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Semi-quantitative method for the assessment of debris supply from slopes to river in ungauged catchments

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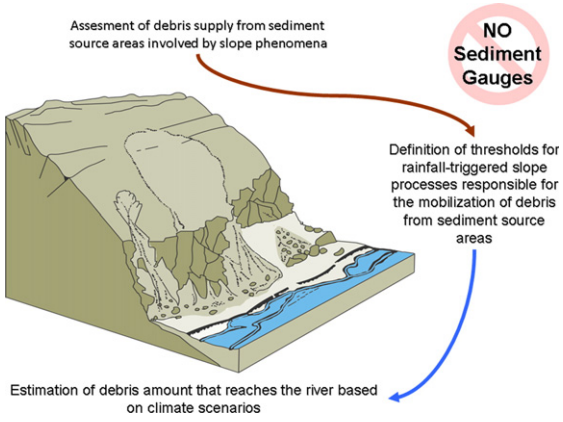
HIGHLIGHTS

- Assessment of debris supply from sediment source areas involved by slope phenomena
- Identification of linkage between sediment sources and downstream areas
- Definition of triggering thresholds for the slope processes involving the sediment source areas
- Estimation of debris amount that reaches the mainstream based on climate scenarios

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents an integrated empirical methodology for assessing the amount of sediment transported from slopes to the main river in absence of a sediment transport monitoring system. The amount of transported sediment is calculated through the characterization of the sediment source areas including the identification of the slope phenomena responsible for the sediment propagation to the main river: shallow landslides, channelized debris flows and deep-seated rotational slides. On this basis, several scenarios related to the climatic conditions are defined: they indicate the number of possible slope phenomena and potential volumes of mobilized unconsolidated material from sediment source areas to the main river. This methodology was finalized and tested in the Maira River basin (south-western Italian Alps) with quite good results.

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1. Introduction

In mountain catchments, geomorphic processes, such as debris flows and landslides, are the main cause of the transfer of sediment from sediment source areas (i.e., areas where the sediment is produced or stored) on the hillslope to the main streams. The effectiveness of these processes in a mountain environment is extremely variable, being strongly influenced by the complex morphological setting of these areas, which plays an important role on the degree of linkage between sediment sources and downstream areas (i.e., sediment connectivity) (Cavalli et al., 2013). The mobilization of the sediment on the hillslope is driven by the climatic conditions responsible for the triggering of these slope phenomena, whose frequency, density and spatial distribution control the amount of sediment transferred to the main stream. Based on the conceptualization of the sediment cascade concept, several approaches and models to assess sediment volumes mobilized from sediment source areas and their transfer to the main stream have been developed in literature (Bovis and Dagg, 1988; Kean et al., 2013; Borga et al., 2014; Prancevic et al., 2014, Gregoretti et al., 2016; Hu et al., 2016). The estimation of debris flow and landslide volumes is of the utmost importance for the assessment of the hazards related to these processes and several studies have addressed this important topic (Dadson et al., 2004; Marchi and D'Agostino, 2004; Brardinoni et al., 2009; Guzzetti et al., 2009; Hovius et al., 2011, Brardinoni et al., 2012; Wang et al., 2015). Marchi and D'Agostino (2004), collected data on debris flow magnitude from 127 basins in the Eastern Italian Alps from different sources (e.g, scientific journals, technical reports, historical documents), and used regression techniques to correlate debris flow volume to the morphometric parameters and geology of the studied catchments. Brardinoni et al. (2012) analysed debris flow data of 77 catchments in the Autonomous Province of Bolzano (northeastern Italy) gathered from a historical database. The authors linked debris flow sediment flux to morphometry, lithologic variability, and sediment availability, combining information on event volumetric deposition, high-resolution digital topography, and Quaternary sediment. Concerning landslides, Brardinoni et al. (2009) estimated the landslide sediment flux across the landscape in formerly glaciated mountain catchments of coastal British Columbia (Canada), exploiting a 70-year inventory. Guzzetti et al. (2009) derived an empirical relationship linking landslide area to landslide volume using data on 677 landslides. Most of the studies focusing on the assessment of debris flow and landslide volumes benefit from data gathered from historical archives or monitoring systems. This issue is difficult to be addressed in ungagged and undocumented catchments.

