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

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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 by multiple formation mechanisms. Analyzing a compilation of natural, experimental, and numerically simulated step-pools, we found that natural variability and hydraulically-set 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 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 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% (Judd and Peterson, 1969; Chin, 1989; Montgomery and Buffington, 1997; Palucis and Lamb, 2017). They provide flow resistance that aids in dissipating the energy of hazardous events (Chin, 2003; Johnson, 2017; Wohl and 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 and Comiti, 2003). Furthermore, step-pool sequences are used as a benchmark of channel recovery in river restoration (Chin and 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 and Wohl, 2005; Church and Zimmermann, 2007; Comiti and Mao, 2012; Richardson and Carling, 2021). Mechanisms linked 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), 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 and Jaeggi, 1982), the antidune mechanism fell from an early place of prominence as alternative mechanisms emphasizing random particle interactions and locations developed (Church and Zimmermann, 2007; Golly et al., 2019; Judd and Peterson, 1969; Lee, 1998; Zimmermann and Church, 2001). Despite calls that it be abandoned (Comiti and Mao, 2012), the antidune mechanism has recently been resurrected and once again put forth as the dominant mechanism behind step-pool formation (Richardson and 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 applicable across field, flume, numerical models, and even bedforms. The framework consists of two statistical measures of variability, which define a simple diagram. Within this space, the relative regularity and randomness of a step sequence becomes readily discernable. We use the 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).

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.

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 and 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 et al., 2010; Zimmermann and Church, 2001), for example, facilitates step formation when grains chain together across a river channel, often in narrow sections (Saletti and Hassan, 2020). Similarly, clustering of sediment around keystones (Golly et al., 2019; Turowski et al., 2013) or in rough patches (Curran & Wilcock, 2005; Erikson et al., 2026b) leads to steps with typically random spacing, since the distribution of initial clusters is itself usually random. Expected spacing for various mechanisms is tabulated in the supporting information (Table S1) and other formation mechanisms beyond those considered here are detailed in existing reviews (Chin and Wohl, 2005; Church and Zimmermann, 2007; Golly et al., 2019).

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 (σ/μ). The second metric is the minimum spacing between steps relative to the mean (x_{min}/μ), 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 (Appendix A 6.1). 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 using a Poisson process (Curran & Wilcock, 2005), which leads to random spacing following an exponential distribution. Assuming a Poisson process assigns equal probability of a step forming to every location, which we adjust by enforcing an exclusion zone (Appendix A 6.2). We normalized the coefficient of variation for a given step sequence by the range between reference lines (CV_N) to indicate if it is closer to the regular reference line ($0 \leq CV_N < 0.5$) or the random reference line ($0.5 < CV_N \leq 1$) (Eq. 1, Appendix A 6.3).

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 $CV_N = 1$).

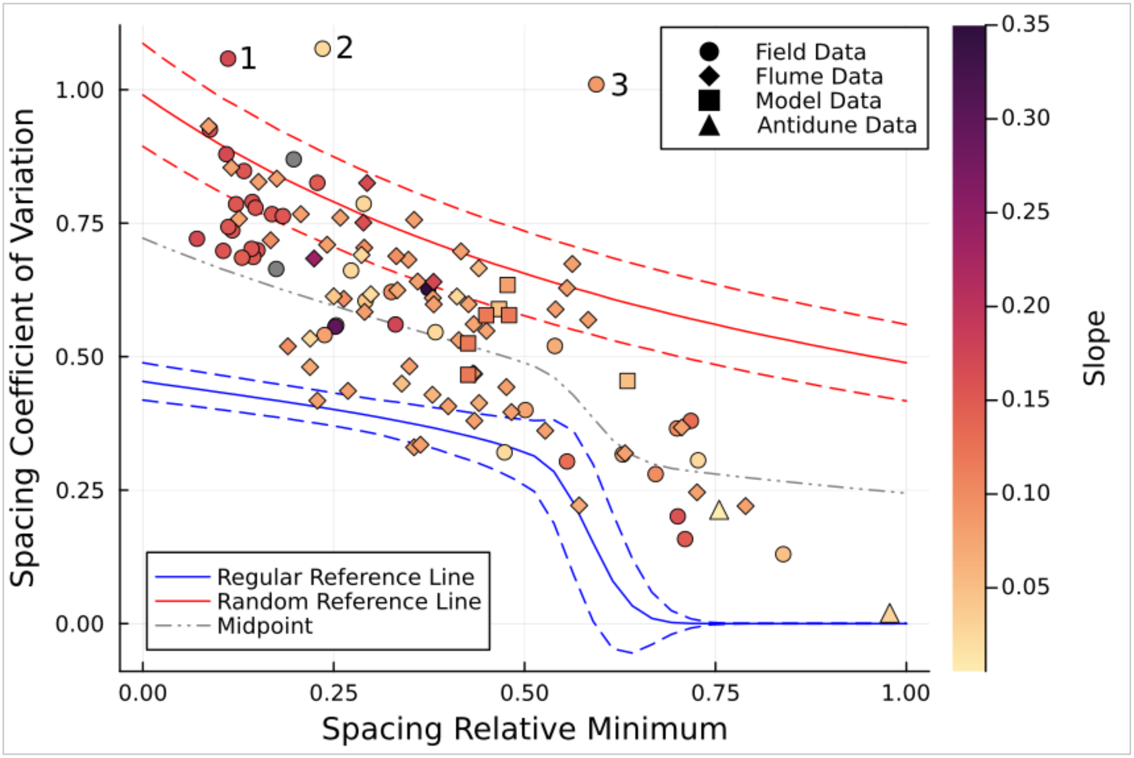

Figure 2: Comparison of data compiled from field, flume, and model step-pool spacing using a diagnostic plot (*n*=131). All points are colored by the slope of the reach in which observations were recorded, with gray points lacking slope information. Solid lines indicate mean values from a Monte Carlo simulation serving as a reference for regular (blue) and random (red) sequences and also correspond to values of $CV_N = 0$ and $CV_N = 1$, respectively (see Fig. 3). 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.

