Step–pool formation models and associated step spacing

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Abstract

Step–pool bedforms develop under conditions of high flow rates and high sediment influx and transport rates. Step setting events are capable of mobilizing and rearranging the large step-forming grain sizes. Thus, observations of the processes of step formation are limited to flume experiments. The results of laboratory experiments involving active transport of widely sorted sediment, including large grains whose deposition readily formed steps, are presented. Over 350 step formations were observed and documented, creating a large data set for detailing and evaluating step formation processes.

Existing step-formation models focus on step development from antidunes, particle clusters, transverse ribs or depositional berms, or from a hydraulic regime that includes cascade flow and hydraulic jumps. These models were developed using field measurements of artificial grade control structures or stable step–pool systems during low flow conditions, or degradational flume experiments where flows elucidated the step–pool bedform in the channel profile but did not create equilibrium transport of the large, step-forming clasts.

This research evaluates the pre-existing formation models and proposes three new models: the rough bed, exhumation and dune models. The rough bed model was dominant throughout the experiments, followed by the exhumation model and then the dune model. A single model was not responsible for all step formations. The rough bed, exhumation and dune models all influenced step development, and every step sequence was created through a mixture of formation processes. This research generated a large data set, where each step spacing is paired with the corresponding step formation model, making it possible to identify a distinct exclusion zone length for each model. Thus, given knowledge of the step formation model, the minimum distance to the next step downstream can be predicted. From the final spacing of a step sequence, it may be possible to deduce the likely formation mechanisms active during a step resetting event. Copyright © 2007 John Wiley & Sons, Ltd.

Keywords: step–pools; gravel-bed rivers; formation processes; bedforms

Introduction

The step–pool bedform, a common feature in steep, narrow channels, is composed of a series of steps and pools (Figure 1). A number of the largest clasts in the channel align horizontally across the channel to create the step riser. A pool scoured by flow tumbling over the upstream step forms the step ‘tread’. Flow becomes supercritical as it approaches the step crest and tumbles into the downstream pool, a hydraulic jump returns the flow to subcritical and flow becomes supercritical as it accelerates over the next step crest.

The geometry of the step–pool bedform can be described by step height and step spacing. Step height scales directly with the size of the large, step-forming grain (Judd, 1963; Judd and Peterson, 1969; Grant et al., 1990; Grant, 1994; Abrahams et al., 1995; Billi et al., 1998; Chin, 1999a; Lenzi, 2001; Zimmermann and Church, 2001), thus the predominant free variable describing step–pool geometry is the spacing. Step formation typically occurs during floods with estimated return intervals of 30 years or more (Grant et al., 1990; Chin, 1999b; Billi et al., 1998; Lenzi, 2001). Debris flows and smaller floods with high rates of sediment influx and transport are also shown to create step sequences (Sawada et al., 1983; Milzow et al., 2006). While step forming grains have been observed to move at flows...
with return intervals as low as 5 years, the majority of steps are deposited by the larger floods with high associated sediment transport rates (Grant, 1994; Billi and Preciso, 2003; Chin, 2003; Lenzi et al., 2004). It is at the large, step-forming flows that the processes of step formation are active.

Step–pool systems are reported in a number of different settings worldwide. Steps are measured in bedrock channels in such diverse settings as along the Nahel Yael in 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 formation of steps (see, e.g., Heede, 1985; Wohl, Madsen, and MacDonald, 1997; MacFarlane and Wohl, 2003). The more common step system is that formed from channel alluvium or sediment deposited in the channel from debris flows. When log steps and large woody debris are removed from a mountain channel, depositional steps form to replace the lost steps (Heede, 1985). Only depositional, alluvial step systems are considered for this research.

