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Monitoring sediment source areas in a debris-flow catchment using terrestrial laser scanning

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ABSTRACT

Geomorphic changes caused by three debris-flow events in a small mountain catchment (Moscardo Torrent, Eastern Italian Alps) were investigated by means of multitemporal terrestrial laser scanning (TLS) surveys over three areas exposed to debris-flow dynamics. For these areas, DEM of Differences (DoDs) with a 0.2 m spatial resolution allowed the assessment of elevation uncertainty as spatially variable by applying the fuzzy inference system (FIS) proposed by Wheaton et al. (2010). Along with two commonly used parameters affecting Digital Elevation Model (DEM) accuracy, such as terrain slope and point density, we developed and employed in the FIS a new index, named Vegetation Noise, that takes into account the disturbance caused by the vegetation cover on the DEM accuracy. The results of volumetric budgets of the surveyed sediment source areas derived from the DoD analysis were compared with debris-flow volumes estimated from flow stage measurements at the instrumented channel reach. On the one hand, the discrepancies arising from this comparison underline the limitations of TLS surveys over morphologically complex areas such as debris-flow catchments. On the other hand, the TLS unveils the geomorphic changes at the scale of the single event, because a terrestrial survey is usually easier to carry out than an aerial one. The analysis of DEM quality and uncertainty indexes correlation may help to refine methods for spatializing elevation errors and improving the reliability of the models.

1. Introduction

Hillslope morphology in mountain catchments has a major influence on water and sediment dynamics related to runoff formation and sediment erosion routing and deposition. Among the geomorphic processes occurring in steep mountain catchments, debris flows can be considered one of the most hazardous phenomena threatening infrastructures and human lives. The assessment of debris-flow magnitude and the quantification of the sediment eroded from hillslope and channels are of extreme importance to improve the knowledge and therefore the management of these phenomena.

Traditional measurement techniques of debris eroded during large events essentially involve the estimation or the measurement of the thickness and areal extent of the material deposited at the foot of the slope, in channels or in the alluvial fan (e.g. Wohl and Pearthree, 1991). The main limitations of this approach are the uncertainty in volume calculation due to the difficulty of estimating deposit thickness and the limited extent of the area that can be surveyed. The availability of repeated (pre- and post-event) Digital Elevation Models (DEMs) can help overcoming these limitations. Coe et al. (1997) carried out one of the first studies dealing with the mapping and measurement of morphological changes induced by a debris flow using pre- and post-event DEMs. The authors used 2-m DEMs derived from repeated aerial stereo-photographs to map hillslope erosion and the downslope distribution of debris due to a debris flow that occurred on a hillslope of the Jake Ridge, Nevada.

Over the last years, remote mapping with high sampling density over large areas, i.e. airborne and terrestrial laser scanning (respectively, ALS and TLS), benefited from significant technological enhancements. These enhancements allowed a refinement of the monitoring techniques of surface morphology and made it possible to obtain DEMs with a resolution of 0.5–1 m in the case of ALS (e.g. Bremer and Sass, 2012; Cavalli et al., 2008; Frankel and Dolan, 2007) and even higher for TLS (e.g. Milan et al., 2007; Schürch et al., 2011).

By examining the changing pattern of surface changes over time it is possible to analyze and understand the related geomorphological dynamics, with the application of the "morphological method" (Ashmore and Church, 1998) as defined for fluvial environment. The analysis can be carried under different perspectives, ranging from the accounting of volumetric (Scheidl et al., 2008) and channel geometry changes (Wasklewicz and Hattanji, 2009) to the correlation of morphometric indexes with different components of the geo-hydrological processes (Cavalli and Marchi, 2008; Glenn et al., 2006; McKean and Roering, 2004; Tarolli et al., 2010).

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Compared to ALS, the TLS technique is more flexible and accurate in particular for the monitoring of steep areas, where ALS incidence angle would lead to a poor survey (Hodgson and Bresnahan, 2004). Nevertheless, TLS is more limited in terms of range and areal coverage. One of the biggest issues of using TLS is the difficulty to achieve homogeneous coverage for large areas without data voids, which are an inevitable consequence of the shadowing effects of a complex surface geometry such as the one typically found in mountain slopes (Buckley et al., 2008; Perroy et al., 2010).

The comparison between DEMs obtained from successive surveys gives the possibility to produce DEM of Difference (DoD) maps, which in turn make it possible to analyze morphological changes in slopes and channels from the quantitative (scour and fill changes in volume) and the qualitative (spatial patterns of erosion and deposition) perspectives (Picco et al., 2013; Scheidl et al., 2008; Theule et al., 2012).

In this context, the assessment of DEM quality is a crucial issue, since errors from different sources propagate into the DoD. Several sources of error, often hard to limit, may occur; they include the accuracy of the surveying instruments, the DEM interpolation method, accounting for vegetation cover and high surface roughness, and the registration of surveys and random errors (Hengl and Reuter, 2009). A solid survey and data processing strategy can therefore play a decisive role in the quality of geomorphic change detection studies (Buckley et al., 2008).

