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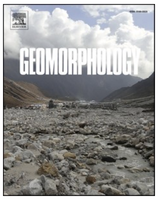

Effects of sediment transport on flood hazards: Lessons learned and remaining challenges

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ABSTRACT

Sediment transport (bedload and suspension) plays a relevant role in the morphological response of river channels to large floods. Sediment load controls erosion and aggradation patterns during high flows, drives the migration of macroforms and contributes to the definition of thresholds for bank erosion and channel instability. Given this influence on channel morphology, it is clear that sediment transport influences both the channel geometry and water stage reached during floods and should therefore be considered in flood hazard analysis. So far, however, legislation on flood hazard and flood management plans still continues to typically disregard sediment transport. This is due mainly to the paucity of available data on sediment transport and the lack of standardized approaches for its integration into flood hazard analysis. The present work, which aims to provide some guidance on how to advance in this issue, has undertaken a bibliometric study and thorough review of the published scientific literature that had previously addressed the implications of sediment transport on flood hazards assessment. This review showed that: i) most studies on the influence of sediment transport on flood risk have focused on mountain streams, as they are highly sensitive systems to changes in sediment supply; ii) research has also focused on explaining historical changes in channel-conveyance capacity and flood frequency based on long-term trends in sediment supply; and iii) recent developments in hydrodynamic and morphodynamic numerical models provide opportunities to explicitly incorporate sediment transport in flood hazard analysis. However, despite the recent advances, we have identified important challenges and discussed needs to better consider sediment transport in flood hazards at different spatial and temporal scales.

1. Introduction

River floods are natural phenomena resulting from a variety of causes, including intense or persistent rainfall (e.g., Hirschboeck, 1988), snowmelt (e.g., Beniston and Stoffel, 2016; Dethier et al., 2020), glacial-lake outbursts (e.g., Benito et al., 2021; Clague and O'Connor, 2021) or the sudden failure of hydraulic infrastructures (e.g., dams, dikes) (e.g., Santos-González et al., 2021). Although floods play an essential role in the geomorphic and ecologic functioning of rivers, they also cause damage to infrastructure and people (Díez-Herrero et al., 2009; Borga et al., 2014; Kreibich et al., 2019), with significant human and economic losses on a global scale (Barredo, 2007). In this respect, floods have been the costliest natural disaster in terms of the total number of people affected during the period 2000–2019 (EM-DAT database; freely accessible online at www.emdat.be). In addition, global hydrological models predict that large areas will be affected by an increase in river flooding in the near future, which could be enhanced by a growing exposure of people to flood hazards (Hirabayashi et al., 2013; Jimenez Cisneros et al., 2014).

River flooding occurs when the capacity of the channel to convey the flow is exceeded, causing the water to rise above the level of the banks and inundating the floodplain and adjacent areas (Ward, 1978; Benito

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and Vázquez-Tarrío, 2022). Hazards associated with river flooding have traditionally been assessed by means of frequency-magnitude analysis, in which hazard levels are defined in statistical terms and expressed as annual exceedance probability or the average return interval of a given discharge (Benito and Vázquez-Tarrío, 2022). The discharges estimated for selected flood quantiles (e.g. 0.01 annual exceedance probability or 100-year flood) are then used for deriving 'flood-hazard' maps that capture the expected inundation extent and/or depth along the study reach (Zimmermann et al., 2005; EXCIMAP, 2007; Díez-Herrero et al., 2009; Moel et al., 2009; Sánchez Martínez and Lastra, 2011; Olcina-Cantos and Díez-Herrero, 2022; Mudashiru et al., 2021). These flood hazard maps are used to identify flood-prone areas, raise awareness among the riverine population and the water authorities, to design flood protection plans and mitigation measures, and to prioritise emergency response.

Diverse data sources and approaches are used to obtain flood hazard maps, including (Mudashiru et al., 2021): (i) hydrological-hydraulic modelling supported by numerical simulation of rainfall runoff and river discharge (e.g. Anselmo et al., 1996); (ii) geomorphological mapping supported by aerial-photo interpretation and field evidence of flooding and river dynamics (e.g. Baker, 1994; Lastra et al., 2008; Magliulo and Valente, 2020); (iii) documentary analysis of historical flood records (e.g. archives, press, watermarks, photographs and videos, human testimonies) (e.g. Fernández et al., 2012; Pichard and Roucaute, 2014); and (iv) palaeoflood reconstruction based on sedimentary and botanical evidence left by floods (e.g., Benito and Díez-Herrero, 2015; Benito et al., 2020a).

Sediment transport is usually overlooked in maps done with these approaches (Nones and Guo, 2023). In particular, the assumptions of clear water flow and fixed boundary channels are common for flood hazard zone delineation based on conventional hydraulic computations (Nones, 2019). However, it is widely known that intense sediment discharges contribute to an increase in the density of water-sediment mixtures (Costa, 1984; Pierson and Costa, 1987; Church and Jakob, 2020; Bodoque et al., 2011; Jakob et al., 2022). This fact ultimately modifies the flow rheology and discharge-stage-flow velocity relationships associated with a given discharge. Additionally, sediment mobilisation and transport during high magnitude floods can also be associated with sudden changes in channel morphology (e.g. river widening, bank erosion; Brenna et al., 2023; Ruiz-Villanueva et al., 2023), which can cause significant damage to riverine facilities and populations (Nones and Pescaroli, 2016). Moreover, changes in channel geometry may have an effect on its capacity to convey the flow and thus modify the water-stage thresholds at which floods occur. In this regard, natural (Gran et al., 2011; Phillips and Jerolmack, 2016; Pfeiffer et al., 2019; Tofelde et al., 2019; Harries et al., 2021) and anthropogenic (e.g. Kondolf, 1997; Rinaldi et al., 2005; Scorpio and Piégay, 2021) variations in the amount of sediment delivered to rivers can lead to changes in streambed elevation and cross-sectional geometry (Schumm and Khan, 1972; Parker, 1978; Church, 2006; Tal and Paola, 2007; Czuba et al., 2010; Métivier and Barrier, 2012; Dingle et al., 2019), potentially altering channel conveyance capacity and flow routing (Slater et al., 2015; Slater et al., 2019). As a result, flood hazard maps based on pre-flood channel morphology or on models that assume a non-movable riverbed or non-erodible banks in alluvial or mountain streams may not be reliable.

Over the last two decades, several studies have addressed the complexity related to the behaviour of sediment transport during floods and its implications on flood hazard, under terms such as 'hydro-geomorphic hazards' (e.g. Arnaud-Fassetta et al. (2005); Jakob et al., 2016), 'river geomorphological hazards' (e.g. Rinaldi et al., 2015; Surian et al., 2020; Brenna et al., 2023) or 'sediment risks' (Liu et al., 2022). However, this has not prevented sediment transport processes from still being frequently overlooked in flood risk studies, as several authors have pointed out (James, 1999; Lane et al., 2007; Arnaud-Fassetta et al., 2009; Raven et al., 2010; Slater et al., 2015; Buffin-Bélanger et al., 2017; Thapa et al., 2022; Nones and Guo, 2023). Unfortunately, still today, many flood hazard studies rarely consider sediment transport and geomorphic changes (Nones et al., 2017; Nones and Guo, 2023).

Bibliometric analysis has already allowed the investigation of some emerging trends in fluvial geomorphology by Piégay et al. (2015) and Pinter et al. (2019). However, to date there have been few bibliometric studies in the field of flood hazards (one exception being Díez-Herrero and Garrote, 2020) and, to the best of our knowledge, no previous bibliometric study has focused on the specific topic of sediment transport in flood hazard assessment. Therefore, in this paper we have decided to conduct a bibliometric analysis of the scientific papers published on flood hazards and their relationship with sediment transport. By doing so, this paper aims at (i) providing a comprehensive and critical review of the existing scientific literature focused on the role of sediment transport and the sediment load in flood hazards, (ii) identifying critical remaining challenges; and (iii) discussing the needs to better consider sediment transport in flood hazards at different spatial and temporal scales. The manuscript begins with an in-depth bibliometric analysis to explore how flood hazard research has evolved by identifying the links between sediment transport processes and flooding. Secondly, the main ideas presented in these papers are extracted and organised to provide a general overview of the main concepts. Finally, we identify several challenges, such as methodological developments and approaches, and discuss the potential to integrate sediment transport into flood risk assessment. We intend this work to contribute to a more careful consideration of sediment transport in flood hazard analysis in the near future.

2. Materials and methods

Bibliometric analysis represents a powerful tool with great potential to highlight useful information that might be disregarded in a simpler bibliographic screening through the cited (and citing) articles of the most relevant papers in a given topic. For the current bibliometric study, we used the Web of Science (WoS) (https://www.webofscience.com/wos/alldb/basic-search). We accomplished our bibliometric analysis in three steps: i) first, we analysed the bibliometric trends of those papers that dealt with flood hazards and risks; ii) then, we analysed the trends in the previous literature on sediment transport in rivers; and finally iii) we explored the bibliometric trends in the scientific literature considering both flood hazards and sediment transport.

To do so, the WoS 'Core Collection' was consulted on 05/18/2023. We started using the Boolean "OR" operator between the following two keywords: "flood hazard" and "flood risk", with "Topic" serving as the searching field. Then, we continued our bibliometric analysis using the Boolean "OR" to combine several keywords: "sediment transport" OR "bedload" OR "suspended sediment" (yet again, with "Topic" as the search field). Up to this point, we analysed the bibliometric trends of the two research areas, flood hazards, and river sediment, each independently of the other. Once this was done, we were interested in analysing the number of published papers that consider both the flood hazard or risk and the role that river sediment plays. To achieve this objective, we combined the records obtained in the two previous analyses, so that "flood hazard OR flood risk" was crossed (by Boolean AND) with "sediment transport" OR "bedload" OR "suspended sediment" (using the searching field "Topic"). Recent literature has also pointed out that flood hazards in fluvial environments include issues closely related to channel morphodynamics, such as bank erosion and channel widening (Rinaldi et al., 2015; Brenna et al., 2023; Ruiz-Villanueva et al., 2023). Channel change processes can be considered in a certain way as the morphological expression of sediment transport. However, relying solely on keyword searches associated to "sediment transport" may not fully capture processes related to channel dynamics. Therefore, the keywords "flood hazard OR flood risk" were also crossed (by Boolean AND) with "bank erosion" OR "channel widening" OR "geomorphic hazards" OR "geomorphological hazards" to include hazards related to the morphological change dynamics in river channels, which are ultimately controlled by sediment erosion, transport and deposition processes. For more details on the search strategy, the databases considered and the number of records obtained, the reader is referred to the supplementary material of this paper.

The compiled data were examined in order to interpret the thematic, temporal and geographical evolution of the previous literature (using the tools available in the WOS platform, for filtering and refining the searches) with a particular focus on analysing the amount of previous research that has explicitly considered sediment transport in the analysis of flood risk. We also analysed the co-occurrence of keywords to determine the main topics associated with the three groups of papers (i.e., 'flood hazards', 'sediment transport', and 'flood hazards + sediment transport'). For this purpose, we used the 'bibliometrix' R-package developed by Aria and Cuccurullo (2017).

Once we had completed the bibliometric analysis, we proceeded to a more thorough evaluation of those scientific articles that dealt with both sediment transport and flood hazards (covering a time interval from 1990 to 2023). From the ~400 papers obtained from the automatic search with the WOS, we made a two-step hand selection. We carried out a first screening based on article title, journal, and authorship. In a second step, we checked the abstracts of the hand-picked papers (in chronological order) and manually selected those that we found the most relevant for further review, taking into account the originality of the methods used (e.g., the modelling approaches, number of aspects considered in relation to sediment transport) and also trying to maintain a diverse selection of topics (e.g., hazards, vulnerability) and study contexts. This selection was completed by manually searching works cited in the selected papers. In this way, we finally identified 52 manuscripts that we read carefully and in depth, extracting and noting the main ideas. As a result, we have prepared a concise and synthetic report of the different aspects where sediment transport has been previously identified as highly relevant to flood hazards. This review is presented in the second part of this paper. Table 1 summarises the papers that we considered most noteworthy and the main ideas that we extracted from them.

3. Bibliometric analysis

3.1. General trends in previous literature focused on flood hazards and risks

We obtained a total of 12,343 records, using the Boolean "OR" operator between the keywords 'flood hazard' and 'flood risk'. The number of outcomes is reduced if we restrict the search using the keyword 'river' (4519 records). Of all these records, 97.2 % are written in English, while German, French, and Spanish only accounted for 0.7, 0.6, and 0.4 % of the results, respectively. Journal articles make up the majority of the selected records (83.0 %). We also looked at the general time trends and we observed how the number of papers on this topic has increased over time, from a few papers in mid-1990 to >1300 publications in 2022 (Fig. 1). Indeed, this is a general trend in scientific publications common to all fields, i.e., the exponential growth in the number of publications over time (Bornmann et al., 2021).

It is noteworthy to observe that four countries alone are affiliation institution countries of almost one-half (51 %) of all records: P.R China (15.4 %), USA (14.7 %), UK (11.7 %) and Italy (9.8 %). The Netherlands (9.2 %) completes the top five. When analysing the production of research publications on the basis of authors, the top 10 positions are occupied by 2 German-based researchers, 2 Netherlands-based researchers, 1 Italian-based researcher, 1 Poland-based researcher, 1 UK-based researcher, 1 Canadian-based researcher, 1 Sweden-based researcher and 1 Switzerland-based researcher. Finally, this global view of flood hazard and risk could be completed by the list of preferred journals for the publication of this type of study: *Water* (5.4 %), *Natural Hazards* (4.9 %), *Journal of Hydrology* (3.5 %), *Journal of Flood Risk Management* (3.5 %) and *Natural Hazards and Earth System Sciences* (2.5 %).

Bibliometric trends have not been static; instead, they have evolved over time. In Table 2, we present a heat map showing the trends in the 15 main journals in which publications on flood hazards have been published. From these results we can draw some conclusions: a) some of the main journals from the decade of 1990/99 continue in the top positions (e.g. *Water Resources Research*; *Water Resources Management; Hydrological Processes*), while others have become less prolific (e.g. *Hydrological processes*; *Geomorphology*); b) in the decade 2000/09 several journals have gained in importance (e.g. *Journal of Flood Risk Management*, *Natural Hazards* or *Natural Hazards and Earth System Sciences*); c) finally, a few recent journals (e.g. *Water; Sustainability*) have become very prolific in publishing flood hazard studies. In summary, the emergence, since the 1990s, of journals specialising in the natural processes responsible for hazards and risks, has absorbed the scientific production that was previously scattered across different journals. More recently, since the 2010s, the effect of open-access journals (such as *Water* and *Sustainability*) is also evident.

The analysis of keyword co-occurrence highlights the existence of three main clusters of themes within the 'flood hazard' literature (Fig. 2A): i. one dominated by keywords related to hydrometeorological drivers of floods and the hazard dimension of flood risks (e.g., 'climate', 'precipitation', 'rainfall', 'frequency analysis', 'events'; blue in the Fig. 2A); ii. a second one somehow related to risk modelling and risk management ('risk', 'management'; red in Fig. 2A); and iii. a third one associated to flood hazards at the catchment scale ('river basin', 'catchment', 'runoff'; green in Fig. 2A) and climate change.

3.2. General trends in previous literature focused on fluvial sediment

Our search in WOS with the Boolean "OR" combination of "sediment transport" OR "bedload" OR "suspended sediment" gave us a total of 36,208 records. This large number was reduced when we restricted the search using the keywords "fluvial" or "river" (3703 records with "fluvial", and 16,177 records with "river"). An examination of these records shows similar trends in language and document type to those described above for 'flood hazards' papers. The affiliation institution countries are again highly confined to a small group: the five countries with the highest contribution (USA – 29.5 %, P.R. China – 18.0 %, UK – 10.2 %, France – 7.7 %, and Canada – 7.2 %) account for about 72.6 % of the total production. When analysing the production of research publications by authors, the top 10 positions are occupied by 3 US-based researchers, 3 UK-based, 2 Spanish-based, and 2 Canadian-based. In terms of preferred journals, the top five include *Geomorphology* (4.3 %), *Earth Surface Processes and Landforms* (3.7 %), *Water Resources Research* (3.0 %), *Journal of Hydrology* (2.8 %), and *Science of the Total Environment* (2.4 %) (Table 3). Then, only one journal, the *Journal of Hydrology,* appears in both the top 5 for flood hazards and sediment transport.

As in the case of the records on flood hazard and risk analysis, some changes have occurred over time (Fig. 1). The temporal evolution of the publications shows that the generalization of the scientific production related to this topic started one decade earlier than that focused on the analysis of flood hazards or risks: the decade 1990/99 is the one that shows a generalized expansion of the scientific production on sediment transport in rivers. In the 1980s (*Earth Surface Process and Landforms*, *Water Resources Research*, or *Catena*) and the 1990s (*Geomorphology*, *Science of the Total Environment*, or *Hydrological Processes*), the journals that are more prolific today started to stand out. Once again, the recent growth of the open-access journal *Water* should be highlighted. One singularity could be outlined in our analysis: the appearance of two journals related to the marine environment, such as the *Journal of Coastal Research* and *Marine Geology*. This could be due to an error in the databases or to articles focused on sediment transport processes in estuaries and river mouths. Therefore, we decided to remove them from the analyses.

Table 1

Summary compilation of previously published research that considered sediment-transport processes in flood hazard studies.

Source	Journal	Type of paper	Objectives	Data /Methods	Study site/Region	Main outcomes
Hey and Winterbottom (1990)	*River Research and Applications*	Study case	Assess river engineering works (gravel-trap) on the Upper River Wharfe	Field data	Wharfe River (UK)	The engineering works (gravel trap) performed according to expectations
Sear et al. (1995)	*Earth Surface Processes and Landforms (ESPL)*	Regional study	Application of sediment to river maintenance	General data collected by the National Rivers Authority	Sence and Shelf Brook Rivers (UK)	A methodology for conducting a ‘fluvial audit is proposed
Stover and Montgomery (2001)	*Journal of Hydrology*	Study case	Linking channel changes and flooding in the Skokomish river	Cross-section data, gauging data	Skokomish River (Washington, USA)	Increased flooding on the Skokomish river as a result of aggradation with progressive reduction in channel’s conveyance capacity
Davies et al. (2003)	*ESPL*	Study case	Understanding the causes of aggradation in the Waiho river and the effects of stopbanks	Physical model	Waiho River (New Zealand)	Aggradation in the Waiho river is caused by the lateral restriction of the channel by stopbanks
Sinnakaudan et al. (2003)	*Environmental Modelling and Software*	Study case	Development a GIS tool that integrates HEC-6 with ArcView to produce a flood risk map	1D Hydraulic modelling (with movable bed)	Pari River (Malaysia)	Flood hazard maps for the Pari river were derived from HEC-6 hydraulic modelling, with sediment transport included in the modelling routine
Arnaud-Fassetta et al. (2005)	*Geomorphology*	Study case	Describe the effects of a large flood in the Guil river valley	Aerial images, multi-date mapping, hydraulic estimations, field survey	Guil River (France)	The effects of this major flood were largely controlled by the local geomorphology
Piégay et al. (2005)	*River Research and Applications*	Conceptual / Review paper	Present a general overview of the erodible river corridor concept	Examples from rivers worldwide (Ain, Tagliamento, Goodwin creek)	Global	Provide guidance on the practical application of the erodible corridor concept
Hürlimann et al. (2006)	*Geomorphology*	Regional study	Assessment of debris-flow hazards	Geologic and geomorphological mapping. 1D numerical modelling	Andorra	A hazard map is produced, together with some recommendations for hazard reduction
Lane et al. (2007)	*ESPL*	Study case	Explore the impacts of long-term and short-term changes in sediment delivery	1D and 2D hydraulic modelling	Wharfe River (UK)	Channel sedimentation can cause about half of the modelled increase in flood extent due to climate change
Neuhold et al. (2009)	*Natural Hazards and Earth System Sciences*	Study case	Incorporating riverbed dynamics and channel changes in flood risk assessment	Semidistributed Precipitation runoff model. Hydraulic and sediment-transport modelling. Flood damage function.	Ill River (Western Austrian Alps)	Several scenarios (hydrology, sediment, bed adjustment) are simulated to provide probability vulnerability models
Arnaud-Fassetta et al. (2009)	*Gémorphologie: relief, processus, environnement*	Conceptual paper	Analyse the role of fluvial geomorphology on flood hazards	Examples from France and Nepal	France, Nepal	Highlight the diversity of concepts and methods that fluvial geomorphology can provide for understanding the spatio-temporal variability of flood hazards
Totschnig et al. (2011)	*Natural Hazards*	Study case	Exploring vulnerability associated to sediment transport in mountain rivers	Inventory data on flood damage from previous events	Three torrents from Austrian Alps	A quantitative vulnerability function applicable to residential buildings located on torrent fans
Davies and McSaveney (2011)	*Journal of Hydrology (NZ)*	Conceptual paper / Regional study	Propose a framework for improving flood risk assessments in New Zealand	Examples taken from previous studies	New Zealand	The impact of climate change on flood risk may be negligible compared to the underestimation of flood risk inherent in current assessment methods; protocols and methods should be improved in active areas-
Bodoque et al. (2011)	*Water Resources Research*	Study case	Determining the discharge of a flow event that took place on 1997	Field observations. 1D hydraulic modelling. Sedimentology	Arroyo Cabrera (central Spain)	The methodological approach proposed here can be applied to hyperconcentrated flows in high-gradient mountainous streams
Radice et al. (2013)	*Journal of Flood Risk Management*	Study case	Exploring the incorporation of sediment transport modelling into the evaluation of flash-flood hazards.	1D morphodynamical model	Mallero River (Italian Al ps)	An adequate characterization of the hazards associated with flash floods cannot be obtained without taking into account the morphological variability associated with sediment transport
Slater and Singer (2013)	*Geology*	Regional study	Examining the relations between riverbed elevation, climate and fluvial discharge	Streamflow and channel measurements for 915 USGS gauging stations	USA rivers	They found nonstationary bed elevation at most sites, and they observed how discharge varies with climate regime in proportion to bed elevation
Totschnig and Fuchs (2013)	*Geomorphology*	Regional study	Analyse the vulnerability of buildings to torrent processes	Event data for several catchments	Austrian Alps	The results suggest that there is no need to distinguish between different sediment-laden torrent processes when assessing the vulnerability of residential buildings to torrent processes
Badoux et al. (2014)	*Natural Hazards and Earth System Science*	Regional study	Estimate the contribution of bedload to damage costs	Swiss flood and landslide damage database	Swiss torrents	Estimate of the contribution of bedload to total damage cost in the 40 years study period

