In situ assessment of the spatial arrangement of step-pool units on eroded rills

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**In situ assessment of the spatial arrangement of step-pool units on
eroded rills**

Abstract

Rills are generated on homogeneous hillslopes by the action of different discharges and evolve morphologically over short timescales due to a strong interaction between the flow and bed morphology. Such an interaction generates a reconfiguration of the bed geometry. Previous works suggest that bed geometry is often characterized by alternation between pools and flat reaches (steps). Each step-pool unit may contribute to hydraulic resistance and affects flow behaviour. The objectives of this work are (i) to assess different (innovative) techniques for the *in situ* assessment of rill bed geometry, (ii) to use these techniques to assess the geometry of eroded rills *in situ* in order to determine the spatial arrangement in the bed macro-scale roughness and (iii) finally to analyse the role of slope and discharge as driving factors associated with the development of these macroforms.

Roughly rectilinear, long rills were formed in the field as a result of combining different slope and discharges. Photogrammetry provided detailed digital elevation models (DEMs) before and after the experiments. The rills were morphologically characterized from the DEMs. In each rill, the presence of step-pools was identified from long profiles according mainly to morphological criteria published elsewhere, but with ad hoc critical threshold values more appropriate for small eroded channels.

1 The minimum slope required for the development of step-pool units seem to be
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1 The minimum slope required for the development of step-pool units seem to be
2 somewhere in between 5% and 15%. Discharge seems to affect pool size or
3 roughness amplitude.

4 There does not seem to be a clear step-pool periodicity. However, external
5 factors could have affected the normal growth and alternation of these
6 structures. Identification of steps and pools from longitudinal elevation profiles
7 can be objectively accomplished using a series of geometric rules originally
8 proposed for rivers and large channels, and adapted to rills.

9 Keywords: rill erosion, eroded channels, step-pool identification, mountain
10 streams

Introduction

The reshaping of the rill bed –i.e., with alternation of step-pools– affects the behaviour of the flow (Di Stefano et al. (2017). For example, Govers (1992) observed that the average velocity of rill flows, unlike large channels, could be predicted on the basis of discharge only, as the effect of the slope was

negligible. This finding was corroborated by other authors (e.g., Nearing et al., 1997; Takken et al., 1998; Giménez and Govers, 2001, Nearing et al., 1999, Di Stefano et al., 2018, 2019). Giménez and Govers (2001) concluded that equations such as Manning's –widely used in the hydraulics of rivers and large channels, in which constant roughness is assumed–would be unsuitable for rills since, as noted above, rill roughness is slope-dependent: the independence of flow velocity of slope implies that bed roughness (expressed as Manning's n or Darcy-Weisbach's f) increases with slope gradient. The experiments by Giménez et al. (2001) suggest that the slope-independency of flow velocity in rills, which was recently confirmed by Di Stefano et al. (2018, 2019), is indeed due to the feedback between bed erosion and bed geometry. The flow in rills eroding loose, homogeneous material was, on average, near critical with an average Froude number near 1 due to the alternation of sections with subcritical flow (the pools) and supercritical flow (the steps). As the Froude number is not controlled by slope gradient it follows that average flow velocity is not controlled by slope gradient.

Thus, the basic assumption that the hydraulics of small, erodible channels can be described using formulae/equations developed from work on relatively large, alluvial rivers is flawed. The first step to a better description of hydraulics in rills is to carry out a comprehensive characterization of rill bed geometry under various conditions and to identify the (role of the) controlling factors. To this aim, field and lab experiments are required. Over recent years several studies have indeed been carried out focusing on the measurement of rill hydraulics and rill geometries, usually in the laboratory (e.g., Peng et al., 2015; Di Stefano et al., 2018). Most of this work, however, focuses on the characterisation of the

1 overall, average flow resistance in rills while less attention is given to the
2 precise mechanisms controlling this resistance and to the precise description of
3 rill bed geometry. The latter is important as understanding the connection
4 between rill erosion and rill hydraulics crucially depends on understanding how
5 rill erosion shapes bed geometry.

