Catena 160 (2018) 261–274

Contents lists available at ScienceDirect

Catena

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

The role of human activities on sediment connectivity of shallow landslides

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ARTICLE INFO

Keywords:
Index of connectivity
Human effects
Landscape evolution
Slope instability
Oltrepò Pavese

ABSTRACT

Sediment connectivity within a catchment depends largely on the morphological complexity of the catchment and is strictly related to the anthropogenic modification of the landscape.

In this context, the present research evaluates the role of anthropogenic effects on landscape modifications and the resulting influence on sediment delivery. An assessment of sediment connectivity was carried out for three different human impact scenarios: (i) drainage system density reduction, (ii) road network variation and (iii) land use changes. In addition, shallow landslides were used as sediment source areas to evaluate the potential connection between these sediment sources and downstream areas (e.g. main channels and road network).

Two small catchments in the Oltrepò Pavese area (Northern Apennines, Italy), with different size and morphological setting, were analysed: the Rio Frate (1.9 km^2) and the Versa (38 km^2) catchments. In both areas, several shallow landslides were triggered in 2009 (Rio Frate and Versa) and in 2013 (Versa).

Results highlight the role of the landscape complexity in coupling/decoupling upstream sediment sources, such as shallow landslides, from the main channel network and roads.

In addition, the analysis identified instability phenomena characterized by high connectivity values, allowing determination of the areas in which mobilized sediment could potentially damage important infrastructures such as the road network or contribute to flooding induced by aggradation or obstruction of the river bed.

The proposed approach provides a methodological framework to help improve watershed and land management strategies, especially in shallow landslides prone-areas.

1. Introduction

Sediment connectivity can be defined as the potential for sediments to move through geomorphic systems (Hooke, 2003). Connectivity analysis appraises the linkages between sediment sources and downstream areas in geomorphic systems (Cavalli et al., 2013a; Heckmann and Schwanghart, 2013). These vary in space and time (Brierley et al., 2006; Bracken et al., 2015;), and the main controlling factors are related to: (i) the morphological complexity of the catchment, such as relief, stream network density, catchment shape, soil type and surface roughness (e.g. Baartman et al., 2013; Borselli et al., 2008; Cavalli et al., 2013a); (ii) the spatial organization of vegetation (Cammeraat, 2002; Foerster et al., 2014); and (iii) anthropogenic modifications of the landscape (land use and drainage system changes, road network configuration (Tarolli and Sofia, 2016). Analysis of the spatial variability of sediment dynamics supports characterization of instability areas that behave as active sediment sources within the catchment in different contexts and environments (Marchi and Dalla Fontana, 2005; Broeckx et al., 2016; Fuller et al., 2016; Li et al., 2016; Surian et al., 2016; Tiranti et al., 2016; Cavalli et al., 2016, 2017). Czuba and Foufoula-Georgiou (2015) developed a dynamic connectivity framework that can be used to analyse the spatial organization of fluxes into persistent clusters in order to identify hotspots of fluvial geomorphic change. In a recent study, Schmitt et al. (2016) developed a modelling framework (CASCADE) to quantify sediment transport from all types of sediment sources to sinks in fluvial networks.

Landscape complexity can be low at a local scale but very high at hillslope and/or catchment scales. For example, with the increase of catchment size, floodplains tend to substitute steep slopes that are usually related to the presence of sediment source areas. These patterns, and associated process interaction, can affect the overall catchment sediment dynamics (De Vente and Poesen, 2005).

Furthermore, through its influence upon surface roughness and local sediment retention capacity, vegetation cover may decrease the

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http://dx.doi.org/10.1016/j.catena.2017.09.025
Received 18 August 2016; Received in revised form 6 September 2017; Accepted 25 September 2017

coupling between upstream and downstream areas (Borselli et al., 2008; Puigdefabregas et al., 1999). Vegetation and vegetation changes significantly affect surface runoff and sediment dynamics on hillslopes, further governing lateral sediment input rates to the channel system (Marsten, 2010; Poeppl et al., 2017). However, its role on sediment connectivity is dynamic in time, reflecting climate changes or land use and management practice modifications (Foerster et al., 2014; López-Vicente et al., 2016).

In addition, the magnitude and temporal evolution of sediment connectivity may vary in response to human activities, such as land use changes, drainage system modifications (Cavalli et al., 2013b; Poeppl et al., 2017) and development of road networks. Many human impacts directly shape surface morphology (Ellis et al., 2006; Ellis, 2011; Vanacker et al., 2014). For example, road construction and urbanization may increase lateral connectivity as they act as efficient overland flow pathways (Booth and Jackson, 1997; Croke and Mockler, 2001; Wemple and Jones, 2003). This may induce major changes in sediment retention and export along the hillslope-channel system (Tarolli et al., 2014a, 2014b).

The assessment of sediments connectivity is essential for estimating source to sink sediment pathways. Disturbances, such as landslides, may disrupt sediment connectivity patterns, and their associated impacts, especially during extreme events. For example, flood events can cause important damages to infrastructures (D'Amato Avanzi et al., 2013; Giannecchini et al., 2012; Kalantari et al., 2017) with significant social and economic side effects.

