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A Holistic Catchment-Scale Framework to Guide Flood and Drought Mitigation Towards Improved Biodiversity Conservation and Human Wellbeing

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ABSTRACT

As climatic extremity intensifies, a fundamental rethink is needed to promote the sustainable use of freshwater resources. Both floods and droughts, including water scarcity, are exacerbating declines in river biodiversity and ecosystem services, with consequences for both people and nature. Although this is a global challenge, densely populated regions such as Europe, East Asia and North-America, as well as the regions most affected by climate change, are particularly vulnerable. To date mitigation measures have mainly focused on individual, local-scale targets, often neglecting hydrological connectivity within catchments and interactions among hydrology, biodiversity, climate change and human wellbeing. A comprehensive approach is needed to improve water infiltration, retention and groundwater recharge, thereby mitigating the impacts of heavy rainfall and floods as well as droughts and water scarcity. We propose a holistic catchment-scale framework that combines mitigation measures including conventional civil engineering methods, nature-based solutions and biodiversity conservation actions. This framework integrates legislation, substantial funding and a governance structure that transcends administrative and discipline boundaries,

enabling coordinated actions across multiple spatial and temporal scales. It necessitates the collaboration of local and regional stakeholders including citizens, scientists and practitioners. A holistic vision for the sustainable management of freshwater resources could have synergistic effects that support biodiversity and mitigate climate change within functional ecosystems that deliver benefits to people.

1 | Introduction

Freshwaters—including groundwaters, rivers, lakes and wetlands—are global hotspots of biodiversity that provide multiple ecosystem services. Rivers, lakes and reservoirs cover only 2.3% of the Earth's surface but host an estimated 9.5% of all described animal species, including one third of vertebrates (Reid et al. 2019). A fundamental prerequisite for this rich and unique biodiversity is the dynamic nature of freshwaters, including fluctuations in water levels and spatial extent. Water-level fluctuations create and sustain habitats, enable succession processes and promote connectivity across multiple spatial and temporal scales, creating some of the most complex, dynamic and diverse ecosystems on Earth (Moayeri and Entezari 2008). At the extremes of these fluctuations, droughts and floods are essential and natural events in freshwaters (Woodward et al. 2016; Parasiewicz et al. 2019).

Natural freshwater ecosystems and their catchments retain more water for longer periods than degraded systems. This water retention capacity—that is, the total amount of water that a system can absorb—is a fundamental yet underappreciated ecosystem function. A high water retention capacity has two profound consequences that provide benefits to people: (1) flood peaks are delayed and reduced (Schüler 2006; Collentine and Futter 2018); and (2) droughts develop more slowly and may have lower peaks in magnitude (Carpenter, Stanley, and Vander Zanden 2011; Dehnhardt et al. 2015; Lal 2020), because retained water is stored in the landscape for longer. Freshwaters also perform essential ecosystem processes, including filtering and storing water, and decomposing organic matter (Carpenter, Stanley, and Vander Zanden 2011; Dehnhardt et al. 2015). Additionally, they offer vital ecosystem services that support human wellbeing, such as climate regulation, clean water provision, fish production, and recreational opportunities including fishing and swimming (Chiesura and De Groot 2003; Lynch et al. 2023).

Reflecting these benefits, humans have traditionally settled along rivers and lakes. Around these settlements, people have cleared forests, drained floodplains and peatlands, and channelized rivers to create arable land and urban areas (Chiu et al. 2017; Kumar and Jayakumar 2020; Vigiak et al. 2021), lowering the water retention capacity of entire catchments (Bronstert 2003; Harden 2006). A low retention capacity accelerates water transfer to downstream areas, increasing flood severity and causing earlier drying of soils and water bodies during droughts in upstream areas. Globally, an estimated 3.4 million km^2 of inland wetlands have been lost since 1700 (Fluet-Chouinard et al. 2023), and in Europe and North America up to 90% of floodplains are cultivated (Tockner and Stanford 2002), both significantly reducing natural water retention capacity. Climate change is exacerbating the risks posed by floods (Blöschl et al. 2020; Merz et al. 2021; Lehmkuhl et al. 2022; Thieken et al. 2021) and droughts (Crausbay et al. 2017; He and Sheffield 2020; Sadiqi et al. 2022; EEA 2024) by increasing their frequency, magnitude (Chiang, Mazdiyasni, and AghaKouchak 2021) and speed of onset (i.e., flash droughts; Walker and Van Loon 2023) and interactions among climatic extremes including droughts, heatwaves and floods (Mukherjee and Mishra 2021; Figure 1), ultimately affecting freshwater biodiversity and ecosystem services (Stubbington et al. 2024).

A reduced water retention capacity often has negative effects on ecosystems, people and human activities including agriculture and forestry. Since 2011, an estimated ~80%–90% of natural disasters have been caused by floods, droughts and severe storms (WHO 2024). Worldwide, > 1.8 billion people (23% of the population) are at risk of severe flooding (Rentschler, Salhab, and Jafino 2022), because human communities have established extensive settlements in high-risk flood zones (Rentschler et al. 2023). Minor or nuisance flooding, such as low levels of inundation of urban areas caused by localized rainfall, does not threaten public safety but disrupts daily activities and can damage property (Moftakhari et al. 2018). Although often overlooked in flood risk management, such floods account for a substantial fraction of total (economic) flood damage due to their high frequency (Moftakhari et al. 2017). Droughts directly affect > 55 million people per year globally and cause severe ecological and economic damage (Turbelin et al. 2023). An estimated 700 million people are at risk of being displaced by droughts by 2030 (WHO 2021, 2024), with disproportionate effects on those living in i.e. poverty and in areas exposed to greater climatic extremity (Winsemius et al. 2018). This is particularly true for the Global South, where major increases in flood frequency have been projected for Southeast Asia, Peninsular India, East Africa and the northern half of the Andes (Hirabayashi et al. 2013).

