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SYSTEMATIC REVIEW

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The role of rewilding in mitigating hydrological extremes: State of the evidence

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Abstract

Landscape rewilding has the potential to help mitigate hydrological extremes by allowing natural processes to function. Our systematic review assessed the evidence base for rewilding-driven mitigation of high and low flows. The review uncovers a lack of research directly addressing rewilding, but highlights research in analogue contexts which can, with caution, indicate the nature of change. There is a lack of before-after studies that enable deeper examination of temporal trajectories and legacy effects, and a lack of research on the scrub and shrubland habitats common in rewilding projects. Over twice as much evidence is available for high flows compared to low flows, and fewer than one third of studies address high and low flows simultaneously, limiting our understanding of co-benefits and contrasting effects. Flow magnitude variables are better represented within the literature than flow timing variables, and there is greater emphasis on modeling for high flows, and on direct measurement for low flows. Most high flow studies report a mitigating effect, but with variability in the magnitude of effect, and some exceptions. The nature of change for low flows is more complex and suggests a higher potential for increased low flow risks associated with certain trajectories but is based on a very narrow evidence base. We recommend that future research aims to: capture effects on both high and low flow extremes for a given type of change; analyze both magnitude and timing characteristics of flow extremes; and examine temporal trajectories (before and after data) ideally using a full before-after-control-impact design.

This article is categorized under:
Human Water > Value of Water
Science of Water > Hydrological Processes
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KEYWORDS

drought, flood risk, nature-based solutions, rewilding

1 | INTRODUCTION

Anthropogenic modifications to the water cycle have exacerbated the economic impacts of hydrological extremes such as floods and droughts. The economic costs of flooding and managing flood hazard globally are vast. In the United Kingdom alone, flooding losses amounted to £333 million from the winter 2019/2020 floods and in England £5.2 billion spending has been allocated to flood and coastal risk management between 2021 and 2027 (Environment Agency, 2020). Extreme low flows can also be economically, as well as ecologically costly (van Loon et al., 2016). Hydrological extremes and damages arising from them are projected to increase substantially with climate change (Kundzewicz et al., 2014) and there is a pressing need to use Nature-based Solutions (NbS) to reduce the impacts of extreme weather on the environment and people (IUCN, 2020). Water resource management is increasingly emphasizing the importance of working with natural ecosystem processes through NbS to create resilient ecosystems that deliver multiple environmental, social, and economic benefits (WWAP, 2018). Prevailing approaches to working with natural processes to mitigate high and low flows, such as Nature-based or Natural Flood Management (NFM; Lane, 2017; Dadson et al., 2017; Bridges et al., 2021) are directly focused on hydrological change and emphasize strategic placement of features in the landscape (e.g., tree planting, ponds, and wetlands, instream wood as "leaky barriers") to optimize attenuation effects. Alongside these hydrologically focused approaches, landscape rewilding is rapidly gaining popularity and driving biodiversity gains (Pereira & Navarro, 2015; Rewilding Britain, 2023), but many of the wider ecosystem service benefits or disbenefits remain unquantified.

Rewilding involves restoring wildness to anthropogenically altered landscapes, often including the reintroduction of missing species (Perino et al., 2019). There is overlap and complementarity between definitions of "rewilding" and "restoration" (Pettorelli & Bullock, 2023), and some debate around definition and utility of the term rewilding (Hayward et al., 2019). Rewilding, however, is generally defined as being more hands-off, minimizing sustained intervention, and emphasizing reinstatement of natural processes while de-emphasizing a return toward a past ecosystem (Corlett, 2016). It is also often, but not exclusively, large-scale (Lawton, 2011). Rewilding has been advocated as a vital tool in reversing global biodiversity decline (Svenning et al., 2016) and dramatic, diverse, and large-scale biodiversity gains have been achieved over relatively short timeframes (Pereira & Navarro, 2015). Types of biodiversity change include natural regeneration of grassland, woodland, and scrubland (Beguería et al., 2003; Tree, 2017), increased soil fauna biodiversity (Andriuzzi & Wall, 2018), and the reintroduction of large herbivores (e.g., cattle, deer, pigs; Tree, 2017; Balfour et al., 2021) and large carnivores (e.g., lynx, wolves) with associated trophic cascade effects (Beschta & Ripple, 2015; Law et al., 2016). Many reintroduced or recolonizing species are effective "ecosystem engineers" (e.g., beavers) capable of modifying resource flows, altering ecosystem functioning, and increasing restoration success (Bailey et al., 2019; Jones et al., 1994).

Importantly, the fundamental principles that underpin rewilding offer potential for much wider-ranging benefits to natural capital assets and ecosystem services but many of these remain largely unexplored and unquantified. Rewilding, by nature and scale, will alter key elements of the water cycle (see Harvey & Henshaw, 2023 for overview and preliminary conceptual model). For example, wilder terrestrial landscapes characterized by removal of or reductions in land management (e.g., Tree, 2018), natural vegetation regeneration (Cerdà et al., 2019), and, sometimes, species reintroductions (large grazing and browsing herbivores; Vermeulen & Nature, 2015, beaver; Brazier et al., 2021, and potentially apex predators such as wolves and lynx; Beschta & Ripple, 2015; Mysterud & Ostbye, 2004) can be expected to drive changes in infiltration rates, soil water storage, overland flow, interception, and evapotranspiration (Harvey & Henshaw, 2023). Wilder river systems, achieved through reduced management, terrestrial landcover change, and/or river restoration approaches (e.g., Cluer & Thorne, 2014), sometimes in conjunction with removal of flow regulation structures (Rideout et al., 2021) can also be expected to increase instream and floodplain roughness (Thomas & Nisbet, 2006), alter floodplain inundation and storage (Addy & Wilkinson, 2019) and conveyance of water through the river network (Harvey & Henshaw, 2023). This generates potential for flood attenuation and low flow alleviation effects, but a full understanding of the nature and magnitude of these effects, and any benefits and/or risks, is lacking. Future support for rewilding projects depends on being able to describe and quantify the range of public benefits that can be delivered, including changes to hydrological extremes.

