Controls on valley width in mountainous landscapes: The role of landsliding and implications for salmonid habitat

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ABSTRACT

A fundamental yet unresolved question in fluvial geomorphology is what controls the width of valleys in mountainous terrain. Establishing a predictive relation for valley floor width is critical for realizing links between aquatic ecology and geomorphology because the most productive riverine habitats often occur in low-gradient streams with broad floodplains. Working in the Oregon Coast Range (western United States), we used airborne lidar to explore controls on valley width, and couple these findings with models of salmon habitat potential. We defined how valley floor width varies with drainage area in a catchment that exhibits relatively uniform ridge-and-valley topography sculpted by shallow landslides and debris flows. In drainage areas >0.1 km^2, valley width increases as a power law function of drainage area with an exponent of ~0.6. Consequently, valley width increases more rapidly downstream than channel width (exponent of ~0.4), as derived by local hydraulic geometry. We used this baseline valley width–drainage area function to determine how ancient deep-seated landslides in a nearby catchment influence valley width. Anomalously wide valleys tend to occur upstream of, and adjacent to, large landslides, while downstream valley segments are narrower than predicted from our baseline relation. According to coho salmon habitat-potential models, broad valley segments associated with deep-seated landsliding resulted in a greater proportion of the channel network hosting productive habitat. Because large landslides in this area are structurally controlled, our findings indicate a strong link between geologic properties and aquatic habitat.

INTRODUCTION

Many of the most compelling patterns expressed on the Earth's surface relate to the organization of channel networks and their associated valleys. Although systematic downstream variations in river channel properties, such as width, depth, and velocity, have been extensively characterized and used for river management since the seminal work of Leopold and Maddock (1953), surprisingly few insights regarding variations in valley floor width have emerged. From experience, one expects that big rivers carve wide valleys and small streams inhabit narrow valleys; however, quantification of this perception and a framework for identifying controls on valley width in mountainous landscapes remain largely unexplored (Dury, 1960; Salisbury, 1980; Martin et al., 2011). Unlike channel width, which is primarily set by feedbacks between flow hydraulics and sediment transport, valley width also reflects the long-term history of aggradation, incision, lateral channel migration, and hillslope-channel interactions. In addition, because valleys span much broader areas than channels, their morphology is more likely to exhibit variations due to changing bedrock properties that regulate the effectiveness of fluvial activity. As a result, it is challenging to disentangle variations in valley floor width in most natural settings (Snyder and Kammer, 2008; Som et al., 2009). Nonetheless, there is a critical need for the systematic characterization of valley floors because these areas transmit water and sediment during flood events as well as provide important habitat for aquatic organisms, such as salmonids.

In mountainous regions, hillslope-channel interactions that influence valley morphology often consist of landslide impingement into fluvially dominated areas. Large landslides can inundate river valleys and overwhelm channels with massive volumes of sediment, which can form stable landslide dams that cause extensive and prolonged aggradation upstream (Ouimet et al., 2007). Thus, numerous studies show that large landslides have the potential to create anomalously wide valleys in portions of the drainage network that might otherwise support landforms shaped exclusively by fluvial action (e.g., Costa and Schuster, 1988; Korup et al., 2006; Hewitt et al., 2008). The extent to which slope failures and other hillslope-channel interactions influence valley morphology across entire drainage basins has not been addressed because most studies focus on individual landslides and the proximal valley condition.

Identifying spatial patterns of valley width is important because the most productive riverine habitat occurs in broad valleys that allow for floodplain development (e.g., Naiman et al., 2010). These broad valleys inherently produce low-gradient channels, can accommodate sinuous planforms, provide off-channel habitats during floods, and dampen episodic inputs of sediment by providing space for the formation of debris flow fans. In addition, low-gradient broad valleys with old-growth forest store the great majority of above-ground and below-ground carbon in mountain streams (Wohl et al., 2012). Understanding the links between hillslope processes and riverine habitat is particularly important for Pacific salmon (*Oncorhynchus* spp.) because these fish are intricately tied to Pacific Rim topography (Montgomery, 2000; Waples et al., 2008).

