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Morphological organization of a steep, tropical headwater stream: The aspect of channel bifurcation

Peyton E. Lisenby [a,*], Michael C. Slattery [a,b], Thad A. Wasklewicz [c]

[a] School of Geology, Energy, and the Environment, Texas Christian University, Fort Worth, TX 76129, USA
[b] Institute for Environmental Studies, Texas Christian University, Fort Worth, TX 76129, USA
[c] Department of Geography, East Carolina University, Greenville, NC 27858, USA

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ABSTRACT

Channel characterization and instream wood surveys demonstrate the spatial complexity of an ungauged, tropical headwater stream (HWS) in the Tilarán Mountains of Costa Rica. Throughout the stream course, we characterized 29 individual reaches based on their morphological organization and instream wood occurrences. Bifurcated reaches were the most numerous and consistently distributed. They also had the highest values of wood abundance and loading and contained the majority of unattached instream wood. We selected two bifurcated reaches for ultrahigh resolution terrestrial laser scanning (TLS) surveys. Orthographic TLS produced millimeter-resolution point cloud data sets from which 2 cm, planimetric-resolution digital elevation models (DEMs) of the channel surface were derived for both reaches. Cross-sectional surveys of these DEMs, using the River Bathymetry Toolkit (RBT), produced hydraulic geometries at two flow levels (high and low) for every meter-length of channel reach. We input these geometries into a one-dimensional, analytical model to demonstrate the downstream evolution of mean stream power through varying morphology elements. Mean stream power variation displays a regular pattern through the vertical modulation of step-pool sequences, but this regular pattern is lost through channel widening and bifurcation. Reach geometric data indicates that increasing width-to-depth ratio is the most notable feature of channel bifurcation and corresponds to a reduction in slope and roughness variation. This primary understanding of channel dynamics denotes the complex organization of a tropical HWS and promotes further research into tropical HWS systems.

1. Introduction

Headwater streams (HWS) represent the foremost integration of climatic, tectonic, lithologic and biologic variables operating within a basin. Headwater streams are often labeled 'complex' or 'high energy' because they display dramatic ranges in flow regime, channel morphology, and biodiversity. Visually, this characterization is easy to accept because few other geomorphic systems can harbor such a broad yet pronounced array of dynamic spatiotemporal features.

Tropical HWS are integrative geo-ecosystems that mandate more comprehensive research approaches. Climatic and biotic accelerated weathering, increased riparian bioproductivity, and seasonally flashy flow regimes only exacerbate the complex linkages already seen in temperate systems (Caine and Mool, 1981; Wohl, 2005; Pike et al., 2010). Further complication arises from their remote locations and topographically challenging field sites. Aside from low accessibility, many of these streams are unmonitored, making it impossible to relate a flow regime record to observed channel change. The physical state of channel features is the most useful tool when characterizing ungauged streams, and it makes accurate and precise spatial surveys a crucial component of an investigation. Although tropical HWS systems are understudied in the literature, they provide great opportunities to observe impressive morphometric adjustments through a range of spatial and temporal scales.

Herein, we present a novel methodology for identifying, surveying, and modeling complex, tropical HWS reaches using channel morphology/wood distribution, orthographic terrestrial laser scanning (TLS), and one-dimensional hydraulic modeling. One-dimensional (1D) modeling demonstrates the evolution of mean stream power through two reaches in an ungauged, tropical, montane HWS in Costa Rica. Coupling our stream-scale morphology classifications with reach-scale hydraulic characterization highlights lateral channel adjustments as a complimentary mechanism with vertical bed transitions in a steep, stepped-bed headwater system. This foundational understanding supports continued multifaceted research in tropical basins and shows the evolution of TLS from an experimental geomorphological tool to one that is applicable and robust in challenging, tropical field sites.

* Corresponding author. Tel.: +1 817 257 7270.
E-mail address: p.e.lisenby@tcu.edu (P.E. Lisenby).

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2. Background

2.1. Channel morphology and instream wood

A visual morphology classification system is a useful, readily available means of classifying reaches and channel segments in HWS. Montgomery and Buffington's (1997) classification system is widely used in temperate basins, and Wohl and Merritt (2008) showed that quantifiable distinctions exist between the visually identified morphology categories. Wooldridge and Hickin (2002) found visual identification to be a proficient method in distinguishing step-pools and cascades based on step-span and grain-size partitioning. To our knowledge, an established classification scheme has not been tailored to tropical drainages, nor has one been designed for especially small catchments. Jackson and Sturm (2002) noted that gradient may not be the dominant controlling variable in stream morphology for low fluvial power, first- and second-order streams. Wohl (2005) characterized headwater tropical river networks as ones that may better approximate alluvial systems in terms of adjustments to channel form. She substantiates this statement by noting significant differences in the controlling variables of tropical systems such as: the absence of past glaciation, increased substrate weathering, accelerated instream wood decay, and flashy, wet-season flow regimes. Therefore, tropical HWS likely do not behave as end-member systems. They do not conform to temperate-bedrock stream classification schemes nor to those schemes derived from higher order drainages; rather, they behave more dynamically, as they have higher degrees of freedom with which to adjust and respond to perturbations. An established classification scheme is still useful, but it may need augmentation to describe unique morphology assemblages. A stepped-bed classification, as proposed and described by Grant et al. (1990) and Comiti and Mao (2012), is appropriate for steep, tropical HWS because it describes a stepped profile formed through grain steps and bedrock scour that is punctuated by individual step-pools, step-pool sequences, and cascading grain arrangements (Fig. 1B). This scheme is more inclusive and gives the field observer a measure of latitude when describing the highly variable and visually chaotic morphology assemblages common in tropical HWS.

