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Reply

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Chanson [this issue] raises some interesting points, and I appreciate the opportunity to clarify and elaborate on the conclusions from *Grant* [1997]. The three issues considered by Chanson are the definition of critical flow, the nonuniform shear stress distribution associated with hydraulic jumps and standing waves, and the application of the conclusion that critical flow is a limiting condition for steep, mobile-bed channels.

As *Chanson* [this issue] and others [e.g., *Henderson*, 1966, equation 2-21, p. 51] point out, Chanson's equation (1) provides a more general definition of critical flow for nonrectangular channels; it equals the square of the Froude number. While explicit inclusion of the slope θ is theoretically correct, the error introduced in calculating the Froude number without it is of the order of $<1\%$ for channel slopes as high as 0.10. For this reason, most formulations exclude the slope correction. Slope was explicitly included in the recast Froude number equation [*Grant*, 1997, equation 2].

The point that the shear stress distribution is nonuniform in both the longitudinal and cross-channel directions is nicely shown by *Chanson*'s [this issue] detailed flow observations. It is precisely this nonuniformity and consequent bed deformation that drives the cyclical growth and collapse of bedforms in sand-bed channels, which, in turn, maintains near-critical flow conditions, as shown by *Grant* [1997, Figure 3]. Moreover, minimum shear stresses below the crests of undular waves with maximums in the troughs tend to localize deposition of clasts, which may lead to step formation in coarse-grained channels [*Grant*, 1997, Figure 5]. The nonuniform cross-channel shear stress distribution (*Chanson* [this issue, Figure 1]) closely parallels the nonuniform cross-channel Froude number distribution, with lowest Froude numbers near the boundary [*Grant*, 1997, Figure 2a]. With high sediment transport rates and Froude numbers both concentrated in the center of the channel, free-surface undulations should be greatest there, as has been noted by others [*Tinkler*, 1997a].

No claim is made that the tendency toward critical flow in steep channels represents an "ultimate simplification," at least in terms of fully predicting the complex, three-dimensional flow field of near-critical flow. As both *Chanson* [this issue] and I point out, near-critical flows are typically both unsteady and rapidly varying conditions that nullify most hydraulic simplifications and for which few models, empirical or otherwise, apply. As noted by *Grant* [1997, p. 353], the use of empirical flow resistance correlations neglects form drag, free-surface instabilities, and hydraulic jumps as sources of energy loss; a comprehensive theory of energy losses in steep channels awaits further work. Chanson's equation (2) is similarly hampered by use of an empirical resistance coefficient. My point was that within the uncertainties introduced by use of empirical coefficients and an assumption of uniform boundary shear stress, a general trend toward critical flow showing good agreement with field data can be observed. This agreement may result, in part, because the velocity measurements used to calculate Froude numbers are typically both time- and space-averaged, thereby integrating some of the unsteady and nonuniform aspects of the flow.

None of the *Chanson*'s [this issue] comments are directed at the central tenet of the paper: to wit that critical flow represents a boundary condition for steep, mobile, and potentially even immobile [i.e., *Tinkler*, 1997a, b] bed channels, maintained by complex interactions between the free surface and the bed. The points raised do highlight the nature of some of those complexities and underscore the importance of recognizing near-critical flow as a "state" in its own right, with a distinctive suite of hydraulic and sedimentalogical features and behaviors. Further efforts should be directed toward testing the applicability of this concept across a range of channel types and flows.

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