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An evaluation of stream characteristics in glacial versus fluvial process domains in the Colorado Front Range

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ABSTRACT

Many of the conceptual models developed for river networks emphasize progressive downstream trends in morphology and processes. Such models can fall short in describing the longitudinal variability associated with low-order streams. A more thorough understanding of the influence of local variability of process and form in low-order stream channels is required to remotely and accurately predict channel geometry characteristics for management purposes, and in this context designating process domains is useful. We define process domains with respect to glacial versus fluvial valleys and lateral confinement of valley segments. We evaluated local variability of process domains in the Colorado Front Range by systematically following streams, categorizing them into stream morphologic type and process domain, and evaluating a number of channel geometry characteristics. We evaluated 111 stream reaches for significant differences in channel geometry among stream types and process domains, location and clustering of stream types on a slope–drainage area (*S*–*A*) plot and downstream hydraulic geometry relationships. Although individual channel geometry variables differed significantly between individual stream types in glacial and fluvial process domains, no single channel geometry variable consistently differentiated all stream types between process domains. Hypothetical *S*–*A* boundaries between bedrock- and alluvial-bed channels proposed in previous studies did not reliably divide bedrock and alluvial reaches for our study sites. Although downstream hydraulic geometry relationships are well-defined using all reaches in the study area, reaches in glacial valleys display much more variability in channel geometry characteristics than reaches in fluvial valleys, less pronounced downstream hydraulic geometry relationships, and greater scatter of reaches on an *S*–*A* plot. Local spatial variability associated with process domains at the reach scale (10^1–10^3 m) overrides progressive downstream relationships in low-order mountain streams of the Colorado Front Range.

1. Introduction

Conceptual models developed for river networks that emphasize progressive downstream trends in channel morphology and processes include the river continuum concept (Vannote et al., 1980), downstream hydraulic geometry (Leopold and Maddock, 1953), and slope–drainage area (*S*–*A*) relationships (Hack, 1957; Sklar and Dietrich, 1998). Although these models are useful for large or lowland rivers, they may not be as applicable for low-order (first- to third-order) streams in mountainous areas because of abrupt downstream changes in geomorphic history (e.g., glaciations: Arp et al., 2007; Brardinoni and Hassan, 2007; and history of landslide-producing variations in valley width: May et al., 2013), geology (e.g., Adams and Spotila, 2005; Wohl, 2005; Thompson et al., 2008), and climate (Wohl, 2010b) within mountainous terrains. These abrupt downstream changes create segmented longitudinal profiles and spatial variability in valley and channel geometry and disturbance regimes over short (10^1–10^3 m) distances in mountain streams, which can have limited ability to readily adjust channel morphology to spatial variation in substrate resistance and sediment supply (Wohl, 2010b). The absence or weak development of progressive downstream trends in mountain river networks indicates the need to focus on reach-scale patterns. We define a reach as a length of channel at least several times the average channel width that has consistent gradient and channel geometry, typically 10^1–10^3 m along low-order mountain streams.

Mountain streams, which are commonly the headwaters for larger river systems, have been less extensively studied than their low-gradient counterparts. Low-order streams typically compose over two-thirds of total stream length of a drainage basin (Freeman et al., 2007), and their abundance and influence on the river network as a whole can be underestimated and inadequately acknowledged from a management perspective (Gomi et al., 2002). The location and spatial abundance of mountain streams make them important sources of sediment, water, nutrients, and organic matter for downstream portions of the river network (Milliman and Syvitski, 1992; Benda et al., 2005). In addition, the small drainage areas and variation in roughness elements associated with mountain streams lead to at least

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temporary storage of organic matter, which in turn provides essential food sources and habitats for the base of the food chain (Gomi et al., 2002). Mountain streams include wide ranges of gradient, light, temperature, water chemistry, substrate, food sources, and species composition, which combine to form a wide variety of habitats (Meyer et al., 2007). All of these features of low-order mountain streams collectively indicate disproportionately high physical and ecological significance of mountain streams in the context of an entire watershed.

Mountain streams are different from their lowland counterparts in their typically steeper gradients and in the influences of local and regional tectonics, alpine glaciation, elevation-related spatial variation in hydrologic regime (snowmelt-dominated versus precipitation-dominated hydrograph), and the strong influence exerted directly on rivers by hillslope sediment dynamics, disturbance regimes, and differences in rock resistance. Lower gradient reaches of mountain streams tend to be transport limited with respect to fine sediments and are response reaches in which changes in sediment supply are likely to cause changes in channel morphology (Montgomery and Buffington, 1997). In contrast, high-gradient reaches of mountain streams tend to have high transport capacity relative to sediment supply because of their steeper bed gradients, so that they are supply limited with respect to pebble-sized and finer sediments (Montgomery and Buffington, 1997). Sediment dynamics in mountainous headwaters are directly related to the diverse morphology in mountain streams. The persistence of a specific stream morphology is maintained by roughness and energy dissipation influenced by sediment dynamics and by larger clasts that are only moved during extreme events (Montgomery and Buffington, 1997; Flores et al., 2006; Thompson et al., 2008).

