Unifying Criterion for the Velocity Reversal Hypothesis in Gravel-Bed Rivers

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Abstract: It has been hypothesized that velocity reversals provide a mechanism for maintaining pool-riffle morphology in gravel-bed rivers—an important habitat for salmonids, which are at risk in many places worldwide and that are the focus of extensive environmental legislation in Europe and North America. However, the occurrence of velocity reversals has been controversial for over 3 decades. We present a simple one-dimensional criterion that unifies and explains previous disparate findings regarding the occurrence of velocity reversals. Results show that reversal depends critically on the ratio of riffle-to-pool width, residual pool depth (difference between pool and riffle elevations), and on the depth of flow over the riffle, suggesting that land management activities which alter channel form or divert water from the channel can have negative impacts on the sustainability of pool-riffle habitat in gravel-bed rivers.

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Introduction

The development of pool-riffle sequences (Fig. 1) is characteristic of both straight and meandering channels with slopes less than 2% and bed material composed of sand, gravel, or cobble (Leopold et al. 1964; Montgomery and Buffington 1997; Knighton 1998). At low and intermediate flows the riffle acts as a hydraulic control on flow through the upstream pool (Richards 1978; 2004), whereas at flood flows the riffle is submerged and functions more as a large-scale roughness element. At low flows the velocity over the steep downstream face of the riffle is higher than through the pool, but it has been hypothesized that velocity increases with discharge at a faster rate through the pool, causing it to exceed the velocity over the riffle as high flows drown out the riffle's control on the water surface slope of the pool (Gilbert 1914; Keller 1971; Lisle 1979). This condition is called velocity reversal and it has been proposed as a mechanism for the maintenance of pool-riffle features, whereby reversal of velocity causes corresponding reversal of shear stress and transport capacity that scours sediment previously deposited in the pool, with the larger clasts being deposited on the downstream riffle due to relatively lower competence (Gilbert 1914; Keller 1971; 1972; Lisle 1979; Clifford and Richards 1992; Keller and Florsheim 1993; Wohl 2000; Milan et al. 2001). Although much is known about the mechanics of pool-riffle channels, there is a lack of consensus regarding the occurrence of velocity reversals, despite over 3 decades of study. Several investigations have shown reversal occurrence (Keller 1971; 1972; Andrews 1979; 1982; Lisle 1979; 1982; Teissyre 1984; O'Connor et al. 1986; Petit 1987; Ashworth and Ferguson 1989; Sear 1992a,b; 1996; Keller and Florsheim 1993; Thompson et al. 1996; 1998; 1999; Booker et al. 2001; Milan et al. 2001; Cao et al. 2003; Wilkinson et al. 2004; MacWilliams et al. 2006), some have found that with increasing discharge the velocity increases at a faster rate through the pool than over the riffle, but have not observed reversal (Richards 1976a,b; 1978; Jackson and Beschta 1982; Carling 1991; Clifford and Richards 1992; Carling and Wood 1994; Robert 1997), and there are some that deny the existence of velocity reversal (Teleki 1972; Bhowmik and Demissie 1982a,b). In this technical note, we use basic hydraulic equations to resolve these differences.

Criterion Development

Channel morphology in gravel-bed rivers is fairly stable during typical flood events (bankfull or mean annual flows), with local scour and fill of bed topography occurring, but without major reconfiguration of the channel planform (Leopold et al. 1964). Hence, pool-riffle sequences can be viewed as quasi-stable features for typical flood events in gravel-bed rivers. Steady flow through a stable pool-riffle sequence with no flow across the banks and neglecting hyporheic (surface-subsurface) exchange, must satisfy principles of mass and energy conservation. For mass conservation, the discharge at the pool cross section must be the same as that at the riffle cross section

$$u_P h_P B_P = u_R h_R B_R \tag{1}$$

where u_P, u_R=pool and riffle cross-sectional average velocities; h_P, h_R=pool and riffle hydraulic mean water depths; and B_P,

