Geomorphology 463 (2024) 109355

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.journals.elsevier.com/geomorphology

Channel changes during and after extreme floods in two catchments of the Northern Apennines (Italy)

Vittoria Scorpio [a,*], Francesco Comiti [b]

[a] Department of Chemical and Geological Sciences, University of Modena and Reggio Emilia, Modena, Italy
[b] Department of Land, Environment, Agriculture and Forestry, University of Padova, Italy

ARTICLE INFO

Keywords:
Channel widening
Riverbank erosion
Channel pattern changes
Valley confinement
Channel recovery
Flood hazard

ABSTRACT

The Nure and Trebbia catchments were affected by an extreme flood event on 13-14th September 2015. This study investigates the morphological responses to the flood of the Nure and Trebbia rivers and 18 tributaries with the aims to: i) quantify channel changes in width and pattern; (ii) identify the morphological and hydrological factors which might have driven channel response; (iii) quantify channel changes which have occurred after the flood event.

Channel changes were characterized by field surveys and geomorphological analysis of multi-temporal orthophotos acquired before (2011), immediately after the flood (2015) and in 2020.

In the tributaries, reach-scale channel widths after the flood reached up to 15 times their pre-flood values, whereas in the main channels the post/pre-flood width ratio attained a maximum value of 4. Augmented channel width in the main rivers was mostly associated with banks and islands erosion, whereas in the tributaries it was also due to deposition of coarse sediments onto the former floodplains. Islands were swept away in the main channels while both island erosion and formation occurred in the tributaries. In terms of channel pattern, pre-flood single-thread reaches displayed mainly multi-thread morphologies after the flood, mostly in response to a sudden input of coarse sediment supply. In the 5 yr following the flood, channels slightly narrowed but still remained wider than in 2011. The narrower reaches before the flood resulted to be the most sensitive to changes even some years after the flood.

Statistical analyses between the channel width changes and a series of variables showed significant positive correlations with confinement index, channel slope, and the local storm rainfall depth. This study confirms how channel widening during large floods – usually neglected in flood hazard mapping and river basin management – is a very important process which must be considered in flood hazard assessment in mountain rivers.

1. Introduction

Infrequent and high-magnitude floods are among the most effective processes in causing dramatic changes on channel morphology in mountain rivers (Stoffel et al., 2016). Significant geomorphic changes have been described as a consequence of high-intensity flood events, including: riverbank erosion (Grove et al., 2013) and associated channel widening (Krapesch et al., 2011; Buraas et al., 2014; Surian et al., 2016; Ruiz-Villanueva et al., 2023), vertical channel changes (Cenderelli and Wohl, 2003; Thompson and Croke, 2013; Hooke, 2016; Scorpio et al., 2018, 2022; Liébault et al., 2024), avulsions and meander migration, floodplains and islands accretion or stripping (Hauer and Habersack, 2009; Comiti et al., 2011; Belletti et al., 2014), sediments erosion or deposition (Magilligan et al., 2015; Nardi and Rinaldi, 2015; Brenna et al., 2020), channel patterns modification (Fratkin et al., 2020). In the last decades, due to the increasing development of remote sensing techniques, large efforts were invested to characterize and understand channel widening during flood events (Krapesch et al., 2011; Rinaldi et al., 2016a; Ruiz-Villanueva et al., 2018). From a geomorphological point of view, channel widening is a natural phenomenon that provides sediments and large wood to the river network (Piégay et al., 2005; Florsheim et al., 2008; Buffin-Bélanger et al., 2015; Piton et al., 2024). However, channel widening can determine losses of agricultural land and damages to infrastructures and buildings (Ruiz-Villanueva et al., 2023). Indeed, in mountain basins flood hazard is not only related to water inundation – as is the case for low-energy, lowland rivers – but

* Corresponding author at: Department of Chemical and Geological Sciences, University of Modena and Reggio Emilia, via Campi 103, 41125 Modena, Italy.
E-mail address: vittoria.scorpio@unimore.it (V. Scorpio).

https://doi.org/10.1016/j.geomorph.2024.109355
Received 29 February 2024; Received in revised form 18 July 2024; Accepted 19 July 2024
Available online 20 July 2024

mostly to sediment transport processes, with channel widening and bed aggradation being the most evident outcomes (Buraas et al., 2014; Mazzorana et al., 2014; Guan et al., 2016; Hooke, 2016;). Despite the importance of flood-scale channel widening, to our knowledge it is very rarely included in flood hazard mapping and river management plans (Comiti et al., 2016; Buffin-Bélanger et al., 2015), possibly also because its prediction is still highly challenging. Therefore, a better quantitative understanding of the factors determining the magnitude of channel changes during large flood events has important implications for the management of river corridors (Piégay et al., 2005; Krapesch et al., 2011; Nardi and Rinaldi, 2015; Mazzorana et al., 2018).

Several studies have been recently published regarding channel widening due to large floods, and most of them indicated how hydraulic variable alone cannot fully explain the river response to floods (Heritage et al., 2004; Nardi and Rinaldi, 2015; Surian et al., 2016; Scorpio et al., 2018; Brenna et al., 2023). In addition to unit flood stream power – the hydraulic variable most widely recognized as crucial in this process - the valley boundary conditions (e.g., confinement index) were found to be very important too (Krapesch et al., 2011; Surian et al., 2016; Thompson and Croke, 2013; Righini et al., 2017; Lucía et al., 2018; Scorpio et al., 2018; Ruiz-Villanueva et al., 2023). Also, most studies highlighted the contribution of other factors such as pre-flood channel pattern valley orientation and gradient, geology, past evolutionary trajectory, temporal sequence of past floods, duration of the flood peak, reach position within the channel network, sediment supply from hillslopes, human interventions and channelization structures (e.g. Magilligan, 1992; Wohl, 1992; Costa and O'Connor, 1995; Cenderelli and Wohl, 2003; Arnaud-Fassetta et al., 2005; Langhammer, 2010; Dean and Schmidt, 2013; Nardi and Rinaldi, 2015; Buraas et al., 2014; Magilligan et al., 2015; Righini et al., 2017; Scorpio et al., 2022).

The capacity of a channel impacted by a severe flood event to adjust back towards its previous geometrical and morphological configuration is a key factor to be assessed for management implications. Resilience is usually defined as the ability of a system to absorb shocks, to avoid crossing a threshold into an alternate and possibly irreversible new state, and to regenerate after disturbances (Sear, 1996; Knighton, 1998; Dufour and Piégay, 2009; Resilience Alliance, 2009; Miller et al., 2010; Fryirs and Brierley, 2013; Fryirs, 2017; Thoms et al., 2018). Recently, Fuller et al. (2019) and Piégay et al. (2020) called for the need to properly use the concept of resilience in the context of fluvial geomorphology, as it can indicate different dynamic characteristics of river systems. The most relevant for our work is the “resilience to pulse disturbances” (as in Fuller et al., 2019, and Piégay et al., 2020), as is the case of a large flood. Following such events, a channel undergoes a recovery trajectory shifting from the post-flood event state to the pre-flood state; such trajectory can assume a series of intermediate states before attaining pre-flood conditions (Hooke, 2016; Phillips and Van Dyke, 2016; Harrison et al., 2017; Räpple et al., 2017). In parallel to large floods, the case of river restoration allowed researchers to gain insights into the progressive morphological changes and vegetation encroachment after a “man-made pulse disturbance” (Dufour and Piégay, 2009), as for example following the channel widening imposed by restoration interventions in the Ahr (Campana et al., 2014) and in the Mareit rivers (Scorpio et al., 2020).

This study analyses the geomorphic effectiveness of a high-magnitude flood – occurred on 13-14th September 2015 – and the subsequent recovery dynamics in the Nure and the Trebbia rivers and their tributaries (northern Apennines, Italy). The specific aims of this paper are: i) to quantify channel changes in width and pattern; (ii) to identify the morphological and hydrological factors which might have driven channel response at the reach scale; (iii) to investigate the dynamics of post-flood channel recovery occurred during the 5 years following the event.

2. Study area

2.1. Geomorphological and geological settings

The Nure and Trebbia rivers are located in the northern Apennines (Fig. 1a) and with a total length of about 75 km and 120 km, respectively, they represent two of the main tributaries of the Po River from the Apennines. Their catchments cover an area of about 430 km^2 (Nure) and 1070 km^2 (Trebbia) and present an elongated shape in the SW-NE direction. The Nure originates at about 1500 m a.s.l., while Trebbia originates at about 1300 m a.s.l., and they join the Po River at about 42 and 47 m a.s.l., respectively. The physiography of the catchment consists of largely mountainous and hilly areas (78 % and 85 % of the total in Nure and Trebbia, respectively).

The two basins have similar geological characteristics, being the bedrock mainly composed of sedimentary rocks, especially sandstones, marls and claystones and some outcroppings of ophiolitic rocks (Fig. 1b). Both basins are mostly forested in the mountainous and hilly sectors (52 % of the Nure's basin area and 44 % of the Trebbia's basin area, Fig. 1c), while agricultural areas cover most of the medium and lower part of the basin (piedmont area) and valley bottoms (28 % and 26 % of basin area).

Climate is temperate with cold winter and dry summer and most of the precipitation occurs during autumn and spring. The mean annual precipitation is approximately 1150 mm in the Nure and 1440 mm in the Trebbia, while mean annual discharge is about 15 m^3/s and 40 m^3/s, respectively.

In the Nure River, the channel is mainly partly confined and locally confined; from upstream to downstream, channel morphologies shift from a single-thread sinuous or a sinuous with alternate bars, to braided or wandering morphologies, before returning to a single-threaded morphology (sinuous and meandering) in the lower plain (Scorpio and Piégay, 2021). In the Trebbia valley floor, the channel morphology is strongly controlled by the physiographic conditions of the valley, with frequent confined meanders in the upper mountain segment, followed by partly confined reaches crossing the hilly areas, and then unconfined reaches with wandering or braided channels along a wide alluvial fan running into in the Po River plain (Bollati et al., 2014). Several streams flow into the Nure and Trebbia rivers (Table 1; Fig. 1a). This study focuses on a segment 35 km long of the Nure River upstream from the town of Ponte dell'Olio (drainage area 337 km^2, Fig. 1a) and on a 52 km long segment of the Trebbia River, approx. at Perino town (drainage area of 860 km^2, Fig. 1a). The analysis involved the montane and hilly portion of the two catchments, and included 10 tributaries of the Nure and 9 tributaries of the Trebbia (Table 1).

2.2. The 13th – 14th September storm event

The Nure and Trebbia basins were affected by an extreme flood on 13-14th September 2015, caused by a rainstorm which lasted approximately 24 h, although the main burst of the storm started at around 5 pm of 13th September and lasted approximately 12 h (Scorpio et al., 2018). Rainfall increased from the South-East towards Nord-West, maximum precipitation and intensities were recorded in the upper part of both basins. Cumulative rainfall depth ranged from 60 to 360 mm in 12 h in the Nure and from 43 to 420 mm in the Trebbia (Scorpio et al., 2018). The maximum intensities reached 108 mm/h and 230 mm in 3 h at the Alpe di Gorreto station and 113 mm/h and 173 mm in 3 h at the Barbageta station (Fig. 1a) in the upper Trebbia basin, whereas in the Nure basin attained values in the order of 80 mm/h and 100 mm in 3 h (Romagna, 2016).

The return periods of rainfalls were estimated in the order of 200 years for rainfall duration of 1 and 3 h (Scorpio et al., 2018), and flood stages recorded at 4 gauging stations (2 for each river, Fig. 2a) were the highest of historical series (Romagna, 2016).

In the upper portions of both basins, slope instability processes

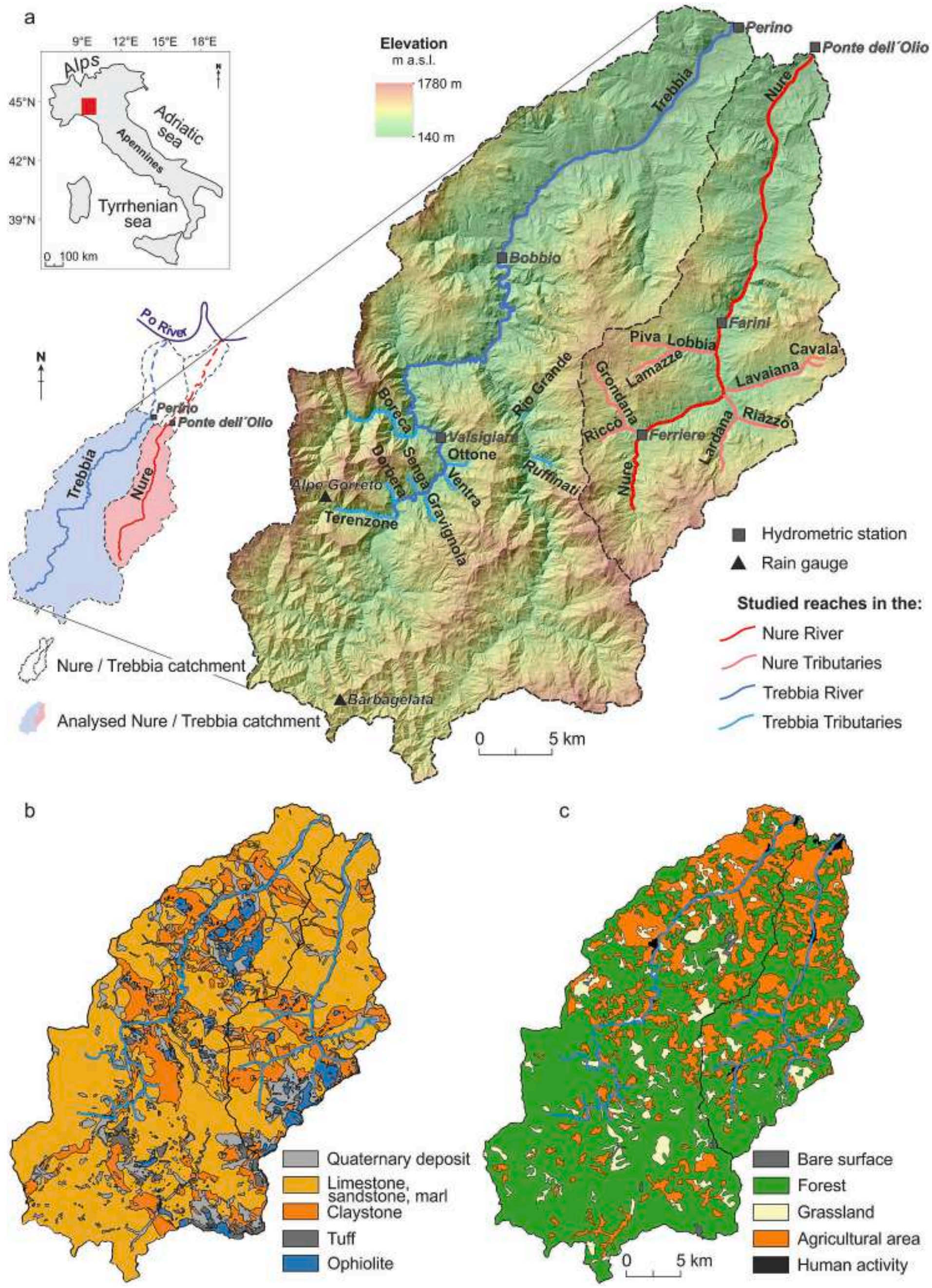

Fig. 1. Location map of the Trebbia and Nure catchments and location of studied rivers (a); geological map (b); and land-use map in 2017 (c), of the Trebbia and Nure basins. Source: https://geoportale.regione.emilia-romagna.it/download.