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Table 1 (*continued*)

Source	Journal	Type of paper	Objectives	Data /Methods	Study site/Region	Main outcomes
Wong et al. (2015)	*Hydrological Processes*	Study case	Study the impacts of morph. changes.	1D-2D hydraulic model	Cockermouth (UK)	Uncertainty in long-profile variability did not affect the flood mapping
Guan et al. (2015)	*International Journal of Sediment research*	Experimental	Investigating the effects of sediment transport in floods	2D numerical model	Virtual experiments	The interactions between flow, sediment transport and geomorphic processes during floods are analysed for several scenarios
Nardi and Rinaldi (2015)	*ESPL*	Study case	Describing the variability in channel response to a flood	Field-survey. Analysis of aerial photo. LIDAR data.	Magra River (Italy)	Large variability in channel response to 2011 flood
Hooke (2015)	*Geomorphology*	Review paper	Review examples from field studies to analyze how the impacts of floods can vary	Review of previous literature		The analysis shows that there is no constant relationship between flood magnitude and morphological/sedimentary response
Slater et al. (2015)	*Geophysical Research Letters*	Regional study	Separate the relative effects of streamflow and channel capacity variability on flood frequency	Gauging data from US rivers	US rivers	Changes in flood hazard due to change in channel capacity were smaller but more numerous than those due to change in streamflow
Lotsari et al. (2015)	*Progress in Physical Geography*	Review paper	Reviewing numerical approaches for simulating future river-channel adjustments	Review paper		Numerical models of increasing complexity have been developed, so there is increasing potential for their application
Jakob et al. (2016)	*Canadian Water Resources Journal*	Conceptual / Review paper	Highlighting the most threatening hydrogeomorphic hazards in mountain regions	Review of previous literature / study cases	Canada	Suggestions for improving the practice of correctly diagnosing the potential for unusual hydro-geomorphic hazards in mountain areas
Pender et al. (2016)	*Journal of Hydraulic Engineering*	Study case	Analyse the sensitivity of flood inundation to changes in channel conveyance	1D hydro-morphodynamical model	Cladew River (England)	Proposing a method for considering sediment-related sensitivity in flood hazard assessment
Guan et al. (2016)	*Journal of Hydrology*	Experimental	Exploring sediment transport and morphological changes during multiple floods	2D hydro-morphodynamical model	Virtual experiments	Cumulative effects of changes in river bed geometry affect local and downstream flood hazards
Radice et al. (2016)	*Water*	Study case	Application of a model to incorporate sediment transport into hazard assessment in a river with severe aggradation	1D hydro-morphodynamical model	Mallero River (Italian Alps)	To develop a framework for proposing scenarios for flood-hazard assessment that incorporate sediment transport
Slater (2016)	*ESPL*	Regional study	Understanding how flood frequency is affected by changes in conveyance capacity	Analysis of data from 41 gauging stations in UK	England and Wales	A 10% change in the channel's transport capacity would result in a change in flood frequency of ∼1.5 days per year, on average, across the 41 selected sites
Hooke (2016)	*Geomorphology*	Study case	Describing geomorphological effects of an extreme flood in a semiarid ephemeral stream	Topographic field surveys	Nogalte, Torrealvilla and Slada sites (Murcia, SE Spain)	High degree of channel adjustments to high magnitude flash floods
Surian et al. (2016)	*Geomorphology*	Regional study	Analyze the geomorphic response of mountain rivers to extreme floods	Analysis of aerial photographs, streamflow data, geomorphological mapping	Apenine Rivers (Italy)	Hydraulic variables alone are not sufficient to explain the channel response to extreme floods, and geomorphological factors (e.g. lateral confinement) should be considered
Rinaldi et al. (2016)	*ESPL*	Study case	Describe the geomorphic response to a large flood	Remote sensing and GIS. Landslide mapping. Field surveys	Magra River (Italy)	A methodological framework is described for using interlinked observations and analyses of the geomorphic impact of an extreme event
Call et al. (2017)	*Water Resources Research*	Experimental	Exploring changes in flood extent under nonstationary conditions for an adjustable channel	Stochastic, reduced complexity model	Virtual experiments / Minnesota rivers (USA)	Intra-annual variability in flood extent depends primarily on variability in hydrology, but intra-annual variability in flood frequency depends primarily on channel adjustment
Sturm et al. (2018a)	*Geomorphology*	Experimental study	Understanding the impact dynamics on buildings caused by sediment transport	Physical scale model	A physical model based on Schnannerbach torrent	Impact forces depend on the dynamics of the sediment deposition processes on the floodplain
Sturm et al. (2018b)	*Journal of Hydrology*	Experimental study	Study on impact forces on buildings	Physical model	Physical model	Clear correlation between flow heights and impact forces on exposed buildings. Bedload transport and deposition processes influence the impact forces
Nones (2019)	*Acta Geophysica*	Study case	Comparing 2D simulations under fixed and mobile bed conditions	2D numerical modeling (hydraulic and morphodynamical)	Secchia River (Italy)	Differences are observed between results obtained with fixed and mobile bed conditions
Fuchs et al. (2019)	*Journal of Hydrology*	Review paper	Review vulnerability assessments for buildings exposed to torrential hazards	Review of previous literature	European Alps	The transferability of functions between case studies is challenging. More research is needed to understand the importance of building design

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Table 1 (*continued*)

Source	Journal	Type of paper	Objectives	Data /Methods	Study site/Region	Main outcomes
Dingle et al. (2019)	*Geomorphology*	Study case	Analyse channel change on Philippine rivers	Optical satellite imagery	Cagayan River (Philippines)	Sediment transport and deposition are key drivers of the observed tropical channel morphodynamics in this region. Channel morphodynamics have implications for how best to manage these types of tropical river systems
Tang et al. (2020)	*Geophysical Research Letters*	Study case	Exploring sensitivity to sediment of rainfall thresholds for debris-flow initiation	Numerical modelling and field monitoring	Chalk Cliffs (Colorado)	Rainfall intensity-duration thresholds become sensitive to sediment supply below a sediment thickness threshold
Dysarz (2020)	*Journal of Flood Risk Management*	Study case	Quantifying the impact of sediment transport on hazards	1D hydro-morphodynamical model	Warta River (Poland)	Development of an algorithm to automate sediment routing, hydraulic modelling and geoprocessing
Sofia and Nikolopoulos (2020)	*Scientific Reports*	Regional study	Understanding changes in flood hazards and different drivers (precipitation, flows and sediment connectivity)	Field data, discharge records, LIDAR high-resolution topography	16 watersheds in Connecticut and Massachusetts	A framework is proposed for connecting flood changes to landscape controls
Basso-Báez et al. (2020)	*Journal of South American Earth Sciences*	Study case	Unravelling the impacts to buildings caused by floods in a river heavily perturbed by a volcanic eruption	Hydrological assessment. 2D hydraulic modelling considering large-wood	Blanco River (Chile)	Proposing a structured, systematic and understandable approach to quantifying the impact of flooding on buildings
Dingle et al. (2020)	*ESPL*	Study case	Explore how sediment dynamics and riverbed changes influence flood hazards in the Karnali river (Nepal)	2D hydraulic model	Karnali River (Nepal)	Regular field measurements of bed elevation and updated DEMs following large sediment-generating events could help improve model inputs in future flood prediction models
Contreras and Escauriaza (2020)	*Natural Hazards and Earth Systems Sciences*	Study case	To gain knowledge into the effects of high sediment concentration on the propagation of floods	2D Hydraulic model	Quebrada de Ramon watershed (Andes, Chili)	Simulations show that sediment concentration has strong impact on flow velocities and water depths. Nevertheless, arrival time of the peak flow or the shape of the hydrograph are not affected by sediment concentration.
Boothroyd et al. (2021)	*Science of the Total Environment (STOTEN)*	Regional study	Analyze the effects of river migration in the vicinity of bridges in Philippines	Landsat satellite imagery, inventory data from public agencies	Philippine rivers	The magnitude of the lateral adjustment is sufficient to suggest the need for a bridge design to accommodate channel dynamics
Di Cristo et al. (2021)	*Water*	Experimental study	Evaluation of the impact forces on structures due to a flood wave	2D-hydro morphodynamical model and 2-phase model	Virtual experiments	Differences are observed between the two tested modelling approaches, which are ascribed to the role of sediment inertia
Liu et al. (2021)	*Frontiers in Earth Science*	Study case	Testing sensitivity of flooding hazard to sediment characteristics	1D numerical model	Xihe River (China)	Sediment concentration had a significantly effect on flood hazard, but was less important than sediment input and particle size
Thapa et al. (2022); Thapa et al. (2022)	*39th IAHR World Congress, Conf. Proceedings; ESPL*	Study case	Exploring the sensitivity of channel morphology to the grain-size of the sediment supply	CAESAR-Listflood landscape evolution model	Nakkhu River (Kathmandu basin, Nepal)	Both grain-size and sediment supply are important for accurate flood hazard mapping in sediment-rich catchments
Liu et al. (2022)	*Catena*	Study case	Understanding the impacts of sediment into flood risk assessment in a 10 km reach	1D hydraulic modelling for simulating different scenarios of sediment inputs	Xihe River (China)	A framework for incorporating sediment into flood risk assessment is tested and illustrated
Brenna et al. (2023)	*Geomorphology*	Study case	Investigating the role played by different types of sediment transport processes in channel widening during floods	GIS work. Aerial photo interpretation. Hydrological and sedimentological analysis	Corvedole River and four tributaries (Dolomites, Italy)	Debris floods can trigger widening processes that are more intense than those that occur in response to water flows
Ruiz-Villanueva et al. (2023)	*STOTEN*	Review paper	Identify the hydraulic and morphological drivers responsible for river widening	Meta-analysis of a large database comprising 1564 river reaches in Europe	Europe	Rivers in the Mediterranean region showed larger widening than rivers from other regions. Valley confinement is a critical morphological variable but is not the only controlling factor
Nones and Guo (2023)	*Geoenvironmental disasters*	Conceptual/ Review paper	Provide evidence on the potential impact of sediments and morphological changes during flooding events	Reviewing 6 significant and well-documented events that happened in mountainous and lowland river basins in Europe	Europe, global	The presented examples show the importance of considering sediment and wood in flood risk management.

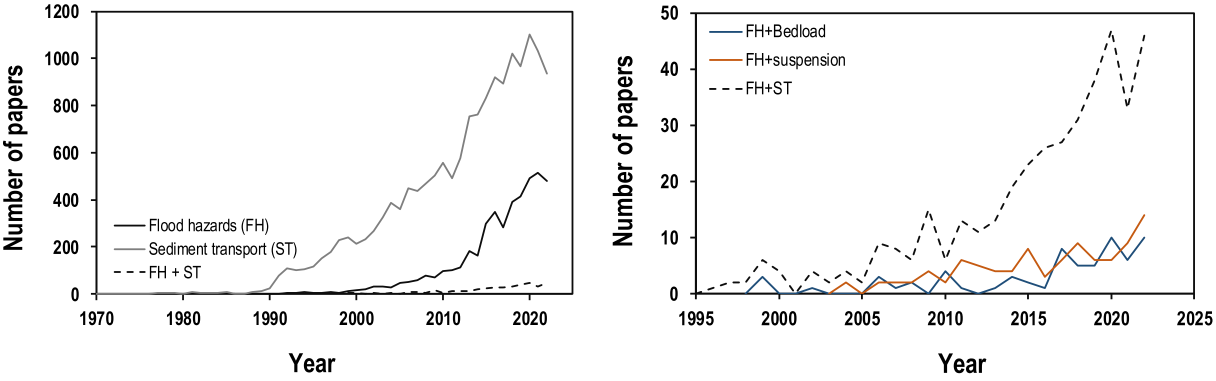


Fig. 1. Temporal evolution of the number of published papers focusing on 'flood-hazards', 'sediment transport' and 'sediment transport + flood hazards' in rivers.

Table 2
Temporal trends in the number of published papers focusing on 'flood-hazards' in rivers in the 15 journals with the highest number of records in the WOS databases. Each column represents a decade, and each cell (of a given column) shows the relative percentage of papers published in each journal. Note that these percentages are estimated from the ratio of the number of articles published in each journal to the total number of papers published in that decade (which includes more journals than the 15 shown here). The total number of papers for each decade (N) is given in the first row (% of N). Cells are coloured on a scale from light (lower percentages) to dark (larger percentages) brown. Grey colour represents periods in which a given journal was not published (or is not represented in the WOS database).

	1970-79	1980-89	1990-99	2000-09	2010-19	2020-23
Source Titles	**% of 15**	**% of 4**	**% of 55**	**% of 431**	**% of 2394**	**% of 1635**
E3S WEB OF CONFERENCES					1.75	0.00
GEOMORPHOLOGY			5.45	3.48	1.04	0.31
HIDROLOGY AND EARTH SYSTEM SCIENCES				2.09	1.96	1.47
HYDROLOGICAL PROCESSES			1.82	3.02	1.25	0.31
INTERNATIONAL JOURNAL OF DISASTER RISK REDUCTION					0.71	2.26
JOURNAL OF FLOOD RISK MANAGEMENT				1.16	3.76	3.73
JOURNAL OF HYDROLOGY	0.00	0.00	5.45	2.78	3.22	4.16
NATURAL HAZARDS			0.00	5.10	5.01	4.77
NATURAL HAZARDS AND EARTH SYSTEM SCIENCES				1.86	2.84	2.32
REMOTE SENSING					0.63	1.90
SCIENCE OF THE TOTAL ENVIRONMENT	0.00	0.00	0.00	0.70	1.38	2.39
SUSTAINABILITY					0.71	3.49
WATER					3.88	9.36
WATER RESOURCES MANAGEMENT			1.82	0.46	1.17	0.86
WATER RESOURCES RESEARCH	0.00	0.00	5.45	1.16	1.67	1.96

The network analysis of keyword co-occurrences shows in this case two main clusters of keywords within the 'sediment transport' literature (Fig. 2B): i. one clearly dominated by the keyword 'suspended sediment', which is associated with terms related to catchment scale controls on sediment production (e.g., 'water', 'soil erosion', 'land-use', 'climate change'; blue in Fig. 2B), and ii. a second grouping of terms related to river morphodynamics, such as 'evolution', 'dynamics', 'erosion' or 'deposition' (red in Fig. 2B). It is interesting to observe how this second cluster is linked to the keyword 'bedload transport', which corresponds well to the control exerted by bedload on channel geometry and planform architecture, particularly in gravel-bed rivers.

3.3. Relative importance given to sediment transport in flood hazards in previous literature

The search in the WOS for the literature considering both flood hazards and sediment-transport (filtered by the term 'river') yielded 411 records. In addition, the search using terms related to planform change dynamics (bank erosion, widening) and geomorphic hazards yielded even fewer results (165 records). Even taking into account all the limitations and shortcomings inherent to any bibliometric analysis (Díez-Herrero and Garrote, 2020), one main idea emerges from the results: most of the previous research on flood hazard (or risk) in rivers does not explicitly consider the role of sediment transport, and vice versa.

What are the trends in these publications when both flood hazards and river sediment transport are considered? When we jointly analysed the two main themes of this bibliometric study, natural hazards and sediment transport, we observed a significant change in the tendencies reported above (Table 4). For example, none of the five more prolific authors had appeared before. However, all of the top five journals (*Geomorphology*, *Water*, *Science of the Total Environment*, *Earth Surface Processes and Landforms* and *Journal of Hydrology*) were already in the previous top 5 for flood risk or river sediment literature. Thus, although there are differences in authors and organizations, the most prolific journals still remain the same. We also analysed trends in dominant disciplines based on the WOS categories of the different papers (Fig. 3). The WOS categories 'Water Resources', 'Environmental Sciences' and 'Geosciences Multidisciplinary' account for the largest number of papers in the three topic groups (i.e., 'flood hazards', 'sediment transport' and 'sediment transport + flood hazards'). However, a larger proportion of papers in the 'sediment transport' and 'sediment transport + flood hazards' groups are included in the 'Geosciences multidisciplinary' and 'Geography Physical' categories than in the 'flood hazard' groups. Similarly, a larger number of papers in the 'flood hazards' literature are classified in the WOS category 'Meteorology Atmospheric Sciences'.

Of the approximately ten thousand flood hazards (or risk) records,

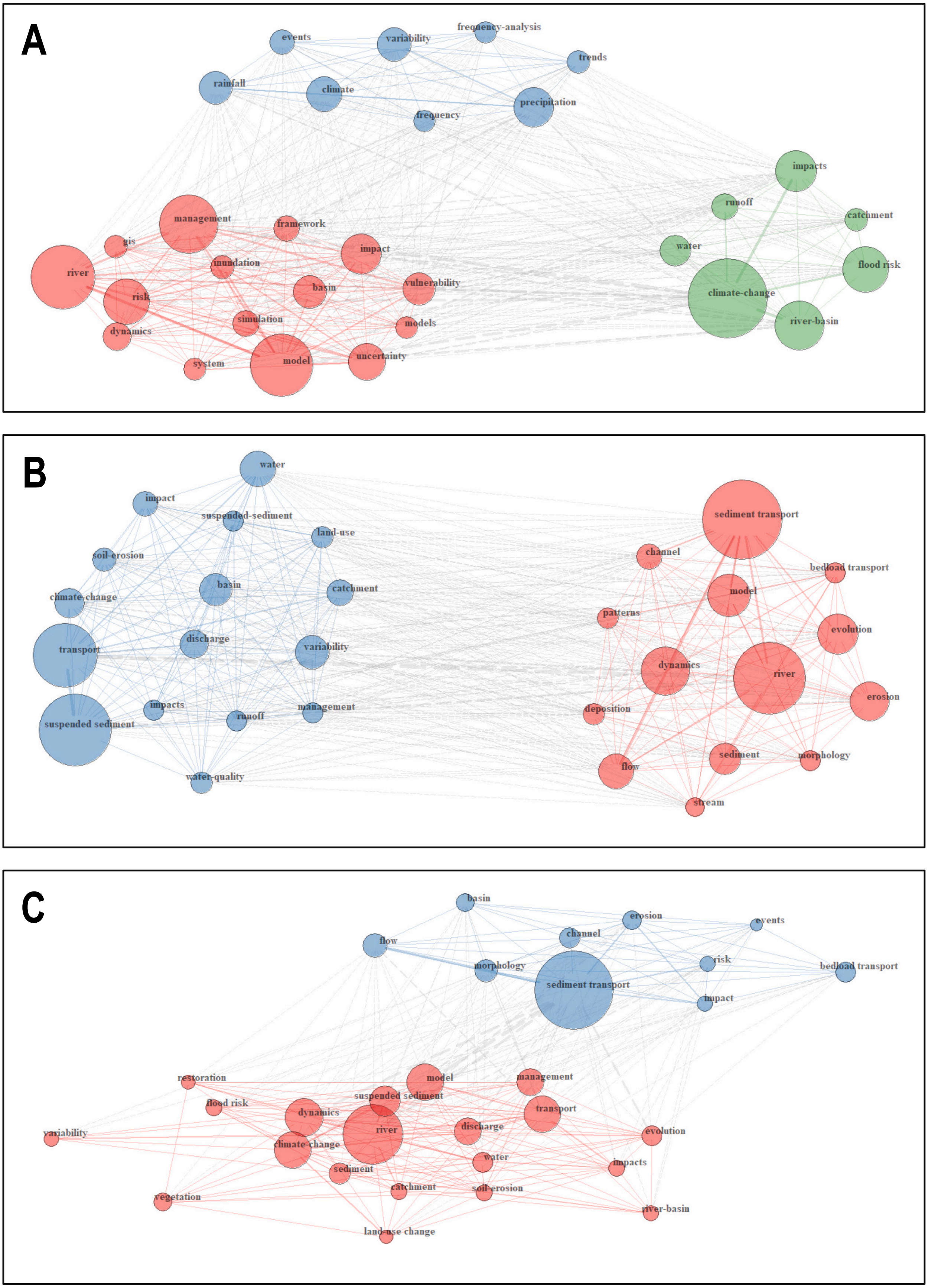
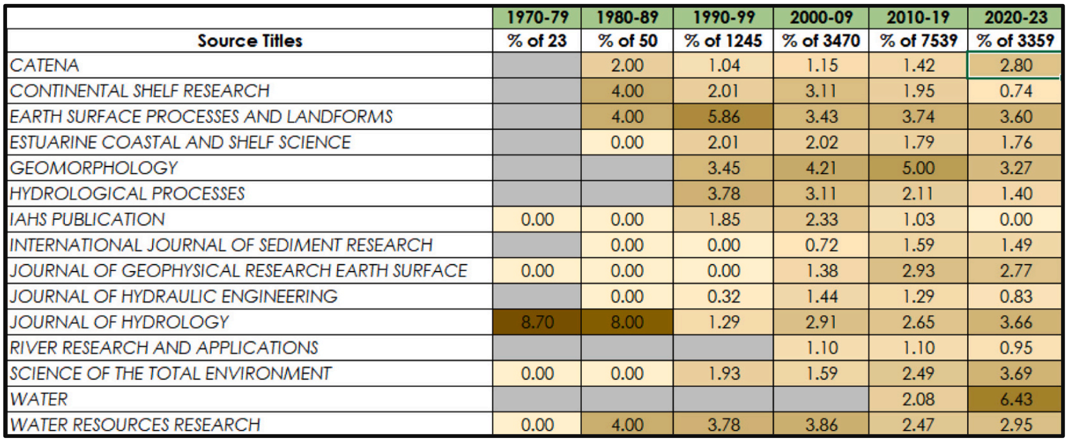


Fig. 2. Results of the keyword co-occurrence analysis done with the 'bibliometrix' R- package (Aria and Cuccurullo, 2017). A) analysis performed on the 'flood hazard' literature; B) analysis performed on the 'sediment transport' literature; C) analysis performed on the 'flood hazard' literature that considered sediment transport.

