Comment on "Characteristic dimensions of the step-pool bed configuration: An experimental study" by Joanna C. Curran and Peter R. Wilcock

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1. Introduction

[1] *Curran and Wilcock* [2005] report an experimental study on the formation of step-pool patterns under active transport of all sediment sizes. They focus on the geometrical properties (step height, H, and step spacing, L) of the bed forms and argue against pattern regularity invoked by previous researchers.

[2] Two major findings emerge from this work: (1) that the formation of a step appears to be equally likely at any location on the bed and, more important, (2) that there exists a so called ''exclusion zone'' larger than the scour hole (pool), next after each step, in which the presence of a new step must be excluded.

[3] Although they measured all relevant flow parameters during experiment, *Curran and Wilcock* [2005] declare unable to find a significant relationship between them and step spacing. The aim of this comment is to provide such a relationship using a quite general result by *Giménez-Curto and Corniero* [2003].

2. Minimum Step Spacing

[4] *Giménez-Curto and Corniero Lera* [1996] have studied the fluid flow over irregular fixed surfaces by introducing spatially averaged Reynolds equations which consider the variation of the fluid domain of averaging, thus allowing the treatment of the flow between bed features. They showed that besides the well known mean viscous and turbulent Reynolds stresses there exists a form induced stress, representing the mean momentum flux due to (non turbulent) flow disturbances introduced by boundary irregularities. This stress requires the existence of vorticity in the disturbed motion to be different from zero and becomes the prevailing stress in cases with bed irregularities of very high amplitude, provided that flow separates from bed features. This is called the jet regime.

[5] As argued by *Giménez-Curto and Corniero* [2003], their equations are also valid for investigating problems with sediment in motion under very general assumptions. In the jet regime, where form induced stress prevails, the hydraulic behavior must be distinguished from that in the rough-turbulent regime, in which Reynolds turbulent stress dominates. The appropriate friction coefficient for open channel flow with bed forms in the jet regime is given by the following expression [see *Giménez-Curto and Corniero Lera*, 2000]:

$$f = 0.52\varepsilon^2 \tag{1}$$

where $f = \tau_0/\rho U_0^2$; τ_0 being the maximum shear stress; ρ the fluid density; and U_0 the bulk averaged velocity (note that the Darcy friction coefficient is equal to $8f$).

$$\varepsilon = (k/\Lambda_0)^{1/3} \tag{2}$$

represents a scale parameter characterizing the magnitude of velocity disturbances; k is the height of bed features (herein $k = \langle H \rangle$, the mean step height); $\Lambda_0 = U_0^2/(g \sin\beta)$ is a length scale defined from the global flow parameters; g is the acceleration due to gravity and β the angle of the mean bed with the horizontal. The flow depth, h, can be related with Λ_0 through the friction coefficient by means of

$$h = \Lambda_0 f \tag{3}$$

[6] Clearly the step-pool configuration represents an extremely high roughness and we expect that water flows over it in the jet regime. This could explain the very different dynamical behavior observed for step-pool and dunes, since turbulent Reynolds stress is always significant in the dune mode. In Figure 1 we show the friction coefficient as observed in the experiments of *Curran and Wilcock* [2005], the stress being calculated as $\tau_0 = \rho g h \sin\beta$. These experiments exhibit a very good agreement with expression (1) and also with *Shen et al.* [1990] measurements over rigid artificial bed forms, thus providing new evidence that when flow separation occurs the effect of sediment transport on bed friction is negligible, as stated by *Giménez-Curto and Corniero* [2003], who showed that the steepness, H/L, of any natural bed form is bounded by a maximum value

$$\left(\frac{H}{L}\right)_{\max} = \frac{f}{\varepsilon} \tag{4}$$

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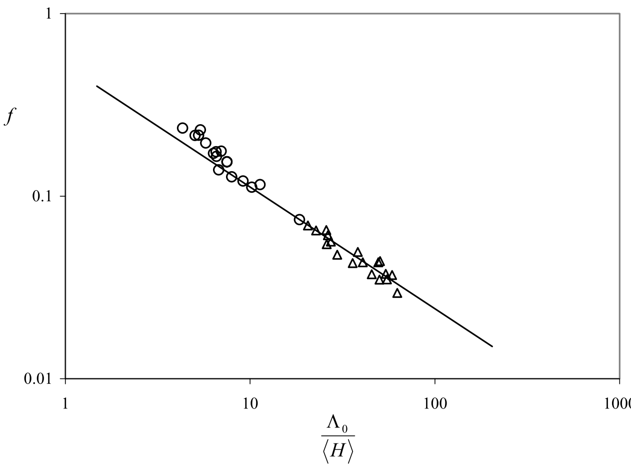