6 As indicated above, one of the possible mechanisms controlling overall flow
7 resistance in rills is the formation of step-pool sequences. However,
8 identification of step-pool units in streams is not straightforward, even in large
9 streams such as mountain rivers (Church and Zimmermann, 2007). The
10 difficulty in distinguishing step-pool streams results from the challenge
11 associated with their objective identification (Church and Zimmermann, 2007).

12 In rills, perhaps the only unequivocal way of objectively identifying step-pools is
13 to analyse velocity distributions along the rill channel. Giménez et al. (2004)
14 worked in a laboratory setting with a non-erodible, detailed reproduction of a rill
15 section where velocity flow was measured by a miniaturized acoustic Doppler
16 velocimeter. They observed a one-directional and accelerating flow on the steps
17 and a multi-directional and highly turbulent flow in the pools. However, this type
18 of data collection is very difficult and time consuming, due to very low water
19 depths and relatively high flow velocities. In addition, the relative short length of
20 the rill that can be studied in the laboratory prevents an analysis of the step-pool
21 spatial arrangement. For an extensive characterization of *in situ* rill geometry
22 simpler approaches are required that can be applied in the field.

23 The objectives of the work presented herein are: (i) to assess different
24 (innovative) techniques for the *in situ* assessment of rill bed geometry, (ii) to use
25 these techniques to assess the geometry of eroded rills *in situ* in order to

determine the spatial arrangement in the bed macro-scale roughness and (iii) finally to analyse the role of slope and discharge as driving factors associated with the development of these macroforms.

Field experiments were carried out on different hillslopes, where rills were formed under different combinations of slope and discharge. From longitudinal elevation profiles obtained for each eroded channel, pools and steps were identified and the arrangement pattern was analysed.

Materials and Methods

Experimental plots

In situ experiments were conducted in an arable field in Olite (Navarre, Spain). The field has a silty loamy topsoil with slight-to-moderate stoniness (Table 1). Within the field 3 rectilinear hillslope sections measuring approximately 20 × 5 m were selected. Each hillslope section had a different slope gradient: 3%, 5%, 15%.

Each plot was tilled (with chisel and rotavator) until a flat surface with a roughness similar to a seedbed was obtained. Then, a gentle depression was created along the centre of the plot, approximately 5 cm deep and 50 cm wide, with a flat bottom, using a rake. This procedure prevented the water applied from flooding over the entire width of the plot so that the resulting eroded channel would be as straight as possible. Next, the soil was moistened up to saturation, and then left to drain until field capacity was reached.

Forty metal nails were homogenously distributed on the plot, acting as ground control points, and the coordinates (xyz) of each nail were determined by a total station.

Experiment protocol

Several hundred photographs from different angles were taken covering the entire experimentation area (photos overlapped by approximately 60%). These images were then utilized to create a high-resolution DEM using Agisoft® PhotoScan Professional edition v1.0. (2013).

Next, a controlled discharge was applied at the upper end of the slope using a hose connected to a nearby irrigation hydrant controlled by a flowmeter.

The application of overland flow led in most experiments to the formation of a clearly discernable rill (Table 2). However, in some rills developed in the lower slopes incipient reaches were observed. During the experiment, flow velocity was determined by the dye-tracing technique (Giménez and Govers, 2001) along a distance of 1 m, at three different locations along the rill. A correction factor of 0.94 was used (Govers, 1992) to prevent velocity overestimation. The average velocity measured at the three locations was assumed to be representative for the average hydraulic conditions in the rill (Table 2).

The experiment continued until steady conditions were reached, i.e., until average flow velocity did not change significantly with time (Giménez and Govers, 2001). This occurred approximately 30–45 minutes after the beginning of the experiment.

Once the rill reached steady state conditions, water depth was determined approximately at the same three locations at which the flow velocity had previously been measured (Table 2). For this purpose, custom-built sensors were employed. These sensors measured the vertical distance from the sensor to the surface of the water and then, once the experiment ended, the same distance up to the dry bed was measured. The difference between both

1 measurements enabled calculation of water depth. The sensors were previously
2 calibrated in the laboratory. Water depth in a shallow stream was measured at 3
3 different points 10 times each; an experimental error of approximately ± 1 mm
4 was found. In addition, rill width was measured at different points along the rill
5 and an average value was calculated.