Many of the existing models of step formation focus on processes by which the step bedform develops from pre-existing sediment and flow conditions in the channel. Steps may form from existing antidunes, particle clusters, transverse ribs, depositional berms or a hydraulic regime that includes cascade flow, hydraulic jumps or local scouring downstream of overfalls (Judd, 1963; McDonald and Day, 1978; Whittaker, 1987; Whittaker and Jaeggi, 1982; Allen, 1983; Grant, 1994; Zimmermann and Church, 2001; Comiti et al., 2005). These models are developed from observations and measurements of step–pool and grade control structures from the field during low-flow conditions or from flume experiments where flows elucidated the step–pool bedform in the channel profile but did not mobilize the step-forming clast. In neither approach are the models the result of observations and measurements made during step formation.

This research presents flume studies designed to identify the processes responsible for step–pool formation. The experimental design includes a broad range of flow rates and sediment transport rates to address questions of how the step–pool bedform develops and the channel conditions most likely to produce step sequences. The experimental design included flow rates that created active transport and deposition of all sediment sizes, including the step-forming grains. This allowed for observation of step–pool formation beginning with the deposition of the step-forming grain.

Review of Existing Models of Step–Pool Formation

Particle cluster model

The particle cluster model is a conceptual model where deposition around a large clast builds first a cluster and then a step (Judd, 1963; Zimmermann and Church, 2001). The step-forming clast is a large immobile clast already present in the channel that acts as a catalyst for deposition of smaller particles during a large flow. As particles accumulate around the step-forming clast, a particle cluster forms, grows to span the channel width and forms a step. Scouring begins immediately downstream to form a pool. Concurrent with formation of the initial step is a standing wave that forms above the step. A series of standing waves develops downstream and induces continued sediment deposition and step formation in the downstream direction. Resultant step sequences have a spacing that is forced by the standing wave train. The surface wave is a critical component of the particle cluster model as initially proposed by Judd (1963), making sediment interaction of secondary importance to step formation.
Migrating hydraulic jump model

McDonald and Day (1978) used the results from a series of flume experiments to develop a model of transverse rib formation that has been extended to model step–pool formation. Bedform formation begins with the accumulation of sediment on the downstream side of a hydraulic jump. A standing wave develops next to the jump, directly over the sediment accumulation. Sediment continues to accumulate under the standing wave, building it into a step bedform. When the height of the standing wave becomes greater than the height of the hydraulic jump by an amount equal to the size of the step, sediment begins to transport through both the standing wave and the hydraulic jump. In response, the standing wave breaks upstream while the step remains in place, now in a subcritical flow field. A new hydraulic jump forms upstream at a distance equal to half the length of the previous standing wave, and the step formation process begins again. The step forming sequence repeats until a series of steps forms, from downstream to upstream in the channel. Through an empirical relationship, McDonald and Day describe bedform spacing as a function of the Froude number and flow depth during formation, emphasizing the importance of the flow field.

Cascade model

The cascade model is a theoretical model of step formation that combines flow hydraulics over a step-forming grain, the drag force acting on the grain and bedform packing effects (Allen, 1983). Step formation begins as a flood flow wanes and flow depth decreases, allowing deposition of the large, step-forming grains. A hydraulic jump forms at the step-forming grain. Sediments deposit around the large clast to build first a cluster and then a step bedform. Supercritical flow redevelops downstream of the step, and the step formation process begins again. The distance between steps is equal to or greater than the distance necessary to redevelop supercritical flow in the channel, and a step sequence forms from the upstream end of the channel to the downstream. Step spacing is a function of the bedform structure, step forming grain size, bed slope and an exclusion zone created through the interaction between the sediment and the flow field.

Antidune model

The antidune model was proposed by Whittaker and Jaeggi (1982) following their observations of steps developing subsequent to antidunes during degradational flume experiments. By this model, the sediment bed deforms first into a series of antidunes in phase with standing waves. Step formation begins as large clasts deposit on the upstream side of each antidune, anchoring the antidune in place. Continued deposition builds the antidunes into steps. The resulting step–pool sequence forms directly from the antidune train, with step spacing equal to the wavelength of the precursor antidune train. Because steps develop from antidunes, the interaction between sediment and flow surfaces necessary for antidune formation is also necessary for step formation. The antidune model is used to explain step formation and spacing in experiments from both the field (Ashida et al., 1984; Chin, 1999b) and the laboratory (Grant and Mizuyama, 1991; Grant, 1994; Rosport and Dittrich, 1995; Chartrand and Whiting, 2000).