Nature-based solutions (NbS) are "actions to protect, sustainably manage, and restore natural or modified ecosystems [...] while benefiting human wellbeing and biodiversity" (Cohen-Shacham et al. 2016). Examples include restoring wetlands such as fens and floodplains, reducing the amount of stormwater runoff entering sewer systems (EEA, 2015), urban green spaces and riparian buffers. While a few NbS such as floodplain reconnection may reduce medium-sized floods, most NbS, such as pond creation and infiltration ditches, typically have limited capacity to reduce larger events (e.g., beyond a 20-year flood; Blöschl 2022). Such NbS have been used by indigenous communities worldwide for millennia (Cassin and Ochoa-Tocachi 2021) and are now incorporated into green infrastructure (Fang, Li, and Ma 2023). NbS and green infrastructure are increasingly recognized by governments worldwide (Debele et al. 2023) and are gaining prominence as part of strategies to enable climate change adaptation (Seddon et al. 2020). The long-established ecological benefits of NbS can mitigate floods and droughts as well as wider climate change impacts, enhance habitat

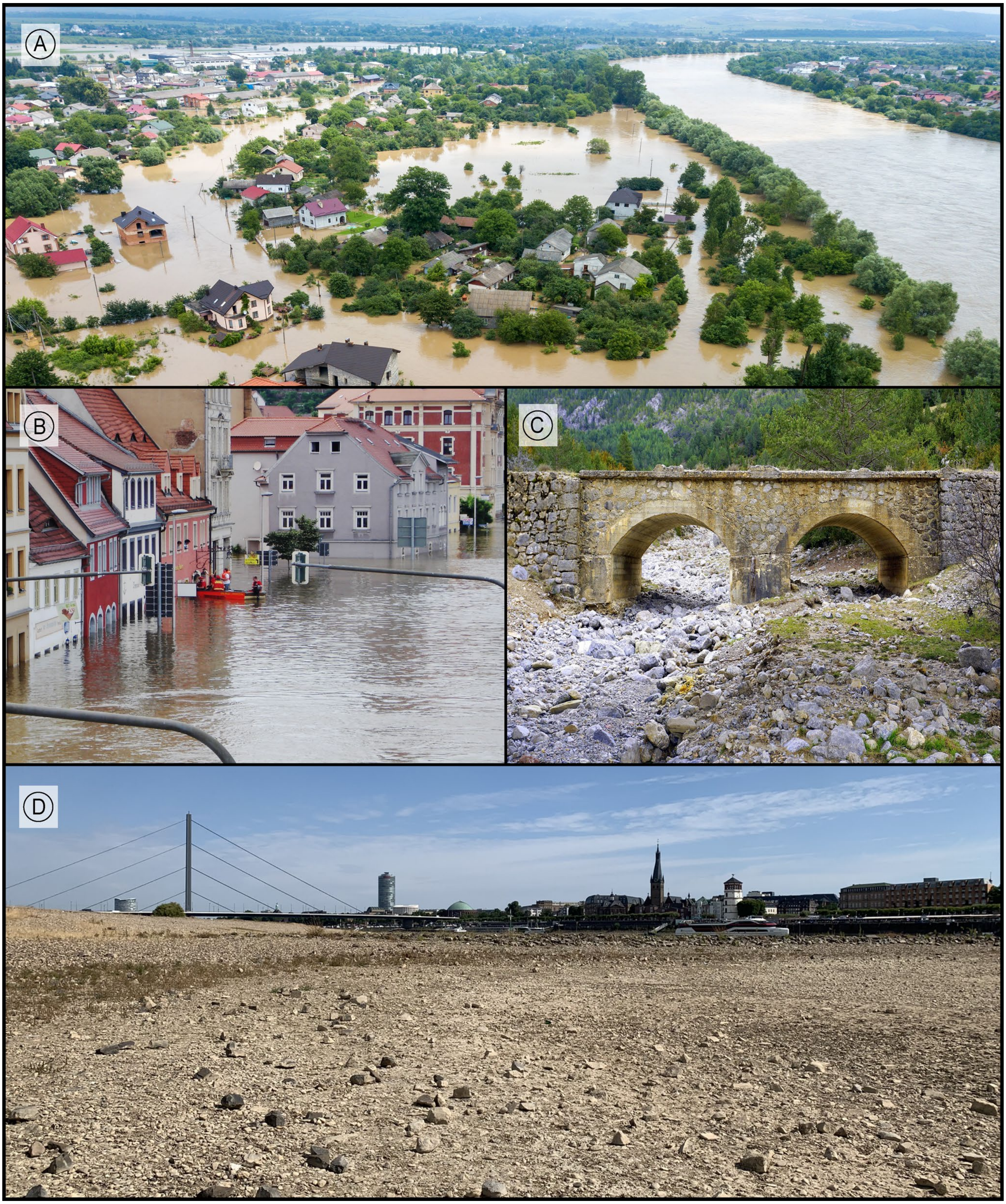

FIGURE 1 | Extreme flood and drought events: Flooding of the Dniester River in Halych, western Ukraine, in 2020 (A) and the Elbe River in Meißen, Germany, in 2013 (B); a dry streambed during drought (C); and the Rhine River in Cologne, Germany, during a drought in 2022 (D). Photos credit: *Pixabay*: Bilanol (A), Lucy Kaef (B), Josep Monter Martinez (C), and IWW/RWTH Aachen (D).

connectivity, support biodiversity (van Rees et al. 2021), meet protected area goals (Tickner et al. 2020; van Rees et al. 2023), increase environmental equity (Bremer et al. 2021) and contribute to ecosystem resilience (Benedict and McMahon 2012).

