

Characteristic dimensions of the step-pool bed configuration: An experimental study

Joanna C. Curran

Department of Geography, Texas State University, San Marcos, Texas, USA

Peter R. Wilcock

Department of Geography and Environmental Engineering, Johns Hopkins University, Baltimore, Maryland, USA

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[1] The dominant dimension of the step-pool bed form is its spacing, which is determined by the locations at which large, step-forming grains are deposited. We conducted laboratory experiments involving active transport of widely sorted sediment, including large grains whose deposition readily formed steps. Direct observation of step development indicates that deposition of step-forming grains was predominantly associated with bed roughness impeding transport or with earlier flow and transport conditions not contemporaneous with step development. Neither mechanism is likely to occur at regular locations on the bed. Measured step spacing was found to follow a Poisson distribution, supporting the conclusion that steps do not develop in preferred or regular locations. This contrasts with previous arguments that regular step spacing develops in response to deposition forced at regular locations beneath water surface waves. We observe neither the regular distribution nor the associated depositional mechanism, although the observed step distribution is well defined with a strong mode that could be interpreted as indicating regular spacing.

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1. Introduction

[2] The step-pool bed configuration, a common feature in steep, mountain channels, is composed of a sequence of steps and pools, which in profile resembles a staircase (Figure 1). Several of the largest particles in the channel align horizontally across the channel to create the step riser. Flow tumbling over the step scours a pool, which forms the step tread.

[3] The geometry of the step-pool bed form can be described by step height and step spacing. Step height scales directly with the size of the largest grain forming the step [Judd and Peterson, 1969; Grant *et al.*, 1990; Chin, 1999a; Grant, 1994; Abrahams *et al.*, 1995; Billi *et al.*, 1995; Chin, 1999a; Lenzi, 2001; H. E. Judd, unpublished dissertation, 1963], and thus the predominant free variable describing step-pool geometry is the spacing. Step spacing is measured as the distance between large, step-forming grains and is therefore established when these grains are deposited. Entrainment, transport, and deposition of these large grains typically occur during exceptionally large floods with estimated return intervals of 30 years or more [Grant *et al.*, 1990; Chin, 1994; Billi *et al.*, 1995; D'Agostino and Lenzi, 1997]. It is during these large flows that step spacing is established and the geometry and dimensions of the step-pool bed form are set. The step-forming grains may rearrange during more frequent floods

with return intervals of 5 years. In these circumstances, existing steps have been observed to break while other steps remain stationary, creating a larger step spacing between selected steps without altering the entire step sequence [Lenzi *et al.*, 2004; Billi and Preciso, 2003].

[4] Step-pool systems have been reported in a number of different settings worldwide. Steps have been measured in bedrock channels in such diverse settings as Israel and the Oregon High Cascades [Bowman, 1977; Wohl and Grodek, 1994; Duckson and Duckson, 1995]. Step-pool systems are also common in heavily forested watersheds in the western United States, where large woody debris contributes to the steps [Wohl *et al.*, 1997; Curran and Wohl, 2003; MacFarlane and Wohl, 2003]. The more common step system is that formed from alluvium. These are depositional step systems, where the step-forming material derives from the local channel alluvium. Only depositional, alluvial step systems are considered for this research.

[5] The spacing between steps within a step-pool configuration is commonly reported to be regular due to the control of channel parameters such as bed slope and grain size. Grant *et al.* [1990] determined that step spacing was regular within each of 21 step-pool configurations in Oregon where the average step spacing was 2.56 m. The same measurements illustrated an inverse relationship between spacing and channel slope, indicating slope control over step spacing. D'Agostino and Lenzi [1997] illustrated a similar inverse dependence of step spacing on channel slope using measurements of step spacing from nine step-pool configurations in the Rio Cordon, Italy, where the average

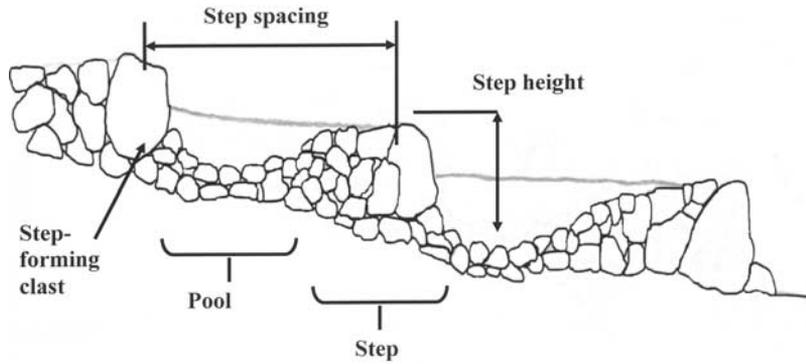


Figure 1. Definition diagram of a step-pool bed form under low flow conditions.

step spacing was 7 m. From a study of 12 step-pool reaches in California, *Chin* [1999a] identified regular step spacing with an average of 5.29 m. *Chin* attributes the regularity of step spacing to the influence of channel slope and discharge at the time of step formation. In further analysis of the same data set, *Chin* [2002] uses spectral analysis to propose the hypothesis that step spacing represents a mutual adjustment of the flow field, sediment bed, and rate of energy expenditure from the channel. Mechanisms proposed to explain regular step spacing, such as the maximum flow resistance hypothesis and the existence of precursor antidunes, all incorporate a strongly coupled interaction between the bed surface and water surface in which water surface waves produce depositional sites at regular intervals [*Judd and Peterson*, 1969; *Whittaker and Jaeggi*, 1982; *Allen*, 1983; *Chartrand and Whiting*, 2000].

[6] Using both field and flume data, *Abrahams et al.* [1995] proposed the hypothesis that steps adjust their spacing to create the maximum resistance to flow. Using data from 12 flume experiments and 18 step-pool configurations

in New York and England, step spacing was shown to fit the relationship $1 \leq H/L/S \leq 2$, where H is step height, L is step spacing, and S is channel slope. Thus step spacing is proportional to the measure of steepness of the step as given by H/L . The data of *Abrahams et al.* [1995] is reproduced in Figure 2 along with measurements of step systems by *Whittaker and Jaeggi* [1982], *Grant* [1994], *Chin* [1994], *Billi et al.* [1995], *D'Agostino and Lenzi* [1997], *Chartrand and Whiting* [2000], *Lenzi* [2001], *Zimmermann and Church* [2001], and *MacFarlane and Wohl* [2003]. Many of the measurements fall outside the range delineated by the maximum flow resistance hypothesis, indicating that steps are arranged according to parameters other than flow resistance in many instances.