Table 3

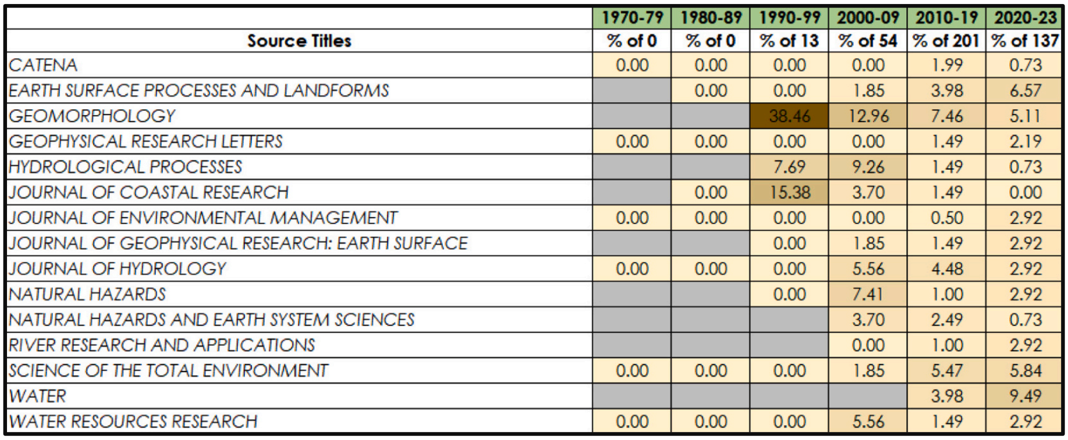
Temporal trends in the number of published papers focusing on 'sediment transport' in rivers in the 15 journals with the highest number of records in the WOS databases. Each column represents a decade, and each cell (of a given column) shows the relative percentage of papers published in each journal. Note that these percentages are estimated from the ratio of the number of articles published in each journal to the total number of papers published in that decade (which includes more journals than the 15 shown here). The total number of papers for each decade (N) is given in the first row (% of N). Cells are coloured on a scale from light (lower percentages) to dark (larger percentages) brown. Grey colour represents periods in which a given journal was not published (or is not represented in the WOS database).



	1970-79	1980-89	1990-99	2000-09	2010-19	2020-23
Source Titles	**% of 23**	**% of 50**	**% of 1245**	**% of 3470**	**% of 7539**	**% of 3359**
CATENA		2.00	1.04	1.15	1.42	2.80
CONTINENTAL SHELF RESEARCH		4.00	2.01	3.11	1.95	0.74
EARTH SURFACE PROCESSES AND LANDFORMS		4.00	5.86	3.43	3.74	3.60
ESTUARINE COASTAL AND SHELF SCIENCE		0.00	2.01	2.02	1.79	1.76
GEOMORPHOLOGY			3.45	4.21	5.00	3.27
HYDROLOGICAL PROCESSES			3.78	3.11	2.11	1.40
IAHS PUBLICATION	0.00	0.00	1.85	2.33	1.03	0.00
INTERNATIONAL JOURNAL OF SEDIMENT RESEARCH		0.00	0.00	0.72	1.59	1.49
JOURNAL OF GEOPHYSICAL RESEARCH EARTH SURFACE	0.00	0.00	0.00	1.38	2.93	2.77
JOURNAL OF HYDRAULIC ENGINEERING		0.00	0.32	1.44	1.29	0.83
JOURNAL OF HYDROLOGY	8.70	8.00	1.29	2.91	2.65	3.66
RIVER RESEARCH AND APPLICATIONS				1.10	1.10	0.95
SCIENCE OF THE TOTAL ENVIRONMENT	0.00	0.00	1.93	1.59	2.49	3.69
WATER					2.08	6.43
WATER RESOURCES RESEARCH	0.00	4.00	3.78	3.86	2.47	2.95

Table 4

Temporal trends in the number of published papers focusing on both on 'flood hazards' and 'sediment transport' in rivers in the 15 journals with the highest number of records in the WOS databases. Each column represents a decade, and each cell (of a given column) shows the relative percentage of papers published in each journal. Note that these percentages are estimated from the ratio of the number of articles published in each journal to the total number of papers published in that decade (which includes more journals than the 15 shown here). The total number of papers for each decade (N) is given in the first row (% of N). Cells are coloured on a scale from light (lower percentages) to dark (larger percentages) brown. Grey colour represents periods in which a given journal was not published (or is not represented in the WOS database).



	1970-79	1980-89	1990-99	2000-09	2010-19	2020-23
Source Titles	**% of 0**	**% of 0**	**% of 13**	**% of 54**	**% of 201**	**% of 137**
CATENA	0.00	0.00	0.00	0.00	1.99	0.73
EARTH SURFACE PROCESSES AND LANDFORMS		0.00	0.00	1.85	3.98	6.57
GEOMORPHOLOGY			38.46	12.96	7.46	5.11
GEOPHYSICAL RESEARCH LETTERS	0.00	0.00	0.00	0.00	1.49	2.19
HYDROLOGICAL PROCESSES			7.69	9.26	1.49	0.73
JOURNAL OF COASTAL RESEARCH		0.00	15.38	3.70	1.49	0.00
JOURNAL OF ENVIRONMENTAL MANAGEMENT	0.00	0.00	0.00	0.00	0.50	2.92
JOURNAL OF GEOPHYSICAL RESEARCH: EARTH SURFACE			0.00	1.85	1.49	2.92
JOURNAL OF HYDROLOGY	0.00	0.00	0.00	5.56	4.48	2.92
NATURAL HAZARDS			0.00	7.41	1.00	2.92
NATURAL HAZARDS AND EARTH SYSTEM SCIENCES				3.70	2.49	0.73
RIVER RESEARCH AND APPLICATIONS				0.00	1.00	2.92
SCIENCE OF THE TOTAL ENVIRONMENT	0.00	0.00	0.00	1.85	5.47	5.84
WATER					3.98	9.49
WATER RESOURCES RESEARCH	0.00	0.00	0.00	5.56	1.49	2.92

only 71 contain the keyword 'bedload'. Moreover, roughly about one-third of these papers were published in the last three years (2020, 2021, and 2022) and almost all of them (except five) were published in the twenty-first century (Fig. 1). Thus, the consideration of bedload in flood risk assessment started three decades later than the first published analysis of flood risk and sediment transport. This could be due to the increased complexity of hydrodynamic modelling when considering sediment transport (bedload in this case); and/or to the scarce availability of bedload data. Due to the scarcity of records, it is difficult to extract any significant trend about journals or authors, but the main journals are those focused on geomorphology and earth surface processes (e.g., *Geomorphology*, or *Earth Surface Process and Landforms*). The results for the combination of 'flood hazard' or 'risk' and 'suspended sediment' are quite similar to those for 'bedload'. Now there is no clear concentration in recent years and the publications are evenly distributed over the last two decades (Fig. 1). Most publications come from the UK and P.R. China, and the main journals do not differ from those mentioned above, such as *Science of the Total Environment, Journal of Hydrology,* or *Geomorphology*. Fig. 4 shows the regional distribution of these publications.

The analysis of keyword co-occurrence outlines the existence of two main clusters in this third group of papers (Fig. 2C): i. one seems to be composed of keywords related to the effects of sediment transport on channel morphology and its subsequent impact on flood risk (e.g. 'morphology', 'channel', 'erosion'; blue in Fig. 2C); ii. a second cluster is integrated by terms related to sediment transport at the catchment scale

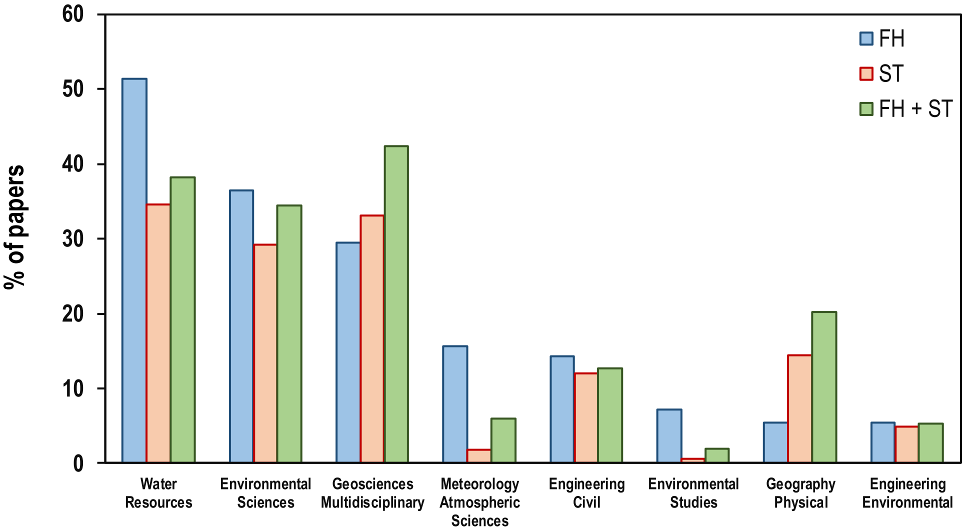


Fig. 3. Trends in the number of published papers according to WOS categories. FH: 'Flood hazards' literature. ST: 'Sediment transport' literature. ST + FH: Literature considering both sediment transport and flood hazards.

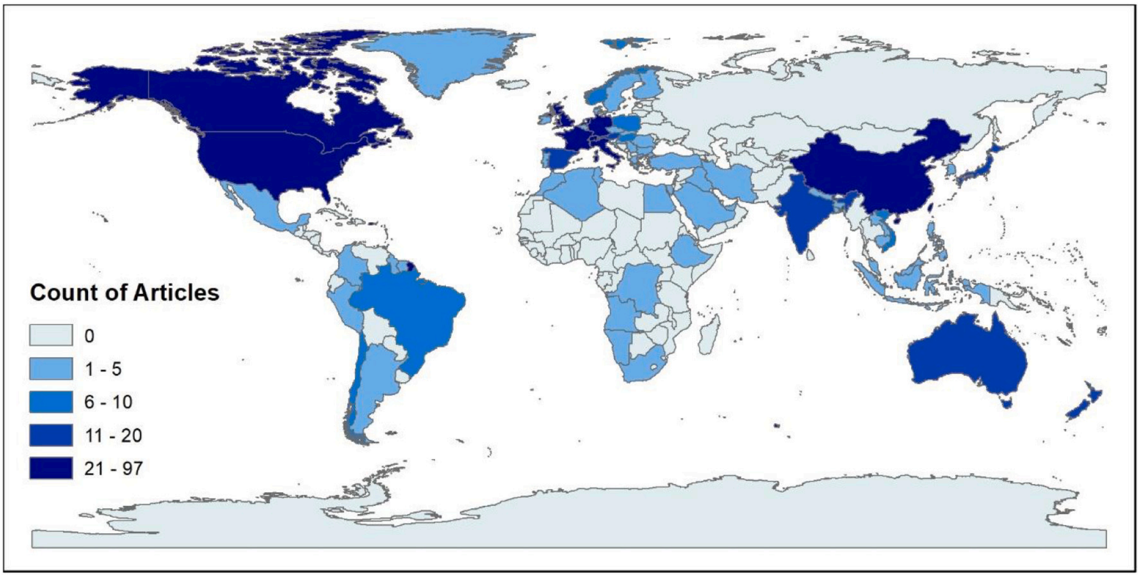


Fig. 4. Map showing the world distribution of papers considering both sediment transport and flood hazards.

('water', 'erosion', 'land-use', 'catchment') and river management ('management', 'restoration'; red in Fig. 2C). It is noteworthy that the first cluster is associated with the term 'bedload transport', while the second group is associated with 'suspended sediment'.

4. Flood hazards and the importance of sediment transport

Once the bibliometric analysis had been carried out, we proceeded to an in-depth analysis of the content of the 52 papers that we selected for further review (see 'Materials and methods' section) and summarized in Table 1. Two main groups of papers could be identified. On the one hand, a large group of articles, mainly integrated by study-case research, focused on the use of different modelling strategies to test the sensitivity of flood-hazard assessments to sediment transport and (event-scale) channel adjustments (e.g. Radice et al., 2013; Nones, 2019), mostly in mountain rivers. On the other hand, another group of articles is represented by regional studies that have explored the drivers of long-term adjustments in channel geometry and riverbed elevation and their influence on flood frequency (e.g. Slater and Singer, 2013; Slater, 2016).

Apart from these studies, which mainly focus on hazards, comparatively less literature has investigated the influence of sediment transport on the vulnerability of exposed people and infrastructure, or on the estimation of damages and risks. Some notable exceptions are Sturm et al. (2018a,b), Fuchs et al. (2019) or Basso-Báez et al. (2020), who analysed the impact forces on buildings related to sediment transport in mountain channels; Totschnig et al. (2011) and Badoux et al. (2014), who evaluated costs associated with sediment transport in Swiss torrents; and Neuhold et al. (2009), who propagated the influence of sediment transport dynamics from hazard to risk. Finally, we also found review studies with a more general focus on the implications of fluvial geomorphic processes for flood hazards (e.g. Arnaud-Fassetta et al., 2009; Davies and McSaveney, 2011; Hooke, 2015; Ruiz-Villanueva et al., 2023).

In summary, we have identified four main topics emerging from published literature: i) the relevance of the transport of large amounts of sediment during large floods for flood hazards in mountain rivers; ii) the uncertainty that sediment transport and channel morphological changes introduce into hazard assessments and maps in large alluvial rivers; iii) how sustained changes in sediment supply can explain long-term trends in channel conveyance capacity and changes in inundation frequency; and iv) the potential influence of sediment transport on damages caused by floods. In what follows, we review and summarize these works, with the aim of providing an overview of the role of sediment transport in flood hazards and how it has been considered in previous research.

4.1. Flood hazards and sediment transport in mountain streams and torrents

The hydrological regime of steep mountain channels is commonly characterized by an alternation between episodic flash-floods and periods of quiescence, during which colluvial sediment can be fed into the channel (Recking, 2012; Attal, 2017). Flash-floods can mobilise large amounts of sediment accumulated during the quiescence periods and disorganise the streambed armour (Gintz et al., 1996; Lenzi et al., 1999; Lenzi, 2004; Church and Zimmermann, 2007; Turowski et al., 2009; Molnar et al., 2010). This sudden mobilisation of large amounts of sediment can lead to widespread deposition and overbank sedimentation in downstream alluvial fans (Arnaud-Fassetta et al., 2005), triggering the collapse of check dams and other infrastructures (Benito et al., 1998), or block bridges or drainage pipes (Boothroyd et al., 2021), thereby producing bed aggradation and raising water levels in the channel. Similarly, mountain streams are supplied with large wood (i.e., fallen trees, trunks, branches, rootwads), by processes like mass movements, debris flows and avalanches, and this wood material can be mobilized during floods (Comiti et al., 2016a,b; Wohl et al., 2019; Ruiz-Villanueva et al., 2019). Large wood affects channel roughness (Wilcox et al., 2006; Manners et al., 2007), flow velocity, stage-discharge relationships and local sediment transport dynamics (Hassan et al., 2007; Hinshaw et al., 2020), and large wood accumulation can divert the water flow and influence sediment paths (Wohl and Scott, 2016). Therefore, the transport and accumulation of large wood during floods can drive changes in channel morphology (e.g., channel avulsion, aggradation, erosion) and/or in flood levels at bridges and dams, which can be critical sources of hazard in mountain rivers (e.g., Ruiz-Villanueva et al., 2014, 2018). Where mountain streams encounter densely populated areas, the damage potential of all these processes is considerable and can result in significant damage or even the loss of lives (Hürlimann et al., 2006; Totschnig et al., 2011; Badoux et al., 2014). A good example of cascading effects occurred during a flash flood in the Francolí River in Eastern Spain (Martín-Vide et al., 2023). Here three bridges failed due to the obstruction caused by a significant accumulation of wood debris. It was shown that the failure of the clogged bridges caused an unusual surge in the flow, exacerbating the flood damage and resulting in the loss of two lives.

However, predicting sediment transport and mobilized sediment volumes in mountain channels is complex because they depend on the sediment supply (Schuerch et al., 2006; Hassan et al., 2007; Yu et al., 2009; Piton and Recking, 2017; Pfeiffer and Finnegan, 2018; Vázquez-Tarrío et al., 2020; Liu et al., 2022), which varies largely in time and space, showing a quasistochastic behaviour. All this introduces a large uncertainty in the local water-stage relationships (Di Baldassarre and Montanari, 2009) and makes it quite complex to obtain robust and reliable estimates of the probability of flooding associated with mountain channels (Liu et al., 2022). As a result, water and river managers often lack the appropriate information and data needed to adequately consider sediment transport when delineating and managing flood-related hazards in mountain areas (Jakob et al., 2016).

The amount and grain-size distribution of in-channel sediment storages can also lead to significant variations in the density, shear resistance, and rheology of the flow for a given value of water discharge (Iverson, 1997; Hungr, 2005; Hungr et al., 2005; Bodoque et al., 2011; Calhoun and Clague, 2018; Church and Jakob, 2020; Brenna et al., 2020; Jakob et al., 2022). In this regard, two extreme conditions of sediment-water mixtures in mountain streams have been defined (Church and Jakob, 2020). On the one hand, there is the bedload and suspended load conditions associated with 'clear water' and 'sediment-laden' flows (with sediment concentrations of up to ~10 % and Newtonian rheology), where sediment transport depends on the balance between sediment cohesion, gravity and flow turbulence. On the other hand, debris flows consist of higher concentrations of bed material (>30 %; Jakob et al., 2022) and show a plastic rheology controlled by momentum transfer through grain-grain collisions (Church and Jakob, 2020). Between these two extremes, there is a large continuum of flow conditions, such as the 'debris-floods' (Jakob et al., 2022) or 'hyperconcentrated-flows' (Bodoque et al., 2011), with relatively high sediment concentrations (typically 10–30 %) and a 'slurry-like' appearance. All of these differences in the rheology of sediment/water mixtures are associated with changes in mean flow velocity and density, local discharge-stage relationships, potential damage associated to floods, and the sporadic occurrence of sudden surges that are very difficult to predict. This again contributes to the uncertainty of assessing flood hazards in mountain streams.