The linkage between flow hydraulics, sediment dynamics, and channel morphology is affected by the occurrence of instream wood in forested headwater basins. The relationship between instream wood and fluvial processes has been extensively described over a wide range of basin and time scales (Piégay and Gurnell, 1997; Brooks and Brierley, 2002; Gurnell et al., 2002). Research in temperate HWS has shown piece dimensions, arrangement, decay rate, and availability compared with flow regime; and transport capacity determines residence time and channel stability. For a single piece or multiple 'jammed' pieces, residence time dictates how long the piece(s) can influence sediment flux and support reach-scale morphologies (Fetherston et al., 1995; Abbe and Montgomery, 1996; Massong and Montgomery, 2000; Hyatt and Naiman, 2001; Abbe and Montgomery, 2003; Faustini and Jones, 2003; Wohl and Goode, 2008; Wohl and Jaeger, 2009; Jones et al., 2011; Wohl et al., 2011). Whether or not a wood piece or jam can remain stable in the channel determines if its distribution will dictate or reflect flow hydraulics. More recent work has investigated instream wood and sediment–morphology–hydraulics relationships in tropical basins (Cadol et al., 2009; Wohl et al., 2009; Cadol and Wohl, 2010, 2011; Wohl et al., 2012). Steep, tropical HWS are largely transport dominated because of high decay rates and seasonal high intensity/frequency storm events; therefore, instream wood distribution is

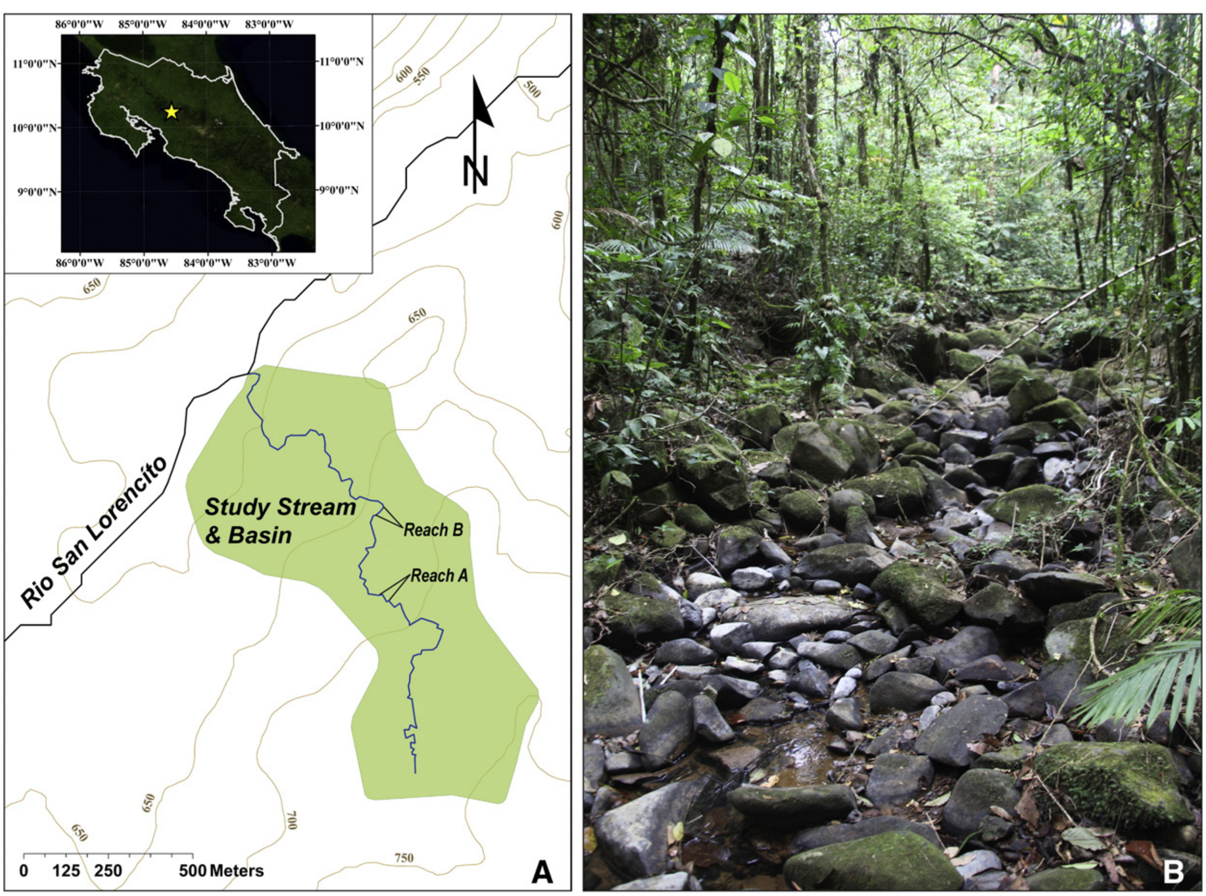

Fig. 1. (A) Study stream and reach locations. (B) Stepped-bed portion of the channel where channel width ≈ 5 m; photo taken in February 2012 during the dry season.