In contrast, conventional civil engineering methods (hereafter, *conventional methods*), including the construction of dikes and water retention basins, are designed to mitigate societal impacts of larger floods, such as those with of 50–100-year return periods (Scussolini et al. 2016; Kron and Müller 2019). However, the effects of conventional methods may be insufficient to offset the increasing flood risk associated with a growing human population, and associated urban and agricultural land use, rapid economic development and climate change (Murray and Ebi 2012; Hirabayashi et al. 2013; Seneviratne et al. 2021). Their limited effectiveness may result from being small-scale and/or for a single purpose such as flood prevention. For example, measures such as dikes accelerate catchment drainage, which may increase flood risk further downstream and lower groundwater levels upstream (Izakovičová, Miklós, and Miklósová 2018). The latter may exacerbate water scarcity, leading to conflicting interests between people living in upstream and downstream areas (Hartmann, Slavíková, and McCarthy 2019; Nelson, Bledsoe, and Shepherd 2020; McKay et al. 2023). In 2022, 2.2 billion people lacked safe drinking water (UNICEF and WHO 2023), and the growing demands of an increasing human population and economic sectors that require water to function effectively (e.g., agriculture and energy production; Shahanas and Sivakumar 2016; Irvine et al. 2020) will further exacerbate the water crisis.

We argue that fundamentally rethinking the integration of conventional and nature-based measures is necessary to effectively mitigate the effects of floods and droughts. Building on previous studies (e.g., Jakubínský et al. 2021; Potočki et al. 2022; van Rees et al. 2023), we suggest that integrated solutions are required to effectively increase a landscape's capacity to retain water. Key components include: (1) implementing biodiversity conservation actions (defined as those that seek to maintain or improve biodiversity, including restoration, protection and management; Langhammer et al. 2024) and managing agricultural, forested and urban land; (2) safeguarding ecosystems that strongly contribute to water retention, such as forests and wetlands, by substantially increasing the spatial extent of legally protected terrestrial and freshwater ecosystems (Schröter et al. 2023); (3) promoting natural and managed groundwater and aquifer recharge (Dillon and Arshad 2016; Salem et al. 2020) to retain water for longer periods and reduce surface evaporation (Salem et al. 2020); (4) using funding options such as the US Greenhouse Gas Reduction Fund (Callahan and DeShazo 2014), the European Green Deal (Fetting 2020) or the World Bank (Goodland 1987; Hickey and Pimm 2011); and (5) improving governance structures, which include local people, to overcome administrative and disciplinary barriers. Management of flood and drought risk should consider freshwaters as hybrid systems, by combining NbS with advanced conventional methods to convert conflicts between humans and ecosystems into mutual benefits (van Rees et al. 2019; Serra-Llobet et al. 2022; Chambers et al. 2023). In addition, flood and drought management measures should be designed to sustain biodiversity and promote ecosystem adaptation to climate change (van Rees et al. 2019, 2023), which requires an integrated approach that enables both people and nature to cope with increasing climatic extremes. Integrating these approaches within catchment-level plans that sufficiently reflect hydrological, ecological and social requirements could promote mitigation of flood and drought risk.

Drawing in particular from our European experience but also informed by international examples, we propose a new framework applied at the catchment scale, which combines existing tools with legislation, funding and governance structures to increase water retention capacity. This framework: (1) integrates conventional methods, NbS, and biodiversity conservation actions, each applied at the local scale but planned and evaluated at the river network and catchment scales; (2) combines various legislative and financial tools; (3) is based on an adapted governance structure; and (4) includes stakeholders from politics, economics, academia and civil society. Such a holistic catchment-scale framework is needed to effectively address current and potential future economic, ecological and societal threats posed by increasingly extreme climatic events including floods and droughts, thus benefiting both humans and ecosystems.

2 | Management of Flood and Drought Risks: From Conventional to Nature-Based to Hybrid Solutions

Conventional flood risk management is dominated by civil engineering approaches such as channelization, dam construction and water diversion, which frequently transfer risks to downstream areas (Triet et al. 2017; Mei et al. 2018; Volpi et al. 2018; Vorogushyn et al. 2018). Furthermore, flood defense is central to flood risk management strategies, but national flood defense strategies are often highly variable, both among and within countries as well as across continents (Gralepois et al. 2016; Kundzewicz et al. 2019; Löschner and Nordbeck 2020). Therefore, while recent discourses have strongly promoted integrated flood risk management approaches, practice lags behind vision (Pahl-Wostl et al. 2013; van Buuren et al. 2018; Raška et al. 2020; Löschner et al. 2021). Catchment-scale water retention capacity—including of floodwaters—strongly depends on land management practices (e.g., drainage, tillage, soil compaction, cultivation methods and planting catch crops) and their effects (Slavíková and Milman 2023). Flood-adapted land-use planning, as is required by the EU Floods Directive (Nones and Pescaroli 2016; Priest et al. 2016), provides an effective means to mitigate flood risk by designating high-risk zones in which certain land management practices are prohibited, and building and wider economic development are restricted (e.g., Godschalk, Kaiser, and Berke 1998; Kühlers et al. 2009; Barredo and Engelen 2010; Rogger et al. 2017; Löschner and Nordbeck 2020). However, population growth and economic pressures often limit the effectiveness of such planning, with conventional methods instead implemented as flood-risk-reduction measures, despite their potential negative effects. Moreover, people protected by conventional flood defenses tend to lose their flood-risk awareness, which may lead to disproportionately greater flood-related damage (Scolobig, De Marchi, and Borga 2012; Schumann 2017). In addition, although conventional methods can be essential in reducing negative impacts of floods (Poulard et al. 2010; Kron and Müller 2019), they—like other measures—may fail during extreme events that exceed previously agreed flood thresholds (Turkelboom et al. 2021).

