1. Introduction

1.1. Past work and question to be addressed

Wood plays an essential role in the morphology and ecology of river systems, from large, low-gradient channels to small, steep mountain streams (Montgomery et al., 2003). Here, we focus on the subset of wood in high-gradient streams known as log steps, formed by a single key member (a dead tree with or without branches and/or bole that is large enough to remain immobile during at least moderate flows) with possible racked wood oriented oblique or perpendicular to flow, forming a step structure usually followed by a plunge pool. Log steps form major roughness elements in high-gradient streams (Marston, 1982; MacFarlane and Wohl, 2003; Wilcox et al., 2011), shift channels and clast interactions in mountain streams in the central Cascade Range of Washington State, USA

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A B S T R A C T

Field surveys of log steps in high-gradient streams investigate the interactions between log steps and clasts to assess whether second-growth wood can form log steps capable of diverting flow and acting as significant roughness elements similar to those formed by old-growth wood. We measure the functional log diameter and step height, as well as visually estimate the clast size in the step of 102 log steps in 15 high-gradient streams in the central Cascade Range of Washington, USA. We compare step height data to measurements of maximum bankfull depth to measure the capability of log steps to divert flow relative to their clast size and log diameter. Step height positively correlates with functional log diameter (p < 0.001) and clast size. Additionally, a threshold clast size exists above which functional log diameter more strongly correlates with step height, indicating that clast size can limit step height. We find that steps with cobble or larger (>64 mm) clasts in the step are 3.7 times more likely to reach or exceed bankfull depth than steps with smaller than cobble clasts in the step. We conclude that it is necessary for steps formed by small logs to have large clasts in the step in order to reach bankfull depth, act as significant roughness elements, and create flow diversions, implying that the potential for second-growth forests to maintain log steps similar to those formed by old-growth logs depends on the size of bed material.

The size of in-channel wood decreases after moderate to intensive logging activity, commonly during or soon after the logging (Bilby and Ward, 1991; Ralph et al., 1994). This occurred in forests across the Pacific Northwest, where salvaging wood from the channel during logging operations was common practice (Bilby and Ward, 1991). Thus, exploring the effects of logging on wood structures such as log steps in high-gradient streams is pertinent in order to understand how logging may change, or has changed, the morphology and, consequently, the ecology of such streams.

We examine the interactions between clasts and log steps formed by second-growth wood in terms of step height and log diameter as a way of inferring the resilience of high-gradient streams dominated by such log steps to the removal of old-growth wood. The height of steps comprised of cobbles and boulders in alluvial streams has been found to positively correlate with the particle size in the step (Chin, 1999); larger clasts are generally able to sustain larger steps (Church and Zimmermann, 2007). Log step height, as well, has been found to strongly, positively correlate with clast size in the step (Wohl et al., 1997). Stable log steps in high-gradient streams are more likely to be formed by immobile wood than by mobile wood (Wohl et al., 1997). If the steps in a channel tend to adjust toward a state of higher

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resistance (Abrahams et al., 1995; Wohl et al., 1997), immobile, old-growth logs could form steps with dimensions controlled primarily by the log’s diameter and with height sufficient to create substantial flow resistance. Indeed, Faustini and Jones (2003) found that a channel flowing through old-growth forest in the Cascade Range of Oregon had old-growth log steps that were much larger and less frequent than steps comprised solely of boulders downstream in a logged reach of the same channel. Essentially, the loss of instream wood resulted in the loss of large log steps. Similarly, Montgomery et al. (1996) and Massong and Montgomery (2000) found that the presence of log steps influenced the distribution and relative abundance of bedrock and alluvial channel beds. Curran and Wohl (2003) found that, in forested channels in the Cascade Range of Washington state, wood formed the highest steps compared to steps formed by boulders. Similarly, David et al. (2011) found that steps comprised of wood and boulders were significantly greater in height than those formed by boulders alone. Wilcox et al. (2011) suggested that steps formed by wood are also more effective at dissipating potential energy than similar steps formed solely from clasts. However, as to whether small wood, such as that recruited from immature second-growth forest, could perform a similar function to old-growth wood in sustaining large step structures is an open question.

