Geomorphology 116 (2010) 107–114

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Debris-flow activity and snow avalanches in a steep watershed of the Valais Alps (Switzerland): Dendrogeomorphic event reconstruction and identification of triggers

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ARTICLE INFO

Article history:
Received 26 August 2009
Received in revised form 12 October 2009
Accepted 15 October 2009
Available online 24 October 2009

Keywords:
Debris flow
Snow avalanche
Dendrogeomorphology
Seasonality
Conifers
Broad-leaved trees
Triggering

ABSTRACT

Debris flows and snow avalanches are common processes in the headwaters of steep watersheds worldwide. In forested areas, dendrogeomorphic analyses of trees affected by debris flows and snow avalanches have regularly been used to date past events. Previous studies have, however, almost never focused on both processes at once, as snow avalanche impacts cannot easily be distinguished from debris-flow scars. In a similar way, tree-ring studies have often been limited to conifers, and sites colonized with broad-leaved forests have been widely disregarded. We report on a case from the Valais Alps (Switzerland) where past debris-flow and snow avalanche activity was dated with intraseasonal precision using different broad-leaved and conifer trees. In total, the analysis of 171 cores, 34 wedges, and 11 crosssections from 93 trees allowed identification of 20 debris-flow and 3 snow avalanche events between A.D. 1930 and 2008. Results also indicate that some of the events would have been missed without the sampling of broad-leaved trees.

1. Introduction

Debris-flow and snow avalanche activity can frequently be observed in the headwaters of steep watersheds where their repeated occurrence usually results in characteristic landforms, such as cone-shaped debris accumulations at the mouth of gullies or torrent valleys. In mountain areas, debris flows are triggered either by intense rainfall, prolonged periods of precipitation, extreme and rapid snowmelt, the outbreak of lakes, or a combination of those triggers (Corominas et al., 1996). Snow avalanches occur in winter and early spring in any location where sufficient snow is deposited and a weak layer formed on inclined surfaces steeper than 30° (Schweizer et al., 2003). Many watersheds are vulnerable to both processes leading to a high damage potential for buildings and infrastructure or even to the loss of lives along their trajectories and on their cones (i.e., Jakob and Hungr, 2005). As a consequence, protection measures are essential for vulnerable areas and facilities, and knowledge about the spatial and temporal behavior of past events is of fundamental importance for the planning of control works and mitigation strategies.

However, for most torrents and avalanche tracks in the Swiss Alps, data exist only for catastrophic or recent events (Rickenmann and Zimmermann, 1993; Zimmermann et al., 1997; SLF, 2000; Gruber and Margreth, 2001). Reliable chronologies spanning several decades or even centuries are, in contrast, often missing, especially for debris flows.

The most accurate technique to reconstruct long-term chronologies of past debris flows or snow avalanches is dendrogeomorphology (e.g., Alestalo, 1971; Stoffel and Bollschweiler, 2008). The method is based on the facts that (i) trees form one increment ring per year in temperate climates and that (ii) trees affected by geomorphic processes will record the event in the form of characteristic growth disturbances (GD) in their tree-ring series (Shroder, 1980; Schweingruber, 1996). Through the determination of the position of the GD within a tree ring, a geomorphic process cannot only be dated to the year, but sometimes even with intraseasonal resolution (Stoffel and Beniston, 2006; Stoffel et al., 2006).

Previous dendrogeomorphic analyses of debris flows focused on the reconstruction of frequencies (Strunk, 1997; Wilkerson and Schmid, 2003) or magnitudes (Stoffel, in press), spatial patterns of past activity on cones (Bollschweiler et al., 2007), minimum ages of abandoned channels (Bollschweiler et al., 2008) or the synchronicity of incidences in neighbouring torrents with different lithologies (Bollschweiler and Stoffel, 2007). Other studies focused on the comparison of reconstructed debris-flow data with archival records on flooding (Stoffel et al., 2005a), or on changes in the seasonality of debris-flow activity (Stoffel et al., 2008a).

Over the last three decades, dendrogeomorphology has been used frequently to create snow avalanche chronologies (Butler and Sawyer,

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doi:10.1016/j.geomorph.2009.10.012

2008, and references therein). While most studies have been performed in North America, only a limited number of studies exist for Europe to date (Muntán et al., 2004; Casteller et al., 2007). Studies have primarily addressed the frequency and spatial distribution of past activity (Patten and Knight, 1994; Hebertson and Jenkins, 2003) or focused on the identification of high-magnitude events (Boucher et al., 2003; Dubé et al., 2004).

Most previous tree-ring studies focused on one of the two processes at a time, although it is not unusual that debris flows and snow avalanches occupy common starting and runout zones. A distinction of geomorphic processes based on dendrogeomorphic methods is possible, either through the intraseasonal position of GD in the growth rings of trees standing on cones affected by debris flows and snow avalanches (Stoffel et al., 2006) or through wood anatomical analyses in the case of snow avalanche and rockfall events occurring at the same time of the year and at the same site (Stoffel and Hitz, 2008).

Notably, most of the aforementioned studies have been performed in crystalline environments (gneiss or granite), and dendrogeomorphic reconstructions did not often focus on regions dominated by limestone and dolomite lithologies (e.g., Strunk, 1997; Butler and Sawyer, 2008; Pelfini and Santilli, 2008; Stoffel et al., 2008b). In addition, most of the studies were performed with conifers and broad-leaved trees have been used only exceptionally for dendrogeomorphic investigations to date (Bryant et al., 1989; Mundo et al., 2007; Casteller et al., 2008; Arbellay et al., in press).

