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Climate-scale modelling of suspended sediment load in an Alpine catchment debris flow (Rio Cordon-northeastern Italy)

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ABSTRACT

Pulsing storms and prolonged rainfall can drive hydrological damaging events in mountain regions with soil erosion and debris flow in river catchments. The paper presents a parsimonious model for estimating climate forcing on sediment loads in an Alpine catchment (Rio Cordon, northeastern Italian Alps). Hydroclimatic forcing was interpreted by the novel $CliSM_{SSL}$ (Climate-Scale Modelling of Suspended Sediment Load) model to estimate annual sediment loads. We used annual data on suspended-solid loads monitored at an experimental station from 1987 to 2001 and on monthly precipitation data. The quality of sediment load data was critically examined, and one outlying year was identified and removed from further analyses. This outlier revealed that our model underestimates exceptionally high sediment loads in years characterized by a severe flood event. For all other years, the $CliSM_{SSL}$ performed well, with a determination coefficient (R^2) equal to 0.67 and a mean absolute error (*MAE*) of 129 Mg y^{-1}. The calibrated model for the period 1986–2010 was used to reconstruct sediment loads in the river catchment for historical times when detailed precipitation records are not available. For the period 1810–2010, the model results indicate that the past centuries have been characterized by large interannual to interdecadal fluctuations in the conditions affecting sediment loads. This paper argues that climate-induced erosion processes in Alpine areas and their impact on environment should be given more attention in discussions about climate-driven strategies. Future work should focus on delineating the extents of these findings (e.g., at other catchments of the European Alpine belt) as well as investigating the dynamics for the formation of sediment loads.

1. Introduction

Mountain landscapes are highly variable and associated with climatic variability and surface processes, which operate over different spatial and temporal scales (Shroder and Bishop, 2004; Slack and Bell, 2006; Goonan et al., 2010; Diodato et al., 2015; Emberson et al., 2016). As such, they are a good indicator of the state of planet Earth with regard to natural climate variability (Pepin and Lundquist, 2008) and help to depict how climate variability can drive instability in the processes associated with hydroclimatic hazards (Wolock and McCabe, 1999; Pauli et al., 2001; Diodato, 2006; Fort, 2015). The Alps, one of the largest mountain range systems of Europe, are among the most vulnerable regions to hydroclimatic hazards such as flash floods, slides, overland flow, mass and debris flows (D'Agostino and Marchi, 2001; Petrucci and Polemio, 2003; Stoffel et al., 2011; Glur et al., 2013). This is mainly owing to the combination of high reliefs, heavy rain/snow events, severe erosion rates, and the nearly unlimited sediment supply from sources such as Quaternary moraine, scree deposits, debris fans, and landslides (Hinderer et al., 2013). Sediment yield from the Alps spans a wide range of values, depending especially on the percentage of glacial cover of the basin and also on the trapping effects of human infrastructures such as reservoirs (Hinderer et al., 2013). Also, past and current climatic conditions determine sediment yield (Syvitski et al., 2005; Bennett et al., 2013), especially in glacierized environments (Micheletti and Lane, 2016). Sediment yield from mountain basins determine the morphology, dynamics, and ecological diversity of rivers but is not usually assessed by direct sediment sampling in rivers. Indeed, sediment yield from Alpine basins is often estimated by quantifying the sedimentation in reservoirs overtime, as more detailed and short-term measurements of suspended sediment and bedload transport in mountain rivers are notoriously expensive and challenging to perform. In fact, only a few long-lasting sediment monitoring programmes are located in

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the Alps, that is, at the Erlenbach in Switzerland (Rickenmann et al., 2012), the Draix in France (Mathys et al., 2003), and the Cordon in Italy (Rainato et al., 2017).

Mathematical models may simulate the combined effects of hydroclimatic forcing, such as the estimation of sediment budgets using—in the absence of distributed spatial and temporal data—the drainage catchment as a homogeneous landscape unit in which sediment fluxes and land surface changes can be calculated (Chiverrell et al., 2009). 'When modelling involves both experience and intuition, it becomes an art to depict the interaction of environmental processes over extensive space and time, although modelling is not an alternative to observations' (Mulligan and Wainwright 2004, p. 8).

Mathematical approaches are useful in reconstructing historical suspended sediment load data in order to have a better understanding of land-atmosphere interactions over historical times (Harvey, 2001). They can also lead to an understanding of land surface sensitivity reflecting the magnitude and frequency of multiple storm events (Arnell, 2011), nested within patterns of longer-term climatic variability on different time scales and operating on different subcatchments (Wolman and Gerson, 1978; Thomas, 2001; Macklin and Lewin, 2008; Murray et al., 2009; Phillips, 2009). Land surface erosion and slope instability are scale-dependent and result from the complex interactions of climate, vegetation geology, geomorphic processes, and human activities (Werrity and Leys, 2001). These scale dependencies imply that landforms are nested-form resulting from the interactions of various processes in a hierarchical manner across a range of spatial and temporal scales (Rasemann et al., 2004; Murray et al., 2009). Over subannual time scales, the amount and distribution of rainfall events determine the degree of chemical and physical weathering of slope materials, the depth of weathered soils, and the vegetation type and cover across a landscape (Howard, 1994; Montgomery and Bolton, 2003). In turn, vegetation cover controls catchment slope through the susceptibility of soil erosion (Borrelli et al., 2016) and the resulting catchment morphological attributes and its sedimentary system dynamics. These natural processes are important factors in determining landscape evolution.