6 At the end of the experiment, another series of photographs was taken so that a
7 DEM of the eroded rill could be constructed.

8 Experiments were performed using seven different discharges and three
9 different slopes, which are reported in Table 2.

10 The discharge values utilized are representative of flows in eroding rills (Bennett
11 et al., 2000).

13 *Identification of step-pool units*

14 The identification of pools –as hydraulic systems– throughout the rill bed is
15 subjective (Zimmermann et al., 2008). The problem lies in the fact that these
16 depressions are not always well-defined and are not therefore always evident
17 from observations of the bed. Two procedures were applied to identify pools.
18 Firstly, pools were identified using so-called pool markers. Secondly, step-pool
19 units were identified from the longitudinal elevation profile of the rill using the
20 identification algorithm proposed by Zimmermann et al. (2008). Both procedures
21 are described below.

22 *Use of pool markers.* Giménez et al. (2004) observed that the concentrated flow
23 in a rill had a significant capacity to transport sediments, including soil
24 aggregates. If the discharge was decreased by approximately 70%, the
25 transport capacity of the flow decreased significantly, resulting in an important

1 deposition of aggregates throughout the channel. This process occurred mainly
2 inside the pools, close to their upstream wall. Here we used this observation to
3 identify pools. After equilibrium conditions were reached and a rill was formed at
4 a specific discharge, the discharge was reduced by 70% compared to the pre-
5 set value. After the reduced discharge was allowed to reach equilibrium
6 surrogate soil aggregates were introduced in the channel all along the rill
7 (approximately 50 surrogate aggregates per linear meter of channel). Flow was
8 subsequently interrupted and a survey of groups of surrogate aggregates along
9 the rill was carried out. We used *Cicer arietinum* seeds as surrogate
10 aggregates. The shape, size and density of these seeds were determined in the
11 lab to be very similar to those of soil aggregates: each seed weighed on
12 average 0,38 gr and had an average diameter of around 6-7mm, while a soil
13 aggregate of similar size weighed on average 0.41 gr.

14 *Use of longitudinal elevation profiles.* Step-pool units were identified from
15 longitudinal elevation profiles digitised along the central axis of the rill, from the
16 corresponding DEM. On these profiles, step-pool units were identified according
17 to the geometric rules proposed by Zimmermann et al. (2008). To this end,
18 different morphological parameters need to be known: (i) maximum and
19 minimum lengths of the step, (ii) minimum length of the pool, (iii) minimum
20 residual depth of the pool, (iv) minimum drop height of the pool, and (v) the
21 minimum slope of the step (Figure 1). All these parameters, except for the
22 slope, are normalised by the width of the channel to ensure comparison with
23 different channels regardless of the size (Zimmermann et al., 2008). The
24 classification algorithm searches for a pool first –from the downstream
25 longitudinal profile end– and then attempts to determine whether there is a step

upstream. Pools and steps are considered as such only if each of the aforementioned morphological parameters are within maximum and minimum threshold values, as proposed by Zimmermann et al. (2008) (Table 3).

As the critical values proposed by Zimmermann et al. (Table 3) are empirical and mainly based on the geometry of rivers, new values that can be applied to rills were determined from the dataset of Giménez et al. (2004) (Table 3). These authors created, under laboratory conditions, an eroded rill (soil texture= silt loam, discharge= $0.001 \text{ m}^3\text{s}^{-1}$ and slope= 5°) that was comparable in dimensions to the rills studied here. Within that rill, the authors identified step-pool units based on the analysis of longitudinal velocity profiles. Besides, the morphology of the rill –and hence of the step-pool units– was characterized in detail from a high-resolution DEM. Using this information, a new set of critical values to be applied in rills was determined by measuring values of pool length (PL), residual depth (RD), drop height (DH) and step length (SL) in each step-pool unit along the longitudinal profile of the experimental rill. Average values of each parameter were finally calculated (Figure 1, Table 3).