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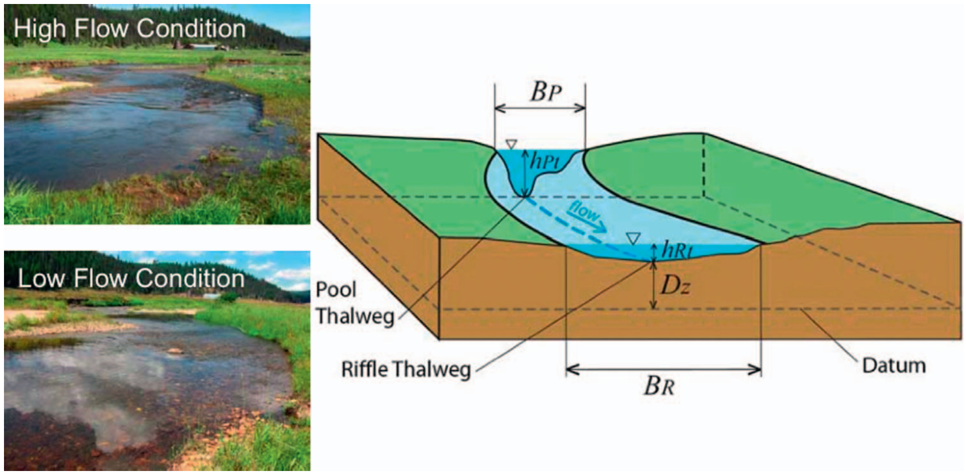

Fig. 1. (Color) Typical gravel-bed stream, Red River, Idaho, at high and low flow, with cartoon of channel morphology showing pool-riffle topography and governing variables of hydraulic analysis. Klein et al. 2007 provide further description of the site.

B_R=pool and riffle water surface widths (Fig. 1). Since by definition the pool is deeper than the riffle ($h_P > h_R$) Eq. (1) implies that the cross-sectional average velocity reversal ($u_P > u_R$) is only possible when the riffle is wider than the pool. For energy conservation, the total energy at the pool cross section must equal that at the riffle cross section plus energy losses between the sections

$$z_{Pt} + h_{Pt} + \alpha_P u_P^2/2g = z_{Rt} + h_{Rt} + \alpha_R u_R^2/2g + (h_e + h_f) \qquad (2)$$

where z_{Pt}, z_{Rt}=pool and riffle thalweg elevations; h_{Pt}, h_{Rt}=pool and riffle thalweg water depths, α_P, α_R=pool and riffle velocity coefficients; h_e accounts for the expansion losses; and h_f represents the friction losses between the pool and riffle. The energy equation is defined here in terms of thalweg depths to explore the effects of cross-sectional shape on velocity reversal, with the thalweg and cross-sectional average depths related as $h_P = \sigma_P h_{Pt}$ and $h_R = \sigma_R h_{Rt}$, where σ is a positive parameter $\leqslant 1$. that depends on the shape of the cross section. Thalweg values were also selected for ease of field measurement, and measurement consistency between observations since part of the velocity reversal controversy may stem from differences in the location where velocities were measured within the pool-riffle sequences.

Combining the mass and energy conservation equations yields

$$\frac{u_P}{u_R} = \frac{\sigma_R}{\sigma_P}\frac{B_R}{B_P} \Bigg/ \left[\frac{Dz + \frac{1}{2g}(\alpha_R u_R^2 - \alpha_P u_P^2) + h_e + h_f}{h_{Rt}} + 1\right] \qquad (3)$$

where Dz=residual pool depth (Lisle and Hilton 1992) defined here as the difference between the pool and riffle thalweg elevations ($z_{Rt} - z_{Pt}$). At the threshold for velocity reversal, the pool and riffle velocities are equal ($u_P = u_R$) and Eq. (3) reduces to

$$\frac{\sigma_R}{\sigma_P}\frac{B_R}{B_P} - 1 = \frac{Dz + h_e + h_f}{h_{Rt}} \qquad (4)$$

The velocity head difference term of the energy equation has been dropped from Eq. (4) because differences in α_P and α_R are assumed to be negligible at high flows (O'Connor et al. 1986; Clifford and Richards 1992) where velocity reversal is expected to take place (i.e., near bankfull) (Keller 1971; Lisle 1979). When velocity reversal occurs, the left-hand side of Eq. (4) will exceed the right-hand side (Caamaño 2008). More specifically, Eq. (4) predicts that reversal will happen when nonuniformity of cross-sectional shape (left-hand side) is greater than the relative depth (ratio of residual depth to flow depth over the riffle), as modulated by energy losses (right-hand side). Dz is considered constant (quasi-stable) for the flows examined here (near bankfull and less), whereas the other variables in Eq. (4) will all change with discharge.