Conventional methods may even increase surface runoff and reduce infiltration, lowering water retention capacity and thus intensifying drought risks (Ternell et al. 2020; Holden et al. 2022). Droughts affect quality of life (Feinstein et al. 2017), food production, drinking water quantity and quality, navigation, cooling of power plants, energy generation by hydropower plants during peak demand (Szalińska, Otop, and Tokarczyk 2018) and various socio-economic sectors (Wilhite and Glantz 1985; Altay and Ramirez 2010). Furthermore, conventional methods often reduce ecological complexity and dynamics, causing biodiversity loss and impairing ecosystem functions and services (Redford and Richter 1999; Bunn and Arthington 2002). In contrast, NbS that mitigate drought impacts include runoff attenuation features such as leaky barriers, which are designed to increase infiltration and subsurface water storage (Lashford et al. 2022), targeted floodwater harvesting and increased groundwater storage (Pavelic et al. 2012). Further measures designed to reduce surface evaporation, increase infiltration, promote subsurface water storage (Dillon and Arshad 2016; Salem et al. 2020) and replenish groundwater (Richts and Vrba 2016) include wetland restoration and creation, harvesting rainwater and collecting excess runoff.

Consequently, integration of conventional methods with NbS and targeted biodiversity conservation actions is increasingly required by national and international legislation (Rodrigues 2006; Caple 2010; Stanturf, Palik, and Dumroese 2014; Seddon et al. 2020). For example, US "Engineering with Nature" practices and urban stream projects in Australia both integrate nature-based and conventional methods to improve flood risk management and ecosystem health (Miller and Boulton 2005; King et al. 2022), and the sponge cities programme in China focuses on enhancing urban water management and resilience to extreme climatic events (Li et al. 2016). However, biodiversity conservation actions including ecosystem protection vary in extent and status, and many legally protected areas are either too small or insufficiently well-managed to effectively and sustainably support biodiversity and related ecosystem services (Chape et al. 2005; Hermoso et al. 2016). Furthermore, designation of protected areas has rarely considered the mitigation of flood and drought risks, although protected areas may have particularly high water retention capacity (Arianoutsou et al. 2012).

Restoration of rivers and their adjacent land, for example by reconnecting channels and their floodplains (exemplified by the Yolo Bypass floodplain reconnection in California, USA; Opperman et al. 2009), revegetating riparian zones and moving levees further from river channels (i.e., levee setbacks; van Rees et al. 2024), can reduce flow velocities, promote infiltration and increase water retention capacity (Jakubínský et al. 2021; Serra-Llobet et al. 2022; Thieme et al. 2023). Such restoration measures thus mitigate both flood and drought risks (Kalantari et al. 2018; Huang et al. 2020; Raška et al. 2022) as well as improving ecosystem health (Keesstra et al. 2018; Lafortezza et al. 2018). However, many river restoration projects are small-scale (Messner and Meyer 2006; Dee, Horii, and Thornhill 2014; Evans and Lamberti 2018), which limits their effects on floods and droughts, and such projects also often fail to enhance biodiversity (Newson and Large 2006; Haase et al. 2013; Poppe et al. 2016). Small-scale projects also typically ignore longitudinal connectivity between upstream and downstream river reaches, lateral links between riparian and terrestrial habitats, and vertical connectivity from surface water to groundwater (Cid et al. 2021).

In the context of flood and drought management, NbS aim to facilitate the infiltration and retention of water in the landscape, thus reducing flood peaks (Huang et al. 2020; Raška et al. 2022), low flows and stream drying (Ternell et al. 2020; Holden et al. 2022). In urban areas, NbS that promote natural water retention capacity can be employed alongside conventional methods. While most rainwater that falls onto urban infrastructure (e.g., buildings and streets) is conveyed via the sewage system into wastewater treatment plants (Corcoran et al. 2010), NbS including green spaces, greening of ditches (van Rees et al. 2023) and roofs, and features such as water retention basins can reduce runoff volumes following small and medium-sized precipitation events by $>50\%$, instead promoting infiltration (Li and Babcock Jr 2014) and thus recharging groundwater (Davis and Naumann 2017).

Additional efforts to increase water retention capacity are also needed in agricultural and forested areas. Agricultural land has a low water retention capacity, and irrigation systems require optimisation to reduce water loss through evaporation and surface runoff (e.g., Deng et al. 2006; Incrocci et al. 2020). Forests have a high water retention capacity; for example, restored areas with 70% forest cover may retain 50% more water compared to areas with only 10% cover (EEA 2015). Water storage capacity in diversified mixed forests is higher than in monoculture plantation forests or in pastures (Zhou et al. 2018; Kercheva et al. 2019; Pereira et al. 2022). While improved irrigation systems as well as natural forests are important globally, both are of particular relevance in the Global South, where water scarcity is greater (Deng et al. 2006).

