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A Quantitative Review of Natural Flood Management Research

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ABSTRACT

Natural flood management (NFM), a subset of nature-based solutions (NBS) in catchment management, attempts to utilize and mimic natural processes in the landscape to reduce flood hazards, and it has been widely applied across Europe and other regions. Despite the wide use of NFM techniques, there is a lack of quantitative evidence for the effectiveness of NFM interventions in flood reduction. This paper examined 454 NFM relevant articles over the past 30 years, and the data they contain. Word frequency and cluster analyses showed changing trends and associations among nature-based flood mitigation research topics, including shifts from localized flood mitigation to catchment-wide flood management strategies, and from wood-related studies to a broader assessment of ecosystem services. Content analysis was conducted on literature directly related to NFM and NBS, revealing that research in large-scale catchments continues to be dominated by modeling approaches. While past reviews have suggested that increased catchment scale and rainfall intensity may diminish the effectiveness of NFM, we did not find strong empirical evidence (field monitoring and modeling) for this in our systematic review, although research at large catchment scale is still lacking. By assessing the confidence in NFM studies, the paper concludes that integrated understanding of a network of combined NFM interventions at a large catchment scale is necessary for future nature-based flood mitigation strategies.

1 | Introduction

Hard engineering solutions to flooding are often difficult to justify and resource across large parts of river basins and flood management is shifting from defense to ecosystem-based adaptation (Iacob et al. 2014). Natural flood management (NFM), a subset of nature-based solutions (NBS), attempts to utilize and mimic natural processes in the landscape to reduce flood hazards (Cooper et al. 2021; Dadson et al. 2017). NFM interventions are considered to provide additional co-benefits including enhancing ecosystem services and improved cost effectiveness of engineered flood management measures (Bark, Martin-Ortega, and Waylen 2021; Dadson et al. 2017). Enhancing temporary and permanent catchment water storage capacity by reforestation, offline storage areas, online (instream) storage via leaky dams, blocking ditches or gullies, changing land cover and soil management, seeks to delay flood peak time and reduce discharge during a rainfall event (Bond et al. 2022; Gao, Holden, and Kirkby 2016; Gao, Ma, and Fu 2016; Ghimire, Wilkinson, and Gillian 2014; Goudarzi et al. 2021; Grayson, Holden, and Rose 2010; Gunnell et al. 2019; Marshall et al. 2009; Nicholson et al. 2012; Nicholson et al. 2020; Quinn et al. 2013; Shuttleworth et al. 2019; Wilkinson et al. 2019). Land cover changes and soil aeration techniques adopted as part of NFM aim to increase soil porosity and encourage infiltration to slow water travel times to main channels (Alaoui et al. 2018; Dixon et al. 2016; Franklin et al. 2007; Marshall et al. 2014; Murphy et al. 2021; Palmer and Smith 2013; Wahren, Schwarzel, and Feger 2012). Some land cover changes seek to increase surface roughness to reduce overland flow velocity and increase peak flow lag times (Archer et al. 2013; Bond et al. 2019; Holden et al. 2008; Roni et al. 2015).

The impact of NFM interventions on flooding at different scales is unclear (Black et al. 2021; Fennell et al. 2022; Goudarzi et al. 2021; Hankin et al. 2020; Lane 2017). Small catchments, in particular, have greater spatial and temporal heterogeneity in response to rainfall events (Merot 2003). NFM benefits to flood reduction observed at smaller scales may also not translate to larger scales (Dixon et al. 2016; Hankin et al. 2021; Wilkinson et al. 2019). For example, simulation of different NFM land cover scenarios in the Rhine basin showed that scenarios that have a significant impact in a sub-catchment do not necessarily have an impact in a larger catchment (Hurkmans et al. 2009), and some studies have concluded that there is no evidence to support the idea that land-cover changes and river restoration measures have the same flood mitigation effects from the plot to hillslope and catchment scales (O'Connell et al. 2007; Rogger et al. 2017; Rowinski et al. 2018).

Despite the wide use of NFM techniques, the effectiveness of NFM interventions in flood reduction lacks quantitative evidence (Dadson et al. 2017; Lane 2017; Wilkinson et al. 2019; Wingfield et al. 2019). To enhance confidence in implementing NFM interventions for flood mitigation, it is imperative that a quantitative synthesis of NFM research literature be used to assess NFM impacts on flood characteristics, including flood peaks and duration. The aim of this paper is to categorize NFM-related studies and determine the nature of the evidence for NFM in impacting flow peaks and lag times. We screened and categorized research outputs according to specific interventions, the rationale of the interventions, and study regions. We quantitatively analyzed word frequencies in the literature to identify research trends on NFM-related topics. We also undertook content analysis and quantitative analysis of numerical results to determine what has been reported in modeling and fieldwork studies at different scales in terms of flood peak reduction and lag time changes. Thus, our paper generated a confidence evaluation for distinctions between study methods, type of interventions, catchment size, and rainfall intensity to help determine the impact and effectiveness of NFM on flood mitigation.

2 | Data and Methods

2.1 | Literature Search

We constructed a dataset of NFM-related techniques and research. To capture journal articles containing potentially related topics, we searched ISI Web of Science (WoS) from 1 January 1900 to 14 November 2022, with search terms as shown:

> TS = ("flood*" AND ("river*" OR "catchment*" OR "river basin*" OR "watershed*") AND ("natural flood management" OR "work* with natur*" OR "nature based solution*" OR "nature-based" OR "build* with nature" OR "slow the flow" OR "leaky dam*" OR "logjam*" OR "woody dam*" OR "in-stream wood*" OR "leaky barrier*" OR "woody debris*" OR "offline storage area*" OR "re-meander*" OR "embankment remov*" OR "reconnect*" OR "soil and land management" OR "soil aeration" OR "sub-soil*" OR "woodland management" OR "floodplain woodland*" OR "riparian woodland*" OR "afforest*" OR "reforest*" OR "grassland management" OR "unimproved grassland*" OR "peatland* restoration" OR "hedge*" OR "headwater drainage" OR "runoff attenuation feature*" OR "grip block*" OR "gully block*" OR "ditch block*" OR "buffer strip*")).

This yielded 1561 papers from 1991 to 2023 (one paper available in November 2022 was formally published in a journal issue in 2023) which included peer-reviewed manuscript articles, conference papers, and book sections. We also identified 132 relevant references that were not found on WoS via Google Scholar, including articles, books, and theses. Studies focused on biology, zoology, water quality, carbon, and wildfire, which did not cover flood impacts were excluded, resulting in a total of 1335 references remaining in the dataset for further screening and categorization (Figure 1).

2.2 | Literature Classification

After excluding 881 non-NFM related articles, each article was screened and manually categorized into one of three main categories (Figure 1): (1) "NFM Basis" group (164 articles), which represents references focused on the basic principles of NFM or NBS techniques, but which did not specifically use the terms NFM or NBS. These sources typically included related research on the role of soil characteristics, vegetation, geomorphology, and landscape restoration in affecting runoff generation processes in river catchments during rainfall events; (2) "NFM Global" group (93 articles). This group represents journal articles and conference papers working at sites outside of Europe referring directly to or mentioning NFM or NBS for flood protection, catchment runoff management, or ecosystem services benefits; (3) "NFM Europe" group (197 articles). These sources were European specific research (including UK) that directly mentioned or utilized NFM and NBS concepts and techniques, including modeling and field research. The dataset of 454 literature was also classified into regions based on the research locations of the studies for spatial analysis, which included: Europe (excluding UK), United States, United Kingdom, Canada, Oceania, China, Asia (excluding China), Africa, South America, and global scale studies.

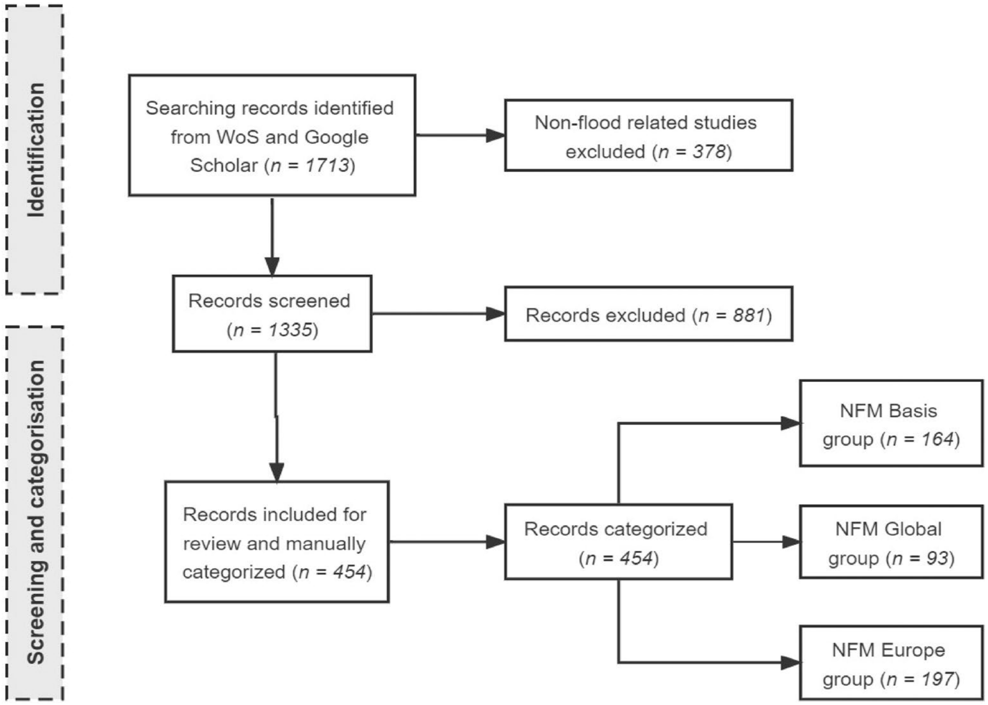

FIGURE 1 | Flow diagram of the literature search, screening protocol, and categorization.

