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Basin-scale analysis of the geomorphic effectiveness of flash floods: A study in the northern Apennines (Italy)

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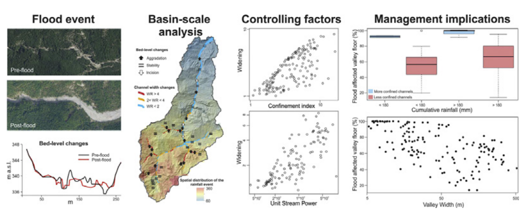
HIGHLIGHTS

- Basin-scale analysis of geomorphic effectiveness of a large flood
- Integrated geomorphological and hydrological-hydraulic approach
- Valley floor of confined channels almost completely reworked by the flood
- Magnitude of channel widening linked to bed elevation changes
- Varied response of floodplains and islands depending on local flood intensity

GRAPHICAL ABSTRACT



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ABSTRACT

Large floods may produce remarkable channel changes, which determine damages and casualties in inhabited areas. However, our knowledge of such processes remains poor, as is our capability to predict them. This study analyses the geomorphic response of the Nure River (northern Italy) and nine tributaries to a high-magnitude flood that occurred in September 2015. The adopted multi-disciplinary approach encompassed: (i) hydrological and hydraulic analysis; (ii) analysis of sediment delivery to the stream network by means of landslides mapping; (iii) assessment of morphological modifications of the channels, including both channel width and bed elevation changes.

The spatial distribution of rainfall showed that the largest rainfall amounts occur in the upper portions of the catchment, with cumulative rainfall reaching 300 mm in 12 h, and recurrence intervals exceeding 100–150 years. The unit peak discharge ranged between 5.2 and 25 $m^3\ s^{-1}\ km^{-2}$. Channel widening was the most evident effect. In the tributaries, the ratio between post-flood and pre-flood channel width averaged 3.3, with a maximum approaching 20. Widening was associated with channel aggradation up to 1.5 m and removal of riparian vegetation. New islands formed due to the fragmentation of the former floodplain. In the Nure River, the average width ratio was 1.7, and here widening occurred mainly at the expenses of islands. Bed level dynamics in the Nure were varied, including aggradation, incision, and overall stability. The flood geomorphic effectiveness was more pronounced in the middle-higher portions of the basin. Planimetric and elevation changes were

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well correlated. Regression analysis of the relationship between widening and morphological/ hydraulic controlling factors indicated that unit stream power and confinement index were the most relevant variables.
The study provides useful insights for river management, especially with regard to the proportion of the valley floor subject to erosion and/or deposition during large events.

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1. Introduction

Floods are among the most relevant natural events causing geomorphological channel changes and fluvial landscape development (Hooke, 2015; Stoffel et al., 2016). Extreme floods induce physical impacts on the channels and the valley bottoms, such as widening (Krapesch et al., 2011), changes in bed level, channel position and patterns, extensive bar formation, erosion and construction of islands (Belletti et al., 2014), meander migration, avulsions, bank erosion (Grove et al., 2013), and floodplain accretion (Hauer and Habersack, 2009). The geomorphic effectiveness of floods has been widely studied worldwide (Wolman and Gerson, 1978; Hooke, 2015; Surian et al., 2016) but, while effects on channel width are documented for several floods, fewer studies describe the vertical changes on channels and floodplains. Generally, deposition occurs on bars and floodplains (Hooke and Mant, 2000; Magilligan et al., 1998; Hooke, 2016). Aggradation is very common immediately downstream of tributary junctions (Sloan et al., 2001; Dean and Schmidt, 2013), where the channel bed presents lower slope (Dean and Schmidt, 2013), or in areas where the valley widens (Cenderelli and Wohl, 2003; Hauer and Habersack, 2009) and channels are unconfined (Thompson and Croke, 2013). Channels experience bed incision (Sloan et al., 2001), especially with floods with low sediment load (Dean and Schmidt, 2013) or downstream of sediment retention sites, such as dams (Hooke and Mant, 2000). Erosion has been found to be most common in narrow, steep reaches where the channel is confined (Cenderelli and Wohl, 2003; Thompson and Croke, 2013).