It can be seen from Eq. (4) that energy losses due to expansion of the flow across the riffle (h_e) or from frictional resistance (h_f) across the pool-riffle sequence both act to cause the velocity reversal to occur at a higher flow depth over the riffle (i.e., higher discharge), or perhaps inhibit the occurrence of velocity reversal altogether.

Criterion Verification

Here, we test a simplified version of the model in which we neglect the head losses (h_e, h_f) and the cross-sectional shape ratio (σ_R/σ_P), resulting in a reversal threshold given by

$$\frac{B_R}{B_P} - 1 = \frac{Dz}{h_{Rt}} \qquad (5)$$

This simplification was done, in part, because those parameters are generally not available in prior studies that might be used to test the model. Furthermore, neglecting the expansion losses (h_e) is justified in the one-dimensional sense due to the difference in velocity head between the pool and riffle tending to zero at reversal (Henderson 1966). In addition, a scale analysis at our Red River study site in northern Idaho (Fig. 1) indicates the frictional resistance (h_f) is an order of magnitude less than the residual depth term (Dz), and the σ ratio may approach a value of one (during bankfull flow at the study site, σ_R/σ_P=0.9 and h_f =0.12 m, compared with a bankfull flow depth of 1.83 m and Dz=0.76 m). These results are by no means universal, but provide some support for our simplifications.

Fig. 2 shows the reversal threshold predicted from Eq. (5), with reversal occurring where $B_R/B_P - 1 > Dz/h_{Rt}$. For a given width ratio (B_R/B_P) and residual pool depth (Dz), the water depth over the riffle thalweg (h_{Rt}) will indicate whether reversal occurs, with deeper flows required for reversal. Furthermore, the riffle must be wider than the pool ($B_R/B_P > 1$) for velocity reversal to

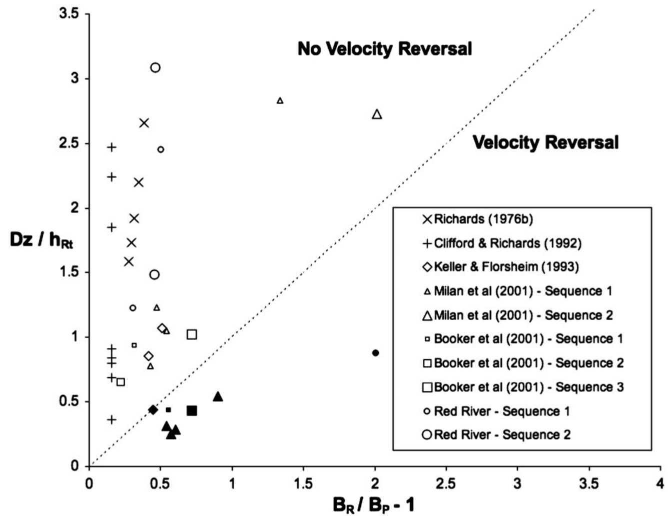

Fig. 2. Comparison of predicted and observed velocity reversal conditions. Dashed line indicates velocity reversal threshold predicted from Eq. (5), and closed symbols indicate observed reversals. Details of how values were obtained from these previous studies are provided by Caamaño 2008.

occur. The distance from the critical line in Fig. 2 is a measure of how pronounced the reversal will be.

We tested this simplified model against published values for five studies of natural pool-riffle sequences (Richards 1976b; Clifford and Richards 1992; Keller and Florsheim 1993; Booker et al. 2001; Milan et al. 2001). These data were supplemented by field measurements made during June and September 2006 at our Red River study site.

Results show that Eq. (5) correctly predicts conditions under which velocity reversals occur (Fig. 2, filled symbols). Moreover, it unifies and explains disparate findings of previous studies.