2.3 | Quantitative Analysis

Analysis of words in titles and abstracts was undertaken to assess the main NFM study topics among the three literature groups—NFM Basis, NFM Global, and NFM Europe—during the period 1991–2022 using word frequency and hierarchical clustering analysis. A quantitative analysis of reported information including catchment size, rainfall intensity, and flood mitigation effects reported in 197 articles within the NFM Europe group was undertaken. The NFM Europe group shared similar nature-based techniques and measures for flood mitigation, and contained similar implementation, modeling, and experimental data and results of these techniques and measures, making articles within the NFM Europe group comparable so that confidence could be assessed to the same degree.

2.3.1 | Word Frequency and Hierarchical Clustering Analysis

Word frequency and hierarchical clustering analysis of word content in titles and abstracts were performed using the "quanteda" and "rainette" packages in R (Barnier 2023; Benoit et al. 2018). Wordclouds were constructed using the "quanteda.textplots" package in R based on the word frequency of each literature group (Benoit et al. 2018). The "rainette" method used in this study was developed from the "Reinert" method (Barnier 2023; Reinert 1983). Hierarchical clustering groups data samples by building a hierarchy of clusters. The simple clustering method by "rainette" is a divisive (top-down) hierarchical clustering applied to a document-term matrix. After removing symbols, English stop words (e.g., an or the), and other distractions in the content, such as publisher information, we identified four main clusters via the Rainette method (Barnier 2023), based on words that occurred at least 15 times. We computed χ^2 values of the grouped matrix and kept the grouping, which corresponds to the highest χ^2 values, as χ^2 values are an indicator of the estimated "distance" between two clusters regarding their term distributions: the higher the value, the more different the two clusters are from each other and *vice versa* (Barnier 2023). Each segment was paired and a χ^2 value was calculated between them and retained in the cluster whose χ^2 values are at a similar level. This process was repeated in the grouped array until there was no reassignment to make the χ^2 higher. Next, we applied hierarchical clustering analysis for NFM Europe to determine any change of topics between two different periods (2006–2018 and 2021–2022). These periods were chosen so that there was an equal number of articles (76 articles) in each group, which means there is a similar chance of words and topics occurring.

2.3.2 | Quantitative Content Analysis

To understand the confidence in the effectiveness of the different NFM or NBS techniques, NFM Europe papers were categorized according to their purpose. The categorization was based mainly on the location of the measures (offline and online), and the two different impacts on surface flow during a rainfall event: increasing water storage capacity and reducing water velocity. Then, articles in NFM Europe were separated using intervention types, resulting in eight separate groupings by NFM techniques plus subgrouping by UK or European study location (Table 1).

We constructed four indicators (flood reduction and delay, the exact value of reduction, researching multiple catchment sizes,

TABLE 1 | Number of articles for NFM techniques and measures grouped by purpose, with the confidence of their effectiveness and references based on Europe and UK research (the "EU" in the table refers to Europe excluding UK) (confidence level details and key references in Table S1).

	Purpose of intervention	NFM technique	Number of articles (*n*)	Confidence in the effectiveness on downstream flood risk reduction
Group A	Slow catchment flow generation and rainfall-runoff processes (off-channel)	Cross slope reforestation Floodplain/riparian reforestation	$n = 19$ (UK) $n = 17$ (EU)	**UK: Low to Medium confidence** **EU: Medium confidence** *Balanced proportion of research methods with several flood reduction conclusions reported; reduced effectiveness highly depends on rainfall intensity and initial soil conditions.*
		Soil and land management (soil aeration, sub-soiling, peatland, woodland, grassland, hedges)	$n = 17$ (UK) $n = 11$ (EU)	**UK: Medium to high confidence** **EU: Medium to high confidence** *Effectiveness results at multiple catchment scales with balanced proportion of research methods reported; lack of empirical evidence at larger scales.*
		Peatland restoration (including gully blocking) Floodplain restoration/reconnection	$n = 9$ (UK) $n = 17$ (EU)	**UK: Low to high confidence** **EU: Low confidence** *Studies in the UK and the EU are dominated by modeling approaches; moderate flood reduction results reported but without empirical evidence for larger-scale effects.*
Group B	Increase surface and subsurface water storage in offline/online areas	Offline storage areas (water retention/detention ponds)	$n = 10$ (UK) $n = 2$ (EU)	**UK: Low to high confidence** **EU: Low to high confidence** *Relatively even proportion of research methods; lack of large catchment scale studies.*
		Online storage areas (grip blocking, drainage/ditch blocking, buffer strips, beaver dams)	$n = 6$ (UK) $n = 2$ (EU)	**UK: Low to high confidence** **EU: Low confidence** *Studies are dominated by evidence from field measurements; lack of upscaling studies.*
		Land cover changes (floodplain/riparian reforestation, floodplain restoration/reconnection, grassland, hedges)	$n = 11$ (UK) $n = 5$ (EU)	**UK: Medium to high confidence** **EU: Low to high confidence** *Relatively even proportion of research methods; moderate flood reduction results of increasing water table depth and soil water storage reported but limited by catchment scales and rainfall intensities.*

(Continues)

TABLE 1 | (Continued)

	Purpose of intervention	NFM technique	Number of articles (n)	Confidence in the effectiveness on downstream flood risk reduction
Group C	Reduce water velocity in channel	Leaky barriers Woody logjams	$n = 15$ (UK) $n = 7$ (EU)	**UK: Low confidence** **EU: Low confidence** *Studies are dominated by evidence from field measurements and indoor physical experiments; lack of upscaling studies; effectiveness highly depends on the catchment scale.*
Group D	Integrated catchment management	Multiple NFM interventions	$n = 29$ (UK) $n = 35$ (EU)	**UK: Medium to high confidence** **EU: Medium to high confidence** *Studies are dominated by research methods of perceptual/conceptual analysis and modeling; effectiveness reported at multiple catchment scales; flood reduction strongly dependent on the location and extension of interventions and limited by rainfall intensity.*

and researching multiple rainfall intensities) to understand the confidence level of each subgroup. Among the eight subgroups for the UK and Europe separately, the number of papers investigating or reporting any of these four indicators was counted in each subgroup. The number of papers was calculated as a percentage of the total number of papers in each subgroup. Weight of confidence was evaluated as low (33^{rd} percentile), medium (33^{rd}–66^{th} percentile), and high (66^{th} percentile) according to the percentage within each subgroup. Further details are provided in Data S2.

For content analysis, papers that recorded exact flood reduction or delay values were classified by their research methods: modeling, fieldwork, hybrid modeling and fieldwork, and perceptual/conceptual analysis. Modeling refers to sources using physically based or statistical modeling, while perceptual/conceptual sources focus on using perception and concept-based evidence to summarize or predict NFM benefits. Next, we extracted reported values of flood discharge reduction and peak discharge delay time, catchment sizes, and rainfall intensities from the NFM Europe group. This was the only group with comparable nature-based flood mitigation interventions.

3 | Spatial and Temporal Analysis of Nature-Based Flood Mitigation Research

3.1 | Spatial and Temporal Distribution of Research Topics

The total number of relevant articles per year progressively increased from 1991 onwards, but NFM Global and NFM Europe articles did not appear until 2003 and 2011, respectively (Figure 2a). Meanwhile, the number of articles each year in NFM Basis (articles focussed on the basic principles of NFM or NBS techniques, but which did not specifically use the terms NFM or NBS) tended to even out and decreased substantially since 2017. The spatial distribution of NFM Basis was found to be consistent with the overall distribution of three literature groups, with a notable emphasis on relevant studies in Europe, particularly in the United Kingdom (Figure 2b).

