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An overview of geomorphic responses to high-magnitude floods: insights into river dynamics and implications for hazard mapping

Abstract: Brenna A., Surian N., *An overview of geomorphic responses to high-magnitude floods: insights into river dynamics and implications for hazard mapping.* (IT ISSN 0391-9838, 2025). In recent decades, the frequency of high magnitude floods has increased across many regions of the world. Such events can trigger geomorphological processes that significantly alter river channels and floodplains, with important implications for flood hazard. This is especially relevant in mountainous and hilly areas, where channel dynamics (e.g., major widening) and sediment transport (e.g., debris floods) play a key role in shaping flood risk. This paper provides an overview of major scientific advancements related to two core aspects: (i) understanding how river channels respond geomorphologically to extreme flood events, and (ii) developing geomorphic tools for assessing and mapping flood-related hazards. Beyond hydraulic variables like stream power, several geomorphic factors are critical in driving channel changes during floods. Key controls include lateral confinement and sediment availability, while the type of sediment transport (e.g., debris floods versus normal water flows) can greatly influence the extent of channel widening. In highly dynamic systems, flood hazard stems not only from inundation but also from channel instability. Recent tools such as morphodynamic corridors delineation have shown promise in predicting these dynamics, although their application remains limited compared to traditional hydraulic methods. Integrating geomorphic approaches into land-use planning and river management can improve hazard assessment by considering the natural variability and evolution of river systems, ultimately supporting more resilient communities and infrastructure.

Key words: Extreme hydrological events, Debris flood, Channel widening, Geomorphic hazard, Mountain streams.

Riassunto: Brenna A., Surian N., *Una panoramica delle risposte geomorfologiche alle piene di elevata intensità: approfondimenti sulla dinamica fluviale e implicazioni per la rappresentazione cartografica della pericolosità.* (IT ISSN 0391-9838, 2025). Negli ultimi decenni, la frequenza delle piene di elevata magnitudo è aumentata in molte regioni del mondo. Tali eventi sono in grado di innescare processi geomorfologici che modificano in modo sostanziale gli alvei fluviali e le relative piane inondabili, con importanti implicazioni in termini di pericolosità. Ciò è particolarmente rilevante nelle aree montane e collinari, dove la dinamica fluviale (es., allargamento degli alvei fluviali) e il trasporto solido (es., piene di detrito) svolgono un ruolo chiave nel determinare il rischio alluvionale. Questo lavoro fornisce una panoramica dei principali avanzamenti scientifici relativi a due aspetti fondamentali, ovvero: (i) comprendere come gli alvei fluviali rispondano da un punto di vista geomorfologico agli eventi di piena, e (ii) sviluppare approcci geomorfologici per la valutazione e la rappresentazione cartografica della pericolosità associata alle piene estreme. Oltre alle variabili idrauliche, fra le quali la potenza della corrente, diversi fattori geomorfologici risultano determinanti nell'influenzare le risposte morfologiche (es., allargamento) degli alvei durante le piene. Tra i principali fattori di controllo si annoverano il grado di confinamento laterale e la disponibilità di sedimenti. Anche la tipologia di fenomeni di trasporto solido (es., piene di detrito rispetto a flussi idrici ordinari) può influenzare in modo sostanziale l'entità della risposta morfologica. Nei corsi d'acqua più dinamici la pericolosità indotta dagli eventi di piena deriva non solo dai fenomeni di esondazione e allagamento, ma anche dall'instabilità morfologica dell'alveo. Strumenti recentemente sviluppati in ambito accademico, fra i quali i "corridoi morfodinamici", hanno mostrato una sostanziale efficacia nel prevedere e rappresentare cartograficamente tali dinamiche. Ciò detto, il loro impiego rimane ancora fortemente limitato rispetto ai metodi idraulici tradizionali. Integrare l'utilizzo di approcci geomorfologici nella pianificazione territoriale e nella gestione fluviale può migliorare la valutazione della pericolosità e contribuire in ultima analisi allo sviluppo di comunità e infrastrutture più resilienti.

Termini chiave: Piene estreme, Piene di detrito, Allargamento degli alvei, Pericolosità geomorfologica, Torrenti montani.

INTRODUCTION

During high-magnitude floods, including those classified as "extreme hydrological events", a river may undergo geomorphological dynamics that can significantly exceed those observed under ordinary hydrological conditions, that is, in relation to events with a high probability of oc-

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currence (Phillips, 2002; Magilligan *et al.*, 2015; Hooke, 2016; Ruiz-Villanueva *et al.*, 2023; Davidson *et al.*, 2024). Intense processes such as bank erosion, avulsion (e.g., Grove *et al.*, 2013) and sediment and wood transport (e.g., Eaton and Lapointe, 2001; Comiti *et al.*, 2016a) can substantially alter the morphological configuration of river channels, affecting both their planimetric features (e.g., Krapesch *et al.*, 2011) and altimetric characteristics (e.g., Hauer and Habersack, 2009; Scorpio *et al.*, 2022).

High-magnitude hydrological events have attracted the attention of many researchers aiming to understand their role in determining the overall river dynamics (e.g., how and for how long such events influence the evolutionary trajectory of a river), and to identify the key hydraulic (e.g., unit stream power, flood duration) and geomorphological (e.g., lateral confinement, sediment sources and their connectivity) factors that may lead to remarkable morphological changes (e.g., Magilligan, 1992; Langhammer, 2010; Dean and Schmidt, 2013; Belletti *et al.*, 2014; Surian *et al.*, 2016). Having said that, it is evident that these flood-triggered geomorphic dynamics also have significant implications in terms of hazard and, particularly in anthropized areas, in terms of risk (Mazzorana *et al.*, 2011). Especially in mountain streams and in dynamic rivers (e.g., braided rivers), channel dynamics can represent a crucial factor for flood hazard mapping and risk mitigation (Mazzorana *et al.*, 2013). In such contexts, the most significant damages are often caused by intense channel changes such as widening processes, which may affect the entire valley floor (Ruiz-Villanueva *et al.*, 2018), and intense sediment transport of coarse particles, which can occur as debris floods or debris flows (Rickenmann and Koschni, 2010; Brenna *et al.*, 2020; Jakob *et al.*, 2022). For this reason, scientific research has advanced internationally to develop approaches and tools aimed at delineating and mapping geomorphological hazard from flood events (e.g., Graf, 2000; Biron *et al.*, 2014; Rinaldi *et al.*, 2015; Mishra and Sinha, 2020).

This paper aims to provide an overview of the most relevant scientific advancements achieved at the international level concerning two main aspects: (i) the understanding of channel geomorphic dynamics (i.e., processes and the relative channel changes) in response to high-magnitude flood events, and (ii) the development of geomorphic approaches and tools aimed to assessing and mapping flood geomorphological hazards. In this context, the main focus is on mountain streams and dynamic alluvial rivers. The paper primarily relies on recently published studies while also presenting some original results from ongoing research carried out by the authors. Lastly, this paper discusses the main knowledge gaps that warrant further research efforts, as well as the current limitations in applying available geomorphological tools to land-use planning and river management processes, particularly in the assessment of geomorphological hazard and risk in the Italian context.

CHANNEL DYNAMICS IN RESPONSE TO HIGH-MAGNITUDE FLOODS

The role of high-magnitude floods on determining abrupt channel changes

In accordance with the classical concept of Lane's balance (Lane, 1956; Dust and Wohl, 2012), the morphology of an alluvial river, organized according to geomorphic units (see Belletti *et al.*, 2017) that generate a specific assemblage with planimetric characteristics (e.g., active channel width, number of flow channels separated by sediment bars) and altimetric features (e.g., cross-sectional geometry), results from the interaction over time between two key controlling variables: the water discharge regime and sediment supply, whose combination determines the sediment transport regime (Thorne, 1997; Church, 2006). This regime operates through processes of entrainment, transport, and temporary deposition of alluvial material, under the influence of the grain size distribution of the available sediment. Additionally, the resulting morphology of alluvial channels is also influenced by local boundary conditions, such as valley longitudinal slope, the space available for channel migration as determined by confinement elements (e.g., valley sides) (Fryirs *et al.*, 2016), the characteristics and grow rate of riparian vegetation (Gurnell, 2014; Gurnell *et al.*, 2016) and, not least, the presence of anthropogenic structures (e.g., filtering dams, bank protections) or interventions (e.g., in-channel mining) (Surian *et al.*, 2011; Surian, 2022; Scorpio *et al.*, 2024).