1.2. Hypotheses

We seek to determine whether small, second-growth wood is capable of performing a geomorphic function (in terms of providing flow resistance and channel migration) similar to large, old-growth wood in small mountain streams. To formulate our hypothesis, we first detail a conceptual model for the formation of a log step (Fig. 1). Immobile logs suspended above the channel, such as those observed by Nakamura and Swanson (1993), could trap large clasts (greater than cobble size) between themselves and the bed, resulting in a wood jam and the accretion of sediment behind the log, eventually forming a log step. Alternatively, a small log that has fallen in contact with the bed could act as a vertical drop structure in a channel and form a downstream plunge pool. The scour from such a pool could result in the creation of a log step. Large steps not entirely formed by wood (i.e., the step height is greater than the log diameter) are generally thought to require large clasts in order to sustain vertical drops greater in height than most other bed roughness elements (Church and Zimmermann, 2007). It would thus seem necessary for the clasts in the bed, or trapped between the log and the bed, to be relatively large in order to sustain a large log step. Otherwise, the clasts would either not be able to sustain a large vertical drop or would not be trapped between the log and the bed. From this, we hypothesize that (i) small, second-growth wood could form large log steps, similar to old-growth wood, by interacting with large clasts on the bed and (ii) for a channel to adjust toward a state of greater resistance and stability in the absence of old-growth wood, large clasts must be present to interact with smaller wood in order to form log steps that are, in form and process, similar to old-growth log steps.

Brummer et al. (2006) suggested that for a wood structure such as a log step to force lateral channel migration via avulsion, it must reach the height of the surrounding banks, unless the banks are simply too confined to allow for channel migration. We hypothesize that log steps formed of smaller clasts will not be able to sustain the vertical drop necessary to reach bankfull depth and cause channel migration, as more clasts would be required to form the drop than are capable of being stacked together. Thus, we expect that second-growth wood in log steps must interact with large clasts to reach bankfull depth and allow channel migration.

2. Field area

We collected data from 102 log steps in 14 ungaged, first- and second-order tributaries of the Middle Fork and in 1 third-order tributary of the South Fork of the Snoqualmie River, located ~60 km east of Seattle, WA in the central Cascade Range (Fig. 2). Stream order was determined by examination of U.S. Geological Survey topographic maps (1:24,000 scale) using the criteria of Strahler (1952). The study reaches run through low-grade metamorphic Cretaceous to Eocene marine sedimentary and igneous rocks of the western mélangé belt, Tertiary granitic rocks, and Eocene volcanic rocks, overlain by Pleistocene glacial deposits and Holocene alluvium (Tabor et al., 1993, 2000). We have observed that these lithologies tend to weather to either cobble- to boulder-sized clasts or to grus. Dominant tree species include western hemlock (Tsuga heterophylla), Douglas-fir (Pseudotsuga menziesii), western redcedar (Thuja plicata), red alder (Alnus rubra), and bigleaf maple (Acer macrophyllum). In this region, the mean diameter of ~200 year Pseudotsuga menziesii has been found to be ~55 cm, while the mean diameter of old-growth stands has been measured at over 180 cm (Pelt and Nadkarni, 2004). This illustrates the substantially smaller diameter of younger, second-growth wood (second-growth in the study sites are <83 years in age) compared to their old-growth counterparts.

