



# From regular to random: a unifying framework for step-pool spacing

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5 **Abstract.** Steep streams frequently display a distinctive step-pool structure where water crests over a near-vertical drop and plunges into a deeper depression in a repeated pattern. Because they naturally moderate the flow of water and sediment in hazardous mountain catchments, step-pools are often installed in stream management and restoration projects. However, emulating step-pool sequences is hindered by debate on whether natural step-pools are themselves regularly or randomly spaced. Here we show that the spacing of step-pool sequences spans a continuum between regularity and randomness driven  
10 by multiple formation mechanisms. Analyzing a compilation of natural, experimental, and numerically simulated step-pools, we found that natural variability and inherent limits on minimum spacing prevent fully regular or random sequences. While certain mechanisms result in comparatively regular or random spacing, no single mechanism dominates step-pool development. Our results resolve longstanding tension between a plethora of proposed formation mechanisms that yield contrasting predictions. Furthermore, the emergent limits on spacing variability provide testable predictions about the  
15 adjustment of sequence spacing following river disturbance that may eventually be used to define concrete targets for stream restoration and hazard management.

## 1 Introduction

Steep headwater streams comprise the majority of total global stream length (Benda et al., 2005). In mountainous regions, transport of floodwaters and sediment through these steep streams is an important natural hazard that causes billions of euros  
20 in damage (Badoux et al., 2014). Naturally arising step-pool sequences – characteristic staircase-like structures in the streambed (Fig. 1) – are prominent in mountain rivers with slopes exceeding about 3%. They provide flow resistance that aids in dissipating the energy of hazardous events (Chin, 2003; Johnson, 2017; Wohl & Thompson, 2000; Yager et al., 2012). Accordingly, step-pools are often engineered (Lenzi, 2002; Zhang et al., 2023) or mimicked with check dams as a form of hazard management (Lenzi & Comiti, 2003). Furthermore, step-pool sequences are used as a benchmark of channel recovery  
25 in river restoration (Chin & Wohl, 2005; Fields et al., 2025).

Effectively using step-pools to inform stream management and to track river recovery requires clearly defined goals for step spacing. However, expectations for step spacing are usually tied to a specifically assumed formation mechanism, on which there is no scientific consensus. Among the numerous proposed formation mechanisms, two diverging expectations emerge (Chin & Wohl, 2005; Church & Zimmermann, 2007; Comiti & Mao, 2012; Richardson & Carling, 2021). Mechanisms linked



30 to channel hydraulics are associated with regular spacing between step crests (Chin, 1999b) while mechanisms linked to channel properties, such as boulder size and location, are associated with random spacing (Zimmermann & Church, 2001). These conflicting expectations make it difficult to forecast step-pool evolution and to establish specific stream restoration targets (e.g., Fields et al., 2025).

Although it is recognized that multiple mechanisms can be active within the same channel (Curran, 2007; Golly et al., 2019),  
35 the formation mechanism preferred within the scientific literature has been continually evolving. This turmoil is best exemplified by the antidune mechanism, which links step-pools to an inherently regular, precursory bedform. Once a commonly invoked explanation for step-pool formation (Chin, 1999a; Grant, 1997; Lenzi, 2001; Whittaker & Jaeggi, 1982), the antidune mechanism fell from an early place of prominence as alternative mechanisms emphasizing random particle interactions and locations developed (Church & Zimmermann, 2007; Golly et al., 2019; Lee, 1998; Zimmermann & Church,  
40 2001). Despite calls that it be abandoned (Comiti & Mao, 2012), the antidune mechanism has recently been resurrected and once again put forth as the dominant mechanism behind step-pool formation (Richardson & Carling, 2021). This vacillation between seemingly incompatible options is reflective of the fact that, without a comparative framework transferable across mechanisms, interpretations of step spacing are restricted by prior assumptions about the formative mechanism.

Here, we present a framework that unifies the diverse step-pool formation mechanisms into a single continuum and is  
45 applicable across field, flume, numerical models, and even other bedforms. We use this framework to evaluate regularity and randomness across a compiled dataset of 131 step-pool sequences with slopes spanning an order of magnitude (~ 3 – 35%) (Erikson et al., 2026a).



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**Figure 1:** A step-pool sequence from Glenn Falls Brook in Fairlee, VT, USA. The individual step and pool components of the structure are identified by arrows.