Due to their extreme conditions in terms of energy (e.g., in terms of unit stream power), high-magnitude floods represent impulsive events that, over relatively short timescales, can substantially alter the sediment discharge regime affecting both the riverbed material dynamics and the alluvial sediments within the fluvial corridor (e.g., Inman and Jenkins, 1999; Moody and Meade, 2008; Dean and Schmidt, 2013; Thompson and Croke, 2013; Mao, 2018; Dumitriu, 2020). Intense flood events can also modify some of the previously mentioned riverine boundary conditions, such as by uprooting and removing riparian vegetation (Edmaier *et al.*, 2015; Garssen *et al.*, 2017), activating new sediment sources, including gully erosion, landslides and debris flows connected to the fluvial network (Korup, 2004; Rickenmann and Koschni, 2010; Mirzaee *et al.*, 2024; Bennett *et al.*, 2025), or modifying the natural confinement (Lapointe *et al.*, 1998; Liébault *et al.*, 2024). Finally, the mechanisms responsible for sediment mobilization and transport during high-magnitude floods may differ from those associated with normal water flows carrying bedload and suspended load typical activated in a river by ordinary competent floods (Brenna *et al.*, 2021). Under such hydrological and energetic conditions, given sufficient sediment supply, highly intense sediment–water flow types exhibiting specific rheological characteristics can be triggered, such as hyperconcentrated flows (dominated by suspended sediment transport; see Beverage and Culbertson, 1964), debris floods (dominated by bedload transport; see Church and Jakob, 2020), and even channelized debris flows (Rickenmann and Koschni, 2010).

In light of this, it becomes clear how high-magnitude floods, through the activation of the various processes mentioned above, represent a type of event capable of causing remarkable morphological changes in river channels and fluvial corridors. Such modifications can occur both in planform and elevation through a wide range of responses, including channel widening (Krapesch *et al.*, 2011), changes in riverbed elevation, channel position, and planform pattern (Sloan *et al.*, 2001; Scoprio and Comiti, 2024), extensive bar formation (Hagstrom *et al.*, 2018), erosion and construction of islands (Belletti *et al.*, 2014), meander migration, cutoff and occurrence of local or catastrophic avulsions (Gearon *et al.*, 2024), bank erosion (Grove *et al.*, 2013), and the reworking of floodplains or fluvial terraces (Moody and Meade, 2008; Hauer and Habersack, 2009).

Among the channel changes triggered by high-magnitude floods, a primary role is played by channel widening, which refers to an increase in the area within a fluvial corridor occupied by low-flow channels and sediment bars (Liébault and Piégay, 2002), whose shape and dynamics are directly controlled by riverbed material transport processes (i.e., bed material load, following Church, 2006). Such abrupt channel widenings can occur through various specific processes (Scorpio *et al.*, 2018), among which the most significant are: (i) bank erosion, induced by the removal of particles through flow entrainment or by sloughing and collapse due to slumping (Davis and Gregory, 1994; Grove *et al.*, 2013) (figs 1a and 1b), and (ii) the reactivation of floodplains (i.e., a geomorphic unit within the fluvial corridor but outside the active channel) due to intense overbank transport of riverbed materials, leading to scouring and deposition processes that generate new incised channels within it (Magilligan *et al.*, 2015) (figs 1c and 1d). Channel widening is one of the most risk-inducing phenomena triggered during high-magnitude floods (Comiti *et al.*, 2016b),

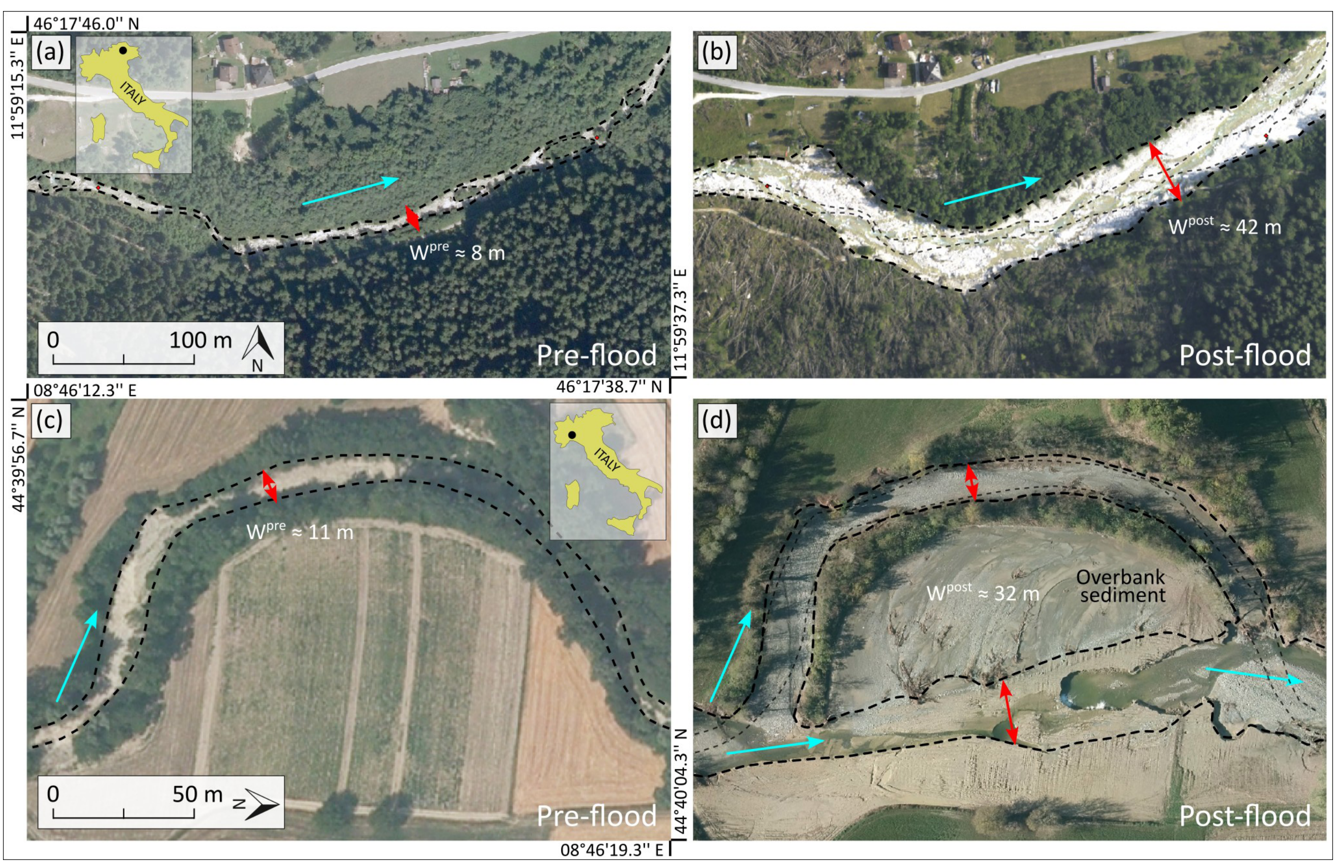

Figure 1 - Examples of channel widenings induced by high-magnitude floods. (a) and (b) refer to the pre-event (2015 aerial photograph) and post-event (2019 aerial photograph) conditions, respectively, of the Tegnas Torrent (Veneto Region, Italy) in relation to the Vaia Storm of October 2018 (see Brenna et al., 2021 for further details). The channel widening is quantifiable with a local width ratio of approximately 5.7 and was primarily induced by bank erosion processes. (c) and (d) refer to the pre-event (2012 aerial photograph) and post-event (2019 aerial photograph) conditions, respectively, of the Albedosa Creek (Piemonte Region, Italy) in relation to the October 2019 flood event (see Mandarino et al., 2021 for further details). The channel widening is quantifiable with a local width ratio of approximately 2.9 and was mainly driven by overbank flooding, coarse sediment transport onto the floodplain and the incision of a new cutoff channel. The dashed black lines delineate the active channel, while the blue arrows indicate the flow direction.

as it can directly impact human features within fluvial corridors (e.g., anthropized valley floors). Moreover, the characterization and quantification of channel widening– expressed in absolute values or as a width ratio (WR), usually calculated at the homogeneous river reach (*sensu* Brierley and Fryirs, 2005) spatial scales as the ratio between active channel widths measured after – W^{post} – and before – W^{pre} – the flood (Krapesch *et al.*, 2011) – is relatively simple compared to the assessment of elevation changes. This is because it mostly relies on remotely sensed planimetric data (e.g., aerial, drone or high-resolution satellite images acquired before and after the flood event), which are more readily available than altimetric data such as topographic sections or Digital Elevation Models (DEMs). For these reasons, the majority of studies on the morphological responses of rivers to floods have focused on assessing this specific channel change, aiming to identify the controlling factors that drove the observed widenings (see Ruiz-Villanueva *et al.*, 2023, and references therein).