Surveyed streams are generally steep, straight, cobble- to boulder-bedded, step-pool to cascade channels that may be adjusting to recent debris flows and anthropogenic alterations. Field observations as well as aerial photography indicate that six of the study reaches have experienced debris flows in the past and are currently incising debris flow deposits, based on the presence of buried in-channel vegetation and massive, poorly sorted deposits of pebble- to coarse boulder-sized clasts. All study reaches are in forests that were logged in the early- to mid-1900s. Although most old-growth wood has been removed via logging or has decayed to the point at which it is no longer geomorphically effective, the channels studied do contain occasional old-growth wood, most of which is buried in debris flow deposits. Streamflow data from a U.S. Geological Survey gage on the Middle Fork of the Snoqualmie River ~6 km downstream from the downstream-most tributary studied on that river indicates that seasonal high flows occur owing to late autumn rainfall and spring snowmelt. The NOAA reports an average annual precipitation for the years 1981–2010 of 247 cm at the Cedar Lake station, ~7 km south of the southernmost study reach.

![Fig. 1. Conceptual model of log step formation.](image-url)
Fig. 2. Hillshade image of field area with study reaches highlighted as bold, black lines. Inset shows Washington State, with the Snoqualmie River watershed delineated in gray, and the Middle and South Fork Snoqualmie watersheds delineated in black. Study reaches are highlighted as bold, black lines, and labeled as in Fig. 5. The latitude and longitude of the approximate center of the map are 47.4714° N –121.5427° W. The study reaches drain into the Snoqualmie River, which drains into the Snohomish River.

3. Methods

3.1. Measurements

Study reaches were reconnoitered to make sure that the entirety of the reach was in second-growth forest (i.e., we observed cut stumps, abandoned roads, and abandoned logging equipment on banks). The length of each study reach was determined by what was accessible and within second-growth forest and usually fell between 0.5 and 1.5 km. We identified log steps (i.e., a log contacting the bed oblique or perpendicular to flow, forming the crest of a step) formed by second-growth wood (having logs similar in diameter to the second-growth trees surrounding the channel, usually < 1 m). For each wood structure identified as a log step, we used a tape with an accuracy of 1 cm to measure the vertical log step height (LSH), from the lowest point in the pool below the step to the top of the step crest, and the sum of the diameter(s) of the log(s) forming the log step, which we have designated as the functional log diameter (FLD). We visually estimated the median clast size in the step, which we categorized into six size categories: fine (<11.3 mm) and coarse (11.3–64 mm) pebbles, fine (64–128 mm) and coarse (128–256 mm) cobbles, and fine (256–512 mm) and coarse (>512 mm) boulders, based on the size classes of Wentworth (1922). We chose calibrated visual estimation over a direct measurement of clast size because of the short time window during the year that these streams experience low flow and our desire to maximize our sample size. We acknowledge that this method has less precision and greater error than direct measurement, but given the broad size groupings, our measurement error does not substantially impact our conclusions. Finally, we measured the bankfull depth of the channels within each study reach by surveying the elevation difference between the thalweg of the channel to bankfull indicators, taking a single elevation measurement for each sample of bankfull depth and recording only the maximum bankfull depth. Measurements of bankfull depth were taken in areas of relatively uniform (i.e., planar) bed morphology to avoid local variability and complications from steps or pools. We used scoured vegetation, changes in vegetation type, changes in slope, and transported vegetation as bankfull flow indicators. The highly variable flow depths of the cascade or step–pool morphology exhibited by the study reaches and the low frequency of bankfull indicators limited the number of bankfull depth measurements we could take in each study reach. However, at least two measurements were taken for each study reach. The median number of measurements per study reach was four. The bankfull depth measurements were averaged to obtain an average bankfull depth for each study reach.

3.2. Analysis

Statistical analysis was performed using SAS. We used a quantile plot and the Shapiro–Wilk test to test for normality and found that all distributions tested were lognormal. We performed a one-tailed, two-sample t-test assuming unequal variance on the log base-10 transformed data between each clast size class and the class below it for the data set of LSH to test for significant differences in mean LSH between each clast size.

We tested for a linear response, equal variance, and normality for the regression of LSH against FLD for log steps with pebble-, cobble-, and boulder-sized clasts in the step, as well as a data set including all measured log steps. We found the assumptions necessary to perform a linear regression met for all relevant transformed distribution correlations except for the correlation between LSH and FLD for log steps with pebble clasts. We performed a linear regression and calculated the $R^2$ value for each relevant correlation between log transformed distributions. We also calculated the Spearman correlation coefficient of the correlation between LSH and FLD for the nontransformed data.