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### 1.1 Mechanism overview

The conceptual class of step-pool formation mechanisms emphasizing hydraulic controls are associated with approximately regular spacing. The antidune mechanism is one example, where variation in flow energy causes organization of material on a riverbed into roughly regular bedforms (antidunes) (Kennedy, 1969), which have been suggested to be nucleation points of developing steps (Whittaker & Jaeggi, 1982). As another example, in the pool-scour mechanism, high-energy flow over a step scours a pool, and the excavated material forms a step downstream (Comiti et al., 2005). As flow moves over the new step, it again plunges to scour a pool, building a sequence of steps in the downstream direction.

A second set of conceptual classes relates step formation to variation in channel characteristics and particle interactions. Particle jamming (Zimmermann & Church, 2001), for example, facilitates step formation when grains chain together across a river channel, often in narrow sections (Saletti & Hassan, 2020). Similarly, clustering of sediment around kestones (Golly et al., 2019; Turowski et al., 2013) or in rough patches (Curran & Wilcock, 2005; Erikson et al., 2026b) leads to steps with matching, typically random, spacing.

### 2 Constructing a comparative framework

Determining whether step-pool spacing should be regular or random requires evaluation criteria that are universally applicable and easily measured. To provide these criteria, we adapt an approach proposed by Golly et al. (2019) using two metrics of spacing variability. The first variability metric is provided by the coefficient of variation, defined as the standard deviation of spacing relative to the mean. The second metric is the minimum spacing between steps relative to the mean, which we call the relative minimum. It accounts for hydraulic effects that limit how close together steps can be.

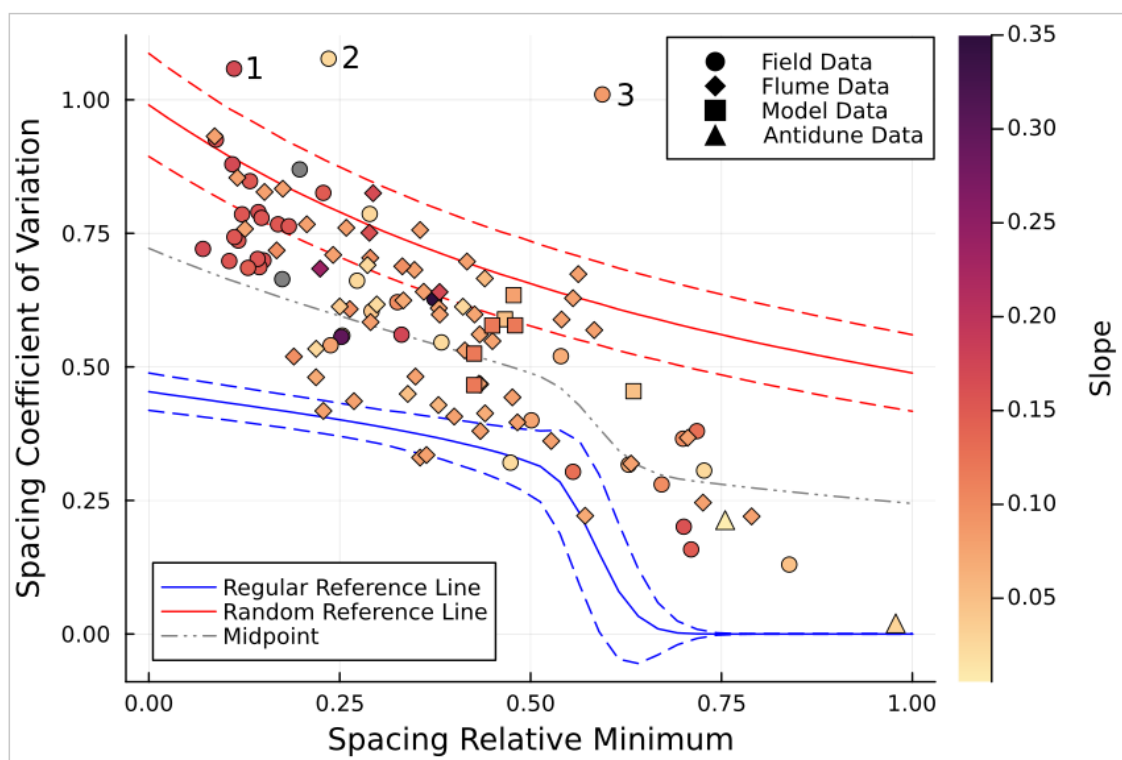
Within the plotting space defined by these metrics we established two reference lines using different starting assumptions. For a “regular reference line,” we added Gaussian noise to an initially perfectly regular step sequence. For a “random reference line,” we simulated a step sequence as a Poisson process (Curran & Wilcock, 2005), which leads to random spacing following an exponential distribution. We normalized the coefficient of variation for a given step sequence by the space between reference lines ( $CV_N$ ) to indicate if it is closest to the regular reference line ( $0 \leq CV_N < 0.5$ ) or the random reference line ( $0.5 < CV_N \leq 1$ ).