Figure 1. Friction coefficient for open channel flow with bed forms in the jet regime. Observations are from *Curran and Wilcock* [2005] (circles) and *Shen et al.* [1990] (triangles). The solid line represents equation (1).

[7] This can be interpreted as the maximum possible height for given spacing or vice versa, the minimum possible spacing for given height. Whereby, an estimation of the minimum step spacing for mean height $\langle H \rangle$ can be given as

$$L_{\min} = \frac{\varepsilon}{f} \langle H \rangle \tag{5}$$

[8] This corresponds with the so called exclusion length observed by *Curran and Wilcock* [2005]. By applying equation (5), with f from (1), to their measurements we obtain values of $L_{\min}$ between 18.2 cm and 25.4 cm, in good agreement with observation.

3. Mean Step Spacing

[9] It must be realized firstly that the ratio of mean step spacing to minimum spacing, $\langle L \rangle / L_{\min}$, is a measure of the spacing irregularity, since a perfectly regular pattern would give a minimum value of this ratio $\langle L \rangle / L_{\min} = 1$. Furthermore, bed form irregularity is directly associated with bed form asymmetry. Indeed, if it is accepted that the lee side of natural sedimentary forms generated under steady flows forms an angle with the horizontal which equals the angle of repose of the material, Φ, the maximum height of the bed form cannot exceed the value $\frac{1}{2} L(\tan \beta + \tan \Phi)$, L representing horizontal spacing between crests. This absolute limit could be attained if the fluid were at rest in the case that the upstream side of the bed form would form the same angle, Φ, with the horizontal, i.e., in the case of a bed form whose crest were symmetrical with respect to a vertical plane. Under fluid flow the limiting steepness is given by the dynamic condition (4), and must be less than the absolute static limit. Then we can write

$$\frac{\langle H \rangle}{\langle L \rangle} < \frac{\langle H \rangle}{L_{\min}} < \frac{1}{2}(\tan \beta + \tan \Phi) \tag{6}$$

[10] Therefore, as the ratio $\langle H \rangle / \langle L \rangle$ grows approaching the static absolute limit, the gap between $\langle H \rangle / \langle L \rangle$ and $\langle H \rangle / L_{\min}$ narrows which means that the pattern becomes more regular and the crests more symmetrical. As a consequence, $\langle L \rangle / L_{\min}$ must decrease with increasing values of the ratio $\langle H \rangle / \langle L \rangle$. Figure 2 demonstrates this statement. Besides *Curran and Wilcock*'s [2005] data we include in Figure 2 the observations by *Zimmermann and Church* [2001] on some natural streams in British Columbia and also those of *Abrahams et al.* [1995] in order to increase the range of data. It must be pointed out that in the latter experiments the static absolute limit of the bed form height that imposes the angle of repose is about two times the above given value. This is because the lee side of the bed form consists of narrow wooden weirs. Therefore we use $\frac{1}{2}\langle H \rangle / \langle L \rangle$ as the abscissa, instead of $\langle H \rangle / \langle L \rangle$, for *Abrahams et al.'s* [1995] data, thus allowing an homogeneous comparison.