The goals of this paper are twofold. First, we seek to define an empirical relation between valley width and drainage area (akin to hydraulic geometry for river channels) in a setting with negligible influence from variable rock properties and deep-seated landslide activity. Our approach uses high-resolution topography generated from airborne lidar to define this baseline relation of valley width in a mountainous catchment shaped by shallow landslides and debris flows. Second, we attempt to relate deviations from this baseline relation in a nearby catchment to deep-seated landsliding. We hypothesize that anomalously wide valley floors develop upstream and adjacent to ancient large landslides, and that these areas provide important habitat for salmon.

METHODS

Study Area

We characterized variations in valley width in the humid, steep, soil-mantled Oregon Coast Range (western United States), which is underlain by the Tyee Formation, a relatively undeformed turbidite sandstone (Heller and Dickinson, 1985). Annual rainfall is between 1 m and 2 m. In upland catchments, sediment transport is dominated by bioturbation and small soil slips on hillslopes (Heimsath et al., 2001), and shallow landslides and debris flows in valley networks (Stock and Dietrich, 2003), making this a logical baseline for our study. Erosion rate data suggest that the Oregon Coast Range may be in approximate flux steady state such that rock uplift balances erosion (Reneau and Dietrich, 1991; Heimsath et al., 2001). Furthermore, the uniform ridge-and-valley topography that characterizes much of the Oregon Coast Range has been presented as evidence for topographic steady state (Reneau

GEOLOGY, April 2013; v. 41; no. 4; p. 503–506 | doi:10.1130/G33979.1 | Published online 7 February 2013

and Dietrich, 1991), although this balance is locally subverted by deep-seated landsliding, lateral migration of rivers, and differential incision (Roering et al., 2005).

We selected Harvey Creek as our reference basin because it is the largest catchment with available lidar data that exhibited relatively uniform ridge-and-valley topography, sculpted primarily by shallow landslides and debris flows (Table 1; Fig. 1). By contrast, we selected the Elk Creek basin, for which lidar data are also available, because it contains numerous deep-seated landslides, identified by Roering et al. (2005). As a result, much of the catchment is characterized by low-gradient, bench-like hillslopes that are distinctly different from the neighboring steep and dissected topography of debris flow–prone terrain. Deep-seated landslides are abundant in the Oregon Coast Range (5%–25% of the landscape), depending on structural and lithologic properties of the Tyee Formation (Roering et al., 2005). Extensive alluvial fills commonly observed upstream of these deep-seated landslides suggest that they are ancient and persistent features.

Measuring Valley Width

To map valley width, we smoothed the gridded bare earth lidar data with a moving window algorithm (Wood, 1996). At each grid node, we fit a second-order weight polynomial to a 15 × 15 node matrix of neighboring points, and calculated slope gradient from the polynomial coefficients. From these slope maps, flat valley floors can be clearly distinguished from the adjacent steep hillslopes, which transition abruptly from the valley floor.

We measured cross sections on the slope map perpendicular to the valley along the mainstem and several major tributaries in the drainage network of Harvey Creek to construct the baseline relation between drainage area and valley width. Measurement spacing corresponded to individual stream reaches in a synthetic channel network developed by Clarke et al. (2008; described in the following). In several small tributaries to Harvey Creek, contemporary debris flow deposits were evident from the lidar-derived topography and were previously mapped (May and Gresswell, 2004) following a major storm in 1996. We omitted these recent debris flow deposits from the data because measurements reflect transiently aggraded conditions and do not represent the actual width of the valley floor in otherwise bedrock channels with thin alluvial cover. This resulted in the omission of 22 data points, of a total of 270 valley width measurements, and were limited to reaches with drainage areas <1.0 km^2. In Elk Creek, valley width was also measured at cross sections on the slope map along the mainstem of the channel in 108 locations. Reaches immediately upstream and adjacent to deep-seated landslides were distinguished from downstream or more distal reaches.

TABLE 1. BASINS IN THE TYEE FORMATION OF THE OREGON COAST RANGE (WESTERN UNITED STATES) USED TO DETERMINE THE EFFECT OF DEEP-SEATED LANDSLIDES ON THE WIDTH OF VALLEYS

Basin	Terrain type	Drainage area (km^2)	Drainage density	Basin relief (m)
Harvey Creek	Shallow landslides and debris flows	22.7	4.61	484
Elk Creek	Deep-seated landslides	16.8	3.90	338