The most important semiquantitative models developed for assessing erosion and suspended sediment load at the catchment scale use environmental factors to characterize drainage catchments in terms of sensitivity to erosion and sediment transport (Borrelli et al., 2014). The limited amount of data requirements and the fact that major erosion processes are considered to some extent make them suited for estimating on-site and off-site effects on soil erosion (de Vente and Poesen, 2005). Despite an increasing recognition of the relevant role that soil erosion plays in the carbon cycle of landscapes (Kuhn et al., 2009; Quinton et al., 2010; Lugato et al., 2016), to the best of the authors' knowledge no efforts have yet been devoted at discovering how climate variability affects soil erosion along multidecadal and century time scales. Indeed, water and especially sediment discharge data are hardly available over such long time scales for most rivers (Walling, 1999). Besides the lack of direct data, the main challenge is to separate the effects of climate change, human activity (e.g., land use changes), and the high natural variability of river basins and to consider the nonstationary sediment records (Walling and Fang, 2003). This also has implications for modelling sediment formation and transport to better understand the changes in past and contemporary suspended sediment loads transported by rivers before predicting future evolution.

The aim of this study is to develop a hydrological model to reconstruct multidecadal variability of suspended sediment load data at catchment scale with relatively low data availability. This novel model, called $CliSM_{SSL}$ (Climate-Scale Model of Suspended Sediment Load), accounts for the effect of multiple sediment sources while considering system complexity and process interactions. $CliSM_{SSL}$ was applied to study the effect of time and space variability of rainstorms on suspended sediment transport in the Rio Cordon (northeastern Italian Alps). The relationships between catchment properties, dominant erosion processes, and sediment load were shown by combining spatial and temporal factors.

2. Environmental setting and modelling

2.1. Study area

Research was conducted in an area among the most active in terms of fluvial sediment load (white box in Fig. 1A). The Rio Cordon is a

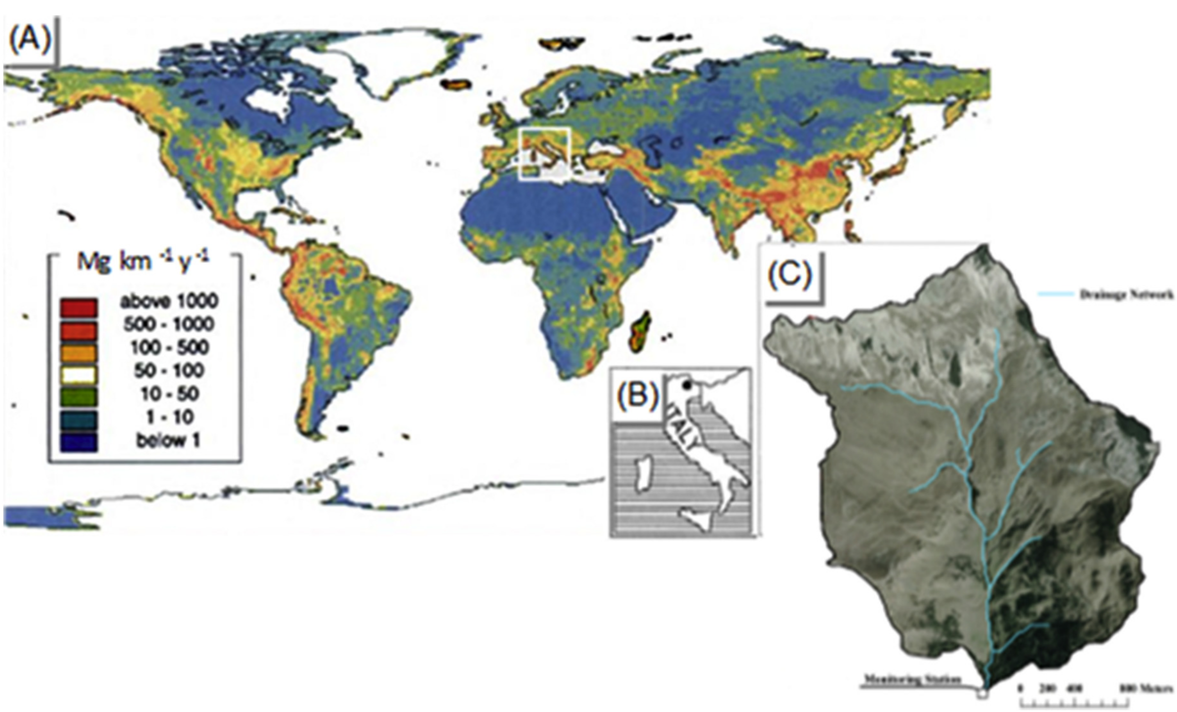

Fig. 1. (A) World transport suspended sediment in river flow (from Kabat et al., 2004). (B, C) Environmental setting of the study area (Rio Cordon catchment) in northeastern Italy (from Rainato et al., 2017).