A range of qualitative and quantitative approaches has been used to assess sediment connectivity. Qualitative approaches are generally based on geomorphological and sedimentological field observations and monitoring of sediment fluxes by means of field instrumentation (Harvey, 2001, 2002; Becht et al., 2005; Brown et al., 2009; Mao et al., 2009; Schlunegger et al., 2009; Beel et al., 2011; Berger et al., 2011; Comiti et al., 2014). Quantitative methods are mainly related to indices and models based on topographic information commonly available in a GIS environment. Borselli et al. (2008) introduced a set of tools for the assessment of connectivity using both GIS data (e.g. land use, DTM) and field observations. In particular, the sediment connectivity index was designed to assess connectivity using only the available landscape information, independently from the event characteristics. This index of connectivity (IC), rather than describing connectivity in the context of specific events, can be used to derive a map representing the potential connectivity among different portions of a watershed.

Reid et al. (2007) proposed a modelling approach, which combines the assessment of landslide-generated sediment, computed using a modified version of SHALSTAB (Montgomery and Dietrich, 1994), with an index of hydrological connectivity based on a network index version of TOPMODEL (Beven and Kirkby, 1979). Schwab et al. (2009) studied the differences in sediment flux from the opposite flanks of an alpine valley related to differences in the predominant erosional processes (landsliding vs. sediment transport in channel systems). Wichmann et al. (2009) developed an integrated modelling of rockfall, slope-type debris flows and channelized debris flows to assess the sediment cascade systems resulting from the interaction of various geomorphic processes. Recently, Cavalli et al. (2013a, 2016) proposed a new version of the topography-based index developed by Borselli et al. (2008) to model sediment transfer pathways and to evaluate the potential connection of sediment source areas with the main channel network and the catchment outlet in mountain catchments.

Available methods have typically been applied to particular landscape settings and associated processes such as landslides, rock falls, and rock avalanches (Calvetti et al., 2000; Agliardi and Crosta, 2003; Dorren and Seijmonsbergen, 2003; Crosta et al., 2004), or debris flows and mud flows (Iverson and Denlinger, 2001; McDougall and Hungr, 2004; Sosio et al., 2008; Pastor et al., 2009). A first attempt to use the quantitative geomorphometric approach (i.e., IC) to evaluate the potential run out of shallow landslides was conducted in the Rendina catchment (Italy) by Borselli et al. (2011). Other recent applications were carried out by Lucía et al. (2015) who analysed shallow landslide run out to quantify Large Wood recruitment during extreme events and by Surian et al. (2016) and Tiranti et al. (2016) who used IC to characterize sediment supply from landslides to the channel network. Nicoll and Brierly (2016) compare IC with field-based measures used to assess landscape (dis)connectivity (e.g., Fryirs et al., 2007a, 2007b; Fryirs, 2013). To date, few researches compared applications of geomorphometric approaches and connectivity concept in shallow landslide analysis.

This paper seeks to address this shortcoming through an explicit analysis of i) the assessment of sediment connectivity in shallow landslide-prone areas to better characterize sediment source areas in landscapes marked by diverse complexity levels; ii) the evaluation of human modification to the landscape and their impact on sediment dynamics with a special focus on sediment mobilized by shallow landslides, in order to promote effective land and watershed management strategies.

2. Study areas

The analysis is carried out in two catchments with different size and morphological setting, both located in Oltrepò Pavese, in the northern termination part of the Apennines (Fig. 1): the Rio Frate (1.9 km^2) and the Versa (38.2 km^2) catchments. Despite the proximity of the Rio Frate and Versa catchments, they present different geomorphological characteristics, which, in turn, are strongly influenced by peculiar geological settings of the catchments.

Rio Frate catchment presents an elevation range between 95 and 295 m a.s.l. The morphological structure is characteristics of the Pede-Apennine margin of Oltrepò Pavese, its morphological structure is closely related to both the lithology and the tectonic/neotectonic setting of the Apennine margin, with prominent altimetric irregularities along ridge lines, and channel network in narrow valleys with marked breaks in slope (Vercesi and Scagni, 1984).

Elevation in the Versa catchment ranges from 128 and 662 m a.s.l. The morphological structure is characteristic of Oltrepò Pavese, with relatively uniform slopes of medium-low gradient, and a well-developed (mature stage) hydrographic network (Mancuso et al., 1996).

Bedrock in the Rio Frate catchment (Fig. 1a), is characterized by a Mio-Pliocenic succession called as “Serie del Margine” (Vercesi and Scagni, 1984), formed by medium low-permeable arenaceous conglomeratic bedrock overlying impermeable silty-sandy marly bedrock and evaporitic chalky marls and gypsum. Superficial soils, derived by bedrock weathering, are mainly clayey-sandy silts and clayey-silty sands. Soil depth ranges between a few centimetres to < 2.0 m.

The Versa catchment (Fig. 1b) is characterized by older bedrock if compared to the Rio Frate catchment, with age ranging from Cretaceous to Miocene. It is composed by marls, calcareous-marls, sandstones and scaly shales, in some cases with few arenaceous intercalation. Soils have a clayey texture extending in some area > 3–4 m thick.

Differences in soil texture affect the geomorphological setting of the study area. The Rio Frate catchment has medium-high gradient hillslopes, which can exceed 35°, and small narrow valleys. In the Versa catchment, the slopes have a low-medium gradient, with values commonly between 15 and 25°.

These geological and geomorphological settings have influenced the land use changes in the two sites.

Gentle slopes in the Versa catchment allowed the high exploitation of agricultural mechanical practices that were introduced since 1950. Optimization of agricultural practices leads to a complete conversion of the territory from arable areas into vineyards, permitting the transformation of the area into a developed economic centre, largely due to the valuable wine production (Persichillo et al., 2017).

In contrast, a large part of the Rio Frate catchment has been abandoned since 1954 with a progressive increase in woods (+17%) and uncultivated areas (+15%) and a drastic decrease in vineyards