Investigating controlling factors on channel widening

Empirical observations conducted over the past decades across numerous case studies have highlighted a wide spectrum of channel widening in response to high-magnitude floods (Ruiz-Villanueva *et al.*, 2023). Width ratios (WR) measured at the reach or sub-reach spatial scale range from minimal (close to 1, indicating no width change) to moderate (WR approximately 2-4) and even intense (WR > 4) or extremely pronounced (WR up to 15-20). Many authors have focused their research on identifying the primary controlling factors that influence the occurrence of more or less intense channel morphological variations, also in a perspective of effective flood hazard assessment and risk management.

The first factors investigated concerned the hydraulic forcing, primarily determined by the hydrological characteristics of the flood event, which represents the energy available over relatively short time scales to drive morphodynamics within a river channel (e.g., Magilligan, 1992; Magilligan *et al.*, 1998; Cenderelli and Wohl, 2003). Among the various parameters considered – including flow discharge, competence, and velocity, shear stress and dimensionless shear stress (e.g., Lenzi *et al.*, 2006; Reid *et al.*, 2019) – stream power and unit stream power have played a particularly significant role (Magilligan, 1992). Stream power (Ω) is the amount of energy the water flowing in a channel exerts on its sides and bottom. When Ω is divided by channel width (w, in m), unit stream power (ω, in W m^{-2}) is obtained (Bagnold, 1977; 1980; Ferguson, 2005) as:

$$\omega = (\rho g Q S) / w \qquad \text{(Eq. 1)}$$

where ρ denotes the water density (kg m^{-3}), g represents the gravity acceleration (9.81 m s^{-2}), Q is the water discharge (m^3 s^{-1}), S is the channel slope (m/m). If the maximum Q occurred at the peak of a flood event is considered (Q_{pk}), the resulting unit stream power calculated for a river section is defined as peak unit stream power (ω_{pk}).

Despite the large number of case studies considered, the observed association between the magnitude of hydraulic parameters alone and the resulting flood geomorphic effectiveness in terms of channel changes remains vague and non-deterministic (e.g., Magilligan *et al.*, 1998; Sambrook Smith *et al.*, 2010). A milestone in this topic was the work of Costa and O'Connor (1995), which was fundamental in conceptualizing the role of flood magnitude and duration in determining geomorphic changes. Their study on flood hydrology and geomorphology following dam failures in the USA have documented exceptionally high peak unit stream power. However, the downstream impacts on channel morphologies remained minimal (i.e., low width ratios), primarily due to the short duration of those floods, which lasted only a few minutes. To better assess the geomorphic effectiveness of floods, a unit stream power graph, that is a representation of distribution of unit stream power over time, provides a more comprehensive representation of flood potential than peak flow magnitude alone. From such graph, total energy expenditure over a flood hydrograph can be calculated, although its effectiveness in driving geomorphic change depends on channel resistance. Costa and O'Connor (1995) developed a conceptual model integrating unit stream power graphs and channel resistance thresholds to better differentiate flood effectiveness in shaping river channels. This model identifies three primary flood types: (i) Long-duration floods with moderate to high energy expenditure but low peak stream power (curve A in fig. 2), which are ineffective in modifying alluvial or bedrock channels; (ii) Medium to long-duration floods with high peak stream power and large total energy expenditure (curve B in fig. 2), which are the most geomorphologically effective due to the optimal combination of power, duration, and energy; (iii) Short-duration floods with high peak stream power but low total energy expenditure (curve C in fig. 2), which, despite their extreme peak values, fail to induce notable geomorphic changes due to their short duration.

It is interesting to note that in the conceptual model by Costa and O'Connor (1995), which is predominantly focused on the combination of hydraulic factors, reference is nonetheless made to an "energy threshold required to trigger geomorphic modifications" (fig. 2), defined as channel resistance. In our view, this initial indication provides a basis for subsequent investigations into the role of boundary conditions, or directly controlling factors, of geomorphological and geological nature in determining the morphogenetic effectiveness of a flood event. Key studies, such as those by Heritage *et al.* (2004), Langhammer (2010), Krapesch *et al.* (2011), Dean and Schmidt (2013), Thompson and Croke (2013), Buraas *et al.* (2014), Magilligan *et* *al.* (2015), and Nardi and Rinaldi (2015), asserted that hydraulic variables alone cannot fully explain a river's morphological response to hydrological events. The authors emphasized the importance of considering additional factors, such as human structures that can constrain channel mobility and floodplain reworking (e.g., bank protections, levees), bedload supply, pre-flood channel arrangement, and lateral confinement, to accurately predict channel's widening in response to a large flood.

In light of this, Rinaldi *et al.* (2016a) developed an integrated approach to investigating the geomorphic responses of rivers to high-magnitude floods. This approach considers a set of key hydraulic and geomorphological factors related to pre-flood conditions (e.g., the extent of the alluvial plain, the presence of artificial structures, the sedimentological characteristics of the channel), event characteristics (e.g., hydraulic and hydrological parameters, sediment delivery, wood dynamics) and post-flood evidence (e.g., field analysis of fluvial deposits, remote sensing mapping of planform channel changes) that can contribute to identifying the most critical reaches in terms of potential widening. Applying the aforementioned integrated approach to investigate the geomorphic responses of rivers in the Italian Apennines to extreme hydrological events, Surian *et al.* (2016) and Scorpio *et al.* (2018) highlighted the need of simultaneously examining multiple controlling factors. Their findings indicate that peak unit stream power, calculated based on the pre-flood channel width (Equation 1), along with lateral confinement (calculated as confinement index = alluvial plain width / pre-event channel width), are the most significant factors in explaining channel widening (fig. 3). In general terms, an increase in unit stream power corresponds to an increase in the width ratio (fig. 3a). Conversely, a higher lateral confinement as determined by the presence of valley slopes or elevated terraces (indicated by a decrease in the numerical value of the confinement index) generally results in reduced channel widening (fig. 3b). Additionally, they identified weaker relationships between channel width ratios and both the percentage of river reach length protected by artificial structures and the sediment supply area.

The mentioned research has significantly enhanced our understanding of how fluvial systems respond to high-magnitude floods. However, the ability to accurately predict morphological changes at finer spatial scales, such as individual river sub-reaches, remains challenging. This limitation is evident from the performance metrics of multiple regression models that relate channel widening to hydraulic and morphological controlling factors (Comiti *et al.*, 2016b; Surian *et al.*, 2016; Scorpio *et al.*, 2018). While the combination of unit stream power and the confinement index, potentially combined with other factors (e.g., bank protection structures), provides insights into general trends, it can still result in a wide range of channel responses at the local spatial scale (i.e., varying width ratios; see fig. 3).

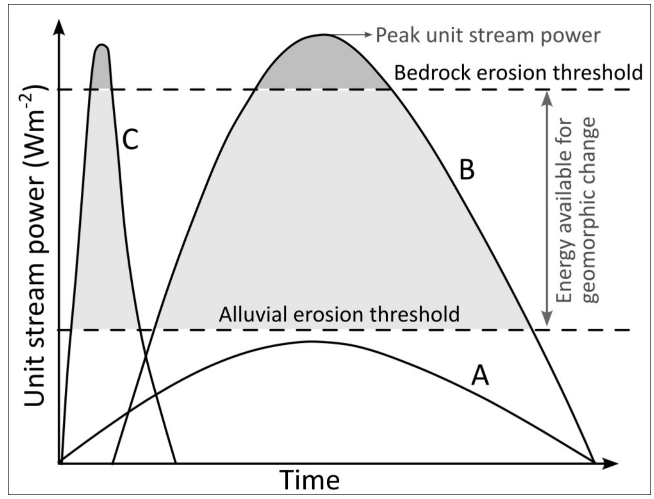

Figure 2 - Conceptual model of Costa and O'Connor (1995) describing the relative role of flow duration and unit stream power in generating channel geomorphic changes. Refer to the text for details on the types of flood events represented by curves A, B, and C.