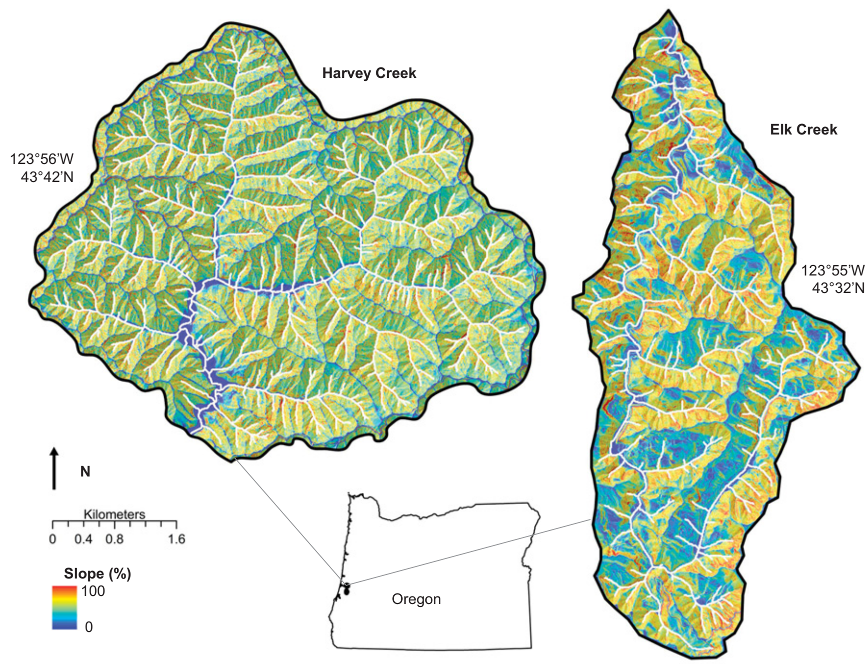

Figure 1. Slope maps created from 20-cm-resolution lidar topography for Harvey Creek (shallow landslide and debris flow terrain) and Elk Creek basins (deep-seated landslide terrain), Oregon (western United States). Local slope gradient was generated from smoothing bare-earth lidar data. Dark blue represents flat areas, grading to yellow for steep hillslopes, and red for nearly vertical cliffs. Broad low-gradient hillslopes in Elk Creek are ancient deep-seated landslides.

Modeling Coho Habitat

The topographically derived stream network developed by Clarke et al. (2008) provided our drainage area and bankfull channel width data. We used these previously published stream layers developed from 10 m digital elevation models (DEMs) instead of developing lidar-based values because the existing stream layers and associated habitat modeling are commonly used in conservation planning and endangered species management (e.g., Burnett et al., 2007), and we wanted our study results to be applicable to fisheries managers. Reach breaks in the stream network were segmented ~20 times the bankfull width of the channel, and the intrinsic potential to provide rearing habitat for coastal coho salmon (*Oncorhynchus kisutch*) was estimated within each stream reach (Burnett et al., 2007). The model is based on empirical evidence from published field studies relating habitat use by juvenile coho salmon to mean annual stream flow, valley width, and channel gradient. The intrinsic potential (IP) for in-stream habitat is calculated as:

$$IP = \left(I_{FLOW} * I_{VWI} * I_{GRADIENT}\right)^{1/3}, \quad (1)$$

where I_{FLOW} is an index of mean annual stream flow, reflecting the need by coho salmon to inhabit channels large enough to supply adequate perennial stream flow. In the Oregon Coast Range, this parameter eliminates very small drainage areas (<1 km^2) from being considered suitable habitat. The second parameter, I_{VWI}, is valley width index, representing the ratio of valley width to the bankfull channel width. This index reflects that narrow valleys have tightly constrained channels with less potential for developing complex habitats preferred by juvenile coho salmon. Valley width in this model is estimated from the distance between hillslopes at a height of five times the bankfull channel width (Clarke et al., 2008). Bankfull channel width is estimated from local hydraulic geometry relations (based on field data from the Oregon Department of Fish and Wildlife and the United States Environmental Protection Agency, cited in Clarke et al., 2008). The third parameter, $I_{GRADIENT}$, is an index of reach-scale channel gradient estimated from the synthetic stream network routed through 10 m DEMs using elevations interpolated from contour lines (Clarke et al., 2008). This index is based on habitat suitability curves indicating that juvenile coho salmon utilize stream reaches with <5% gradient and increase in density as gradient decreases (Nickelson, 1998; Rosenfeld et al., 2000). The component indices are equally weighted, and values of IP range between 0 and 1. Large IP values indicate greater potential for providing high-quality habitat.