Forest and wood-related studies were distributed evenly across time and were identified across all regions examined. Studies from 1991 to 2000 focused on understanding the impact of riparian woodland management and previous afforestation (Bren 1993; Brown, Harper, and Peterken 1997; Buttle 1994; Decamps, Pinay, and Naiman 1998; Fahey and Jackson 1997; Nelson et al. 2000; Piegay 1997; Piegay and Bravard 1997; Youngblood and Zasada 1991). In several studies, woodland management was studied for flood mitigation purposes (Al-Weshah and El-Khoury 1999; Bren 1993; Fahey and Jackson 1997), and some studies quantified the influence of forests on catchment hydrological conditions (Buttle 1994; Cadier 1996; Nagasaka and Nakamura 1999; Nelson et al. 2000; Piegay 1997; Piegay and Bravard 1997). Studies in the US, Canada, and Japan suggested that land clearing and tree harvesting as a result of agricultural and industrial practices beginning in the 1950s have significantly heightened flood risks in riparian and floodplain areas (Nelson

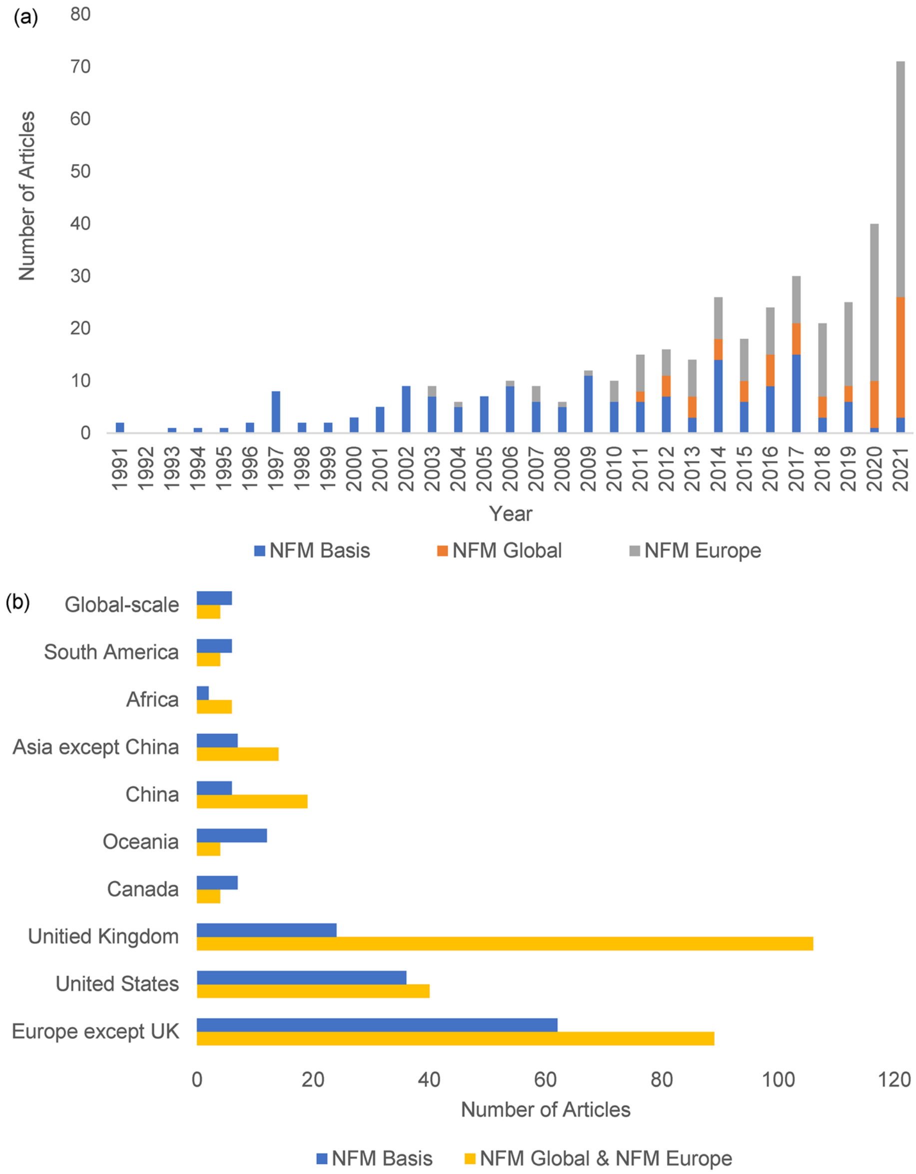

FIGURE 2 | The number of published articles in NFM Basis, NFM Global, and NFM Europe groups for (a) complete years in the time-series; (b) the 10 different regions.

et al. 2000; Slaymaker 2000). For instance, a study in Japan found 22,500 ha of deforestation increased flood peaks by 1.5 to 2.5-fold and shortened peak lag times by 7 h in ~300 km^2 catchment (Nagasaka and Nakamura 1999). Riparian forest has been evidenced as providing flood buffering effects by enhancing hydraulic roughness during channel overflows to the floodplain and slowing flows during extreme flood events in France (Piegay and Bravard 1997). However, the efficacy of such measures is dependent upon the location, tree species and spatial distribution of the trees in the landscape (Buttle 1994; Nelson et al. 2000).

The term NFM did not appear in the study period 2001–2010 but there was a wide range of studies determining the hydrological impacts of land-use changes. These studies included the impact of different land-use types, scales of land-use change, seasonal characteristics of land use, and field measurement versus modeling studies (Archer, Climent-Soler, and Holman 2010; Bormann and Klaassen 2008; Hurkmans et al. 2009; Lopez-Moreno, Begueria, and Garcia-Ruiz 2006; O'Connell et al. 2007; Petty and Douglas 2010; Vásquez-Méndez et al. 2010). The most frequent keywords in article titles and abstracts were related to reforestation and restoration research in the catchment. However, more specific topics also emerge, such as the "improvement" of soil properties and changes to hydraulic conductivity via tree roots (Emmanouloudis, Takos, and Spanos 2002; Nakamura et al. 2002), the changes in floodplain surface roughness associated with hedges (Cobby et al. 2003), and the use of buffer strips to mitigate flooding (Evrard et al. 2007). Large woody debris (LWD) received more attention during 2001–2010 than 1991–2000 period, with nine articles studying their dynamics and their interactions with river discharge, sediment movement, and channel regime during rainfall events (Angradi et al. 2004; Faustini and Jones 2003; Seo and Nakamura 2009; Webb and Erskine 2003; Wyzga and Zawiejska 2005). Several forest-related studies demonstrated that afforestation reduced sediment transport and volume to the river channels (Hughes et al. 2001; Keesstra 2002; Keesstra et al. 2005; Liebault and Piegay 2002), as well as reducing both subsurface and surface runoff to reduce flood discharge (Anderson, Rutherfurd, and Western 2006; Andreassian 2004; Bahremand et al. 2006; Lambs and Muller 2002; Ranzi, Bochicchio, and Bacchi 2002; Verbunt, Zwaaftink, and Gurtz 2005; Yao et al. 2009). For example, a modeling study of a large catchment in Slovakia predicted that a 50% increase in forest areas can decrease the flood peak discharge by 12% (Bahremand et al. 2006), while a monitoring study in Japan showed that the presence of a 36-year old forest reduced mean annual runoff by 11% by decreasing the runoff/precipitation ratio and increasing the evapotranspiration/precipitation ratio (Yao et al. 2009).

Articles from the period 2011–2022 were not limited to the direct effects of individual land-cover types and utilized more developed techniques for monitoring and modeling hydrological changes. The proportion of studies focusing on woodland during this period declined in comparison to the previous two decades. Instead, researchers shifted their focus toward investigating how land-cover changes have impacted runoff by influencing soil properties and surface roughness (Humann et al. 2011; Palmer and Smith 2013; Viola et al. 2014; Zheng, He, and Wu 2012). Remote sensing, aerial photography, and GIS techniques have been used extensively to observe and map long-term changes in land cover, landscape, and sediment movement (Diaz-Redondo et al. 2021; Dufour et al. 2015; Frazier et al. 2012; Hajdukiewicz and Wyzga 2019; Hlozek 2014; Kasai et al. 2019; Keeton et al. 2017; Martinez-Fernandez et al. 2017; Miklin and Cizek 2014; Solin, Feranec, and Novacek 2011; Zhang et al. 2014). Hydraulic and hydrological models are commonly used for hydrological simulation at various scales (Gasser et al. 2019; Keesstra et al. 2014; Munoz-Mas et al. 2017; Pattison et al. 2014; Schilling et al. 2014), while fieldwork and experiments are used for long-term monitoring at small scales (Gao, Holden, and Kirkby 2016; Gao, Ma, and Fu 2016; Kochel et al. 2016; Palmer and Smith 2013; Solin, Feranec, and Novacek 2011). A wide range of management-based research became a major study area during the 2011–2022 period, including investigations into post-flood LWD and the associated problems of debris blockages, which have the potential to increase flood risks (Gasser et al. 2018; MacVicar and Piegay 2012; Ruiz-Villanueva et al. 2014a, 2014b; Ruiz-Villanueva et al. 2017; Schmocker, Detert, and Weitbrecht 2013; Schmocker et al. 2014). Investigations into the development of new flood mitigation strategies such as channel-floodplain reconnection and restoration (Dawson et al. 2017; Eekhout et al. 2015; Hester et al. 2016; Wohl, Lane, and Wilcox 2015) were also dominant at this time.