The role of sediment transport processes in driving intense channel widening

Among the factors identified by Rinaldi *et al.* (2016a) for the effective characterization, interpretation, and ultimately prediction of geomorphic responses to a flood event, the recognition of sediment transport processes occurring along a stream during high-magnitude floods has long been the least thoroughly considered aspect in the geomorphological literature. The main limitation arises from the common assumption that sediment transport processes occur exclusively in the form of clear water flows (also referred to as streamflow or normal streamflow; Pierson and Costa, 1987), involving bedload and suspended load (Nones, 2019). However, it is known that, particularly during high-magnitude events, sediment transport can occur through different mechanisms, namely highly intense sediment–water flow types with high densities such as hyperconcentrated flows, debris floods, and channelized debris flows (Li *et al.*, 1997; Rickenmann and Koschni, 2010; Bodoque *et al.*, 2011; Church and Jakob, 2020; Brenna *et al.*, 2020, 2021; Jakob *et al.*, 2022). This limitation is primarily due to the challenges associated with field characterization of such intense transport processes, particularly during their occurrence, as well as the lack of numerical models capable of effectively simulating them (e.g., Ferguson and Church, 2009; Alexander and Cooker, 2016). Nevertheless, it is evident that sediment transport processes can play a crucial role in the morphological response of river channels to large floods. Such processes govern erosion and aggradation patterns during high flows, drive the migration of macroforms, and contribute to defining thresholds for bank erosion and channel instability. Given their significant influence on channel morphology, sediment transport processes can also shape the channel geometry established during floods and should therefore be accounted for in order to improve the accuracy of predictions related to abrupt channel widening, especially for local and detailed evaluations (see Vázquez-Tarrío *et al.*, 2024, and references therein).

In recent years, Brenna *et al.* (2020, 2021, 2023) have focused particularly on the morphogenetic role of debris floods, defined as "water-driven flood flows with high bedload transport" (Church and Jakob, 2020), during which the streambed may be completely destabilized, causing massive movement of sediment (Hungr *et al.*, 2014) mobilized as a slurry-like flow, which can be characterized as an incipient granular mass flow (Manville and White, 2003). Debris floods are a common phenomenon in high-gradient channels with abundant coarse sediment (e.g., mountain streams). Their occurrence is typically triggered during extreme flood events in response to intense hydrological forcing or downstream of tributaries that supply large volumes of mobile and freshly eroded sediment to the receiving stream (Brenna *et al.*, 2021). Church and Jakob (2020) and Jakob *et al.* (2022) observed that debris floods often lead to extraordinary channel widening due to extensive bank erosion. Supporting this notion, preliminary findings by Brenna *et al.* (2021), who investigated channel changes in a stream in the Dolomites (Italy) following the severe flood event of October 2018 (Vaia Storm; see figs 1a and 1b), revealed that, for the same unit stream power, channel widening in reaches affected by debris floods was two to three times greater than in sites that at the same peak unit stream power experience ordinary water flows (fig. 4). Their analysis was based on post-event geomorphological and sedimentological field surveys of flood deposits con-

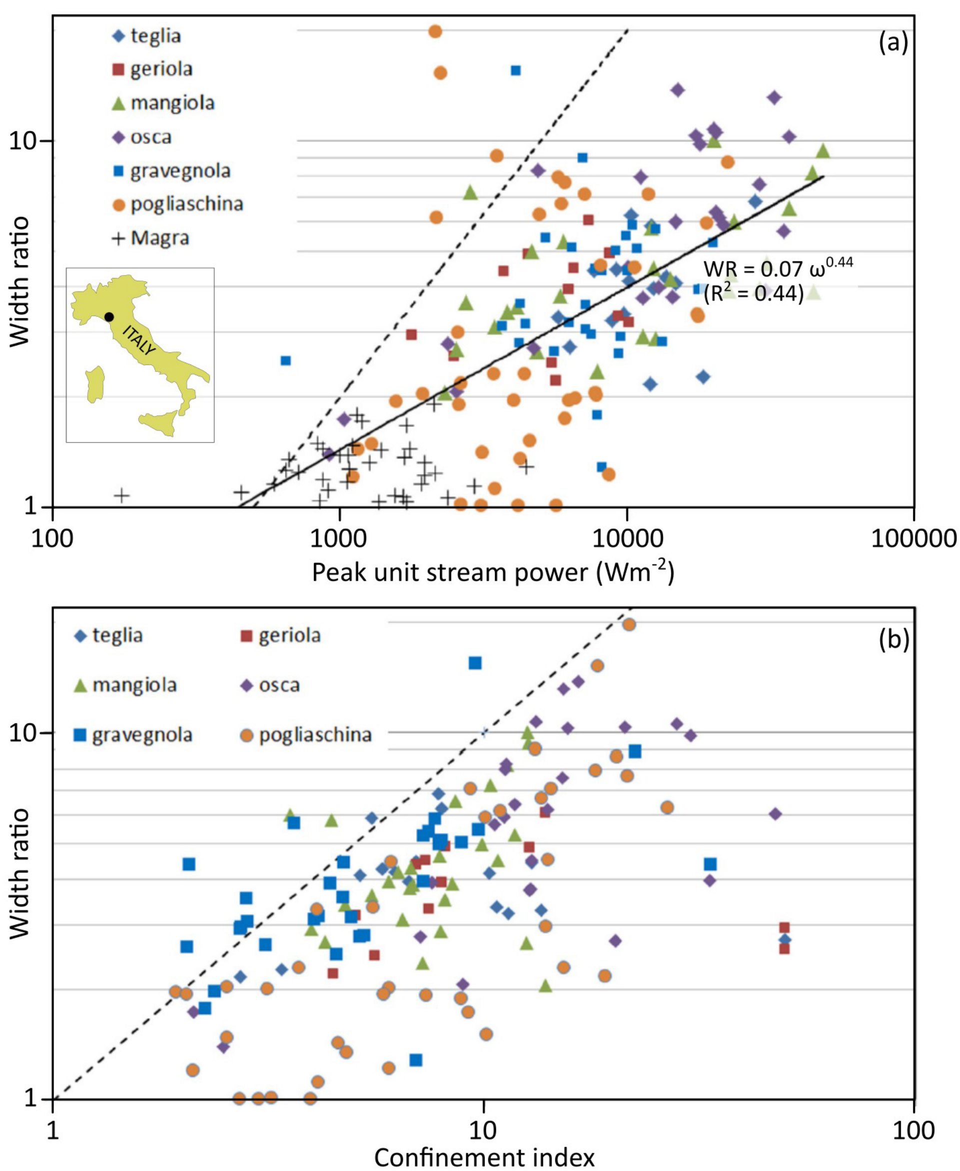

Figure 3 - Scatterplots of width ratio versus (a) unit stream power calculated based on the pre-event channel width and (b) confinement index (i.e., alluvial plain width / pre-event channel width) for the study reaches investigated by Nardi and Rinaldi (2015), Comiti *et al.* (2016b) and Surian *et al.* (2016) in rivers of the Norther Apennines (Italy) affected by a high-magnitude flood in October 2011. The solid line represents the best fit equation; the dashed lines represent the upper envelope curve (a) and the 1:1 relationship (b).

ducted following the protocol developed by Brenna *et al.* (2020), which allowed them to determine the dominant transport processes (i.e., clear water flows, debris floods and debris flows) triggered at the local scale during the flood. This result suggests that, in addition to the classic hydraulic (e.g., unit stream power) and geomorphological (e.g., lateral confinement) controlling factors, the flow type may also be a critical variable for accurately characterizing and predicting abrupt channel widening at the river reach scale.

Expanding the dataset, Brenna *et al.* (2023) further investigated the role of debris floods in driving extreme channel widening during high-magnitude events. Based on a series of observations from the Cordevole River basin (Dolomites, Italy), these authors found that, although statistically significant relationships exist among width ratio, pre-flood unit stream power, and channel confinement, a considerable number of river sub-reaches that experienced intense widening (defined as width ratio > 4) exhibited channel modifications far exceeding (on average +67% in terms of width ratios) the predictions provided by statistical models developed for the entire dataset. All those intensely widened sub-reaches were most likely affected by debris floods during the Vaia Storm in 2018. These findings suggest that the various flow types responsible for sediment transport in mountain rivers drive diverse morphological channel responses to flooding. Debris floods, in particular, represent a transport process that often induces substantially more intense channel changes compared to those driven by water flow alone. However, debris flood occurrence does not necessarily and automatically result in major channel widening. Indeed, other boundary conditions, such as high lateral confinement imposed by valley sides, can inhibit or significantly constrain the morphogenetic potential of debris floods.

