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Channel morphology and bed-load yield in fluvial, formerly-glaciated headwater streams of the Columbia Mountains, Canada

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ABSTRACT

This study examines channel-reach morphology and bedload yield dynamics in relation to landscape structure and snowmelt hydrology in headwater streams of the Columbia Mountains, Canada. Data collection relies on field surveys and geographic information systems analysis in conjunction with a nested monitoring network of water discharge and bedload transfer. The landscape is characterized by subdued, formerly-glaciated upland topography in which the geomorphic significance of landslides and debris flows is negligible and fluvial processes prevail. While the spatial organization of channel morphology is chiefly controlled by glacially imposed local slope in conjunction with wood abundance and availability of glacigenic deposits, downstream patterns of the coarse grain-size fraction, bankfull width, bankfull depth, and stream power are all insensitive to systematic changes of local slope along the typically stepped long profiles. This is an indication that these alluvial systems have adjusted to the contemporary snowmelt-driven water and sediment transport regimes, and as such are able to compensate for the glacially-imposed boundary conditions. Bedload specific yield increases with drainage area suggesting that fluvial re-mobilization of glacial and paraglacial deposits dominate the sedimentary dynamics of basins as small as 2 km^2. Stepwise multiple regression analysis shows that annual rates of sediment transfer are mainly controlled by the number of peak events over threshold discharge. During such events, repeated destabilization of channel bed armoring and re-mobilization of sediment temporarily stored behind LWD structures can generate bedload transport across the entire snowmelt season. In particular, channel morphology controls the variability of bedload response to hydrologic forcing. In the present case studies, we show that the observed spatial variability in annual bedload yield appears to be modulated by inter-basin differences in morphometric characteristics, among which slope aspect plays a critical part.

1. Introduction

Steep headwater streams are a distinct class of channels with characteristic morphologies, processes, and dynamics (Gomi et al., 2002; Hassan et al., 2005). They constitute the outermost, steeper portion of the drainage network that conveys sediment and wood fluxes from hillslopes to high-order streams. In headwater streams, colluvial and fluvial processes coexist, consequently, the magnitude and frequency of sediment and wood inputs operated by mass wasting exert a primary control on channel morphology (Grant et al., 1990; Benda and Dunne, 1997) and bedload transport (Gomi and Sidle, 2003).

The spatial distribution of channel-reach morphology has been explained as the expression of the relative interaction between sediment supply and transport capacity (Montgomery and Buffington, 1997, 1998). In this regard, the downstream progression of channel types along a concave-up longitudinal profile reflects a general shift from supply-limited conditions (colluvial reaches, boulder-cascades, and step-pools) to transport-limited ones (riffle-pools), with increasing opportunities for in-channel storage (Church, 1992).

In high-energy headwater streams the movement of bedload material, the sediment fraction that builds channel architecture, exhibits high spatial and temporal variability in relation to peak flow, the history of mass-wasting activity, and in-channel storage conditions (Gomi and Sidle, 2003). Seasonal variations in bedload yield have been explained with episodic sediment inputs from adjacent hillslopes and from LWD structures (Lisle, 1986; Gintz et al., 1996; Gomi and Sidle, 2003). For example, the latter authors show how the typical exhaustion-like seasonal pattern of bedload (clockwise hysteresis) associated with the maximum annual flood can be reversed (counter-clockwise hysteresis) locally by landslide sediment supply. Short-term bedload transport variations in mountain streams are usually associated with the break-up and subsequent re-establishment of the bed armor layer (Gomi and Sidle, 2003; Hassan et al., 2005).

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Although important progress has been made in understanding the hydro-geomorphology of humid, steep headwater channels, in mountain environments headwater streams are not necessarily synonymous with mass-wasting dominated systems. In fact, large portions of tectonically-active and inactive orogens exhibit hydro-climatic (e.g., continental) and topographic boundary conditions (e.g., plateau-like topography) that do not favor a sediment transport regime dominated by rapid shallow failures. For example, in British Columbia fluvially-dominated headwater streams drain over 30% of the Canadian Cordillera, including the Interior Plateau and portions of the Columbia Mountains and Rocky Mountains (Holland, 1964).

This typology of headwater systems, which has been largely neglected, may present unique morphodynamics. An understanding of their hydro-geomorphic functioning is fundamental for addressing problems of forest management, landscape evolution, aquatic ecology, and conservation biology. To our knowledge no study has examined fluvially-dominated headwater streams considering both morphological and sediment transport aspects. This paper reports one of the first comprehensive accounts on headwater streams in which mass wasting disturbance is not prevalent.

The objectives of this paper are to (1) examine the spatial variability of channel-reach morphology and cross-sectional channel variates at the watershed scale, (2) evaluate bedload sediment dynamics in relation to hydrologic variability, (3) elucidate linkages between channel morphology and bedload transport, and (4) evaluate the effects of topographic and sedimentary glacial imprints on channel morphodynamics. We pursue these objectives through an experimental set up that relies on a nested network of hydrologic stations and in-channel sediment traps in Cotton Creek, a forested, fluvially-dominated watershed of the southern Columbia Mountains, Canada.

2. Study area

Cotton Creek (22.1 km^2, Fig. 1a), is a forested, mountain basin of the Purcell Range, Columbia Mountains physiographic region, British Columbia (Holland, 1964). Elevation ranges from 900 m a.s.l. in proximity of Moyie Valley floor, to 2018 m along the south-eastern divide of the basin. Channel gradient in the basin, ranging between 3 and 40%, does not support debris-flow initiation. Our observations are consistent with findings from prior work conducted in neighboring Selkirk and Monashee Ranges of the Columbia Mountains, according to which landslide and debris-flow initiation is rare on slopes at <47% (Jordan, 2002).