3.2 | Global NFM Studies

From 1991 to 2022, there was a shift in research focus in the NFM Global group from examining the impacts of floods on ecosystems, geomorphology, and hydrology to investigating the effects of land cover and landscape changes on flood characteristics. The representation and emphasis of nature-based flood risk management strategies vary across different regions of the world. Except for extensive research on upstream water conservation and restoration of wetlands and forests (Fan et al. 2022; Kabeja et al. 2020; Li et al. 2022; Shih and Chen 2021; Wu et al. 2020; Yu et al. 2015), Chinese studies have recently focused on nature-based urban flood management (Chia, Wang, and Chen 2020; Shen et al. 2019), such as the Sponge Cities Program, which uses urban green infrastructure and underground drainage systems to manage surface water floods (Peng et al. 2022; Qi et al. 2021; Zhai et al. 2021). Studies conducted in other regions of Asia, such as Thailand, have modeled the impact of different land-use types and combined implementation of conservation practices on catchment flood management (Jamrussri and Toda 2017; Kheereemangkla et al. 2016; Trisurat, Eawpanich, and Kalliola 2016). The rationale behind these measures is "more space for water," both in the upstream and downstream areas, as well as in cities. Studies in Asia have shown that these nature-based measures provide better flood mitigation than traditional structural flood controls (Lo, Huang et al. 2021; San Liew et al. 2021; Sonu, Mohammed, and Bhagyanathan 2022; Zheng, Wang, and Liu 2022). These studies highlight the variability and effectiveness of nature-based, non-structural flood measures under urban planning and climate change.

US-based studies also focus on specific measures including upstream, riparian, and river channel restoration for flood attenuation, via reforestation, floodplain rehabilitation, river channel re-meandering, channel-floodplain reconnection and wetland restoration (Boughton and Pike 2013; Federman, Scott, and Hester 2022; Kurki-Fox et al. 2022a, 2022b; Lau and Franklin 2013; Maxwell et al. 2021; Sholtes and Doyle 2011; Worley et al. 2022). These studies support the storm water mitigation and flood resilience benefits of nature-based restoration measures and have indicated positive evaluation results both in terms of long-term planning and cost-effectiveness. A new concept called "Distributed Flood Attenuation" integrating all flood management measures in the catchment, beyond those mentioned above, also covers structural and non-structural distributed water storage (Antolini and Tate 2021; Wohl 2021). Instream wood and logjams are commonly discussed in the US and Canadian literature. There has been a shift in research from how to avoid logjam hazards in flood events to using and replacing logjams to mitigate flooding and reduce channel erosion (Kramer et al. 2017; Wohl et al. 2016; Wohl and Scamardo 2021).

In the period 1991–2022, the US had a similar number of NFM Basis and NFM Global studies, while Europe had the highest number of NFM Basis studies (Figure 2b). However, the number of studies focused on NFM and NBS studies was greater in the UK compared to other regions. Canada and Oceania have produced NFM Basis papers on the topic, but have not produced any papers directly using NFM and NBS measures, at least as far as is reported in the literature, and possess only a limited number of relevant studies discussing the potential of ecosystem-based adaptation to flooding (Biron, Buffin-Bélanger, and Massé 2018; Daigneault, Brown, and Gawith 2016; Westbrook, Ronnquist, and Bedard-Haughn 2020). In Africa and Asia, research hotspots on land

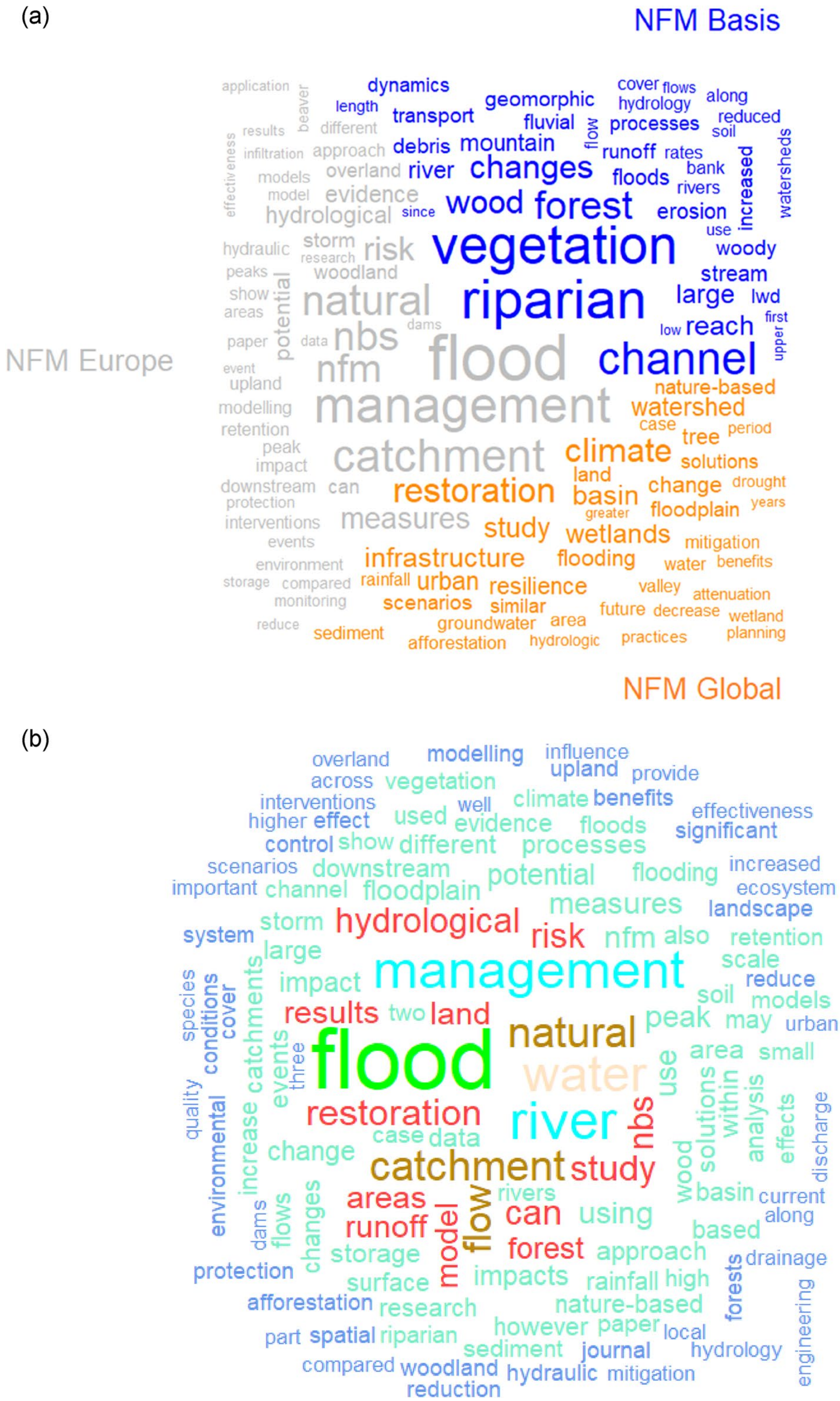

FIGURE 3 | Wordcloud map of the titles and abstracts of articles: (a) for the combined three literature groups (NFM Basis, NFM Global, and NFM Europe); (b) for the NFM Europe group only. The size of a word is proportional to the word frequency in the title and abstracts of papers, the colors in b represent seven levels calculated by equal intervals of word frequency.

management and NBS for flood risk reduction exist, indicating a significant potential for sustainable solutions compared to the traditional flood risk management strategies that have been employed in these regions. Furthermore, these regions exhibit significant market and research potential for sustainable solutions in the future.

4 | Analysis of Recent Trends and Dynamics Among Main Study Topics

4.1 | Trends of Keywords and Main Topics

Although the different literature groups share similar theoretical premises for solving flooding problems, the focus of studies varies. The most frequent keyword in NFM Basis was "vegetation," with a concentration in locations such as "riparian" or "mountain" areas, river "channel" or "reach" (Figure 3). This indicates the focus of relevant foundation studies on the hydrological impact of riparian and hillslope vegetation in the catchment (Anderson, Rutherfurd, and Western 2006; Dufour, Rodriguez-Gonzalez, and Laslier 2019; Keeton et al. 2017; Mosner et al. 2011; Rowinski et al. 2018). Studies in NFM Global started to focus on "restoration," "infrastructure" and "wetlands" within "river" and "basin" in response to climate and ecosystem resilience since 2011 (Boughton and Pike 2013; Daigneault, Brown, and Gawith 2016; Hobbie and Grimm 2020; Lo, Huang et al. 2021; Muldavin et al. 2017; Opperman and Galloway 2022; Wu et al. 2020).

High-frequency keywords indicate that studies in NFM Europe focused on the impacts of flood risk reduction measures including "decrease," "reduced," "resilience," "mitigation," "retention," and "protection" (Figure 3a). "Model" was the most common research method used in NFM Europe and respectively appears in three wordcloud levels developed on word frequency with much higher frequency than other research methods (red, green, and blue in Figure 3b). "Restoration" and "forest" were the two most frequently mentioned interventions, with a higher frequency of the former. The high-frequency term "flow," "hydrological" and "runoff" reflect that these studies sought to understand the effects on hydrological conditions. These studies seek evidence for "hydrological" and "hydraulic" effects (including "overland" flow, "infiltration," and flood "peaks") of NFM and NBS measures through modeling or monitoring methods (Barnsley et al. 2021; Birkinshaw, Bathurst, and Robinson 2014; Black et al. 2021; Hankin et al. 2021; Lane and Milledge 2013; Lockwood et al. 2022; Metcalfe et al. 2017a, 2017b), while exploring their "potential" in other fields (Auster, Barr, and Brazier 2022; Barber and Quinn 2012; Kowalska et al. 2021; Wilkinson et al. 2014).