In light of these findings, from a predictive perspective and in terms of implications for geomorphological hazard assessment, identifying the river network reaches where debris flood phenomena may occur can be crucial for evaluating the potential for intense channel widening. Indeed, predicting channel widening solely based on statistical models derived from large datasets that do not differentiate between various transport processes can lead to a significant underestimation of the channel changes occurring at specific sites potentially affected by debris floods, and consequently, an underestimation of geomorphological hazard. The potential occurrence of a debris flood at a channel site during a severe hydrological event can be reasonably hypothesized based on a detailed morphological and sedimentological characterization of the river network. In the context of mountain rivers, Brenna *et al.* (2021) highlighted that debris flood initiation is associated with high hydrological forcing capable of inducing local unit stream power exceeding approximately 4000-5000 Wm^{-2} or the presence of debris flow channels supplying large amounts of sediment to the receiving stream. Additionally, several factors can promote the occurrence of such transport processes, including steep channel slopes (e.g., > 4%), narrow channel widths (e.g., < 15 m), the presence of non-cohesive banks prone to erosion, and the absence of boulders in the riverbed that could otherwise limit its mobility. In addition to these basic criteria, morphometric (e.g., Wilford *et al.* 2004; Ilinca, 2021) and more complex holistic approaches including numerical modelling (e.g., Jakob *et al.*, 2022; Baggio *et al.*, 2024; Po *et al.*, 2024) are also being recently developed to assess the likelihood of localized debris flooding in steep streams during high-magnitude flood events. Currently, there are few studies on the potential occurrence of debris floods in the context of large gravel-bed rivers. While theoretically possible (Church and Jakob, 2020), the wide channel cross-sections and relatively low gradients are conditions that do not promote reaching of high unit stream power values, even during extreme hydrological events, and thus in triggering such processes.

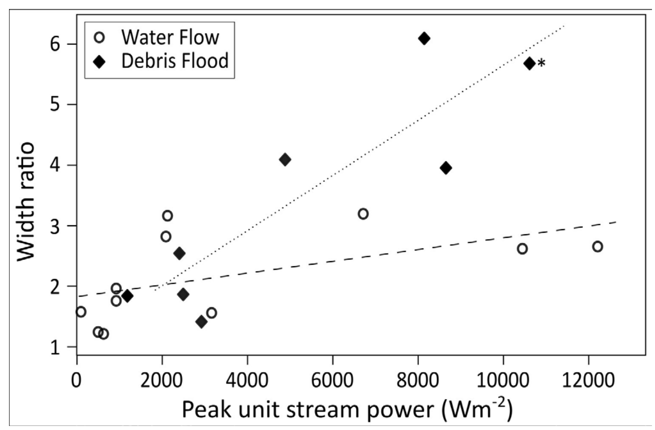

Figure 4 - Scatterplot of width ratio versus unit stream power calculated based on the pre-event channel width for the study reaches investigated by Brenna *et al.* (2021) in the Tegnas Torrent (Dolomites, Italy) affected by a high-magnitude flood in October 2018. Reaches affected by water flow and debris flood during the event are differentiated. Dashed and dotted lines are linear regression lines determined between the width ratios and peak unit stream power for reaches affected by water flows and debris floods, respectively. The asterisk (*) indicates the reach of the Tegnas Torrent shown in figs 1a and 1b.

Evidence of limited channel widening in response to high-magnitude floods

As mentioned earlier, the widening of alluvial river channels in response to high-intensity events is highly variable ranging from limited to extremely pronounced (Ruiz-Villanueva *et al.*, 2023). While many authors have focused on case studies characterized by paroxysmal morphological responses – partly due to their greater relevance in terms of hazard – we consider it valuable to present a series of case studies in which planimetric channel changes were more limited than expected. In some cases, the limited morphological changes can be attributed solely to the hydrological characteristics of flood events, where peak unit stream power values are high but of very short duration (Case C of the conceptual model by Costa and O'Connor (1995); see fig. 2). However, in other cases, even in response to intense hydrological events with sufficient energy to potentially induce notable geomorphic changes (Case B of the conceptual model by Costa and O'Connor (1995); see fig. 2), only minimal or moderate channel widening has been observed. A situation of this kind was described by Righini (2017) and Borga *et al.* (2019) in relation to the virtually absent widening of the Lierza Creek (Veneto Region, Italy) in response to an extremely intense flood that occurred in 2014. In the authors' recent experience, at least two original case studies fall into this category, for which a brief analysis based on unpublished data is provided below.

The first case considered is that of the Misa River (Marche Region, Italy; drainage area of 379 km²), which was impacted by an extreme meteorological event on September 15, 2022 (Brenna *et al.*, 2025). During this event, ap-

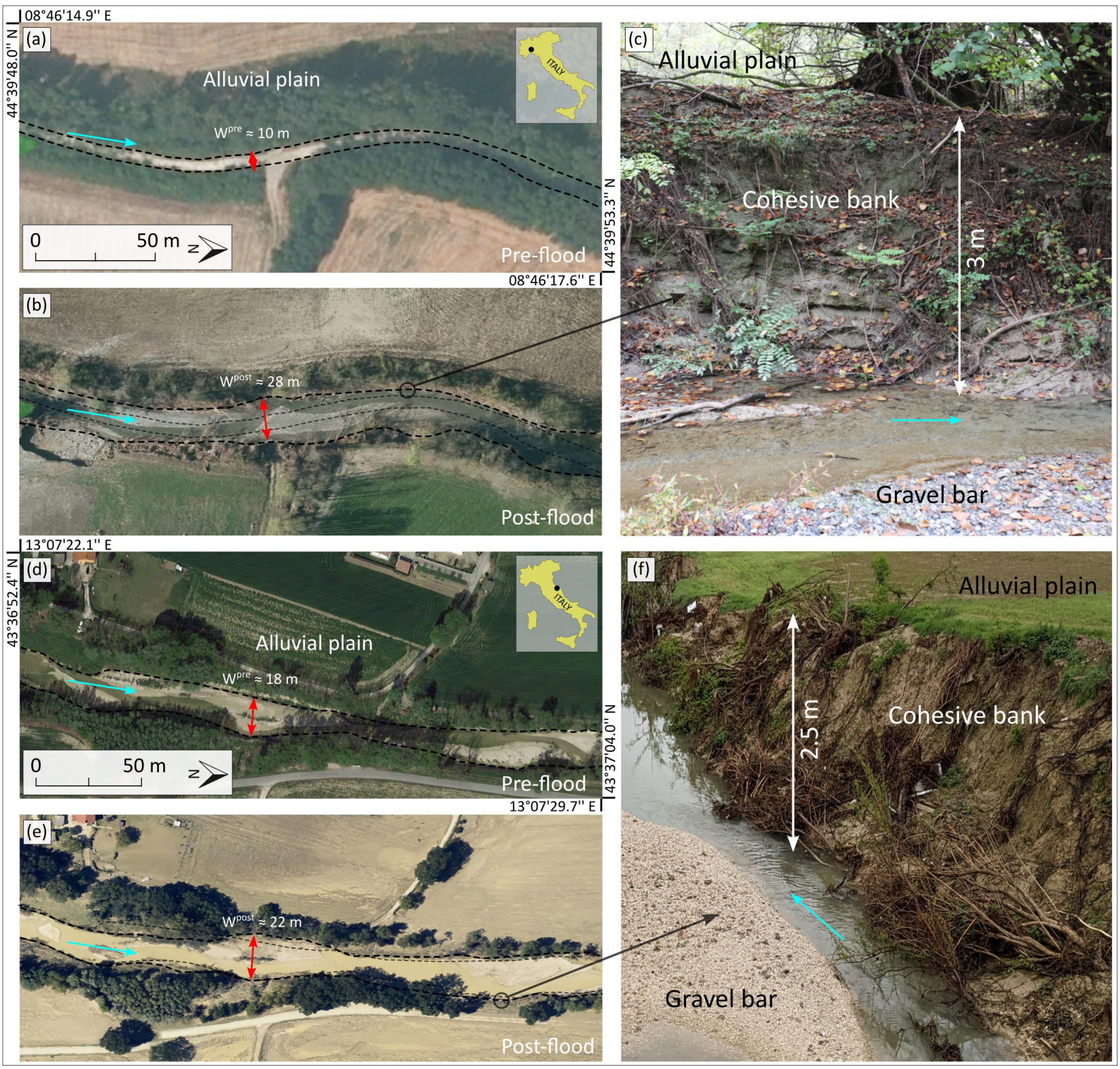

Figure 5 - Examples of moderate to limited channel widenings induced by 2019 and 2022 high-magnitude floods in the Albedosa Creek (a, b; width ratio = 2.9) and Misa River (d, e; width ratio = 1.2), respectively. The dashed black lines delineate the active channel, while the blue arrows indicate the flow direction. Panels (c) and (f) present field photographs of the cohesive banks that characterize these rivers within the study areas.

proximately 400 mm of cumulative rainfall occurred within about four hours, corresponding to an estimated return period of 1000 years (Boccanera *et al.*, 2022). This intense rainfall event triggered severe flooding in several streams along the Adriatic side of the central Apennines, including the Misa River (Morelli *et al.*, 2023). In its hilly sector, this gravel-bed river is characterized by an average slope of 0.5% and a single-thread sinuous channel morphology, with an average channel width ranging between 5 and 30 meters. The banks of the river predominantly exhibit a (sub)vertical geometry. From a compositional perspective, purely cohesive banks are dominant, alongside some composite banks where fine cohesive materials prevail, interspersed with mudstone bedrock and gravelly strata. The second case study concerns the Albedosa Creek (Piemonte Region, Italy; drainage area of 44 km²), which was impacted by an extreme meteorological event on October 21-22, 2019. In this case as well, rainfall was extremely intense, with cumulative 24-hour values approaching 500 mm and an estimated return period of approximately 500 years (ARPA Piemonte, 2019). This event triggered exceptionally intense floods in the streams of the Orba River Basin, including the Albedosa Creek (Mandarino *et al.*, 2021). The stream features a predominantly gravel-bed channel, with sand materials in its terminal segment, an average slope of 0.7%, and a single-thread sinuous channel morphology. The pre-flood average channel width consistently remains below approximately 10 meters. The banks are composed almost entirely of cohesive materials.

