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Debris flow initiation and sediment recharge in gullies

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ABSTRACT

Landslides that enter gullied low-order drainages can either initiate debris flow or stop, depositing sediment in the channel. This process is one of the most common ways that debris flows initiate, but little attention to date has been paid to evaluating the factors that affect whether or not the initial landslide will become a debris flow or deposit sediment in the channel. Statistically significant parameters that determine whether slope failures become debris flows or act to recharge in-channel sediment are channel gradient, angle of entry of failure into the channel, initial failure volume, and the amount of in-channel stored sediment. Steeper channels, low angles of entry, lower volumes of in-channel sediment, and larger initial failures were more likely to result in debris flows. This study found that as the volume of in-channel stored sediment increased, the volume of initial failure required to initiate a debris flow also increased. This result calls into question the simple supply-limited model of cyclical debris recharge and debris flow in low-order gullied drainages and suggests a negative feedback mechanism between debris accumulation and debris flow susceptibility.

1. Introduction

Debris flows form a class of slope failures (Varnes, 1978) encompassing a wide range of characteristics and varying widely in magnitude (Jakob, 2005), composition (Coussot and Meunier, 1996), and mechanism of initiation (Coe et al., 2008). Debris flows are recognized as a significant hazard in mountainous areas. Many researchers have focused on prediction of their occurrence (e.g., Bathurst et al., 1997; Ho et al., 2000; Giannecchini et al., 2007) and estimation of their magnitude and runout distance (e.g., Johnson et al., 2000; Hungr et al., 2007; Miller and Burnett, 2008) in order to reduce associated risk. In addition, debris flows have been shown to be an important process controlling the transport of sediment and woody debris from hillslopes to channels in mountainous areas, with implications for channel form and riparian habitat (Hogan, 1987; Hogan and Schwab, 1991).

Four general types of debris flows have been distinguished: (i) slope failures on planar slopes that begin as landslides and become debris flows during their movement downslope (Iverson et al., 1997; Gabet and Mudd, 2006); (ii) slope failures in low-order streams that become debris flows when they enter the stream channel (Campbell, 1975; Van Steijn, 1996). Campbell (1975) termed this process "soil slip–debris flow" but "debris slide–debris flow" is more accurate as the debris may include unweathered parent material as well as soil; (iii) debris flows in low-order streams that initiate from high runoff and/or overland flow mobilizing sediment, with no associated landslide (Berti et al., 1999; Cannon et al., 2001); and (iv) debris flows that initiate from high runoff at the lower limit of bedrock channels where runoff erodes overbank colluvial deposits (Johnson and Rodine, 1984; Larsen et al., 2006).

Climate, topography, and lithology affect which types of debris flows occur in different locales. For instance, the second type of debris flow is most common in maritime, cold to temperate climates such as the Pacific coast of North America or northwestern Europe (Campbell, 1975; Anderson and Sitar, 1995; Van Steijn, 1996; Benda and Dunne, 1997).

Not all low-order drainages are subject to debris flows. Up to 80% of the landscape area in mountainous areas consists of headwater streams (Schumm, 1956; Shreve, 1969), but studies of representative portions of mountainous terrain showed that only 25–30% of the landscape area consisted of gullied terrain susceptible to debris flow (Howes, 1987; Millard et al., 2002; Rollerson et al., 2002). The discrepancy has been explained by physiographic factors, with the Melton ratio useful for discriminating between low-order catchments subject to flooding, debris flood, and debris flow (Wilford et al., 2004). The low-order drainages subject to debris flow therefore form a distinct subpopulation of all low-order watersheds, often referred to as gullies (Takahashi, 1991; Nistor and Church, 2005).

Characterization of debris flow hazard from gullies requires identification of a gully together with understanding of the magnitude and frequency of debris flow occurrence. Gullies are distinctive landforms, typically consisting of an upper section comprising one or more zero-order basins (with or without steep headwalls); a mid-

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section consisting of a steep, confined channel with relatively steep sidewalls; and often a fan or cone at the lower end where the gully intersects a valley floor. The ease of identifying gullies, however, is offset by the more complex nature of debris flow frequency and magnitude.

Debris flow occurrence in gullies has been characterized as either supply-limited or transport-limited (Bovis and Jakob, 1999; Glade, 2005; Jakob et al., 2005). In transport-limited gullies, a high volume of readily entrainable sediment is present, and whenever a storm of sufficient magnitude occurs, a debris flow will result. In contrast, in the simplest model of supply-limited gullies, the volume of entrainable sediment is limited, and a storm of sufficient magnitude may not initiate a debris flow unless enough sediment is available. Glade (2005) presented a typical scenario: for a gullied drainage in Iceland, a storm producing a 10-year flood (Q10) is sufficient to initiate a debris flow when the gully is full of sediment. Once the debris flow occurs, the gully is evacuated of debris. Debris in the gully is recharged by solifluction and rockfall, which are slow processes. If another Q10 event occurs before the debris has recharged to some threshold value, no debris flow will result because of insufficient sediment availability.

For supply-limited gullies where the initiation mechanism is debris slide–debris flow, the volume of the resultant debris flow will equal the volume of the initial debris slide plus the volume of sediment entrained from the gully. As gully length increases, the relative contribution of the initial failure volume will decrease, and the total debris flow volume will approach more closely the volume of entrained sediment and depend strongly on the length of channel travelled by the debris flow (May, 2002; VanDine and Bovis, 2002). Therefore, understanding the processes that recharge debris to the gully is crucial for evaluating debris flow hazard.