4.2 | Hierarchical Clustering for Topic Association

In the hierarchical clustering results, vertical ordering within a cluster is by word frequency from highest to lowest; the contribution of each word to the association χ^2 of that cluster is indicated by the length of the bar, where blue is a positive correlation and red is a negative correlation. Whereas in the horizontal axis, the presence of a link connecting two clusters indicates that they are associated, and the length of the longitudinal link reflects the magnitude of their association χ^2; clusters that are not connected by a line segment are mutually exclusive. For example, clusters shown in Figure 4 vertically reflect the change in the frequency of keywords, and horizontally represent the association and mutual repellence that exists between the different research topics. Words cluster 1 includes perspectives and components of NFM and NBS with management strategy perspectives (e.g., solutions, approaches, knowledge, review) and characterization based on sustainability or other ecological and biological parameters (e.g., restoration, ecosystem,

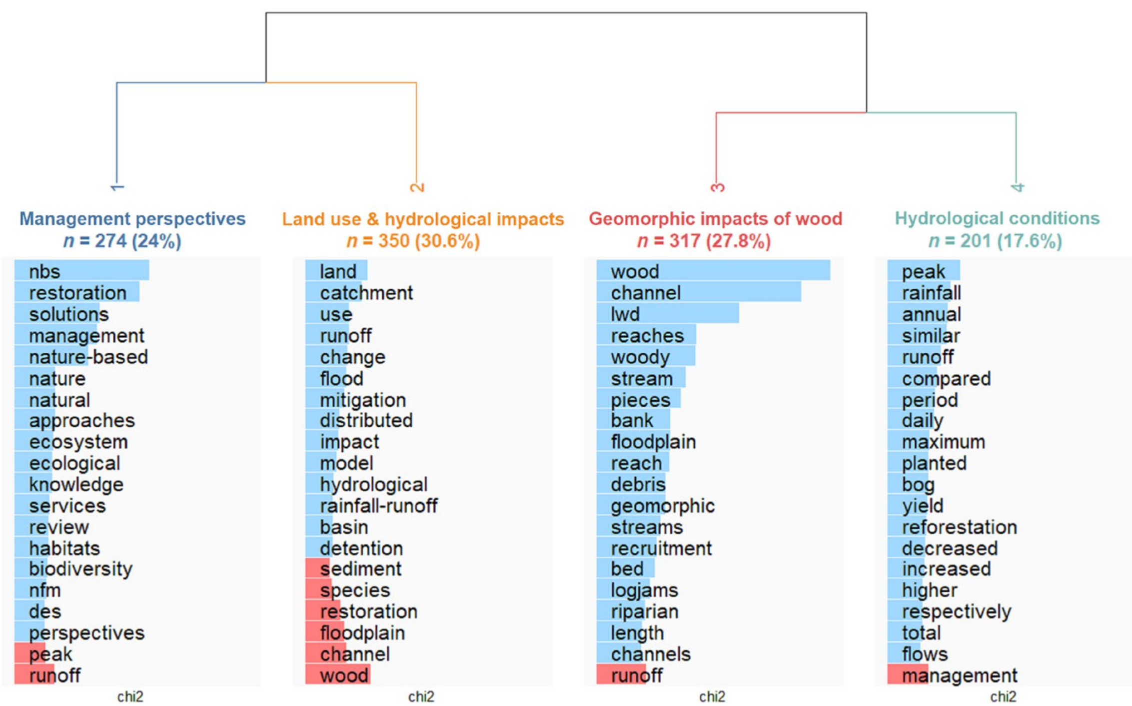

FIGURE 4 | Divisive hierarchical clustering for the combined three literature groups (NFM Basis, NFM Global and NFM Europe). *n* is the number of word segments in each cluster. The length of blue and red bars under a word is proportional to the frequency, at which the word appears in the titles and abstracts in its home cluster (blue represents positive relationship, red represents negative relationship). The length of the longitudinal link between the two clusters represents the sum of the Association χ^2 values between them.

ecological services, habitats, biodiversity). Words cluster 2 focuses on relationships between distributed land use and land change features in the catchment (basin) and hydrological impacts (e.g., flood mitigation, runoff, rainfall-runoff, detention), which are mainly based on modeling research. Words cluster 3 encompasses geomorphic impacts (e.g., recruitment, logjams, length) of wood and LWD in variable river sections (e.g., channel, reach, stream, bank, floodplain, bed, riparian). Words cluster 4 consists of the functioning and dynamics of hydrological conditions (e.g., peak, rainfall, runoff, flows, similar, compared, maximum, yield, decreased, increased) related to vegetation (e.g., planted, bog, restoration) over different temporal scales (e.g., annual, daily, period, total).

Words cluster 1 "Management perspectives" and 2 "Land use and hydrological impacts" are highly connected, where the words with a higher percentage (blue bars in Figure 4) have a stronger correlation to the other clusters. However, there are some terms that might be considered related but are negatively correlated with each other. The strength of negative association (red bars in Figure 4) refers to the probability of these irrelevant words that do not appear in the same word segment when high-frequency keywords appear within it. For example, some terms of flood mitigation (e.g., peak, runoff) are incompatible with "management" in cluster 1; several keywords on ecological benefits (e.g., species, restoration) and geomorphology (e.g., sediment, floodplain, channel, wood) contradict the focus of cluster 2. This also exists between words clusters 3 "Geomorphic impacts of wood" and 4 "Hydrological conditions," where the term "runoff" related to the hydrological topic was negatively associated with wood-related topics in cluster 3. This is consistent with the patterns observed in cluster 1. The keyword "management" from cluster 1 shows an inverse relationship with the hydrological keywords in cluster 4.

The divisive hierarchical clustering results of NFM Europe (Figure 5) also showed similar grouping content to Figure 4. However, because the terms "land use" and "land change" were replaced by "land management" and their impacts were not emphasized in NFM Europe, when words cluster 2 "Land use and hydrological impacts" in Figure 4 compared to cluster 1 "Hydrological impacts" in Figure 5, this research focus was missing. Instead, the terms of NFM and NBS in words cluster 1 "Management perspectives" were further divided into two separate clusters for the management and the ecological services aspects (words clusters 3 "Ecological impacts" and 4 "Management perspectives" in Figure 5).

The cluster of studies on catchment hydrology (words cluster 1 "Hydrological impacts" in Figure 5) represented the highest proportion of articles (38.3%) in NFM Europe. These studies are highly associated with the research of "wood" and "woody debris" manually installed within the catchment which provides a flood mitigation and storage role (Black et al. 2021; Dixon et al. 2016; Ferguson and Fenner 2020a, 2020b; Lo, Smith et al. 2021; Lo et al. 2022; Metcalfe et al. 2018; Norbury et al. 2021; Thomas and Nisbet 2012). Not all NBS studies refer to flooding issues and the hydrological impacts of their measures. The NBS studies often focused more on the integrated benefits of the implementation of these interventions, where ecological and environmental functions are more intensively mentioned (Albert et al. 2021; Eekhout et al. 2020; Ellis, Brazier, and Anderson 2021; Guerrero, Haase, and Albert 2018, 2022; Pugliese et al. 2022; Rey 2021; Schmidt, Guerrero, and Albert 2022; Turkelboom et al. 2021). Although the correlation indicated by the Association χ^2 values between clusters 3 and 4 is weaker than that between hydrology and instream wood studies, the overlap between NBS and NFM studies and ecological services and environmental protection studies is higher than with catchment hydrology, and most of these studies do not tackle hydrology-related topics (Andrikopoulou et al. 2021; Keesstra et al. 2018; Spray et al. 2022; Tsaryk et al. 2020; Turconi et al. 2020; Turkelboom et al. 2021).

For NFM Europe, there are differences between the periods of 2006–2018 and 2021–2022. In terms of clusters, cluster 2 "Land use and hydrological impacts" (46.6%) in 2006–2018 (Figure 6a) corresponds to cluster 1 "Management perspectives" (44.5%) in 2021–2022 (Figure 6b). The proportion of wood-related research decreased from 39.3% to 19.3% over time and became more associated with ecological service topics ("ecosystem", "species," and "biodiversity"), while the proportion of hydrology-focused research ("overland," "flow," "peak," and "discharge") increased from 14.1% to 36.2%. The term "NFM" disappeared from words cluster 1 "Management perspectives" in 2021–2022 (Figure 6b), which means the contribution of "NFM" to the relevance of topics declined significantly, and its position was replaced by "NBS" in 2021–2022. However, the change in the frequency of "NBS" and "NFM" did not affect the trend toward hydrology-related studies, which implies both NFM and NBS studies are focusing on the hydrological effects as their potential benefits (Dadson et al. 2017; Dixon et al. 2016; Kumar et al. 2021; Raska et al. 2022; Standen, Costa, and Monteiro 2020; Tafel et al. 2022; Wilkinson et al. 2019). In this context, the association between hydrological studies and NFM and NBS and wood-related studies became stronger respectively. The composition of the hydrology cluster also changed, from focusing on flood peaks and rainfall to addressing overland flow, storms, and flood events. This indicates that research in NBS and NFM is increasingly focusing on the hydrological effects during the entire flood process and the interaction between subsurface and surface water (Bond et al. 2020; Costa et al. 2021; Edokpa et al. 2022; Ellis, Anderson, and Brazier 2021; Ferguson and Fenner 2020a, 2020b; Monger et al. 2022a, 2022b; Revell et al. 2021; Revell, Rubinato, and Blackett 2022; Shuttleworth et al. 2019; Wallace et al. 2021; Westbrook, Ronnquist, and Bedard-Haughn 2020).