(debris flows/debris floods, debris slides and slope toe erosion) were triggered during the storm, most of them were coupled to the channel network, contributing in terms of sediment supply in the study reaches (Scorpio et al., 2018; Ciccarese et al., 2020).

2.3. Available knowledge on past channel changes in the Trebbia and Nure rivers

Bollati et al. (2014) analyzed channel evolution between 1954 and 2010 in a segment of the lower Trebbia River, located immediately downstream those considered in this study. They identified a phase of major adjustments - between 1954 and 1992 - dominated by channel narrowing (average channel width was 437 m in 1954 and only 159 m in 1992) and bed incision (between 2 and 4 m, occurred in the period 1950s–1980s), mainly due to intensive in-channel sediment mining. Since 1992, the narrowing trend stopped and a moderate widening took place, initially despite some further bed incision, whereas after 2000s, local aggradation was observed, and average channel width attained about 200 m in 2010. The partial recovery in the Trebbia River was deemed to be a consequence of the reduction in sediment removal.

Scorpio and Piégay (2021) analyzed changes in channel width that occurred between 1877 and 2015 along the mountainous and the upper piedmontal segments of Nure River, as well as in 2 reaches of the Lardana and Lavaiana creeks, major tributaries of the Nure. In the Nure, the average channel width was 361 m in 1877, then it decreases to 205 m in 1954 and 159 m in 1976; minimum channel width of 100 m was attained between 1980s and 1990s. After then, the channel showed some moderate widening, as in 2011 the average channel width was 120 m. Also,

Table 1
Main physiographic characteristics of the studied rivers.

River	Main catchment	Drainage area (km^2)	Max / min basin elevation (m)	Channel length (km)	Average channel slope (%)	Number of studied reaches
Nure	Nr	307	1773–250	37.8	1.76	48
Cavala	Nr	5	1333–629	1.5	11.30	8
Grondana	Nr	23	1540–650	5.5	7.53	18
Lamazze	Nr	6	1402–653	2.0	9.78	11
Lardana	Nr	30	1710–487	7.3	7.97	16
Lavaiana	Nr	32	1333–520	6.3	4.05	15
Lobbia	Nr	22	1430–452	3.0	7.01	17
Piva	Nr	8	1430–653	2.4	10.85	12
Riazzo	Nr	11	1160–535	2.3	7.03	9
Riccó	Nr	6	1540–653	3.3	10.42	21
Trebbia	Tr	859	1780–136	52	0.73	33
Boreca	Tr	51	1722–344	7.8	2.43	18
Dorbera	Tr	8	1650–533	1.4	7.09	9
Gravignola	Tr	9	1520–500	0.8	6.86	7
Ottone	Tr	7	1221–485	1.5	10.85	10
Rio Grande	Tr	13	1356–380	0.3	4.83	5
Ruffinati	Tr	9	1578–410	1.9	9.37	10
Senga	Tr	4	1646–510	0.4	14.98	6
Terenzone	Tr	19	1581–535	4.3	3.15	12
Ventra	Tr	6	1429–484	0.9	6.92	9

Codes for main catchments: Nr = Nure; Tr = Trebbia.

the Lardana and Lavaiana creeks underwent channel narrowing from 130 m and 62 m in 1954, to 57 m and 33 m in 2011 and minimum values of 53 m and 22 m in the 1980s–1990s, respectively.

Analysis of past flood events reveals that two large flood events occurred in 1953 and in 2000 along the Trebbia River, with estimated peak discharge of 3430 and 2475 m^3/s, respectively (Bollati et al., 2014). Information on magnitude and sequence of floods in the Nure catchment was not available.

3. Materials and methods

Morphological changes and processes induced by the September 2015 flood event were assessed through field surveys and remote sensing analysis of multi-temporal orthophotos (2011–2015). Morphological and hydrological factors that induced morphological changes during the flood were studied through statistical analysis. Analysis of channel changes that occurred after the flood were assessed by comparing orthophotos taken in 2015 and 2020.

3.1. Field surveys: Grain size analyses and processes characterization

A field survey was carried out along the study rivers between November 2015 and February 2016, allowing the collection of information on grain sizes and qualitative observations of processes inducing channel changes and sediment supply.

For 20 reaches (see section 3.2) along the tributaries, the maximum grain size (*Dmax*) of the sediments mobilized during the flood were measured. The intermediate axis (b-axis) of 15 to 20 of the largest mobilized clasts at each reach was assessed using a ruler. For the same reaches channel-bed morphology was assigned according to the classification of mountain channels proposed by Montgomery and Buffington (1997).

3.2. Remote sensing: Morphological characteristics and analysis of morphological changes

Planform changes were the main focus of the study. Three sets of aerial photos, before (2011), immediately after (2015), and five year after the flood (2020) were used for a GIS analysis of the morphological changes in the river corridor (ESRI ArcGis 10.4 and QGIS Desktop 3.22.16). Pre-flood orthophotos (ground resolution of 0.5 m) were taken in 2011 (https://servizigis.regione.emilia-romagna.it/wms/agea2011_rgb), they were considered representative of the channel at the time of the event because floods geomorphically effective did not occur between 2011 and September 2015. Post-flood orthophotos (ground resolution of 0.2 m) were taken on 25th October 2015 a few weeks after the flood. Most recent available orthophotos (ground resolution of 0.2 m) were taken in 2020 (https://servizigis.regione.emilia-romagna.it/wms/agea2020_rgb) and used to quantify channel forms 5 years after the flood occurrence.

Channel, island, and alluvial plain margins were manually digitized as polygons from 2011, 2015 and 2020 orthophotos. The term ‘channel’ refers to the active channel, which includes low-flow channels and unvegetated or sparsely vegetated bars. Islands are in-channel surfaces covered by woody vegetation, and the floodplain consists of recent and lowest terrace, adjacent to the active channel, frequently flooded (1–3 years), and mainly covered by riparian woody vegetation (Belletti et al., 2013).

Studied channels (total of 139 km; 68 km in the Nure basin and 71 km in the Trebbia basin) were partitioned into 293 reaches (Table 1) applying the GIS-based approach proposed by Ferencevic and Ashmore (2012). The subdivision into reaches took into account the changes in channel slope, the occurrence of discontinuities as confluences of tributaries, the changes in lateral confinement, in valley orientation, in channel width and in planform pattern (Brierley and Fryirs, 2005; Rinaldi et al., 2013). The analysis was carried out by means of a 5-m resolution Digital Terrain Model (DTM) derived from a 1:5000-scale. Length of obtained reaches ranged from a minimum of 69 m in the Rio Grande Stream to a maximum of 3960 m in the Trebbia River.

From the 2020 orthophotos, the average channel width (W_{2020}), the number (nI_{2020}) and extension (I_{2020}) of islands and the channel pattern were defined (see below for more details) at the reach scale. The morphological parameters estimated before (2011) and after the flood event (2015) were the channel width (W_{2011}, W_{2015}), the channel pattern, the floodplain width (F_{2011}, F_{2015}), the number (nI_{2011}, nI_{2015}) and the extension of islands (I_{2011}, I_{2015}), and the confinement index (Ci_{2011}, Ci_{2015}). Channel width was calculated for all years (2011, 2015 and 2020) as the ratio between the area of the channel reach's polygon and its length. Planform changes of the channel induced by the flood were expressed in terms of metric difference in channel width (ΔW) and by the width ratio (Wr). $Wr_{2015\text{–}2011}$ was computed as the ratio between the channel width after (2015) and the channel width before (2011) the flood (Krapesch et al., 2011), and it allowed us to estimate the geomorphic effect of the flood on channel width.

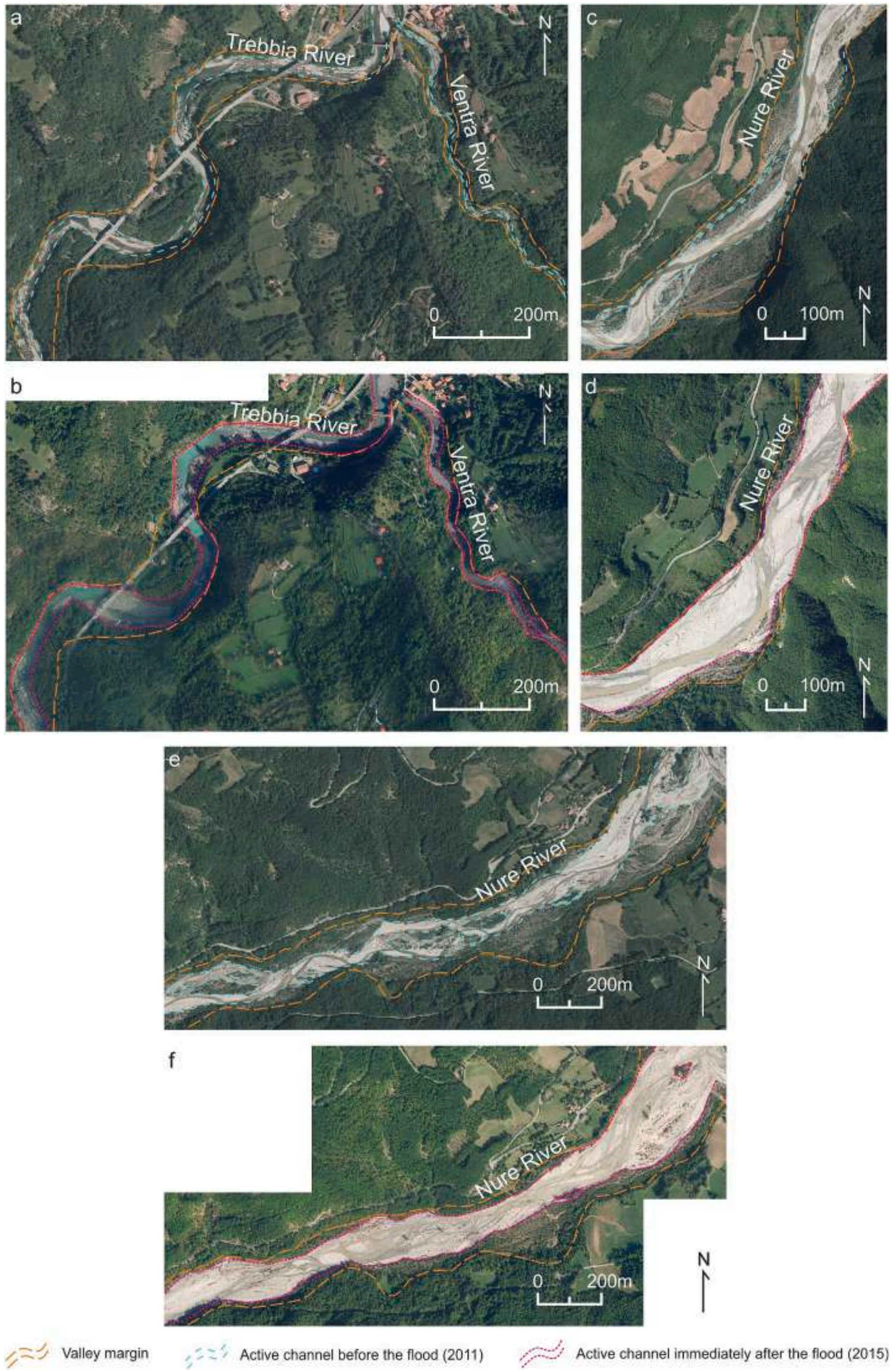

Fig. 2. Orthophotos taken in 2011 (pre-flood; a, c, e) and 2015 (immediately after the flood; b, d, f) in the Trebbia, Ventra (tributary of the Trebbia) and Nure rivers.

$Wr_{2020\text{–}2015}$ and $Wr_{2020\text{–}2011}$ were computed as the average active channel width measured in 2020 and the average active channel width measured in 2015 and 2011, respectively; it was quantified to analyze active channel changes five years after the flood and to compare the amount of changes with the channel width before the flood (2011) and during the flood (2015).

Channel patterns were classified according to the following channel types (Rinaldi et al., 2016b): braided (*B*), anabranching (*A*), wandering (*W*), sinuous with alternate bars (*SAB*), sinuous (*S*) and meandering (*M*). Changes in the islands were characterized by accounting the difference in term of number (ΔnI) and areal extension (ΔI). Floodplain width was estimated as the ratio between the polygon floodplain area associated to the reach and the reach's length. Changes in floodplain width were quantified with the *Fr* ratio that, consistently with the *Wr*, was computed as the ratio between the floodplain width after and the floodplain width before the flood. The confinement index was calculated as the ratio between the valley bottom width and the channel width. All the above-mentioned morphometric parameters are affected by errors related to orthophoto resolution and interpretation and polygons digitalization. The absolute error was estimated to be in the order of 1–2 m.

Other morphometric parameters were extracted at reach scale from the DTM using GIS tools (spatial analyst and hydrological geoprocessing in ESRI ArcGis 10.4), such as reach minimum elevation (*h*), channel slope (*S*), drainage area (*BA*), average cumulative rainfall (R) in the draining catchment. Channel slope was assessed as the difference in elevation divided by the planimetric distance relative to each reach. Map of spatial distribution of cumulative rainfall was already produced in Scorpio et al. (2018). For each reach the mean cumulative precipitation registered at the catchment was computed. The stream power index (*SPI*) proposed by Marchi and Dalla Fontana (2005) was used as a surrogate for stream power, it was calculated as the product of the channel slope (*S*) and the square root of the drainage area (*BA*).