Channel widening, expressed in terms of width ratio (Krapesch *et al.*, 2011), was assessed by applying the standard procedure commonly adopted in similar studies (e.g., Surian *et al.*, 2016; Scorpio *et al.*, 2018; Brenna *et al.*, 2023) involving the manual digitization of the active channel before and after the flood event, followed by the calculation of corresponding channel widths. These operations were carried out using high-resolution aerial photographs or satellite images acquired in April 2022 (pre-flood) and September 2022 (post-flood) for the Misa River, and in 2012 (pre-flood) and November 2019 (post-flood) for the Albedosa Creek (fig. 5). In both cases mentioned, despite the intensity of the flood events and the relatively low lateral confinement (ranging from unconfined to partially confined), the bank erosion triggered by extreme flood events resulted in generally limited channel widening (fig. 5). The estimated with ratios range from small (with minimum average width ratios calculated at the reach scale of 1.1 and 1.4 for the Misa and Albedosa rivers, respectively) to moderate (with maximum average width ratios calculated at the reach scale of 3.1 and 3.5 for the Misa and Albedosa rivers, respectively). In the literature, it is well established that the lateral dynamics of river channels, particularly in response to flood events, can be significantly constrained when banks are predominantly composed of cohesive sediments (e.g., mud) or bedrock. This is due to the greater resistance to erosion these materials offer compared to non-cohesive coarse sediments such as sand and gravel (Simon *et al.*, 2000; Pizzuto *et al.*, 2010; Pitlick *et al.*, 2013; Konsoer *et al.*, 2016; Righini *et al.*, 2017; Borga *et al.*, 2019). The clear dominance of cohesive banks thus appears to have played a crucial role in these case studies, leading to reduced bank erosion and consequently relatively modest channel widening, despite the magnitude of the flood events. It is nevertheless interesting to highlight the occurrence of other impactful geomorphological effects, including localized avulsions and meander cutoffs (fig. 1d), the uprooting and removal of riparian vegetation by overbank flows (figs 6a-c), and the transport and deposition of coarse material onto the alluvial plain (fig. 6d-f). Such processes were likely promoted by the limited widening of the active channel inhibited by the presence of erosion-resistant cohesive banks. This, in turn, led to a consequential increase in unit stream power, concentrated within a relatively stable channel cross-section. Similar conditions leading to geomorphological processes and dynamics comparable to those described here have been reported in previous studies, including Righini (2017) and Magilligan *et al.* (2015).

In light of this evidence, it becomes clear that a comprehensive and detailed characterization of fluvial systems is essential for studying the processes induced by high-magnitude hydrological events and defining the expected morphological changes, which can represent potential sources of hazard and risk. While the importance of characterizing certain controlling factors has already been widely demonstrated and is therefore commonly considered in geomorphological studies (e.g., various hydraulic and hydrological parameters, lateral confinement), further investigations will be necessary for others (e.g., bank characteristics) in the future.

DELINEATING AND MAPPING FLOOD GEOMORPHOLOGICAL HAZARD

Geomorphic tools for channel dynamics assessment

While geomorphologists have long been interested in the effectiveness of large floods in shaping riverscapes (e.g., Bretz, 1925; Wolman and Miller, 1960; Baker, 1977), the development of geomorphological tools and methods specifically designed to assess channel dynamics and geomorphological hazard in response to intense hydrological events is a more recent advancement (e.g., Simon and Downs, 1995; Graf, 2000; Chin and Gregory, 2005; Biron *et al.*, 2014; Buffin- Bélanger *et al.*, 2015). In the European context, the development of such tools has been accelerated by the enactment of the European Union Water Framework Directive and the Floods Directive (European Commission, 2000, 2007), both of which emphasized the need

Figure 6 - Examples of geomorphological processes induced by a high-magnitude flood occurred in October 2019 in the Albedosa Creek (Piemonte Region, Italy). Panels (a) (pre-flood condition), (b) (post-flood condition), and (c) (field photograph) depict a site where significant uprooting and removal of riparian vegetation occurred due to overbank flows. Panels (d) (pre-flood condition), (e) (post-flood condition), and (f) (field photograph) illustrate a site where the transport and deposition of gravelly clasts and sands onto the alluvial plain took place. These materials formed an overbank sediment lobe, which is mapped with red lines in panel (e). The dashed black lines delineate the active channel, the green lines delineate the alluvial plain limit, while the blue arrows indicate the flow direction.

for an integrated management approach to fluvial systems that incorporates hydromorphology. In Italy, the National Institute for Environmental Protection and Research (ISPRA) developed a geomorphological framework known as IDRAIM (Sistema di valutazione IDRomorfologica, AnalisI e Monitoraggio dei corsi d'acqua; Rinaldi *et al.*, 2015, 2016b), which aims to support river management by explicitly considering both river quality and flood hazard. The framework includes three tools specifically designed to assess channel dynamics. The first two are indices created to classify, at the reach scale: (i) the degree of ordinary channel dynamics resulting from progressive changes occurring over a medium-to-long time scale, not including the possible responses to extreme flood events (Morphological Dynamics Index, MDI), and (ii) the likely abrupt channel response to high-magnitude to extreme flood events (Event Dynamics Classification, EDC).

The definition of the MDI is based on a set of eleven indicators structured into three main components (morphology and processes; artificiality; channel adjustments), evaluated through a scoring system that assigns a dynamic class to the river reach, ranging from very low to very high (Rinaldi *et al.*, 2015). However, for the purposes of this study, the EDC index is of greater interest, as it is used to assess the most likely channel responses to extreme flood events with a reference return period of 100 years – representing the most severe scenarios considered in flood risk analysis under the EU Floods Directive. EDC aims to assess the expected degree of change to channel boundaries (and therefore of potential hazard) that a given river reach is likely to experience in response to flood-induced geomorphological dynamics, ranked into four classes (very high; high; medium; low). The final EDC assessment is carried out by combining two key aspects evaluated through logical procedures based on flow charts (fig. 7): (i) assessment of the expected magnitude of morphological changes taking place during the event (I: very relevant; II: relevant; III: intermediate; IV: small) and (ii) assessment of the clogging probability at critical cross-sections such as bridges (H: High; L: low).