Summary and Conclusions

Our analysis shows that the threshold for velocity reversal can be predicted from simple one-dimensional hydraulic equations, with the role of residual pool depth (Dz) emphasized here for the first time. As the residual depth of the pool becomes smaller relative to the riffle thalweg depth it is more likely that velocity reversal will occur and conversely a very deep pool may never achieve reversal. Hence, velocity reversal may be less important for maintaining established (large) pools, than for scouring pools that have aggraded and are in danger of filling in completely. For example, it is possible to envision a pool gradually aggrading over time until Dz is reduced to the point where velocity reversal occurs at high flows. If the velocity reversal is linked to a commensurate reversal of shear stress (Lisle 1979; Milan et al. 2001) and transport capacity (Lisle 1979; Booker et al. 2001), then the pool will scour relative to the riffle, counteracting some portion of the prior pool filling. Conditions when this might not occur include abnormally large sediment loadings to streams that give inadequate time for the pool to scour or when the width of the pool is increased relative to that of the riffle due to lateral scour (recall that B_P must be less that B_r for cross-sectional average velocity reversal to occur. This increase in B_P could occur due to removal of riparian vegetation that destabilizes the banks of the pool, or by livestock breaking down the banks near the pool as the deeper pool water is a preferred drinking location. While it is well known that livestock can cause channel widening and loss of pools (McDowell and Magilligan 1997), this phenomenon has not been previously linked to mechanics of velocity reversal and its effects on pool maintenance.

Critical conditions for velocity reversal can be influenced by a variety of factors, but the generality of the criterion given by Eq. (4) makes it broadly applicable to different conditions. For example, differences in channel planform may cause different thresholds for velocity reversal; because water depths in riffles are higher in meandering pool-riffle sequences (Richards 1976a), the reversal discharge is expected to be smaller than in a similar straight reach. Nevertheless, both conditions will be represented by Eq. (4). Similarly, the effects of wood debris on velocity reversal can also be represented by Eq. (4), providing the wood-forced channel morphology is used and additional energy losses from the wood are accounted for (Shields and Gippel 1995). The simplicity of the approach in terms of how the energy equation is applied makes it broadly applicable to all types of flow conditions and obviates some of the complexities of prior studies (Keller and Florsheim 1993; Carling and Wood 1994; Wilkinson et al. 2004). However, our one-dimensional treatment of the problem does not account for the spatial and temporal variation of local (point) velocity reversal (MacWilliams et al. 2006), which may be important in some applications.

An important result of our approach is that the velocity reversal criterion does not require the riffle to control the flow through the pool-riffle sequence. The flow depth over the riffle thalweg (h_{Rt}) can be influenced by downstream controls whose backwaters extend through the riffle (for example, due to a manmade structures, deposited wood debris or downstream restoration measures). Similarly, both watershed and reach-scale alterations can be represented by the proposed criterion. Examples include reduction in Dz due to increased sediment delivery associated with wildfires or basin development, and changes in B_R/B_P as a consequence of natural loss of climax vegetation, livestock grazing, or channel restoration.

Pool-riffle sequences plotting close to the velocity reversal threshold represent reaches in which reversal occurrence is particularly susceptible to changes in the watershed and the reach itself. The habitat diversity provided by pool-riffle sequences is critically important for different life stages of many aquatic animals including salmon and trout (Montgomery et al. 1999; Moir et al. 2004), with many stocks of these fish at risk worldwide due to overharvest, hatcheries, dams, and loss of spawning and rearing habitat in gravel-bed rivers (Nehlsen et al. 1991; Montgomery 2003). Our velocity reversal criterion is a useful metric for those working on stream restoration or stream management as it provides a direct link to the expected sustainability of pools.

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Notation

The following symbols are used in this technical note:

α_P, α_R = pool and riffle velocity coefficients;
B_P, B_R = pool and riffle water surface widths;
Dz = residual pool depth defined as difference between pool and riffle thalweg elevations (z_{Rt}-z_{Pt});
h_e = expansion energy losses;
h_f = friction energy losses;
h_P, h_R = pool and riffle mean water depths;
h_{Pt}, h_{Rt} = pool and riffle thalweg water depths;
u_P, u_R = pool and riffle cross sectional average velocities;
z_{Pt}, z_{Rt} = pool and riffle thalweg elevations; and
σ_P, σ_R = positive parameter $\leqslant 1$ corresponding with cross-section shape.

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