The motivation for this review of the evidence base arose from our identification of a developing knowledge gap between assumed hydrological benefits of rewilding and the availability of evidence from hydrological monitoring and modeling at active rewilding sites. In this paper, we use a systematic review to (i) assess the state of the existing evidence on rewilding-driven changes to hydrological processes and hydrological extremes (floods and low flows) and (ii) identify key knowledge gaps and priorities for future hydrological research on rewilding, with a focus on temperate zone environments.

2 | LITERATURE REVIEW

A systematic review was conducted following the established Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Page et al., 2021). This involved identification of published studies from databases (Web of Knowledge, Scopus) and from key review texts using pre-defined search terms (see Supporting Information 1). Papers were screened for relevance to the topic and full text retrieved for relevant articles. Full text articles were assessed for eligibility (see Supporting Information 1) and data extracted from retained sources. The review included studies published up to February 2022. We hypothesized a lack of research specific to nature recovery and rewilding approaches, and therefore also included relevant analogue environments in our eligibility criteria, specifically natural systems, and landscape recovery trajectories such as regenerative agriculture or sustainable land management. The relevant studies were identified based on the following inclusion criteria: (1) focus on freshwater or terrestrial environments within biomes relevant to temperate zones, but not exclusively from the UK; (2) study conducted within rewilding, natural system, or other land management contexts relevant to a rewilding trajectory (see Supporting Information 1); (3) addresses hydrological processes; (4) refers to mitigation of hydrological extremes (floods and/or low flows). In total our searches identified 291 relevant studies, comprising 133 review or opinion pieces and 158 empirical studies. The discussion in this paper focuses on the 158 empirical studies. Inevitably, our systematic review will not capture all relevant papers on this topic, but we sought to achieve a representative sample of literature by employing combinations of rewilding-relevant terminology and hydrological process-based terminology in our search strings (see Supporting Information 1).

Biomes and ecosystem functional groups captured in each study were classified according to IUCN categories (Keith et al., 2020). Studies were also categorized as to whether the title and/or abstract contained key environmental context terms relevant to rewilding and nature recovery (land abandonment, restoration, natural flood management, nature-based solutions, beaver). Locational data for study sites were extracted, including geographic coordinates where possible. For the UK, study locations from the published literature were also compared to the geographic location of rewilding sites in rewilding Britain's rewilding network at the time the review was conducted (Rewilding Britain, 2023).

We identified whether studies examined effects on high or flood flows, low flows, or both. Studies were also classified according to research design: Before-After-Control-Impact pairs (BACI); Before-After (BA); Control-Impact (CI) including paired catchment studies; and Other (i.e., non-comparative studies). For BACI studies, we classified the flow variables used to assess effects on hydrological extremes into four groups according to whether they addressed high flow magnitude (peak discharge or outflow variables, Q_{10}, Q_5, Q_1), high flow timing (lag or transit time, time to peak, exceedance time, return period, flood duration), low flow magnitude (5 year 7 day low flow, annual 7 day mean/min, baseflow/low flow, min daily Q, Q_{355}, Q_{90}, Q_{95}, Q_{99}) or low flow timing (no flow days, low flow pulse duration). Full descriptions of the variables are provided in Supporting Information 1. We also produced a qualitative classification of evidence types and assigned categories to each article based on (i) the nature of evidence provided for alterations to causal hydrological processes; and (ii) the nature of evidence for a mitigating effect on high or low flows (measured, modeled, or inferred in each case). We categorized overall outcomes of the high flow papers according to whether they had an attenuating effect on high flows or increased them (or reported no/negligible change), and whether this effect was identified as variable in magnitude. Increases in lag time, or reductions in peak flow magnitude would represent an attenuating effect, while the opposite effects represent an increase in high flows. We took the same approach for low flow papers, identifying whether the trajectory of landscape change was associated with increased water levels under low flow conditions and/or shorter durations of low flow periods (i.e., potential for reduced low flow stress) or the reverse which would indicate potential for increased low flow stress. A small proportion of papers contained one or more trajectories that represent the "reverse" of a rewilding process (19 papers; 30 cases), for example, change from natural forest to grazed grassland, meaning that we classified the outcome as the reverse of what was reported in the paper, to reflect what would be relevant to rewilding-driven change (i.e., increase in woody vegetation in this case). Our discussion below acknowledges that legacy effects may influence the nature of these relationships.