3 | A Holistic, Catchment-Scale Framework Combining Conventional Methods, NbS, Biodiversity Conservation Actions and Legislation

A catchment-scale perspective is required to significantly increase the water retention capacity of landscapes by focusing on its most relevant components, that is, (1) the river network and its riparian zones, (2) floodplains, (3) urban areas, and (4) agricultural and forested areas. For each of these catchment components, the approaches outlined above can be combined to more effectively reduce flood and drought risks (Figure 2).

(1) Considering river networks and their riparian zones, restoration projects are commonly implemented to improve naturalness, for example by creating buffer strips (Cole, Stockan, and Helliwell 2020) and other runoff attenuation features (Lashford et al. 2022) that increase local water retention; and by reconnecting humans and rivers, for example by increasing access for local residents, to increase acceptance of restoration measures (Deffner and Haase 2018; Linton and Pahl-Wostl 2023). In the EU, the Water Framework Directive has been a major driver of river restoration, but only 40% of European surface water bodies achieve good or high ecological status or potential (Kristensen et al. 2018), while $>40\%$ of rivers are significantly affected by hydromorphological alterations (Kristensen, Solheim, and Austnes 2013). To address such ongoing impacts, the recently enacted EU Nature Restoration Law (https://environment.ec.europa.eu/topics/nature-and-biodiversity/nature-restoration-law_en) aims to restore at least 30% of the EU's land areas by 2030. To achieve this, the law (among others, such as the EU Habitats Directive and the Birds Directive) aims to restore at least 25,000 km of the total 1,649,489 km European river length,

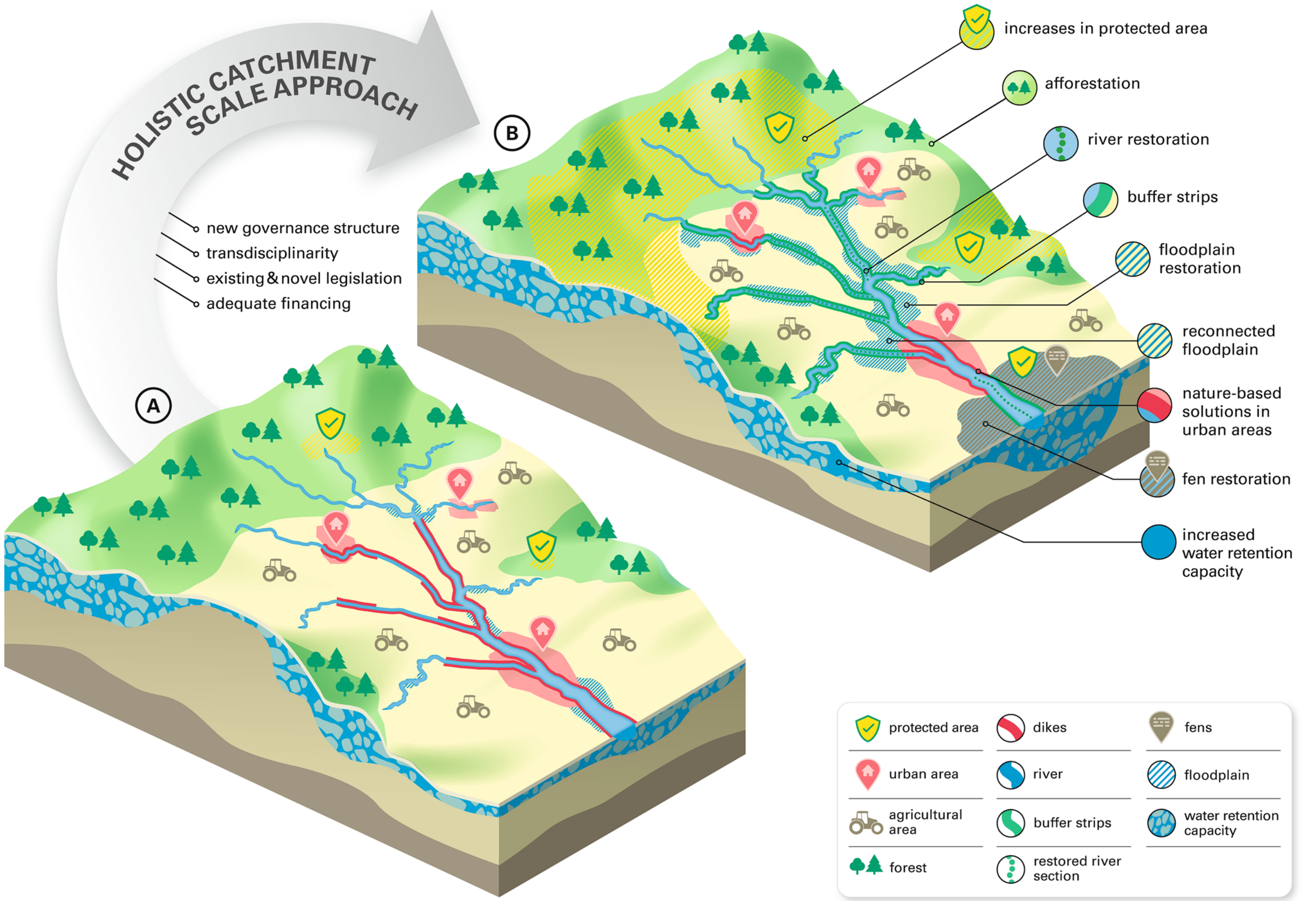

FIGURE 2 | An example of (A) the current situation and (B) a holistic catchment-scale framework that combines conventional civil engineering methods, nature-based solutions, and biodiversity conservation actions to improve water retention capacity, supported by legislation, funding and a new governance structure.

entailing large-scale improvement and re-establishment of biodiverse habitats, and including increases in green space and river connectivity, the latter via barrier removal (Belletti et al. 2020). While this ambitious new law provides important opportunities for the restoration and safeguarding of European rivers, its implementation faces several challenges (Stoffers et al. 2024) and the extent to which related actions will increase water retention capacity remains to be seen.