[7] Regularity in step spacing is commonly attributed to the spacing of a precursor antidune configuration [*Whittaker and Jaeggi*, 1982; *Grant*, 1994; *Rosport and Dittrich*, 1995; *Chin*, 1999a; *Chartrand and Whiting*, 2000; *Lenzi*, 2001]. According to this argument, antidunes form at high discharges in steep streams and deposition of coarse grains is

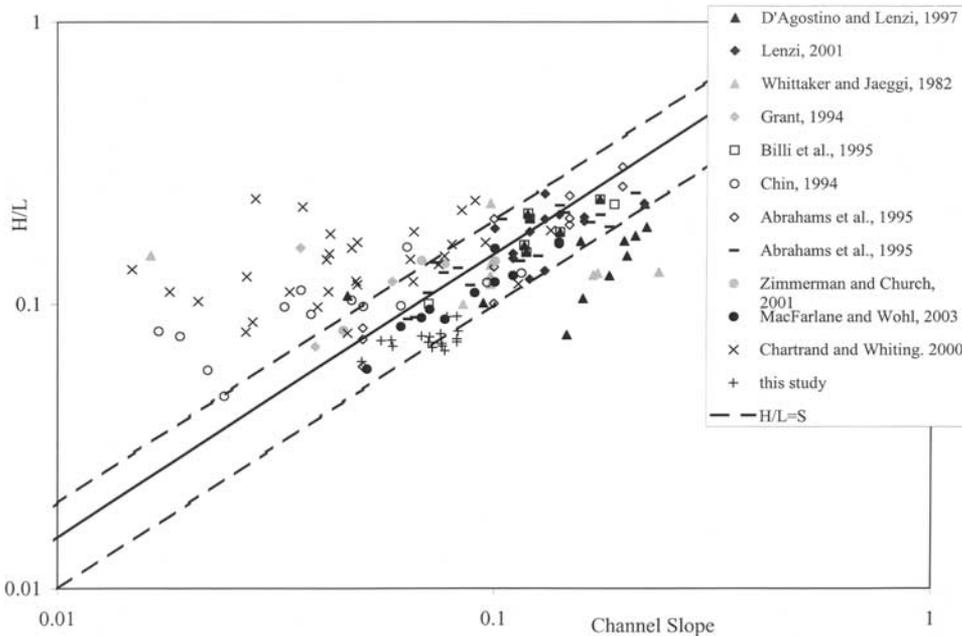


Figure 2. Maximum flow resistance proposed by *Abrahams et al.* [1995] shown with existing field and flume measurements of step spacing. H is step height, L is step spacing, S is channel slope, and H/L is a measure of step steepness.

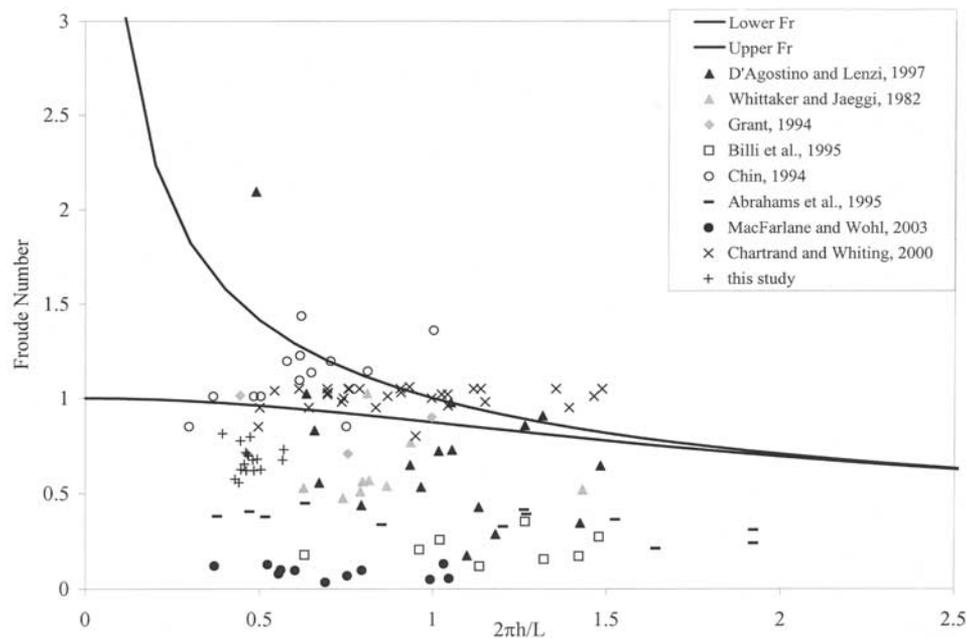


Figure 3. Antidune stability diagram from *Kennedy* [1963]. The area within the curves represents stable antidune formation. Here h is estimated flow depth at the step and L is step spacing.

focused beneath a regular train of waves in the water surface. Steps and pools emerge as flows on the falling limb scour mobile grains from between the coarse-grained deposits to develop the pools, leaving the coarse grains to form the steps. *Chin* [1999a] extended the theory of step formation from antidunes in an attempt to explain the initial antidune spacing. By reconstructing the formation discharges for step-pool configurations in California, she has theorized that discharge is the primary control over both the antidune and subsequent step spacing.

[8] Evidence for the antidune mechanism comes primarily from flume experiments. The appropriate combination of steep flume slope, high discharge, and zero sediment supply can form a train of water surface waves that is similar to the waves associated with the antidune configuration in sand beds. Deposition of grains entrained from the flume bed is focused under the water surface waves such that the initial plane bed degrades into a stepped configuration in which the spacing of the steps matches that of the precursor antidunes [*Whittaker and Jaeggi*, 1982]. The final step spacing plots either proximal to or within the antidune stability field defined by *Kennedy* [1963]. The stability diagram is reproduced in Figure 3 along with data from step systems measured by *Whittaker and Jaeggi* [1982], *Grant* [1994], *Chin* [1994], *Abrahams et al.* [1995] (flume data), *Billi et al.* [1995], *D'Agostino and Lenzi* [1997], *Lenzi* [2001], *Zimmermann and Church* [2001], *Chartrand and Whiting* [2000], and *MacFarlane and Wohl* [2003]. While the data of *Chin* [1994] and *Chartrand and Whiting* [2000] plot within the antidune stability field, the majority of the measurements fall well below the lower limit.