3.3. Statistical analysis

Exploratory correlation analysis among the morphological changes induced by the flood, in particular channel width changes (*Wr*), and the potential controlling factors were quantified using the Spearman's coefficient due to their non-normal distributions. The analyzed explanatory variables were listed at section 3.2. Also, a principal component analysis (PCA) was applied to the database of variables listed at section 3.2.

Analyses were performed for all reaches together and for reaches along the two main rivers (Nure and Trebbia) only, and along all tributaries. Reaches were also grouped according to their morphological characteristics, in particular physiographic unit, lateral confinement, channel slope, channel pattern and channel-bed morphology. As to the physiographic units, they are equivalent to the 'landscape units' of Brierley and Fryirs (2005). Following the classification proposed in Rinaldi et al. (2013), three classes were recognized: M = mountain, H = hilly, and HP = high plain. As to lateral confinement, three valley settings were differentiated (Brierley and Fryirs, 2005): confined (C), partly

Fig. 3. Effects of the 15th September flood 2015 in the Trebbia River (a); channel widening through coarse sediment deposition on the former floodplain in the Grondana (b, c, tributary of the Nure), in the Lardana (d, tributary of the Nure), in the Gravignola (e, tributary of the Trebbia) and in the Rio Grande (f, tributary of the Trebbia) creeks; view of channel aggradation in the Dorera (g, belonging to the Trebbia basin); vegetation and bank erosion in the Senga (h, belonging to the Trebbia) and Lavaiana (I, belonging to the Nure) creeks; hillslope toe erosion, bed aggradation and newly formed inset channels in the Ventra (j, tributary of the Trebbia), Riccò (k, tributary of the Nure) and Gravignola (l, tributary of the Trebbia) creeks.

confined (P), and laterally unconfined (U) reaches. Lateral confinement was defined by combining two aspects: the degree of confinement, which is the percentage of channel banks directly in contact with hillslopes or ancient terraces (Brierley and Fryirs, 2005), and the confinement index as defined at section 3.2 (Rinaldi et al., 2013). Regarding channel slope, the whole data set was analyzed considering two subgroups: < 4 % and ≥ 4 %, following Surian et al. (2016).

Differences between groups of reaches were tested applying the pairwise non-parametric Mann-Whitney tests. For all analyses, statistical significance was set to p-value <0.05. Statistical analyses were conducted within the statistical software R version 4.0.0 (R Core Team, 2020).

4. Results

4.1. Channel changes induced by the 13 - 14th September 2015 flood

Channel widening occurred in most of the studied reaches as a consequence of the September 2015 flood (Figs. 2 and 3). Most reaches in the two main rivers presented pre-flood width (W_{2011}) ranging from 10 to 184 m in the Nure and from 37 to 132 m in the Trebbia; after the flood, channel width increased to ranges 18–228 m and 46–164 m, respectively (Fig. 4a and 1S supplementary material). In the Nure, $Wr_{2015–2011}$ presented median values of 1.6, but in 11 reaches it exceeded 2, with maximum values of 4.2 at reach 17; in the Trebbia, $Wr_{2015–2011}$ with median values of 1.2, never exceeded 1.8 (Fig. 4b). Tributaries presented a lower median W_{2011} (Fig. 4a; ranges: 1–77 m in the Nure catchment and 1–38 m in the Trebbia catchment), but they experienced greater widening (Fig. 4b), with median $Wr_{2015–2011}$ of 3.5 and 2.7, and maximum values up to 11.5 and 15.5, in the Nure and Trebbia tributaries, respectively (Fig. 4b). Overall, relative widening ($Wr_{2015–2011}$) was more intense in the channels which were narrower prior to the flood event (Fig. 4a). Nevertheless, when considering widening in absolute terms (ΔW, Fig. 4c), this parameter was larger in the main rivers (median = 35.8 and 13.1 m, and maximum = 71.3 and 62.5 m in the Nure and Trebbia rivers, respectively), whereas in the tributaries it did not exceed about 10 m on average (median = 10.4 and 11 m, and maximum = 64.8 and 40.5 m in the Nure and Trebbia

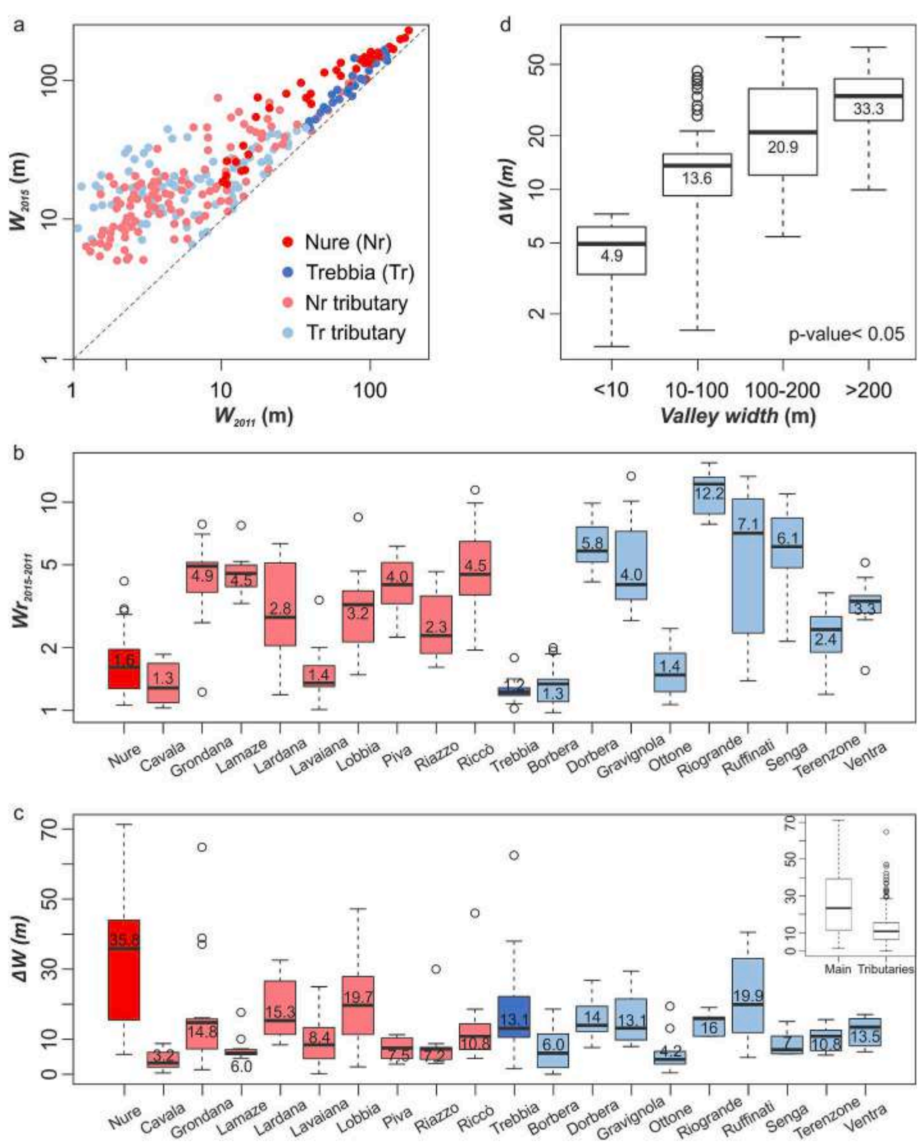

Fig. 4. Active channel width before the flood (2011) vs active channel width after (2015) the flood (a), both axes are in logarithmic scale, for same data in non-logarithmic scale see Fig. 1S, supplementary material. Box and whiskers plots: of $Wr_{2015–2011}$ in the studied reaches (b); of absolute channel width changes in meters in the main rivers and in their tributaries (c); of absolute channel width changes for four groups of average valley width. All box and whiskers plots show median and interquartile range (25th and 75th percentiles), numbers in the box refer to the median values.

catchments, respectively). Notably, absolute widening (ΔW) increased with the increase of the valley width, with values in the order of few meters in valley narrower than 10 m, to 30 m on average in valleys larger than 200 m (Fig. 4d). The highest width ratios were observed in the Rio Grande, Ruffinati and Senga rivers (tributaries of the Trebbia River), with channel after the flood >6 times the initial channel width (Fig. 4b). Impressive widening was experienced also by the Dorbera, Grondana, Riccò, Lamazze, Gravignola, and Piva rivers, undergoing significant channel widening (between 4 and 6). All these streams were very narrow before the flood - with initial channel widths <10 m - and quite steep as well, with channel gradients >5 % (Fig. 4b).

Before the flood, only 12 % of studied reaches were confined, as most were partly confined (57 %) and unconfined (30 %). Immediately after the flood - due to the channel widening - most reaches became confined (59 %), while partly confined reaches decreased to 35 % and most unconfined reaches almost disappeared (6 %). Considering the two main rivers only, in the Nure partly confined reaches prevailed both before and after the flood (71 % before and 69 % after), unconfined reaches decreased from 27 % before the flood to the 13 % after the flood, while confined reaches increased from 2 % before to 19 % after. In contrast, the Trebbia River presented a high percentage of confined reaches also before the flood (38 % before and 44 % after), while partly confined reaches decreased as the consequence of the channel widening (from 63 % before, to 56 % after). In relation to valley confinement, $Wr_{2015\text{–}2011}$ attained higher average values in the reaches that were partly confined and unconfined before the flood and then turned to confined conditions after the flood (Fig. 5a and b). This trend is confirmed also when analyzing separately reaches in the main channels (Fig. 5c) and in the tributaries (Fig. 5d). Remarkably, reaches featuring the larger widening were steeper (Fig. 5e) and located in the upper-medium part of the basins, within the mountain and hilly physiographic units (Fig. 5f).

The September 2015 flood greatly impacted islands. Islands mainly decreased in number and extension in the main channels, whereas both islands erosion (17 % of the total number of reaches) and island formation through floodplain dissection (29 % of the total number of reaches) were observed in the tributaries (Fig. 6a, b). Focusing on island dynamics in the tributaries, it turns out that widening and new islands formation are positively related (Fig. 6c); these reaches presented higher values of CI_{2011} (wider valleys before the flood) and also wider valley floor (Fig. 6d) and stepper gradient (Fig. 6e) with respect to reaches where islands became reduced by the flood. Finally, the formation of new islands – through the floodplain dissection process – seem to be associated with stronger hydrological forcing, being higher in reaches affected by higher storm rainfall amounts (Fig. 6f).

Channel widening was associated with changes in morphological pattern (Fig. 2). Before the flood, in the main river channels the most represented planform morphologies were sinuous (35 %), wandering (29 %) and sinuous with alternated bars (21 %); braided represented 10

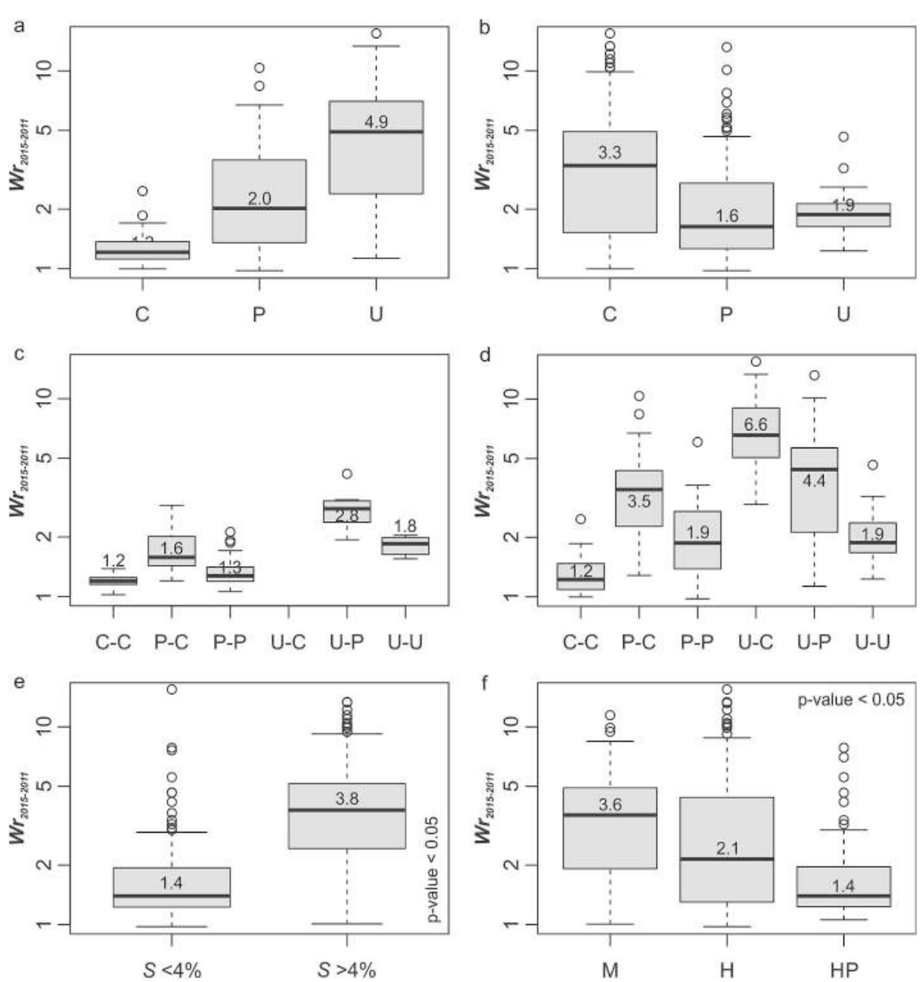

Fig. 5. Box and whiskers plots of $Wr_{2015\text{–}2011}$ in: confined, partly confined and unconfined reaches before (2011) the flood (a); and after (2015) the flood (b); in reaches shifting from a pre-flood confinement setting (first letter) to a post-flood confinement setting (second letter) in the main channels (Nure and Trebbia, c) and in the tributaries (d). Code for valley confinement: confined (C), partly confined (P) and unconfined (U). Box and whiskers plots of $Wr_{2015\text{–}2011}$ in: not-steep reaches (S < 4 %) and steep reaches (S > 4 %) (e); reaches flowing through different physiographic units (M = mountain; H = hilly; HP = high plain) (f). All box and whiskers plots show median and interquartile range (25th and 75th percentiles), numbers in the box refer to the median values.