Scouring Formation model

Comiti et al. (2005) developed the scouring model after examining similarities between the dimensionless characteristics and geometries of natural step–pool sequences and artificial grade control structures. Natural and artificial steps are comparable in form, indicating similarity of formation process. Steps develop in the same manner as the depositional berms that deposit downstream of scour pools. A hydraulic jet descending from the overfall of an upstream grade control structure has energy to scour the bed sediment, creating both a pool and a depositional berm just downstream of the pool. A step is formed in the same manner as the berm, only now it is due to deposition downstream of the pool associated with a step bedform. As flow tumbles over the upstream step, it scours a pool, and eroded sediment from the pool deposits to build the downstream step. Spacing between steps depends on both the energy in the falling hydraulic jet and the drop geometry.

Methods

The flow conditions under which steps form are too infrequent to allow a field study of step-forming processes. A useful alternative is to perform a series of step-forming experiments in a laboratory flume. Laboratory experiments not only allow for control of the flow and sediment transport conditions, but also provide the opportunity to observe the
formation of many step–pool bedforms directly. Flume experiments typically begin with a flat sediment bed and a random distribution of grain sizes throughout the bed, but natural channels reset step spacing from pre-existing step sequences. Thus it is important to create a large number of step sequences in the flume experiments rather than develop a single step sequence per experiment. In these flume runs the sediment bed was fully mobile. Steps continued to form and break throughout each run, creating hundreds of different step sequences. Every step formation was observed directly through the walls of the laboratory flume, providing an unambiguous basis for evaluating the various step–pool models. Any interaction between the bed and water surfaces during deposition of the step-forming grain was observed, and both the requirements for step formation and the dominant step-forming processes were identified.

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. The grain size of the sediment extended from 0.5 to 64 mm, with \( D_{50} = 14 \) mm, 7.4% sand and 8.3% in the 45–64 mm size class.

The sediment size distribution and flume width, \( b \), were chosen to produce favorable step-forming conditions based on previous observations in flumes (Grant, 1994; Whittaker and Jaeggi, 1982; Rosport and Dittrich, 1995; Table I) and in the field (Grant et al., 1990; Stuve, 1990; Schmidt and Ergenzinger, 1992; Lenzi, 2001). The \( D_{50} \) fraction represents the largest grain size available in the sediment, making it slightly larger than the \( D_{50} \) size fraction. The ratio of step-forming grain size, \( D_{50} \), to flume width is particularly important for the formation of steps, as it determines the number of large grains needed to span the channel to create the step riser. The \( D_{50}/D_{10} \) ratio and \( D_{50} \) are a check on the similarity of the overall grain size distribution between the flume sediment and those sediments measured in previous flume and field step sequences. Values of \( D_{50}/D_{10} \) for our experimental sediments fall within the range of those observed in the field and values of \( b/D_{50} \) fall at the lower end of field observations, in order to promote step development in the flume. Church and Zimmermann (2006) propose that the ratio of channel width to step-forming grain size will play a critical role in step stability and spacing. This hypothesis is not addressed in these experiments, as a single grain size distribution was observed to form steps and only one ratio of \( b/D_{50} \) was tested.

Data for this study were collected during experiments described in detail by Curran and Wilcock (2005) and summarized here. During a total of 17 flume runs, flow rates mobilized all sediment sizes, including the large step-forming grain size (Table II), while sediment feed rates spanned an order of magnitude. A 7 cm thick sediment bed was created and screeded flat prior to each run. During 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. Measurements began after the channel achieved a steady-state transport condition.