To determine whether steps with large clasts (greater than or equal to cobble size) were more likely than steps with small clasts (less than cobble size) to be greater than bankfull depth, we performed Fisher’s exact test to determine the one-sided $p$ value corresponding to the alternative hypothesis that the proportion of steps with large clasts that were higher than bankfull depth was greater than the proportion of steps with small clasts that were higher than bankfull depth. We then calculated the odds ratio corresponding to the odds of a step with large clasts having a height that is greater than bankfull depth compared to the odds of a step with small clasts having a height that is greater than bankfull depth. Finally, we calculated the exact 85% confidence interval for this odds ratio. We used a relatively low confidence
interval for this statistic because we observed log steps to have significant variability in form (i.e., log step height fails to fully capture the three-dimensional variability of natural steps) and because we are attempting to model a temporally dependent process (the formation and development of the step) as a process with only two steps (either the step has or has not reached bankfull depth).

4. Results and discussion

We found that for all log steps, the correlation between functional log diameter and step height (Fig. 3) is positive. This indicates that larger wood is capable of sustaining larger log steps, as others have found in other regions (Wohl et al., 1997). However, when we classify steps by the size of the clast in the step, a threshold clast size becomes apparent below which this correlation becomes weaker and below which log transformed LSH and FLD data fail to linearly correlate (Table 1). Notably, our parametric tests indicate a significant threshold between pebble and cobble or greater size clasts in the step, while the nonparametric tests indicate a slightly less significant threshold. The threshold is most likely physically significant, considering the greater power of parametric tests compared to nonparametric alternatives. The height of log steps with pebble size clasts in the step is less of a power of parametric tests compared to nonparametric alternatives.

When we examine step height as a function of clast size, we find that steps with larger clasts have larger step heights (Fig. 4). From visual inspection of the data, steps with cobble- to boulder-sized clasts apparently are generally larger than those with pebble-sized clasts in the step. This is consistent with our conceptual model of how log steps may form either by trapping clasts between a suspended log and the bed or by scouring a step beneath a log that falls in contact with the bed (Fig. 1). If clasts are too small, they will not be trapped between a suspended log and the bed and will not be structurally stable enough to form a significant vertical drop, preventing the immobile log, regardless of its size, from forming a drop any larger than its diameter.

In our comparison of log step height to bankfull depth, we found that the p value corresponding to Fisher’s exact test was 0.07. This indicates that log steps with cobble or larger clasts in the step are significantly more likely (at a 90% confidence level) than those with smaller than cobble clasts to meet or exceed bankfull depth. Specifically, a step with cobble or larger clasts in the step reaching or exceeding bankfull depth is 3.7 times more likely to reach or exceed bankfull depth than a step with smaller than cobble clasts in the step. The exact 85% confidence interval on this odds ratio is between 1.03 and 19.01. In addition to this analysis, a visual inspection of Fig. 5 indicates that many steps with large clasts do exceed bankfull depth, while very few steps with small clasts do so. However, Fig. 5 indicates that some steps with large clasts did not reach bankfull depth, suggesting that having large clasts in the step is a necessary, but not sufficient, condition for a step made from small, second-growth wood to reach bankfull depth. That is, a step may have recently formed in a channel with coarse material, but the scour pool beneath the step may take multiple flow events to enlarge before the step reaches its maximum height. This is consistent with our conceptual model (Fig. 1), as the log steps we observed that had large clasts in the step but did not reach bankfull depth may still be adjusting toward a greater step height by continuing to scour the pool beneath the step. For a log step to effectively create lateral channel diversion, it must be able to interact with large clasts. An example of a log step that has successfully diverted flow is shown in Fig. 6.