The occurrence of debris flows, debris floods or 'clear water' flows for a given rainfall depends largely on the sediment availability and supply conditions in the channel (Bovis and Jakob, 1999; Theule et al., 2012; Bel et al., 2017; Liu et al., 2022), making challenging to associate flood-hazards to specific rainfall thresholds (Jakob et al., 2016; Liu et al., 2022). If the flow can be characterized in the field (e.g., Brenna et al., 2020), then we may need to use models to get a more detailed flood hazard assessment in terms of area affected or intensity. However, most hydraulic or hydrodynamic models are good at simulating 'clear water' flows but are unable to reproduce the behaviour of flows with other rheologies, such as debris or hyperconcentrated flows (Lee et al., 2016; Chauchat et al., 2017). Similarly, most of the existing sediment transport formulae included in hydraulic modelling software were developed for 'clear water' and steady flow conditions, which makes them questionable when applied to the highly unsteady conditions of flash-floods with large amounts of sediment (Yu et al., 2012; Alexander and Cooker, 2016). In addition, long-term data are often lacking, so it is not easy to assign a frequency to a given flow type and establish rainfall intensity-duration (ID) thresholds (Marchi et al., 2009; Borga et al., 2014; Nikolopoulos et al., 2016). Furthermore, the sensitivity of these thresholds to sediment availability, which can change rapidly over time, has been relatively unexplored. Tang et al. (2020) is a remarkable exception, combining numerical modelling and field monitoring to explore how sediment supply influences rainfall ID thresholds for debris flows in Chalk Cliffs (Colorado, USA). Considering all the above, it seems evident that sediment transport is an important source of uncertainties in the assessment of flood hazards in mountain channels (Fig. 5).

4.2. Flood hazards and sediment transport in alluvial rivers

In piedmont valleys, as well as in the lower-order reaches of the drainage networks, the supply of sediment, coming mainly from the headwaters and the intermountain tributaries, together with the general downstream decrease in valley slope (and consequently in flow competence), results in a progressive sediment infilling of river valleys and to the development of alluvial rivers. In this context, floods with the capacity to erode and transport sediment shape the channel geometry and the floodplain.

In these alluvial settings, conventional flood hazard map delineations are based on the extent of inundation observed during previous floods and/or on the results of hydraulic modelling for discharges resulting from magnitude-frequency analysis (Piégay et al., 2005). However, for a given flow discharge, the extent to which water overflows the riverbanks is controlled by the conveyance capacity of the channel (Lane et al., 2007; Slater, 2016; Call et al., 2017; Slater et al., 2019; Sofia and Nikolopoulos, 2020). In this regard, erosion and deposition may modify the water discharge-stage relations and flood inundation (Fig. 6). In-stream sediment deposition and bedform migration

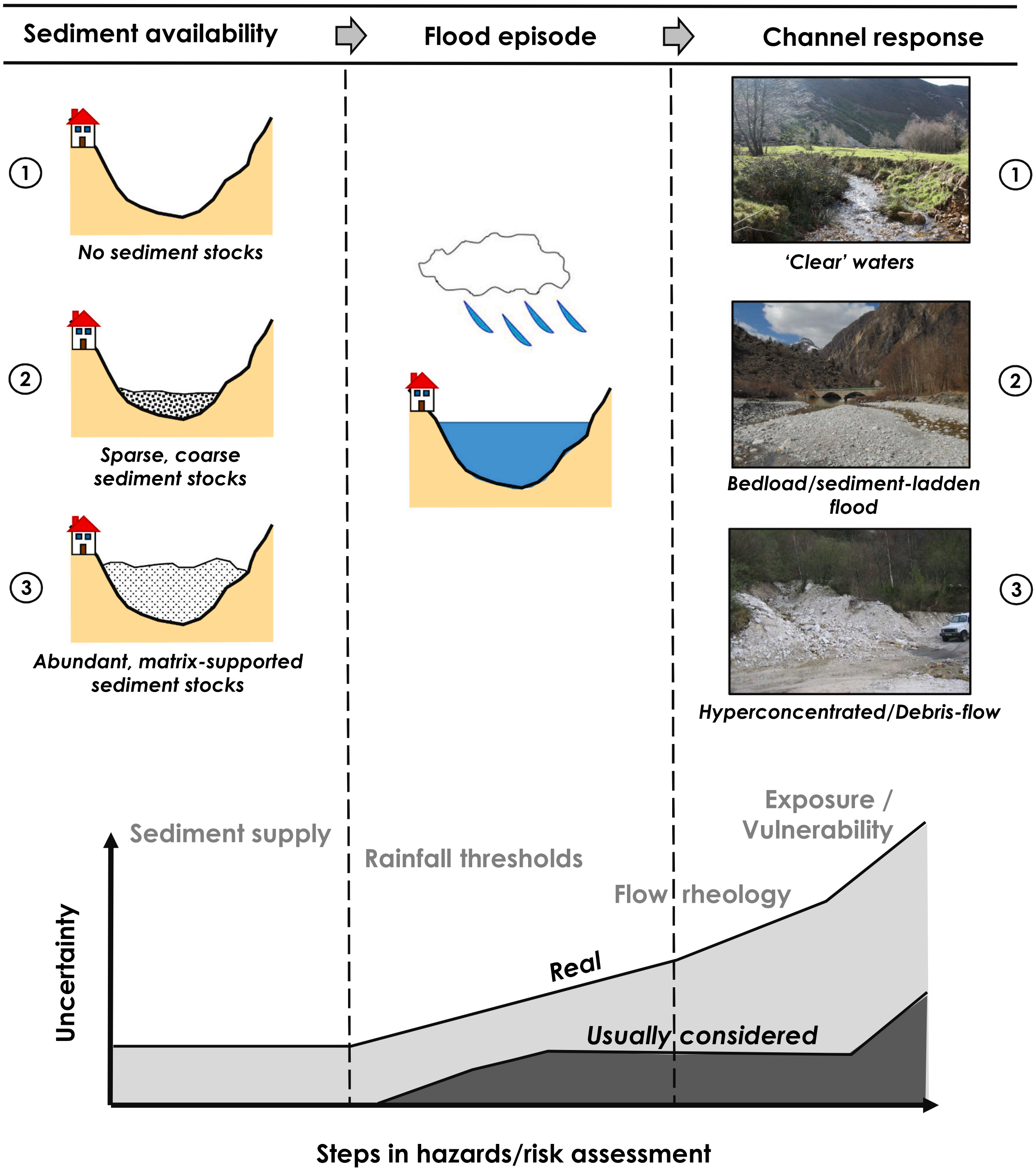


Fig. 5. Mountain channels typically exhibit a large spatiotemporal variability in the amount of sediment available. As a consequence, the response of the channel to a given flow or rainfall episode can be very different in terms of flow rheology, depending on the sediment available on the channel. In this regard, this figure aims to illustrate how the stochastic nature of sediment-supply to mountain channels introduces large uncertainties in sediment availability that propagate through the different steps of the hazards assessment (light grey in the lower graph). For instance, uncertainties in sediment availability may involve uncertainties in our ability to forecast the inundated surface and water depths for a given flow, which in turn means uncertainty in the estimates of the number of vulnerable elements exposed at risk. The global uncertainty is then larger than the uncertainty usually considered in the more common flood hazard assessments (dark grey in the lower graph).

during flooding may produce changes in channel capacity and form-roughness, potentially leading to changes in flood risk (Nones, 2019). Furthermore, erosive processes such as scour-and-fill of the riverbed, bank erosion, or channel avulsion can lead to significant morphological adjustments during extreme floods (Nardi and Rinaldi, 2015; Hooke, 2016; Surian et al., 2016; Magliulo et al., 2021), modifying the channel geometry and the discharge-thresholds for overbank flow. In some cases, erosion and deposition could 'compensate' each other, leaving the capacity to convey the flow unchanged despite intense morphological adjustments. In addition, depending on the magnitude of flood and its duration, sediment erosion and deposition in the main channel and floodplain may modify the residence time of water in the floodplain, altering flow routing and flood-wave attenuation, with potential impacts on downstream flood hazards (Guan et al., 2016). All this is a source of uncertainty in flood hazard assessments.

Moreover, intense sediment transport during high-magnitude flood events can trigger strong and abrupt morphological changes, such as massive bed aggradation/incision, bar-edge trimming, bank erosion, channel avulsion and/or macro-bedform propagation (Comiti et al., 2016a,b; Davidson and Eaton, 2018; Francalanci et al., 2020; Dunne and Jerolmack, 2020). These processes are the morphodynamic expression of strong sediment mobilisation and transport during extreme floods, and can be a source of major damage to buildings, agricultural land, bridges (Boothroyd et al., 2021), dams (Santos-González et al., 2021)

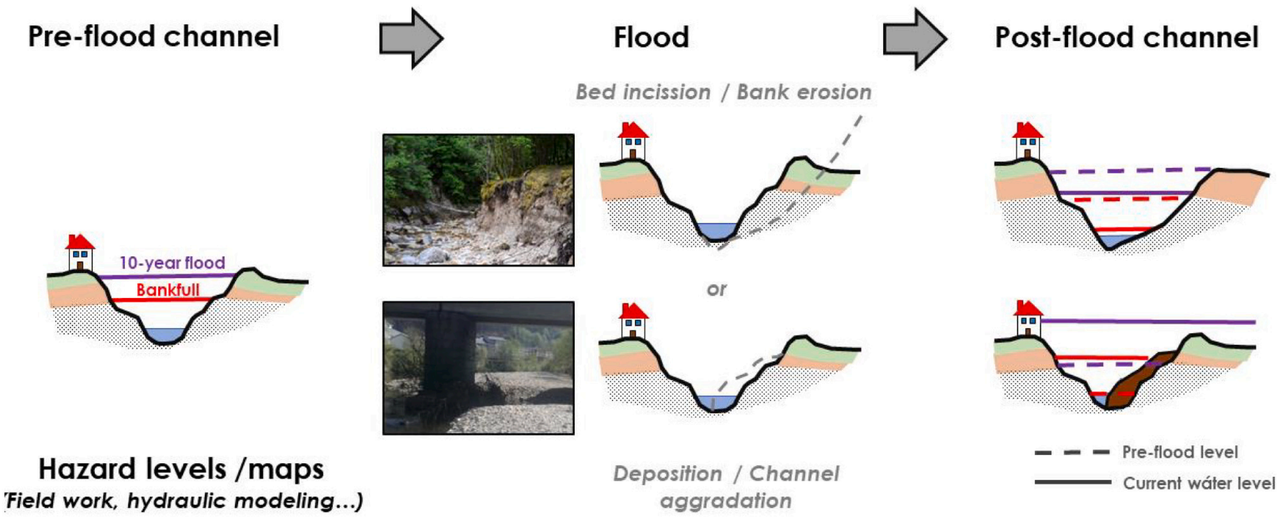


Fig. 6. This scheme illustrates how changes in bed level during floods in alluvial rivers (through incision, bank erosion and aggradation) can cause changes in conveyance capacity. Changes in channel morphology can also alter bed roughness and hence flow-stage relationships.

and other infrastructures (Nones and Pescaroli, 2016). In response to channel planform dynamics, river management strategies often include hard bank protection, which in many cases can lead to increased sedimentation and flood risks (Davies et al., 2003; Siviglia et al., 2008). In addition, bank and island erosion during high-magnitude floods can lead to the uprooting recruitment of trees, so alluvial rivers can also transport a significant amount of large wood (e.g., Ghaffarian et al., 2020; Ruiz-Villanueva et al., 2019). The transported large wood debris can become trapped in narrow reaches, at bridges or dams (Cicco et al., 2018), increasing flood hazards and damage. Furthermore, the transport of large wood is also a driver of morphological adjustments during extreme floods in alluvial rivers. These potential cascading effects introduce an additional source of uncertainty in flood hazard assessments.

In summary, active sediment transport during floods can lead to strong changes in channel geometry and morphology (Rinaldi et al., 2016). As outlined above, three different data sources have traditionally been used to produce flood hazard maps for alluvial rivers: i. results from 1D/2D hydraulic models; ii. geomorphological evidence of flood activity in the floodplain and channel identified during fieldwork; and/or iii. historical records of past floods. However, these methods implicitly assume stationary conditions for the channel geometry (Piégay et al., 2005; Rinaldi et al., 2015; Call et al., 2017), meaning that future floods will inundate floodplains as in the past (geomorphological method); or that the channel macroforms, roughness, or riverbed level do not evolve during the course of a flood hydrograph (hydraulic modelling method). In this regard, sediment transport introduces large uncertainties in hazard estimations, with implications on flood hazard map delineation using these common approaches.

Morphodynamic numerical models have been developed over the last decade, providing tools to simulate bed evolution and incorporate sediment transport into flood simulations (Guan et al., 2015; Williams et al., 2016; Lotsari et al., 2017). The conceptual and numerical basis for these models has long existed (Exner, 1920; Parker, 2006), but the recent spread of high-resolution topography (Vericat et al., 2017) and the improvements in the computational capacities of desktop computers have facilitated the development and expansion of these models (Radice et al., 2013; Lotsari et al., 2017) and opened the door for their use in flood-hazard studies.

For instance, Neuhold et al. (2009) applied a 1D-morphodynamical model coupled to a semi-distributed hydrological model to simulate multiple scenarios of sediment supply in the River Ill (Western Austria Alps, ~1300 km^2 catchment area). In doing so, these authors determined the sensitivity of inundation boundaries in flood-hazard maps to sediment supply and attempted to propagate uncertainties into the risk assessment. Similarly, Nones (2019) performed two sets of numerical simulations on a tributary of the Po River (Secchia River, Italy; 2300 km^2 catchment area), using the same hydrological input but changing the modelling conditions, and observed significant differences in the flooded surface between simulations performed with fixed and movable bed conditions. In contrast, Wong et al. (2015) used a 1D-model to test the effects of large changes in bed elevation associated with an extreme flood in a gravel-bed river from northern England, and reported that sediment transport had little effect on flood extent. However, that case study corresponds to a gravel-bed river with a low sediment supply and is constrained by valley walls (Hooke, 2015), so the observations reported may be largely site-specific. In any case, all these works already highlight the enormous potential of hydro-morphodynamic models for exploring the influence of sediment transport and improving flood-hazard assessments. However, the application of these models is challenged by the difficulty of defining some input parameters, such as the sediment supply into the reach. In addition, the complexity of morphodynamical models is still high. They need to be calibrated/validated with field data (Lotsari et al., 2017), which are not always easy to collect. Nevertheless, the recent spread and development of high-resolution topography is expanding our ability to acquire this kind of data (Vericat et al., 2017). However, the existing commercial morphodynamic software primary focus on modelling changes in bed elevation and are still in their infancy regarding the realistic simulation of bank retreat and bar-edge trimming (Vericat et al., 2017; Stecca et al., 2017). Numerical modelling of bank erosion and lateral channel migration remains challenging due to the absence of a detailed deterministic description of the underlying physics and the complexities associated with integrating a bank erosion algorithm into morphodynamic models (Stecca et al., 2017). This constraint hampers the current capacity of these models to adequately predict how channels respond to exceptionally severe floods.

4.3. *Effects of changes in sediment supply on flood hazards*

There is a growing interest in studying how flood hazards will evolve worldwide in the coming decades in relation to global change and predicting their near-future trends (Kundzewicz et al., 2014; Lotsari et al., 2015; Poff, 2014; O'Briain, 2019; Blöschl et al., 2020; Benito et al., 2020b). In this context, rivers should be understood as dynamic entities, whose geometry, morphology, and bed roughness change over time in response to variations in the hydrologic regime and/or sediment supply driven by climate variability and/or land cover change (Lane et al., 2007; Tal and Paola, 2007; Czuba et al., 2010; Gran et al., 2011; Wohl et al., 2015; Phillips and Jerolmack, 2016; Micheletti and Lane, 2016; Machado et al., 2017; Slater et al., 2019; Scorpio and Piégay, 2021). Therefore, to the extent that channels evolve in response to these different environmental signals, adjustments in channel geometry and roughness may affect conveyance capacity, discharge-stage relations, and thus flood frequency.

That said, several studies have explored how changes in channel geometry and morphology may affect the frequency of flooding. For instance, Slater and Singer (2013) and Slater et al. (2015) analysed data from 915 US Geological Survey gauging stations for the period 1950–2011 and separated changes in flood frequency related to streamflow variability from those related to changes in channel flood conveyance capacity. They reported that changes in channel conveyance capacity were more minor but more numerous, and outlined their relevance for flood hazard management. In fact, as they explain, their results may have underestimated the importance of changes in channel geometry in flood hazard, because the USGS often places gauges in locations with relatively stable channel geometry. In a similar study, Slater (2016) examined 20 years of gauging records from 41 stations in England and Wales (UK) and documented how a 10 % change in the flood conveyance capacity of the channel could explain an average change in the frequency of flooding of 1.5 days. Call et al. (2017) used a stochastic, reduced complexity model to explore how non-stationary flow regimes and/or channel geometry amplify or attenuate the frequency and extent of flood inundation in rivers from Minnesota (USA). Their results suggest that the annual extent of the flooded area depends mainly on the variation in peak flows, but the changes in channel width primarily control the frequency of flood inundation. Slater et al. (2019) also analysed data from 67 US rivers (over seven decades) and examined the strength of covariation between channel geometry and different modes of climate variability (El Niño-Southern Oscillation, Atlantic Multidecadal Oscillation, and Arctic Oscillation). The study shows that two-thirds of the rivers analysed have channel contraction/expansion phases consistent with changes in streamflow and precipitation driven by climate variability.

In summary, this previous research highlights that flood frequency in alluvial rivers is far from stationary, with a significant amount of temporal variability that can be attributed to changes in channel geometry and morphology. The consequence is that flood-hazard assessments in alluvial streams derived from snapshot studies based on present-day bankfull geometry or historical flood records cannot be projected too far into the future to the extent that a channel is expected to evolve (Czuba et al., 2010). In this regard, changes in sediment supply driven by catchment-scale controls (e.g. land-use change, rainfall variability, climate) and anthropic impacts (e.g. dams, gravel mining) are a major control on river morphology and planform, which may shift in response to large-scale sediment supply (aggradation–degradation, widening-narrowing) cycles (Hassan et al., 2007). Accordingly, channel conveyance capacity and discharge-stage-flow velocity relations might differ depending on where the river is aggrading or degrading and/or widening or narrowing (Stover and Montgomery, 2001; Lane et al., 2007; Raven et al., 2010; Davies and McSaveney, 2011; Slater and Singer, 2013; Hooke, 2015).

Therefore, our ability to forecast near-future trends in flood hazards using only field and historic flood evidence may be compromised if we overlook occasional sediment inputs (e.g., landslides) or changes in sediment supply derived from human interventions (e.g. dams, channelization). In temperate regions worldwide, it has been widely reported how rivers have undergone significant morphological changes following catchment-scale land-use changes in recent decades (Liébault and Piégay, 2002; Rinaldi et al., 2005; Simon and Rinaldi, 2006; Wohl, 2019, 2020; Scorpio and Piégay, 2021; Magliulo et al., 2021) and are expected to continue to evolve (Downs and Piégay, 2019). In this respect, some studies have already analysed decadal trends in channel geometry in response to variability in sediment-supply. For example, Stover and Montgomery (2001) analysed 45 years of data on changes in channel geometry for the Skokomish River (Washington, USA). They reported a significant increase in the frequency of flood frequency without a comparable increase in peak flows. They attributed these trends to channel aggradation as a result of land-use changes (timber harvesting, road construction) impacting the sediment supply. More recently, Magliulo et al. (2021) documented several phases of changes in channel width in the Tammaro river (Italy), driven by land-use changes (i.e., sediment supply), rainfall variability and extreme floods.

Thus, flood hazard delineations derived from the interpretation of old aerial photographs and field evidence of historical floods may be arguable without actually considering whether the river is currently in an aggrading, degrading, or equilibrium stage (Stover and Montgomery, 2001; Hooke, 2015) (Fig. 7), especially in active tectonic areas or in catchments undergoing rapid land-use change (Lane et al., 2007; Thapa et al., 2022; Thapa et al., 2023). Some attempts have already been made to include sediment transport in flood hazard studies in order to improve flood frequency predictions in the coming decades in response to land-cover change and climate variability (Lane et al., 2007; Lotsari et al., 2015; Pender et al., 2016; Dysarz, 2020). For example, Lane et al. (2007, 2008) used hydraulic modelling to illustrate how channel sedimentation in the gravel-bed River Wharfe (UK) could increase the extent of flooding compared to that expected from climate variability. Similarly, Rodriguez-Lloveras et al. (2016) used a hydro-sedimentary model to evaluate the relative impact of climate vs land-use change in the sediment yield of Mediterranean watersheds and concluded that land use is the primary factor inducing changes in sediment production. Likewise, Bussi et al. (2016) forecasted the relative influence of climate and land-use change on future suspended sediment yields in the River Thames (UK) and concluded that the relative effect of climate vs land-use change on suspended sediment yields was spatially variable across their study catchment. More recently, Dingle et al. (2020) developed a 2D hydrodynamic model for the Karnali River (Terai basin, Nepal) and tested several scenarios of variable bed elevation to simulate the flood response to bed aggradation and incision. They reported that changes in bed elevation could result in significant variations in the extent of flooding. However, despite these previous studies, the topic of how river sediment routing systems will respond to climate and environmental changes in the coming decades has been uncommon (Lane, 2013; Spencer and Lane, 2017).