5 | NFM Techniques by Target Benefits

5.1 | Understanding Confidence in NFM and NBS Techniques

To understand the confidence level of each NFM technique and measure, we categorized intervention type into four groups (Group A-D) by purpose and eight subgroups by NFM techniques and study regions of UK and Europe excluding UK (EU). Confidence levels were evaluated by four indicators for eight subgroups for the UK and EU separately (the evaluation process and data are provided in Data S2).

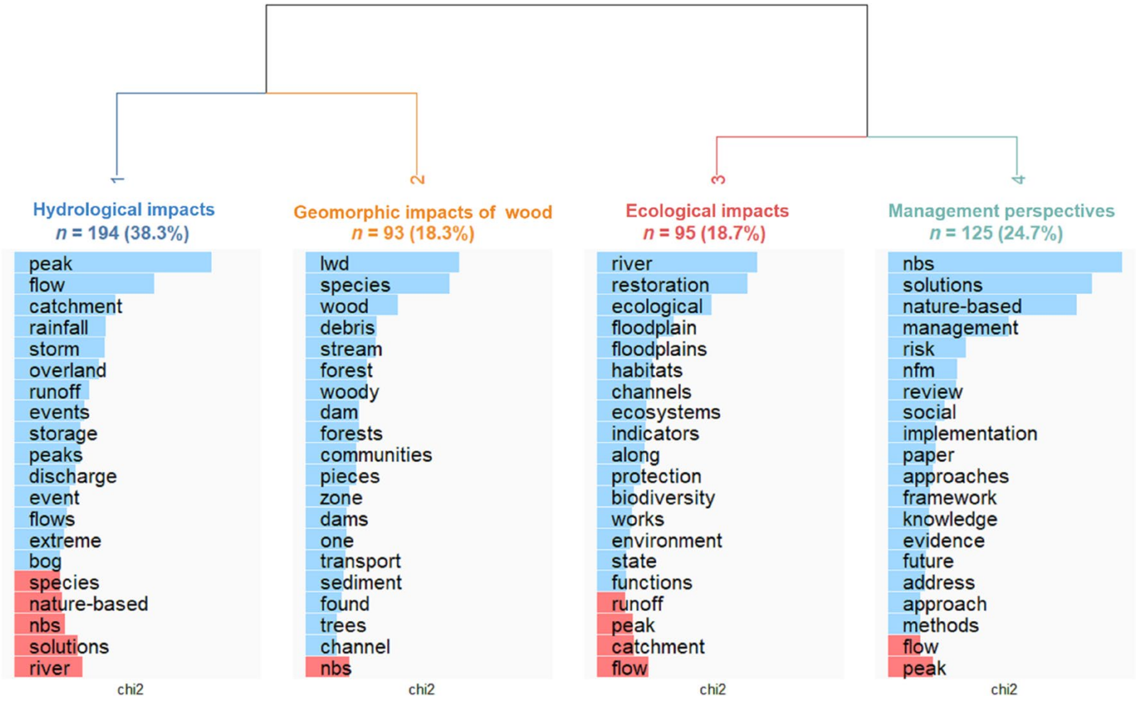

FIGURE 5 | Divisive hierarchical clustering for the "NFM Europe" literature group. *n* is the number of word segments in each cluster. The length of blue and red bars under a word is proportional to the frequency that the word appears in the titles and abstracts under its home cluster (blue represents positive relationship; red represents negative relationship). The length of the longitudinal link between the two clusters represents the sum of the Association χ^2 values between them.

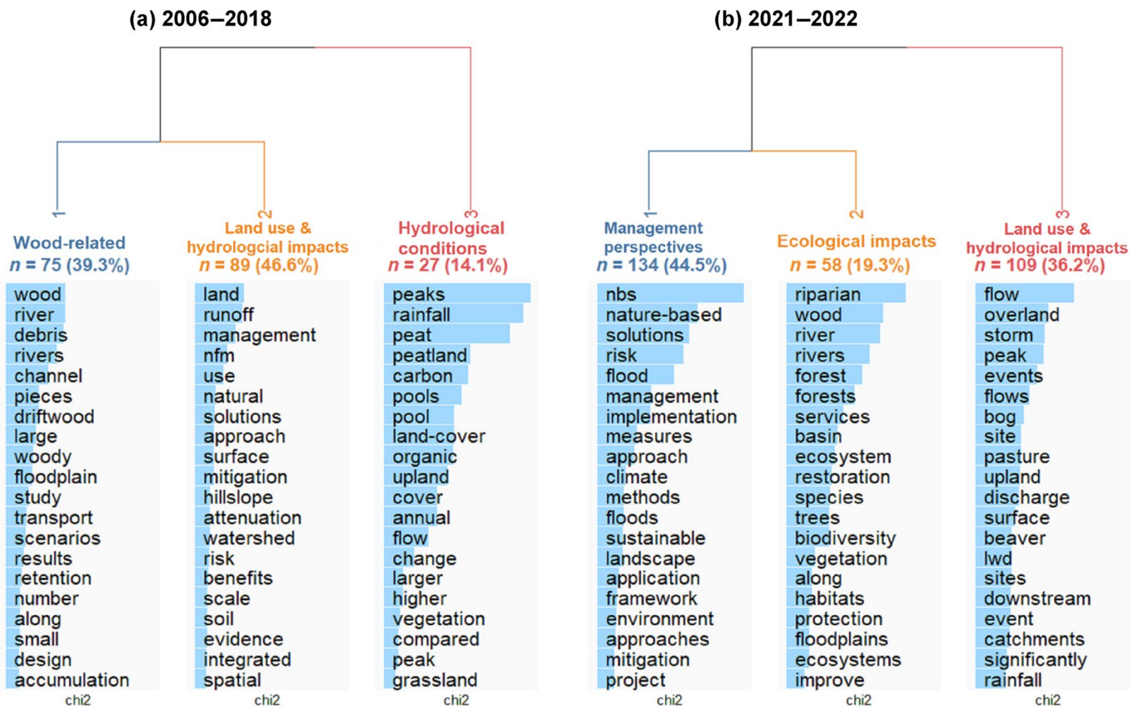

FIGURE 6 | Changes in research topics and keywords by cluster analysis (Divisive hierarchical clustering, Rainette method, excluding words frequency < 10 times) of title and abstract contents for the periods 2006–2018 and 2021–2022. These periods were chosen as they contain the same number of articles (76 articles for each). *n* is the number of word segments in each cluster. The length of blue bars under a word is proportional to the frequency that the word appears in the titles and abstracts under its home cluster. The length of the longitudinal link between the two clusters represents the sum of the Association χ^2 values between them.