The observed channel complexity in our field sites complicates the likelihood and manner in which a log step will form from second-

### Table 1

Sample size (n), slope (m), intercept (b), \( R^2 \), and two-sided p values for linear correlations between log step height (LSH) and functional log diameter (FLD) of log transformed data, and Spearman correlation coefficients (Rs) and p values for Rs on all raw data correlations.

<table>
<thead>
<tr>
<th>Clast size</th>
<th>n</th>
<th>m</th>
<th>b</th>
<th>( R^2 )</th>
<th>p</th>
<th>Rs</th>
<th>p for Rs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pebble</td>
<td>14</td>
<td>0.61</td>
<td>1.86</td>
<td>0.42</td>
<td>0.01</td>
<td>0.64</td>
<td>0.01</td>
</tr>
<tr>
<td>Cobble</td>
<td>45</td>
<td>0.65</td>
<td>2.21</td>
<td>0.57</td>
<td>&lt;0.0001</td>
<td>0.72</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Boulder</td>
<td>43</td>
<td>0.59</td>
<td>2.66</td>
<td>0.62</td>
<td>&lt;0.0001</td>
<td>0.73</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>All Steps</td>
<td>102</td>
<td>0.76</td>
<td>1.89</td>
<td>0.61</td>
<td>&lt;0.0001</td>
<td>0.72</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

Fig. 3. Plot of functional log diameter and log step height, with log step height data points categorized by clast size in step. Spearman correlation coefficients (Rs) are 0.64 for pebble, 0.72 for cobble, and 0.73 for boulder. The 25th and 75th percentiles of the bankfull depth data across all study reaches are shown by dashed lines. Table 1 shows regression coefficients, \( R^2 \), and p values for linear regressions on the raw data as well as the log transformed data, and Spearman correlation coefficients with associated p values for the raw data.
growth wood. For example, we observed a log that had fallen across the channel in situ, with its roots still partially anchored in the channel’s right bank, but the upper portion of the log lay suspended on other trees on the floodplain across the channel. This resulted in a log whose height above the bed started at nearly zero near the roots, and increased to over 1.5 m on the left bank (Fig. 7). The right side of the log, which was near the bed, was able to trap clasts between itself and the bed. On the left side of the channel, the log was suspended by trees on the bank, causing the space between the log and the bed to be much greater than the size of the largest clasts. The suspension of the log on only one side of the channel formed a partially spanning log step that resulted in significant aggradation behind the trapped clasts on the right side of the channel and more channelized flow on the left side, where channel width had decreased and the bank had begun to erode. This example illustrates how a log step structure can divert flow and cause channel migration. A reach with large clasts could possibly anchor smaller logs that might otherwise be mobile, although this effect was not examined in this study.

![Box and whisker plot of step height of surveyed log steps stratified by clast size. Whiskers represent minimum and maximum range of data. Top and bottom of boxes represent the third and first quartiles, respectively. Line in box represents median. Steps with >512 mm clasts in the step are significantly (p < 0.0001) larger than steps with 256–512 mm clasts, and steps with 128–256 mm clasts in the step are significantly (p < 0.0001) larger than those with 64–128 mm clasts in the step. All other clast size classes are not significantly larger than the next smaller clast size at a 95% significance level.](image1)

**Fig. 4.** Box and whisker plot of step height of surveyed log steps stratified by clast size. Whiskers represent minimum and maximum range of data. Top and bottom of boxes represent the third and first quartiles, respectively. Line in box represents median. Steps with >512 mm clasts in the step are significantly (p < 0.0001) larger than steps with 256–512 mm clasts, and steps with 128–256 mm clasts in the step are significantly (p < 0.0001) larger than those with 64–128 mm clasts in the step. All other clast size classes are not significantly larger than the next smaller clast size at a 95% significance level.

