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Channel response to extreme floods: Insights on controlling factors from six mountain rivers in northern Apennines, Italy

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ABSTRACT

This work addresses the geomorphic response of mountain rivers to extreme floods, exploring the relationships between morphological changes and controlling factors. The research was conducted on six tributaries of the Magra River (northern Apennines, Italy) whose catchments were affected by an extreme flood (estimated recurrence interval > 100 years in most of the basins) on 25 October 2011. An integrated approach was deployed to study this flood, including (i) analysis of channel width changes by comparing aerial photographs taken before and after the flood, (ii) estimate of peak discharges in ungauged streams, (iii) detailed mapping of landslides and analysis of their connectivity with the channel network.

Channel widening occurred in 35 reaches out of 39. In reaches with channel slope < 4% (here defined as *nonsteep* reaches), average and maximum ratios of post-flood and pre-flood channel width were 5.2 and 19.7 (i.e., channel widened from 4 to 82 m), respectively. In steep reaches (slope ≥ 4%), widening was slightly less intense (i.e., average width ratio = 3.4, maximum width ratio = 9.6). The relationships between the degree of channel widening and seven controlling factors were explored at subreach scale by using multiple regression models. In the steep subreaches characterized by higher confinement, the degree of channel widening (i.e., width ratio) showed relatively strong relationships with cross-sectional stream power, unit stream power (calculated based on pre-flood channel width), and lateral confinement, with coefficients of multiple determination (R^2) ranging between 0.43 and 0.67. The models for the nonsteep subreaches provided a lower explanation of widening variability, with R^2 ranging from 0.30 to 0.38; in these reaches a significant although weak relation was found between the degree of channel widening and the hillslope area supplying sediment to the channels.

Results indicate that hydraulic variables alone are not sufficient to satisfactorily explain the channel response to extreme floods, and inclusion of other factors such as lateral confinement is needed to increase explanatory capability of regression models. Concerning hydraulic variables, this study showed that the degree of channel widening is more strongly related to unit stream power calculated based on pre-flood channel width than to cross-sectional stream power and to unit stream power calculated with post-flood channel width. This could suggest that most width changes occurred after the flood peak. Finally, in terms of hazard, it is crucial to document the type and magnitude of channel changes, to identify controlling factors, and most importantly, to develop tools enabling us to predict where major geomorphic changes occur during an extreme flood.

1. Introduction

Geomorphic effectiveness of large floods has been long studied and debated (e.g., Wolman and Miller, 1960; Gupta and Fox, 1974; Wolman and Gerson, 1978; Magilligan, 1992; Costa and O'Connor, 1995; Phillips, 2002; Kale and Hire, 2004; Thompson and Croke, 2013; Magilligan et al., 2015). A major issue has been the role of large floods in comparison to more frequent floods with lower magnitude. Several studies have contributed to developing the concept of effective and formative discharge proposed originally by Wolman and Miller (1960), pointing out that (i) it may be more appropriate to consider a range of discharges rather than a single formative discharge (Pickup and Rieger, 1979; Surian et al., 2009) and (ii) large floods may play a major role in certain fluvial systems such as steep channels (Johnson and Warburton, 2002; Lenzi et al., 2006), in ephemeral streams in arid and semiarid areas (Harvey, 1984; Reid et al., 1998; Hooke and Mant, 2000), and in bedrock channels (Jansen, 2006).

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Another major research question concerns the factors controlling channel response to a large flood event. Most works have focused mainly on hydraulic variables (e.g., unit stream power, flow duration above a critical threshold; see Magilligan, 1992; Cenderelli and Wohl, 2003; Kale, 2007; Krapesch et al., 2011; Magilligan et al., 2015) but, as suggested by Costa and O'Connor (1995), understanding and prediction of channel and floodplain response to a large flood should incorporate additional factors. Some works have confirmed that hydraulic forces may not be sufficient to explain geomorphic effects (e.g., Heritage et al., 2004; Nardi and Rinaldi, 2015), and consequently, attempts have been made to include other factors. For instance, human interventions and structures have been considered by Langhammer (2010); bedload supply and pre-flood channel planform by Dean and Schmidt (2013); lateral confinement by Thompson and Croke (2013); a bend stress parameter by Buraas et al. (2014).

This work deals with an extreme flood that occurred in the Magra River catchment (northern Apennines, Italy) on 25 October 2011. Channel widening, the dominant geomorphic effect of this event along the channel network, was analyzed in six subcatchments by comparing aerial photographs taken before and after the flood. The working hypothesis was that explanation of geomorphic effects requires models that include other variables (e.g., lateral confinement, sediment supply) besides hydraulic-related variables (cross-sectional or unit stream power). The main aim was thus to explore the relationship between channel widening and a range of controlling factors. Other specific questions addressed were (i) which channel width (i.e., pre- or post-flood width) should be considered to calculate unit stream power in order to have a better explanation of channel response?; and (ii) is sediment supply from hillslopes (i.e., landslides) a key factor driving channel changes in mountain environments?