The reconstruction of past process activity normally aims at understanding current and potential future evolutions including possible impacts of a future greenhouse climate (Stoffel et al., 2008a) or the identification of triggers of past events (Bacchini and Zannoni, 2003). Rainfall intensity–duration thresholds for debris flows were first introduced by Caine (1980) and have since undergone continuous application and development, summarized by Guzzetti et al. (2008) using rainfall data of known and well-documented events. Pelfini and Santilli (2008) identified precipitation thresholds for debris-flow events that have been previously reconstructed with dendrogeomorphic methods.

Avalanches are triggered either naturally (e.g., rapid loading from special precipitation conditions) or through artificial triggers (e.g. skiers, gas injection, helicopter bombing or artillery; Schweizer et al., 2003). Meteorological factors measured by automatic weather stations are often applied to forecast avalanche probability, but the formation process is too complex to corrrelate events with data from nearby snowgauge stations (National Research Council, 1990). Studies on avalanche triggers therefore concentrate on the physical processes in the snow layer and the interaction between snow layer and terrain (e.g., McClung and Schweizer, 1999).

This study presents a coupled debris-flow and snow avalanche reconstruction based on dendrogeomorphic methods. We investigate the headwaters of a steep watershed in a calcareous environment where (i) debris-flow and snow avalanche activity is reconstructed with intraseasonal resolution using conifer and broad-leaved trees, (ii) the utility of injured broad-leaved trees for dendrogeomorphic studies is analyzed, and where (iii) debris-flow triggering rainfall events are identifed.

2. Study area

The watershed investigated is the Meretschibach located on the north-facing slope of the Rhone valley in southern Switzerland (Valais, 46° 18′ N./7° 40′ E.; Fig. 1). From its source at Untere Meretschialp (1920 masl), the torrent flows mostly in a northern direction along the border of the two municipalities Agarn and Leuk-Susten to its confluence with the Rhone River at about 620 masl. The mean slope angle of the torrent averages 21.5° and ranges from 8° on the cone to 33.7° in the upper part of the torrent. Debris flows and snow avalanches develop outside the main channel at the northern slope of the Meretschihorn (2567 masl). In the upper catchment (average slope angle 33°), large amounts of extensively fractured calcareous material is stored in talus slopes. The debris-flow system at Meretschibach is transport-limited (supply-unlimited) and material is therefore readily available for entrainment by debris flows. Three active debris-flow channels enter the Meretschibach between 1160 and 860 masl. Snow avalanches can either follow the debris-flow channels and affect the upper part of the torrent or fall west of the main channel.

Located in one of the driest regions in Switzerland, mean annual rainfall at the nearby climate station Sierre amounts to 612 mm (mean annual value for the period 1901–2007; MeteoSwiss, 2008). Maxima occur in winter (December and January) as well as in August when heavy thunderstorms (convective precipitation) are common. From the climate data and based on archival evidence from neighbouring catchments, we can assume that avalanche activity is restricted to a period between November and early April. Debris flows occur between late-April and mid-October, which roughly corresponds with the local growth period of trees. Local trees form light earlywood cells between early May and mid-July, and the darker latewood cells are produced from mid-July through late October.

The vast majority of the watershed is covered with a dense forest consisting mainly of Norway spruce (*Picea abies* (L.) Karst.) and broad-leaved trees, including Grey alder (*Alnus incana* DC), European Mountain ash (*Sorbus aucuparia* L.), Pubescent birch (*Betula pubescens* Erh.), and Great maple (*Acer pseudoplatanus* L.). In the uppermost reaches of the catchment (1900 masl) and close to timberline, a limited number of European larch (*Larix decidua* Mill.) and Swiss stone pine (*Pinus cembra* L.) trees can be found. The surface of the cone is used as pasture and occupied by the village of Agarn.

Data on past debris-flow events is scarce and includes information on six events since 2000: October 2000 (2 events), 31 July 2002, 21 May 2003, 19 August 2003, and 29 July 2008 (Municipality of Agarn, 2008; personal observation). As a result of the large debris-flow events in October 2000, two retention basins and deflection dams were constructed on both sides of the torrent at the level of the cone in 2007. Snow avalanches are less common at Meretschibach, with the most recent event on record in 2001 (Kanton Wallis, 2008).

3. Material and methods

3.1. Field methods

An accurate identification of forms and deposits related to past debris-flow and snow avalanche activity is crucial, as a basis for the selection of trees to be sampled. The first analytical step, therefore, consists of in a geomorphic mapping of forms and deposits at a scale of 1:500. Geographical position system (GPS) devices could not be used in the steep channel because of the topography of the terrain and the forest cover; this is why mapping was conducted using compass, tape measure, and inclinometer.

Based on the detailed geomorphic map and an inspection of their morphology, trees showing visible growth disturbances (GD) resulting from past geomorphic activity were preferably sampled. The sampling was conducted either with an increment borer, a hand saw, or a chain saw. Sampling focused on the debris-flow transportation zone between 760 m and 860 m to avoid areas disturbed by humans.

Conifers were sampled with increment borers, allowing for an extraction of ~5.5-mm-thick cores with a maximum length of 40 cm. At least two cores were taken per tree, one in the flow direction, the other one from the opposite side. In the case of visible wounds, additional cores were taken from the overgrowing callus. Sampling height and position were chosen depending on the type of disturbance and following the recommendations provided by Stoffel and Bollschweiler (2008, 2009). Sampling of broad-leaved trees focused on stems with visible scars. A wedge was extracted from the wound and the