The influence of changes in sediment supply on channel morphological adjustments should also be considered when assessing the long-term feasibility of human constructions and infrastructures (e.g., Vázquez-Tarrío et al., 2023) or for the smart implementation of river restoration programs (Guzelj et al., 2020). A failure to consider sediment transport may lead to increased flood hazards. A good example is the Waihoa River in New Zealand (Davies et al., 2003; Hicks et al., 2021). This is a braided river where bed aggradation, promoted by flood protection works, is leading to unprecedented rates of bed elevation and a sustained increase in flood hazards (Hicks et al., 2021). On this point, the areas adjacent to reservoirs should also be outlined (Kondolf et al., 2014; Espa et al., 2019). Sustained sediment trapping by dams may reduce the storage capacity of reservoirs and alter their ability to absorb and laminate the floods, thereby increasing flood hazards in adjacent areas. In addition, sediment is preferentially deposited at the tail of reservoirs, thus increasing flood levels in these areas.

4.4. Sediment transport and flood-damage models

Flood risk is the result of flood magnitude and frequency (hazard), the elements at risk (exposure), and their vulnerability (Fuchs et al., 2019). As sediment transport and geomorphic changes can introduce large uncertainties in the estimations of water levels and the extent of inundation and damage for a given discharge (Fig. 8), they can also result in the over- or underestimation of the number of exposed elements

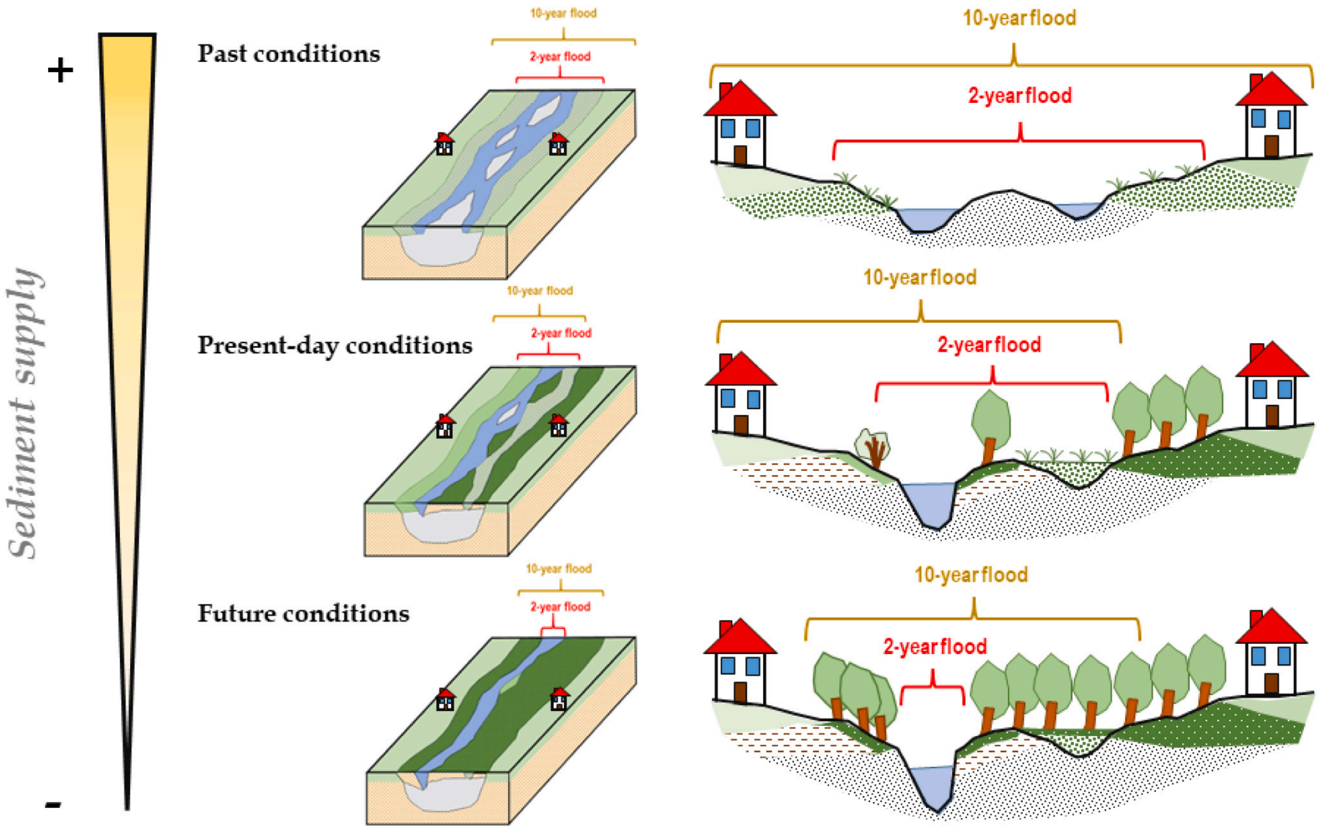


Fig. 7. This figure illustrates how long-term changes in sediment-supply (e.g., due to land-use changes, dams) at the catchment scale can trigger a cascade of morphological changes in the channel (i.e., channel metamorphosis), such as bed incision/aggradation, channel straightening, narrowing or encroachment. This may be associated with changes in channel conveyance capacity, bed roughness and hence flow-stage relationships. In the particular case depicted in this scheme, we show a wandering channel that, following a long-term, sustained reduction in sediment supply, experienced a quick exhaustion of gravel sediment and bed lowering, with a decrease in the lateral extent reached by floods.

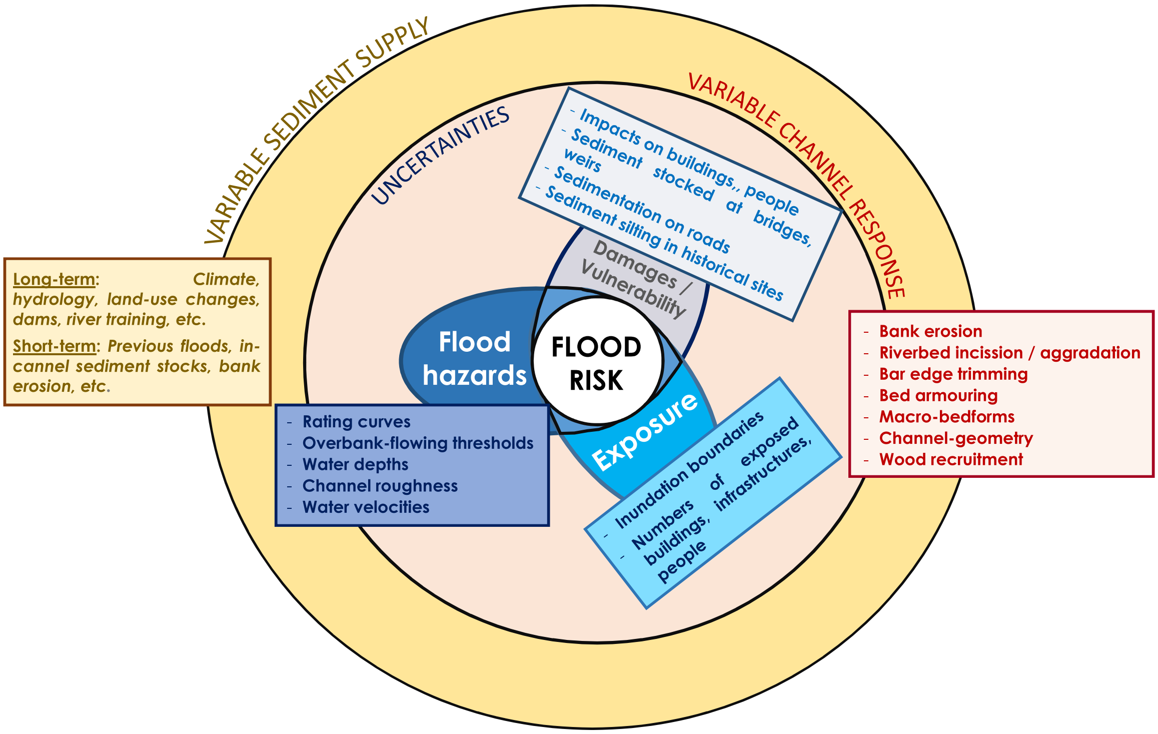


Fig. 8. Chart summarizing how the uncertainties associated with sediment-transport processes may propagate through the different steps of flood-risk assessment.

and people (Neuhold et al., 2009).

Sediment transport may also influence the vulnerability of exposed elements and the damage expected. However, this has rarely been considered in flood damage models, even though the sediment load can considerably increase the damage associated with a given water level (Totschnig et al., 2011). For instance, bed-load transport and deposition processes strongly influence the impact forces on infrastructure and buildings (Sturm et al., 2018a,b; Basso-Báez et al., 2020; Di Cristo et al., 2021). In this regard, the mechanical impact of coarse sediments on vehicles, houses, and people can cause important injuries to people and even loss of life (Sturm et al., 2018b,a). Furthermore, in mountain areas, flow rheology varies with sediment concentration (Pierson and Costa, 1987), which may in principle lead to varying potential damage and vulnerability (Ciurean et al., 2017; Fuchs et al., 2019; Luo et al., 2020a, b). However, Totschnig and Fuchs (2013) compared vulnerability functions for fluvial sediment transport and debris flow and concluded that there is no need to distinguish between different processes when assessing the physical vulnerability of buildings.

In alluvial rivers, widespread suspended sedimentation from overbank flows can quickly accumulate on roads, infrastructures, and cultural heritage, severely complicating rescue and reconstruction efforts after flood peaks (Díez-Herrero et al., 2009). Furthermore, overbank sedimentation can also be associated with the dispersal of contaminants that can pose long-term threats on human populations (Dennis et al., 2003; Ciszewski and Grygar, 2016; Nones and Pescaroli, 2016), especially when the inundated surfaces include cropland and irrigated areas. In addition, in both mountain and alluvial channels, sediment accumulation can cause bridges to become clogged and can deviate the flow on the abutments and cause them to scour. All of this can lead to the collapse, failure or burial of bridges and road segments (Ciurean et al., 2017; Martín-Vide et al., 2023).

5. Discussion

5.1. Bibliometric analysis

Bibliometric analysis provides a reliable picture of the state of research on the role of sediment transport in flood hazards, despite limitations in the use of WoS, namely its focus on academic journals, lack of technical reports and grey literature, and bias towards English-language journals. Bibliometric analysis shows that the two studied topics (flood hazards/risks and sediment transport) have an extensive publication record when considered separately, but a limited publication number when combined with the Boolean “AND”. On the one hand, previous research on flood hazards/risks has often not considered the role of sediment transport and how channel morphodynamics may change the hazard maps or risk level. On the other hand, most studies on river sediment do not focus on flood hazard or risk, but are mostly interested in sediment production, transport rates, geomorphic changes or water quality. In addition, when looking at the country where the leading authors are based or the preferred journals, our analysis also shows some notable differences between the ‘sediment transport’ and the ‘flood hazards’ literature. In this sense, it could be argued that these two research topics constitute two relatively independent ‘research programs’ or ‘traditions’ within the broader field of fluvial geomorphology, albeit with a certain and undeniable permeability between them.

We attribute this primarily to the intricate process of integrating sediment transport into hydrodynamic models, which is determined by four key factors. Firstly, the scarcity of sediment transport records, such as grain size and transport rate data, limits the availability of essential input data for morphodynamic modelling. Secondly, the riverbed sediment exhibits heterogeneous and spatiotemporal variability concerning grain size, armouring layer development and sediment availability (Gomez and Soar, 2022). Thirdly, substantial uncertainties in sediment transport estimates arise from the non-linear response of sediment transport to water discharge (Recking, 2013a). Lastly, the existing numerical tools have inherent limitations for simulating bank erosion, bard-edge trimming, and channel widening in real-world scenarios (Vericat et al., 2017; Stecca et al., 2017). These uncertainties are challenging to incorporate into flood hazard maps normally demanded by river managers. Instead, hazard analysis has focused preferentially on the representativeness of the channel topo-bathymetry and discharge recurrence estimates (e.g., Benito and Díez-Herrero, 2015; Choné et al., 2021; Garrote et al., 2021), which are frequently considered the two factors causing the most significant uncertainty in flood hazard delineation.

On the other hand, sediment transport researchers have mostly been concerned with basic or fundamental questions, such as understanding the mechanics of sediment transport, exploring the limits of the different methods for measuring sediment transport in the field (e.g., Vericat et al., 2006), or searching for an adequate model to calculate sediment transport (Recking, 2013b). Most applied works focused on understanding anthropogenic impacts (e.g., dams, land-use changes) on sediment production and continuity, and river restoration (Downs and Piégay, 2019; Piégay et al., 2023). Conversely, sediment studies have often disregarded the implications of sediment transport on flood hazards, probably because of the inherent complexity of including sediment transport in hazard assessments mentioned above and the difficulty in monitoring sediment transport during floods.

In addition, we must not forget issues related to how scientific research is usually conducted. As seen above, researchers in both subjects show a certain tendency to publish in different journals, work in different research institutions and very likely attend different types of meetings and workshops. This may also have contributed to reducing the exchange between the two fields of study.

5.2. Remaining challenges: implications for future studies

The first idea to emerge from our review is that mountain and alluvial rivers represent two distinct domains in terms of the existing relationships between sediment transport and flood hazard. Mountain streams are closer to the sediment-producing areas, so their sediment availability is highly dependent on inputs from slope processes and, as a result, they are more sensitive to variations in sediment supply. On the other hand, sediment inputs to alluvial rivers during floods usually come from the river bed and banks, and they show a greater capacity to adjust to changes in sediment supplies. Consequently, in alluvial rivers, the autogenic dynamics of change during floods, such as bank erosion, bar edge trimming, bar migration, meander chute cut-off, channel avulsion, etc., have a greater influence on flood hazards than the sediment transport processes themselves.

In this sense, we believe that differentiated strategies between these two main domains should be followed in the incorporation of sediment transport into flood hazard assessment. In mountain streams, continuous monitoring of in-channel sediment storage and sediment source areas can provide key information to determine the available sediment storage in the channel and to anticipate the effects of a given flood discharge. This type of information could also help to define rainfall intensity-duration (ID) thresholds for runoff-generated debris flows that account for the availability of in-channel sediment, as suggested by Tang et al. (2020). In addition, developments in geophysical methods appear promising for measuring bedload transport (Rickenmann, 2017). This opens the door to using these techniques in order to establish local sediment-rating curves and monitor sediment transport in real-time (e.g. Lekach and Enzel, 2021; Coviello et al., 2022), providing key inputs for morphodynamic and flood hazard models (Hürlimann et al., 2019).

In the case of alluvial rivers, 1D or 2D morphodynamic models are suitable approaches to evaluate the uncertainties in the assessment of hazards associated with large floods, overcoming some of the drawbacks associated to traditional hydraulic (fixed bed) models (see Radice et al., 2013, 2016; Wong et al., 2015; Guan et al., 2016; Lotsari et al., 2017;

Oliver et al., 2018; Nones, 2019; Fieman et al., 2020). In this regard, recent advances in high-resolution topographic methods (LiDAR, SfM photogrammetry) and the general spread of relatively cheap acquisition platforms (e.g., drones) make it possible from now on to accomplish a detailed diachronic analysis of geomorphic changes after floods (e.g. Wheaton et al., 2013; Calle et al., 2015) or spatially distributed characterizations of riverbed roughness (Vázquez-Tarrío et al., 2017). This provides a very useful tool for calibrating and validating the outcomes of morphodynamic models and improving flood hazard assessments. Therefore, a meaningful workflow for flood hazard assessment in alluvial rivers with active sediment transport dynamics shall involve morphodynamic modelling under different sediment supply scenarios (volumes, grain-size). Based on the outputs of these simulations, it might be possible to define uncertainty bands around inundated surface boundaries, as already attempted by Neuhold et al. (2009), Pender et al. (2016), Radice et al. (2016) and Dysarz (2020). The results of these models could be calibrated and validated with geomorphological and diachronic topographic information. This workflow would allow the definition of different hazard levels depending on the amount of sediment supplied to the channel.

While 1D and 2D morphodynamic models can enhance the resources and tools for evaluating flood inundation hazards, particularly for determining uncertainties in inundation boundaries, their utility is constrained when addressing the hazards stemming from significant channel morphological changes, such as bank instability or avulsion. Consequently, reliance on alternative geomorphological analysis and data sources becomes essential (Rinaldi et al., 2015). In this regard, other research strategies for both mountain and alluvial river settings include inventories of landslide and potential sediment delivery areas (e.g., banks undergoing active erosion) which can help to evaluate the potential sediment delivery to the channel during extreme floods. Similarly, the collection of post-flood observations (deposits, geomorphic features) is essential for understanding the behaviour of sediment transport during large floods (Rinaldi et al., 2016; Fieman et al., 2020). Photo-interpretation and field observations help to identify potentially sensitive areas (Simon and Downs, 1995; Chin and Gregory, 2005), such as channel expansion and contractions, or potential critical reaches for further detailed analysis (Mazzorana et al., 2011). At the same time, the use of historical photographs provides helpful information on lateral channel mobility and the extent of the erodible corridor at different spatio-temporal scales (Piégay et al., 1997; Piégay et al., 2005; Biron et al., 2014).

Regarding vulnerability, field observations and experimental studies are valuable to assess the effect of sediment load on buildings and infrastructure (Sturm et al., 2018b,a). Such studies can help to improve estimates of the impact of floods on buildings, infrastructure, and people, and could be incorporated into flood-damage functions (e.g., Roos et al., 2003; Walliman et al., 2013; Dottori et al., 2016; Jalayer et al., 2016). Thus, different damage and vulnerability models could be proposed depending on the amount of sediment carried by a given flood. Such sediment-sensitive vulnerability models could be coupled with morphodynamic simulations to present different scenarios of flood damage, which can ultimately assist river managers in their decision-making.

Finally, climate-change studies in rivers have often overlooked sediment transport (Lane et al., 2008; Lane, 2013). However, in the current context of global environmental change, many rivers are expected to undergo morphological changes in response to climate change, as well as changes in hydrological regime and variations in sediment supply from headwaters (Lane, 2013; Lotsari et al., 2015; Spencer and Lane, 2017; Magliulo et al., 2021). As a result, flood risk maps and flood management plans prepared for today's conditions may not necessarily be valid for conditions in the near future, leading to inappropriate risk awareness and mitigation measures. A better understanding of sediment transport processes within flood risk assessment can partially overcome these shortcomings and improve flood hazard assessment of evolving channel beds. This would be more relevant in those regions where episodic volumes of sediment are periodically supplied to the channel-network or where legacy sediment pulses propagate along the river (James, 2010; Sims and Rutherfurd, 2017), leading to decadal and secular oscillations in riverbed levels, such as in earthquake-prone regions (Davies and McSaveney, 2011; Fan et al., 2019), post-wildfire catchments (Moody and Martin, 2004; Murphy et al., 2018, 2019), areas subject to land-clearing for agriculture or timber harvesting (Gomez et al., 2003), or channels subjected to extractions or injections of bed material.

The analysis of the geomorphic trajectory followed by a given reach during the last decades could be used to propose different scenarios for the near-future trends in the conveyance capacity of the channel, accounting for the more likely human impacts and the predictions of climate change models, in line with the work carried out by Call et al. (2017). In addition, there has been a development in recent decades of numerical models that are able to model the changes in the fluvial landscape following changes in climate, hydrology, and sediment supply at the catchment scale, i.e., the so-called 'landscape evolution models' (LEMs) (Martin and Church, 2004; Chen et al., 2014; Temme et al., 2017; Martínez-Fernández et al., 2018; Nones, 2020). These LEMs models may be coupled with future climate change or land cover change scenarios to simulate the (catchment scale) response of fluvial landscapes in the coming decades (Coulthard et al., 2013; Meadows, 2014; Hancock et al., 2015; Coulthard and Macklin, 2001; Gioia and Schiattarella, 2020; Ramirez et al., 2020; Thapa et al., 2022; Thapa et al., 2023). Nevertheless, there are still some limitations to be considered in the application of LEM that need to be considered. These are related to the difficulties in their calibration/validation, in the selection of model parameters (Gioia and Schiattarella, 2020), or their physical simplifications, which may warrant further research.