Essential to this study are the observations of step-forming grain deposition and subsequent step development from the flume runs. Two video cameras were used to film the entire working length of the flume. Each camera captured 1.8 m of flume length, enabling an overlap of 10 cm. Mirrors placed on the wall behind the flume allowed the cameras to record both the near and far sides of the flume. The mirrors provided a check of the step bedforms to be sure that they spanned the channel width and were not a result of wall effects. Review of the videotapes provided the location, height and total time of existence of each step, along with a description of the process by which the step-forming grain(s) 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. Step spacing was measured as the distance from the new step to the next step upstream.

It was not possible to measure the instantaneous water and sediment surfaces over the length of the flume while the flume was running because of the high flow and transport rates. Thus, sediment and water surfaces were measured

| Table I. Sediment and channel ratios from field and flume experiments |
|------------------|-------------------|-------------------|-------------------|
| Overall          | Range from        | Range from        | These            |
|                  | flume studies     | field studies     | experiments      |
| \( D_{50}/D_{10} \) | 1:89              | 1:23–2:00         | 0:47–3:00        | 1:46             |
| \( D_{50}/D_{50} \) | 3:20              | 2:15–7:86         | 2:07–3:96        | 3:13             |
| \( D_{50}/D_{10} \) | 28:00             | 5:00–52:00        | 1:49–54:29       | 21:90            |
| \( D_{50}/D_{50} \) | 6:67              | 2:60–6:67         | 0:67–13:00       | 7:00             |
| \( b/D_{50} \)   | 6:27              | 2:64–8:33         | 5:88–20:69       | 2:34             |
| \( b/D_{50} \)   | 46:25             | 10:15–111:10      | 19:38–75:42      | 10:71            |
Step–pool formation models and associated step spacing

Table II. Measured and calculated parameters from the flume experiments

<table>
<thead>
<tr>
<th>Run ID</th>
<th>( Q ) m(^3) s(^{-1} )</th>
<th>( Q_s ) g m(^{-1}) s(^{-1} )</th>
<th>flow depth ( m )</th>
<th>bed slope</th>
<th>velocity ( m ) s(^{-1} )</th>
<th>Froude Number</th>
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<td>0·077</td>
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<td>0·082</td>
<td>0·65</td>
<td>0·796</td>
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</table>

from still images taken from the videotape for both sides of the flume and 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.

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 (Table II). Froude numbers were calculated from mean velocities and depths, and varied between 0·56 and 0·81. Previous laboratory experiments, which typically used clear water flow and focused on flow over existing step bedforms 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). Froude numbers for step-forming flows in 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). Where field measurements of flow velocity and depth were made during step mobilizing events, calculated Froude numbers range from 0·7 to 1·8 (Billi et al., 1998; Lenzi, 2001; Billi and Preciso, 2003).

Results

There were a total of 384 steps formed during these runs through three distinct mechanisms. The step formation processes are visible on the videotapes and detailed here.

Rough Bed

As the name implies, this process is associated with a rough bed surface (Figure 2). The sediment bed surface was rarely smooth during the high flow and sediment transport rates in these experiments, and coarse surface patches developed on the bed. Step formation began with deposition of a step-forming grain on the rough area of the bed surface, as the grain encountered an obstacle preventing its continued transport. The rough area remains poorly defined as an irregular area of bed surface composed of a range of grain sizes. There is not a preferential grain size that accumulates to create the rough areas. After the step-forming grain deposited, additional sediments accumulated around it, forming a clast jam or cluster that eventually spanned the channel width to form a step. The only apparent control over the depositional location of the step-forming grain was the rough patch on the bed surface, which impeded further downstream motion. Deposition was not associated with water surface waves. The rough bed process was the most common process of step formation, accounting for 63% of all steps.
Figure 2. Photograph sequence of the rough bed step formation process. (a) An uneven bed surface without any steps. (b) A large, step-forming grain depositing on the channel bed in the middle of the photo. (c) The new step has formed by deposition around the large grain. The step has been formed by the rough bed process. The downstream pool and hydraulic jump are also visible in the photograph. This figure is available in colour online at www.interscience.wiley.com/journal/espl