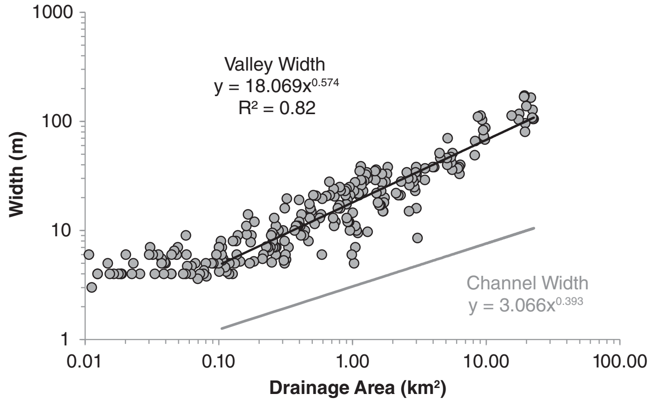

Figure 2. Baseline relation between drainage area and valley floor width for Harvey Creek in debris flow–prone terrain of central Oregon Coast Range (western United States). Circles indicate valley width measurements from lidar; gray line indicates hydraulic geometry predictions of channel width. Fluvial domain of power law relation occurs at drainage area >0.1 km².

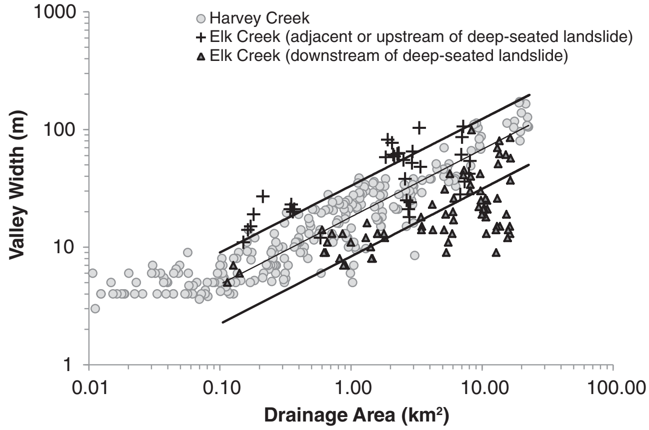

Figure 3. Deep-seated landslide terrain of Elk Creek (Oregon, western United States) overlain on baseline relation between valley width and drainage area from Harvey Creek. Bold lines represent prediction intervals around regression line (thin dark line) for baseline relation.

RESULTS

Our analysis of Harvey Creek reveals a power law relation between drainage area and valley width in shallow landslide and debris flow terrain for drainage areas >0.1 km² (Fig. 2). The exponent for this relation is ~0.6, which indicates that the rate of increase in valley width with drainage area outpaces channel width (exponent of ~0.4), as predicted from local hydraulic geometry. This basic valley width–drainage area relation only applies to the fluvial process domain, as identified by a similar scaling break in the relation between drainage area and channel slope (Montgomery and Foufoula-Georgiou, 1993; Stock and Dietrich, 2003), thereby distinguishing valleys carved by fluvial incision and those carved by debris flows. In our data this scaling break occurred at a drainage area of 0.1 km². Below this threshold, there was no corresponding decrease in valley width with drainage area, and valley width remained constant at ~4 m. In small drainages, debris flows are the primary mechanism for carving valleys, which results a high drainage density (Table 1), and valley width appears to be set by the width of bedrock hollows, which are the primary source of shallow rapid landslides that trigger debris flows in this area (Dietrich and Dunne, 1978; Reneau and Dietrich, 1991).

We used the Harvey Creek area-width relation as a baseline for comparing how valley floor width varies in a nearby catchment with numerous ancient deep-seated landslides. In Elk Creek, valley width also increases with drainage area, but the trend exhibits much more variability, yet this variability is systematic. Anomalously wide valleys tend to occur upstream of and adjacent to ancient large landslides (53% of the data exceed the prediction interval developed from the baseline relation), indicating aggradation above persistent landslide dams (Fig. 3). Although aggradation is extensive, there is no evidence that these ancient landslide deposits currently block fish passage. Valleys downstream of slope failures were narrower than predicted from our power law area-width relation (49% of the data are less than the prediction interval), suggesting that valley constriction and the localized decrease in sediment supply below aggraded valleys has restricted valley widening.