3 | AVAILABILITY OF EVIDENCE FROM REWILDING AND ANALOGUE SYSTEMS

In total, 158 papers were retained based on our inclusion criteria. Many of these included more than one field site or change trajectory relevant to rewilding, yielding 326 data records for different environmental contexts and trajectories. None of the retrieved papers on hydrological extremes referred directly to rewilding in the title or abstract, reflecting a significant lack of targeted research on the hydrological outcomes of landscape rewilding. This might partially reflect time lags in terminology changes ("rewild" entered the Oxford English Dictionary in 2010 and "rewilding" was one of Collins Dictionary's "top ten words of 2019") and in publication of longer-term monitoring research. Our process-based search strings (see Supplementary Material 1), however, were designed to capture relevant studies using different but related terminology (e.g., restoration, land abandonment, nature-based solutions) or comparisons of semi-natural versus degraded systems. Just under a third of papers (29%; 46 papers) referred to one or more related environmental context terms in the title or abstract: restoration (26 papers), natural flood management (15), nature-based solutions (10), beaver (12), and land abandonment (4). The remainder and majority (71%) of papers are drawn from a range of intensive land use settings such as croplands, pasture, and plantation forestry, as well as semi-natural forest, shrubland, and freshwater settings (Figure 1). Existing evidence is therefore primarily drawn from analogue landcover settings rather than studies directly addressing rewilding and nature recovery. While these settings are helpful in indicating expected trajectories of change, they may also have some important distinctions from rewilding-driven landcover changes. A small number of our retained studies (5) involved before/after comparisons where the "before" scenario was a natural or semi-natural system and the "after" a degraded state. Given the low numbers of studies overall, we retained these but using such comparisons to indicate change in the reverse direction can be problematic since legacy effects in degraded landscapes may alter the recovery time and trajectory (see Section 5.1).

The most commonly occurring ecosystem functional groups were pastures, fields, and croplands within the intensive land use biome, and montane and deciduous forests and woodlands. In contrast, shrublands occurred less frequently within the data set. This lack of research on shrubland environments represents an important knowledge gap since lowland rewilding and land abandonment trajectories commonly report successional stages in shrubland vegetation and scrub-woodland mosaics through natural vegetation regeneration (e.g., Garcia-Ruiz et al., 2010; Tree, 2017; Broughton et al., 2021; Vicente-Serrano et al., 2021). These vegetation types are spatially complex and temporally dynamic and are likely to characterize future nature recovery projects in temperate environments, but our findings highlight a limited evidence base for understanding associated hydrological change.

We synthesized the principal trajectories of landscape change among the retained papers into 18 subcategories within five broad categories of: reduced agricultural intensity, increasing woody vegetation cover, river and wetland restoration, NFM measures, and plantation forestry. Figure 2 summarizes the main landscape change trajectories identified within the papers. Overall, trajectories of change in terrestrial environments are approximately twice as common within the literature than trajectories focused directly on changes in river and wetland systems. The most common rewilding-relevant change trajectory was the increase in woody vegetation cover which includes changes in forest structure such as species, maturity, and management (e.g., Robinson et al., 2003; Belmar et al., 2018) as well as cover (e.g., Buechel et al., 2022). Hydrological response to different levels of agricultural intensity (e.g., Berdeni et al., 2021; Bond et al., 2021; Cerdà et al., 2021) and the hydrological functioning and restoration of rivers and wetlands (e.g., Clilverd et al., 2013; Dixon et al., 2016; Quin & Destouni, 2018) were also relatively common in our retained papers, and the hydrological outcomes of more recent and innovative approaches to river restoration such as "stage zero" (Cluer & Thorne, 2014) are likely to represent future contributions to the evidence base. Removal of flow

