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Assessment of erosion and deposition in steep mountain basins by differencing sequential digital terrain models

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ABSTRACT

Digital elevation models (DEMs) built from repeated topographic surveys permit producing DEM of Difference (DoD) that enables assessment of elevation variations and estimation of volumetric changes through time. In the framework of sediment transport studies, DEM differencing enables quantitative and spatially-distributed representation of erosion and deposition within the analyzed time window, at both the channel reach and the catchment scale. In this study, two high-resolution Digital Terrain Models (DTMs) derived from airborne LiDAR data (2 m resolution) acquired in 2005 and 2011 were used to characterize the topographic variations caused by sediment erosion, transport and deposition in two adjacent mountain basins (Gadria and Strimm, Vinschgau - Venosta valley, Eastern Alps, Italy). These catchments were chosen for their contrasting morphology and because they feature different types and intensity of sediment transfer processes. A method based on fuzzy logic, which takes into account spatially variable DTMs uncertainty, was used to derive the DoD of the study area. Volumes of erosion and deposition calculated from the DoD were then compared with post-event field surveys to test the consistency of two independent estimates. Results show an overall agreement between the estimates, with differences due to the intrinsic approximations of the two approaches. The consistency of DoD with post-event estimates encourages the integration of these two methods, whose combined application may permit to overcome the intrinsic limitations of the two estimations. The comparison between 2005 and 2011 DTMs allowed to investigate the relationships between topographic changes and geomorphometric parameters expressing the role of topography on sediment erosion and deposition (i.e., slope and contributing area) and describing the morphology influenced by debris flows and fluvial processes (i.e., curvature). Erosion and deposition relations in the slope-area space display substantial differences between the Gadria and the Strimm basins. While in the former erosion and deposition clusters are reasonably well discriminated, in the latter, characterized by a complex stepped structure, we observe substantial overlapping. Erosion mostly occurred in areas that show persistency of concavity or transformation from convex and flat to concave surfaces, whereas deposition prevailingly took place on convex morphologies. Less expected correspondences between curvature and topographic changes can be explained by the variable sediment transport processes, which are often characterized by alternation of erosion and deposition between different events and even during the same event.

1. Introduction

The appraisal and quantification of sediment dynamics in steep mountain catchments is critical for improving our understanding of geomorphic sediment cascades. Beside the monitoring of sediment fluxes at instrumented channel reaches (e.g., Mathys et al., 2003; McArdell et al., 2007; McCoy et al., 2010; Comiti et al., 2014; Rainato et al., 2016), several methods are available for inferring spatially-distributed sediment dynamics from the quantification of geomorphic change associated with erosion and deposition (e.g., Brasington et al., 2000; Lane et al., 2003; Wheaton et al., 2010).

The estimation of geomorphic change from repeated surveys was first performed on cross section and longitudinal profiles in order to infer transfer rates from volumetric estimates mainly at the channel unit and the reach scale (Martin and Church, 1995; Ham and Church, 2000; Brewer and Passmore, 2002; Vale and Fuller, 2009). A morphological budget assessment based on multi-temporal Digital Elevation Models (DEMs) represents a significant improvement as it overcomes limitations of the traditional approach mainly due to the uncertainty deriving from the interpolation of valley cross section data over larger areas (Lane et al., 1994; Brasington et al., 2000; Fuller et al., 2003; Berger et al., 2011; Bennett et al., 2012). Fuller et al. (2003)

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demonstrated that DEM-based comparisons provide more reliable estimates of sediment transfer compared to discrete cross-sections, as the latter can lead to substantial volumetric change underestimation.

When multi-temporal DEMs are available, the geomorphic change in time is inferred by DEM of Difference (DoD) grids, in which the elevation difference between old and new surfaces, hence erosion and deposition, is computed at the cell scale (Lane et al., 2003; Wheaton et al., 2010).

In order to obtain the volumes of eroded and deposited material and compute a sediment budget of a geomorphic system, the elevation difference is multiplied by the area of the raster cell. However, several studies have stressed the importance of assessing DEM uncertainty and error propagation to obtain a reliable DoD map (Brasington et al., 2000; Lane et al., 2003; Wheaton et al., 2010; James et al., 2012).

In the last two decades, significant advances, especially in Light Detection And Ranging (LiDAR) technology (Tarolli, 2014 and references therein) have been instrumental for developing new methodologies for the study of geomorphic properties, such as surface roughness (McKean and Roering, 2004; Cavalli and Marchi, 2008), surface texture (Trevisani et al., 2012) and sediment connectivity (Cavalli et al., 2013), as well as for improving DoD reliability (e.g., Wheaton et al., 2010; Theule et al., 2012; Anders et al., 2013; Croke et al., 2013; Picco et al., 2013; Vericat et al., 2014).