Exhumation

Exhumation step formation occurred when localized bed erosion made a previously buried step bedform prominent in the bed profile (Figure 3). The step-forming grain was already present in the sediment bed, having been deposited and buried earlier in the flume run. When the bed eroded, either locally or through the headward movement of a knick-point, the step-forming grain buried in the bed sediments was exhumed. The large clast may be solitary or part of a step bedform that was buried earlier in the run. Either way, erosion makes the large clast prominent in the bed profile, allowing for step formation. Through this process a once buried step reformed or a new step developed around an exhumed step-forming grain. This model was responsible for 25% of all observed step-pool formations.
Dune

The dune step formation model is associated with low, symmetrical dunes that periodically formed in the channel (Figure 4). These bedforms had no slip face, but did exhibit a dune-like grain trajectory in which grains eroded from the stoss side of the dune deposited on the lee side. The first event in dune formation was deposition of a few grains (smaller than the step-forming grain size) to create a slight deformation of the bed surface. The water surface quickly developed an in-phase surface wave over these grains. The time interval between initiation of the dune on the bed surface and formation of the water surface wave was on the order of seconds and was only discernable when the video was played in slow motion. Further sediment accumulation built the dune and its associated in-phase water surface wave to a height of order 10–15 cm (0.67–1.0 when scaled by channel width). A dune became a step when a step-forming grain deposited on the upstream side of the dune, causing the dune to steepen and grow to span the channel width. Dunes were in phase with the surface waves, and did not migrate in the channel.
While dune formation was not uncommon, most dunes formed and dissipated without developing into steps. In approximately 10% of the cases in which a step formed through the rough bed process, a dune train developed downstream of the step. Of these dune trains, approximately 25% developed into one or, occasionally, two steps. In the majority of cases (13% of all steps and 85% of all dune steps), a step developed on only the first dune in the train. The result was a two step sequence: the first formed by the rough bed process and the second formed from the first dune downstream of the step. In a minority of cases (2% of all steps and 15% of dune trains), a step developed on the second dune, forming a three step sequence: the first step by the rough bed process and the next two steps from the dune train. Any remaining dunes washed out subsequent to step formation. The three step sequence was most likely when multiple dunes developed to a comparable height prior to step formation on the first dune. When multiple dunes developed into steps, the overall formation sequence was similar to the antidune model. However, the dune step-forming process accounted for only 12% of all steps in this research.
### Table III. Frequencies of each step formation processes by run

<table>
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<th>Run ID</th>
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<th>Rough Bed</th>
<th>Exhumation</th>
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**Discussion of Step-forming Models**

There is not one single mechanism by which steps formed in any single experiment. The rough bed, exhumation and dune step formation processes were all active in these experiments, but at varying frequencies (Table III). While the occurrence rates of the models varied, there are some consistent trends. The rough bed model was dominant, occurring in every run with a frequency ranging from 50% in Run 13 to 76.5% in Run 18. After rough bed, steps formed through the exhumation process with a frequency ranging from 4.3 to 50%. The dune model was not present in every run, and only reached a maximum frequency of 21.7%. Interaction between the water and sediment surfaces is an essential part of step formation in the dune model. The infrequency of the dune model illustrates a dominance of those processes involving grain interaction during step formation. Combining the number of steps formed through the rough bed and exhumation models, 88% of steps develop without locational control provided by a flow field associated with other steps or flow obstructions.

The relative frequencies of the rough bed, exhumation and dune step formation models are examined with respect to both the dependent and independent flow and sediment parameters. The dominance of the rough bed process is evident across all sediment transport and flow rates (Figures 5 and 6). As the sediment transport rate increases by an order of magnitude, the occurrence of the exhumation process decreases and the frequency of the dune process increases. The corresponding increase in dune processes with increasing sediment transport rate indicates that a large amount of mobile sediment is necessary for the formation of dune trains. Because step formation occurs during flood events when sediment supply and transport rates are high, the dune model plays an important, although minor, role in step formations. The decrease in exhumation processes with increasing sediment transport rate indicates a limit on channel erosion under conditions of high sediment supply and transport. Any trend between step forming models and flow rate is less readily apparent. A slight decrease in the frequencies of both exhumation and dune processes as flow rate increases results in an overall increase in the rough bed process. However, the trends are not strong, as the exhumation model frequency decreases by less than 10% and the dune model by less than 5%.