The widely used channel classification system developed by Montgomery and Buffington (1997) for mountain streams focuses on reach-scale channel geometry. Channel geometry is categorized in terms of dominant bedform (cascade, step–pool, plane-bed, pool–riffle, dune–ripple), and we refer to these categories as stream types. This classification is widely used in part because much resource management focuses at the reach-scale (Wohl et al., 2007), where stream type can be used to predict aquatic communities and habitats or areas of hyporheic exchange (e.g., Montgomery et al., 1999; Buffington et al., 2004; Buffington and Tonina, 2009; Bellmore and Baxter, 2013). Stream type correlates with reach-scale gradient (Montgomery and Buffington, 1997; Wohl and Merritt, 2005, 2008; Wohl et al., 2007) and with gradient combined with an index of specific stream power based on drainage area (Flores et al., 2006). This is particularly useful in a management context because reach-scale gradient can be readily extracted and mapped from remote data such as digital elevation models (DEMs), which facilitate mapping the spatial distribution and abundance of stream type (e.g., Buffington et al., 2004). Individual categories of stream type differ in their response to changes in water and sediment yield, as well as types and abundance of aquatic and riparian habitats (Wohl et al., 2007). Sklar and Dietrich (1998) proposed that consistent correlations exist between stream substrate type and channel slope–drainage area (*S*–*A*), such that reaches of similar substrate will plot distinctly in *S*–*A* space.

Individual stream types can occur within diverse process domains. A process domain is a spatially discrete area that is characterized by a distinct geomorphic history and assemblage of geomorphic processes, which together create distinctive landforms and disturbance regimes (size, frequency, duration of floods, and debris flows) (Montgomery, 1999). Process domains can be used to understand and predict sediment input, transport, and storage in streams, as well as ecological structure along and within stream segments (Wohl and Merritt, 2005; Wohl, 2010a; Polvi et al., 2011; May and Lisle, 2012). Disturbance regimes can physically modify expected or progressive downstream trends by influencing sediment and water dynamics, which in turn dictate channel morphology and stream type.

Process domains identified for the Colorado Front Range emphasize lateral valley-bottom confinement and geomorphic history (Polvi et al., 2011; Wohl et al., 2012). Lateral valley-bottom confinement is differentiated into confined, partly confined, and unconfined valleys based on the ratio of active channel width to valley-bottom width. Geomorphic history is differentiated into glacially formed valleys above ~2430 m elevation and fluvially formed valleys at lower elevations. Glacially and fluvially formed valleys also have distinct hydroclimatology and disturbance regimes. Glacially formed valleys have snowmelt floods and long (ca. 300–400 y) recurrence intervals for fires (Veblen and Donnegan, 2005) and associated debris flows. Fluvially formed valleys have snowmelt floods and rainfall flash floods resulting from convective storms. Fire recurrence intervals are much shorter (ca. 40–100 y) (Veblen and Donnegan, 2005), and debris flows resulting from fires and from convective storms are more common than at higher elevations. Glaciation widened and deepened valleys, created steep valley walls and headwalls, and flattened the lower portions of glacial valleys (Anderson et al., 2006; Amerson et al., 2008). These effects on previously glaciated valleys have decoupled hillslope processes from inner stream valleys so that stream channels flow through valleys that are not necessarily adjusted to current fluvial sediment, water, and disturbance regimes but to inherited glacial terrain and characteristics (Brardinoni and Hassan, 2007; Arp et al., 2007; Klaar et al., 2009). In contrast, streams in unglaciated valleys likely have maintained their coupling with hillslopes and have created and maintained their own channels according to historical and current sediment, water, and disturbance regimes.

Both glacial and fluvial valleys in the Colorado Front Range include all three levels of valley confinement and also contain diverse stream types. As a result of the differences in hillslope–channel coupling and disturbance regime between glacial and fluvial valleys, we hypothesize that individual stream types have statistically different geometry between glacial and fluvial process domains. In other words, even though step–pool channel segments are present in glacial and fluvial valleys, and are clearly different than cascade or pool–riffle channel segments, step–pool channels in glacial valleys will be a statistically distinct population from step–pool channels in fluvial valleys. To test this hypothesis, we systematically examine whether consistent differences in channel geometry and gradient within a stream type exist between glacial and fluvial process domains in the Colorado Front Range.

Because we expect geomorphic history to strongly influence stream geometry, we also hypothesize that (i) the *S*–*A* relations proposed by Sklar and Dietrich (1998) will not adequately describe observed patterns of channel substrate type in the Front Range, and (ii) downstream hydraulic geometry relations will differ significantly between glacial and fluvial process domains. Each of the three hypotheses reflects our expectations that local geomorphic history will influence contemporary channel geometry strongly enough to create significant differences between process domains.

Much of the previous research regarding trends in channel geometry of mountain streams either (i) comes from climate and tectonic regimes that differ from the semiarid, tectonically stable Colorado Front Range, such as the U.S. Pacific Northwest region (Montgomery and Buffington, 1997; Montgomery, 1999; Buffington et al., 2004; Brardinoni and Hassan, 2007; Buffington and Tonina, 2009) or southeastern Australia (Thompson et al., 2008), (ii) was not designed to include the entire range of channel types we examine here (e.g., Wohl and Merritt, 2005, 2008), or (iii) does not explicitly evaluate how correlations between channel type and potential control variables differ between process domains.

2. Study area

The mountainous portions of the four catchments (North St. Vrain Creek, Glacier Creek, Big Thompson River, Cache la Poudre River) surveyed in this study begin at the eastern side of the continental divide in Rocky Mountain National Park, Colorado (Fig. 1). Streams within each