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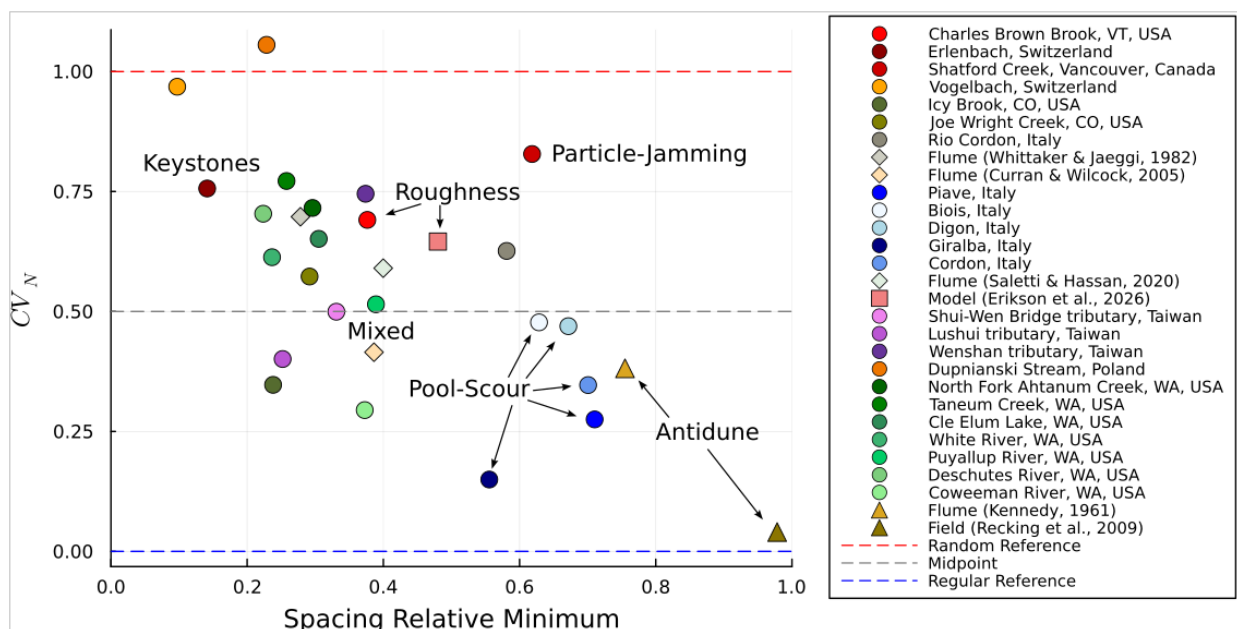


### 3 Deciphering regularity and randomness

Step-pool sequences from the compiled dataset span nearly the full range of possible relative minimum spacing (possible: 0-1; observed: 0.07-0.84) (Fig. 2). The observed range of coefficients of variation is well-bounded by the reference lines with only three observations deviating from those bounds. Both the reference lines and the compiled data demonstrate a reduction in coefficient of variation as relative minimum spacing increases, deviating from complete regularity (constant value  $CV_N = 0$ ) or complete randomness (constant value  $CV_N = 1$ ).



**Figure 2:** Comparison of data compiled from field, flume, and model step-pool spacing using a diagnostic plot ( $n=131$ ). All points are colored by the slope of the reach in which observations were recorded, with gray points lacking slope information. Solid lines indicate mean values from a Monte Carlo simulation serving as a reference for regular (blue) and random (red) sequences. Dashed lines represent one standard deviation in each direction from the estimated mean. The gray dotted and dashed line is the midpoint between the two reference lines. The three points above the random reference line are sequentially labeled. Point 1 is from large wood steps in the Vogelbach (Switzerland), Point 2 is from Charles Brown Brook (USA) after a flood, and Point 3 is from a reach of Shatford Creek (Canada) also featuring large wood.