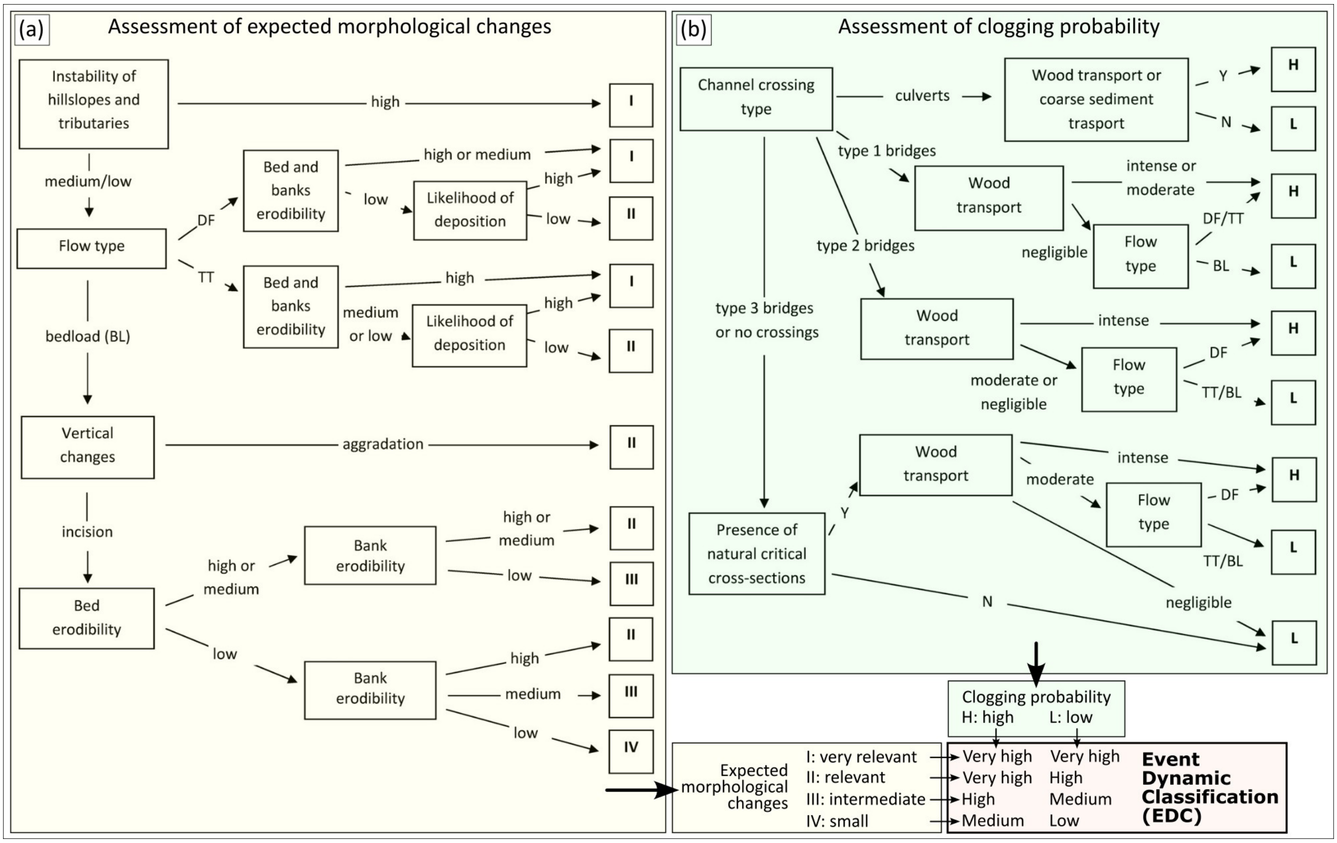

Figure 7 - Flow charts for the assessment of Event Dynamics Classification (EDC) at the reach scale on the basis of (a) expected morphological changes (specific diagram for confined and semi-confined reaches; the version for unconfined reaches is available in Rinaldi et al., 2016b) and (b) clogging probability during the reference extreme event. DF: debris flows; TT: transitional transport (debris floods and hyperconcentrated flows); BL: bedload transported by clearwater flows. Redrawn from Rinaldi *et al.* (2015).

Details on the procedures to follow for addressing the flowcharts in fig. 7 can be found in Rinaldi *et al.* (2015), in the IDRAIM handbook along with its response guide (Rinaldi *et al.*, 2016b), and in previous studies that have applied EDC tool (e.g., Comiti *et al.*, 2016b; Di Francesco and Carlino, 2024). Having said that, here it is interesting to emphasize that the criteria leading to the definition of the dynamic classes are largely based on knowledge of fluvial processes triggered by high-magnitude events, as made available over the years through numerous studies cited in the previous section of this work. Consider, for instance, the phenomena of intense sediment transport, classified as debris flow (DF) and transitional transport (TT) flow types within the EDC methodology (fig. 7). Among these, debris floods – previously clarified as being responsible for significant channel widening (Church and Jakob, 2020; Brenna *et al.*, 2023) – are included. Consistent with this, TT cases lead to expected morphological changes classified as relevant (II) or very relevant (I), sometimes also increasing clogging probability due to the intense transport of large wood frequently associated with such flow conditions (e.g., Martín-Vide *et al.*, 2023). The criteria and methodologies previously outlined for identifying river network sites potentially susceptible to debris floods (e.g., Wilford *et al.*, 2004; Brenna *et al.*, 2021; Jakob *et al.*, 2022) are therefore of fundamental importance from a predictive perspective. The same applies to the assessment of bank erodibility based on bank material and type (e.g., Konsoer *et al.*, 2016; Righini *et al.*, 2017), which, under certain conditions, directly determines the class of expected morphological changes (fig. 7).

Both MDI and EDC provide information on the expected magnitude of channel dynamics for a given river reach at a one-dimensional scale. To generate geomorphic hazard maps, this information must be integrated with a two-dimensional analysis that delineates the areas within the fluvial corridor likely to be impacted by river dynamics. For this purpose, River Morphodynamic Corridors were proposed in IDRAIM (Rinaldi *et al.*, 2016b) and were developed starting from similar approaches proposed since the 1990s (e.g., Dutto, 1994; Malavoi *et al.*, 1998). The River Morphodynamic Corridors can be defined as planform domains that include the current active channel and areas of the adjacent alluvial plain that were affected in the past or may be affected in the future by its lateral dynamics (Rinaldi *et al.*, 2016b). Two corridors are defined: (i) the Morphodynamic Corridor (MC), the narrower, where channel dynamics are highly likely to occur even in the absence of extreme events; and (ii) the Event Morphodynamic Corridor (EMC), a wider zone encompassing portions of the alluvial plain that can be influenced by channel dynamics primarily during extreme floods. The MC corresponds to the Morphological Dynamics Index (MDI) in terms of the processes considered, while the EMC is associated with extreme events comparable to those used as reference in the Event Dynamics Classification (EDC) and can be directly associated with the mapping of the geomorphic flood hazard related to a reference hydrological event. The procedure for the delineation of the MC and EMC is illustrated in detail in Rinaldi *et al.* (2015; 2016b) and Brenna *et al.* (2024), and includes the following steps implemented at the reach-scale mainly by Geographic Information System (GIS) analysis: (i) reconstruction of historical planform positions of the active channels for determining the areas affected by fluvial dynamics in the past; (ii) definition of possible future erosion by extrapolating the mean rate of bank retreat for a given reach; (iii) delineation of the alluvial plain by recognition of natural elements of confinement (e.g., hillslopes, ancient terraces); and (iv) identification of anthropic structures preventing lateral channel mobility.

Recently, Brenna *et al.* (2024) applied the IDRAIM methodology to delineate MCs and EMCs in the Cordevole River catchment (Italian Dolomites). The study aimed to evaluate the effectiveness of morphodynamic corridors in predicting morphological channel changes induced by a severe hydrological event – the 2018 Vaia flood – specifically in terms of localized maximum channel widening. Their findings indicate that the morphodynamic corridors effectively delineate areas where planform channel dynamics are most likely to occur. In particular, the EMC proved to be a reliable predictor of channel widening triggered by extreme flooding (fig. 8). However, the study also identified some limitations of the approach: it does not account for erosion processes that may affect valley slopes or fluvial terraces, which can lead to the widening of the alluvial plain (e.g., Lapointe *et al.*, 1998; Diodato *et al.*, 2017; Liébault *et al.*, 2024). Despite this limitation, the analysis demonstrated that the methodology provides a robust framework for mapping and assessing flood hazards driven by river channel dynamics. When combined with hydraulic modelling to evaluate inundation processes (e.g., Pavesi *et al.*, 2022; Selvam and Antony, 2023), River Morphodynamic Corridors enable a comprehensive assessment of flood hazards, specifically in dynamic rivers where inundation processes may not represent the main component of hazard.

That said, there is a need to expand testing across different river types and environmental settings. There is also room for improving the geomorphic tools currently available for assessing channel dynamics. This can be achieved by integrating recent advances in geomorphological knowledge, such as the growing recognition of the importance of debris floods and the connections between hillslope and fluvial networks processes (e.g., Brenna *et al.*, 2023; Bennett *et al.*, 2025). In addition, the rapid development of data acquisition and processing techniques for fluvial monitoring through remote sensing provides significant opportunities to refine geomorphic approaches for hazard assessment. For instance, current satellite imagery (e.g., Sentinel-2) enables precise evaluation of bank retreat direction and rate, as well as overall morphological changes (Bozzolan *et al.*, 2023). This could lead to improved mapping of River Morphodynamic Corridors through more robust and refined assessments of bank dynamics, ultimately enhancing the delineation of potential future erosion zones. Furthermore, the increasing availability of (semi-)automated data processing capabilities (e.g., Carbonneau and Bizzi, 2024) now makes it theoretically possible to scale up the application of such tools significantly, opening the door to potential regional or even global applications. Considering the spatial resolution of freely accessible satellite data (e.g., 10 m/pixel for Sentinel-2 imagery), such approaches are currently applicable to medium-to-large rivers (i.e., with an active channel at least 30-40 m wide). The applicability of the aforementioned tools remains more limited in the context of mountain streams, most of which are relatively narrow and flow under spatially variable confinement conditions, with highly heterogeneous bank (and hillslope) material composition.