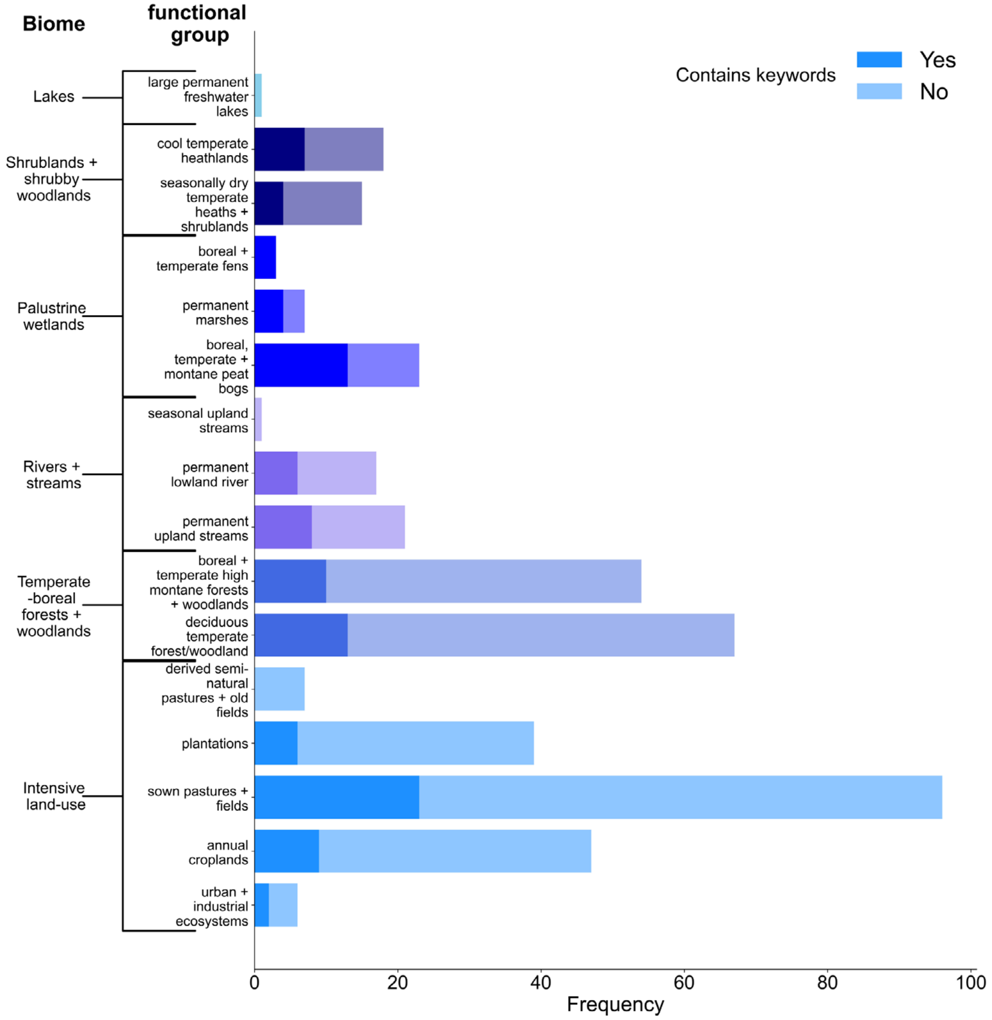


FIGURE 1 Ecosystem functional groups that characterize published studies, distinguishing between studies that contained nature recovery related keywords (land abandonment, restoration, nature-based solutions, natural flood management, beaver) in the title and abstract in darker shading. Note that multiple functional groups can be associated with the same study, and all are shown here together with the respective biomes.

regulation structures was beyond the scope of our systematic review searches but may represent an important precursor to rewilding actions in many freshwater systems (Rideout et al., 2021). NFM measures were fewer and supplied by 10 papers. We retained a small number of papers that included trajectories associated with plantation forestry but note that hydrological response may differ significantly in comparison to natural forest (e.g., Fahey & Jackson, 1997; Hawtree et al., 2015). Some papers contained multiple trajectories, for example, Smith et al. (2020) examine hydrological response to the interaction of river and wetland restoration and beaver recolonization and Dixon et al. (2016) combine the effects of instream large wood and riparian forest cover. Several papers contributed large numbers of trajectory records, for example, flow attenuation by beaver dams across multiple sites (Puttock et al., 2021), extensive multi-catchment analysis of the hydrological impact of afforestation (Buechel et al., 2022) or agricultural intensity (Ries et al., 2020) or changes in forest characteristics (Brogna et al., 2017; Belmar et al., 2018) and meta-analysis of NFM projects (Iacob et al., 2014).

Our searches did not return references exploring the role of large animals such as bison, hippopotamus, and elephants which can also alter riparian ecosystems and flood regimes and contribute to climate change mitigation (Malhi et al., 2022). Such animals can have ecosystem engineering effects that alter hydrological processes, for example, hippopotamus-created drainage networks in wetlands (Deocampo, 2002; McCarthy et al., 1998), and are globally threatened (Ripple et al., 2015). Relative to long-term (e.g., Pleistocene) norms, contemporary ecosystems are simplified and depleted in megafauna in most ecosystems outside Africa (Fløjgaard et al., 2022). The influence of large terrestrial wild