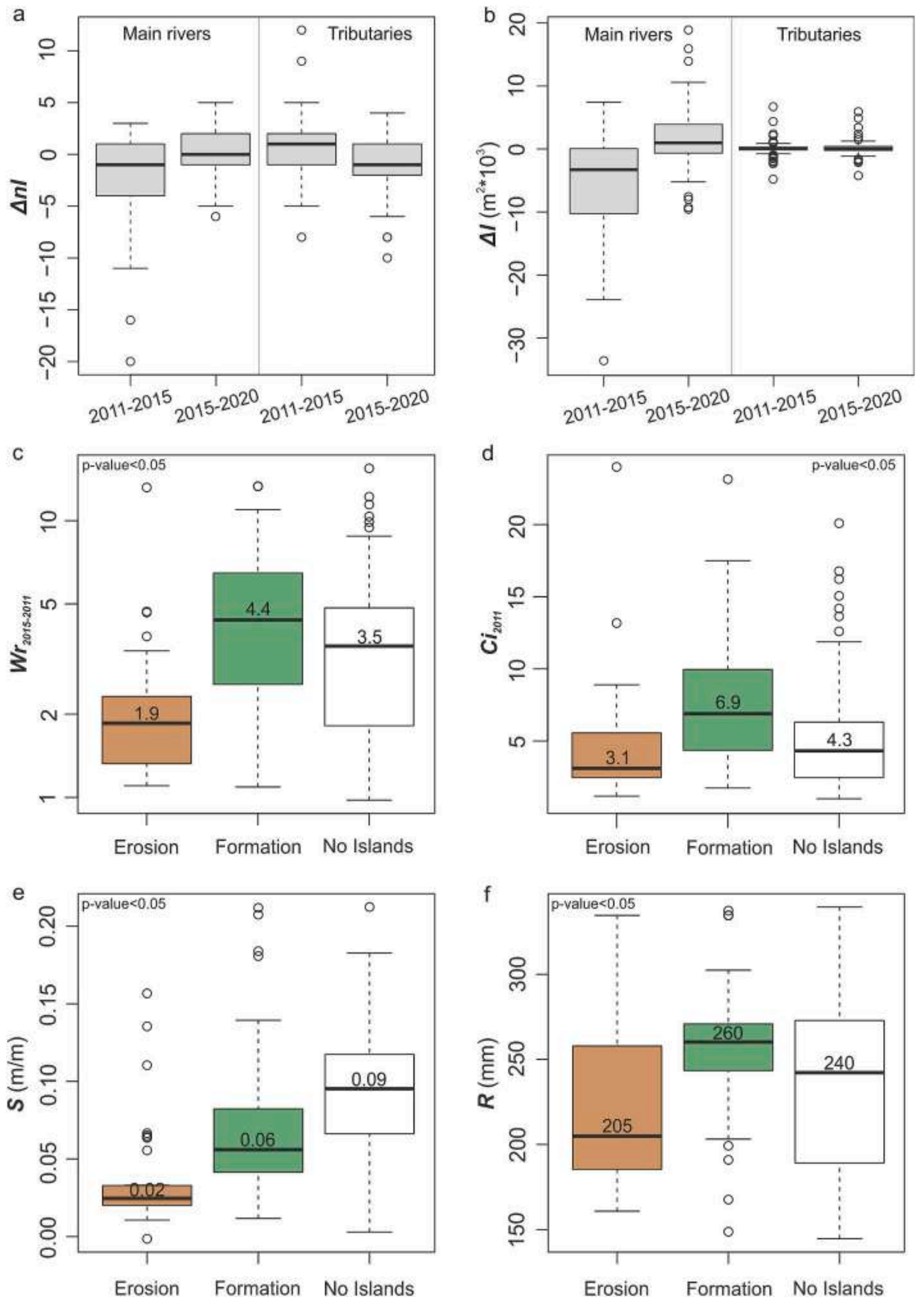

Fig. 6. Box and whiskers plots of differences in the number of islands (a, Δnl) and extension of the islands (b, Δl) in the main rivers (Nure and Trebbia) and in the tributaries between 2011 and 2015 and between 2015 and 2020. Box and whiskers plots of reaches with erosion, formation of island during the flood or no presence of island with respect to: $Wr_{2015-2011}$ (c); confinement index before the flood (Ci_{2011}, d); average channel slope (S, e); average cumulative rainfall (R, f). All box and whiskers plots show median and interquartile range (25th and 75th percentiles), numbers in the box refer to the median values.

% of the analyses reaches and meandering only 5 %. After the flood there was a marked increase in reaches with alternated bars (32 %) and braided (27 %) patterns, whereas wandering (26 %) and sinuous reaches (10 %) decreased. A different pattern distribution characterized tributaries, in fact before the flood, 80 % of these reaches presented a sinuous and 9 % a wandering planform morphology. Braided and sinuous with alternated bars, composed only 3 % of the total reaches respectively, and anabranching represented 4 % of total dataset. After the flood the number of reaches with a sinuous pattern decreased (46 %) and most reaches shifted to wandering (21 %), braided (19 %), and sinuous reaches with alternated bars patterns (12 %). The wider reaches (> 20 m) in both periods - before and after the flood – were characterized by multithread and transitional morphologies (Fig. 2S supplementary material). Reaches in the main river channels experiencing the most intense widening were those where a shift towards a wandering pattern occurred, independently from the initial morphology (Fig. 7a). In these reaches, an increased presence of bars was observed during the field surveys. In the tributaries, reaches with largest $Wr_{2015-2011}$ were those presenting sinuous morphology before the flood (Fig. 7b). In this context, it is worth to note that the formation of high-energy anabranching reaches (Rinaldi et al., 2016b) after the flood, mainly originated from sinuous pattern. As shown at Fig. 6, this pattern was generated as a consequence of the formation of new dissection islands from the fragmentation of the former floodplain.

Field survey in the analyzed tributaries reaches revealed that channel widening was positively related to the maximum grain size of the

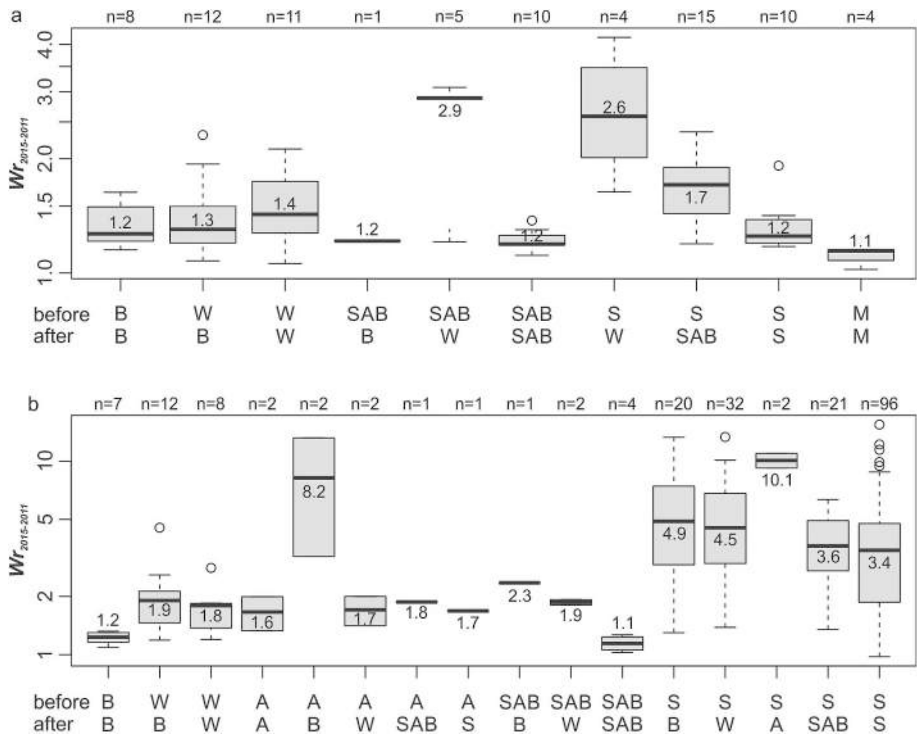

Fig. 7. Distribution of planimetric responses in relation to channel morphology before (2011) and after the flood (2015) in the main rivers (Nure and Trebbia, a) and in the tributaries (b). Codes for patterns: braided (B), anabranching (A), wandering (W), sinuous with alternate bars (SAB), sinuous (S) and meandering (M). All box and whiskers plots show median and interquartile range (25th and 75th percentiles), numbers in the box refer to the median values.

mobilized sediments (Fig. 8a). Maximum grain size reached higher values in the reaches confined after the flood (Fig. 8b) and did not present any statistical differences among the cascade and rapids bed morphology, while was significantly lower in the reaches with a plane bed morphology (Fig. 8c).

4.2. The factors controlling channel widening during the September 2015 flood

An exploratory analysis of univariate relationships between $Wr_{2015–2011}$ and the morphological characteristics described at section 3.2 shows a large scatter, and moreover such relations appear to largely differ for reaches in main rivers and in the tributaries (see some examples in Fig. 9). Specifically, all plots show large variability in width ratios mostly for the steeper, narrower, and less confined reaches, draining basins smaller than 25 km^2 (Fig. 9).

The Spearman correlation matrix (Fig. 10) shows that $Wr_{2015–2011}$ presents a significant positive correlation with Ci_{2011} both when considering the complete data set and dividing reaches into homogeneous categories (e.g., main rivers, tributaries, confined after the flood, partly confined or unconfined after the flood). Notably, for the tributary reaches, a significant positive correlation was found between $Wr_{2015–2011}$ and the cumulative storm rainfall (*R*). In all categories, $Wr_{2015–2011}$ showed a negative correlation with the channel width before the flood (W_{2011}) and the basin area (*BA*) and a positive correlation with the channel slope (*S*). $Wr_{2015–2011}$ resulted to be also significantly correlated with floodplain extension *Fr*, as channel widening occurred at expenses of the floodplain. This is particularly obvious for the confined channel after the flood (2015), where the former floodplain was completely eroded.

In summary, exploratory analysis shows that widening was more intense in the channels which were less confined (higher Ci_{2011}) and narrower prior to the flood event (W_{2011}), with higher average slope (*S*), with smaller drainage areas (*BA*) and that received higher precipitation during the storm (R) (Fig.10).

The PCA analysis – performed using the parameters described at section 3.2 – was used to investigate the relations between $Wr_{2015–2011}$ and the selected variables, as well as to highlight differences and similitudes among the studied rivers. The first two axis explain about 55 % of the total variance present within the dataset (Fig. 11), with the reaches of the main river channels (Nure and Trebbia) lying in the right side the plot (quadrants I and II). These reaches were mainly related to the size of the channels (W_{2011}, W_{2015}) of the drainage basins (*BA*) and to presence of islands (nI_{2011}, I_{2011}, nI_{2015}, I_{2015}). They flow mainly through the high plain and in few cases through the hilly physiographic units. Streams lying mainly in quadrant III (e.g., Lamazze, Piva, Ottone, Cavala, Lobbia, Grondana and Riccò) appeared mostly related to the channel slope (*S*), the channel elevation (*h*) and the stream power index (*SPI*). These channels flowing through the mountain and hilly physiographic units, were mainly partly confined before the flood and shifted towards confined settings during the flood. They maintained the original sinuous pattern even after the flood and presented average channel slope of about 9 % and average elevation of 680 m a.s.l. (maximum elevation 990 m a.s.l.).

Channel reaches plotting in quadrant IV experienced the larger widening (Rio Grande, Senga Dorbera, Gravignola), and presented a positive relation with the confinement index before the flood (Ci_{2011}) and the cumulative rainfall (*R*). These reaches were unconfined or partly confined before the flood and became partly confided or confined after. In all of them, the pattern was a sinuous morphology before the flood, whereas a variety of morphologies developed immediately after the flood, with the appearance of anabranching, wandering and braided patterns, besides some sinuous reaches. These reaches presented an average slope of about 6 %.

4.3. Channel changes 5 years after the flood

The comparison of 2015 vs 2020 orthophotos - a period characterized by ordinary floods only – show interesting changes in terms of channel width, pattern configuration and islands dynamics.

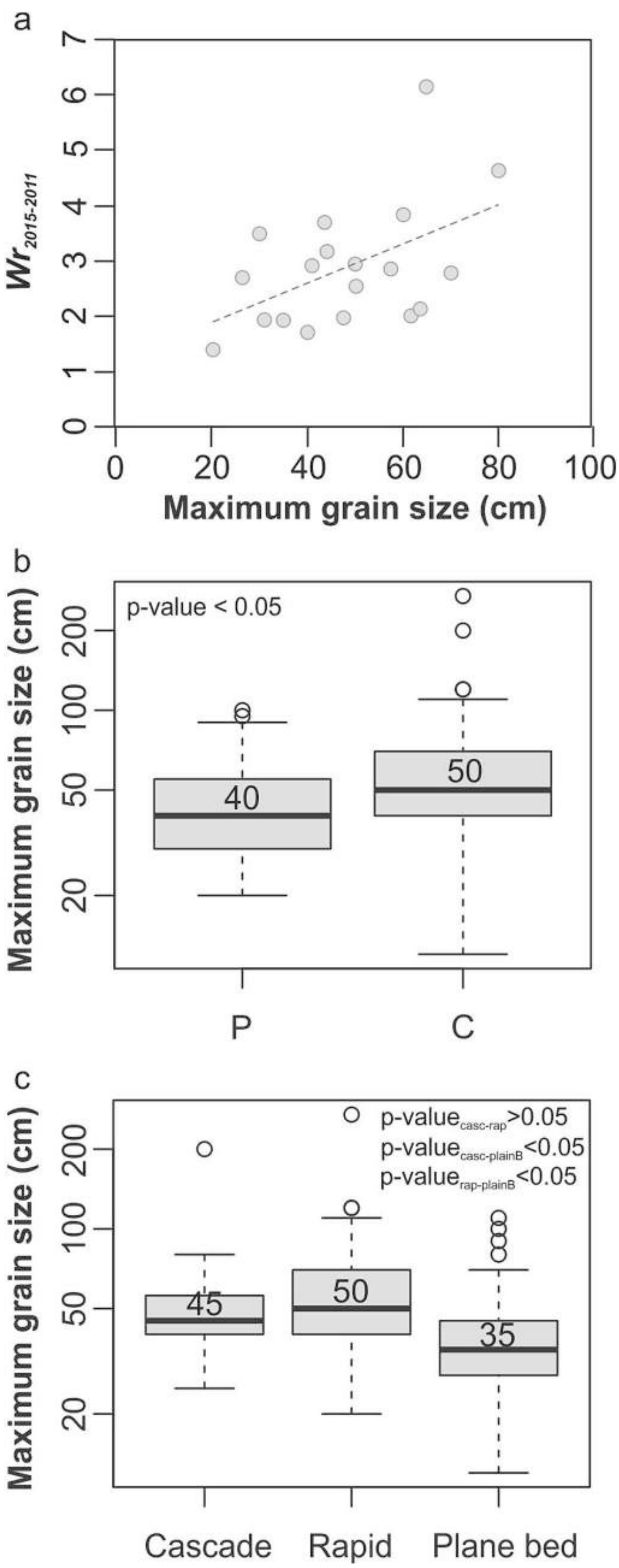

Fig. 8. Scatterplot of $Wr_{2015–2011}$ versus maximum grain size of the mobilized sediments (a). Box and whiskers plots of maximum grain size: in partly confined (P) and confined (C) reaches after the flood (b); for different bed morphologies (c). All box and whiskers plots show median and interquartile range (25th and 75th percentiles), numbers in the box refer to the median values.