**Figure 3:** Mean positions in Fig. 2 averaged by source shown relative to the space between reference lines. The Range Normalized Coefficient of Variation ( $CV_N$ ) is the y-axis of Fig. 2 now normalized by the space between the red and blue line to show where within the envelope points occur. The upper and lower dashed lines correspond to the random and regular reference lines in Fig. 2 and the dashed gray line indicates the middle point between them.

110 Eighteen of the 27 averaged data sources, excluding antidunes, are closest to the random reference line, while the remaining 9 are closest to the regular reference line (Fig. 3). However, most sequences are situated somewhere between these lines rather than closely clustering around them. For example, the flume experiments of Curran & Wilcock (2005) featured mechanisms leading to both regular and random spacing in the same run, and, on average, are only slightly closer to the regular reference line than random reference line ( $CV_N = 0.42$ ). Field sites that have been explicitly tied to mechanisms related to roughness ( $CV_N = 0.69$ ), keystones ( $CV_N = 0.76$ ), and particle jamming ( $CV_N = 0.83$ ) plot closest to the random reference line, matching the expectation that they generate irregular sequences. Sites that have been explicitly tied to the pool-scour mechanism are closest to the regular reference line ( $0.15 \leq CV_N \leq 0.48$ ), near to antidunes ( $CV_N = 0.04$  &  $CV_N = 0.39$ ) and match expectations. Notably, the flume experiments of Whittaker & Jaeggi (1982), from which the antidune mechanism was first proposed, plot closer to the random reference line than the regular reference line ( $CV_N = 0.70$ ) and are generally in an opposite corner of the plot than true antidunes (Fig. 3).

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## 125 4 Discussion

Step-pool sequences are rarely fully random or fully regular (Fig. 2). Full regularity is prevented by irreducible variation and randomness is limited by the effects of an exclusion zone (Fig. 2), the region behind an upstream step where hydraulic effects prevent a new step from forming (Curran & Wilcock, 2005; Giménez-Curto & Corniero, 2006). Any isolated set of observations would, therefore, fail to match a truly regular (Curran & Wilcock, 2005; Zimmermann & Church, 2001) or truly  
130 random (Curran & Wohl, 2003; Milzow et al., 2006) comparison. At the same time, sequences tied to a specific formation mechanism usually fall close to the reference line expected for that mechanism. That means attempts to refute one mechanism or validate another can both suffer from incomplete representation. For example, because the exclusion zone restricts minimum spacing, sequences can appear statistically distinguishable from a random distribution despite essentially being as random as physically possible. Sample size, similarly, can misrepresent a sequence since small sample sizes may not converge to the true  
135 mean and limit the accuracy of the minimum spacing as a proxy for the exclusion zone (Fig. S1). When examining the full compiled dataset, step-pool sequences occupy a continuum between the bounds imposed on randomness and regularity (Fig. 2).

Unlike the other mechanisms, the antidune mechanism of Whittaker & Jaeggi (1982) is not situated as expected within the continuum, but rather plots similarly to steps formed through the roughness mechanism (Fig. 3). As Whittaker & Jaeggi (1982)  
140 themselves noted, roughness influenced initial bedform structure and only their lowest sloping experiments were consistent with antidune formation when using calculated flow depth. Beyond challenging the notion that the antidune mechanism dominates step formation (cf., Richardson & Carling, 2021), it seems likely that a roughness-based mechanism (Curran & Wilcock, 2005; Erikson et al., 2026b) better explains the observations from their flume experiments.

The other exceptions to expectation are the three points beyond the random reference line (see Fig. 2). These cases illustrate  
145 how the random reference line might be used as a diagnostic tool. A point may eschew from the random reference line in a reach with spacing artificially forced closer than a natural hydraulically-driven exclusion zone or in a reach with isolated step clusters. In the case of artificially close steps, wood-constructed steps in particular reaches of the Vogelbach (Point 1) (Milzow et al., 2006) and of Shatford Creek (Point 3) (Zimmermann & Church, 2001) potentially lead to a small relative minimum compared to steps formed by other processes (Montgomery et al., 1995). High variability from wood-forced steps for a given  
150 relative minimum spacing is consistent with greater randomness in the reach measured by Wilcox et al. (2011) than the reach measured by Comiti (2003) despite both being from a similar region of Italy. Exemplifying the case of isolated clusters, newly developed steps in Charles Brown Brook (Point 2) were concentrated around rough patches following a dam removal with



large gaps between clusters (Erikson et al., 2026b; Fields et al., 2025). Such clustering can result in a small relative minimum despite an overall large variability.