[11] The result of a linear logarithmic regression of all data in Figure 2 gives −0.50 for the slope and 0.021 for the axis intersection (the correlation coefficient is 0.84). This result strongly suggests a formal relation

$$\frac{\langle L \rangle}{L_{\min}} = \sqrt{\frac{\langle L \rangle}{\langle H \rangle}} \tag{7}$$

which is represented as the solid line in Figure 2. Very interestingly, this expression (7) can be rewritten using (5) as

$$\langle L \rangle = \left(\frac{\varepsilon}{f} \right)^2 \langle H \rangle \tag{8}$$

[12] If, as showed by *Curran and Wilcock* [2005], the step spacing distribution would depend on only two parameters (the minimum and the mean spacing) our results (5) and (8) prove that the entire geometric properties of any step-pool configuration are given from the mean step amplitude $\langle H \rangle$ and the fundamental

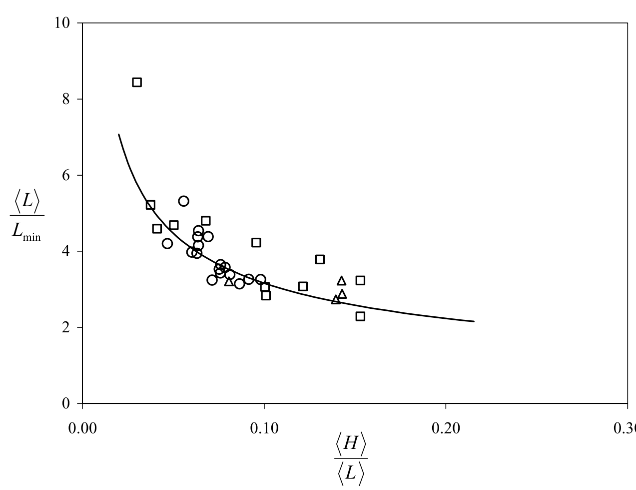

Figure 2. Ratio between mean and minimum step spacing versus a measure of steepness. Observations are from *Curran and Wilcock* [2005] (circles), *Abrahams et al.* [1995] (squares), and *Zimmermann and Church* [2001] (triangles). The solid line represents equation (7).

Table 1. Relation Between Observed Morphology in the Vogelbach, as Measured by *Milzow* [2004], and the Flow Properties That Formed It

Category	$\langle H \rangle$, m	$\langle L \rangle$, m	ε	Λ_0, m	h, m	U_0, m/s	Q, m^3/s
1	0.23	2.68	0.563	1.29	0.21	1.52	1.8
2	0.32	4.39	0.519	2.29	0.32	2.03	3.6
3	0.45	6.20	0.518	3.24	0.45	2.42	6.0
4	0.63	8.29	0.530	4.23	0.62	2.76	9.4
5	1.17	15.61	0.526	8.04	1.16	3.81	24.3
Mean	0.56	7.46	0.527	3.83	0.55	2.63	8.0

parameter f/ε of the flow that has generated the step-pool pattern.

4. Application to Natural Streams

[13] Very recently, *Allen and Hoffman* [2005] have applied the concept of maximum steepness as given by *Giménez-Curto and Corniero* [2003] to relate remarkable giant wave ripples found at stratigraphic levels associated with the aftermath of the Neoproterozoic glaciation with the wave climate that could generate them. Their study led to the conclusion that this climatic transit was characterized by extreme meteorological conditions.

[14] This idea can also be applied to infer flood conditions in steep natural streams from just the geometrical properties of the bed. As an example we consider the Vogelbach, a small mountain stream in Central Switzerland with a mean width of 5.5 m and mean bed slope $\tan\beta = 0.187$, whose step-pool morphology has been studied in detail by *Milzow* [2004]. The mean height and spacing of the five step categories that he was able to identify from the step height spectrum can be seen in Table 1. By applying equation (8), together with (1), we calculate the parameter ε corresponding to the flow that formed each step-pool category. Then it is obtained the length scale Λ_0 from which the flow velocity and depth are immediately calculated, thus allowing the estimation of the flow rate Q (see Table 1).

[15] From a comparison with observed floods (the maximum measured flow rate since 1984 is 6.3 m^3/s [*Milzow*, 2004]) we conclude that category 1, the smallest steps, are the consequence of annual adjusting, like the observations of *Zimmermann and Church* [2001] in British Columbia. The second category corresponds to the largest flood of the last two years, whereas the third category appears to have been formed by the largest flood of the last ten years. Category 4 represents steps larger than the overall mean, which have been formed by floods with recurrence interval over hundred years. The largest steps of category 5 are due to extremely large floods with very large recurrence intervals, perhaps millenniums.

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