In most rivers, during this period channels slightly narrowed but still remain wider than in 2011 (Fig. 12a). Except for some reaches, mainly in the Gravignola, Rio Grande and Ottone creeks, channel widths in 2020 resulted on average 0.9 times the channel widths right after the flood (2015) in both main rivers and 0.8 times the tributaries' widths ($Wr_{2020–2015}$, Fig. 11b). With respect to 2011 – pre-flood conditions - channels in 2020 were wider by a factor 2.4 in the tributaries, 1.4 in the Nure and 1.1 in the Trebbia, on average ($Wr_{2020–2011}$, Fig. 12b).

In the tributaries, post-flood narrowing was mainly related to the encroachment by pioneer vegetation on lateral bars formed within the wide channel shaped by the 2015 flood. Such bars progressively evolved to incipient floodplains. During this process, many of the dissection islands formed in 2015 have been included in the new floodplain, and thus the number and extension of the islands has slightly declined between 2015 and 2020 (Fig. 6a, b).

In the Nure and Trebbia rivers, the location of banks in 2020 approximatively corresponded with that in 2015 - except for some local lateral migration – but channel width resulted narrower in 2020 with respect to 2015, as new islands colonized by woody riparian vegetation appeared, mainly in the same positions where vegetation was removed by the 2015 flood. Fig. 6a, b clearly shows the increase in islands in the two main rivers, that also lead to the appearance of the anabranching pattern in some reaches (Fig. 12c). Such vegetation encroachment and associated channel narrowing in turn led to an increased presence of sinuous channels, both in the main rivers and in the tributaries, at the expenses of more complex morphologies typical of wider channels (Fig. 12c, d).

5. Discussion

5.1. Geomorphic response of rivers to an extreme flood in the Italian Apennines

In this study, a geomorphic response analysis to an extreme storm was performed at the catchment scale in two basins of the Northern Apennines, where the main planform response consisted in channel widening and in changes of the morphological pattern.

This study confirms that channel widening occurred through different processes, including bank retreat, overbank deposition and stripping of vegetation; distinct styles of channel widening occurred in the main and wider channels and in narrower tributaries. At a practical level, the distinction between different processes leading to channel widening is important for sound river corridor management, where the mitigation of flood risk must take into account such processes when predicting and mapping flood hazard.

Channel widening along the main river channels of the Nure and Trebbia was mostly associated with the lateral bank erosion and island destruction. Channel widening in the Nure was more intense than in the Trebbia in term of both width ratio and absolute widening, even though the Nure catchment was hit by a rainstorm characterized by a slightly lower maximum intensity. This result confirms the key role of valley confinement in controlling channel widening, as the Trebbia channel presented a high percentage of confined reaches before the flood, and narrower valleys with respect to the Nure also in terms of average channel width (average valley width 200 m in the Nure; 150 m in the Trebbia; $Ci_{2011} = 2.5$ in the Nure and $Ci_{2011} = 2.1$ in the Trebbia). In addition, it is worth to mention than in the Nure the percentage of pre-existing islands (−89 %) was much higher than in the Trebbia (− 42 %). In this light, the presence of wider valleys and more extended islands before the flood allowed a more intense channel widening in the Nure with respect to the Trebbia River.

Field surveys revealed that in the tributaries, channel widening was mainly associated with lateral erosion and in the some reaches with remarkable coarse sediment deposition, with thickness up to 2 m onto the former floodplain (Fig. 3).

The same trend showed by the typology of channel widening is

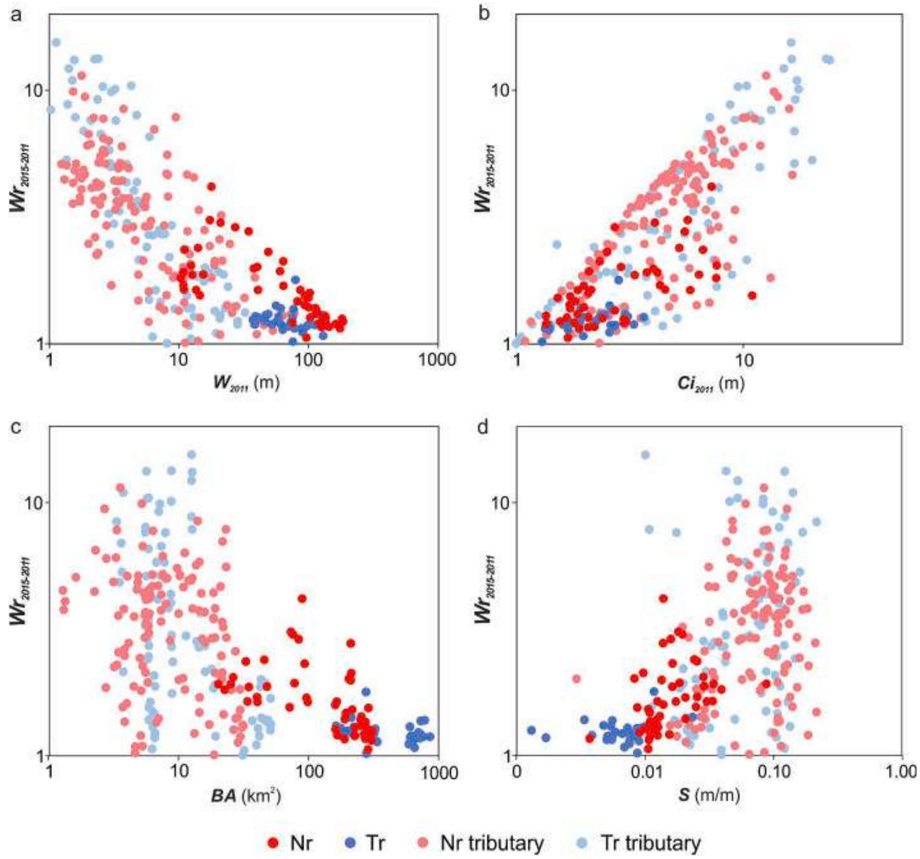

Fig. 9. Scatterplot of width ratios ($Wr_{2015-2011}$) versus channel width before the flood (W_{2011}, a) confinement index (Ci_{2011}, b), basin area (*BA*, c) and average reach slope (*S*, d). Nu and Tr stand for Nure and Trebbia, respectively.

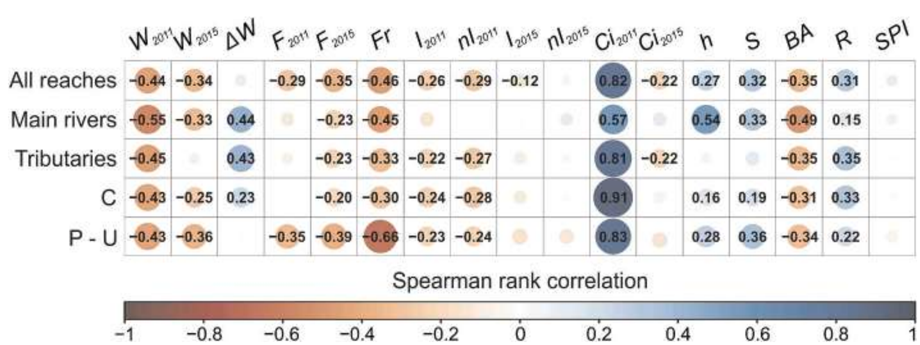

Fig. 10. Spearman correlation matrix of $Wr_{2015-2011}$ and the morphologic and hydrometric controlling factors. Red and blue colors show a negative and positive correlation, respectively, and white color shows no significant correlation. Color intensity and the size of the circle are proportional to the correlation coefficients. The values inside the matrix show the Spearman rank value, (only significant correlations are reported, *p*-value <0.05). Codes: W_{2011} active channel width before the flood (2011); W_{2015} active channel width immediately after the flood (2015); ΔW metric difference in channel width; F_{2011} floodplain width before the flood (2011); F_{2015} floodplain width after the flood (2015); *Fr* floodplain ratio; I_{2011} and nI_{2011} islands area and number before the flood (2011); I_{2015} islands area and number after the flood (2015); Ci_{2011} and Ci_{2015} confinement index before (2011) and after (2015) the flood; *h* average reach elevation; *S* average reach slope; *BA* basin area; *R* cumulative storm rainfall in the catchment; *SPI* stream power index.

reflected also by islands dynamics. In the main channels and in some tributary, islands were completely removed, while in most tributary new islands appeared. These processes were found not randomly distributed, but strictly related to flow energy, as the formation of new islands was observed in reaches with steeper gradient that received higher rainfall, these conditions resulted in the fragmentation of the former floodplain; on the contrary the stripping of vegetation from preexisting islands was more common in channel reaches characterized by lower energetic conditions (Gurnell and Petts, 2006; Bertoldi et al., 2010; Surian et al., 2015).

A spatial distribution of planform morphologies changes was observed, specifically in relation with rainfall distribution, valley floor width and the morphometric characteristics of the valley (e.g., slope and valley width and confinement). Along the tributaries, reaches that maintained their initial sinuous pattern were those located at higher elevations, presenting steep channel beds and lateral constraints after the flood. Minor channel widening was observed along these reaches for a high degree of lateral confinement. Their dominant process for widening was lateral erosion, enhanced by high values of unit flood stream power. However, the strong correlation between valley width,

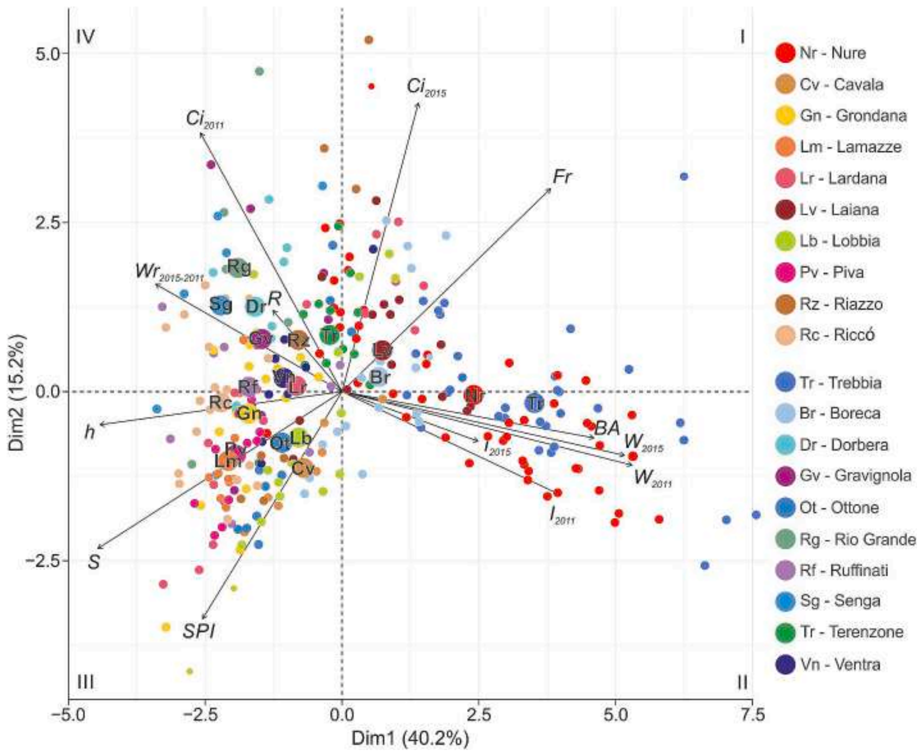

Fig. 11. Results of the PCA performed on the 15 study rivers (293 reaches).

channel width and pattern changes may probably hide the importance of other morphometric and morphological factors. Reaches in the tributaries that changed more significantly their channel pattern, in particular from single-thread to braided, wandering or anabranching, were located in the wider valleys. They were mainly partly-confined or unconfined even after the flood. Differently from the previous group, in these reaches also overbank deposition determined channel widening. In the main channels - and particularly along the Nure River – reaches shifted mainly towards braided, wandering and sinuous with alternated bars patterns. The Trebbia River resulted more stable in its planform morphology, as most reaches maintained their exiting channel configuration, thus the lateral constraint appeared to have played a key role in the spatial distribution of the observed channel changes.

Due to the lack of data, it was not possible to assess bed-level changes and changes in bed armouring or to assess the relative contribution of different sediment source areas, as done in Scorpio et al. (2018). In this previous work limited to the Nure River, field survey analysis, remoted observations and quantitative comparison of multitemporal topographic cross-sections allowed us to qualitatively analyze sediment sources. In particular, in the headwater catchments, slope instability processes in form of debris flows/debris floods, debris slides, moved sediments into the tributaries. Similar geomorphic processes were described during other storm events (Rickenmann et al., 2016; Surian et al., 2016; Scorpio et al., 2022; Liébault et al., 2024). Frequent toe erosion processes at the base of the hillslopes were observed in most tributaries; they caused local erosion of the bedrock and of thin colluvial materials, but volume of involved sediments were generally relatively small. In most of the analyzed reaches, coarse sediments originated from floodplain and island erosion as the consequence of the lateral migration of the banks. In the confined reaches sediment supply came from channel-connected mass wasting processes (Scorpio et al., 2018; Pitscheider et al., 2024). In particular, sediment supply was the result of cascading processes that occurred in the upstream channel network, which was characterized by a marked level of sediment connectivity due to the absence of both Pleistocene glaciers in the study areas (which typically bring in a legacy of disconnecting landforms such as valley steps, moraines, and wide valley bottoms (see e.g., Cavalli et al., 2013 and Scorpio et al., 2022) and of tectonically-driven sediment "buffer" features. In the tributaries, transported sediment volumes increased downstream step by step along every subsequent reach, as long as sediments stopped at the confluence with the main channels, where the topographic condition (gentler slope, lower valley confinement) was responsible for the sediment deposition. In the Nure channel, the multitemporal topographic cross-sections (Scorpio et al., 2018) indicate that sediment flux decreased downstream. Aggradation up to 1.4 m (median 0.4 m) was observed in the higher-medium valley sections, in particular downstream of the confluences with some major tributaries (Lardana, Lavaiana, Lobbia rivers). Moving downstream bed level changes become smaller (maximum aggradation about 0.8 m, average aggradation = 0.3 m) and vertical bed stability prevailed. Some incision was documented in the reaches having the higher values of unit stream power and characterized by the higher confinement (Scorpio et al., 2018).

