The writer wishes to congratulate the authors for their very interesting development on step-pool streams. Recent advances on stepped channel flows with fixed-bed provide additional information on the topic. The discusser will show that the maximum flow resistance condition implies a characteristic flow pattern.

For stepped channel flow above a fixed bed, two types of flow regimes can be distinguished: a succession of free-falls at low discharges called nappe flow regime (fig. 1), and a skimming flow regime (fig. 2).

At very low discharges, the flow at each step consists of a free-falling jet impacting on the pool and followed by a fully-developed hydraulic jump. With increasing flow rates or decreasing step length L, the hydraulic jump is affected by the edge of the downstream step, and eventually disappears (fig. 1). For larger discharges or smaller step lengths, the flow becomes a skimming flow. In the skimming flow regime, the water flows as a coherent stream, skimming over the steps and cushioned by the recirculating fluid trapped between them (fig. 2). In the step corners, recirculating vortices develop and are maintained through the transmission of shear stress from the water flowing past the edge of the steps.

The transition between nappe and skimming flow is a function of the discharge and the step geometry. The author (CHANSON 1994) showed that skimming flow regime occurs for discharges larger than a critical value defined as:

\[
\frac{(h_c)_{\text{onset}}}{L} = S \times (1.057 - 0.465 \times \tan \theta) \quad \text{(fixed-bed channel with horizontal steps)} \tag{1}
\]

where \(L\) is the step length measured parallel to the mean channel slope and \((h_c)_{\text{onset}}\) is the characteristic critical depth. Skimming flow regime occurs for \(h_c > (h_c)_{\text{onset}}\), where \(h_c\) is the critical flow depth.

Let us consider now the concept of 'maximum flow resistance' in natural step pools. In a nappe flow regime, the presence (or not) of hydraulic jumps is a dominant parameter. Hydraulic jumps have a great erosive power (e.g. CHOW 1959, HAGER 1992). In a nappe flow regime with fully-developed hydraulic jumps, the jumps will contribute greatly to the erosion of step bottoms (below the jumps), leading to the step destruction. A new step arrangement with smaller step lengths will then take place. The waters will flow as a nappe flow with partially-developed jumps or ultimately without hydraulic jumps.

In skimming flow down flat-slope streams (i.e. \(\theta < 30\) degrees), the discusser (CHANSON 1995) showed that maximum flow resistance is achieved for the largest relative roughness \(H/h\): i.e., for the smallest discharges at a given step height.
These considerations suggest that the equilibrium bed profile for 'maximum flow resistance' corresponds to a nappe flow regime without hydraulic jump or to a skimming flow at low discharges: i.e., the flow conditions are near the transition between nappe and skimming flow.

On figure 3, the authors' data for maximum flow resistance and equilibrium bed profile are compared with experimental data characterising the onset of skimming flow (i.e. transition between nappe and skimming flow regime) on fixed-bed channel with horizontal steps. Figure 3 shows a close agreement between all sets of data. It confirms that the bed profile of 'maximum flow resistance' on step-pool streams is achieved for flow conditions near the transition between nappe and skimming flow.

REFERENCES


NOTATION

\( g \) gravity constant (m/s^2);

\( H \) step height (m)

\( h \) flow depth (m) measured normal to the mean channel slope;

\( h_c \) critical flow depth (m); for a rectangular channel: \( h_c = \frac{3}{4} \frac{q_w^2}{g} \)

\( (h_c)_{\text{onset}} \) critical flow depth (m) at the onset of skimming flow;

\( L \) distance (m) between step edges measured parallel to the bed slope;

\( l \) step length (m);

\( q_w \) discharge per unit width (m^2/s);

\( S \) bed slope: \( S = \sin \theta \);

\( \theta \) mean channel slope.
Fig. 1 - Nappe flow regime above a stepped channel

Fig. 2 - Skimming flow regime above a stepped channel

Skimming flow on steep-slope channel

Skimming flow on flat-slope channel
Fig. 3 - Comparison between the maximum flow resistance conditions (ABRAHAMS et al. 1995) and the onset of skimming flow (experimental data on fixed bed with horizontal steps and equation (1))