6. Conclusions

In this paper, we have carried out a review of the scientific literature to date with the dual aim of investigating how sediment dynamics influence flood hazards and how this issue has been considered in previous flood hazard assessments. We summarize the main conclusions of our review in the following list of bullet points:

- Our bibliometric analysis revealed that there is no large body of literature that has explicitly considered sediment transport in flood hazard research (∼2–5 % of the total flood hazard publications). Nevertheless, the influence of sediment transport and changes in channel morphology on flood conveyance and flood frequency has been recognized and highlighted in some studies. However, much of this research has been study-case focused and sparse (Table 4), and few systematic and integrated studies have been undertaken.
- Sediment transport has an evident influence on flood hazards. In the short-term, during large floods, sediment transport and deposition may result in abrupt rapid changes in channel planform, such as bank erosion and channel avulsion, posing substantial risks to both people and infrastructure. Additionally, sediment transport and deposition during floods can induce modifications in channel geometry, planform, and bed roughness, thereby affecting flow-stage relationships. Over the long-term, changes in the sediment supply result in channel adjustments that can lead to changes in its conveyance capacity.
- Sediment transport is therefore responsible for significant uncertainties in the estimation of flood extent and flood hazard assessment. This concern is particularly relevant in the case of mountain streams, which are close to sediment-producing areas and exhibit considerable variability in sediment supply. In addition, mountain regions are particularly sensitive to climatic and hydrologic variability.
- Fortunately, new field-observation techniques and numerical modelling tools have been developed in the last decades, improving

our ability to deal with sediment transport in flood hazard studies. Continuous monitoring of sediment transport, together with the incorporation of sediment transport into the workflows and routines used to analyse uncertainties and sensitivities in flood evaluations, may help to increase our ability to assess and manage flood risks.

Declaration of competing interest

The authors 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

No data was used for the research described in the article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2023.108976.

References

Alexander, J., Cooker, M.J., 2016. Moving boulders in flash floods and estimating flow conditions using boulders in ancient deposits. Sedimentology 63, 1582–1595. https://doi.org/10.1111/sed.12274.

Anselmo, V., Galeati, G., Palmieri, S., Rossi, U., Todini, E., 1996. Flood risk assessment using an integrated hydrological and hydraulic modelling approach: a case study. J. Hydrol. 175, 533–554. https://doi.org/10.1016/S0022-1694(96)80023-0.

Aria, M., Cuccurullo, C., 2017. Bibliometrix: an R-tool for comprehensive science mapping analysis. J. Informet. 11 (4), 959–975. https://doi.org/10.1016/j.joi.2017.08.007.

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, Southern French Alps). Geomorphology 66 (1–4), 41–67. https://doi.org/10.1016/j.geomorph.2004.03.014 (Special Issue on "Geomorphological hazard and human impact in mountain environments").

Arnaud-Fassetta, G., Astrade, L., Bardou, E., Corbonnois, J., Delahaye, D., Fort, M., Gautier, E., Jacob, N., Peiry, J.-L., Piégay, H., Penven, M.-J., 2009. Fluvial geomorphology and flood-risk management. Geomorphol. Relief Process. Environ. 15 (2) https://doi.org/10.4000/geomorphologie.7554.

Attal, M., 2017. Linkage between sediment transport and supply in mountain rivers. In: Gravel-bed Rivers. John Wiley & Sons, Ltd, pp. 329–353. https://doi.org/10.1002/9781118971437.ch12.

Badoux, A., Andres, N., Turowski, J.M., 2014. Damage costs due to bedload transport processes in Switzerland. Nat. Hazards Earth Syst. Sci. 14 (2), 279–294. https://doi.org/10.5194/nhess-14-279-2014.

Baker, V.R., 1994. Geomorphological understanding of floods. Geomorphology 10 (1–4), 139–156. https://doi.org/10.1016/0169-555X(94)90013-2.

Barredo, J.I., 2007. Major flood disasters in Europe: 1950-2005. Nat. Hazards 42, 125–148. https://doi.org/10.1007/s11069-006-9065-2.

Basso-Báez, S., Mazzorana, B., Ulloa, H., Bahamondes, D., Ruiz-Villanueva, V., Iroumé, A., Picco, L., 2020. Unravelling the impacts to the built environment caused by floods in a river heavily perturbed by a volcanic eruption. J. S. Am. Earth Sci. 102, 102655 https://doi.org/10.1016/j.jsames.2020.102655.

Bel, C., Liébault, F., Navratil, O., Eckert, N., Bellot, H., Fontaine, F., Laigle, D., 2017. Rainfall control of debris-flow triggering in the Réal Torrent, Southern French Prealps. Geomorphology 291, 17–32. https://doi.org/10.1016/j.geomorph.2016.04.004 (Special Issue on 'SEDIMENT DYNAMICS IN ALPINE BASINS').

Beniston, M., Stoffel, M., 2016. Rain-on-snow events, floods and climate change in the Alps: events may increase with warming up to 4°C and decrease thereafter. Sci. Total Environ. 571, 228–236. https://doi.org/10.1016/j.scitotenv.2016.07.146.

Benito, G., Díez-Herrero, A., 2015. Palaeoflood hydrology: reconstructing rare events and extreme flood discharges. In: Shroder, J.F., Paron, P., Di Baldassarre, G. (Eds.), Hydro-meteorological Hazards, Risk and Disasters. Elsevier, pp. 65–104. https://doi.org/10.1016/B978-0-12-394846-5.00003-5.

Benito, G., Vázquez-Tarrío, D., 2022. Hazardous processes: flooding. In: Shroder, J.F. (Ed.), Treatise on Geomorphology (2nd Edition), Vol. 9. Elsevier, pp. 715–743. https://doi.org/10.1016/B978-0-12-818234-5.00081-X chapter 9.30.

Benito, G., Grodek, T., Enzel, Y., 1998. The geomorphic and hydrologic impacts of the catastrophic failure of flood-control-dams during the 1996-Biescas flood (Central Pyrenees, Spain). Z. Geomorphol. 42 (4), 417–437. https://doi.org/10.1127/zfg/42/1998/417.

Benito, G., Harden, T., O'Connor, J., 2020a. Quantitative Paleoflood Hydrology, in: Reference Module in Earth Systems and Environmental Sciences. https://doi.org/10.1016/B978-0-12-409548-9.12495-9.

Benito, G., Sanchez-Moya, Y., Medialdea, A., Barriendos, M., Calle, M., Rico, M., Sopeña, A., Machado, M.J., 2020b. Extreme floods in small mediterranean catchments: long-term response to climate variability and change. Water 12, 1008. https://doi.org/10.3390/w12041008.

Benito, G., Thorndycraft, V.R., Medialdea, A., Machado, M.J., Sancho, C., Dussaillant, A., 2021. Declining discharge of glacier outburst floods through the Holocene in central Patagonia. Quat. Sci. Rev. 256, 106810 https://doi.org/10.1016/j.quascirev.2021.106810.

Biron, P.M., Buffin-Bélanger, T., Larocque, M., Choné, G., Cloutier, C., Ouellet, M., Demers, S., Olsen, T., Desjarlais, C., Eyquem, J., 2014. Freedom space for rivers: a sustainable management approach to enhance river resilience. Environ. Manag. 54, 1056–1073 (2014). https://doi.org/10.1007/s00267-014-0366-z.

Blöschl, G., Kiss, A., Viglione, A., Barriendos, M., Böhm, O., Brázdil, R., Coeur, D., Demarée, G., Llasat, M.C., Macdonald, N., Retsö, D., Roald, L., Schmocker-Fackel, P., Amorim, I., Bělínová, M., Benito, G., Bertolin, C., Camuffo, D., Cornel, D., Doktor, R., Elleder, L., Enzi, S., Garcia, J.C., Glaser, R., Hall, J., Haslinger, K., Hofstätter, M., Komma, J., Limanówka, D., Lun, D., Panin, A., Parajka, J., Petrić, H., Rodrigo, F.S., Rohr, C., Schönbein, J., Schulte, L., Silva, L.P., Toonen, W.H.J., Valent, P., Waser, J., Wetter, O., 2020. Current European flood-rich period exceptional compared with past 500 years. Nature 583, 560–566. https://doi.org/10.1038/s41586-020-2478-3.

Bodoque, J.M., Eguiba, M.A., Díez-Herrero, A., Gutiérrez-Pérez, I., Ruíz-Villanueva, V., 2011. Can the discharge of a hyperconcentrated flow be estimated from paleoflood evidence? Water Resour. Res. 47 https://doi.org/10.1029/2011WR010380.

Boothroyd, R.J., Williams, R.D., Hoey, T.B., Tolentino, P.L.M., Yang, X., 2021. National-scale assessment of decadal river migration at critical bridge infrastructure in the Philippines. Sci. Total Environ. 768, 144460 https://doi.org/10.1016/j.scitotenv.2020.144460.

Borga, M., Stoffel, M., Marchi, L., Marra, F., Jakob, M., 2014. Hydrogeomorphic response to extreme rainfall in headwater systems: flash floods and debris flows. J. Hydrol. 518, 194–205. https://doi.org/10.1016/j.jhydrol.2014.05.022.

Bornmann, L., Haunschild, R., Mutz, R., 2021. Growth rates of modern science: a latent piecewise growth curve approach to model publication numbers from established and new literature databases. Humanit. Soc. Sci. Commun. 8, 224 (2021). https://doi.org/10.1057/s41599-021-00903-w.

Bovis, M.J., Jakob, M., 1999. The role of debris supply conditions in predicting debris flow activity. Earth Surf. Process. Landf. 24, 1039–1054. https://doi.org/10.1002/(SICI)1096-9837(199910)24:11<1039::AID-ESP29>3.0.CO;2-U.

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. https://doi.org/10.1016/j.geomorph.2020.107413.

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. https://doi.org/10.1016/j.geomorph.2023.108650.

Buffin-Bélanger, T., Demers, S., Montané, A., 2017. In: Vinet, F. (Ed.), 10 - Hydrogeomorphology: Recognition and Evolution of the Flood Phenomenon, Floods. Elsevier, pp. 167–191. https://doi.org/10.1016/B978-1-78548-268-7.50010-9.

Bussi, G., Dadson, S.J., Prudhomme, C., Whitehead, P.G., 2016. Modelling the future impacts of climate and land-use change on suspended sediment transport in the River Thames (UK). J. Hydrol. 542, 357–372. https://doi.org/10.1016/j.jhydrol.2016.09.010.

Calhoun, N.C., Clague, J.J., 2018. Distinguishing between debris flows and hyperconcentrated flows: an example from the eastern Swiss Alps. Earth Surf. Process. Landf. 43, 1280–1294. https://doi.org/10.1002/esp.4313.

Call, B.C., Belmont, P., Schmidt, J.C., Wilcock, P.R., 2017. Changes in floodplain inundation under nonstationary hydrology for an adjustable, alluvial river channel. Water Resour. Res. 53, 3811–3834. https://doi.org/10.1002/2016WR020277.

Calle, M., Lotsari, E., Kukko, A., Alho, P., Kaartinen, H., Rodriguez-Lloveras, X., Benito, G., 2015. Morphodynamics of an ephemeral gravel-bed stream combining Mobile Laser Scanner, hydraulic simulations and geomorphological indicators. Zeitschrift für Geomorphol. Suppl. Issues 59. https://doi.org/10.1127/zfg_suppl/2015/S-59196.

Chauchat, J., Cheng, Z., Nagel, T., Bonamy, C., Hsu, T.-J., 2017. SedFoam-2.0: a 3-D two-phase flow numerical model for sediment transport. Geosci. Model Dev. 10, 4367–4392. https://doi.org/10.5194/gmd-10-4367-2017.

Chen, A., Darbon, J., Morel, J.-M., 2014. Landscape evolution models: a review of their fundamental equations. Geomorphology 219, 68–86. https://doi.org/10.1016/j.geomorph.2014.04.037.

Chin, A., Gregory, K.J., 2005. Managing urban river channel adjustments. Geomorphology 69, 28–45. https://doi.org/10.1016/j.geomorph.2004.10.009.

Choné, G., Biron, P.M., Buffin-Bélanger, T., Mazgareanu, I., Neal, J.C., Sampson, C.C., 2021. An assessment of large-scale flood modelling based on LiDAR data. Hydrol. Process. 35 (8), e14333 https://doi.org/10.1002/hyp.14333.

Church, M., 2006. Bed material transport and the morphology of alluvial river channels. Annu. Rev. Earth Planet. Sci. 34, 325–354. https://doi.org/10.1146/annurev.earth.33.092203.122721.

Church, M., Jakob, M., 2020. What is a debris flood? Water Resour. Res. 56, e2020WR027144 https://doi.org/10.1029/2020WR027144.

Church, M., Zimmermann, A., 2007. Form and stability of step-pool channels: research progress. Water Resour. Res. 43 https://doi.org/10.1029/2006WR005037.

Cicco, P.N.D., Paris, E., Ruiz-Villanueva, V., Solari, L., Stoffel, M., 2018. In-channel wood-related hazards at bridges: a review. River Res. Appl. 34, 617–628. https://doi.org/10.1002/rra.3300.

Ciszewski, D., Grygar, T.M., 2016. A review of flood-related storage and remobilization of heavy metal pollutants in river systems. Water Air Soil Pollut. 227, 239. https://doi.org/10.1007/s11270-016-2934-8.

Ciurean, R.L., Hussin, H., van Westen, C.J., Jaboyedoff, M., Nicolet, P., Chen, L., Frigerio, S., Glade, T., 2017. Multi-scale debris flow vulnerability assessment and direct loss estimation of buildings in the Eastern Italian Alps. Nat. Hazards 85, 929–957. https://doi.org/10.1007/s11069-016-2612-6.

Clague, J.J., O'Connor, J.E., 2021. Chapter 14 - glacier-related outburst floods. In: Haeberli, W., Whiteman, C. (Eds.), Snow and Ice-related Hazards, Risks, and Disasters, Second edition. Elsevier, pp. 467–499. https://doi.org/10.1016/B978-0-12-817129-5.00019-6.

Comiti, F., Lucía, A., Rickenmann, D., 2016a. Large wood recruitment and transport during large floods : a review. Geomorphology 23–39. https://doi.org/10.1016/j.geomorph.2016.06.016.

Comiti, F., Righini, M., Nardi, L., Lucía, A., Amponsah, W., Cavalli, M., Surian, N., 2016b. Channel Widening During Extreme Floods : How to Integrate it Within River Corridor Planning ?, in: Interpraevent 2016.

Contreras, M.T., Escauriaza, C., 2020. Modeling the effects of sediment concentration on the propagation of flash floods in an Andean watershed. Nat. Hazards Earth Syst. Sci. 20, 221–241. https://doi.org/10.5194/nhess-20-221-2020.

Costa, J.E., 1984. Physical geomorphology of debris flows. In: Developments and Applications of Geomorphology. Springer, Berlin, Heidelberg, pp. 268–317.

Coulthard, T.J., Macklin, M.G., 2001. How sensitive are river systems to climate and land-use changes? A model-based evaluation. J. Quat. Sci. 16, 347–351. https://doi.org/10.1002/jqs.604.

Coulthard, T.J., Neal, J.C., Bates, P.D., Ramirez, J., Almeida, G.A.M., de, Hancock G.R., 2013. Integrating the LISFLOOD-FP 2D hydrodynamic model with the CAESAR model: implications for modelling landscape evolution. Earth Surf. Process. Landf. 38, 1897–1906. https://doi.org/10.1002/esp.3478.

Coviello, V., Vignoli, G., Simoni, S., Bertoldi, W., Engel, M., Buter, A., Marchetti, G., Andreoli, A., Savi, S., Comiti, F., 2022. Bedload fluxes in a glacier-fed river at multiple temporal scales. Water Resour. Res. 58, e2021WR031873 https://doi.org/10.1029/2021WR031873.

Czuba, J.A., Czuba, C.R., Magirl, C.S., Voss, F.D., 2010. Channel-conveyance Capacity, Channel Change, and Sediment Transport in the Lower Puyallup, White, and Carbon Rivers, Western Washington (USGS Numbered Series No. 2010–5240). https://doi.org/10.3133/sir20105240.

Davidson, S.L., Eaton, B.C., 2018. Beyond regime: a stochastic model of floods, bank erosion, and channel migration. Water Resour. Res. 54, 6282–6298. https://doi.org/10.1029/2017WR022059.

Davies, T., McSaveney, M., 2011. Bedload sediment flux and flood risk management in New Zealand. J. Hydrol. N. Z. 50 (1), 181–190.

Davies, T.R.H., McSaveney, M.J., Clarkson, P.J., 2003. Anthropic aggradation of the Waiho river, Westland New Zealand: microscale modelling. Earth Surf. Process. Landf. 28, 209–218. https://doi.org/10.1002/esp.449.

Dennis, I.A., Macklin, M.G., Coulthard, T.J., Brewer, P.A., 2003. The impact of the October–November 2000 floods on contaminant metal dispersal in the River Swale catchment, North Yorkshire, UK. Hydrol. Process. 17, 1641–1657. https://doi.org/10.1002/hyp.1206.

Dethier, E.N., Sartain, S.L., Renshaw, C.E., Magilligan, F.J., 2020. Spatially coherent regional changes in seasonal extreme streamflow events in the United States and Canada since 1950. Sci. Adv. 6 (49) https://doi.org/10.1126/sciadv.aba5939.

Di Baldassarre, G., Montanari, A., 2009. Uncertainty in river discharge observations: a quantitative analysis. Hydrol. Earth Syst. Sci. 13, 913–921. https://doi.org/10.5194/hess-13-913-2009.

Di Cristo, C., Greco, M., Iervolino, M., Vacca, A., 2021. Impact force of a geomorphic dam-break wave against an obstacle: effects of sediment inertia. Water 13 (2), 232. https://doi.org/10.3390/w13020232.

Díez-Herrero, A., Garrote, J., 2020. Flood risk analysis and assessment, applications and uncertainties: a bibliometric review. Water 12, 2050. https://doi.org/10.3390/w12072050.

Díez-Herrero, A., Lain-Huerta, L., Llorente-Isidro, M., 2009. A handbook on flood hazard mapping methodologies. In: Publications of the Geological Survey of Spain (IGME), Series Geological Hazards /Geotechnics No. 2, 190 pp., Madrid (Spain).

Dingle, E.H., Paringit, E.C., Tolentino, P.L.M., Williams, R.D., Hoey, T.B., Barrett, B., Long, H., Smiley, C., Stott, E., 2019. Decadal-scale morphological adjustment of a lowland tropical river. Geomorphology 333, 30–42. https://doi.org/10.1016/j.geomorph.2019.01.022.

Dingle, E.H., Creed, M.J., Sinclair, H.D., Gautam, D., Gourmelen, N., Borthwick, A.G.L., Attal, M., 2020. Dynamic flood topographies in the Terai region of Nepal. Earth Surf. Process. Landf. 45, 3092–3102. https://doi.org/10.1002/esp.4953.

Dottori, F., Figueiredo, R., Martina, M.L.V., Molinari, D., Scorzini, A.R., 2016. INSYDE: a synthetic, probabilistic flood damage model based on explicit cost analysis. Nat. Hazards Earth Syst. Sci. 16 (12), 2577–2591. https://doi.org/10.5194/nhess-16-2577-2016.

Downs, P.W., Piégay, H., 2019. Catchment-scale cumulative impact of human activities on river channels in the late Anthropocene: implications, limitations, prospect. Geomorphology 338, 88–104. https://doi.org/10.1016/j.geomorph.2019.03.021.

Dunne, K.B.J., Jerolmack, D.J., 2020. What sets river width? Sci. Adv. 6 (41) https://doi.org/10.1126/sciadv.abc1505.

Dysarz, T., 2020. Development of methodology for assessment of long-term morphodynamic impact on flood hazard. J. Flood Risk Manag. 13 (4), e12654 https://doi.org/10.1111/jfr3.12654.

Espa, P., Batalla, R.J., Brignoli, M.L., Crosa, G., Gentili, G., Quadroni, S., 2019. Tackling reservoir siltation by controlled sediment flushing: impact on downstream fauna and related management issues. PLoS ONE 14, e0218822. https://doi.org/10.1371/journal.pone.0218822.

EXCIMAP, 2007. Handbook on Good Practices for Flood Mapping in Europe. European Exchange Circle on Flood Mapping.

Exner, F.M, 1920. Zur physik der dunen, sitzberAkad. Wiss Wien 129 (2a), 929–952 (In German).

Fan, X., Scaringi, G., Korup, O., West, A.J., van Westen, C.J., Tanyas, H., Hovius, N., Hales, T.C., Jibson, R.W., Allstadt, K.E., Zhang, L., Evans, S.G., Xu, C., Li, G., Pei, X., Xu, Q., Huang, R., 2019. Earthquake-induced chains of geologic hazards: patterns, mechanisms, and impacts. Rev. Geophys. 57, 421–503. https://doi.org/10.1029/2018RG000626.

Fernández, E., Colubi, A., González-Rodríguez, G., Anadón, S., 2012. Integrating statistical information concerning historical floods: ranking and interval return period estimation. Nat. Hazards 62, 459–483. https://doi.org/10.1007/s11069-012-0094-8.