155 Beyond the existing data compilation, expectations for step-pool spacing evolution may be informed by the continuum in two ways. First, step-pool spacing can change in time at a single site without a clear signature of regularity or randomness, meaning channel equilibrium, as used in stream restoration, might benefit from redefinition away from a static spacing goal and toward objectives that accommodate a range of configurations and multiple processes (Zhang et al., 2023). Second, the random reference line, as an upper bound on randomness, predicts the trajectory of step-pool spacing for channels that may not be in  
160 an equilibrium state. Testing this prediction may ultimately allow the random reference line to be used as an indicator of river adjustment. For example, in the context of a growing number of dam removals (O'Connor et al., 2015), channel equilibrium metrics, such as the ratio of mean spacing to channel width, are used to estimate morphologic channel recovery (Fields et al., 2025). This metric has the limitations that channels with no step-pools or infinitely wide channels both fall into the typical equilibrium range (0 - 4), and it is tied to assumptions of regularity (Chin & Phillips, 2007). Because the random reference line  
165 instead is explicitly tied to channel hydraulics, it may provide a more robust assessment of channel equilibrium.

## 5 Conclusion

Observations of both regular and random spacing in different settings have led to contrasting expectations for what the variability of step-pool spacing should be. We defined a continuum to unify once disparate observations across natural,  
170 experimental, and numerical step-pool sequences. Consideration of a particular site, assumptions about formation mechanisms, and overly restrictive data criteria can all hide the fact that no singular mechanism dominates step-pool formation. In contrast, our data compilation clarifies that natural sequences are neither truly regular nor truly random and that the natural step-pool spacing spectrum spans a wide range between these bounds. This result emphasizes the complexity of river processes which can hamper the effectiveness of hard engineering structures and channel design criteria in replicating natural, temporally  
175 dynamic, and mixed-mechanism step-pools (Chin & Wohl, 2005; Simon et al., 2007).

## 6 Appendix A

### 6.1 Diagram Construction

Adapting a diagram first presented by Golly et al. (2019), we construct a diagnostic space for evaluating the degree of regularity and randomness of step-pool sequences using two metrics. Specifically, we use the coefficient of variation (standard deviation  
180 normalized by mean) of step spacing and relative minimum step spacing (minimum spacing normalized by mean). We introduce the relative minimum to account for the effect of step-pool exclusion zones, where the hydraulic influence of an upstream step prevents a new step from forming (Curran & Wilcock, 2005). As the exclusion zone lengthens, less space is



185 available for steps to emerge, limiting the maximum possible coefficient of variation. Since a general approach of measuring the exclusion zone length does not exist, we use the simpler measurement of minimum step spacing as a proxy. Together, the coefficient of variation and relative minimum define broadly applicable spacing metrics using readily obtainable measurements.

## 6.2 Reference Lines

To facilitate assessment of how regular or random a step-pool sequence is, Golly et al. (2019) added two reference lines to the diagnostic plot. Unlike Golly et al. (2019) we assumed a fixed reach length rather than a fixed number of steps when generating these reference lines, leading to different boundaries. Considering that even antidunes usually lack perfect regularity, we added Gaussian noise to an initially perfectly regular step sequence and generated a “regular reference line” by adjusting the spacing of the initial sequence (further details in the supplement). We repeated this process for each minimum allowed spacing 100,000 times as part of a Monte Carlo simulation to estimate the aggregate mean and standard deviation of the individual coefficients of variation and minimum to mean spacing ratios. We also present an alternative algorithm in the supplementary information (Fig. S2). We note that alternative ways of generating the regular reference line increase the degree of apparent randomness, with only step sequences associated with the pool-scour mechanism being closest to the regular reference line in the least conservative approach (Fig. S3). Because the addition of Gaussian noise sometimes caused steps to violate the minimum spacing constraint, we implemented a routine to adjust step positioning until all steps in the sequence had valid positions. We detail this routine in the supplementary information.