[9] *Zimmermann and Church* [2001] examined the step-spacing data of *Abrahams et al.* [1995], *Wohl et al.* [1997], *Chin* [1999a] and measured 36 step-pool configurations in British Columbia. They examined the statistical significance of the data, focusing on the maximum, minimum, and coefficients of variation reported for each step sequence

and found that the range in step spacings given for each individual reach was often of factor 10. The variability in measured step spacing within individual channel reaches was large, and *Zimmerman and Church* concluded that there was no evidence of regular step spacing. Given the large amount of variability, they hypothesized that step spacing is set by the location of large, immobile keystone grains. The locations of the keystone grains may be random, indicating that steps may not follow a regular spacing.

[10] The key conditions under which step spacing is set are those that produce transport and deposition of the step-forming grains. In the field, such conditions are too infrequent (of order 30+ year return interval) as well as unsafe for direct observation. While step-forming grains have been observed to move at flows with return intervals as low as 5 years, the majority of steps are set by the larger floods [*Grant*, 1994; *Billi and Preciso*, 2003; *Chin*, 2003; *Lenzi et al.*, 2004]. An explanation of step formation from field measurements is also difficult because variables which may influence step spacing, such as grain size, discharge, channel width, flow depth, and channel slope, tend to covary, making it impossible to separate their effects. As a result, it is difficult to use field data to resolve, for example, whether a downstream variation in step spacing is due to a reduction in grain size relative to channel width or to a reduction in channel slope. Given the difficulties associated with field investigation of the formative mechanisms of the step-pool bed form, experiments in laboratory flumes provide an important substitute, provided that representative conditions of flow and transport are used. Laboratory experiments permit direct observation of the step-forming mechanism and the control and accurate measurement of the flow and transport conditions.

[11] The focus of many previous flume experiments has been on the mechanisms by which the characteristic step and pool geometry develops from an initially flat bed containing a wide range of grain sizes [*Whittaker and*

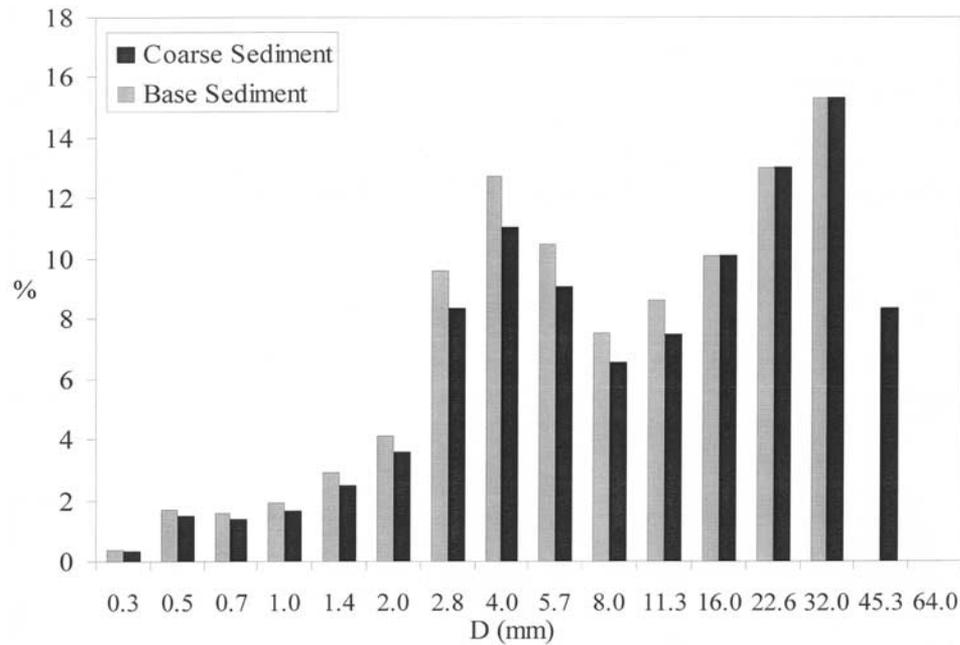


Figure 4. Grain size distributions for the base and coarse sediments. Numbers on the abscissa represent the lower value of each size bin.

Jaeggi, 1982; Grant, 1994; Rosport and Dittrich, 1995]. These are degradational flows, where the step pool sequence becomes visible in the channel profile as overlying sediment is removed. We term these “step-elucidating flows” to distinguish them from larger flows that involve transport and deposition of the largest, step-forming grains. We term the latter “step-setting flows” because the depositional location of step-forming grains, and therefore the spacing and overall geometry of the step-pool configuration, are determined at these flows.

[12] Here we report on flume studies designed to investigate the characteristic dimensions of the step-pool bed configuration. Because we were especially interested in determining whether regular step spacing, and the mechanisms invoked to explain regular spacing, would occur in step-setting flows, the flows used in our experiments produced active transport and deposition of all sediment sizes, including the largest step-forming grains. Steps formed readily and were visible during the experiments, allowing measurements of step spacing and direct observations of the step-forming mechanisms. The range of flow and transport conditions used provide a data set from which any connections linking step spacing to the channel flow and transport parameters can be identified and statistically summarized. Thus our focus is on step-setting transport conditions, rather than the subsequent step-elucidating flows, which help to sculpt the ultimate step-pool bed form but do not strongly influence its dimensions.

[13] In addition to using step-setting flows, two other aspects of our experiments were of particular importance in evaluating the prevalence of regular step spacing. First, the sediment used was widely sorted and included large grains capable of providing a “keystone” to anchor subsequent development of a step-pool bed form. One of the two sediment mixtures used in these experiments produced distinct step-pool forms under a range of flow and transport conditions; the other sediment, which lacked the coarsest

fraction of the first, formed only weak steps or no steps at all. Second, the experiments involved the development of hundreds of individual step-pool bed forms, such that the number of observations is sufficient to describe the distribution of step dimensions. All of the flume runs were videotaped and the mechanism by which each step formed was directly observed, so that there was no ambiguity regarding step-forming mechanism.

2. Methods

[14] The experiments were conducted in a small tilting flume of 0.15 m width, 0.3 m depth, and 5.2 m length with 3.5 m working length. The flume walls were clear acrylic, allowing direct observation of the transport. Water was recirculated, and discharge was held nearly constant during each run. Sediment was fed into the upstream end of the flume and collected as it exited the downstream end. Two sediment mixtures were used in these experiments; both were subsets of the widely graded mixture previously described by Wilcock and McArdeil [1993, 1997]. The grain size of the first, or base, sediment extended from 0.5 to 45.3 mm, with $D_{50} = 10$ mm and 8.5% sand. Grains in the 45–64 mm size class were added to the base sediment to produce the second, coarse sediment, with $D_{50} = 14$ mm, 7.4% sand, and 8.3% in the 45–64 mm size class (Figure 4). The mean specific gravity of the sediment was 2.61. The specific density for grains between 4.0 and 8.0 mm, which contained some chalky limestone fragments, was 2.49. The fractions between 8.0 and 32 mm contained a larger portion of mafic materials, giving a mean specific gravity between 2.69 and 2.73.