Debris slides that do not initiate a debris flow appear to present a significant source of debris recharge. The proportion of debris slides that result in a debris flow appears to be regionally variable, and reported numbers may also vary significantly based on study methodology, as small slides under forest canopies that do not result in debris flows may be difficult to detect from aerial photographs (Brardinoni and Church, 2004); nonetheless, estimates may be obtained from the relevant literature. For instance, Rood (1990), studying the Queen Charlotte Islands of British Columbia, reported that only about one-third of debris slides resulted in a debris flow. Benda and Dunne (1997) reported that "most" shallow landslides in the Oregon Coast Range evolved into debris flows; but May and Gresswell (2003), studying the same region, reported many landslides that did not initiate debris flows, finding that 20% of total in-channel sediment recharged between debris flows was derived from landslides. Globally, recent studies have reported that the proportion of landslides that initiate debris flows varies from 14% to 56%, with climate, lithology, and vegetation implicated as potentially significant control factors (Crosta et al., 2003; Guadagno et al., 2005; Gabet and Mudd, 2006; Imaizumi et al., 2007).

The main objective of this study was to explore the effects of in-channel stored sediment (ICSS) on debris flow initiation in an attempt to evaluate the recharge threshold for debris flow initiation suggested by the supply-limited theory (Glade, 2005; Jakob et al., 2005). Little research to date has been conducted on this subject. We evaluated a number of debris slides, some of which had resulted in debris flows and some of which had not, in order to determine which factors control whether an initial slide evolves into a debris flow or recharges sediment in the gully. We expected that gullies with low amounts of in-channel sediment would not have recharged sufficiently for debris slides to initiate debris flows and that, consequently, failures entering the channel would be more likely to deposit sediment. We also hypothesized that larger initial failures would be more likely to initiate debris flows, as would failures into channels with steeper gradient (Bovis and Dagg, 1992; Iverson, 1997). Finally, we expected that the angle of entry of the failure into the channel would be significant, with low angles of entry more likely to result in debris flow than angles approaching the perpendicular (Benda and Dunne, 1987).

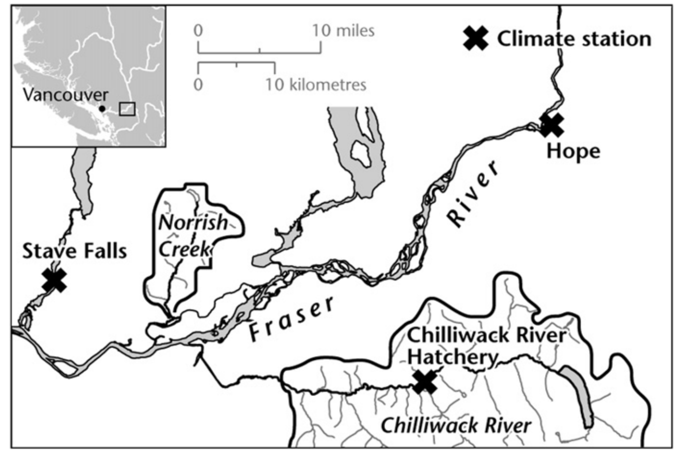

Fig. 1. Study location of Norrish Creek and Chilliwack River, British Columbia, Canada. Crosses mark the locations of representative climate stations.

2. Study area

2.1. Location, physiography, geology and bioclimatology

This study was conducted on Norrish Creek and Chilliwack River, located about 100 km east of Vancouver, British Columbia, Canada, respectively on the north and south sides of the Fraser valley. Norrish Creek is located in the southernmost Pacific Ranges of the Coast Mountains, while Chilliwack River is located in the Skagit Range of the Cascade Mountains (Fig. 1). The two watersheds share similar bioclimatic conditions, while differing somewhat in surficial and bedrock geology. Both watersheds have been extensively logged over the past hundred years or so, with a mosiac of recent logging, mature second growth, and patches of old growth.

The Norrish Creek watershed has an area of 117 km^2 and is underlain primarily by plutonic rocks of the Coast Plutonic Complex (Roddick, 1965). Thick deposits of basal till are the most common surficial material within the Norrish drainage basin. Maximum relief is ~1000 m, and the area consists of forested ridges with only minimal area above the tree line. Norrish Creek is located within the Coastal Western Hemlock biogeoclimatic zone, while upper elevations within the watershed fall within the Mountain Hemlock biogeoclimatic zone. Mean annual precipitation in Norrish Creek is ~3000 mm (MSC, 2005). The winter snowpack above 800 m is often in excess of 2 m peak depth; lower elevations within the watershed are located in a transitional rain-on-snow zone subject to transient snowpack during the winter months.

The Chilliwack River watershed measures 1230 km^2 and is underlain primarily by rocks of the Chilliwack terrane, consisting of marine sedimentary, volcanic, and metamorphic rocks. Portions of the watershed are underlain by Tertiary plutonic rocks of the Chilliwack batholith. (Monger, 1970, 1989). Surficial materials common within the Chilliwack valley include basal and ablation till and colluvial deposits as well as glaciofluvial and glaciolacustrine terraces. Maximum relief is ~2200 m, with extensive ridge systems above tree line, as well as some remnant pocket glaciers. Mean annual precipitation as recorded at the Chilliwack River Hatchery (elevation 250 masl) is ~1500 mm, but is significantly higher at higher elevations on windward slopes within the watershed, estimated at up to 3000 mm. Annual alpine snowpack is similar to or greater than Norrish Creek. The principal biogeoclimatic zones within the Chilliwack valley are Coastal Western Hemlock and Mountain Hemlock, as described for Norrish Creek.