For a “random reference line,” we simulated a step sequence as a Poisson process (Curran & Wilcock, 2005), which leads to random spacing. This consisted of randomly sampling spacings from an exponential distribution and rejecting spacings that fell below the minimum constraint. Because we used a fixed reach length as a final constraint, we removed steps that went beyond the end of the reach. This resulted in a variable number of steps across the simulations despite the same number of initial samples being drawn. The number of steps in each sequence was most variable when the minimum spacing was similar to the mean.

## 6.3 Range Normalized Coefficient of Variation

210 To aid in assessing how regular or random a step sequence was, we normalized the coefficient of variation ( $CV$ ) for a given step sequence by the space between reference lines as:

$$CV_N = \frac{CV - y_g}{y_e - y_g}, \quad \text{Eq. (1)}$$

where  $y_g$  is the coefficient of variation at the regular reference line and  $y_e$  is the coefficient of variation at the random reference line. We refer to this metric as the range normalized coefficient of variation ( $CV_N$ ).



## 215 **Code and data availability**

The data are available in the form of a data publication (Erikson et al., 2026a), which includes all the spacing observations from field sites, flume experiments, and numerical simulations. The data publication is currently accessible through a review link and will be finalized with this manuscript. Code for the simulations is currently accessible in a GitHub repository ([https://github.com/cmerikson/StepPool\\_ReferenceLines](https://github.com/cmerikson/StepPool_ReferenceLines)), but will also be included in the data publication.

## 220 **Supplement link**

The link to the supplement will be included by Copernicus, if applicable.

## **Author contributions**

CE and JT designed the methodology and developed the code used for analysis. CE performed the investigation and created the figures with supervision from JT. CE prepared the manuscript with contributions from JT.

## 225 **Competing interests**

The authors declare that they have no conflict of interest

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## **Acknowledgements**

This work benefitted from discussion with Alexandre Badoux, Joanna Curran, and Jordan Fields. We also thank Ellen Wohl, Marwan Hassan, Peter Molnar, Chendi Zhang, Fiona Gabriel and Volker Weitbrecht for help with compiling data as well as  
235 Sibashish Dash and Samidha Revankar for field assistance.



## Financial support

## Review statement

The review statement will be added by Copernicus Publications listing the handling editor as well as all contributing referees according to their status anonymous or identified.

## 240 References

- Badoux, A., Andres, N., & Turowski, J. M. (2014). Damage costs due to bedload transport processes in Switzerland. *Natural Hazards and Earth System Sciences*, 14(2), 279–294. <https://doi.org/10.5194/nhess-14-279-2014>
- Benda, L., Hassan, M. A., Church, M., & May, C. L. (2005). Geomorphology of Steepland Headwaters: The Transition from Hillslopes to Channels. *JAWRA Journal of the American Water Resources Association*, 41(4), 835–851. <https://doi.org/10.1111/j.1752-1688.2005.tb03773.x>
- 245 Chin, A. (1999a). On the origin of step-pool sequences in mountain streams. *Geophysical Research Letters*, 26(2), 231–234. <https://doi.org/10.1029/1998GL900270>
- Chin, A. (1999b). The morphologic structure of step-pools in mountain streams. *Geomorphology*, 27(3), 191–204. [https://doi.org/10.1016/S0169-555X\(98\)00083-X](https://doi.org/10.1016/S0169-555X(98)00083-X)
- 250 Chin, A. (2003). The geomorphic significance of step-pools in mountain streams. *Geomorphology, Mountain Geomorphology - Integrating Earth Systems, Proceedings of the 32nd Annual Binghamton Geomorphology Symposium*, 55(1), 125–137. [https://doi.org/10.1016/S0169-555X\(03\)00136-3](https://doi.org/10.1016/S0169-555X(03)00136-3)
- Chin, A., & Phillips, J. D. (2007). The self-organization of step-pools in mountain streams. *Geomorphology, Mountain Rivers II: Channel Processes*, 83(3), 346–358. <https://doi.org/10.1016/j.geomorph.2006.02.021>
- 255 Chin, A., & Wohl, E. (2005). Toward a theory for step pools in stream channels. *Progress in Physical Geography*, 29(3), 275–296. <https://doi.org/10.1191/0309133305pp449ra>
- Church, M., & Zimmermann, A. (2007). Form and stability of step-pool channels: Research progress. *Water Resources Research*, 43(3). <https://doi.org/10.1029/2006WR005037>
- Comiti, F. (2003). *Local scouring in natural and artificial step pool systems* [PhD dissertation]. University of Padova.