[15] The sediment size distribution and flume width, b , were chosen to provide favorable step-forming conditions based on previous observations in flumes and in the field and to scale the sediment sizes measured in the field [Whittaker and Jaeggi, 1982; Grant et al., 1990; Stuve,

Table 1. Measured and Calculated Parameters From Experiments Using the Coarse Sediment

Run ID	Q_s , $\text{m}^3 \text{s}^{-1}$	Q_s , $\text{G m}^{-1} \text{s}^{-1}$	Flow Depth, cm	Bed Slope	Velocity, $\text{m}^2 \text{s}^{-1}$	Average Step Spacing, cm	Average Step Height, cm
1B	0.0046	110	6.6	0.077	0.46	66.3	6.5
11	0.0046	750	6.7	0.071	0.45	96.8	5.4
16	0.0046	1000	6.3	0.076	0.49	87.6	5.6
2B	0.005	110	6.7	0.082	0.50	64.4	5.9
7B	0.005	475	6.2	0.058	0.54	88.9	5.6
12	0.005	750	6.4	0.076	0.52	60.1	5.2
12B	0.005	750	6.6	0.083	0.50	88.1	6.1
17	0.005	1000	6.0	0.082	0.56	69.1	5.2
17B	0.005	1000	6.3	0.075	0.53	76.3	5.8
22	0.005	1250	6.3	0.078	0.53	73.8	5.8
8	0.0055	475	6.7	0.071	0.55	90.7	5.8
13	0.0055	750	6.5	0.071	0.57	85.0	6.9
18	0.0055	1000	7.1	0.068	0.52	97.6	6.2
23	0.0055	1250	6.5	0.055	0.56	94.6	5.7
5	0.0065	110	6.6	0.050	0.66	102.6	4.8
15	0.0065	750	7.2	0.059	0.60	77.0	5.5
20	0.0065	1000	6.7	0.082	0.65	86.9	6.6

1990; Schmidt and Ergenzinger, 1992; Chin, 1994; Grant, 1994; Rosport and Dittrich, 1995; D'Agostino and Lenzi, 1997; Chartrand and Whiting, 2000]. The ratio of step-forming grain size, D_{SFG} , to flume width is particularly important for the formation of steps, as it determines the number of large grains needed to span the channel and create the step riser. The D_{SFG} fraction represents the largest grain size available in the sediment, making it slightly larger than the D_{90} size fraction. The overall grain size distribution as represented by the D_{SFG}/D_{50} and D_{50}/D_{10} ratios is used to check the similarity between the flume sediment used in these experiments against sediments measured in previous flume and field step sequences. Values of D_{SFG}/D_{50} for our experimental sediments fell within the range of those observed in the field and values of b/D_{SFG} fell at the narrow end of field observations, in order to promote step development in the smooth-walled flume [Grant *et al.*, 1990; Stuve, 1990; Schmidt and Ergenzinger, 1992; Chin, 1994; D'Agostino and Lenzi, 1997; Chartrand and Whiting, 2000; Crowe, 2002].

[16] This study consists of a total of 28 flume runs. Eleven runs were conducted using the base sediment, and 17 runs were conducted with the coarse sediment. In both cases, water discharge was chosen from a set of four flow rates between 0.0046 and 0.0065 $\text{m}^3 \text{s}^{-1}$, and sediment was fed into the flume at one of five constant rates between 110 and 1250 $\text{g m}^{-1} \text{s}^{-1}$ (Table 1). Flow rates were chosen such that the shear stresses generated would create active transport of all sediment sizes, including the large step-forming grain size. The sediment feed rates were chosen to span an order of magnitude. As sediment exited the flume, the large grains were set aside and counted. In the coarse sediment, the 45–64 mm grains were recorded individually. For the base sediment, the total number of 32–45 mm grains exiting the channel was recorded approximately every 2 min. For each run the bed aggraded to an equilibrium slope, verified by a match between the feed rate and transport rate of the largest grain size in the sediment. Evaluations of the transport of smaller size fractions indicated that the largest size was the last to reach a condition of steady state transport. The time to reach an equilibrium transport condition varied from as little as 45 min to over 800 min, depending on the rates of flow and sediment feed.

[17] An essential part of the analysis was the direct observation of the deposition of step-forming grains and subsequent step development in order to identify the depositional mechanism and the associated hydraulic and transport conditions. Two video cameras were used to film 3.5 m, or the entire working length, of the flume. Each camera captured 1.8 m of flume length, enabling an overlap of 10 cm. Mirrors were used to produce a split image of both the near and far sides of the flume. The mirrors allowed for a check of the step bed forms to be sure that they spanned the channel width and were not a result of wall effects. The location, height, and total time of existence of each step were determined from review of the videotapes, along with a description of the mechanism by which the step-forming grains deposited and the subsequent step-pool feature developed. Step height was measured as the distance between two parallel lines fit by eye to the highest point of the step and the lowest part of the associated pool. Step location was measured at the highest point in the step.

[18] It was not possible to measure the water or sediment surfaces accurately while the flume was running because of the shallow flow depth and irregular surfaces created by the high flow and transport rates. Sediment and water surfaces were measured on the videotape for both sides of the flume and then averaged to create bed and water surface profiles. Flow depth was calculated as the difference between the water and bed surfaces. Profiles were measured for each minute of run time after the bed reached an equilibrium transport condition.

[19] Water discharge was measured using a calibrated relation for head loss in a bend in the water return pipe. Mean velocity was calculated as the ratio of discharge to flow area using the channel width and the mean flow depth determined from the videotape (Table 1). The Froude number was calculated from mean velocity and depth, and varied between 0.56 and 0.81. In previous laboratory experiments, which typically used zero sediment feed and tended to focus on flow over existing step bed forms rather than the deposition of step-forming grains, reported Froude numbers between 0.80 and 2.15 [McDonald and Day, 1978; Whittaker and Jaeggi, 1982; Grant, 1994; Rosport and Dittrich, 1995; Chartrand and Whiting, 2000; MacFarlane and Wohl, 2003]. Froude numbers for step-forming flows in

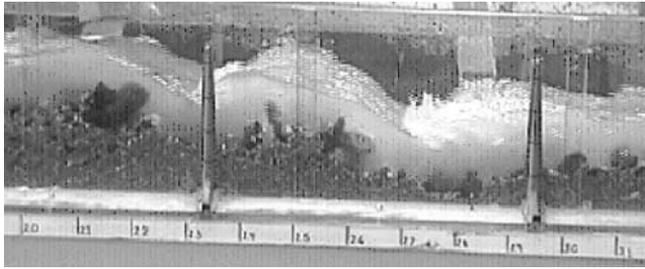


Figure 5. Photo showing a developed step-pool sequence during a flume experiment. Two steps, located at 2.1 and 2.5 m, are shown in this photo. See color version of this figure in the HTML.

the field, based on estimates of the flow necessary to mobilize the step-forming grain size, range between 0.623 and 1.12 [Grant *et al.*, 1990; Stuve, 1990; Chin, 1999b; Chartrand and Whiting, 2000]. The only field observations of flows that reset step spacing are from the Rio Cordon where the Froude number is estimated to have been 1.70 and an Ethiopian mountain stream with estimated Froude numbers between 0.7 and 1.8 [Billi *et al.*, 1995; Billi and Preciso, 2003].