5.2. Morphological response to the flood in the long-term trajectory of channel changes

In order to discuss the effects of the flood event in relation to the past changes, the historical evolution of channel width before the flood (see section 2.3) is valuable. According to previous studies regarding the Nure River (Scorpio and Piégay, 2021), channel width decreased by −44 % (on average) between 1954 and 1998, while some channel widening was already in progress in 2010s (+11 % on average between 1988 and 2012; Fig. 13a). Published studies on past evolutionary trajectories on the analyzed reaches of the Trebbia River are not available, but visual comparison of oldest available aerial photographs (1954) and the channel mapped after the 2015 flood allowed us to make some qualitative consideration (Fig. 13b). In both main rivers, active channel in 1954 occupied most of the valley bottom (73 % in median, but up to 96 % in the Nure; and even higher values in the Trebbia, Fig. 13a, b, c). After the flood in 2015 the channel took up 64 % (median value) of the valley bottom in the Nure (Fig. 13c). In both rivers the 1954 active channel was not affected by direct human impact, and sediments flux

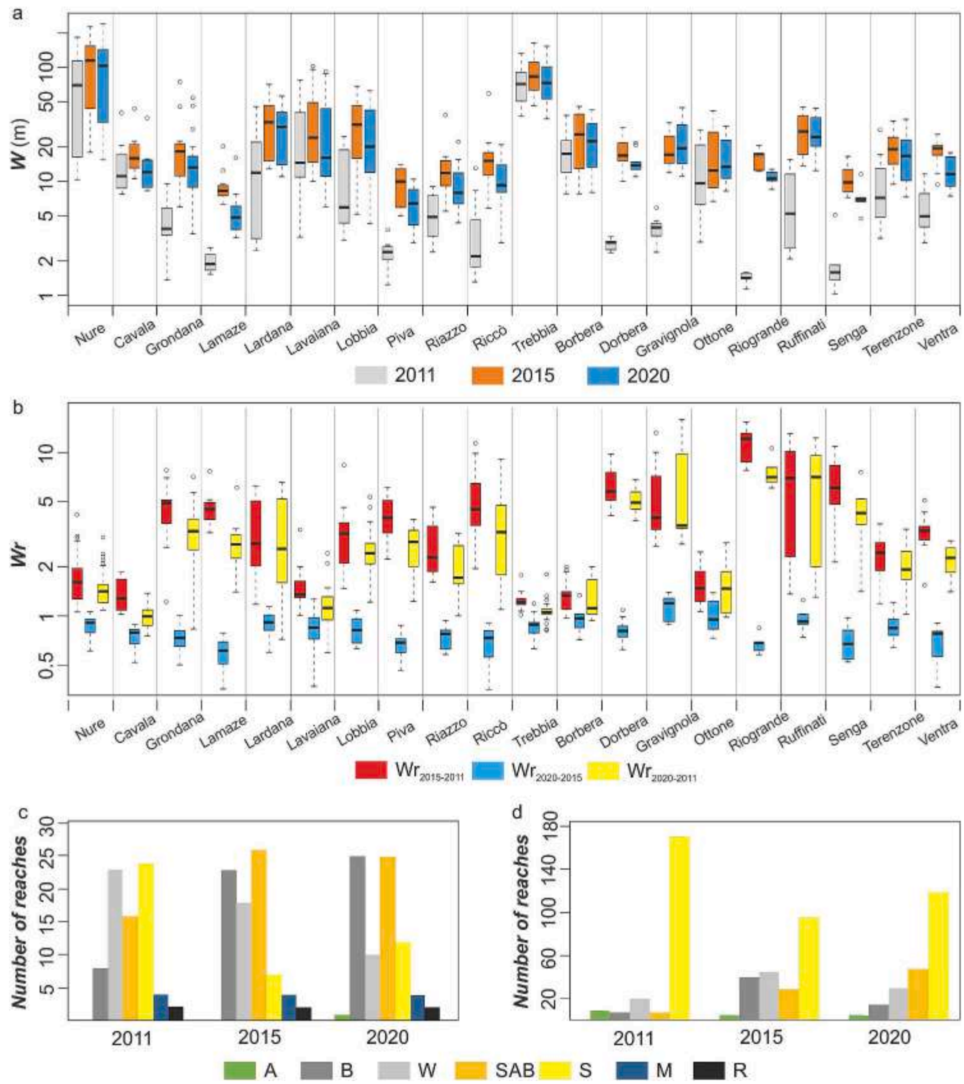

Fig. 12. Box and whiskers plots of channel width (*W*) in 2011, 2015 and 2020 in the studied rivers (a); of *Wr*, comparing channel width changes (b) between 2015 and 2011 ($Wr_{2015-2011}$; pre and immediately after the flood), between 2020 and 2015 ($Wr_{2020-2015}$; during and 5 years the flood) and between 2020 and 2011 ($Wr_{2020-2011}$); distribution of channel patters in 2011, 2015 and 2020 in the Nure and Trebbia rivers (c) and in their tributaries (d). Codes channel patterns: anabranching (A), braided (B), wandering (W), sinuous with alternate bars (SAB), sinuous (S), meandering (M), straight (R).

presented a very low degree of disconnection along the tributaries (Bollati et al., 2014; Scorpio and Piégay, 2021). Therefore, the channel extent in 1954 can be assumed as corresponding approximately with the maximum width within the historical range of variability (HRV, sensu Wohl and Rathburn, 2013). In the Nure River, the response to the 2015 flood was mainly within the HRV, although some reaches showing a levelling and other where the channel width after the 2015 flood exceeded those in 1954 (Fig. 13d, e). In general, the channel after the flood resulted much larger in the reaches that were wider even in 1954 (Fig. 13f). In the Trebbia, the maximum width within the HRV was approximately reached during the flood. Low channel width changes – in the long term and in relation to the 2015 flood - were observed in those reaches flowing though the villages and thus fixed by channelization and levees.

Nardi and Rinaldi (2015) highlighted how previous morphological conditions on longer (last 100–150 years) and shorter (last 10–15 years) timescales might have some influence on the channel response to flood events, and such role has been stressed in Piégay et al. (2020). Previously, Toone et al. (2014) showed that between 1948 and 2006 the Drôme River experienced four large floods. Besides the magnitude of the storms, the channel responded differently to each flood, as other conditions such as the sequence of anthropogenic impacts and the degree of vegetation establishment along the banks and the slopes have been modifying the sediment regime between two consecutive floods. In the Trebbia and Nure rivers, the scarcity of data relative to past floods (see section 2.3) did not allow us to analysis the link between changes in channel width and the occurrence of floods over the last century, but the channel narrowing until 1990s indicate a decrease in sediment supply from the hillslopes (Scorpio and Piégay, 2021) coupled to the effect of in-channel gravel mining.

5.3. Comparison of channel widening with other catchments

Widening was extremely variable among the Trebbia and Nure rivers and their tributaries. The new river width after the flood was up to 15 times the pre-flood channel width in the tributaries (median Wr 3.3) and up to 4 times in the main channels (median Wr 1.3). Similar ratios of widening in response to a single flood are not unusual in rivers with similar morphology, physiographic and climatic conditions (Ruiz-Villanueva et al., 2023). Values estimated in this study are in fact in the same ranges of geomorphic response than those found for other mountain rivers of Europe (Table 2).

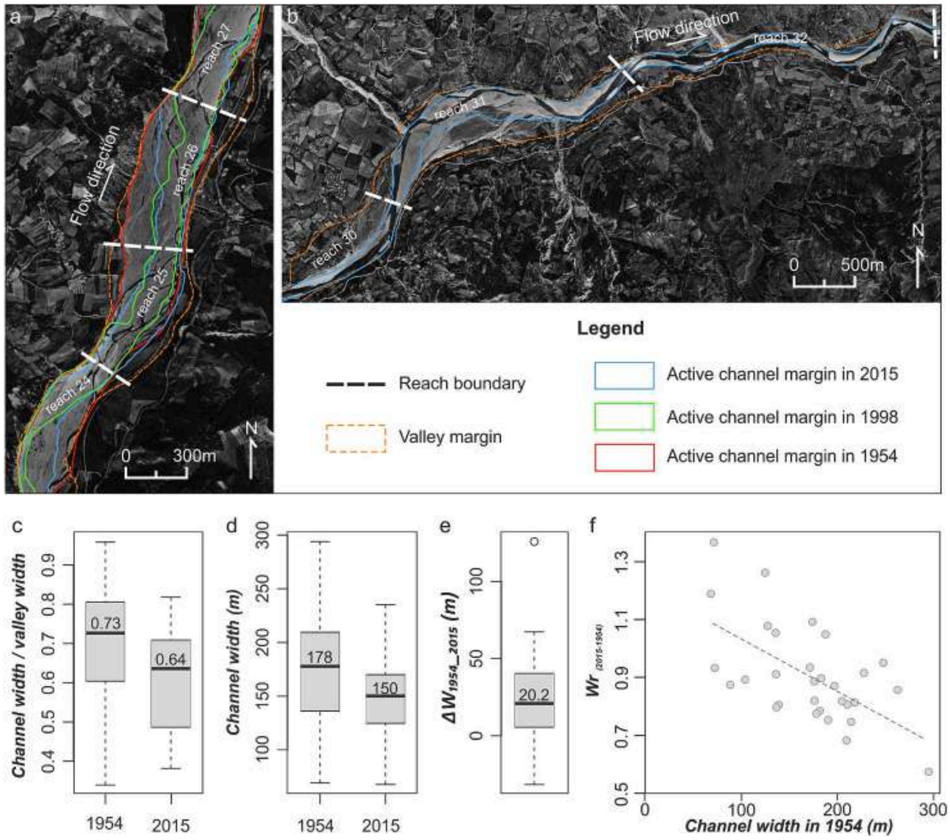

Fig. 13. Valley bottom margins and active channel margins in 1954, 1998 and 2015 (after the flood) at reaches 24, 25 and 26 of the Nure River, plotted on the orthophoto in 1954 (a); valley bottom margins and active channel margins in 2015 (after the flood) at reaches 30, 31 and 32 of the Trebbia River plotted on the orthophoto in 1954 (b). Box and whiskers plots of (data refer to the Nure River only): channel width / valley width ratio in 1954 and 2015 (c); channel width in 1954 and 2015 (d); absolute channel width changes between channel width in 1954 and in 2015 (e); all box and whiskers plots show median and interquartile range (25th and 75th percentiles), numbers in the box refer to the median values. Scatterplot of channel width changes ratio ($Wr_{2015-1954}$) versus channel width in 1954 in the Nure River (f).

Table 2
Comparison of median and maximum *Wr* detected in this study for the Nure and Trebbia catchment and those in other rivers in Europe affected by extreme floods over the last decades.

River / Basin	Country	Data of flood	Basin area min/max km^2	Median Wr	Maximum Wr	Source
Trebbia	Italy	September 2015	163 / 860	1.2 (Trebbia)	1.8 (Trebbia)	This study
Nure	Italy	September 2015	20 / 307	1.6	4.2	Scorpio et al., 2018 This study
Trebbia tributaries	Italy	September 2015	1 / 32	2.7	15.5	This study
Nure tributaries	Italy	September 2015	3 / 51	3.5	11.5	Scorpio et al., 2018 This study
Trisanna Lech Bregenzerach Rosanna Alfenz	Austria	August 2005	172/1211	<2.0	6.4	Krapesch et al., 2011
Magra	Italy	October 2011	1707	1.3	1.6	Nardi and Rinaldi, 2015
Magra Tributaries	Italy	October 2011	0.12 / 38	3.6	19.7	Surian et al., 2016
Mannu Bitti Posada	Italy	November 2013	230 / 553	3.5	6.2	Righini et al., 2017
Emme	Switzerland	July 2014	0.2 / 94	1.5	4.8	Ruiz-Villanueva et al., 2018
Orlacher	Germany	May 2016	6	3.1	5.2	Lucía et al., 2018
Grimm	Germany	May 2016	30	6.9	13.7	Lucía et al., 2018
Stolla bach	Italy	August 2017	1.5 / 40	2.0	5.0	Scorpio et al., 2022
Cordovole	Italy	October 2018	25 / 857	1.9	16.0	Brenna et al., 2023
Vésubie	France	October 2020	392	4	19	Liébault et al., 2024
Roya	France	October 2020	671	2.3	14	Liébault et al., 2024

This study confirmed the valley confinement as a critical morphological variable that controls channel widening during extreme flood events and - similarly to Ruiz-Villanueva et al., 2018 – it recognized the role of the cumulative rainfall amount as a parameter explaining the spatial variability in the magnitude of the geomorphic changes. Other studies on mountain rivers have found that channel widening is the result of a complex interaction between hydrological and hydraulic parameters, in particular the unit stream power, and of a set of morphological and morphometric variables, in particular the confinement index (Krapesch et al., 2011; Surian et al., 2016; Thompson and Croke, 2013; Lucía et al., 2018; Scorpio et al., 2018; Brenna et al., 2023; Ruiz-Villanueva et al., 2023). In the Nure catchment the relationship of width ratio with unit stream power and confinement index was tested by Scorpio et al. (2018). In this study, due to the lack of peak discharges data in most rivers of the Trebbia catchment it was not possible to examine this relationship.

An inverse relationship was found between channel widening (Wr_{flood}) and the channel width before the flood (W_{pre}, Fig. 14a), which was expected as already exposed in other studies (Krapesch et al., 2011; Comiti et al., 2016; Lucía et al., 2018; Ruiz-Villanueva et al., 2018; Liébault et al., 2024). Comparison with channel widening during other floods in Italy (Nardi and Rinaldi, 2015; Surian et al., 2016; Scorpio et al., 2022; Brenna et al., 2023; Table 2), showed a broad spectrum of Wr_{flood} (ranging between 1 and 19, Fig. 14a) and ΔW (ranging between 1.3 and 140 m, Fig. 14b) in the narrower rivers ($W_{pre} < 10$ m), whereas reaches having a W_{pre} higher than 50 m never experienced a Wr_{flood} higher than 2 and ΔW lower than 10 m, with few exceptions (Fig. 14). This confirms the high sensitivity of narrower reaches – if not already confined - to widen during floods, where the entire valley bottom can be potentially occupied by the channel during an extreme flood event, as it was also confirmed by our results showing that many reaches in the headwater catchments, became confined after the storm.