![Plot of log step heights and average bankfull depth for each study reach. Log step height data points (squares, Xs, and circles) are classified by clast size in step. Average bankfull depth is the average of all maximum bankfull depth measurements (elevation difference from thalweg to bankfull depth indicators) for each individual study reach.](image2)

**Fig. 5.** Plot of log step heights and average bankfull depth for each study reach. Log step height data points (squares, Xs, and circles) are classified by clast size in step. Average bankfull depth is the average of all maximum bankfull depth measurements (elevation difference from thalweg to bankfull depth indicators) for each individual study reach.
We interpret our results to indicate that second-growth wood can form log steps that reach bankfull height in high-gradient streams when the wood interacts with large clasts. That is, large clasts are a necessary condition for the formation of log steps that are capable of diverting flow. Although we cannot determine the height of the old-growth log steps present prior to logging on the study reaches, we can use our results to make some inferences about how the second-growth steps we observed compare in function to old-growth log steps. By interacting with large clasts, second-growth steps are capable of rising higher than bankfull depth. When a log step reaches bankfull depth, this maximizes resistance during a bankfull flow, as a step that reaches bankfull depth has a higher likelihood of remaining unsubmerged, preventing it from experiencing skimming flow and associated lower resistance (Comiti et al., 2009). By this measure, second-growth steps that have attained bankfull depth have likely reached a height at which their resistance and contribution to channel-bed stability are maximized for a given channel during a bankfull discharge. This suggests that second-growth log steps that reach bankfull depth are performing comparably to old-growth log steps in terms of providing hydraulic resistance. The channel itself may have changed in dimension since the removal of old-growth wood, however, which would complicate this interpretation.

Given that log steps can allow high-gradient channels to adjust toward a state of higher roughness and stability (MacFarlane and Wohl, 2003; Wilcox et al., 2011), we infer that, in the presence of large clasts, small wood can indeed form log steps that create a similar magnitude of energy dissipation as old-growth log steps.

Because step height is more strongly related to functional log diameter in streams with coarser bed material (cobbles or larger), such coarse-bedded streams are more morphologically resilient (can maintain large steps) to changes in wood size than streams with fine bed material. Specifically, streams with cobble- to boulder-sized clasts are more likely to form log steps that reach or exceed bankfull depth with small, second-growth wood in the step. Thus, in order to assess the potential implications of forestry on small, high-gradient channels, grain size must be taken into account. We also suspect that, because weaker lithologies tend to produce smaller clasts (Collins and Dunne, 1989; Massong and Montgomery, 2000), channels flowing over weaker lithologies may be less resistant, in terms of maintaining step geometry and associated flow resistance, to a loss of large wood.

Our results may also be applicable in other environments, such as the Colorado Rockies, where old-growth trees tend to be of comparable size to the Pacific Northwest second-growth examined in this study. The threshold between pebble- and cobble- or greater-sized clasts in the step that allows step height to be a function of log diameter would likely apply to such forested regions. For instance, a high gradient reach with mostly fine bed material that experiences a significant wildfire may take considerably longer to return to a pre-burn state in terms of forming log steps than one with coarse bed material.

5. Conclusions

Through an examination of the relationships between clast size comprising the step and log step height, we found that second-growth logs can indeed form log steps that are sufficiently high to laterally divert flow and thus are likely comparable in function to their old-growth counterparts, provided large clasts are available with which the logs can interact. Where this is the case, second-growth log steps can likely form elements that adjust towards a state of greater roughness, similar to steps formed by old-growth wood. We have found a threshold grain size above which log step height is more significantly controlled by functional log diameter, indicating that step height and corresponding flow resistance can be impacted by the size of the clasts forming log steps. From this, we conclude that clast size must be an

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Fig. 6. Log step diverting flow. Log step, old low flow channel, and new low flow channel are labeled.

Fig. 7. Log step partially in contact with bed. Flow is from background to foreground. Note top of backpack behind log step and rock hammer stuck in log for scale. Log traps clasts where it is near the bed, diverting flow to the left side of the channel where the log is suspended on a tree.
important consideration when determining the effects of changes in the size of instream wood on high-gradient channels.

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