River management implications

To date, considering both the Italian and broader European contexts, the application of aforementioned geomorphic knowledge and operative tools in land-use planning and river management remains limited. Flood hazard mapping continues to rely predominantly on hydraulic approaches, focusing on the identification of inundation-prone areas (e.g., Antony *et al.*, 2020; Mudashiru *et al.*, 2022; Selvam and Antony, 2023). As a result, there is a significant gap in hazard and risk assessment, particularly in river network segments (e.g., steep channels, dynamic gravel-bed rivers) where channel dynamics play a dominant or at least equivalent role compared to inundation processes. This limitation in hazard and risk assessment, especially in highly anthropized contexts, may become even more pronounced in the short term due to the increasing frequency of extreme meteorological events and, consequently, high-magnitude floods (Kundzewicz *et al.*, 2018; Blöschl *et al.*, 2020; Rentschler *et al.*, 2023).

Focusing specifically on the Italian context, the use of tools to assess morphological dynamics by competent agencies remains uncommon. In the implementation of the EU Floods Directive (European Commission, 2007), Italy introduced the "Flood Risk Management Plans" (FRMPs) starting from 2015-2016. These plans, coordinated at the River

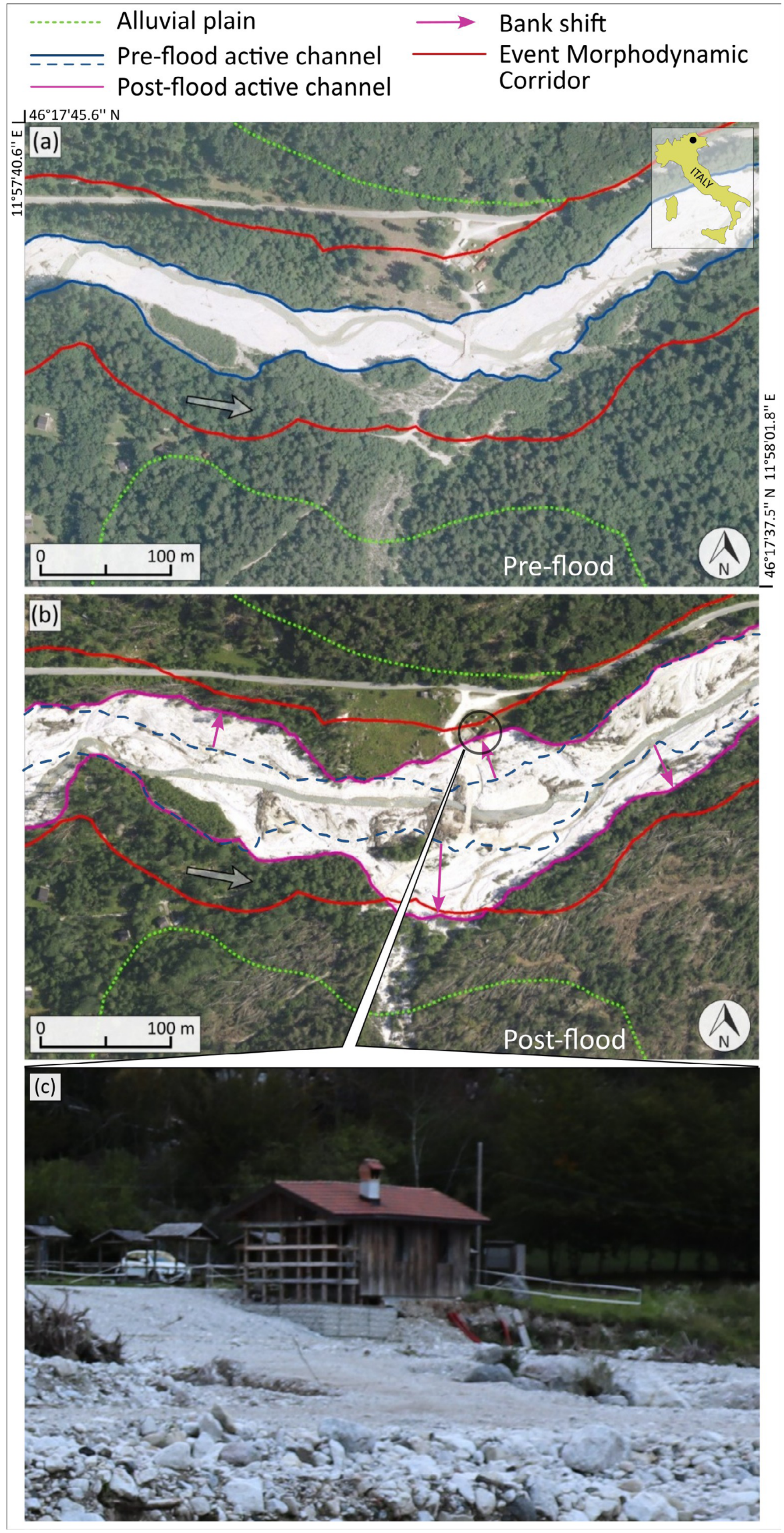

Figure 8 - Example of an Event Morphodynamic Corridor (EMC) delineated along a reach of the Tegnas Torrent (Veneto Region, Italy), with a comparison to channel widening caused by a high-magnitude flood during the Vaia Storm in October 2018. Panels (a) and (b) show the pre-event (aerial photograph from 2015) and post-event (aerial photograph from 2019) conditions, respectively. Panel (c) is a field photograph of a site where maximum bank retreat occurred, resulting in damage to a building located within the area identified by the EMC as potentially affected by channel dynamics during extreme hydrological events. Data used to produce this figure are from Brenna *et al.* (2024).

Basin District level, aim to define flood hazard maps and develop planning and management strategies for risk reduction (https://www.isprambiente.gov.it/pre_meteo/idro/Piani_gest.html). However, the definition of flood hazard within these FRMPs is often limited to inundation scenarios. Geomorphological dynamics are rarely considered, and exclusively for streams in mountainous and hilly physiographic settings. Even in such cases, FRMPs tend to rely on modeling approaches or, occasionally, on morphometric assessment methodologies (e.g.: https://sigma.distrettoalpiorientali.it/portal/index.php/direttiva-alluvioni/pgra-2021-2027/piano_approvato_2021/). Geomorphic tools developed to date – such as those within the IDRAIM framework, which were specifically designed for the Italian context to assess river dynamics (e.g., MDI, EDC, and morphodynamic corridors) – are generally not taken into account.

CONCLUSION

Understanding of river dynamics in relation to high-magnitude floods has significantly improved over the past few decades. The most notable advancements have concerned the investigation of morphodynamic processes triggered by extreme events, which are capable of producing remarkable morphological changes – among which channel widening plays a prominent role. Moreover, considerable efforts have been devoted to identifying the main hydraulic-hydrological and geomorphological factors controlling the occurrence of such processes and associated abrupt channel changes.

This body of geomorphological knowledge has led to the development of specific approaches and tools aimed at assessing and mapping geomorphological hazard associated with high-magnitude events. In the Italian context, the IDRAIM methods, designed to evaluate channel dynamics, represent one of the most significant contributions in this field. Currently, both in Italy and across Europe – and with few exceptions (e.g., Québec, Canada; https://www.environnement.gouv.qc.ca/ministere/consultation-modernisation/guide-methodologique.pdf) globally – the use of such tools remains limited in favour of predominantly hydraulic approaches, which focus almost exclusively on the issue of overbank inundation. Given the effectiveness and relative ease of application of the various geomorphological approaches currently available, it is hoped that their implementation by competent agencies will progressively increase. Integrating these approaches into land-use planning and river management strategies could substantially enhance their effectiveness by accounting for the dynamicity of fluvial systems. In particular, these tools allow for the inclusion of a wider range of natural processes that contribute to geomorphological hazard and, potentially, to risk affecting people, communities, and critical infrastructure.

AUTHORS CONTRIBUTION

Andrea Brenna: conceptualization, funding acquisition, methodology, investigation, and writing – initial draft. Nicola Surian: conceptualization, funding acquisition, methodology, investigation, supervision and writing – reviewing and editing.

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