3. Results

[20] We found that very few weak steps developed with the base sediment, whereas the coarse sediment, which was identical to the base sediment except for the addition of 45–64 mm grains to a concentration of 8.3% (Figure 4), formed robust and distinct steps over the full range of flow and transport conditions (Figure 5). A critical factor in creating realistic steps in the laboratory is the availability of large grains that can act as keystones. The analysis here focuses on results from the 17 runs conducted with the coarse sediment.

[21] Step height was measured from the top of the step to the base of the pool (Figure 1). The height of the step scales directly with the size of the step-forming grain. In our case, step height was consistently set by the largest grain size available, grains falling in the fraction from 45 to 64 mm. Our finding that step height is directly related to step-forming grain size is in agreement with the previously reported results [Judd and Peterson, 1969; Grant *et al.*, 1990; Chin, 1999a; Grant, 1994; Abrahams *et al.*, 1995; Billi *et al.*, 1995; Chin, 1999a; Lenzi, 2001; H. E. Judd, unpublished dissertation, 1963].

[22] The key event in the development of step spacing is the deposition of the step-forming grain or grains. Although not every instance in which a large grain deposited on the bed resulted in the subsequent development of a step, every step required the initial deposition of a step-forming grain. Every grain deposition/step formation sequence during the flume runs (384 total) was observed directly through the walls of the laboratory flume, providing an unambiguous basis for evaluating the mechanism leading to the formation of each step and its spacing relative to other steps. The spacing of every newly formed step was measured relative to the next step upstream.

[23] Measurements of flow and sediment parameters were made during each run to test for a possible correlation between step spacing and either bed slope, flow depth,

discharge, sediment feed rate, or flow velocity (Table 1). We were unable to find a significant relationship between any of the measured parameters and step spacing. The often cited inverse relationship between step spacing and bed slope was not apparent in our data.

[24] We identified three mechanisms for step formation, and all three mechanisms were active in every step-forming flume experiment. The most common mechanism (60%) begins with the initial deposition of the step-forming grain in a rough area of the bed surface or where the grain encounters an obstacle preventing its continued transport. Once this grain comes to a halt, additional sediment accumulates around it, forming a clast jam or cluster that eventually spans the channel width to form a step. Flow tumbling over the step crest then scours a pool immediately downstream of the step. The only apparent feature producing the depositional location of the step-forming grain was a bed obstacle impeding farther downstream motion. There were no obvious waves in the water surface associated with the deposition of the step-forming grain. Therefore the location of the step and its spacing relative to other steps is not associated with water surface waves generated from an existing step or antidune wave train.

[25] In the second step-forming mechanism, the step-forming grain is already present in the sediment bed, having been deposited and buried earlier in the flume run. Local bed scour then exhumes the large grain until it becomes prominent in the bed profile. Once exposed, deposition around the large grain creates a step and tumbling flow over the step crest scours a pool downstream. This mechanism was responsible for 24% of all observed step-pool formations. The depositional mechanism and controls on the location of the step-forming grain are unknown, although they are clearly unrelated to the flow field present at the time of step formation. Together, this mechanism and the rough bed mechanism account for 84% of the observed step-forming events. In neither case is the location of the step forced by the presence of water surface waves or any apparent interaction between the bed surface and the water surface.

[26] The third step-forming mechanism, accounting for 16% of all steps we observed and measured, was associated with low, symmetrical dunes that would periodically form in the channel (Figure 6). These bed forms have no slip face, but do exhibit a dune-like grain trajectory in which grains eroded from the stoss of the dune are deposited on its lee. In approximately 10% of the cases in which a step formed through the obstacle mechanism, a train of one or two dunes formed on the bed surface downstream of the step. The first event in dune formation is deposition of a few grains (smaller than the step-forming grain size) to create a slight

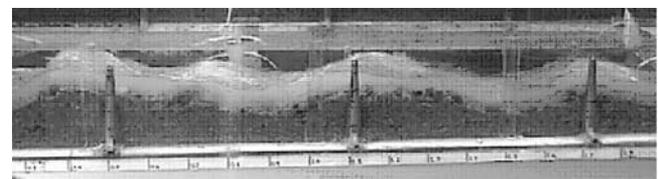


Figure 6. Photo of a sequence of dunes developing downstream of a step. This dune sequence is typical of those that later develop into a step sequence. See color version of this figure in the HTML.

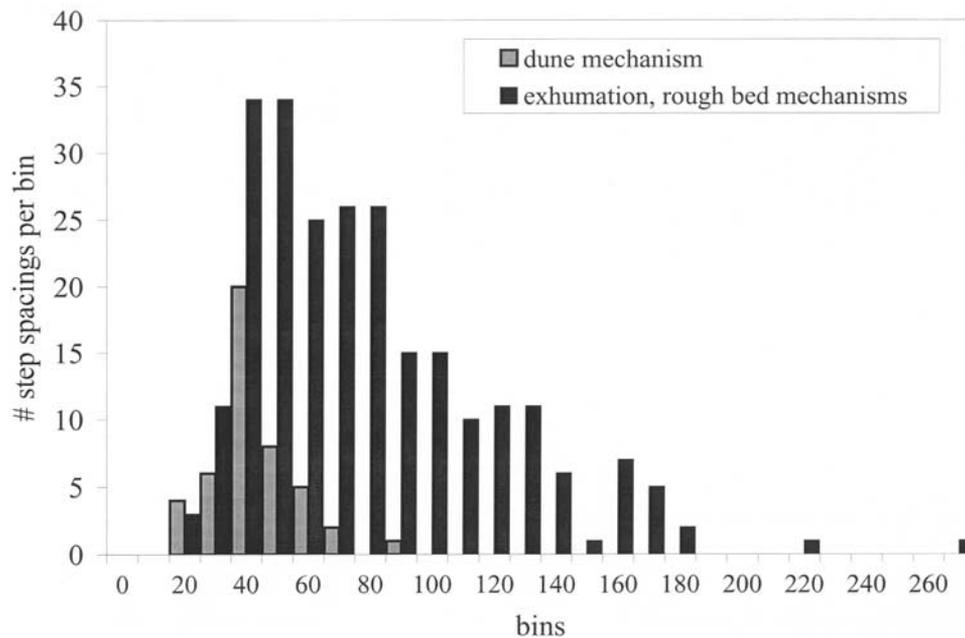


Figure 7. Spacing for 384 steps formed during the experiments. Separate histograms given for steps developed from the rough bed and exhumation mechanisms and from the dune mechanism. Numbers on the abscissa represent the lower value for each spacing bin.