- 260 Comiti, F., Andreoli, A., & Lenzi, M. A. (2005). Morphological effects of local scouring in step–pool streams. *Earth Surface Processes and Landforms*, 30(12), 1567–1581. <https://doi.org/10.1002/esp.1217>
- Comiti, F., & Mao, L. (2012). Recent Advances in the Dynamics of Steep Channels. In *Gravel-Bed Rivers* (pp. 351–377). John Wiley & Sons, Ltd. <https://doi.org/10.1002/9781119952497.ch26>
- Curran, J. C. (2007). Step–pool formation models and associated step spacing. *Earth Surface Processes and Landforms*,  
265 32(11), 1611–1627. <https://doi.org/10.1002/esp.1589>
- Curran, J. C., & Wilcock, P. R. (2005). Characteristic dimensions of the step-pool bed configuration: An experimental study. *Water Resources Research*, 41(2). <https://doi.org/10.1029/2004WR003568>
- Curran, J. H., & Wohl, E. E. (2003). Large woody debris and flow resistance in step-pool channels, Cascade Range, Washington. *Geomorphology, Interactions between Wood and Channel Forms and Processes*, 51(1), 141–157.  
270 [https://doi.org/10.1016/S0169-555X\(02\)00333-1](https://doi.org/10.1016/S0169-555X(02)00333-1)
- Erikson, C. M., Turowski, J. M., Curran, J. C., Wohl, E., & Badoux, A. (2026). *Compilation of Step-Pool Stream Sequence Spacing* [Dataset]. GFZ Data Services. <https://doi.org/10.5880/GFZ.AVXH.2026.002>
- Erikson, C. M., Warburton, K. L. P., & Renshaw, C. E. (2026). A Roughness-Based Model for Incipient Step-Pool Formation in Alluvial Streams. *Journal of Geophysical Research: Earth Surface*, 131(3), e2025JF008564.  
275 <https://doi.org/10.1029/2025JF008564>
- Fields, J. F., Renshaw, C. E., Dethier, E. N., & Magilligan, F. J. (2025). The longer arc of channel recovery post-dam removal. *Geomorphology*, 468, 109442. <https://doi.org/10.1016/j.geomorph.2024.109442>
- Giménez-Curto, L. A., & Corniero, M. A. (2006). Comment on “Characteristic dimensions of the step-pool bed configuration: An experimental study” by Joanna C. Curran and Peter R. Wilcock. *Water Resources Research*, 42(3).  
280 <https://doi.org/10.1029/2005WR004296>
- Golly, A., Turowski, J. M., Badoux, A., & Hovius, N. (2019). Testing models of step formation against observations of channel steps in a steep mountain stream. *Earth Surface Processes and Landforms*, 44(7), 1390–1406. <https://doi.org/10.1002/esp.4582>