Usually the assessment of DEM accuracy is achieved by comparing the DEM with a second, more accurate, surface (Brasington et al., 2000, 2003; Wood, 1996) or with Ground Control Points (Brasington et al., 2000, 2003; Buckley and Mitchell, 2004; Lane et al., 2003; Milan et al., 2007).

The evaluation of vertical elevation uncertainty, which is a critical issue for distinguishing real geomorphic changes from noise (Fuller et al., 2003), is tightly connected to DEM accuracy assessment. Many studies assume propagated DEM uncertainty in DoDs as being uniform (Brasington et al., 2000; Fuller et al., 2003), by specifying a minimum level of detection ($_{min}$LoD) to discriminate actual surface change from noise, therefore considering changes above this $_{min}$LoD as real.

A more sound approach considers DEM elevation uncertainty as spatially variable. Accordingly, DoD uncertainty can be estimated by analyzing slope (Scheidl et al., 2008), wet or dry areas (Brasington et al., 2003; Lane et al., 2003), point cloud quality (Schürch et al., 2011) or a combination of slope, point density and GPS quality (Wheaton et al., 2010).

The aim of this paper is to analyze surface changes due to erosion and deposition in a debris-flow prone basin in the Eastern Italian Alps (Moscardo Torrent catchment) over two years. We performed multitemporal TLS surveys over three areas exposed to debris-flow dynamics.

Special attention was paid to assess elevation uncertainty as spatially variable. A new index taking into account the loss of accuracy caused by vegetation cover was developed and combined with more common and used parameters (e.g., slope and point density) in DoD calculations by using the fuzzy inference system (FIS) method proposed by Wheaton et al. (2010).

Lastly, we compared volumetric budgets of the surveyed sediment source areas, derived from DoD analysis, with debris-flow volumes estimated at the monitoring site.

2. Study area

2.1. The Moscardo Torrent

The Moscardo Torrent (Fig. 1) is a small stream in the Eastern Italian Alps, whose catchment drains an area of 4.1 km^2. Elevation ranges

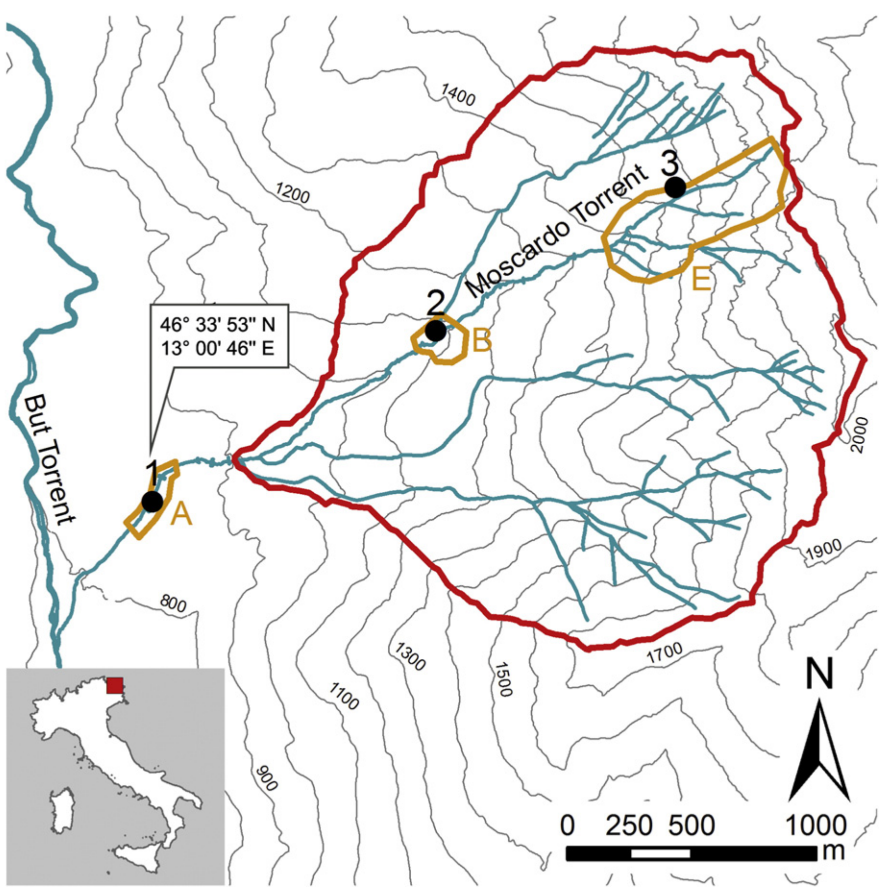

Fig. 1. Location map of the Moscardo Torrent basin. (1) Instrumented channel stretch; (2 and 3) rain gauges; (A, B, E) TLS surveyed areas.