deformation of the bed surface. The water surface quickly develops an inphase surface wave. The time interval between initiation of the dune on the bed surface and formation of the water surface wave is of the order of seconds and discernable on the videotape only when played in slow motion. Further sediment accumulation builds the dune and its associated in-phase water surface wave until it reaches a height of order 10–15 cm.

[27] Dune formation was not uncommon during the runs, and the majority of dunes form and dissipate without forming steps. Approximately 25% of the dune trains develop into one or, occasionally, two steps. This occurs when a step-forming grain deposits on the upstream side of the dune, increasing its height and trapping other grains until a step is formed. In the majority of cases (13% of all steps and 85% of all dune steps), a step develops on only the first dune in the train. The result is a series of two steps; the first formed by the obstacle mechanism and the second formed from the first dune downstream of the step. In a minority of cases (15% of dune trains and 2% of all step formations) a third step developed on the second dune, forming a three-step sequence: the first step formed by the obstacle mechanism and the second two steps from the dune train. The three-step sequence was most likely when multiple dunes developed to a comparable magnitude prior to step formation on the first dune. When steps formed through the dune mechanism, the step spacing was equal to the precursor dune spacing, which was highly regular (average dune spacing 43 cm with standard deviation 14 cm) for our flow and sediment.

[28] Combining steps formed by obstructed transport and exhumation, 84% of steps formed without locational control provided by the flow field associated with other steps or flow obstructions. The locations of the remaining 16% of the steps were determined by an interaction between the water surface and bed surface associated with regular dune

spacing. It is worth noting, however, that flow depth over the dunes was quite uniform in the absence of, or prior to, step formation (Figure 6). The step-forming grain deposited on the upstream side of the dune over which it could not pass. Because the dune locations were established with interaction between the sediment and water surfaces, the subsequent step spacing is indirectly influenced by the water surface wave.

[29] For 384 steps formed in the 17 runs with the coarse sediment, we measured the location of each step as the distance immediately downstream from the next step upstream. We observed that deposition of a step-forming grain rarely (4.8%) occurred within 30 cm of an existing step. This region (which we term the exclusion zone) includes the scour hole (or pool) produced by flow plunging over the step as well as a zone of acceleration where flow exits the pool. An exclusion zone occurred for all three step-forming mechanisms, with an average length of 30 cm for steps located by the rough bed and exhumation mechanisms and 40 cm for steps developed from dunes. The existence of the exclusion zone cannot be fully explained by the presence of the pool. Pool lengths were measured for each step pool pair as the distance from the downstream face of the step, and the average pool length was 18 cm (standard deviation 6 cm; Figure 1). Thus the pool accounts for approximately half the distance of the exclusion zones. When divided by the average size of the keystone grain, the dimensionless lengths of the exclusion zones are 5.6 and 8.8, respectively.

[30] The distribution of step spacing for the steps located by the rough bed and exhumation mechanisms shows a strong mode at 30–50 cm, few spacings smaller than 30 cm, and a broad tail extending to larger step spacings (Figure 7). The overall distribution has a distinct mode, with an exponentially shaped tail toward greater step spacing, such that a large majority of steps have spacings between 30 and

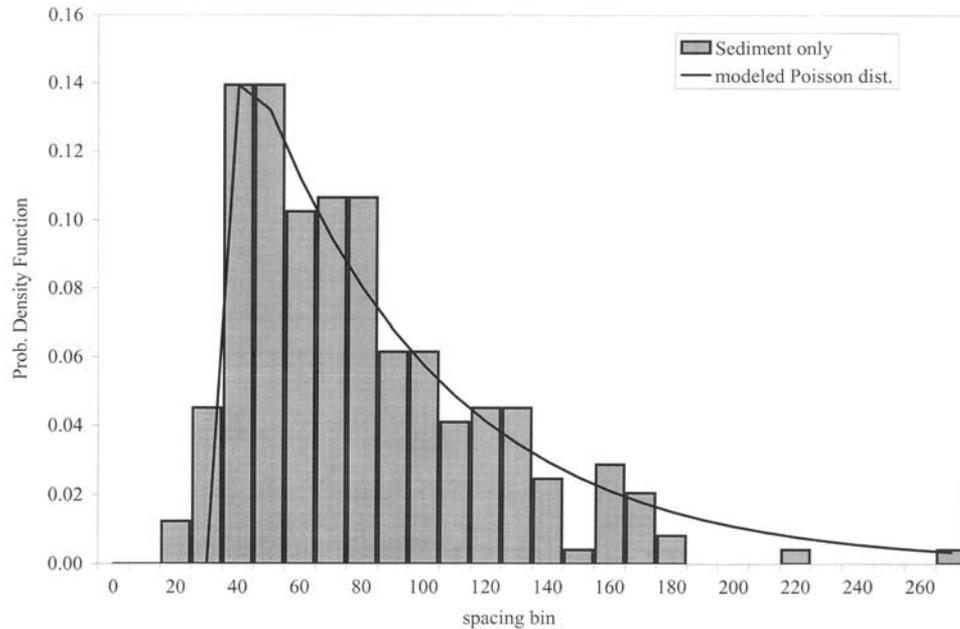


Figure 8. Histogram of step spacing for steps formed through the rough bed and exhumation mechanisms. A Poisson distribution is fitted to the spacing data. Numbers on the abscissa represent the lower value for each spacing bin.

80 cm. Step spacing between 30 and 50 cm accounts for 28% of the steps, and 60% of step spacings fall between 30 and 80 cm. Only 5.7% of the steps have spacing smaller than 30 cm from the next upstream step.

[31] Step spacing for the dune steps has a symmetrical distribution with a dominant mode at 40–50 cm (Figure 7). There are near equal numbers of steps with spacings both greater than and less than the major mode. This step type describes only 16% of all the observed step formations.