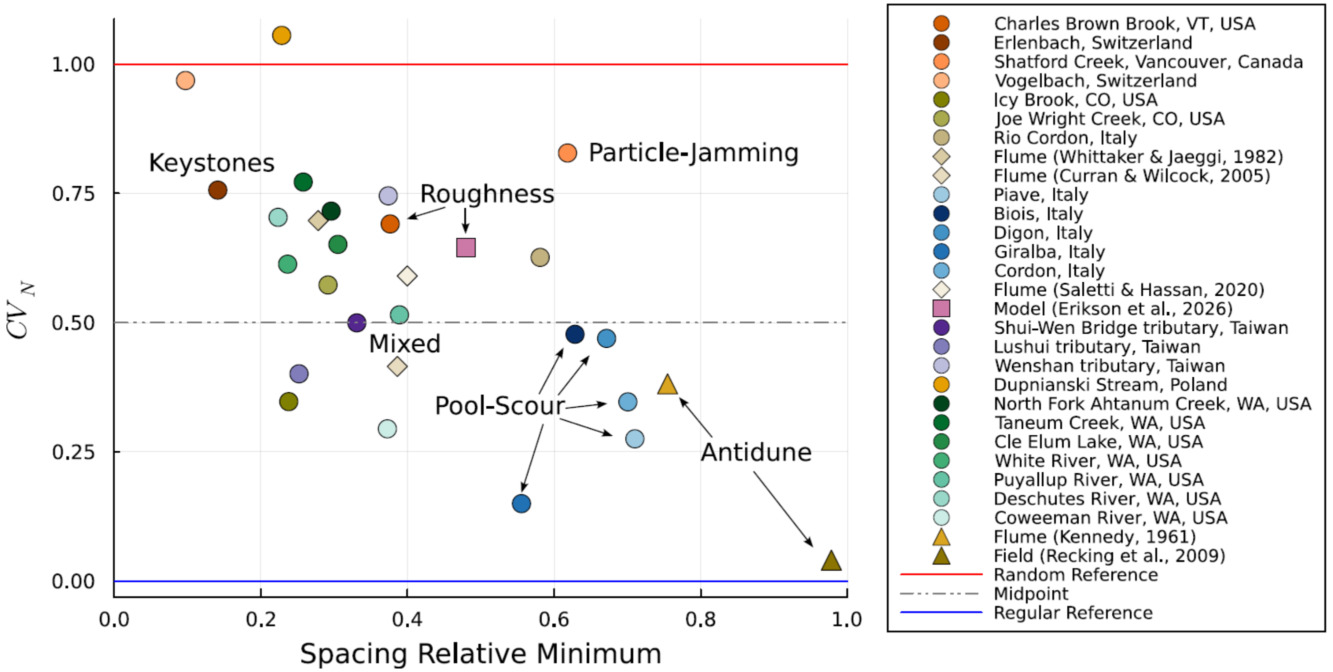

Figure 3: Mean positions in Fig. 2 averaged by source shown relative to the space between reference lines. The Range Normalized Coefficient of Variation (CV_N) is the y-axis of Fig. 2 now normalized by the y-axis space between the red and blue lines in Fig. 2 to show where within the envelope points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

Eighteen of the 27 averaged data sources, excluding antidunes, are closer to the random reference line than the regular reference line, while the remaining 9 are closer to the regular reference line than the random 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 ($CV_N = 0.42$) (diamond under "Mixed" label, Fig. 3). 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. Numerical simulations based on roughness also plot closer to the random reference line than regular reference line on average ($CV_N = 0.65$) (Text S3). 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 the expectation that steps associated with these mechanisms should exhibit regularity. The coefficient of variation does not display strong correlation with channel slope (Fig. S1). Notably, the flume experiments of Whittaker & Jaeggi (1982) (upper left gray diamond, Fig. 3), 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).

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 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 mean and limit the accuracy of the minimum spacing as a proxy for the exclusion zone (Fig. S2, Text S4). 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) 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 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 hydraulicly-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 and 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 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.

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 (Chartrand et al., 2011; Zhang et al., 2023). The need for adaptable definitions of equilibrium is further emphasized by variation in step stability (Golly et al., 2019; Waters and Curran, 2012), as well as step evolution in response to the same perturbation within a single sequence (Chartrand et al., 2011; Lenzi, 2001). 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 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 and Phillips, 2007). Because the random reference line 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, 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 dynamic, and mixed-mechanism step-pools (Chin and 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 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 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. S3). 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. S4). 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 modified Poisson process (Curran & Wilcock, 2005), which leads to random spacing. The emergence of random spacing comes from the assumption that the location of each step is independent from other steps and that all possible location have an equal probability of a step forming. The simulation consisted of randomly sampling spacings from an exponential distribution and rejecting spacings that fell below the minimum constraint to account for the role of an exclusion zone. 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

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:

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

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).

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), but will also be included in the data publication.

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.

Competing interests

The authors declare that they have no conflict of interest

Disclaimer

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