The new set of morphological critical values was then compared with data from the present study. Within the different rills obtained *in situ* in the experiments in study, 10 different reaches presenting at least three or four well-defined step-pools each were selected based on visual inspection (Figure 2).

Next, from the longitudinal profiles of those reaches, the values of the critical parameters (i.e., PL, RD, DH and SL) were determined and average values obtained. These critical values were very similar to those previously obtained using the Giménez et al. (2004) data set. The Zimmermann' et al. approach was programmed in Java.

1 In addition, an elevation profile before rill formation was obtained in
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1 In addition, an elevation profile before rill formation was obtained in
2 correspondence with the points of the rill central axis subsequently developed
3 (Figure 3, grey line).

4 After each experiment we also conducted a visual survey of the rill and
5 attempted to visually identify step-pool units. We used this information to have
6 in advance, as a reference, a rough estimate of the total number of step-pool
7 units.

8 The Zimmermann et al. (2008) algorithm only detects the presence of step-pool
9 units, but does not analyze whether or not these features show periodicity.
10 Spectral analysis (Fast Fourier Transform, FFT) and the data diagnosis
11 framework based on nonlinear time series methods (Huffaker et al., 2016) were
12 applied to detect possible periodicity in the macroforms along the longitudinal
13 profile of the rill. The height values were previously corrected for the overall rill
14 slope using regression analysis, so that an array of corrected height values (Z_c)
15 was obtained. The nonlinear time series technique basically enables the
16 extraction of possible periodic components of different intensities from a raw
17 dataset.

18 Finally, in order to obtain quantitative information about rill macroroughness
19 each array of correct height values Z_c were first smoothed by using the Douglas
20 and Peucker's (1973) data reduction tool (programmed in Java) with a tolerance
21 band of 20 mm. Then, from this profile with fewer Z_c values the 20 mm peak
22 frequency index f_{20} (Giménez and Govers, 2001) was determined as

$$f_{20} = N_p / 2 \quad (1)$$

where N_p is the number of peaks per unit of length in the longitudinal rill profile.

Results

Evaluation of pool identification techniques

Visual inspection of longitudinal profiles before and after each experiment showed a clear increase in the macroforms for the different rill beds especially at greater slope due to bed erosion (Figure 3). In fact, the f_{20} –hence, large roughness frequency– was only significantly related to slope and not discharge (Table 4). However, macroforms themselves do not necessarily indicate the presence of step-pool units.

The number of pools detected using pool markers (i.e., surrogate aggregates) were around the expected ones according to visual inspection of the beds. Nevertheless, these results must be interpreted with caution. For example, it was observed that the presence of gravel –with an equivalent diameter over 15–20 mm– on the bed sometimes resulted in the accumulation of surrogate aggregates. Similarly, accumulation of surrogate aggregates also occurred in some channel bends (Figure 4).

The application of the automatic step-pool unit recognition procedure, with the critical values originally proposed by Zimmermann et al. (2008) (Table 3) yielded, in general, a significant overestimation of the total number of step-pool units (see Figure 5, Zimmermann). When these critical values were replaced by the ones defined *ad hoc* for our experiments, the identification of step-pool sequences was much more realistic (see Figure 5, Zimmermann mod).

Step-pool units identified by the Zimmerman et al. algorithm were also detected by pool markers in approximately 70% of the times (see Figure 5, pool markers). However, since the technique based on the use of pool markers was more sensitive to experimental errors than the Zimmerman algorithm, we will only use

the results obtained using the Zimmerman algorithm with adjusted critical values in the rest of the paper (see Table 3, “this work”).

Step-pool unit identification and spatial arrangement

The number of step-pools per unit of length detected in the rill longitudinal profiles at 15% slope significantly increased, in comparison with the longitudinal profiles before experiments (Table 5). Regarding the rills formed on low slopes (3–5%), although they showed an increment on macroroughness especially on the roughness frequency (see above) (Table 4). it did not result in the reconfiguration of the rill bed in step-pool units (Table 5). It should be noted that as mentioned above in the experiments carried out on lower slopes, unlike those on the steepest one (15%), the erosive flow did not always trigger well-developed channels (Figure 6), originating reaches with scarcely defined cross sections.