The drainage network has a dendritic pattern consisting of two main tributaries: Elk Creek (5.7 km^2) and Upper Cotton Creek (10.3 km^2). The former, in comparison to Upper Cotton Creek, is characterized by lower elevation (Fig. 2a), and lower slope (Fig. 2b). With respect to aspect, Elk exhibits a comparatively greater proportion of terrain facing south (i.e., S, SE, and SW; Fig. 2c) at the expense of north-facing topography (i.e., N and NE). Dominantly south-facing slopes imply higher incoming solar radiation, hence faster snowmelt runoff. As a result, a substantial portion of Elk Creek basin is snow free at least 2 weeks earlier than Upper Cotton Creek (Jost et al., 2007).

The area is underlain by middle Proterozoic meta-sedimentary rocks of the Purcell Group. Silty-sandy, compact, matrix-supported basal till is the dominant surficial material in Cotton Creek and blankets much of the catchment from the lower elevations up to the ridge crests (Fig. 1b). More loosely consolidated, gravelly ablation till is present as veneers and blankets the northern slopes of the watershed above about 1500 m. Sandy, gravelly glaciofluvial deposits with relict meltwater channels occur in association with the ablation till.

At the peak of the last glacial period Cotton Creek was overridden by the Cordilleran Ice sheet that extended south-westward into the Moyie Valley from the Rocky Mountain Trench (Clague et al., 1980). Relict glacial topography suggests that shallow valley-side glaciers descended westward and northward coalescing in Cotton Creek valley before flowing into the main Moyie Valley glacier. Surficial material

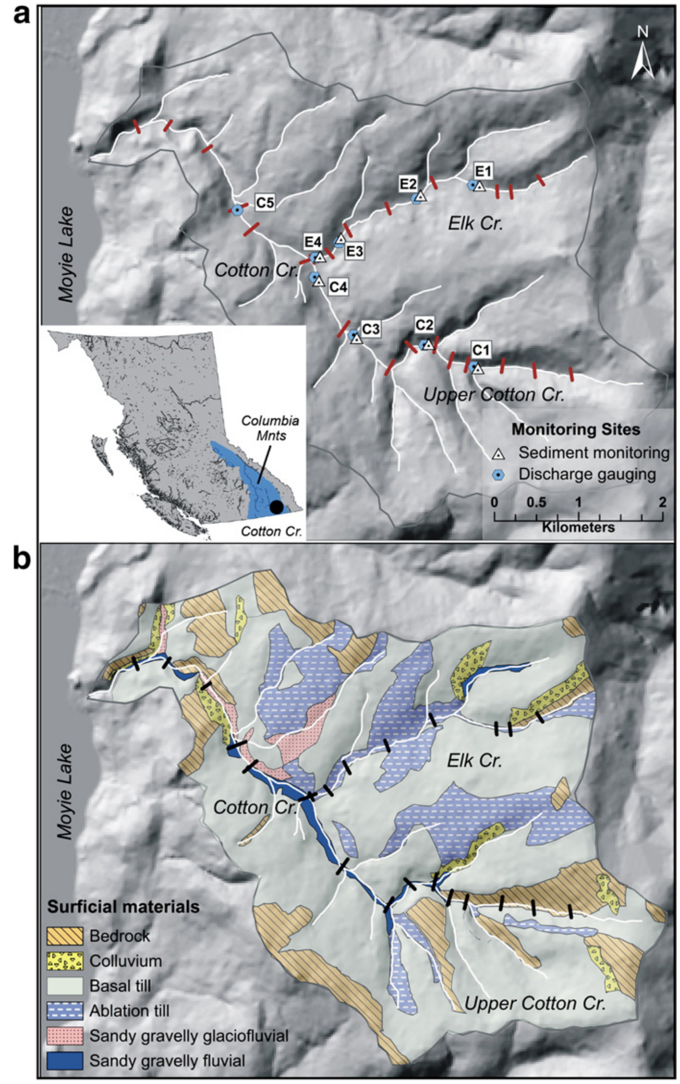

Fig. 1. Maps of the Cotton Creek basin showing (a) the shaded relief with the locations of reach breaks (red breaks) and monitoring stations; and (b) the distribution of the surficial materials. Terrain mapping complies with British Columbia Terrain Stability TSIL C survey level (Howes and Kenk, 1997) and as such entailed ground truthing in 50% of the polygons.

mapping (Fig. 1b) indicates that tributaries of both Upper Cotton and Elk contained pro-glacial deposits (e.g., glaciofluvial deposits, Fig. 1b) suggesting that these drainages were ice-free while the surface of the Cordilleran Ice Sheet occupying the Rocky Mountain Trench was still above the highest ridge tops (Ryder, 1981; Jackson and Clague, 1991; Ryder et al., 1991). Glaciofluvial and ablation deposits have been reworked and deposited as paraglacial fluvial deposits (Fig. 1b) along the length of Upper Cotton and Cotton Creek (below Elk confluence). A small kame terrace (identified as glaciofluvial, Fig. 1b) along the lower reaches of Cotton Creek likely marks the elevation of the ice surface in the Moyie Valley directly to the west that persisted while pro-glacial meltwater streams were flowing out of the tributary valleys.

Today the region has a continental climate. Precipitation (600 mm annually) falls mainly as snow between October and March. An average maximum snow accumulation of 400 mm (snow water equivalent), measured on April 1st since 1971, is reported at the Moyie Mountain snow pillow (1840 m a.s.l; B.C. Ministry of Environment) located 7 km south of Cotton Creek. Stream flows in the southern Purcell Mountains rise rapidly in mid April to mid May in response to solar-