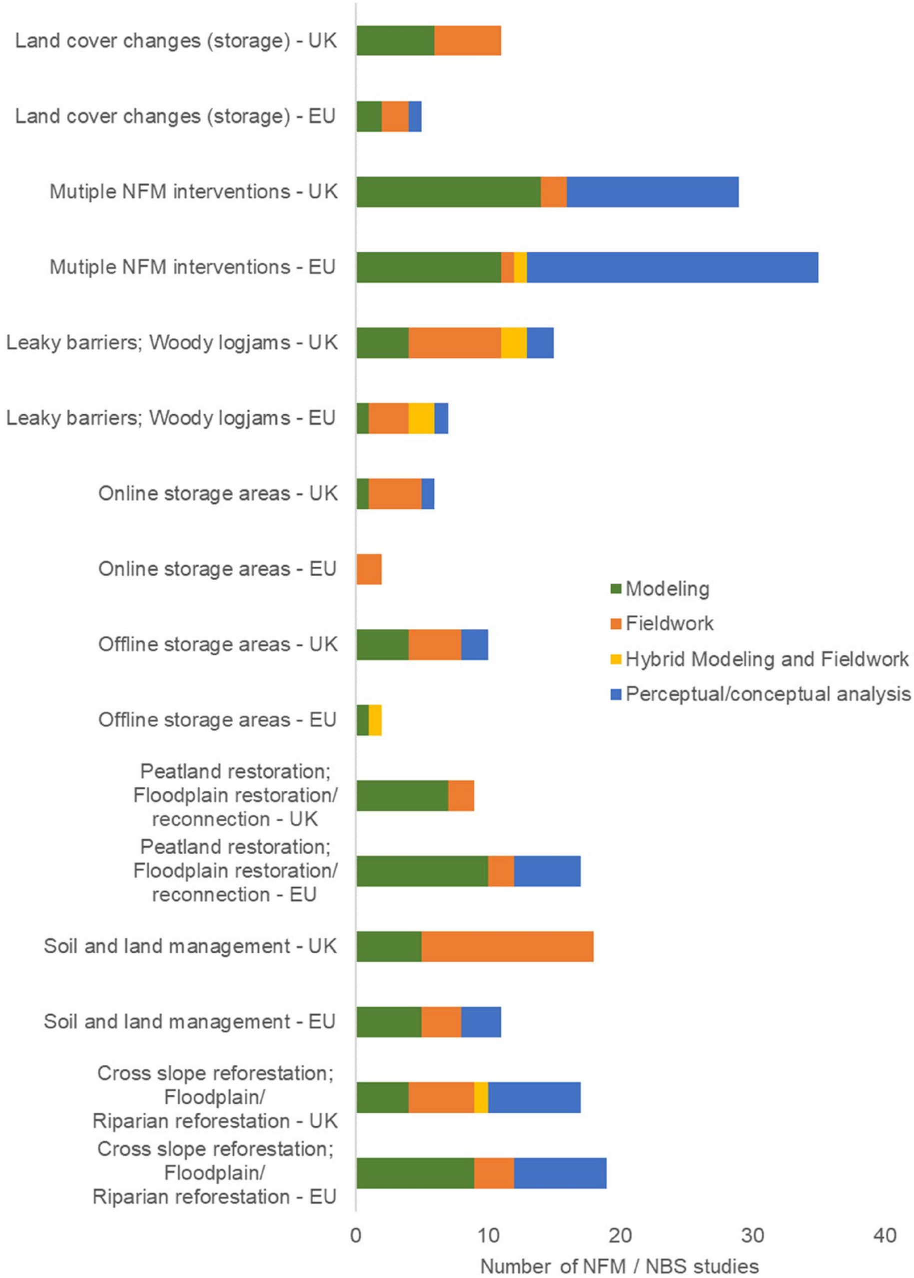

FIGURE 7 | Number of NFM/NBS studies in the UK and other EU regions using research methods of modeling, fieldwork, hybrid modeling and fieldwork, and perceptual/conceptual analysis, grouped by purpose (the same as groups shown in Table 1).

Reviewing the literature within Group A, which focused on studies that slow catchment flow generation and rainfall-runoff processes (off-channel) (Table 1), the highest confidence aligns with soil and land management and reforestation which had the largest number of studies. The share of fieldwork, modeling, and perceptual/conceptual evaluation studies among reforestation effects on flooding is relatively balanced (Figure 7). The contribution of reforestation to flood mitigation effectiveness also comes from a variety of aspects, including reducing overland flow associated with decreased soil saturation, slowing rainfall-runoff processes by increasing soil hydraulic conductivity and soil water storage, as well as increasing surface roughness to attenuate surface runoff (Buechel, Slater, and Dadson 2022; Chandler et al. 2018; Mihalcea 2017; Mongil-Manso, Navarro-Hevia, and San Martin 2021; Murphy et al. 2021; Revell et al. 2021; Revell, Rubinato, and Blackett 2022; Thomas and Nisbet 2007). The effectiveness of reducing flood flow is more dependent on the number of measures employed within the catchment and the original soil conditions than on the area of the intervention and its proportion of the catchment area (Page et al. 2020; Peskett et al. 2021). In contrast to the other two intervention types (soil and land management and catchment restoration) in Group A, there is no literature indicating that the effect of reforestation on flood risk reduction within catchments changes significantly with the catchment scale.

Maintaining the same criteria of evaluation, Group B (increase surface and subsurface water storage in offline/online areas) has a greater range of confidence levels than Group A. Combining the three intervention types, the number of fieldwork and modeling studies is almost equal (Figure 7). The reduction of peak discharge by online and offline storage areas is effective and notable in both fieldwork and modeling results (Table S1). However, the location of offline storage features is the most important factor, which depends on the soil type, number, and spatial distribution of these features in the catchment (Bezak et al. 2021; Fennell et al. 2022; Graham et al. 2022; Metcalfe et al. 2017a, 2017b; Metcalfe et al. 2018; Nicholson et al. 2020). In contrast, impacts due to land-cover changes have more uncertainty. Modeling and fieldwork studies have an equal proportion in total, but the majority of modeling studies are from large-scale studies of reforestation and restoration which lack the before-after observed data for comparison, while grassland and hedges studies are dominated by fieldwork with less evidence for downstream reduction (Richet, Ouvry, and Saunierareas 2017). There was variability in the results of restoration studies, where the intervention did not significantly increase water storage or overland flow in the floodplain in a fieldwork-based study (Shuttleworth et al. 2019), while the modeling results showed a 6-fold increase in overland flow storage volume and additional catchment surface storage (Addy and Wilkinson 2021; Clilverd et al. 2016; Goudarzi et al. 2021).

Modeling and experimental studies for leaky dams and woody logjams in Group C have a similar number of studies and both demonstrated significant flood mitigation and peak travel time delay effects at the local scale where the interventions were implemented, independent of rainfall intensity (Kitts 2010; Norbury et al. 2021; Thomas and Nisbet 2012). However, the effectiveness of leaky dams and woody logjams is limited by the catchment scale and mostly only has localized effects in the implemented tributaries or areas. There is still uncertainty about the impact of intensive implementation of leaky dams and woody logjams in small tributaries, where increasing their number does improve the peak reduction, but their location within the tributary and the contribution of the tributary to the entire catchment are important limiting factors (Follett, Schalko, and Nepf 2021; Hankin et al. 2020; Leakey et al. 2020).

Studies in Group D have two main purposes: to establish a GIS-based database to support spatial targeting and planning of future NFM and NBS measures; and to assess the effectiveness and cost–benefit of integrated catchment flood management strategies based on existing or designed scenarios. Their findings imply differences in the effectiveness of combining different interventions in the same catchment and implementing individual interventions. A recent empirical study has demonstrated that both single and combinations of several types of NFM measures can effectively increase the lag time of flood peaks (Black et al. 2021), beyond Dadson et al.'s (2017) and Barnsley et al.'s (2021) proposed 20 km^2 scale limit. Importantly, this indicates that NFM can be considered in isolation or combination with other forms of flood risk management at larger catchment scales, as an integrated catchment flood management strategy.

5.2 | Quantitative Analysis: Catchment Size and Rainfall Intensity Impact on NFM Effectiveness

A total of 88 papers clearly showed that NFM/NBS can be effective in reducing flood peaks, and 41 of them gave specific values of peak discharge reduction or delay. The studies from Europe (excluding UK) had a lower proportion of literature concluding that flood peak discharge is reduced or delayed compared to the UK studies. 34.3% of multiple intervention studies and 25.9% of individual intervention studies reported a reduction, with only 11.4% and 6.9%, respectively, mentioning exact reduction values. Because NBS interventions in the Europe group were more biased in examining the combined benefits delivered, such as ecosystem services and recreational benefits, the proportion of papers that specifically evidenced flood reduction was relatively low. Studies of multiple interventions in Europe had a higher rate of peak reduction results than studies of single interventions, or for the UK. This is because European studies were more often using multiple interventions of NBS as an integrated catchment strategy than in the UK.

The proportion of articles with flood reduction results drawn from the different study methods also varied considerably. We classified study methods into modeling, fieldwork, hybrid modeling and fieldwork, and perceptual/conceptual analysis. Overall, the highest proportion of flood peak reduction results was from modeling studies in the NFM/NBS literature dataset, followed by fieldwork, hybrid modeling and fieldwork, and perceptual/conceptual analysis. Results from modeling approaches are the most targeted to flood issues (Figure 8), with 65.8% of studies concluding flood reduction effects, whereas this rate is reduced to 43.1% and 42.9% in studies by fieldwork and hybrid modeling and fieldwork methods respectively. The same is true for studies using only fieldwork methods, with 21.6% giving specific reduction or delay values while none of perceptual/conceptual analysis studies give a reduction or delay value. The studies that do not give specific values all demonstrate observations that are mostly indirect evidence of reduced water velocity, increased soil infiltration rates, or water storage, but are limited by the spatial distribution of the concentrated sampling sites, which makes it more difficult to provide direct evidence of attenuated flood peaks in the channels.

For the content analysis, there was no significant correlation between the maximum flood peak discharge reduction and catchment size or rainfall intensity ($p = 0.440$; $p = 0.306$) (Figure 8); an important and novel finding contrasted with previous studies, which have suggested that the attenuation effect on flood peaks is likely to decrease with increasing catchment scale and rainfall intensity, or that effects would only be local (Barnsley et al. 2021; Bezak et al. 2021; Costa et al. 2021; Dadson et al. 2017; Dixon et al. 2016; Ellis, Anderson, and Brazier 2021; Kay et al. 2019; Lane 2017, fig. 3; Leakey et al. 2020; Norbury et al. 2021; Page et al. 2020; Pattison 2010; Thomas and Nisbet 2012; Wahren, Schwarzel, and Feger 2012; Wilkinson et al. 2019).