The number of step-pool units in the 15%-slope rills did not seem to be related to, or controlled by, the discharge (Table 5). Instead, pool size seems to be controlled by discharge: at a constant slope (15%), pool heights (H) showed a clear increasing trend with discharge ($p < 0.05$) (Figure 7). However, as the increase of pool height (H, Figure 1) was accompanied by a more or less proportional increase in pool length (PL, Figure 1), pool steepness (H/PL) remained approximately constant, regardless of discharge (Figure 8).

Step-pool frequency

In the four rills formed on the highest slope (15%), the average distance between two successive step-pools (SL, Figure 1) for all the discharges was 38

cm, or 4.3 times the average width of the rills. However, these data presented high variability (Coefficient of Variation of SL=130%). It should be noted that in each rill long reaches were observed where SL values were close to the average but with considerably smaller variation (Coefficient of Variation of SL~50%) (see zoom in Figure 9).

FFT analysis did not reveal periodicity in the macroforms in any of the four 15%-slope rills. However, application of the technique presented by Huffaker et al. (2016) exhibited behaviour similar to a sine function, but this only explained a maximum of 15% of the general shape of the longitudinal profiles. The periodicity of this signal was different in each rill analysed and varied between approximately 0.6 and 1 m (see Figure 10). This range of values is close to what was observed experimentally, but the low “intensity” of this signal prevented conclusions from being drawn.

Finally and as expected, average flow velocity for all the rills was not significantly affected by slope but was dependent on discharge (Table 6).

Discussion

In mountain rivers, the step-pool units are formed by the progressive accumulation of dragged material –for example, stones and trunks– which in turn form small dams throughout the channel and a pool is then formed downstream each dam. The formation process of pools in rills, instead, occurs because of *scouring* of the soil (cohesive material) and is not promoted by dragging and accumulation of material at the pool entrance. The pools that are formed by scouring slowly move upstream due to erosion at their headwall and

1 this may lead to some deposition at their downstream side. However, we never
2 observed that in a rill bed soil aggregates would be blocked and smaller
3 particles would accumulate around them creating a sort of dam as occurs in
4 mountain streams. In any rill, a more potent and erosive discharge than the
5 originating one would not cause a deletion of existing pools, but rather an
6 enlargement of them as deduced from Giménez et al.(2007). A larger pool
7 would dissipate more energy compensating the extra energy provided by the
8 higher discharge.

9 Despite these differences in formation mechanisms of steps and pools in rills
10 and in mountain rivers, step-pools could be seen as periodic bedforms that
11 reflect a fundamental mutual adjustment between flow and channel morphology
12 in both channels.

13 The algorithm proposed by Zimmermann et al. (2008) is an empirical technique
14 for the identification of steps and pools in longitudinal elevation profiles, based
15 on arbitrary geometric thresholds. Therefore, it may misclassify some step-pool
16 units. Moreover, the possibility that the presence of some gravel on the rill bed
17 altered the rill longitudinal profiles (and somehow affected the results obtained
18 by this algorithm) should not be discarded. For instance, in mountain streams
19 the distributions of pool spacings could be significantly affected by the presence
20 of large, rough features (e.g., logs and rocks) whose diameters are in the same
21 scale as the water depths (Grant et al., 1990). This is the case herein with
22 gravel sized approximately 15-20 mm which is approximately also the average
23 rill water depth (Table 2).

24 In addition, during the validation of their algorithm, Zimmermann et al. (2008)
25 warned that, in a few cases, specific step-pool units identified in situ and also

1 visible in their respective longitudinal profile were however not recognized by
2 the algorithm due to the relatively small size. In a single rill, both small and large
3 pools could coexist (Giménez and Govers, 2001). Herein some depressions
4 similar to well-developed pools but smaller in size –especially not very deep–
5 were observed in situ along some long reaches, in different rills. Therefore, the
6 possibility that some small pools were eventually not detected by application of
7 the Zimmermann et al. (2008) procedure has not been ruled out.