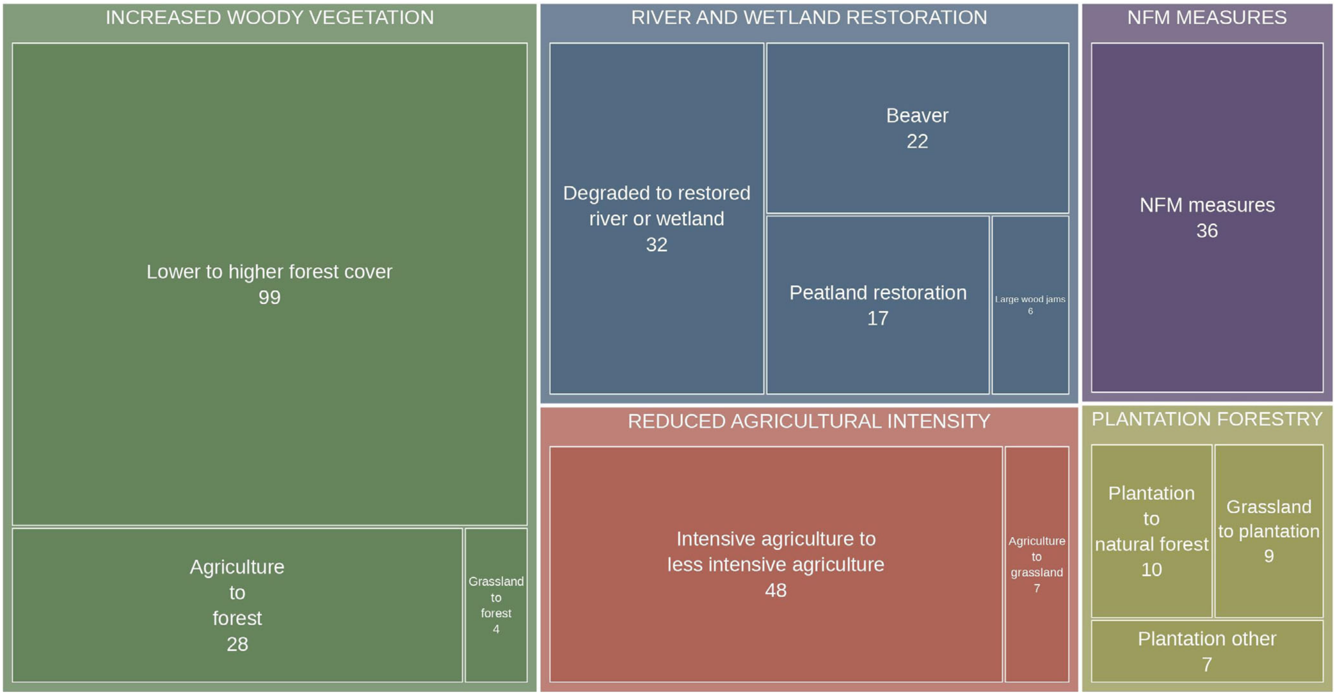


FIGURE 2 Frequency of occurrence of different landscape change trajectories in the retained papers. Boxes are scaled to the number of data records for that trajectory. Note that $n = 325$ because some papers contained multiple trajectories. The "plantation other" category groups low frequency plantation trajectories for brevity (plantation forestry to peatland/moorland or grassland, or agriculture/peatland to plantation).

animals on hydrological systems would therefore have been more widespread across temperate environments in the past (Moss, 2015; Brown et al., 2018) and research in this area is needed within the context of rewilding and species reintroductions.

4 | TEMPORAL AND SPATIAL TRENDS IN PUBLISHED STUDIES

The earliest study in our data set was published in 1988 and publications on the rewilding-relevant changes to hydrological extremes have increased through time (Figure 3). Only small numbers of publications were contributed annually (<2 per year on average) until around 2000 and publication increased more rapidly in the last two decades, with 41% of studies published since 2017 alone. The first paper referring to restoration in the title or abstract was published in 2003, while terms natural flood management and nature-based solutions do not appear in titles or abstracts until 2014 and 2017 respectively. The knowledge base is therefore relatively "young" and is rapidly developing.

The spatial distribution of study locations is partly constrained by our research focus on temperate zone biomes, with the vast majority of field sites in Europe (72% of records), USA (10%), and Australasia (6%). The most commonly occurring countries are UK, Germany, USA, Belgium, Spain, and New Zealand. Multiple study locations also found in Brazil, China, and Canada (Figure 4). There is a notable absence of studies from France (0) and Italy (1). Figure 4 also plots UK study locations from our review alongside the locations of rewilding sites in Rewilding Britain's published Network (Rewilding Britain, 2023) to enable comparison of project locations and published study locations. There are some striking differences between the distribution of rewilding projects and the distribution of published studies and many individual rewilding projects did not return any published hydrological studies in our searches. In particular, there is a lack of studies published in more central and eastern regions despite a number of rewilding projects in these areas. Some of these deviations will reflect the time lags involved in the collection and publishing of data on post-rewilding change, but even so, the pattern suggests a significant lack of active hydrological monitoring at rewilding sites in the United Kingdom.

