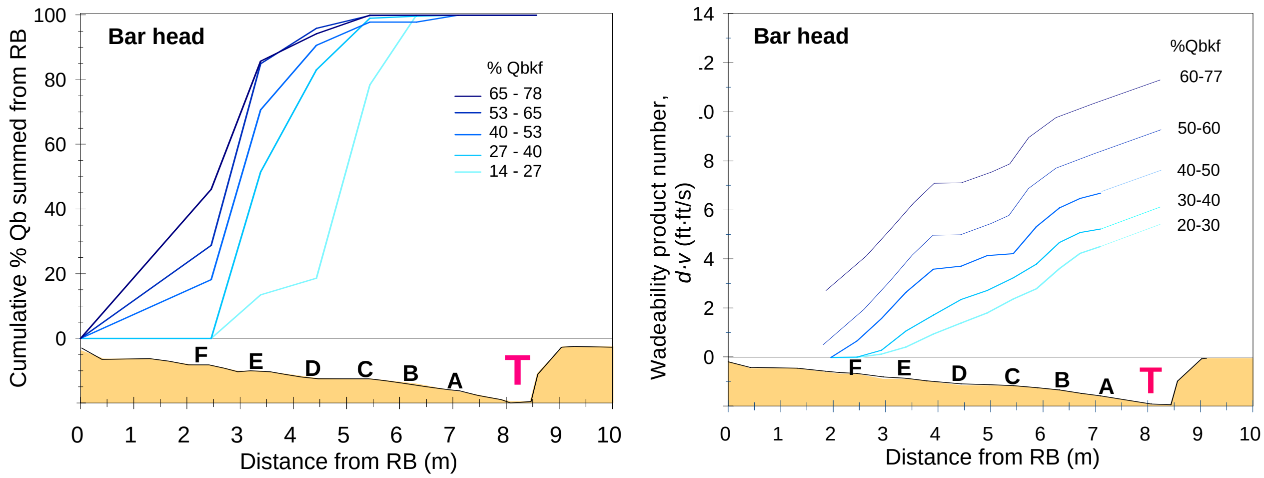

Figure 6 Cumulative percent of total cross-sectional gravel transport (summed over sampling locations starting at the shallow part of the stream) for flows 20 to 70% of bankfull (left). Wadeability of the cross-section for increasing flow (right).

DISCUSSION AND CONCLUSION

Combined results from our field studies suggested that in a coarse gravel-bedded mountain stream with a meandering thalweg, gravel travels over the head of the submerged bar along the inside bankward side, proceeds diagonally over the bar and then towards the thalweg near the bar apex. Detailed measurements on two neighboring cross-sections between a pool exit and the head of the point bar in a mountain stream verified this transport path. The path of gravel transport in mountain streams with a meandering thalweg thus is predictable from stream morphology and generally follows the path modeled and measured for the coarsest bedload in sand-bedded streams.

The observed shift in gravel transport towards the inside bank occurred when flows increased from 20 to 80% of bankfull flow. It is unknown whether this bankward trend continues for flows larger than bankfull or when transport rates are very high. The observed gravel transport path may change during high sediment supply when subsequent high transport rates may change the local channel morphology. Gravel transport may also deviate from its predicted path in stream bends if local hydraulics are influenced by non-moveable boundaries such as bedrock outcrops or large woody debris, which may cause different spatial patterns of bedload transport. However, under moderate flow and transport conditions that formed freely in a moveable gravel bed, knowledge of the gravel transport path over a submerged bar can be used when designing a sampling scheme. Measurements of gravel bedload could be concentrated or intensified at the location of maximum transport in order to increase the accuracy obtained from a preset number of samples. If wadeability is an issue, sampling can be limited to the shallow portion of the stream over the upstream part of a submerged point bar, where wading is possible while other parts of the stream no longer permit this, without neglecting a substantial portion of bedload.

A few caveats are associated with sampling across a bar head, though. Flow hydraulics at this location are influenced by the asymmetrical cross-sectional shape; they are subject to strong secondary flows and thus not well suited to characterize the general hydraulic conditions of the reach which are customarily measured within a straight reach or across a riffle. Note also that sand follows a downstream path that is different from the one followed by gravel. The majority of sand does not travel over the bankward part of the bar head but rather the bar tail. Bedload transport rates measured for a specified flow across the bar head may also differ slightly from those measured on a nearby riffle. In our study, the rating curve across the bar head was slightly steeper, because the very onset of fine gravel particle motion occurred at somewhat higher flows than on the riffle, while during the largest measured flows transport rates on the bar were slightly higher. However, compared to not being able to collect samples at all, the slight shift in the rating curve poses a relatively small inaccuracy.

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