Recent studies have demonstrated the capability of DEM differencing for assessing areal and volumetric changes in relatively short gravel-bed channel reaches undergoing ordinary flows, by means of Terrestrial Laser Scanning (TLS) (Picco et al., 2013), and for larger areas, encompassing channel and inundated floodplain affected by a catastrophic flood, through Airborne Laser Scanning (ALS) (Croke et al., 2013); both studies have considered the spatial variability of the vertical error affecting TLS- and ALS-derived surface in DoD analysis. Also, the morphological changes associated to river restoration in a single-thread Alpine river were analyzed by differencing DEMs obtained through bathymetric ALS (Campana et al., 2014). James et al. (2012) have utilized detailed historical topographic surveys (older than 70 years) to derive LiDAR-derived Digital Terrain Models (DTMs) in a gully system and in two large rivers and compared these with more recent (and more accurate) DTMs through DoD analysis, and have demonstrated that DoD analysis in gully and large riverine systems can be extended to several decades, if accurate historical data are available and the investigated geomorphic change is larger than DoD uncertainties.

DEM differencing was successfully applied for monitoring mass wasting processes (see Jaboyedoff et al., 2012 for a review), permitting to identify patterns of erosion and deposition and quantify relevant mobilized volumes (e.g., Corsini et al., 2007; Scheidl et al., 2008; Baldo et al., 2009; Bull et al., 2010; Bremer and Sass, 2012; DeLong et al., 2012; Bossi et al., 2015). The combined use of remote sensing and DEM differencing can improve the assessment of volumetric sediment budget associated with debris flows, helping the prediction of the magnitude of such

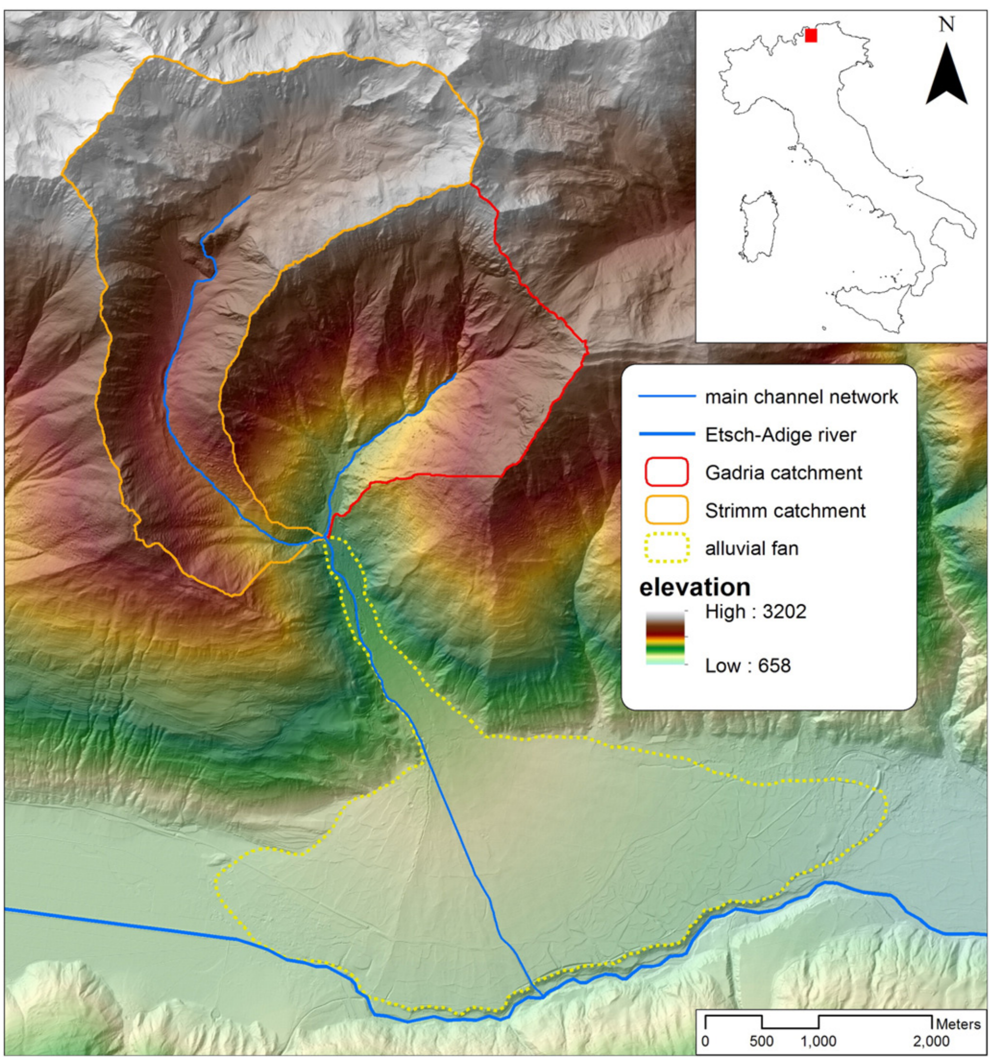

Fig. 1. Location and topographic map of the Gadria and Strimm catchments.