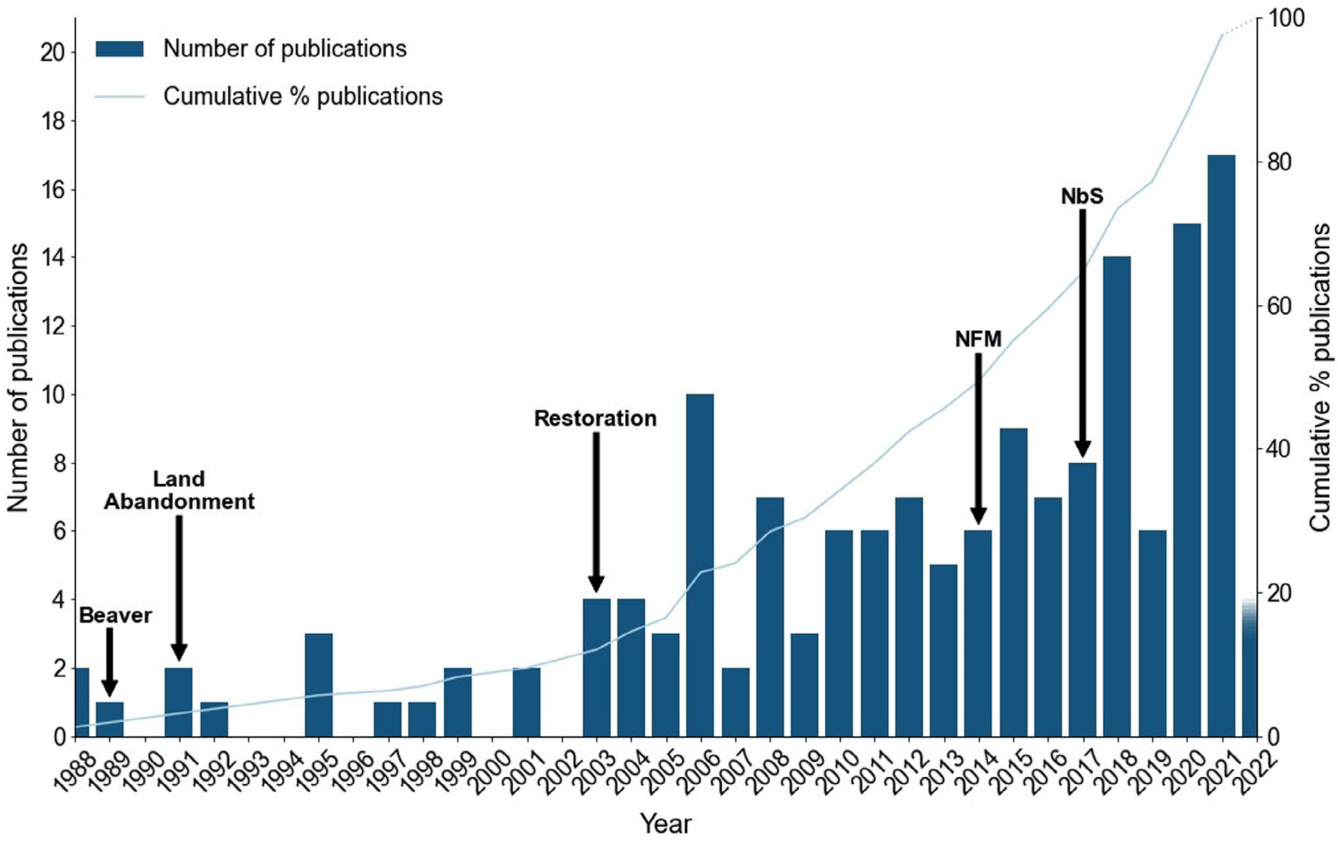


FIGURE 3 Temporal trends in published empirical studies meeting our eligibility criteria, showing yearly totals and cumulative number of sources. Text labels show the first appearance of related keywords (land abandonment, restoration, natural flood management, nature-based solutions, beaver) within the title or abstract of papers in our data set.

5 | TRENDS AND GAPS IN HYDROLOGICAL RESEARCH ON REWILDING

5.1 | Research design

The most frequently occurring study types were modeling studies, followed by longer-term field monitoring (Figure 5). Comparatively fewer studies incorporated field or laboratory experimentation, which can contribute useful insight into the causal processes behind observed changes in hydrological extremes. Examples include laboratory flume experiments on controls on wood jam afflux (Muhawenimana et al., 2021) and field experiments on hillslope hydrology (Marshall et al., 2009), runoff reaction from extreme rainfall events (Ries et al., 2020) and floodplain retention (Carling et al., 2020). While most articles (85%) adopted some form of comparative research design, the vast majority were control-impact studies (61% of all papers) enabling quantitative spatial comparisons to be drawn between degraded and restored or natural states. In contrast, less than 25% of studies collected data before and after a change in land use or land cover, enabling direct examination of hydrological change through time. Fewer studies still (9%) adopted a full BACI design. While the statistical power of BACI designs is reduced by low sample sizes, they have been shown to outperform CI designs in multiple accuracy metrics (Christie et al., 2019). Within a rewilding and nature recovery context, the lack of before and after data limits our understanding of the potential legacy effects from previous land use. For example, soil compaction can inhibit hydrological functioning over long timescales (Tempest et al., 2014), physicochemical barriers or time lags may influence species recolonization (e.g., Sarremejane et al., 2017) and recovery of soil mycorrhizal communities may be impacted by legacy land use (e.g., Säle et al., 2015).

5.2 | Addressing high and low flows

Our review found more than twice as much evidence available for effects on high flows (145 papers) compared to low flows (58 papers; Figure 6). The majority of papers (72%) addressed *either* low or high flows while only 28% of articles