Bed slope, flow depth and Froude number define the channel conditions under which steps are likely to form (Figure 7). Steps developed over slopes between 5 and 8.5%, but were more frequent at bed slopes of 8.0% or more (Figure 7(a)). The total number of steps was greater when the flow depth was between 6.5 and 6.9 cm (0.43–0.46 when scaled by channel width), although step formation did occur outside this range (Figure 7(b)). The limited range of flow depths measured in these experiments makes the significance of this relationship weak. Observation of hydraulic jumps at the steps suggests localized areas of supercritical flow during the flume runs, which may have influenced the frequency of step formation, but this could not be tested with the available experimental equipment. Froude number was calculated using the average flow velocity and flow depth during each run, which masks any...
Figure 5. The average frequencies of the rough bed, exhumation and dune step formation models versus the sediment transport rates (g m\(^{-1}\) s\(^{-1}\)) used in these experiments.

Figure 6. The average frequencies of the rough bed, exhumation and dune step formation models versus the flow rates (m\(^3\) s\(^{-1}\)) used in these experiments.
Figure 7. The average frequencies of the rough bed, exhumation and dune step formation models versus (a) bed slope, (b) flow depth (cm) and (c) Froude number for these runs. The bed slopes and flow depths are measured. The Froude numbers are calculated using the average flow depths and flow velocities for each run.

localized supercritical flow. There was apparent preferential step formation when the channel-length average Froude number was between 0.65 and 0.70 (Figure 7(c)). Analysis of the patterns of step frequency with bed slope, flow depth and Froude number indicates that step bedforms are most likely to form on a steep channel under a subcritical average flow regime where flow depth is slightly less than one-half the channel width.
Connection to Step Spacing

Step spacing is best described as a modified Poisson function (Curran and Wilcock, 2005) where the distance scale is translated to account for the length of the exclusion zone. An exclusion zone exists immediately downstream of each step as the channel length within which a second step does not form (Figure 1). Curran and Wilcock (2005) developed Equation (1) to describe the step spacing function.

\[ f(x) = \lambda e^{-\lambda(x-x_0)} \]

where \( f(x) \) is the frequency of a step spacing of value \( x \), \( \lambda = 1/\beta \), where \( \beta \) is the mean of the modified distribution and \( x_0 \) is the length of the exclusion zone. The length of the exclusion zone can be empirically fit to a relationship that includes the upstream bedform steepness and the resistance provided by the jet regime flow (Giménez-Curto and Lera, 2005). The good fit of the expression of Giménez-Curto and Lera to the step spacings measured in these experiments indicates that the length of the exclusion zone can be predicted with knowledge of the associated step formation model, step height, flow velocity and bed slope (Curran and Wilcock, 2006). The fit provides further evidence that different formation processes lead to variations in bedform steepness and downstream flow regime.

Each step formation model has an associated exclusion zone length, and it is through the length of the exclusion zone that the different step-formation models influence step spacing. Through model simulations of step sequences, Milzow et al. (2006) found the spatial organization of steps to be strongest between a new step and the next step downstream. This region corresponds to the area within which the exclusion zone influences step spacing. A detailed explanation of the derivation of exclusion zone lengths is provided by Curran and Wilcock (2005). The exclusion zone associated with the rough bed model averages 32 cm (2·1 when scaled by the channel width), and for the exhumation model, it averages 40 cm (2·7 when scaled by channel width). The dune model is best fit by a normal distribution rather than the modified Poisson distribution due to the influence of regularly spaced surface waves over deposition of the step-forming grain. The mean of the normal distribution is 43 cm (2·9 when scaled by channel width), and no steps form at a distance less than 20 cm (1·3 when scaled by channel width) from the nearest upstream step. Thus, 20 cm can be considered the exclusion zone associated with the dune model.