8 As we already explained, the results obtained from the Zimmerman algorithm
9 should be interpreted with some caution. However, its application ensures an
10 *objective* classification of steps and pools, facilitating therefore comparisons
11 across works, as presented herein. While calculations for individual rills are
12 uncertain it is obvious that not all rills are characterised by step-pool systems
13 and that such systems only developed at a sufficiently steep slope (in this case
14 above 5%). According to the experiments carried out herein, the minimum slope
15 required for the development of step-pool units in rills seems to be between 5%
16 and 15%.

17 Also in mountain rivers the occurrence of step-pool units was evident only in
18 channels having an average slope steeper than 3–5% (e.g., Montgomery and
19 Buffington, 1997; Billi et al., 1998; Wohl and Thompson, 2000) or even higher
20 than 17% (Zimmermann and Church, 2001). Instead, lower slopes are more
21 likely to render so-called lonely step-pool units (Church, 2002). In mountain
22 rivers, a pronounced increase in the number of step-pools per unit of channel
23 length was observed with an increase in the average slope (e.g., Hayward,
24 1980; Heede, 1981; Chin, 1989; Wohl and Grodek, 1994; Duckson and
25 Duckson, 2001).

According to Judd (1964), the relationship between pool separation (SL, Figure 1) and channel slope (S) can be expressed as:

$$SL = H / (C Sz) \quad (1)$$

where H is the height of the pool (Figure 1), and C and Z are constants. Equation (1) confirms the direct relationship between the number of pools per unit of channel length and the slope.

Based on lab experiments and observations of mountain rivers, Abrahams and Li (1995) concluded that the step-pools (formed due to accumulations of cobbles and boulders transverse to the direction of flow) adjusted their form in such a way as to maximise flow resistance. This occurred when

$$1 \leq (H/PL)/S \leq 2 \quad (2)$$

where H, PL and S are pool height, pool length (Figure 1) and average slope of the river, respectively. This means that the loss of elevation head –and hence energy drop– over the pool length exceeds that due to the average head loss along the channel.

In our 15%-slope rills the average value of the (H/PL)/S ratio was 2.3 which roughly agrees with the findings of Abrahams and Li (1995).

Our findings suggest that discharge affects mainly pool size –height and length in rills (Figure 7 and Figure 8). This reconfiguration of pool shape is in agreement with findings of Bennett et al. (2000). They carried out flume experiments at different discharges and a constant slope to study headcut development by concentrated flows. They observed that the erosive potential of the headcut impinging jet increased as flow discharge increased, leading to a proportional increment on both headcut maximum scour depth (~H) and the horizontal distance from the upstream headcut wall to this maximum depth

(~PL). Therefore, headcut became progressively larger but its aspect ratio was conserved. Thus, an increase in discharge seems to induce an increase in roughness height –i.e., size of pools– rather than in roughness or step-pool frequency.

To the best of the authors' knowledge, there have been no studies devoted to the analysis of possible periodicities in the appearance of step-pools in eroded rills. However, systematic and regular spacing of these hydraulic units was reported in mountain rivers with a frequency ranging from less than one to four channel widths (Chin, 1989; Marston, 1982; Grant et al., 1990). Nevertheless, other studies did not show any clear periodicity in step-pool development (Heede, 1981; Duckson and Duckson, 2001; Zimmermann and Church, 2001). This lack of periodicity could be explained by the interaction of several factors, such as the presence of vegetation or rock outcroppings in the bed, and also sudden bends or changes in direction of the riverbed that in some way prevented a regular morphological sequence from being developed (Wertz, 1966). We did not find a clear periodicity in our eroding rills. As is sometimes the case in mountain rivers, the exact location of pools in rills be controlled by local variations, e.g. in bed resistance against erosion and/or the presence of rock fragment initiating scour.

The absence of a slope effect on average rill flow velocity was confirmed (e.g., Govers 1992, Nearing et al., 1997, 1999, Di Stefano et al., 2018) (Table 6). The hydraulic conditions in the rill will then result from a certain equilibrium between the erosive agent (the water) and the resistance offered by the soil (Giménez and Govers, 2001).