The aim of this paper is to develop a semi-quantitative indirect method for the assessment of the cumulative sediment volumes considering several catchment outlets within the Maira River (Piedmont Region, Italy) channel bed taking into account sediment supply from hillslopes.

2. Study area

The Maira River is a river of Alpine origin and its watershed is characterized by a total drainage surface of 1118 km^2 at the confluence with the Po River. The Maira catchment develops for 59% in mountainous areas. Its basin shape is rather elongated, wider in the highest part and narrower in the lowest part. The catchment orientation goes from west to north-east and maximum, mean and minimum elevations are respectively 3310, 1129 and 231 masl.

Before joining the Po River, the Maira River crosses several municipalities, both in its mountainous and lower reaches. The major tributaries in the mountain reach are characterized by a rather low mean discharge.

The Maira's hydrological regime is typically alpine, with high flow period usually in spring, with important snowmelt contributions, and tending to dry up in summer. The Maira catchment is equipped with one water level sensor (at Busca) and ten rain gauges (Fig. 1).

In the early 1900s, two high altitude reservoirs were constructed in the municipalities of Acceglio (Saretto) and San Damiano Macra, with reservoir volumes of 0.14 and 0.29 Mm^3 respectively. Both are still operating hydropower plants. Unfortunately, data concerning sediment accumulation within the two reservoirs are scarcer and characterized by a very discontinuous historical series focused only on silt fraction. For this reason, data from reservoirs are cannot be used to estimate the sedimentation rate.

The geology of the Maira Valley is characterized mainly by metamorphic rocks (calcareous rocks, calc-schists, mica schists, gneisses and quartzites). These rocks are linked to three main structural domains: Dora-Maira Unit (continental margin unit with its terrigenous Mesozoic sedimentary successions; it is mainly represented by mica schists and gneisses outcropping in the lower part of the valley), Calc-schists and "Green stones" Unit, which is present in the middle-southern part (calcareous metamorphic rocks, dolomites, calc-schists, but also ophiolites) and Brianzonese Complex (various metamorphic rocks of sedimentary and volcanic origin: limestones, dolostones, quartzites, rhyolites, etc.) in the upper part of the Maira Valley (Fig. 2).

The Maira Valley land cover is the one typical of Alpine valleys, characterized by a low percentage of territory occupied by urban areas (0.56% of the total area), a significant presence of outcropping bedrock (10.55% of the total area) at the valley head; 99.4% of the valley is covered by vegetation of which 84.5% consists in natural vegetation and only 4.39% of agricultural and pastoral areas distributed mainly in the lower sectors (Fig. 3).

3. Methods

Considering the lack of a direct sediment transport monitoring system in the Maira catchment and the inconsistency of data from artificial reservoirs, we are proposing a semi-quantitative indirect method in order to estimate the sediment volume contribution from slopes.

In detail, the integrated methodology consists of the following points:

1) identification and characterization of sediment source areas by photogrammetric observations, field surveys and historical archives exploitation. The sediment source areas identified as mobilizable coincide, excluding talus, with sediment deposited by previous slope phenomena (mainly landslide and debris flow deposits) showing signs of recent activity or not yet stabilized by natural or artificial factors;
2) determination of sediment source areas connected to the main river through a connectivity analysis based on the slope morphometric index;
3) identification and characterization of slope phenomena responsible for sediment source areas mobilization in order to estimate a volume of potential mobilizable unconsolidated material;
4) identification of the triggering causes of slope phenomena and, where possible, determination of their triggering threshold values;
5) establishment of some scenarios of particle mobilization volumes from slopes, based on triggering threshold evaluation (specific triggering thresholds are defined through the values of precipitation recorded at historical initiations for each slope process considered);
6) detailed analysis of a well-documented single event as a testbed (case study) of the integrated method.

In this section, the different approaches that contribute to the establishment of the integrated method are explained in detail.

3.1. Sediment source areas characterization and sediment connectivity analysis

Sediment source areas were identified by means of aerial photo interpretation and field survey. Only the sediment source areas showing