Steps have an equal likelihood of formation at any distance downstream of an existing step outside of the exclusion zone associated with the formation process of the upstream step. Therefore, the exclusion zone represents the minimum step spacing associated with the step’s formation model. In each experiment, a combination of step formation models was active such that every step sequence formed through a mix of different step formation processes. Steps were only spaced within 32 cm when the associated formation process was the dune model. Where the step spacing was larger, steps were formed by either the rough bed or exhumation processes.

Step spacing histograms provide a means to analyze the influence of different step formation mechanisms. Because the rough bed process is dominant in all flume runs, its influence in any particular run is difficult to isolate. Figure 8 illustrates the step spacing histogram and the formation model frequencies for run 5, where the flow rate was 0·0065 m³ s⁻¹ and the sediment transport rate was 110 g m⁻¹ s⁻¹. There are no steps formed by the dune process and no steps spaced within 60 cm (or four channel widths). The combination of only rough bed and exhumation formation processes is expressed by the lack of any closely spaced steps. The opposite of this extreme is run 12, where the flow rate was 0·005 m³ s⁻¹ and the sediment transport rate was 750 g m⁻¹ s⁻¹ (Figure 9). The dune process has its highest frequency of any run, 21·7% of all step formations. On the corresponding step spacing histogram (Figure 9(b)), steps occur as close together as 20 cm (or 1·3 channel widths), which is the minimum step spacing possible under the dune model.

Evaluation of the Existing Step–pool Models

Direct observation and measurements from these experiments provide an opportunity to evaluate the particle cluster, migrating hydraulic jump, cascade, antidune and scouring models of step formation. While some of the pre-existing models include elements that are observed in these experiments, none provides a complete description.

The particle cluster model is similar to the rough bed model in that sediment forms first a particle cluster and then a step. However, a critical difference exists in the mobility of the step-forming grain. In the particle cluster model, the large clast is not deposited, but is stationary on the bed surface while smaller grains deposit around it. What is observed in the rough bed process is deposition of a mobile step-forming grain where there is a rough patch on the bed surface that impedes continued downstream transport, which is in agreement with the particle cluster model as proposed by Zimmermann and Church (2001). Important to the particle cluster model is the formation of a
downstream sequence of steps that are in phase with the surface waves. In these experiments, steps continually formed and broke with little, if any, interaction between the bed and water surfaces.

The association of a hydraulic jump with the step bedform is the only similarity between the migrating hydraulic jump model (McDonald and Day, 1978) and the observed step formations. In the migrating jump model, steps form from the downstream to upstream end of the channel concurrent with the upstream movement of a hydraulic jump. In these experiments a hydraulic jump only develops subsequent to step formation as the flow tumbling over the step crest scours a pool. The jump is not part of the step-forming process. Channel conditions during the experiments of McDonald and Day involved unisize sediment and low flow depths, leading to Froude numbers in excess of 2.0.

Similarity between the models presented here and the cascade model (Allen, 1983) exists in the concept of an exclusion zone. In the cascade model, the exclusion zone is the distance necessary to redevelop supercritical
flow downstream of a step. These experiments have shown the exclusion zone to consist of the pool immediately downstream of the step and a distance downstream that varies with the associated step formation model. The exclusion zone length is a function of step formation model, step height, flow velocity and bed slope.

The core of the antidune model by Whittaker and Jaeggi (1982) is the description of steps forming from a precursor train of antidunes. The dune formation model shows some consistency with this process, although the dune trains during these experiments did not extend over the length of the channel and not all dunes formed steps. The dune model is the only formation model that includes interaction between the bed sediment and the water surface to form steps. Thus, the steps formed on the second and third dunes to develop downstream of an existing step do have a formation process and spacing as described by the antidune model. However, the dune model accounts for a minority of the 384 observed step formations.