According to habitat-potential models developed for coho salmon, more productive habitat occurs in low-gradient stream reaches with broad valleys (expressed as high IP values). Broad valley segments associated with aggradation upstream of deep-seated landslides in Elk Creek resulted in a larger proportion of the fish-bearing channel network (stream reaches with >1 km² catchment area) hosting productive habitat as compared to Harvey Creek (Fig. 4), and the differences between distributions were statistically different ($p < 0.025$; 1-sided 2-sample Kolmogorov-Smirnov test).

DISCUSSION AND CONCLUSIONS

Basic empirical relations, such as hydraulic geometry, have proven to be valuable tools with practical applications that range from large-scale

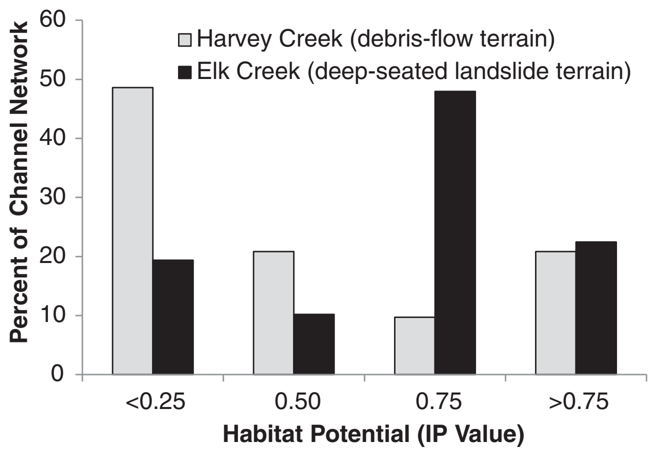

Figure 4. Intrinsic habitat-potential (intrinsic potential, IP) index values for Harvey Creek (Oregon, western United States) in debris flow–prone terrain compared to Elk Creek in deep-seated landslide terrain of Oregon Coast Range. Higher IP values indicate higher habitat potential for coho salmon.

landscape evolution modeling (e.g., Turowski et al., 2008) to site-specific habitat assessments for riverine fishes (e.g., Rosenfeld et al., 2007). We documented a power law relation between valley floor width and drainage area that indicates that the rate of valley widening outpaces the rate of channel widening. Our data also revealed that in small drainage areas (<0.1 km^2), valley width is constant, reflecting the signature of debris flow activity that is also evident in slope-area relations (Stock and Dietrich, 2003).

In addition to identifying a basic relation between drainage area and valley width, we were able to link hillslope and channel processes by exploring the effect of deep-seated landslides on riverine habitat. Deep-seated landslides caused wide valley segments to occur higher in the channel network than would otherwise be expected. These broad valley segments perched in mountain drainages can increase the diversity of habitats and lead to a greater abundance of productive habitats (based on IP values). The limiting factor for coho salmon in Oregon coastal streams has been identified as winter rearing habitat (Solazzi et al., 2000), which is most prevalent in low-gradient broad valley segments. The IP model was specifically designed to identify streams in these valley types (Burnett et al., 2007). The I_{FLOW} index simply eliminates channels too small to support fish, leaving the remaining (and often correlated) parameters of I_{VWI} and $I_{GRADIENT}$ to drive the index value. In the Oregon Coast Range, debris flows have also been found to affect riverine habitat (e.g., Benda and Dunne, 1997); however, all of the in-channel debris flow deposits we observed occurred above the distribution of fish.

Although this study focused on the effect of deep-seated landslides for determining deviations from the power law width-area relation, other anomalies are ripe for future research. It is yet to be determined how the role of rock strength, rock type, prior sea level in coastal mountains, and persistent knickpoints can affect the width-area relation.

ACKNOWLEDGMENTS

Lidar-based topography was made available by the Oregon Lidar Consortium. Logistical support for this study was provided by the Meierjurgen Fellowship for Visiting Scientists in the Department of Geological Sciences at the University of Oregon, and additional support was provided by the James Madison University Geo-Spatial mini-grant program. Many insightful conversations with Jill Marshall greatly enhanced this investigation.

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Manuscript received 22 August 2012
Revised manuscript received 10 November 2012
Manuscript accepted 12 November 2012

Printed in USA