4. Discussion

[32] For the majority of step-forming events, the depositional location of the step-forming grain was controlled either by local properties of the bed or by flow and transport conditions earlier in the flume run. Because there is no contemporary mechanism likely to produce a regular spacing of the minor bed obstructions or earlier conditions producing deposition of the step-forming grain, we conclude that no preferred depositional location exists for almost 90% of the steps we observe. This differs from the case in which regular step spacing is forced by deposition of grains beneath an existing train of water surface waves. If the local conditions producing deposition of a step-forming grain are randomly distributed on the bed, such that each location on the bed is an equally likely depositional site, the unidirectional transit of potential step-forming grains can be considered a Poisson process. As a potential step-forming grain passes an existing step, an equal probability of deposition at any location (downstream of the exclusion zone) will produce a distribution of step spacings that is Poisson. To account for the exclusion zone, we use a Poisson distribution in which the distance scale is translated by an amount x_0 , the length of the exclusion zone

$$f(x) = \lambda e^{-\lambda(x-x_0)}, \quad (1)$$

where $\lambda = 1/\beta$ and β is the mean of the modified distribution.

[33] We fit the modified Poisson distribution to step-spacing observations grouped into 10-cm bins. When fit to the steps formed by the rough bed and exhumation mechanisms, the mean spacing is $\beta = 60$ cm with an exclusion zone $x_0 = 30$ cm (Figure 8). The statistical fit of the Poisson distribution has a significance level 0.05 while a normal distribution was rejected at all significance levels using the Kolmogorov-Smirnov goodness-of-fit test [Ang and Tang, 1975]. The probability that a step-forming grain will actually deposit at any location is equal to the probability of grain deposition for that bin (except in the exclusion zone) times the probability of a grain reaching that bin, calculated as one minus the sum of the depositional probabilities for upstream locations.

[34] The correspondence between a Poisson distribution and the observed step spacing, together with the prevalence of observed step-forming mechanisms unlikely to be associated with a regular pattern, suggests that the majority of step locations, rather than being determined by forced deposition at preferred sites driven by an interaction between the bed and water surfaces, are better represented by a model in which deposition of a step-forming grain is equally likely at any location on the bed. More than half of the step-forming grains deposited in locations dictated by the local roughness of the bed, and one quarter of the step-forming grains deposited under earlier conditions with no connection to the flow field at the time the step developed. It is worth noting that the resulting Poisson distribution, for the apparent depositional probabilities in our experiments, can produce the appearance of regular step spacing. The modal spacing (30–50 cm, or roughly 10 times the size of the step-forming grain) represents almost one third of the steps, and 60% of the steps had spacing between 30 and 80 cm.

[35] For dune steps, depositional location of the step-forming grain is influenced by the location of the next upstream step and involves some interaction between the water and sediment surfaces. In this case, the step spacing is

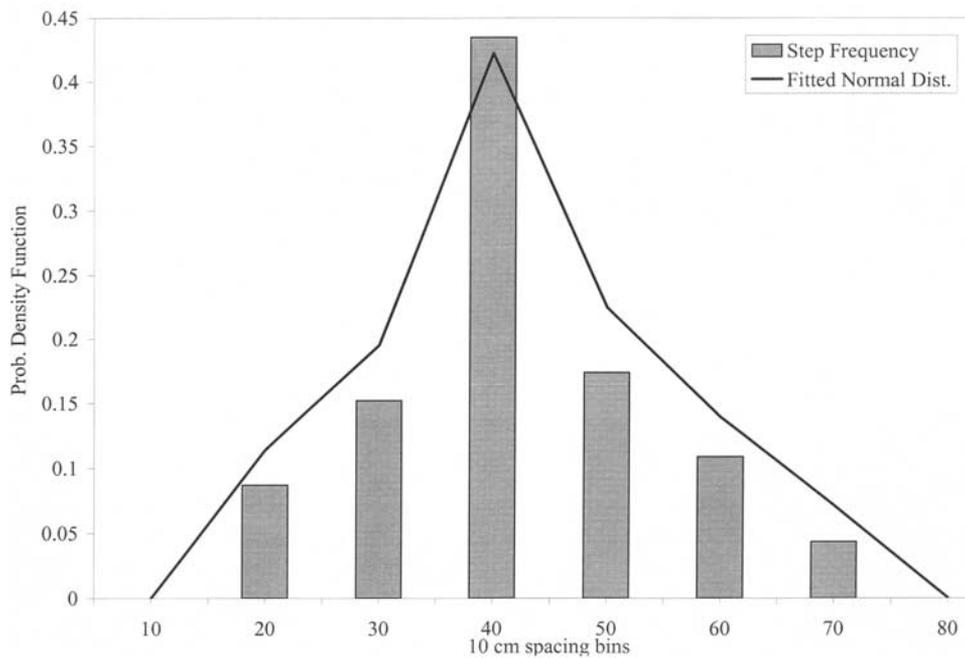


Figure 9. Distribution of step spacings for the dune steps illustrated by a histogram. A normal distribution is fitted to the spacing data. Numbers on the abscissa indicate the lower value of each spacing bin.

more regular. Using the Kolmogorov-Smirnov goodness-of-fit test, both Poisson and lognormal distributions were rejected. The data are well fit (significance level 0.05) by a normal distribution with mean 43 cm and standard deviation 14 cm (Figure 9).

[36] Our experimental results differ from previous findings in two related ways. First, we do not observe that step spacing is regular in the sense that it has a symmetrical distribution about a mean. Rather, we find that step spacing is better fit by a Poisson distribution, which indicates that there are no strongly preferred locations for step formation. Second, the step-forming mechanisms we observe differ from those invoked to explain regular step spacing, such as the maximum resistance to flow and the precursor antidune mechanisms. The mechanisms resulting in regular step spacing are based on an interaction between the bed surface and the water surface in which existing steps set up a flow field that induces deposition of subsequent steps under surface waves at a regular distance from the existing steps [Judd and Peterson, 1969; Allen, 1983; Grant, 1994; Billi *et al.*, 1995; Rosport and Dittrich, 1995; Chin, 1999a]. None of the steps we observed formed via such a mechanism, and most formed via a mechanism that would tend to have no preferred location. Further, the data from these experiments do not fall within either the region of antidune stability or in the area defining the maximum resistance to flow (refer to Figures 2 and 3). Our data, like much of the existing step-spacing data, plot outside these regions, indicating formation mechanisms other than the maximum resistance to flow and the antidune hypothesis, both of which involve interaction between the bed and water surfaces.