Conclusions

In eroded rills there is mutual adjustment between rill flow and rill bed morphology. Reshaping of the rill bed may be revealed by the generation of step-pool units. However, while step-pool formation can occur in rills, it is not the only mechanism through which hydraulics-erosion feedback is manifested. At low slopes erosion leads to a ‘roughening’ of the rill bed, i.e. weaker zones erode faster than more resistant zones. However, the erosive force of the flow is not big enough to organise the bed into a step-pool system. This is most likely due to the fact that local erosion remains limited. As no clear, deep pools are formed at low slopes there will also not be any clearly distinguishable steps. Nevertheless, also on low slopes, the rill bed-hydraulics interaction is strong enough to have a manifest effect on rill hydraulics, such that equilibrium flow velocities are indeed independent of slope. The minimum slope required for the development of step-pool units seemed to be somewhere in between 5% and 15%. In addition, discharge seems to affect pool size, i.e. roughness amplitude. However, it is not clear whether there is an approximately constant distance between step-pool units. External factors, such as the presence of gravel in the rill bed, could have somehow affected the normal growth and frequency of these morphological features. Further experiments must be carried out, in laboratory settings, using homogeneous soils and combining different discharges and slopes. Identification of step-pool as hydraulic units is a challenging task to achieve without a detailed information about rill flow characteristics such as flow velocity. Two innovative techniques were assessed. One of them using in situ

pool markers and another one by applying geometric rules along the longitudinal elevation profiles of the rill's central axis. Identification of steps and pools from longitudinal elevation profiles can be objectively carried out by using the series of geometric rules proposed by Zimmermann et al. (2008). A new set of threshold values, more appropriate for small eroded channels such as rills, were proposed herein.

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Figures captions

Figure 1 Sketch of a rill bed depicting the parameters used in the rule-based classification algorithm to characterize steps and pools (after Zimmermann et al., 2008). DH: Drop height; PL: Pool length; RD: Residual Depth; SL: Step length; H: Pool height; S: step slope.

Figure 2: Part of the longitudinal profile of the rill developed at slope=15% and $Q = 0.16 \text{ m}^3 \text{ h}^{-1}$ (see the complete longitudinal profile in Figure 3). Three step-pool units are clearly observed. This is an example of a rill reach used to evaluate the new set of critical values of the Zimmermann's et al. algorithm obtained from Giménez's et al. (2004) dataset. (see Table 3, This work). See text for more details.

Figure 3. Longitudinal profiles before (grey) and after (black) experiments corresponding to a slope of 15% and discharge of (a) $0.9 \text{ m}^3 \text{ h}^{-1}$ (b) $0.78 \text{ m}^3 \text{ h}^{-1}$ (c) $0.36 \text{ m}^3 \text{ h}^{-1}$ and (d) $0.16 \text{ m}^3 \text{ h}^{-1}$.

Figure 4. Plant view of part of a rill developed at slope=5% and $Q = 5 \text{ m}^3 \text{ h}^{-1}$. Low-gradient rills were usually not entirely rectilinear as intended.

Figure 5. Example of different set of pools identified in a rill elevation profile (slope: 15%, discharge: $0.78 \text{ m}^3 \text{ h}^{-1}$ following (i) Zimmermann et al.(2008) procedure with original critical values (Zimmermann), (ii) Zimmermann et al. (2008) procedure with adjusted critical values (Zimmermann mod) and (iii) using pool markers.

Figure 6. Pictures of a well-defined (below) and incipient (above) reaches of the same rill developed at slope=5% and $Q = 2.5 \text{ m}^3 \text{ h}^{-1}$. Red arrows roughly indicates the mean rill width (0.15m).

Figure 7. Pools heights of the rills developed at 4 different discharges and a single slope (15%). Black and red dashed lines inside boxes are median and average values, respectively.

Figure 8. Pool steepness –i.e., pool height H (see Figure 7) over pool length PL– at different discharges and a single slope (15%). Median value of H/PL is around 0.35.