We were able to address such questions in relatively small catchments (drainage areas between 8.5 and 38.8 km^2) because an integrated approach was deployed to study this flood event (Rinaldi et al., 2016). Besides the analysis of morphological changes, the approach includes field measurements coupled to a rainfall-runoff model to estimate peak discharges in the ungauged streams, detailed mapping of landslides and analysis of sediment connectivity, as well as information concerning other fundamental aspects of the event (e.g., sedimentological characterization of flood deposits, dynamics of large wood transport; Lucía et al., 2015).

2. Study area

2.1. General setting

The Magra River catchment is located in the northern Apennines (northwestern Italy) and covers an area of 1717 km^2, ranging from a maximum elevation of 1901 m asl to sea level (Ligurian Sea) (Fig. 1). The catchment is characterized by ridges with a NW-SE direction, associated to thrust faults, which define two main subcatchments: the Magra (1146 km^2) and the Vara (571 km^2) subcatchments. The catchment is mainly composed of sedimentary rocks (predominantly sandstones and mudstones), with some outcrops of magmatic (ophiolites) and metamorphic rocks. The climate is temperate, with dry summers and most precipitation occurring in autumn. The mean annual precipitation is 1707 mm, reaching maximum values of about 3000 mm in the upper part of the catchment. The Magra catchment is predominantly forested (about 66% of the whole catchment), while urban areas are relatively small and mostly located at low elevations.

2.2. The extreme event on 25 October 2011: rainfall distribution and intensity

Rainfall maps for the study event were obtained based on data collected by the Monte Settepani meteorological radar placed at 1386 m asl on the Apennines, at the border between the Piemonte and Liguria regions. The radar data were processed for a number of error sources (Marra et al., 2014) and were merged with rain-gauge

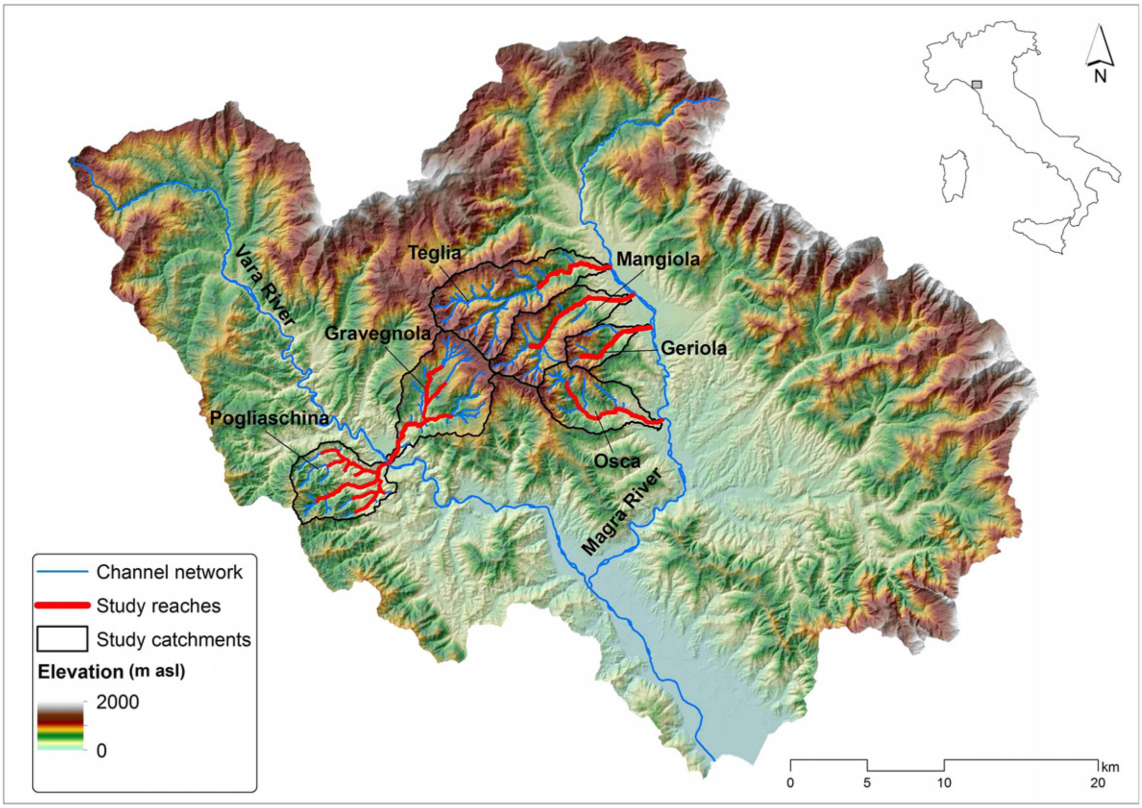

Fig. 1. Location map of the Magra River catchment, the six study catchments, and the study reaches.