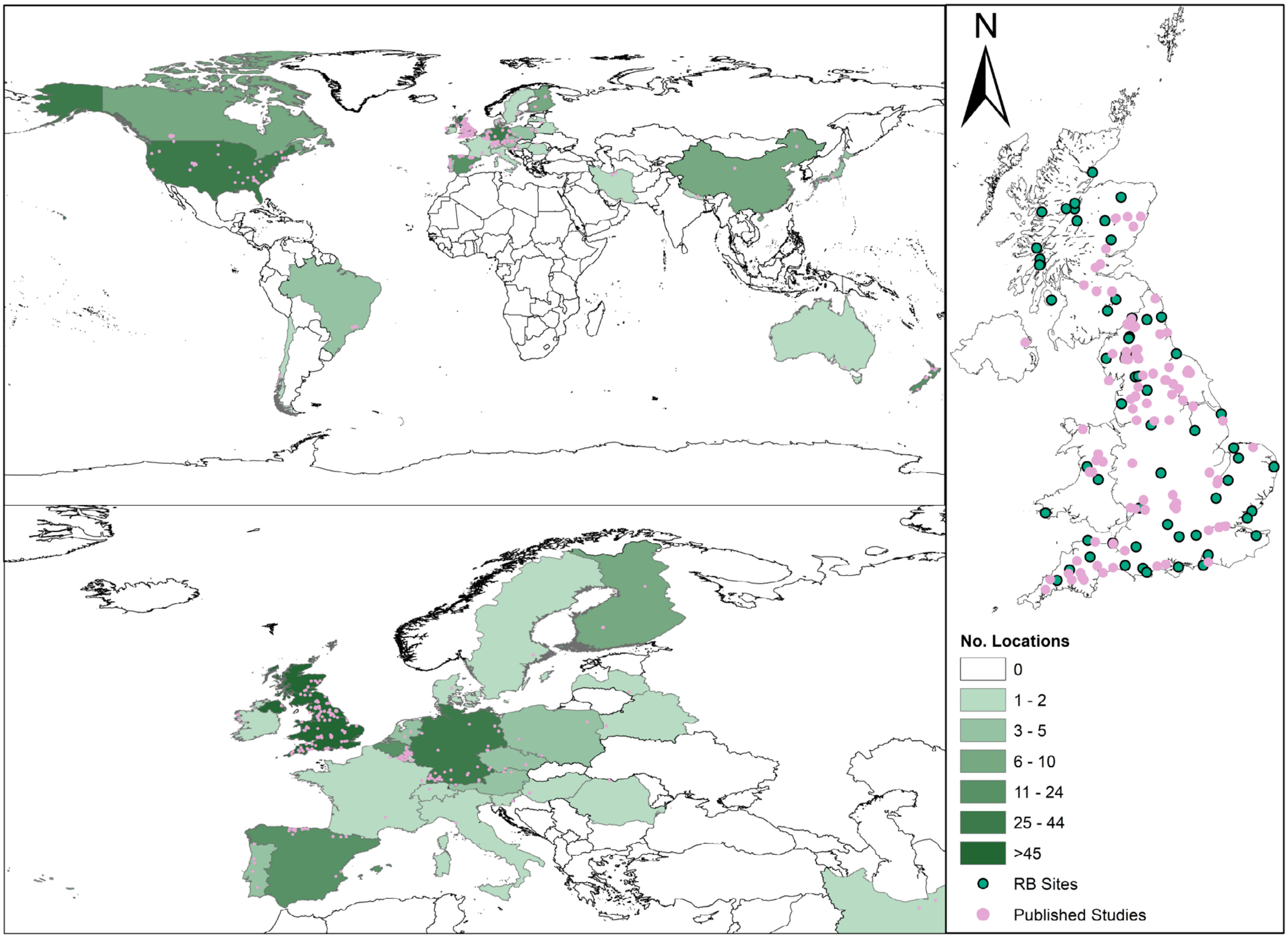


FIGURE 4 Map showing the frequency of published articles by country (shading) and the locations of study sites (where data are available) globally (top left) and in greater detail for European sites (bottom left). UK inset map (right) compares the location of UK rewilding sites listed on the Rewilding Britain Rewilding Network (Rewilding Britain, 2023) with the location of published UK studies within our data set.

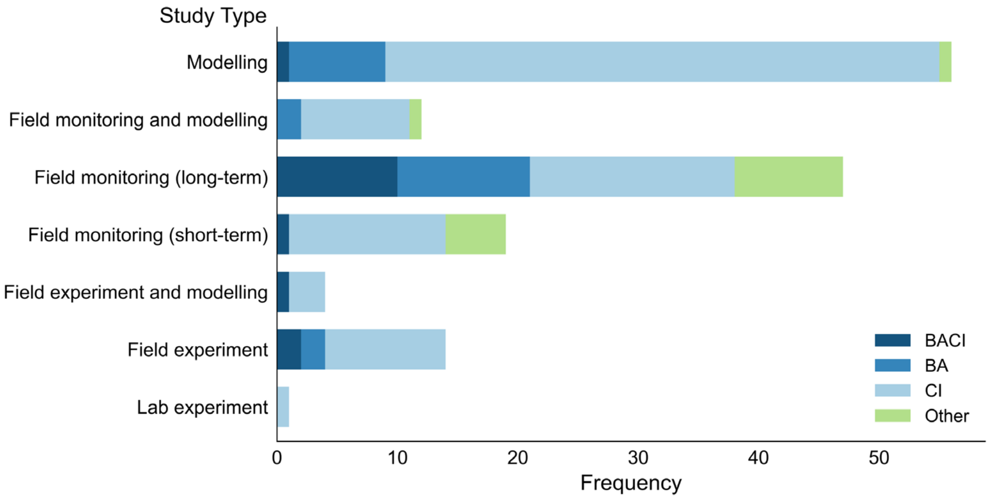


FIGURE 5 Study type and research design for empirical studies retained from our searches. Breakdown shows Control-Impact (CI), Before-After (BA), and Before-After-Control-Impact (BACI) alongside other research designs.

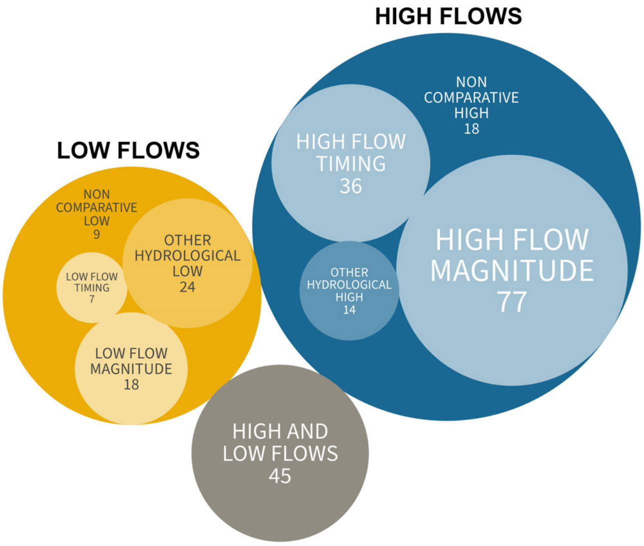


FIGURE 6 Outer circles show the total number of papers addressing high flows (blue), low flows (yellow), and high and low flows simultaneously (gray). Within the high and low flow circles, subcategories show frequency of occurrence of flow magnitude and timing variables among the comparative studies (before/after or control/impact). Non-comparative studies do not contain data to enable before/after or control/impact comparisons. The "other hydrological" category refers to comparative studies reporting variables other that peak/low flow timing or magnitude properties.