(2) Floodplains have particularly high conservation value (Cvijanović 2022) and provide more services than most other ecosystems (Jakubínský et al. 2021), in particular due to their high water retention capacity. However, comprehensive restoration measures have not been widely applied in floodplains, limiting their considerable potential to enhance flood and drought risk mitigation. Removal of levees and historic drainage channels, raising riverbeds and thus groundwater levels, and enhancement of hydromorphological naturalness are common floodplain restoration measures (Rohde, Hostmann, and Peter 2006; Stoffers et al. 2024; Stoltefaut et al. 2024). In addition, invasive non-native trees and deep-rooted tall forbs can be cleared to promote groundwater recharge (Stromberg et al. 2007; Holden et al. 2022).

(3) In urban areas, the management of flood and drought risk is restricted in scope and spatial extent (Oswald et al. 2023). Direct urban flood damage can be significantly reduced by conventional methods such as dikes and dams, but at the expense of ecosystem health. Thus, a comprehensive approach to urban planning and development should combine blue (water-related), green (vegetation-based), and gray (human-made) infrastructure—including NbS such as green spaces or bioswales, which increase floodwater infiltration and simultaneously reduce debris and pollutants—to create more sustainable, resilient and liveable towns and cities (Frantzeskaki 2019). Ultimately, restricting construction of new buildings and infrastructure in floodplains combined with innovative flood protection measures could reduce risks to life and property (Hertin et al. 2003).

(4) The remaining catchment typically covers the largest area, providing extensive opportunities to implement targeted measures designed to increase water retention capacity, particularly in managed landscapes such as agricultural areas and forest plantations. For example, water infiltration rates are twice as high and overland flow is lower in native or fully restored forests compared to disturbed or managed forest plantations (Meli et al. 2024). The Kunming-Montreal Global Biodiversity Framework aims to support global biodiversity recovery by reversing ecosystem degradation and by increasing protected areas up to 30% by 2030 (Joly 2022; Hughes and Grumbine 2023). Designating additional protected areas to achieve this goal may provide new opportunities to implement flood and drought mitigation measures that

both increase water retention capacity and promote biodiversity conservation.

4 | A Holistic Framework Requires New Governance Structures and Broader Funding

Current governance structures pose significant challenges to catchment-scale initiatives. Typically, responsibilities are fragmented and distributed among local, regional and national authorities without effective vertical coordination. Furthermore, activities are poorly coordinated across sectors such as water, forestry, nature protection and agriculture, and the performance of policy coordination for the mitigation of flood and drought risks is rarely evaluated (Löschner and Nordbeck 2020). Therefore, establishment of new governance structures should focus on systemic goals and tasks and the integration of multiple landscape functions rather than sectoral objectives (1, Box 1). However, the political, cultural and socioeconomic context—including existing legislative frameworks, cultural norms, social inequalities and power dynamics—strongly influence the workability and success of governance structures. In this regard, our approach may require country-specific adaptation to reflect national conditions as well as general differences between the Global North and Global South. Innovative governance structures should be established to develop catchment-scale master plans that guide management of entire landscapes. Such initiatives require the active involvement, coordination and cooperation of a broad range of stakeholder groups including environment agencies, water management authorities, sectoral ministries (e.g., agriculture, energy), local urban planning departments and task-specific coordination bodies (Vollmer et al. 2018, 2021; Bezerra et al. 2021; Farwig et al. 2024). Local communities play a crucial role both in developing a vision for future ecosystems and in implementing measures to achieve this vision. Citizens can be involved through standardized participatory processes such as public consultations, local advisory panels and community-led monitoring initiatives, tailored to the social and cultural context. Such processes can be implemented via funded projects that promote consistent engagement of local communities including indigenous people and integration of their voices and needs into planned actions.

All stakeholder groups should be involved at a strategic level from an early stage, to promote identification and resolution of potential conflicts and synergies within a collaborative process that fosters trust and innovation and avoids polarized debates. This could be achieved by establishing regional topic centers based on catchment boundaries, to bring together all stakeholders (2, Box 1). In particular, landowner involvement is crucial, because these stakeholders often need to either change land-use practices or sell their land to enable implementation of measures that increase water retention capacity. To ensure implemented measures are both locally applicable and underpinned by robust scientific evidence, engaged research approaches—which incorporate stakeholder input throughout a project—could be implemented by involving researchers in on-the-ground projects, fostering partnerships between academic institutions, authorities and local communities, and emphasizing the co-generation of knowledge. Accordingly, involvement of universities and research institutions could increase both cooperation among discipline-specific experts and systemic thinking across disciplines, institutions and geographic regions. Finally, regional topic centers should engage stakeholders in continuous dialog and transparent decision-making processes, to enhance decision-making quality, accountability, ownership and commitment among all parties (Vollmer et al. 2018, 2021).

BOX 1 | Key Recommendations for Stakeholders and Policymakers.