[37] Although neither the majority of the observed step-forming mechanisms nor the measured step spacing support the conclusion that steps are regularly spaced, the step-spacing distribution we observe does have some appearances

of regularity. This can be attributed to the influence of the dune step formation mechanism, although it is responsible for a minority of all step formations. The spacing distribution has a well-defined mode, and 60% of steps fall within 30 cm of the mean spacing (Figure 7).

[38] Our observation that the majority of steps have a location and spacing that depend on the depositional locations of step-forming grains rather than an interaction between the bed and water surfaces is consistent with the analysis of Zimmermann and Church [2001]. From field measurements of step-pool reaches at low flow, they suggest that step formation occurs when mobile particles deposit around a grain so large that it is not moved by normal flows. Thus steps develop without any specific or regular interaction from the water surface and need not have a regular spacing. Their field evidence did not evaluate the locations of the step-forming grains themselves, but their conclusion that steps form around available step-forming grains is consistent with our direct observations of step formation in the flume.

[39] Using previously published data of step spacing, we fit a modified Poisson distribution to field measurements and flume measurements scaled to represent field measurements (Figure 10). The histogram includes the step-spacing measurements of Whittaker and Jaeggi [1982], Whittaker [1987], Grant *et al.* [1990], Chin [1994], Grant [1994], Abrahams *et al.* [1995] (field data), Billi *et al.* [1995], Rosport and Dittrich [1995], D'Agostino and Lenzi [1997], Chartrand and Whiting [2000], Zimmermann and Church [2001], and MacFarlane and Wohl [2003]. When fit to the published step spacings, the mean spacing is $\beta = 6.0$ m with an exclusion zone of 3.2 m, and the statistical fit of the Poisson distribution is significant to the 0.05 level using the Kolmogorov-Smirnov goodness-of-fit test [Ang and Tang, 1975]. The good fit of the modified Poisson distribution to

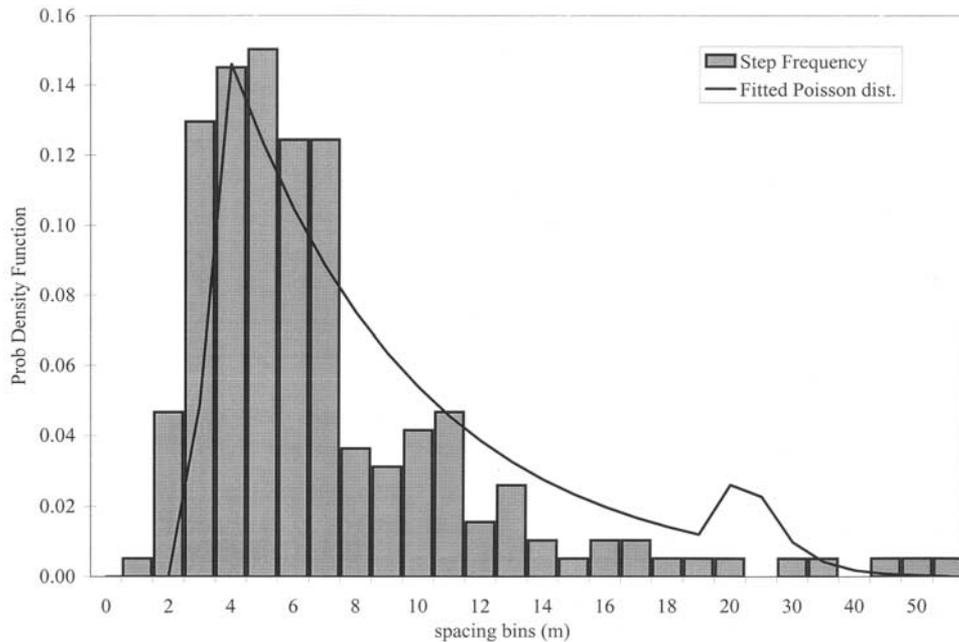


Figure 10. Histogram of the step spacing as reported by Whittaker and Jaeggi [1982], Whittaker [1987], Grant *et al.* [1990], Chin [1994], Grant [1994], Abrahams *et al.* [1995] (field data), Billi *et al.* [1995], Rosport and Dittrich [1995], D'Agostino and Lenzi [1997], Chartrand and Whiting [2000], Zimmermann and Church [2001], and MacFarlane and Wohl [2003]. A modified Poisson distribution is fitted to the data. Numbers on the abscissa indicate the lower value of each spacing bin.

both flume and field step spacing indicates that the mechanisms by which steps form include those without any interaction between the bed and water surfaces. The histogram of step spacings from the literature is similar in shape to the histogram generated from our flume data (refer to Figures 10 and 7), indicating that our results are not a unique occurrence and that our mechanisms of step formation may be applicable beyond the flume situation.

5. Conclusions

[40] We conducted flume experiments designed to examine the characteristic dimensions of the step-pool bed configuration. Key elements of the experiments were the use of sediment with sufficient coarse, step-forming grains to form steps and the use of transport conditions under which large, step-forming grains were transported and deposited, thereby fixing their locations and the positions of individual steps and allowing direct observation of the step-forming mechanism. The size of the step-forming grains sets the step height, and the spacing between their depositional locations sets the step spacing.

[41] We find that there is almost no regular spacing between depositional locations of step-forming grains or the subsequent steps. In our direct observations of step formation, the majority of steps do not form in locations forced by flow perturbations associated with preexisting steps or wave trains in the water surface. The flow control occurs within an exclusion zone immediately below existing steps, where local flow conditions nearly always prohibit deposition of new step-forming grains. Beyond the exclusion zone, there is not a preferred location for the deposition sites for step-forming grains. The distribution of steps can be approximated with a Poisson distribution, modified to

account for the presence of the exclusion zone, supporting the conclusion that there are no preferred depositional locations for steps. The modified Poisson distribution is shown to fit step-spacing measurements from this study as well as previously reported field data.

[42] The absence of regular step spacing is consistent with our observations of the mechanisms producing deposition of step-forming grains. For 84% of the 384 steps observed in our experiments, the depositional location of step-forming grains is controlled by either local condition on the bed impeding further transport or by earlier flow and transport conditions unassociated with the development of the step. In both cases, there is no component of the step-depositing event that would give rise to a preferred spacing between grains. This is in contrast to previous explanations of step-forming mechanisms, which invoke a strongly coupled interaction between the bed surface and the free surface of the stream. We did not observe the regular step spacing that these previous mechanisms were developed to explain.

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J. C. Curran, Department of Geography, Texas State University, 601 University Drive, San Marcos, TX 78666, USA. (jc49@txstate.edu)

P. R. Wilcock, Department of Geography and Environmental Engineering, Johns Hopkins University, Baltimore, MD 21218, USA.