Fieman, D.M., Attal, M., Addy, S., 2020. Geomorphic response of a mountain gravel-bed river to an extreme flood in Aberdeenshire, Scotland. Scott. J. Geol. 56, 101–116. https://doi.org/10.1144/sjg2019-005.

Francalanci, S., Lanzoni, S., Solari, L., Papanicolaou, A.N., 2020. Equilibrium cross section of river channels with cohesive erodible banks. J. Geophys. Res. Earth 125, e2019JF005286. https://doi.org/10.1029/2019JF005286.

Fuchs, S., Keiler, M., Ortlepp, R., Schinke, R., Papathoma-Köhle, M., 2019. Recent advances in vulnerability assessment for the built environment exposed to torrential hazards: challenges and the way forward. J. Hydrol. 575, 587–595. https://doi.org/10.1016/j.jhydrol.2019.05.067.

Garrote, J., González-Jiménez, M., Guardiola-Albert, C., Díez-Herrero, A., 2021. The manning's roughness coefficient calibration method to improve flood hazard analysis in the absence of river bathymetric data: application to the urban historical Zamora City Centre in Spain. Appl. Sci. 11, 9267. https://doi.org/10.3390/app11199267.

Ghaffarian, H., Piégay, H., Lopez, D., Riviere, N., MacVicar, B., Antonio, A., Mignot, E., 2020. Video-monitoring of wood discharge: first inter-basin comparison and recommendations to install video cameras. Earth Surf. Process. Landf. 45 (10), 2219–2234. https://doi.org/10.1002/esp.4875.

Gintz, D., Hassan, M.A., Schmidt, K.-H., 1996. Frequency and magnitude of bedload transport in a mountain river. Earth Surf. Process. Landf. 21, 433–445. https://doi.org/10.1002/(SICI)1096-9837(199605)21:5<433::AID-ESP580>3.0.CO;2-P.

Gioia, D., Schiattarella, M., 2020. Modeling short-term landscape modification and sedimentary budget induced by dam removal: insights from LEM application. Appl. Sci. 10, 7697. https://doi.org/10.3390/app10217697.

Gomez, B., Soar, P.J., 2022. Bedload transport: beyond intractability. R. Soc. Open Sci. 9, 211932 https://doi.org/10.1098/rsos.211932.

Gomez, B., Banbury, K., Marden, M., Trustrum, N.A., Peacock, D.H., Hoskin, P.J., 2003. Gully erosion and sediment production: Te Weraroa Stream, New Zealand. Water Resour. Res. 39 https://doi.org/10.1029/2002WR001342.

Gran, K., Montgomery, D.R., Halbur, J., 2011. Long-term elevated post-eruption sedimentation at Mount Pinatubo, Philippines. Geology 39, 367–370. https://doi.org/10.1130/G31682.1.

Guan, M., Wright, N.G., Andrew, Sleigh P., 2015. Multiple effects of sediment transport and geomorphic processes within flood events: modelling and understanding. Int. J. Sediment Res. 30, 371–381. https://doi.org/10.1016/j.ijsrc.2014.12.001.

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. https://doi.org/10.1016/j.jhydrol.2016.04.004.

Guzelj, M., Hauer, C., Egger, G., 2020. The third dimension in river restoration: how anthropogenic disturbance changes boundary conditions for ecological mitigation. Sci. Rep. 10, 13106. https://doi.org/10.1038/s41598-020-69796-0.

Hancock, G.R., Lowry, J.B.C., Coulthard, T.J., 2015. Catchment reconstruction – erosional stability at millenial time scales using landscape evolution models. Geomorphology 231, 15–27. https://doi.org/10.1016/j.geomorph.2014.10.024.

Harries, R.M., Gailleton, B., Kirstein, L.A., Attal, M., Whittaker, A.C., Mudd, S.M., 2021. Impact of climate on landscape form, sediment transfer and the sedimentary record. Earth Surf. Process. Landf. 46, 990–1006. https://doi.org/10.1002/esp.5075.

Hassan, M.A., Smith, B.J., Hogan, D.L., Luzi, D.S., Zimmermann, A.E., Eaton, B.C., 2007. 18 Sediment storage and transport in coarse bed streams: scale considerations. In: Habersack, H., Piégay, H., Rinaldi, M. (Eds.), Developments in Earth Surface Processes, Gravel-bed Rivers VI: From Process Understanding to River Restoration. Elsevier, pp. 473–496. https://doi.org/10.1016/S0928-2025(07)11137-8.

Hey, R.D., Winterbottom, A.N., 1990. River engineering in National Parks: the case of the River Wharfe, UK. Regul. Rivers Res. Manag. 5, 35–44. https://doi.org/10.1002/rrr.3450050104.

Hicks, D.M., Baynes, E.R.C., Measures, R., Stecca, G., Tunnicliffe, J., Friedrich, H., 2021. Morphodynamic research challenges for braided river environments: lessons from the iconic case of New Zealand. Earth Surf. Process. Landf. 46, 188–204. https://doi.org/10.1002/esp.5014.

Hinshaw, S., Wohl, E., Davis, D., 2020. The effects of longitudinal variations in valley geometry and wood load on flood response. Earth Surf. Process. Landf. 45, 2927–2939. https://doi.org/10.1002/esp.4940.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kanae, S., 2013. Global flood risk under climate change. Nat. Clim. Chang. 3, 816–821. https://doi.org/10.1038/nclimate1911.

Hirschboeck, K.K., 1988. Flood hydroclimatology. In: Flood Geomorphology. John Wiley and Sons, New York (USA), pp. 27–49.

Hooke, J.M., 2015. Variations in flood magnitude–effect relations and the implications for flood risk assessment and river management. Geomorphology 251, 91–107. https://doi.org/10.1016/j.geomorph.2015.05.014 (Special Issue on 'Emerging geomorphic approaches to guide river management practices').

Hooke, J.M., 2016. Geomorphological impacts of an extreme flood in SE Spain. Geomorphology 263, 19–38. https://doi.org/10.1016/j.geomorph.2016.03.021.

Hungr, O., 2005. Classification and terminology. In: Jakob, M., Hungr, O. (Eds.), Debris-flow Hazards and Related Phenomena, Springer Praxis Books. Springer, Berlin, Heidelberg, pp. 9–23. https://doi.org/10.1007/3-540-27129-5_2.

Hungr, O., McDougall, S., Bovis, M., 2005. Entrainment of material by debris flows. In: Debris-flow Hazards and Related Phenomena. Springer Praxis Books. Springer, Berlin, Heidelberg. https://doi.org/10.1007/3-540-27129-5_7.

Hürlimann, M., Copons, R., Altimir, J., 2006. Detailed debris flow hazard assessment in Andorra: a multidisciplinary approach. Geomorphology 78, 359–372. https://doi.org/10.1016/j.geomorph.2006.02.003.

Hürlimann, M., Coviello, V., Bel, C., Guo, X., Berti, M., Graf, C., Hüb, J., Miyata, S., Smith, J.B., Yin, H.-Y., 2019. Debris-flow monitoring and warning: review and examples. Earth Sci. Rev. 199 https://doi.org/10.1016/j.earscirev.2019.102981, 26 pp.

Iverson, R.M., 1997. The physics of debris flows. Rev. Geophys. 35, 245–296. https://doi.org/10.1029/97RG00426.

Jakob, M., Clague, J.J., Church, M., 2016. Rare and dangerous: recognizing extra-ordinary events in stream channels. Can. Water Resour. J. 41, 161–173. https://doi.org/10.1080/07011784.2015.1028451.

Jakob, M., Davidson, S., Bullard, G., Busslinger, M., Collier-Pandya, B., Grover, P., Lau, C.-A., 2022. Debris-flood hazard assessments in steep streams. Water Resour. Res. 58, e2021WR030907 https://doi.org/10.1029/2021WR030907.

Jalayer, F., Carozza, S., De Risi, R., Manfredi, G., Mbuya, E., 2016. Performance-based flood safety-checking for non-engineered masonry structures. Eng. Struct. 106, 109–123. https://doi.org/10.1016/j.engstruct.2015.10.007.

James, A., 1999. Time and the persistence of alluvium: River engineering, fluvial geomorphology, and mining sediment in California. Geomorphology 31, 265–290. https://doi.org/10.1016/S0169-555X(99)00084-7.

James, L.A., 2010. Secular sediment waves, channel bed waves, and legacy sediment. Geogr. Compass 4, 576–598. https://doi.org/10.1111/j.1749-8198.2010.00324.x.

Jimenez Cisneros, B.E., Oki, T., Arnell, N.W., Benito, G., Cogley, J.G., Doll, P., Jiang, T., Mwakalila, S.S., MacCracken, S., Mastrandrea, P.R., White, L.L., 2014. Freshwater resources. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Gimma, B., Kissel, E. S., Levy, A.N. (Eds.), Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 229–269.

Kondolf, G.M., 1997. Hungry water: effects of dams and gravel mining on river channels. Environ. Manag. 21 https://doi.org/10.1007/s002679900048.

Kondolf, G.M., Gao, Y., Annandale, G.W., Morris, G.L., Jiang, E., Zhang, J., Cao, Y., Carling, P., Fu, K., Guo, Q., Hotchkiss, R., Peteuil, C., Sumi, T., Wang, H.-W., Wang, Z., Wei, Z., Wu, B., Wu, C., Yang, C.T., 2014. Sustainable sediment management in reservoirs and regulated rivers: experiences from five continents. Earth's Future 2, 256–280. https://doi.org/10.1002/2013EF000184.

Kreibich, H., Thaler, T., Glade, T., Molinari, D., 2019. Preface: damage of natural hazards: assessment and mitigation. Nat. Hazards Earth Syst. Sci. 19, 551–554. https://doi.org/10.5194/nhess-19-551-2019.

Kundzewicz, Z.W., Kanae, S., Seneviratne, S.I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L.M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G.R., Kron, W., Benito, G., Honda, Y., Takahashi, K., Sherstyukov, B., 2014. Flood risk and climate change: global and regional perspectives. Hydrol. Sci. J. 59, 1–28. https://doi.org/10.1080/02626667.2013.857411.

Lane, S.N., 2013. 21st century climate change: where has all the geomorphology gone? Earth Surf. Process. Landf. 38, 106–110. https://doi.org/10.1002/esp.3362.

Lane, S.N., Tayefi, V., Reid, S.C., Yu, D., Hardy, R.J., 2007. Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. Earth Surf. Process. Landf. 32, 429–446. https://doi.org/10.1002/esp.1404.

Lane, S.N., Reid, S.C., Tayefi, V., Yu, D., Hardy, R.J., 2008. Reconceptualising coarse sediment delivery problems in rivers as catchment-scale and diffuse. Geomorphology 98 (3–4), 227–249. https://doi.org/10.1016/j.geomorph.2006.12.028.

Lastra, J., Fernández, E., Díez-Herrero, A., Marquínez, J., 2008. Flood hazard delineation combining geomorphological and hydrological methods: an example in the Northern Iberian Peninsula. Nat. Hazards 45, 277–293. https://doi.org/10.1007/s11069-007-9164-8.

Lee, C.-H., Low, Y.M., Chiew, Y.-M., 2016. Multi-dimensional rheology-based two-phase model for sediment transport and applications to sheet flow and pipeline scour. Phys. Fluids 28, 053305. https://doi.org/10.1063/1.4948987.

Lekach, J., Enzel, Y., 2021. Flood-duration-integrated stream power and frequency magnitude of >50-year-long sediment discharge out of a hyperarid watershed. Earth Surf. Process. Landf. 46, 1348–1362. https://doi.org/10.1002/esp.5104.

Lenzi, M.A., 2004. Displacement and transport of marked pebbles, cobbles and boulders during floods in a steep mountain stream. Hydrol. Process. 18, 1899–1914. https://doi.org/10.1002/hyp.1456.

Lenzi, M.A., D'Agostino, V., Billi, P., 1999. Bedload transport in the instrumented catchment of the Rio Cordon: part I: analysis of bedload records, conditions and threshold of bedload entrainment. Catena 36, 171–190. https://doi.org/10.1016/S0341-8162(99)00016-8.

Liébault, F., Piégay, H., 2002. Causes of 20th century channel narrowing in mountain and piedmont rivers of southeastern France. Earth Surf. Process. Landf. 27, 425–444. https://doi.org/10.1002/esp.328.

Liu, H., Yi, Y., Jin, Z., 2021. Sensitivity analysis of flash flood hazard on sediment load characteristics. Front. Earth Sci. 9, 683453 https://doi.org/10.3389/feart.2021.683453.

Liu, H., Du, J., Yi, Y., 2022. Reconceptualising flood risk assessment by incorporating sediment supply. Catena 217, 106503. https://doi.org/10.1016/j.catena.2022.106503.

Lotsari, E., Thorndycraft, V., Alho, P., 2015. Prospects and challenges of simulating river channel response to future climate change. Prog. Phys. Geogr. Earth Environ. 39 (4), 483–513. https://doi.org/10.1177/0309133315578944.

Lotsari, E., Calle, M., Benito, G., Kukko, A., Kaartinen, H., Hyyppä, J., Hyyppä, H., Alho, P., 2017. Topographical changes caused by moderate and small floods in a gravelly ephemeral river – 2D morphodynamic simulation approach (preprint). Earth Surf. Dyn. 6, 163–185. https://doi.org/10.5194/esurf-2017-52.

Luo, H., Zhang, L., Wang, H., He, J., 2020a. Multi-hazard vulnerability of buildings to debris flows. Eng. Geol. 279, 105859 https://doi.org/10.1016/j.enggeo.2020.105859.

Luo, H.Y., Fan, R.L., Wang, H.J., Zhang, L.M., 2020b. Physics of building vulnerability to debris flows, floods and earth flows. Eng. Geol. 271, 105611 https://doi.org/10.1016/j.enggeo.2020.105611.

Machado, M.J., Medialdea, A., Calle, M., Rico, M.T., Sánchez-Moya, Y., Sopeña, A., Benito, G., 2017. Historical palaeohydrology and landscape resilience of a Mediterranean rambla (Castellón, NE Spain): floods and people. Quat. Sci. Rev. 171, 182–198. https://doi.org/10.1016/j.quascirev.2017.07.014.

Magliulo, P., Valente, A., 2020. GIS-based geomorphological map of the Calore River Floodplain near Benevento (Southern Italy) overflooded by the 15th October 2015 event. Water 12, 148. https://doi.org/10.3390/w12010148.

Magliulo, P., Bozzi, F., Leone, G., Fiorillo, F., Leone, N., Russo, F., Valente, A., 2021. Channel adjustments over 140 years in response to extreme floods and land-use change, Tammaro River, southern Italy. Geomorphology 383, 107715. https://doi.org/10.1016/j.geomorph.2021.107715.

Manners, R.B., Doyle, M.W., Small, M.J., 2007. Structure and hydraulics of natural woody debris jams. Water Resour. Res. 43 https://doi.org/10.1029/2006WR004910.

Marchi, L., Cavalli, M., Sangati, M., Borga, M., 2009. Hydrometeorological controls and erosive response of an extreme alpine debris flow. Hydrol. Process. 23, 2714–2727. https://doi.org/10.1002/hyp.7362.

Martin, Y., Church, M., 2004. Numerical modelling of landscape evolution: geomorphological perspectives. Prog. Phys. Geogr. Earth Environ. 28, 317–339. https://doi.org/10.1191/0309133304pp412ra.

Martínez-Fernández, V., Van Oorschot, M., De Smit, J., González del Tánago, M., Buijse, A.D., 2018. Modelling feedbacks between geomorphological and riparian vegetation responses under climate change in a Mediterranean context. Earth Surf. Process. Landf. 43, 1825–1835. https://doi.org/10.1002/esp.4356.

Martín-Vide, J.P., Bateman, A., Berenguer, M., Ferrer-Boix, C., Amengual, A., Campillo, M., Corral, C., Llasat, M.C., Llasat-Botija, M., Gómez-Dueñas, S., Marín-Esteve, B., Núñez-González, F., Prats-Puntí, A., Ruiz-Carulla, R., Sosa-Pérez, R., 2023. Large wood debris that clogged bridges followed by a sudden release. The 2019 flash flood in Catalonia. J. Hydrol. Reg. Stud. 47, 101348 https://doi.org/10.1016/j.ejrh.2023.101348.

Mazzorana, B., Comiti, F., Volcan, C., Scherer, C., 2011. Determining flood hazard patterns through a combined stochastic–deterministic approach. Nat. Hazards 59, 301–316. https://doi.org/10.1007/s11069-011-9755-2.

Meadows, T., 2014. Forecasting Long-term Sediment Yield From the Upper North Fork Toutle River, Mount St. Helens, USA. PhD thesis,. University of Nottingham.

Métivier, F., Barrier, L., 2012. Alluvial Landscape Evolution: What Do We Know About Metamorphosis of Gravel-bed Meandering and Braided Streams?. In: Gravel-bed Rivers John Wiley & Sons, Ltd, pp. 474–501. https://doi.org/10.1002/9781119952497.ch34.

Micheletti, N., Lane, S.N., 2016. Water yield and sediment export in small, partially glaciated Alpine watersheds in a warming climate. Water Resour. Res. 52, 4924–4943. https://doi.org/10.1002/2016WR018774.

Moel, H. de, Alphen, J., Aerts, J.C.J.H., 2009. Flood maps in Europe - methods, availability and use. Nat. Hazards Earth Syst. Sci. 9, 289–301. https://doi.org/10.5194/nhess-9-289-2009.

Molnar, P., Densmore, A.L., McArdell, B.W., Turowski, J.M., Burlando, P., 2010. Analysis of changes in the step-pool morphology and channel profile of a steep mountain stream following a large flood. Geomorphology 124, 85–94. https://doi.org/10.1016/j.geomorph.2010.08.014.

Moody, J., Martin, D., 2004. Wildfire impacts on reservoir sedimentation in the western United States. In: Proceedings of the Ninth International Symposium on River Sedimentation October 18–21, 2004, Yichang, China.

Mudashiru, R., Sabtu, N., Abustan, I., Balogun, W., 2021. Flood hazard mapping methods: a review. J. Hydrol. 603 (A), 126846 https://doi.org/10.1016/j.jhydrol.2021.126846.

Murphy, B.P., Yocom, L.L., Belmont, P., 2018. Beyond the 1984 perspective: narrow focus on modern wildfire trends underestimates future risks to water security. Earth's Future 6, 1492–1497. https://doi.org/10.1029/2018EF001006.

Murphy, B.P., Czuba, J.A., Belmont, P., 2019. Post-wildfire sediment cascades: a modeling framework linking debris flow generation and network-scale sediment routing. Earth Surf. Process. Landf. 44, 2126–2140. https://doi.org/10.1002/esp.4635.

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. https://doi.org/10.1002/esp.3636.

Neuhold, C., Stanzel, P., Nachtnebel, H.P., 2009. Incorporating river morphological changes to flood risk assessment: uncertainties, methodology and application. Nat. Hazards Earth Syst. Sci. 9, 789–799. https://doi.org/10.5194/nhess-9-789-2009.

Nikolopoulos, E.I., Marra, F., Borga, M., 2016. Uncertainty in Estimation of Debris-flow Triggering Rainfall. In: Natural Hazard Uncertainty Assessment. American Geophysical Union (AGU), pp. 319–328. https://doi.org/10.1002/9781119028116.ch21.

Nones, M., 2019. Dealing with sediment transport in flood risk management. Acta Geophys. 67, 677–685. https://doi.org/10.1007/s11600-019-00273-7.

Nones, M., 2020. On the main components of landscape evolution modelling of river systems. Acta Geophys. 68, 459–475. https://doi.org/10.1007/s11600-020-00401-8.

Nones, M., Guo, Y., 2023. Can sediments play a role in river flood risk mapping? Learning from selected European examples. Geoenviron. Disasters 10, 20 (2023). https://doi.org/10.1186/s40677-023-00250-9.

Nones, M., Pescaroli, G., 2016. Implications of cascading effects for the EU Floods Directive. Int. J. River Basin Manag. 14, 195–204. https://doi.org/10.1080/15715124.2016.1149074.

Nones, M., Gerstgraser, C., Wharton, G., 2017. Consideration of hydromorphology and sediment in the implementation of the EU water framework and floods directives: a comparative analysis of selected EU member states. Water Environ. J. 31, 324–329. https://doi.org/10.1111/wej.12247.

O'Briain, R., 2019. Climate change and European rivers: an eco-hydromorphological perspective. Ecohydrology 12 (5), e2099. https://doi.org/10.1002/eco.2099.

Olcina-Cantos, J., Díez-Herrero, A., 2022. Technical evolution of flood maps through Spanish experience in the European framework. Cartogr. J. 59 (1), 55–68. https://doi.org/10.1080/00087041.2021.1930678.

Oliver, J., Qin, X.S., Larsen, O., Meadows, M., Fielding, M., 2018. Probabilistic flood risk analysis considering morphological dynamics and dike failure. Nat. Hazards 91, 287–307. https://doi.org/10.1007/s11069-017-3126-6.