Figure 9. Longitudinal profiles of rills –vertical exaggeration=4– developed at slope of 15% and discharge of (a) $0.16 \text{ m}^3 \text{ h}^{-1}$, (b) $0.36 \text{ m}^3 \text{ h}^{-1}$, (c) $0.78 \text{ m}^3 \text{ h}^{-1}$ and (d) $0.9 \text{ m}^3 \text{ h}^{-1}$. Grey bands indicate reaches identified as a step-pool units according to the classification algorithm (Table 3, This work). SL: step length (see Figure 1).

Figure 10. Example of spectrum analysis by Huffaker et al. (2016) applied in the detrended longitudinal elevation profile (blue line) corresponding to the rill formed at S:15% and $Q: 0.9 \text{ m}^3 \text{ h}^{-1}$. The techniques separated series of elevation values into a signal (brown line) and noise (not shown). Signal explains only 15% of the general shape of the longitudinal profile. Signal periodicity is between 0.6 and 1 m.

Table 1. Physical-chemical characteristics of the experimental soil.

Grain size classes, %	Values
< 2 μm	19.4
> 50 μm	27.8
2 – 50 μm	52.8
Organic matter, %	0.98
Carbonate, %	45.1
Active lime, %	9.18
Electric conductivity, dS m^{-1}	0.18

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Table 2. Rill flow characteristics

Slope (%)	Average Width (m)*	Q (m ³ h ⁻¹)	Steady state average velocity (ms ⁻¹)	Average water depth (mm)
3	0.180	1.60	0.45	6
3	0.200	5.00	0.48	6
5	0.160	2.50	0.44	30
5	0.140	5.00	0.51	11
15	0.060	0.16	0.20	2
15	0.090	0.36	0.25	17
15	0.107	0.78	0.30	7
15	0.098	0.90	0.35	9

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Table 3. Critical values of the parameters used in the classification algorithm proposed by Zimmermann et al. (2008). Values are normalized by the average rill width (W) (see Table 2). Original: critical values originally proposed by Zimmermann et al. (2008); This work: Zimmermann's et al. (2008) critical values defined ad hoc for this work.

	Original	This work
Maximum step length	2 W	– ⁽¹⁾
Minimum step length	0.0225 W	1 W
Minimum pool length	0.10 W	0.16 W
Minimum residual depth	0.0023W	0.066 W
Minimum drop height	0.033 W	0.058 W
Minimum step slope	average slope >10°	0°

⁽¹⁾ No maximum step length was fixed

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2 Table 4. Multiple regression analysis for rills^a

	Coefficient	Standard Error	t	p
Intercept	-0.153	0.65	-0.236	0.82
S	0.123	0.042	2.88	0.03
Q	1.27 E-4	1.29 E-4	0.98	0.37

3 ^a Dependent variable is peak frequency f20; independent variables are slope S
4 and discharge Q. Here, t is Student's t value, and p is probability coefficient is
5 zero. R² = 0.61, standard error of estimate is 0.411, F= 6.37, p= 0.042, and n=8.
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Table 5. Number of step-pool units per unit of rill length identified by the modified Zimmermann's et al. (2008) algorithm before (no rill) and after (with rill) experiments.

Slope (%)	Q (m ³ h ⁻¹)	N° step-pool units per unit of rill length	
		Before	After
3	1.60	-	0
3	5.00	0	0
5	2.50	0	0
5	5.00	0.08	0.08
15	0.16	0.5	2.75
15	0.36	0.09	1.24
15	0.78	0.27	0.62
15	0.90	0	1.13

1 Table 6 Multiple regression analysis for rills^a

	Coefficient	Standard Error	t	p
Intercept	0.295	0.073	4.06	0.01
S	-0.00284	0.005	-0.59	0.58
Q	162.902	51.7	3.14	0.02

2 ^a Dependent variable is velocity; independent variables are slope S and
3 discharge Q. Here, t is Student's t value, and p is probability coefficient is zero.
4 $R^2 = 0.82$, standard error of estimate is 0.046, $F = 17.5$, $p = 0.005$, and $n = 8$.

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For Peer Review

Figure 1

Figure 4

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Figure 5

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Figure 6