Floods also control island patterns (Belletti et al., 2014). During floods, channels widen by removing woody vegetation from the islands. Floods, however, may also increase island number, as floodplains can be fragmented by the formation of new channels (Gurnell et al., 2001; Comiti et al., 2011; Belletti et al., 2014). Belletti et al. (2014) assert that flood return period is the main representative parameter for island development and spatial density. High magnitude floods increase island fragmentation, while low magnitude floods promote vegetation establishment and island coalescence. However, in the Tagliamento River, Surian et al. (2015) showed that significant vegetation erosion is determined also by relatively frequent floods, i.e. floods with a recurrence interval of about 1–2.5 years. On the other hand, extensive island erosion, in large braided rivers, seems to happen only for floods >10–20 years (Comiti et al., 2011; Surian et al., 2015).

Numerous studies have tried to determine the main factors controlling channel response to extreme flood events. Most of these studies focused on the influence of hydraulic variables, e.g. flow duration, magnitude, frequency, flow competence, flood power, duration of effective flows, sequence of events, unit stream power (Costa and O'Connor, 1995; Magilligan, 1992; Magilligan et al., 1998; Cenderelli and Wohl, 2003; Kale, 2007; Magilligan et al., 2015). However, some recent studies confirmed that hydraulic variables alone cannot fully explain the river response to floods (Heritage et al., 2004; Surian et al., 2016). In the light of these studies, they stress the important role of sediment supply, boundary conditions, flood flow patterns, valley orientation, antecedent channel conditions (Harvey, 2001; Cenderelli and Wohl, 2003; Hauer and Habersack, 2009; Dean and Schmidt, 2013; Buraas et al., 2014; Lallias-Tacon et al., 2017) and of artificial structures, e.g. embankments, weirs, rip-raps (Arnaud-Fassetta et al., 2005). In particular, valley confinement was found to be a key factor (Hauer and Habersack, 2009; Thompson and Croke, 2013; Surian et al., 2016; Righini et al., 2017). As shown by Thompson and Croke (2013), floods can cause only limited lateral erosion and widening in confined channels. Also, high stream power and narrow valley widths inhibit deposition processes (Hooke, 2016) and tend to favor channel incision. In unconfined channels, floods mainly cause channel widening and in-channel or floodplain aggradation.

Importantly, most of the previous studies were conducted on single rivers, without the possibility to analyze the spatial variability of the event magnitude in relation to the distribution of the rainfall event. On the other hand, Sloan et al. (2001) demonstrated that the effects on tributaries were markedly stronger compared to those observed in the main channel.

The present study analyses the geomorphic response of the Nure River basin, located in northern Italy, to a high-magnitude flood that occurred in September 2015. Approximately 38 km of the channel length of the Nure River and of 9 of its tributaries were analyzed. The specific aims of this study are: i) to quantify the channel morphological changes (width and bed elevation); ii) to quantify the response of vegetated surfaces (floodplains and islands); iii) to provide a basin-scale understanding of such morphological changes; iv) to assess the relative role of the different hydrological and morphological factors controlling the flood geomorphic effectiveness. Finally, some implications of our results for river corridor management, specifically in terms of the definition of flood hazard, are discussed.

2. Study area

The Nure River is located in the northern Apennines (northwestern Italy), and its catchment drains an area of 430 km^2, elongated in the SW-NE direction (Fig. 1a). The Nure originates at about 1500 m a.s.l. and flows to the Po River after a total length of 75 km. The maximum elevation of the catchment is 1773 m a.s.l., the average is 800 m a.s.l. The basin is mainly composed of sedimentary rocks, especially sandstones and mudstones with some outcrops of volcanic rocks. Its physiography is mostly composed of mountains and hilly landscape (78% of the total area) (sensu Rinaldi et al., 2013). The Nure catchment is mostly forested in the mountainous and hilly sectors, while agricultural areas cover most of the lower part of the basin.

The mean annual precipitation is approximately 1150 mm; climate is temperate with cold winter and dry summer and most of the precipitation occurs during autumn and spring. Most of the Nure River is characterized by unconfined channel reaches, except for the upper part of the basin (above 850 m a.s.l.) where a narrow valley is present. From upstream to downstream, channel morphology shifts from sinuous to a sinuous with alternate bars (and/or wandering) to braided morphology, before returning to single-thread morphologies (sinuous and meandering) in the lower plain.

Several tributaries flow into the Nure River within its montane basin. These are mainly single-thread channels, except in their wider, most downstream reaches where sinuous with alternate bars or wandering patterns can establish.

The river network in Nure catchment features a very limited extent of artificial structures, except for the reaches crossing urban areas (e.g. Ferriere, Farini and Bettola) where the Nure is channelized and stabilized by grade-control structures. Before 2015, major flood events occurred in 1889 and 1910 (http://www.adbpo.it/on-multi/ADBPO/

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