Parker, G., 1978. Self-formed straight rivers with equilibrium banks and mobile bed. Part 2. The gravel river. J. Fluid Mech. 89, 127–146. https://doi.org/10.1017/S0022112078002505.

Parker, G., 2006. 1D Sediment Transport Morphodynamics With Applications to Rivers and Turbidity Currents. Ebook freely available at. http://hydrolab.illinois.edu/people/parkerg/default.asp.

Pender, D., Patidar, S., Hassan, K., Haynes, H., 2016. Method for incorporating morphological sensitivity into flood inundation modeling. J. Hydraul. Eng. 142, 04016008 https://doi.org/10.1061/(ASCE)HY.1943-7900.0001127.

Pfeiffer, A.M., Collins, B.D., Anderson, S.W., Montgomery, D.R., Istanbulluoglu, E., 2019. River bed elevation variability reflects sediment supply, rather than peak flows, in the uplands of Washington State. Water Resour. Res. 55, 6795–6810. https://doi.org/10.1029/2019WR025394.

Pfeiffer, A.M., Finnegan, N.J., 2018. Regional variation in gravel riverbed mobility, controlled by hydrologic regime and sediment supply. Geophys. Res. Lett. 45, 3097–3106. https://doi.org/10.1002/2017GL076747.

Phillips, C.B., Jerolmack, D.J., 2016. Self-organization of river channels as a critical filter on climate signals. Science 352, 694–697. https://doi.org/10.1126/science.aad3348.

Pichard, G., Roucaute, É., 2014. Sept siècles d'histoire hydroclimatique du Rhône d'Orange à la mer. Mediterranée Rev. Géographique Pays Méditerranées Hors-Série, 200 pp.

Piégay, H., Cuaz, M., Javelle, E., Mandier, P., 1997. Bank erosion management based on geomorphological, ecological and economic criteria on the Galaure River, France. Regul. Rivers Res. Manag. 13, 433–448. https://doi.org/10.1002/(SICI)1099-1646(199709/10)13:5<433::AID-RR467>3.0.CO;2-L.

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.

Piégay, H., Kondolf, G.M., Toby, Minear J., Vaudor, L., 2015. Trends in publications in fluvial geomorphology over two decades: a truly new era in the discipline owing to recent technological revolution? Geomorphology 248, 489–500. https://doi.org/10.1016/j.geomorph.2015.07.039.

Piégay, H., Arnaud, F., Belletti, B., Cassel, M., Marteau, B., Riquier, J., Rousson, C., Vazquez-Tarrio, D., 2023. Why consider geomorphology in river rehabilitation? Land 12, 1491. https://doi.org/10.3390/land12081491.

Pierson, T.C., Costa, J.E., 1987. A rheologic classification of subaerial sediment-water flows. GSA Rev. Eng. Geol. https://doi.org/10.1130/REG7-p1.

Pinter, N., Brasington, J., Gurnell, A., Kondolf, G.M., Tockner, K., Wharton, G., Yarnell, S.M., 2019. River research and applications across borders. River Res. Appl. 35, 768–775. https://doi.org/10.1002/rra.3430.

Piton, G., Recking, A., 2017. The concept of travelling bedload and its consequences for bedload computation in mountain streams. Earth Surf. Process. Landf. 42, 1505–1519. https://doi.org/10.1002/esp.4105.

Poff, N., 2014. Rivers of the Anthropocene? Front. Ecol. Environ. 12, 427. https://doi.org/10.1890/1540-9295-12.8.427.

Radice, A., Rosatti, G., Ballio, F., Franzetti, S., Mauri, M., Spagnolatti, M., Garegnai, G., 2013. Management of flood hazard via hydro-morphological river modelling. The case of the Mallero in Italian Alps. J. Flood Risk Manag. 6 (3), 197–209. https://doi.org/10.1111/j.1753-318X.2012.01170.x.

Radice, A., Longoni, L., Papini, M., Brambilla, D., Ivanov, V.I., 2016. Generation of a design flood-event scenario for a mountain river with intense sediment transport. Water 8, 597. https://doi.org/10.3390/w8120597.

Ramirez, J.A., Zischg, A.P., Schürmann, S., Zimmermann, M., Weingartner, R., Coulthard, T., Keiler, M., 2020. Modeling the geomorphic response to early river engineering works using CAESAR-Lisflood. Anthropocene 32, 100266. https://doi.org/10.1016/j.ancene.2020.100266.

Raven, E.K., Lane, S.N., Bracken, L.J., 2010. Understanding sediment transfer and morphological change for managing upland gravel-bed rivers. Prog. Phys. Geogr. Earth Environ. 34 (1), 23–45. https://doi.org/10.1177/0309133309355631.

Recking, A., 2012. Influence of sediment supply on mountain streams bedload transport. Geomorphology 175–176, 139–150. https://doi.org/10.1016/j.geomorph.2012.07.005.

Recking, A., 2013a. An analysis of nonlinearity effects on bed load transport prediction. J. Geophys. Res. Earth 118, 1264–1281. https://doi.org/10.1002/jgrf.20090.

Recking, A., 2013b. Simple method for calculating reach-averaged bed-load transport. J. Hydraul. Eng. 139 (1) https://doi.org/10.1061/(ASCE)HY.1943-7900.0000653.

Rickenmann, D., 2017. In: Tsutsumi, D., Laronne, J.B. (Eds.), Bedload Transport Measurements With Geophones, Hydrophones, and Underwater Microphones (Passive Acoustic Methods), Gravel-bed Rivers. https://doi.org/10.1002/9781118971437.ch7.

Rinaldi, M., Wyzga, B., Surian, N., 2005. Sediment mining in alluvial channels: physical effects and management perspectives. River Res. Appl. 21, 805–828. https://doi.org/10.1002/rra.884.

Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2015. A methodological framework for hydromorphological assessment, analysis and monitorin (IDRAIM) aimed at promoting integrated river management. Geomorphology 251, 122–136. https://doi.org/10.1016/j.geomorph.2015.05.010.

Rinaldi, M., Amponsah, W., Benvenuti, M., Borga, M., Comiti, F., Lucía, A., Marchi, L., Nardi, L., Righini, M., Surian, N., 2016. 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. https://doi.org/10.1002/esp.3902.

Rodriguez-Lloveras, X., Buytaert, W., Benito, G., 2016. Land use can offset climate change induced increases in erosion in Mediterranean watersheds. Catena 143, 244–255. https://doi.org/10.1016/j.catena.2016.04.012.

Roos, W., Waarts, P., Vrouwenvelder, A., 2003. Damage to Buildings. Delft Cluster Paper.

Ruiz-Villanueva, V., Bodoque, J.M., Díez-Herrero, A., Bladé, E., 2014. Large wood transport as significant influence on flood risk in a mountain village. Nat. Hazards 74, 967–987. https://doi.org/10.1007/s11069-014-1222-4.

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 Surf. Dyn. 6 (4), 1115–1137. https://doi.org/10.5194/esurf-6-1115-2018.

Ruiz-Villanueva, V., Mazzorana, B., Bladé, E., Bürkli, L., Iribarren-Anacona, P., Mao, L., Nakamura, F., Ravazzolo, D., Rickenmann, D., Sanz-Ramos, M., Stoffel, M., Wohl, E., 2019. Characterization of wood-laden flows in rivers. Earth Surf. Process. Landf. 44, 1694–1709. https://doi.org/10.1002/esp.4603.

Ruiz-Villanueva, V., Piégay, H., Scorpio, V., Bachmann, A., Brousse, G., Cavalli, M., Comitti, F., Crema, S., Fernández, E., Furdada, G., Hajdukiewicz, H., Hunzinger, L., Lucía, A., Marchi, L., Moraru, A., Piton, G., Rickenmann, D., Righini, M., Surian, N., Yassine, R., Wyzga, 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.

Sánchez Martínez, F.J., Lastra, Fernández J., 2011. Guía Metodológica para el desarrollo del Sistema Nacional de Cartografía de Zonas Inundables.

Santos-González, J., Gómez-Villar, A., González-Gutiérrez, R.B., Corella, J.P., Benito, G., Redondo-Vega, J.M., Melón-Nava, A., Valero-Garcés, B., 2021. Geomorphological impact, hydraulics and watershed- lake connectivity during extreme floods in mountain areas: the 1959 Vega de Tera dam failure, NW Spain. Geomorphology 375, 107531. https://doi.org/10.1016/j.geomorph.2020.107531.

Schuerch, P., Densmore, A.L., McArdell, B., Molnar, P., 2006. The influence of landsliding on sediment supply and channel change in a steep mountain catchment. Geomorphology 78, 222–235. https://doi.org/10.1016/j.geomorph.2006.01.025.

Schumm, S.A., Khan, H.R., 1972. Experimental study of channel patterns. GSA Bull. 83, 1755–1770. https://doi.org/10.1130/0016-7606(1972)83[1755:ESOCP]2.0.CO;2.

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.

Sear, D.A., Newson, M.D., Brookes, A., 1995. Sediment-related river maintenance: the role of fluvial geomorphology. Earth Surf. Process. Landf. 20, 629–647. https://doi.org/10.1002/esp.3290200706.

Simon, A., Downs, P.W., 1995. An interdisciplinary approach to evaluation of potential instability in alluvial channels. Geomorphology 12, 215–232. https://doi.org/10.1016/0169-555X(95)00005-P.

Simon, A., Rinaldi, M., 2006. Disturbance, stream incision, and channel evolution: the roles of excess transport capacity and boundary materials in controlling channel response. Geomorphology 79 (3–4), 361–383. https://doi.org/10.1016/j.geomorph.2006.06.037 (Special Issue on "37th Binghamton Geomorphology Symposium").

Sims, A.J., Rutherfurd, I.D., 2017. Management responses to pulses of bedload sediment in rivers. Geomorphology 294, 70–86. https://doi.org/10.1016/j.geomorph.2017.04.010 (Special Issue on 'Anthropogenic Sedimentation').

Sinnakaudan, S.K., Ghani, A.A., Ahmad, M.S.S., Zakaria, N.A., 2003. Flood risk mapping for Pari River incorporating sediment transport. Environ. Model. Softw. 18 (2), 119–130. https://doi.org/10.1016/S1364-8152(02)00068-3.

Siviglia, A., Repetto, R., Zolezzi, G., Tubino, M., 2008. River bed evolution due to channel expansion: general behaviour and application to a case study (Kugart River, Kyrgyz Republic). River Res. Appl. 24, 1271–1287. https://doi.org/10.1002/rra.1095.

Slater, L.J., 2016. To what extent have changes in channel capacity contributed to flood hazard trends in England and Wales? Earth Surf. Process. Landf. 41, 1115–1128. https://doi.org/10.1002/esp.3927.

Slater, L.J., Singer, M.B., 2013. Imprint of climate and climate change in alluvial riverbeds: Continental United States, 1950-2011. Geology 41, 595–598. https://doi.org/10.1130/G34070.1.

Slater, L.J., Singer, M.B., Kirchner, J.W., 2015. Hydrologic versus geomorphic drivers of trends in flood hazard. Geophys. Res. Lett. 42, 370–376. https://doi.org/10.1002/2014GL062482.

Slater, L.J., Khouakhi, A., Wilby, R.L., 2019. River channel conveyance capacity adjusts to modes of climate variability. Sci. Rep. 9, 12619. https://doi.org/10.1038/s41598-019-48782-1.

Sofia, G., Nikolopoulos, E.I., 2020. Floods and rivers: a circular causality perspective. Sci. Rep. 10, 5175. https://doi.org/10.1038/s41598-020-61533-x.

Spencer, T., Lane, S.N., 2017. Reflections on the IPCC and global change science: time for a more (physical) geographical tradition. Can. Geogr. 61, 124–135. https://doi.org/10.1111/cag.12332.

Stecca, G., Measures, R., Hicks, D.M., 2017. A framework for the analysis ofnoncohesive bank erosion algorithmsin morphodynamic modelling. Water Resour. Res. 53, 6663–6686. https://doi.org/10.1002/2017WR020756.

Stover, S.C., Montgomery, D.R., 2001. Channel change and flooding, Skokomish River, Washington. J. Hydrol. 243, 272–286. https://doi.org/10.1016/S0022-1694(00)00421-2.

Sturm, M., Gems, B., Keller, F., Mazzorana, B., Fuchs, S., Papathoma-Köhle, M., Aufleger, M., 2018a. Understanding impact dynamics on buildings caused by fluviatile sediment transport. Geomorphology 321, 45–59. https://doi.org/10.1016/j.geomorph.2018.08.016.

Sturm, M., Gems, B., Keller, F., Mazzorana, B., Fuchs, S., Papathoma-Köhle, M., Aufleger, M., 2018b. Experimental analyses of impact forces on buildings exposed to fluvial hazards. J. Hydrol. 565, 1–13. https://doi.org/10.1016/j.jhydrol.2018.07.070.

Surian, N., Righini, M., Lucía, A., Nardi, L., Amponsah, W., 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/10.1016/j.geomorph.2016.02.002 (Special Issue on 'Floods in Mountain Environments').

Tal, M., Paola, C., 2007. Dynamic single-thread channels maintained by the interaction of flow and vegetation. Geology 35, 347–350. https://doi.org/10.1130/G23260A.1.

Tang, H., McGuire, L.A., Kean, J.W., Smith, J.B., 2020. The impact of sediment supply on the initiation and magnitude of runoff-generated debris flows. Geophys. Res. Lett. 47, e2020GL087643 https://doi.org/10.1029/2020GL087643.

Temme, A.J.A.M., Armitage, J., Attal, M., van Gorp, W., Coulthard, T.J., Schoorl, J.M., 2017. Developing, choosing and using landscape evolution models to inform field-based landscape reconstruction studies. Earth Surf. Process. Landf. 42, 2167–2183. https://doi.org/10.1002/esp.4162.

Thapa, S., Creed, M.J., Sinclair, H.D., Mudd, S.M., Attal, M., Muthusamy, M., Ghimire, B. N., 2022. Modelling the impact of sediment grain size on flooding in the Kathmandu basin, Nepal. In: Conference Proceeedings of the 39th IAHR World Congress, Granada (Spain). https://doi.org/10.3850/IAHR-39WC2521711920221802.

Thapa, S., Sinclair, H.D., Creed, M.J., Mudd, S.M., Attal, M., Borthwick, A.G.L., Ghimire, B.N., Scott Watson, C., 2023. The impact of sediment flux and calibre on flood risk in the Kathmandu Valley, Nepal. Earth Surf. Process. Landf. 1–22. https://doi.org/10.1002/esp.5731.

Theule, J.I., Liébault, F., Loye, A., Laigle, D., Jaboyedoff, M., 2012. Sediment budget monitoring of debris-flow and bedload transport in the Manival Torrent, SE France. Nat. Hazards Earth Syst. Sci. 12, 731–749. https://doi.org/10.5194/nhess-12-731-2012.

Tofelde, S., Savi, S., Wickert, A.D., Bufe, A., Schildgen, T.F., 2019. Alluvial channel response to environmental perturbations: fill-terrace formation and sediment-signal disruption. Earth Surf. Dyn. 7, 609–631. https://doi.org/10.5194/esurf-7-609-2019.

Totschnig, R., Fuchs, S., 2013. Mountain torrents: quantifying vulnerability and assessing uncertainties. Eng. Geol. 155, 31–44. https://doi.org/10.1016/j.enggeo.2012.12.019.

Totschnig, R., Sedlacek, W., Fuchs, S., 2011. A quantitative vulnerability function for fluvial sediment transport. Nat. Hazards 58, 681–703. https://doi.org/10.1007/s11069-010-9623-5.

Turowski, J.M., Yager, E.M., Badoux, A., Rickenmann, D., Molnar, P., 2009. The impact of exceptional events on erosion, bedload transport and channel stability in a step-pool channel. Earth Surf. Process. Landf. 34, 1661–1673. https://doi.org/10.1002/esp.1855.

Vázquez-Tarrío, D., Borgniet, L., Liébault, F., Recking, A., 2017. Using UAS optical imagery and SfM photogrammetry to characterize the surface grain size of gravel bars in a braided river (Vénéon River, French Alps). Geomorphology 285, 94–105. https://doi.org/10.1016/j.geomorph.2017.01.039.

Vázquez-Tarrío, D., Piégay, H., Menéndez-Duarte, R., 2020. Textural signatures of sediment supply in gravel-bed rivers: revisiting the armour ratio. Earth Sci. Rev. 207, 103211 https://doi.org/10.1016/j.earscirev.2020.103211.

Vázquez-Tarrío, D., Peeters, A., Cassel, M., Piégay, H., 2023. Modelling coarse-sediment propagation following gravel augmentation: the case of the Rhône River at Péage-de-Roussillon (France). Geomorphology 428, 108639. https://doi.org/10.1016/j.geomorph.2023.108639.

Vericat, D., Church, M., Batalla, R.J., 2006. Bedload bias: comparison of measurements obtained using two (76 and 152 mm) Helley-Smith samplers in a gravel-bed river. Water Resour. Res. 42, 1–13. https://doi.org/10.1029/2005WR004025.

Vericat, D., Wheaton, J.M., Brasington, J., 2017. Revisiting the Morphological Approach. In: Gravel-bed Rivers. John Wiley & Sons, Ltd, pp. 121–158. https://doi.org/10.1002/9781118971437.ch5.

Walliman, N., Baiche, B., Odgen, R., Tagg, A., Escarameia, M., 2013. Estimation of repair costs of individual non-domestic buildings damaged by floods. Int. J. Saf. Secur. Eng. 3, 289–305. https://doi.org/10.2495/SAFE-V0-N0-1-16.

Ward, R.C., 1978. Floods: A Geographical Perspective. Macmillan Press, London (UK).

Wheaton, J.M., Brasington, J., Darby, S.E., Kasprak, A., Sear, D., Vericat, D., 2013. Morphodynamic signatures of braiding mechanisms as expressed through change in sediment storage in a gravel-bed river. J. Geophys. Res. Earth 118, 759–779. https://doi.org/10.1002/jgrf.20060.

Wilcox, A.C., Nelson, J.M., Wohl, E.E., 2006. Flow resistance dynamics in step-pool channels: 2. Partitioning between grain, spill, and woody debris resistance. Water Resour. Res. 42 (5) https://doi.org/10.1029/2005WR004278.

Williams, R.D., Brasington, J., Hicks, D.M., 2016. Numerical modelling of braided river morphodynamics: review and future challenges. Geogr. Compass 10, 102–127. https://doi.org/10.1111/gec3.12260.

Wohl, E., 2019. Forgotten legacies: understanding and mitigating historical human alterations of river corridors. Water Resour. Res. 55, 5181–5201. https://doi.org/10.1029/2018WR024433.

Wohl, E., 2020. Rivers in the Anthropocene: the U.S. perspective. Geomorphology 366, 106600. https://doi.org/10.1016/j.geomorph.2018.12.001 (Special Issue on "The Binghamton Geomorphology Symposium: 50 years of Enhancing Geomorphology").

Wohl, E., Scott, D.N., 2016. Wood and sediment storage and dynamics in river corridors. Earth Surf. Process. Landf. 42 (1), 5–23. https://doi.org/10.1002/esp.3909.

Wohl, E., Bledsoe, B.P., Jacobson, R.B., Poff, N.L., Rathburn, S.L., Walters, D.M., Wilcox, A.C., 2015. The natural sediment regime in rivers: broadening the foundation for ecosystem management. BioScience 65, 358–371. https://doi.org/10.1093/biosci/biv002.

Wohl, E., Kramer, N., Ruiz-Villanueva, V., Scott, D.N., Comiti, F., Gurnell, A.M., Piegay, H., Lininger, K.B., Jaeger, K.L., Walters, D.M., Fausch, K.D., 2019. The natural wood regime in rivers. BioScience 69, 259–273. https://doi.org/10.1093/biosci/biz013.

Wong, J.S., Freer, J.E., Bates, P.D., Sear, D.A., Stephens, E.M., 2015. Sensitivity of a hydraulic model to channel erosion uncertainty during extreme flooding. Hydrol. Process. 29, 261–279. https://doi.org/10.1002/hyp.10148.

Yu, G., Wang, Z., Zhang, K., Chang, T., Liu, H., 2009. Effect of incoming sediment on the transport rate of bed load in mountain streams. Int. J. Sediment Res. 24, 260–273. https://doi.org/10.1016/S1001-6279(10)60002-9.

Yu, X., Hsu, T.-J., Jenkins, J.T., Liu, P.L.-F., 2012. Predictions of vertical sediment flux in oscillatory flows using a two-phase, sheet-flow model. Adv. Water Resour. 48, 2–17. https://doi.org/10.1016/j.advwatres.2012.05.012 (Special Issue on 'Two-Phase Modeling of Sediment Dynamics').

Zimmermann, M., Pozzi, A., Stoessel, F., 2005. VADEMECUM: Hazard Maps and Related Instruments. The Swiss System and Its Application Abroad, Capitalization of Experience. PLANAT, the Swiss National Platform Natural Hazards.