1. **Establish new governance structures** with coordination bodies and regional topic centers, fostering multi-stakeholder collaboration.
2. **Define catchment-scale operational planning units** in consultation with all stakeholders, to promote cooperation and a focus on systemic goals and holistic management.
3. **Develop catchment-scale management plans** informed by all relevant available information, including on flood and drought risks and measures already applied.
4. **Combine and implement conventional methods, NbS and biodiversity conservation actions** at local, river network and catchment scales, supported by adequate planning and evaluation.
5. **Integrate blue, green and gray infrastructure** in urban planning, including restriction of floodplain construction and use of innovative flood protection measures.
6. **Enhance water retention, infiltration, groundwater recharge and storage** through afforestation, improved management of agricultural, forested and urban land, wetland restoration and floodplain reconnection.
7. **Expand legally protected areas**, including forests and wetlands, to safeguard key ecosystems and to enhance their water retention capacity.
8. **Design actions that promote co-benefits** of mitigation measures, including biodiversity gain, climate adaptation, carbon sequestration, water resource management and water quality improvement.
9. **Leverage funding options** such as the European Green Deal or World Bank funds, including the creation of incentives for water-conscious farming and near-natural land uses.
10. **Use legislation** such as the Kunming-Montreal Global Biodiversity Framework and the EU Nature Restoration Law to motivate actions that increase water retention capacity.
11. **Acknowledge limitations** of any measures in extreme events and enhance disaster preparedness and management strategies to mitigate their impacts.

The Kunming-Montreal Global Biodiversity Framework aims to double global biodiversity funding to at least US$200 billion per year by 2030 (Streck 2023). In the EU, the EU Biodiversity Strategy for 2030 requires annual funding of €48 billion, covering various aspects including nature restoration (€6–8 billion), the Natura 2000 protected areas network and green infrastructure (€11.8 billion; Nesbit et al. 2022). In the USA, the Green New Deal framework seeks to tackle climate change and economic inequality through public policy initiatives, including measures to reduce flood and drought risks by promoting sustainable land use and green infrastructure (Galvin and Healy 2020). The related Greenhouse Gas Reduction Fund has allocated US$27 billion to support, among others, climate projects, and to ensure that underserved communities benefit from climate action initiatives (US EPA 2024). Similarly, the Australian Technology Investment Roadmap drives climate action and innovation, with a total commitment of AUD$20 billion until 2030 to support low-emission technologies, including clean hydrogen, carbon capture and storage, energy storage and soil carbon measures. These measures are designed to mitigate climate change effects and thus flood and drought risks (Srinivasan et al. 2021; Debele et al. 2023). Furthermore, leveraging World Bank funds could provide substantial support for the proposed holistic framework, through loans, grants and technical assistance designed to enhance sustainable development and biodiversity conservation initiatives globally (Hickey and Pimm 2011; Wade 2021) (9, Box 1).

Although global public investment (i.e., allocation of financial resources by governments) in biodiversity has steadily increased in relation to national GDP (Seidl et al. 2020), only 1% and 5% of invested funds are allocated to initiatives focusing on risk mitigation and management (which includes NbS) and addressing climate impacts, respectively (UN Environment 2019). These capital investments (including economic instruments and funding for biodiversity; OECD 2018) have proven insufficient for global achievement of the Aichi Biodiversity Targets (Berghöfer et al. 2017), thus creating conflicts among stakeholders (Zhang et al. 2012; Brink et al. 2016; Dale et al. 2019). In addition, financing for NbS and biodiversity conservation actions remains highly variable and insufficient due to restrictive monetary policies worldwide (e.g., European Investment Bank 2023; IEEP 2023).

In contrast, the EU allocates approximately 36% of its budget (€58.4 billion per year as of 2019; Pe'er et al. 2020) to its Common Agricultural Policy (CAP; Schmedtmann and Campagnolo 2015). Member states are required to invest at least 25% of their CAP funds in 'eco-schemes' that emphasize environmental, climate or animal welfare considerations, and to dedicate at least 35% of rural development spending to such schemes (Nesbit et al. 2022). However, the CAP and its eco-schemes and agri-environmental measures rarely address water retention capacity, limiting flood and drought mitigation (Gorton, Hubbard, and Hubbard 2009; Heyl et al. 2021). Linking payments to water-conscious farming could provide additional funds and incentives for coordination that improves the effectiveness of individual measures. Further funding resources are established through the European Green Deal, a set of policy initiatives which aim to make the EU climate neutral by 2050 and provide access to ~€1 trillion of associated capital. Such new funding mechanisms could support measures such as afforestation, which increases both carbon storage and catchment-scale water retention capacity.

In addition, incentives for landowners to change land-use practices or to sell their land are needed. Investment by insurance companies (i.e., through 'flood and drought credits' similar to 'carbon credits'), reinsurance companies (i.e., by reducing premiums) and private investors, and investments in near-natural and/or risk-minimizing land uses, are also needed to complement other financial tools (Slavíková, Hartmann, and Thaler 2020).