- Grant, G. E. (1997). Critical flow constrains flow hydraulics in mobile-bed streams: A new hypothesis. *Water Resources Research*, 33(2), 349–358. <https://doi.org/10.1029/96WR03134>
- 285
- Johnson, J. P. L. (2017). Clustering statistics, roughness feedbacks, and randomness in experimental step-pool morphodynamics. *Geophysical Research Letters*, 44(8), 3653–3662. <https://doi.org/10.1002/2016GL072246>
- Kennedy, J. F. (1969). The Formation of Sediment Ripples, Dunes, and Antidunes. *Annual Review of Fluid Mechanics*, 1(Volume 1, 1969), 147–168. <https://doi.org/10.1146/annurev.fl.01.010169.001051>
- 290 Lee, A. J. (1998). *The hydraulics of steep streams* [Ph.D., University of Sheffield (United Kingdom)]. <https://www.proquest.com/docview/1887043265/abstract?parentSessionId=CjQbhJw1CcZaZ024EcG%2BZLgR669X15MnfrZgs40SFw%3D&sourcetype=Dissertations%20%20Theses>
- Lenzi, M. A. (2001). Step–pool evolution in the Rio Cordon, northeastern Italy. *Earth Surface Processes and Landforms*, 26(9), 991–1008. <https://doi.org/10.1002/esp.239>
- 295 Lenzi, M. A. (2002). Stream bed stabilization using boulder check dams that mimic step-pool morphology features in Northern Italy. *Geomorphology*, 45(3), 243–260. [https://doi.org/10.1016/S0169-555X\(01\)00157-X](https://doi.org/10.1016/S0169-555X(01)00157-X)
- Lenzi, M. A., & Comiti, F. (2003). Local scouring and morphological adjustments in steep channels with check-dam sequences. *Geomorphology, Mountain Geomorphology - Integrating Earth Systems, Proceedings of the 32nd Annual Binghamton Geomorphology Symposium*, 55(1), 97–109. [https://doi.org/10.1016/S0169-555X\(03\)00134-X](https://doi.org/10.1016/S0169-555X(03)00134-X)
- 300 Milzow, C., Molnar, P., McArdell, B. W., & Burlando, P. (2006). Spatial organization in the step-pool structure of a steep mountain stream (Vogelbach, Switzerland). *Water Resources Research*, 42(4). <https://doi.org/10.1029/2004WR003870>
- Montgomery, D. R., Buffington, J. M., Smith, R. D., Schmidt, K. M., & Pess, G. (1995). Pool Spacing in Forest Channels. *Water Resources Research*, 31(4), Article 4. <https://doi.org/10.1029/94WR03285>
- 305 O’Connor, J. E., Duda, J. J., & Grant, G. E. (2015). 1000 dams down and counting. *Science*, 348(6234), Article 6234. <https://doi.org/10.1126/science.aaa9204>
- Richardson, K., & Carling, P. A. (2021). Morphology and origin of alluvial step-pools: A synthesis of experimental and field data from formative flows. *Earth-Science Reviews*, 222, 103823. <https://doi.org/10.1016/j.earscirev.2021.103823>



- 310 Saletti, M., & Hassan, M. A. (2020). Width variations control the development of grain structuring in steep step-pool dominated streams: Insight from flume experiments. *Earth Surface Processes and Landforms*, 45(6), 1430–1440. <https://doi.org/10.1002/esp.4815>
- Simon, A., Doyle, M., Kondolf, M., Shields Jr., F. d., Rhoads, B., & McPhillips, M. (2007). Critical Evaluation of How the Rosgen Classification and Associated “Natural Channel Design” Methods Fail to Integrate and Quantify Fluvial Processes and Channel Response1. *JAWRA Journal of the American Water Resources Association*, 43(5), Article 5. <https://doi.org/10.1111/j.1752-1688.2007.00091.x>
- 315 Turowski, J. M., Badoux, A., Leuzinger, J., & Heggin, R. (2013). Large floods, alluvial overprint, and bedrock erosion. *Earth Surface Processes and Landforms*, 38(9), Article 9. <https://doi.org/10.1002/esp.3341>
- Whittaker, J. G., & Jaeggi, M. N. R. (1982). Origin of Step-Pool Systems in Mountain Streams. *Journal of the Hydraulics Division*, 108(6), 758–773. <https://doi.org/10.1061/JYCEAJ.0005873>
- 320 Wohl, E. E., & Thompson, D. M. (2000). Velocity characteristics along a small step–pool channel. *Earth Surface Processes and Landforms*, 25(4), 353–367. [https://doi.org/10.1002/\(SICI\)1096-9837\(200004\)25:4<353::AID-ESP59>3.0.CO;2-5](https://doi.org/10.1002/(SICI)1096-9837(200004)25:4<353::AID-ESP59>3.0.CO;2-5)
- Yager, E. M., Dietrich, W. E., Kirchner, J. W., & McArde, B. W. (2012). Prediction of sediment transport in step-pool channels. *Water Resources Research*, 48(1), Article 1. <https://doi.org/10.1029/2011WR010829>
- 325 Zhang, C., Hassan, M. A., Saletti, M., Zimmermann, A. E., Xu, M., & Wang, Z. (2023). A Unit-Scale Framework for Designing Step-Pool Sequences. *Journal of Hydraulic Engineering*, 149(1), 04022033. [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0002033](https://doi.org/10.1061/(ASCE)HY.1943-7900.0002033)
- Zimmermann, A., & Church, M. (2001). Channel morphology, gradient profiles and bed stresses during flood in a step–pool channel. *Geomorphology*, 40(3), 311–327. [https://doi.org/10.1016/S0169-555X\(01\)00057-5](https://doi.org/10.1016/S0169-555X(01)00057-5)

330