Figure 9. Comparison graphs for run 12, with a flow rate of 0.005 m$^3$ s$^{-1}$ and sediment transport rate of 750 g m$^{-1}$ s$^{-1}$. (a) The frequency of the step formation models during the run; (b) the step spacing histogram, where step spacing is separated into 10 cm bins. Notice the high frequency of the dune process and the correspondence of steps with spacing of 20 cm.
The scouring model of Comiti et al. (2005) has similarities to both the cascade model as described by Allen (1983) and the exhumation model presented here. Both the exhumation model and the scouring model rely on localized bed erosion. In the case of the scouring model, the erosion downstream of one step causes the deposition responsible for formation of the next step and establishes the spacing between the two steps. In the exhumation model, erosion of the channel bed continues in the upstream direction until a step-forming grain is uncovered in the bed. The eroded sediment travels downstream and does not redeposit as a new bedform. The scouring model provides an explanation for the exclusion zone that is tied to the energy of the flow as it descends from the upstream overfall, which is in turn a function of overfall geometry. There is good agreement between the exclusion zone of the scouring model and the empirical description of the exclusion zone given by Giménez-Curto and Lera (2005). The scouring model by Comiti and others provides an explanation for step spacing and the deposition of a step downstream of an existing step. The exhumation and rough bed models provide an explanation for step formation independent of the presence of an upstream step.

Conclusions

Step forms are created during flows capable of moving the large, step-forming clasts. Direct observation of these events is essentially impossible in the field, making laboratory experiments a necessary alternative for exploring the processes that create step–pool sequences. A number of different models have been proposed for step formation, including the particle cluster, migrating hydraulic jump, cascade, antidune and scouring formation models. This research provides a means to evaluate these models using 384 step formation and step sequence observations from flume runs using mixed size sediment and combining four flow rates with five sediment transport rates. The data set from these experiments includes measurements of the step spacing between each step and the next upstream step as well as detail of each step formation process. While elements from the existing step models correspond to the observed step formation processes, none of the models is fully verified.

Three new step formation models are proposed: the rough bed, exhumation and dune models. In both the rough bed and exhumation models, step formation occurs without interaction between the sediment and water surfaces. A large clast becomes prominent on the channel bed, either by deposition at a rough surface patch or by local upstream erosion, and deposition around this large keystone clast creates a step. In the dune process, the bed downstream of a step develops a series of dunes that are in phase with surface waves. Steps develop when a step-forming grain deposits on the first, and occasionally second, dunes in the train. Of these processes, the rough bed is responsible for the majority (63%) of step formations. The exhumation process forms 25% of the steps, and 12% of steps form by the dune process.

Step spacing is best expressed as a Poisson distribution modified to include an exclusion zone (Curran and Wilcock, 2005). The length of the exclusion zone is a function of the step formation process, and establishes a minimum step spacing associated with step formation model. The dune model has the shortest exclusion zone at 20 cm (1·3 when scaled by channel width). In experiments with a high frequency of the dune formation process, the average step spacing is low. Where channel conditions lead to a high frequency of steps formed by the exhumation model, which has a 40 cm exclusion zone length (2·7 when scaled by channel width), there are few closely spaced steps and the average step spacing for the sequence is larger.

A single step formation model never accounted for more than half the steps formed during any experiment. If a snapshot was taken during a flume run, the step sequence would consist of steps formed by a combination of the three processes. The frequency of each step formation model can be linked to the transport conditions in the channel. These experiments observed steps during periods of high flow and sediment transport rates, and the relative frequency of the dune model increased as the volume of sediment in transport increased. Therefore steps deposited during high rates of sediment influx and transport may be more closely spaced and appear more regularly spaced. When the flow in the channel mobilizes the step-forming grains but there is a lower sediment transport rate, the exhumation and rough bed models dominate. The resulting step sequence will not have any closely spaced steps and the average step spacing will be larger. The association of step spacing with step formation models and channel characteristics provides a more complete picture of the step formation process.

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