5 | Exploiting Co-Benefits and New Opportunities

Our proposed holistic catchment-scale framework (Table 1) offers various co-benefits beyond flood and drought mitigation. For example, damage to infrastructure will decline, and water availability for ecosystems, agriculture, industry and domestic use will increase, promoting long-term sustainable water use (Botzen et al. 2017). Certain nature-based flood and drought mitigation measures could also act as 'natural climate solutions' that promote wider climate change adaptation, for example large-scale creation of green spaces and wetland restoration (Schulte et al. 2022). Actions to restore riparian vegetation could promote urban cooling (Emilsson and Sang 2017; Ellis et al. 2024) and moderate water temperature increases in small to medium-sized streams (Rutherford et al. 1997; Davies-Colley et al. 2009; Johnson et al. 2024). The US Engineering with Nature initiative provides further examples of NbS related co-benefits, highlighting successful past practices, advancing current and future capabilities, and showcasing a range of positive outcomes (Bridges et al. 2018). Furthermore, measures including afforestation and urban greening function as substantial carbon sinks (Hall et al. 2015; Wohl et al. 2017), which could support progress towards net-zero carbon emission targets while also improving water quality by retaining sediment and reducing pollutant-laden runoff (Kayranli et al. 2010; O'Geen et al. 2010; Hall 2024). As another example of co-benefits, combined (municipal wastewater and stormwater) sewer overflow systems are a major source of chemical pollution in rivers, especially during heavy rainfall and flood events, which could be mitigated by constructed wetlands that intercept dissolved and particle-bound pollutants (Pistocchi et al. 2019; Rizzo et al. 2020). Afforestation and wider restoration of riparian zones concomitantly mitigate air pollution, offer recreational opportunities and benefit ecosystem health (van den Bosch and Sang 2017). Finally, human wellbeing can be enhanced through NbS and biodiversity conservation actions, thereby leveraging ecosystem services (Seddon et al. 2020).

6 | Challenges, Conclusions and Outlook

We argue that combining conventional methods, NbS and biodiversity conservation actions at the catchment scale can reduce the impacts of flood and drought events while benefiting biodiversity, ecosystem health and human wellbeing. However, even the most effective risk management cannot eliminate the impacts of exceptional—and unprecedented—flood and drought events that exceed the designed levels of the measures taken (e.g., floods with a > 100-year return period; Kreibich et al. 2022). Enhanced preparedness and disaster management could support adaptation to exceptional events that overwhelm integrated combinations of measures, such as those proposed in our holistic framework. Moreover, some elements of our framework may

TABLE 1 | Key aspects of the holistic catchment-scale framework to guide flood and drought mitigation.

Challenge		
Human population expansion and climate change have increased flood and drought risks. Conventional civil engineering methods focus on local targets, neglecting catchment-scale connectivity.		
Solution		
A combination of measures, legislation and financial resources implemented at the catchment scale could increase infiltration and water retention capacity.		
Measures	Conventional methods	Dams, channelization and local defenses are intended to reduce flood damage in urban and agricultural areas, but often increase drought risks and cause ecological losses.
	Nature-based solutions (NbS)	NbS help to improve ecosystems and biodiversity, but effectively mitigate only lower-magnitude floods and droughts.
	Biodiversity conservation actions	Measures including floodplain and wider habitat restoration and improving river and river–landscape connectivity enhance biodiversity and mitigate floods and droughts.
Legislation		Legislation including the Kunming-Montreal Global Biodiversity Framework and the European Nature Restoration Law could motivate actions that increase water retention capacity.
Financial resources		The US Green New Deal, Australia's Technology Investment Roadmap and the EU Common Agricultural Policy are among the potential funding sources but are insufficient for flood and drought mitigation.
Synthesis		
Co-benefits		Our framework benefits biodiversity, the economy, human wellbeing, climate change mitigation, carbon sequestration, air quality, recreation and ecosystem health.
Requirements		New governance structures focusing on systemic goals and tasks and involving multiple stakeholders, regional topic centers and political will are required.
Challenges and limitations		Our framework will not eliminate impacts of extreme events (e.g., floods with a > 100-year return period) but reduces their frequency and magnitude; improved societal disaster preparedness is also needed.

lack tangible implementation options. For example, although there is an increasing consensus among academic and practitioner scientists on the measures that enhance water retention capacity, this consensus can be lost when people are personally affected, such as when reconnecting rivers to their floodplains reduces flooding of downstream settlements but prevents intensive agricultural land use and thus affects farmers' income. Even when landowners are consulted from the planning stage and their incomes are unaffected, they may not agree to change land-use practices or to sell their land. Sufficient scientific evidence is available to support practice, and implementation is first and foremost a governance challenge—one which can be addressed through political will and leadership.

Author Contributions

Phillip J. Haubrock: conceptualization (equal), visualization (equal), writing – original draft (equal), writing – review and editing (equal). **Rachel Stubbington:** writing – original draft (equal), writing – review and editing (equal). **Nicola Fohrer:** writing – review and editing (supporting). **Henner Hollert:** writing – review and editing (supporting). **Sonja C. Jähnig:** conceptualization (supporting), writing – original draft (supporting), writing – review and editing (supporting). **Bruno Merz:** writing – original draft (supporting), writing – review and editing (supporting). **Claudia Pahl-Wostl:** writing – original draft (supporting), writing – review and editing (supporting). **Holger Schüttrumpf:** writing – original draft (supporting), writing – review and editing (supporting). **Doerthe Tetzlaff:** writing – original draft (supporting), writing – review and editing (supporting). **Karsten Wesche:** writing – original draft (supporting), writing – review and editing (supporting). **Klement Tockner:** conceptualization (supporting), funding acquisition (lead), writing – original draft (supporting), writing – review and editing (supporting). **Peter Haase:** conceptualization (equal), supervision (lead), visualization (equal), writing – original draft (equal), writing – review and editing (equal).

Conflicts of Interest

Sonja Jähnig is a senior editor at WIREs Water but was not involved in any of the editorial steps related to the manuscript. The other authors have no conflicts of interest to declare.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Related WIREs Articles

Challenges in modeling and predicting floods and droughts: A review.

Exploring drought-to-flood interactions and dynamics: A global case review.

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