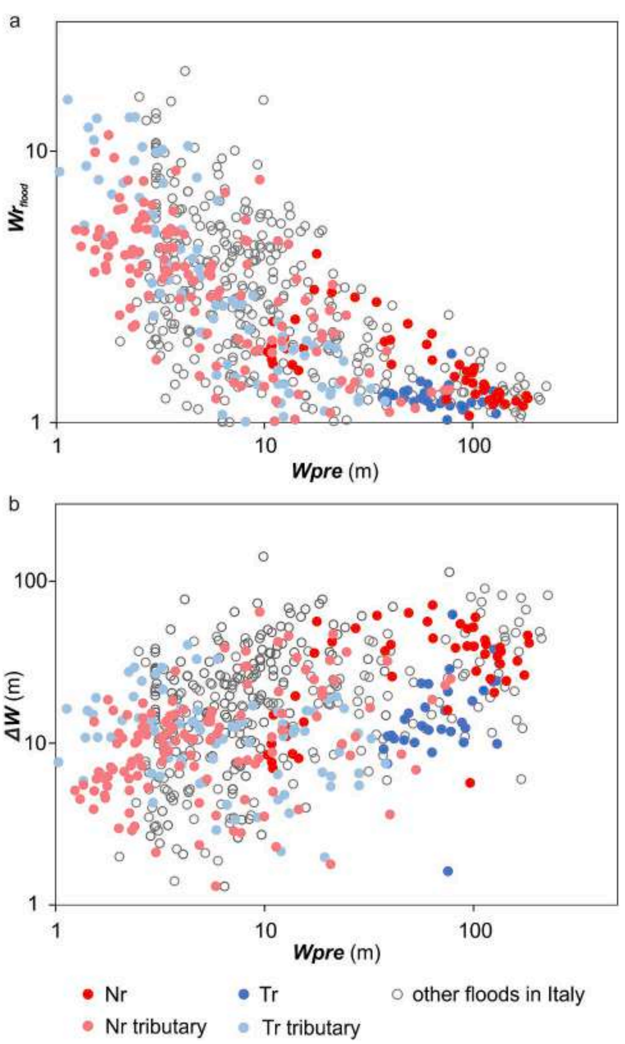

Fig. 14. Scatterplot of: width ratios caused by the flood (Wr_{flood}, a) and absolute widening (ΔW, b) versus channel width before the flood event for the Trebbia and Nure rivers and tributaries, compared with width data of other flood events that occurred in the Italian Alps and Apennines (Nardi and Rinaldi, 2015; Surian et al., 2016; Scorpio et al., 2022; Brenna et al., 2023).

5.4. *Channel changes after an extreme event: Recovery pathway to pre-flood condition*

This study showed that geomorphic character and behavior of the rivers in the Nure and Trebbia basins has been fundamentally altered by the flood in 2015. The analyzed rivers were very sensitive to changes, as after the flood they shifted to different channel types, and widened due to bank and island erosion as well as for overbank depositions.

Five years after the 2015 flood, the study channels are apparently on a recovery trajectory to their pre-flood condition in terms of active channel vs vegetation extension within the fluvial corridor. All channels narrowed - although the widening caused by the flood has not yet been completely absorbed - and new riparian vegetation encroached on islands and on the newly-formed incipient floodplains, and the channel patterns shifted towards simpler morphologies, mainly sinuous. Between 2015 and 2020 only ordinary floods occurred, unable to strengthen the geomorphic changes induced by the extreme flood in 2015, and the absence of large floods in this period have most likely contributed to the marked vegetation encroachment and associated channel narrowing. Comparison of the evolutionary trajectories before, immediately after and 5 years after the flood, reveals that while channel widening was more intense in the narrower channels before the flood, the channel width determined by the 2015 flood remained more stable over the 5-year time in the wider reaches, i.e., in the main channels and in the distal reaches of the major tributaries. This outcome might support the identification of those river reaches with higher potential for passive restoration (Kondolf, 2011; Ruiz-Villanueva et al., 2023).

During the storm in 2015 debris flows and landslides coupled to the Nure and Trebbia rivers and tributaries were triggered. Orthophotos taken in 2020 show that such hillslopes and landforms became stabilized by vegetation, and thus their sediment supply to the channels have surely decreased in the 2015–2020 period. Conversely, changes in structural sediment connectivity did not occur in the same period. Indeed, rates of sediment supply from upstream and the ability of the channel network to transfer sediments downstream are key factors for determining the type and timing of channel recovery after large floods (Brierley and Fryirs, 2005; Fuller et al., 2019; Räpple et al., 2017; Piégay et al., 2020; Steger et al., 2022).

In the analysis of channel changes after a flood it is also important to consider river sensitivity over different temporal scales; channel changes in the analyzed rivers could lead towards a further channel narrowing, i.e., towards a channel pattern similar to those present in 2011, unless a new flood occurs. However, we must highlight how 5 years after a pulse disturbance (i.e., in this case the 2015 flood) is too short of a time to draw definite conclusions about the recovery dynamics to either static or dynamic "steady state" conditions, in terms of channel width and morphology (Habersack and Piégay, 2008; Piégay et al., 2020). The interpretation of temporal changes and trajectories in the Nure and Trebbia rivers would highly benefit from a longer monitoring period, in the order of a few decades.

6. Conclusions

This study analyzed the geomorphic effects in channel network of two mountain catchments caused by a storm characterized by high intensity rainfall and analyzes the channel recovery towards pre-flood conditions after 5 years. Most relevant planimetric response of the active channels to the flood event was a significant increase in channel width, caused by bank erosion, stripping of in-channel riparian vegetation, and the overbank deposition of bedload deposits on the former floodplain. The study highlighted the different responses to the flood between the main channels (Nure and Trebbia rivers) and their tributaries. The channel width after the flood was up to 15 times the pre-flood channel width in the tributaries and up to 4 times in the main channels. Increase in channel width in the Nure and Trebbia rivers was associated with lateral erosion of the banks and destruction of vegetated surfaces within the channel; in their tributaries, the widening was the result of lateral erosion and the deposition of coarse sediments over the former floodplain. Due to channel widening, most reaches became confined after the flood, while unconfined reaches almost disappeared. As further consequence of the channel widening, islands decreased in number and extension in the main channels, while both processes of island erosion and formation of new dissection islands were observed in the tributaries.

The September 2015 flood caused an increased presence of wandering, braided, and sinuous with alternated bars patterns. Magnitude and style for widening was related to the rainfall amount and to the morphologic and morphometric characteristics of the valley. Widening was more intense in the channels that were less confined and narrower prior to the flood event, with higher average slope, smaller drainage areas and that received much higher precipitation during the storm. This study confirmed the key role of valley confinement in controlling the channel widening and showed that precipitation resulted a statistically significant variable to explain channel widening in the tributaries. Analyzed rivers were very sensitive to changes, even some years after the flood, as all channels and especially tributaries progressively narrowed although the widening caused by the flood was not yet been completely absorbed. New riparian vegetation encroached on islands and on the new incipient floodplains and the channel patterns shifted towards simpler patterns, mainly sinuous. Findings from this study represent a step forward in understanding geomorphic processes in mountain rivers, and confirmed that flood hazard in mountain environments is often related to the geomorphic impacts of sediment transport processes (Hooke, 2016; Guan et al., 2016; Scorpio et al., 2022). Nevertheless, channel widening is usually neglected in the European flood hazard mapping (Floods Directive, European Commission, 2007), and river basin management. Finally, this study highlighted that the knowledge of the areas susceptible to channel widening is crucial for determining the minimum space demand (e.g., the 'Erodible Corridor Concept' by Piégay et al., 2005; the 'Freedom Space for Rivers' by Biron et al., 2014 and the 'Event morphodynamic corridor' by Rinaldi et al., 2015) in mountain rivers, where the limited space for buildings and infrastructure causes an increase in geomorphological risk (Habersack et al., 2009; Krapesch et al., 2011).

CRediT authorship contribution statement

Vittoria Scorpio: Writing – original draft, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Francesco Comiti:** Writing – original draft, Methodology, Investigation.

Declaration of competing interest

Vittoria Scorpio reports financial support was provided by University of Modena and Reggio Emilia. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

Funding for the lead author's work comes from the research project "Effetti del cambiamento climatico e dell'impatto antropico sui corsi d'acqua nei contesti alpini ed appenninici" funded by "FAR2022", University of Modena and Reggio Emilia. The authors are grateful to the Agenzia interregionale per il Fiume Po and to the Regione Emilia-Romagna for providing maps and orthophotos.

Authors thank Davide Cadignani for supporting some remote sensing data editing and Marco Borga and Francesco Marra for providing the cumulative rainfall map.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2024.109355.

References

Resilience Alliance, 2009. Assessing and managing resilience in social-ecological systems: a practitioner's workbook, Version 1.0. http://wiki.resalliance.org/index.php/Main_Page.
Arnaud-Fassetta, G., Cossart, E., Fort, M., 2005. Hydro-geomorphic hazards and impact of man-made structures during the catastrophic flood of June 2000 in the Upper Guil catchment (Queyras, French Alps). Geomorphology 66, 41–67.
Belletti, B., Dufour, S., Piégay, H., 2013. What is the relative effect of space and time to explain the braided river width and island patterns at a regional scale? River Res. Appl 37, 57–71. https://doi.org/10.1002/rra.2714.
Belletti, B., Dufour, S., Piégay, H., 2014. Regional assessment of the multi-decadal changes in braided riverscapes following large floods (example of 12 reaches in South East of France). Adv. Geosci. 37, 57–71. https://doi.org/10.5194/adgeo-37-57-2014.
Bertoldi, W., Zanoni, L., Tubino, M., 2010. Assessment of morphological changes induced by flow and flood pulses in a gravel bed braided river: the Tagliamento River (Italy). Geomorphology 114, 348–360.
Biron, P.M., Buffin-Bélanger, T., Larocque, M., Choné, G., Cloutier, C.-A., Ouellet, M.-A., Demers, S., Olsen, T., Desjarlais, C., Eyquem, J., 2014. Freedom space for rivers: a sustainable management approach to enhance river resilience. Environ. Manag. 54 (5), 1056–1073.
Bollati, I.M., Pellegrini, L., Rinaldi, M., Duci, G., Pelfini, M., 2014. Reach-scale morphological adjustments and stages of channel evolution: the case of the Trebbia River (northern Italy). Geomorphology 221, 176–186.
Brenna, A., Marchi, L., Borga, M., Zaramella, M., Surian, N., 2023. What drives major channel widening in mountain rivers during floods? The role of debris floods during a high-magnitude event. Geomorphology 430, 108650.
Brenna, A., Surian, N., Ghinassi, M., Marchi, L., 2020. Sediment–water flows in mountain streams: recognition and classification based on field evidence. Geomorphology 371, 107413.
Brierley, G.J., Fryirs, K.A., 2005. Geomorphology and River Management: Applications of the River Style Framework. Blackwell, Oxford.
Buffin-Bélanger, T., Biron, P.M., Larocque, M., Demers, S., Olsen, T., Chone, G., Ouellet, M.-A., Cloutier, C.-A., Desjarlais, C., Eyquem, J., 2015. Freedom space for rivers: an economically viable river management concept in a changing climate. Geomorphology 251, 137–148. https://doi.org/10.1007/s00267-014-0366-z.
Buraas, E.M., Renshaw, C.E., Magilligan, F.J., Dade, W.B., 2014. Impact of reach geometry on stream channel sensitivity to extreme floods. Earth Surf. Process. Landf. 39, 1778–1789.
Campana, D., Marchese, E., Theule, J.I., Comiti, F., 2014. Channel degradation and restoration of an Alpine river and related morphological changes. Geomorphology 221, 230–241.
Cavalli, M., Trevisani, S., Comiti, F., Marchi, L., 2013. Geomorphometric assessment of spatial sediment connectivity in small alpine catchments. Geomorphology 188, 31–41. https://doi.org/10.1016/j.geomorph.2012.05.007.
Cenderelli, D., Wohl, E., 2003. Flow hydraulics and geomorphic effects of glacial-lake outburst floods in the Mount Everest Region. Nepal. Earth Surf. Process. Landf. 28, 385–407.
Ciccarese, G., Mulas, M., Alberoni, P.P., Truffelli, G., Corsini, A., 2020. Debris flows rainfall thresholds in the Apennines of Emilia-Romagna (Italy) derived by the analysis of recent severe rainstorms events and regional meteorological data. Geomorphology 358, 107097. https://doi.org/10.1016/j.geomorph.2020.107097.
Comiti, F., Da Canal, M., Surian, N., Mao, L., Picco, L., Lenzi, M.A., 2011. Channel adjustments and vegetation cover dynamics in a large gravel bed river over the last 200 years. Geomorphology 125, 147–159.