There is also a large body of literature in our dataset that utilizes modeling or field data and demonstrates that the effectiveness of interventions does not change with increasing catchment size or magnitude of rainfall events, which can support our findings of no significant correlation between them. These studies suggest that the effectiveness of flood attenuation can be amplified by combining and placing multiple measures over a larger catchment scale than a single measure in a local area (Black et al. 2021; Ferreira et al. 2020; Gao, Holden, and Kirkby 2017; Goudarzi et al. 2021; Graham et al. 2022; Metcalfe et al. 2017a,

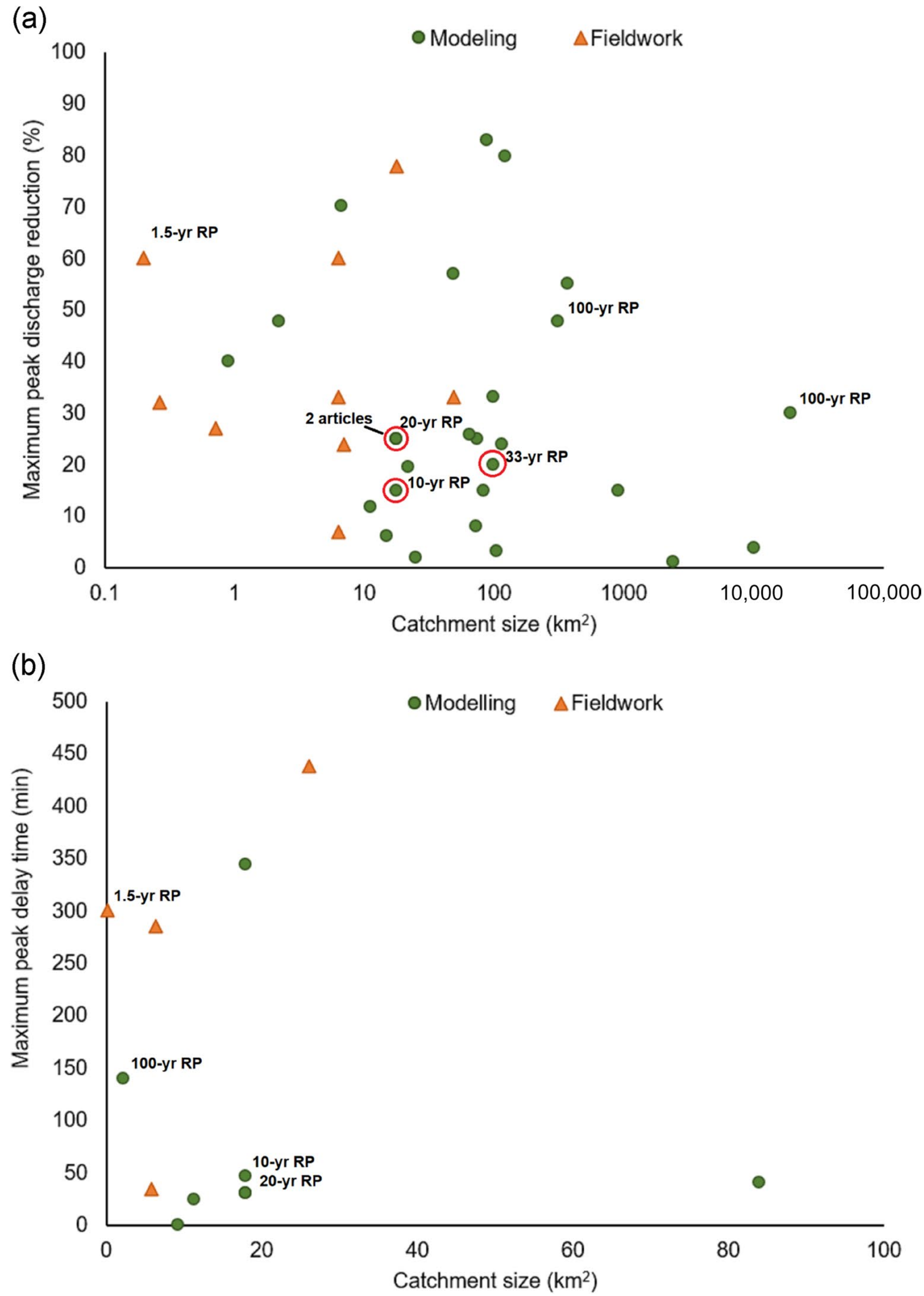

FIGURE 8 | Peak discharge reduction (a) and delay time (b) values from literature in the NFM/NBS studies grouped against catchment size. Corresponding return period labels have been added where available.

2017b; Nicholson et al. 2020; Puttock et al. 2021; Ramsbottom et al. 2019). Although there is heterogeneity among different catchments, the results from one field-based study showed a maximum delay time of 7.3 h measured in a 26 km^2 headwater catchment by implementing a combination of multiple measures (207 ha woodland planting, 116 large log structures, 31 flow attenuation ponds and 2.9 km of previously straightened river channel re-meandered, with embankment removed) within a 69 km^2 catchment (Black et al. 2021). The maximum peak discharge reduction rates of 80% and 83% highlighted in Figure 8 were modeled from catchments of 122 and 88 km^2 (Gabriels, Willems, and Van Orshoven 2022; Mihalcea 2017). The largest catchment scale study was carried out by modeling, which predicted a 30% reduction of peak discharge for a catchment of 19,224 km^2 (Terencio et al. 2020). There is no strong empirical evidence from the combined set of field, modeling, and hybrid studies showing that the effectiveness of NFM and NBS interventions on peak discharge reduction and peak delay decreases with increasing catchment size (Figure 8). While there are some smaller peak discharge reduction values using modeling methods for catchments of 1000 km^2 or above, the number of cases is too small for any effect to be confirmed (Figure 8a).

Nevertheless, there are more small-scale studies than large ones and so further large-scale studies are required to help understand where to locate NFM measures within a catchment and how these measures will respond to future flood events.

There was no significant correlation between the flood reduction effects of interventions and rainfall intensity ($p=0.306$). The comparison of different rainfall intensity impacts used in studies can be categorized into two types: precipitation totals (mm; 7 articles) and event return period (years; 14 articles). Our finding, contrary to earlier literature which suggested that effectiveness could be limited by increasing rainfall intensity (Archer, Climent-Soler, and Holman 2010), opens up the possibility for large-scale, long-term implementation of NFM/NBS at the catchment scale. Some field evidence from northern England showed that the percentage of peak discharge reduction during high-magnitude storm events was lower than for low-magnitude storm events (Dadson et al. 2017; Ferguson and Fenner 2020a, 2020b; Nicholson et al. 2020). However, at the larger catchment scale, the decrease of peak discharge responds more significantly to higher magnitude events due to the possibility of using expandable field storage (Hankin et al. 2021; Kay et al. 2019). Two studies conducted at large catchment scales (315 and 19,234 km^2) for extreme rainfall events (100-year return period) yielded peak discharge reductions of 48% and 30%, respectively (Reinhardt et al. 2009; Terencio et al. 2020). This indicates further evidence is required to develop an understanding of the effectiveness of NFM for higher magnitude events. However, the evidence for understanding the impacts of rainfall intensity on NFM effectiveness is limited, as only 8 out of 41 articles with relevant data have reported the peak reduction or delay values with the return period of rainfall events (Figure 8). A key problem is that, depending on the characteristics of rainfall patterns and catchment antecedent conditions, the effect of NFM features on peak discharge reduction in different storm events may vary. The timings of discharge from NFM features might contribute to the timings of peak discharge and flow concentration, which is a potential issue for further research. Considering catchment scales of NFM may be related to the synchronization of runoff peaks, NFM impact assessment on flood risk should be upscaled to immediate sub-catchments and downstream catchment areas.

6 | Conclusions

This review identified several key findings in NFM and related studies. Over the last decade, the number of NFM and NBS related studies has rapidly increased globally with the greatest concentration in the European region. Between 1991 and 2022, the research focus has shifted from examining the impacts of floods on ecosystems, geomorphology, and hydrology to investigating how land cover and landscape changes affect flood characteristics. A shift in keyword frequency indicates a broader evolution in NFM and NBS studies: from flood mitigation to flood management strategies, from localized hydrological impacts to catchment-wide flood processes, and from wood-related studies to broader ecosystem services assessments. There has been a notable transition in research focus from single to multiple interventions for flood mitigation, with a high proportion of studies using modeling methods.

This review, after integrating data and results from NFM and related studies during the past 30 years, concludes that the existing evidence suggests that NFM interventions maintain their flood mitigation effects regardless of catchment size or the magnitude of rainfall intensity. Modeling studies dominate this field and generally predict that NFM and NBS measures are effective for flood mitigation. Importantly, flood mitigation effectiveness of interventions did not appear to diminish with increasing catchment size and rainfall intensity. While numerous large-scale studies, mainly modeling-based, have reported significant flood attenuation and peak flow delays, confidence in NFM and NBS interventions remains limited by variables such as their location and extent, rainfall intensity, catchment antecedent conditions, and catchment scale. Literature evidence suggests that implementing multiple interventions enhances the effectiveness of NFM and NBS. However, more experimental evidence, such as modeling the construction of a network of NFM interventions with physically-based models in large-scale catchments, monitoring the downstream impacts of different NFM intervention types in large-scale catchments, and monitoring the combined effects of different NFM interventions, is needed to provide a more comprehensive understanding of the effectiveness of NFM. Thus, it is critical to design intervention networks at the catchment scale to support spatial models that can aid decision-making.

Author Contributions

Qiuyu Zhu: conceptualization (equal), data curation (equal), formal analysis (equal), investigation (equal), methodology (equal), visualization (equal), writing – original draft (lead), writing – review and editing (equal). **Megan Klaar:** supervision (equal), writing – review and editing (equal). **Thomas Willis:** supervision (equal), writing – review and editing (supporting). **Joseph Holden:** supervision (equal), writing – review and editing (equal).

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

Related WIREs Articles

Natural flood management

Representing natural and artificial in-channel large wood in numerical hydraulic and hydrological models

Role of forested land for natural flood management in the UK: A review

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.