Comiti, F., Righini, M., Nardi, L., Lucía, A., Amponsah, W., Cavalli, M., Surian, N., 2016. Channel widening during extreme floods: how to integrate it within river corridor planning? 13th Congress Interpraevent 2016. Lucerne (Switzerland) 477–486.
Costa, J.E., O'Connor, J.E., 1995. Geomorphically effective floods. In: Costa, J.E., Miller, A.J., Potter, K.W., Wilcock, P.R. (Eds.), Natural and Anthropogenic Influences in Fluvial Geomorphology (the Wolman Volume). American Geophysical Union, Washington, DC, pp. 89–104.
Dean, D.J., Schmidt, J.C., 2013. The geomorphic effectiveness of a large flood on the Rio Grande in the big Bend region: insights on geomorphic controls and post-flood geomorphic response. Geomorphology 201, 183–198.
Dufour, S., Piégay, H., 2009. From the myth of a lost paradise to targeted river restoration: forget natural references and focus on human benefits. River Res. Appl. 25, 568–581. https://doi.org/10.1002/rra.1239.
European Commission, 2007. Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the Assessment and Management of Flood Risks. Off. J. (L 288/27, 6/11/2007, Brussels, Belgium, 8 pp.).
Ferencevic, M.V., Ashmore, P., 2012. Creating and evaluating digital elevation model-based stream-power map as a stream assessment tool. River Res. Appl. 28, 1394–1416.
Florsheim, J.L., Mount, J.F., Chin, A., 2008. Bank erosion as a desirable attribute of rivers. BioScience 58, 519–529.
Fratkin, M.M., Segura, C., Bywater-Reyes, S., 2020. The influence of lithology on channel geometry and bed sediment organization in mountainous hillslope-coupled streams. Earth Surf. Process. Landf. 45, 2365–2379. https://doi.org/10.1002/esp.4885.
Fryirs, K.A., 2017. River sensitivity: a lost foundation concept in fluvial geomorphology. Earth Surf. Process. Landf. 42, 55–70.
Fryirs, K.A., Brierley, G.J., 2013. Geomorphic Analysis of River Systems: An Approach to Reading the Landscape. Wiley-Blackwell, Hoboken.
Fuller, I.C., Gilvear, D.J., Thoms, M.C., 2019. Death RG. Framing resilience for river geomorphology: Reinventing the wheel? River Res. Appl. 35, 91–106. https://doi.org/10.1002/rra.3384.
Grove, J.R., Croke, J., Thompson, C., 2013. Quantifying different riverbank erosion processes during 852 an extreme flood event. Earth Surf. Process. Landf. 38, 1393–1406 (Doi: 853 101002/esp3386).
Guan, M., Carrivick, J.L., Wright, N.G., Sleigh, P.A., Staines, K.E.H., 2016. Quantifying the combined effects of multiple extreme floods on river channel geometry and on flood hazards. J. Hydrol. 538, 256–268.
Gurnell, A.M., Petts, G., 2006. Trees as riparian engineers: the Tagliamento River, Italy. Earth Surf. Process. Landf. 31, 1558–1574.
Habersack, H., Piégay, H., 2008. River restoration in the Alps and their surroundings: past experience and future challenges. In: Habersack, H., Piégay, H., Rinaldi, M. (Eds.), Gravel-Bed Rivers VI: From Process Understanding to River Restoration. Elsevier, pp. 703–735. https://doi.org/10.1016/S0928-2025(07)11161-5.
Habersack, H., Burgel, J., Kanonier, A., 2009. FloodRisk II – Deepening and Crosslinking of Trend Setting Strategies for Integrative Flood Management. Federal Ministry of Agriculture, Forestry, Environment and Water Management, Wien, Synthesebericht, pp. 1–259.
Harrison, L.R., Pike, A., Boughton, D.A., 2017. Coupled geomorphic and habitat response to a flood pulse revealed by remote sensing. Ecohydrology 10 (5), 1–13. https://doi.org/10.1002/eco.1845.
Hauer, C., Habersack, H., 2009. Morphodynamics of a 1000-year flood in the Kamp River, Austria, and impacts on floodplain morphology. Earth Surf. Process. Landf. 34, 654–682. https://doi.org/10.1002/esp.1763.
Heritage, G.L., Large, A.R.G., Moon, B.P., Jewitt, G., 2004. Channel hydraulics and geomorphic effects of an extreme flood event on the Sabie River, South Africa. Catena 58, 151–181.
Hooke, J.M., 2016. Morphological impacts of flow events of varying magnitude on ephemeral channels in a semiarid region. Geomorphology 252, 128–143.
Knighton, D., 1998. Fluvial Forms and Processes: A New Perspective, 2nd ed. Routledge, p. 400. https://doi.org/10.4324/9780203784662.
Kondolf, M. G., 2011. Setting goals in river restoration: when and where can the river "heal itself"?. In: Book Editor(s): Andrew Simon, Sean J. Bennett, Janine M. Castro. Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches.
Krapesch, G., Hauer, C., Habersack, H., 2011. Scale orientated analysis of river width changes due to extreme flood hazard. Nat. Hazards Earth Syst. Sci. 11, 2137–2147.
Langhammer, L., 2010. Analysis of the relationship between the stream regulations and the geomorphologic effects of floods. Nat. Hazards 54, 121–139.
Liébault, F., Melun, G., Piton, G., Chapuis, M., Passy, P., Tacon, S., 2024. Channel change during catastrophic flood: example of storm Alex in the Vésubie and Roya valleys. Geomorphology 446, 109008. https://doi.org/10.1016/j.geomorph.2023.109008.
Lucía, A., Schwientek, M., Eberle, J., Zarfl, C., 2018. Planform changes and large wood dynamics in two torrents during a severe flash flood in Braunsbach, Germany 2016. Sci. Total Environ. 640–641, 315–326. https://doi.org/10.1016/j.
Magilligan, F.J., 1992. Thresholds and the spatial variability of flood power during extreme floods. Geomorphology 5, 373–390.
Magilligan, F.J., Buraas, E.M., Renshaw, C.E., 2015. The efficacy of stream power and flow duration on geomorphic responses to catastrophic flooding. Geomorphology 228, 175–188.
Marchi, L., Dalla Fontana, G., 2005. GIS morphometric indicators for the analysis of sediment dynamics in mountain basins. Environ. Geol. 48, 218–228.
Mazzorana, B., Nardini, A., Comiti, F., Vignoli, G., Cook, E., Ulloa, H., Iroumé, A., 2018. Toward participatory decision-making in river corridor management: two case studies from the European Alps. J. Environ. Plan. Manag. 61 (7), 1250–1270. https://doi.org/10.1080/09640568.2017.1339593.
Mazzorana, B., Simoni, S., Scherer, C., Gems, B., Fuchs, S., Keiler, M., 2014. A physical approach on flood risk vulnerability of buildings. Hydrol. Earth Syst. Sci. 18, 3817–3836. https://doi.org/10.5194/hess-18-3817-2014.
Miller, F., Osbahr, H., Boyd, E., Thomalla, F., Bharwani, S., Ziervogel, G., Walker, B., Birkmann, J., Van der Leeuw, S., Rockström, J., 2010. Resilience and Vulnerability: Complementary or Conflicting Concepts? Ecol, Soc, p. 15.
Montgomery, R.D., Buffington, J.M., 1997. Channel-reach morphology in mountain drainage basin. Geol. Soc. Am. Bull. 109 (5), 596–611.
Nardi, L., Rinaldi, M., 2015. Spatio-temporal patterns of channel changes in response to a major flood event: the case of the Magra River (Central-Northern Italy). Earth Surf. Process. Landf. 40, 326–339.
Phillips, J.D., Van Dyke, C., 2016. Principles of geomorphic disturbance and recovery in response to storms. Earth Surf. Process. Landf. 41 (7), 971–979. https://doi.org/10.1002/esp.3912.
Piégay, H., Chabot, A., Le Lay, Y.-F., 2020. Some comments about resilience: from cyclicity to trajectory, a shift in living and nonliving system theory. Geomorphology 367.
Piégay, H., Darby, S.E., Mosselman, E., Surian, N., 2005. A review of techniques available for delimiting the erodible river corridor: a sustainable approach to managing bank erosion. River Res. Appl. 21, 773–789. https://doi.org/10.1002/rra.881.
Piton, G., Cohen, M., Flipo, M., Nowak, M., Chapuis, M., Melun, G., Robert, Y., Andréis, N., Liébault, F., 2024. Large in-stream wood yield during an extreme flood (storm Alex, October 2020, Roya Valley, France): estimating the supply, transport, and deposition using GIS. Geomorphology 446, 108981. https://doi.org/10.1016/j.geomorph.2023.108981.
Pitscheider, F., Steger, S., Cavalli, M., Comiti, F., Scorpio, V., 2024. Areas simultaneously susceptible and (dis-)connected to debris flows in the Dolomites (Italy): regional-scale application of a novel data-driven approach. J. Maps 20 (1), 1–14. https://doi.org/10.1080/17445647.2024.2307549.
Räpple, B., Piégay, H., Stella, J.C., Mercier, D., 2017. What drives riparian vegetation encroachment in braided river channels at patch to reach scales? Insights from annual airborne surveys (Drôme River, SE France, 2005–2011). Ecohydrology 10, e1886. https://doi.org/10.1002/eco.1886.
Rickenmann, D., Badoux, A., Hunzinger, L., 2016. Significance of sediment transport processes during piedmont floods: the 2005 flood events in Switzerland. Earth Surf. Process. Landf. 41, 224–230. https://doi.org/10.1002/esp.3835.
Righini, M., Surian, N., Wohl, E., Marchi, L., Comiti, F., Amponsah, W., Borga,M., 2017. Geomorphic response to an extreme flood in two Mediterranean rivers (northeastern Sardinia, Italy): analysis of controlling factors. Geomorphology 290, 184–199. doi: https://doi.org/10.1016/j.geomorph.2017.04.014.
Rinaldi, M., Amponsah, W., Benvenuti, M., Borga, M., Comiti, F., Lucìa, A., Marchi, L., Nardi, L., Righini, M., Surian, N., 2016a. An integrated approach for investigating geomorphic response to extreme events: methodological framework and application to the October 2011 flood in the Magra River catchment. Italy. Earth Surf. Process. Landf. 41, 835–846. https://doi.org/10.1002/esp.3902.
Rinaldi, M., Gurnell, A.M., González del Tánago, M.G., Bussettini, M., Hendriks, D., 2016. Classification of river morphology and hydrology to support management and restoration. Aquat. Sci. 78, 17–33. https://doi.org/10.1007/s00027-015-0438-z.
Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2013. A method for the assessment and analysis of the hydromorphological condition of Italian streams: the Morphological Quality Index (MQI). Geomorphology 180–181, 96–108.
Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2015. A methodological framework for hydromorphological assessment, analysis and monitoring (IDRAIM) aimed at promoting integrated river management. Geomorphology 251, 122–136.
Romagna, Arpae Emilia, 2016. Rapporto sull'evento alluvionale del 2015 1–44. https://ambiente.regione.emilia-romagna.it/it/geologia/geologia/dissesto-idrogeologico/rapporti-sulle-frane/rapporto-evento-alluvionale-14-09-2015.
Ruiz-Villanueva, V., Badoux, A., Rickenmann, D., Böckli, M., Schläfli, S., Steeb, N., Stoffel, M., Rickli, C., 2018. Impacts of a large flood along a mountain river basin: the importance of channel widening and estimating the large wood budget in the upper Emme River (Switzerland). Earth Surface. Dynamics 6, 1115–1137. https://doi.org/10.5194/esurf-2018-44.
Ruiz-Villanueva, V., Piégay, H., Scorpio, V., Bachmann, A., Brousse, G., Cavalli, M., Comiti, F., Crema, S., Fernández, E., Furdada, E.G., Hajdukiewicz, H., Lucía, A., Marchi, L., Moraru, A., Piton, G., Rickenmann, D., Righini, M., Surian, N., Yassine, R., Wyżga, B., 2023. River widening in mountain and foothill areas during floods: Insights from a meta-analysis of 51 European Rivers. Sci. Total Environ. 903, 166103 https://doi.org/10.1016/j.scitotenv.2023.166103.
Scorpio, V., Piégay, H., 2021. Is afforestation a driver of change in italian rivers within the Anthropocene era? Catena 198, 105031. https://doi.org/10.1016/j.catena.2020.105031.
Scorpio, V., Crema, S., Marra, F., Righini, M., Ciccarese, G., Borga, M., Cavalli, M., Corsini, A., Marchi, L., Surian, N., Comiti, F., 2018. Basin-scale analysis of the geomorphic effectiveness of flash floods: a study in the northern Apennines (Italy). Sci. Total Environ. 640–641, 337–351. https://doi.org/10.1016/j.
Scorpio, V., Andreoli, A., Zaramella, M., Moritsch, S., Theule, J., Dell'Agnese, A., et al., 2020. Restoring a glacier-fed river: past and present morphodynamics of a degraded channel in the Italian Alps. Earth Surf. Process. Landf. 45 (12), 2804–2823. Available from: https://doi.org/10.1002/esp.4931.
Scorpio, V., Cavalli, M., Steger, S., Crema, S., Marra, F., Zaramella, M., Borga, M., Marchi, L., Comiti, F., 2022. Storm characteristics dictates sediment dynamic and geomorphic changes in mountain channels: a case study in the Italian Alps. Geomorphology 403, 108173. https://doi.org/10.1016/j.geomorph.2022.108173.
Sear, D.A., 1996. Sediment transport processes in pool–riffle sequences. Earth Surf. Process. Landf. 21, 241–262.

Steger, S., Scorpio, V., Comiti, F., Cavalli, S., 2022. Data-driven modelling of joint debris flow release susceptibility and connectivity. Earth Surf. Process. Landf. 47 (11), 2740–2764. https://doi.org/10.1002/esp.5421.

Stoffel, M., Wyżga, B., Marston, R.A., 2016. Floods in mountain environments: a synthesis. Geomorphology 272, 1–9. https://doi.org/10.1016/j.geomorph.2016.07.008.

Surian, N., Barban, M., Ziliani, L., Monegato, G., Bertoldi, W., Comiti, F., 2015. Vegetation turnover in a braided river: frequency and effectiveness of floods of different magnitude. Earth Surf. Process. Landf. 40, 542–558. https://doi.org/10.1002/esp.3660.

Surian, N., Righini, M., Lucìa, A., Nardi, L., Amponsah, M., Benvenuti, M., Borga, M., Cavalli, M., Comiti, F., Marchi, L., Rinaldi, M., Viero, A., 2016. Channel response to extreme floods: insights on controlling factors from six mountain rivers in northern Apennines Italy. Geomorphology 272, 78–91. https://doi.org/https://doi.org/10.1016/j.geomorph.2016.02.002.

Thompson, C., Croke, J., 2013. Geomorphic effects, flood power, and channel competence of a catastrophic flood in confined and unconfined reaches of the upper Lockyer valley, Southeast Queensland, Australia. Geomorphology 197, 156–169.

Thoms, M.C., Piégay, H., Parsons, M., 2018. What do you mean, 'resilient geomorphic systems'? Geomorphology 305, 8–19. https://doi.org/10.1016/j.geomorph.2017.09.003.

Toone, J., Rice, S.P., Piégay, H., 2014. Spatial discontinuity and temporal evolution of channel morphology along a mixed bedrock-alluvial river, upper Drôme River, Southeast France: Contingent responses to external and internal controls. Geomorphology 205, 5–16.

Wohl, E.E., 1992. Bedrock benches and boulder bars: floods in the Burdekin Gorge of Australia. Geol. Soc. Am. Bull. 104 (6), 770–778.

Wohl, E., Rathburn, S., 2013. Guest Editorial: introduction to special issue on historical range of variability. Earth Surf. Process. Landf. 38, 213–2016. https://doi.org/10.1002/esp.3357.