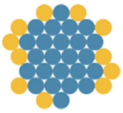
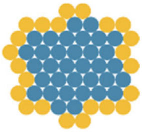
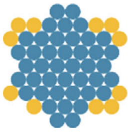
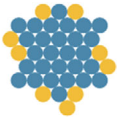
addressed low and high flows concurrently (Figure 6). This is an important evidence gap since similar types of land-cover change can have differing effects on the mitigation of high and low flows. For example, increases in woody vegetation can reduce flows across the flow duration curve, and hence can deliver attenuation of flood flows (Monger et al., 2022; Murphy et al., 2021) but can also increase low flow stresses in some contexts (Buechel et al., 2022; Vicente-Serrano et al., 2021). In contrast, beaver reintroductions have been linked with alleviation of both flood flow and low flow stresses downstream of beaver dam and wetland systems (Puttock et al., 2017; Brazier et al., 2021). Simultaneous consideration of high and low flows therefore represents an important focus for future work on nature-based solutions for mitigating hydrological extremes. Mitigating effects also depend on the receptor, for example, the downstream flood attenuation benefits of instream wood jams (including beaver dams) rely on the acceptability of localized upstream increases in floodplain inundation and storage (Keys et al., 2018; Thomas & Nisbet, 2012). Greater emphasis on low flows is required in future monitoring, particularly within the context of climate change. This can be supported by wider infrastructure development programmes, for example, the UKRI Natural Environment Research Council (NERC) Floods and Droughts Research Infrastructure (FDRI) programme in the United Kingdom (CEH, 2022).

Data are richest for flow magnitude compared to timing variables for both high and low flow extremes (Figure 6). Since efforts to attenuate floods and low flow emphasize the "slowing the flow" of water through the landscape (Dadson et al., 2017; Lane, 2017), flow timing variables should be given greater attention in published studies alongside the magnitude variables which are currently better represented.

5.3 | Mitigation of high and low flows: Evidence types and outcomes

We identified eight possible evidence categories for our reviewed articles according to whether causal hydrological processes and the mitigation of extremes were measured, modeled, or inferred, respectively (Table 1). We distinguished studies modeling extremes further into those where model development and parameterization was directly informed by site-specific field measurement of hydrological or hydraulic processes (type 4, e.g., Fiener & Auerswald, 2005; Jackson et al., 2008), studies where site-specific data or knowledge informed parameterization but hydrological or hydraulic process representation is governed by model selection (type 5, e.g., Hankin et al., 2021), and studies where model parameterization is achieved through use of parameter values predefined on the basis of simple proxies such as land cover type (type 6, e.g., Wübbelmann et al., 2021). We found no examples of category 2 in our review (direct measurement of effects on extremes combined with modeling of local hydrological processes) but have included it here since such

TABLE 1 Classification of evidence types for studies in our data set and the nature of their contribution to the evidence base, together with the frequency of occurrence of each evidence type for high flow analyses (blue circles; $n = 145$) and low flow analyses (yellow circles; $n = 58$).

	Evidence for			
	Altered hydrological processes	**Mitigation of extremes**	**Contribution**	**Frequency**
1	Local (plot/site level) hydrological processes quantified through *measurement*	Runoff/streamflow quantified through *measurement*	Provides evidence for/against mitigating effect and develops process understanding of causal mechanisms	
2	Local (plot/site level) hydrological processes quantified through physical or numerical *model*		Provides evidence for/against aggregate mitigating effect, enables evaluation of relationships/ interactions among causal mechanisms	
3	Causal hydrological processes responsible for changes to extreme flows are *inferred*		Provides for/against an aggregate mitigating effect but unable to directly attribute to causal mechanisms	
4	Local (plot/site level) hydrological processes quantified through *measurement*	Runoff/streamflow computed using physical or numerical *model*	Develops process understanding of altered hydrology and estimation of mitigating effect	
5	Parameter changes based on site-specific data/knowledge generate expected response		Evidence for/against mitigating effect and evaluation of relationships/interactions among causal mechanisms	
6	Parameter changes based on simple proxies generate expected response		Provides evidence for/against mitigating effect based on existing understanding of landcover change	
7	Local (plot/site level) hydrological processes quantified through *measurement*	Wider impacts on hydrological extremes *inferred* but not directly quantified through measurement or modeling	Process understanding of how rewilding-driven biodiversity change manifests in local hydrological processes	
8	Local (plot/site level) hydrological processes quantified through physical or numerical *model*		Evaluation of relationships and interactions among causal mechanisms	

Note: Total $n = 203$ since some studies included the analysis of high and low flows.

studies may exist beyond our review and may be undertaken to contribute to the evidence base. All seven remaining categories were found within our sample, with some variation in frequency between high and low flow examples (Table 1).

Overall, flow extremes were most commonly directly measured (44% of analyses) followed closely by modeling approaches (36%) with the remaining 20% inferring effects on flow extremes based on the analysis of causal hydrological processes. Proportions of evidence types differ between high and low flows studies, however. Interestingly, a higher proportion of low flow studies (57%) directly quantified the impact on hydrological extremes, rather than modeling or inferring impacts, compared to only 39% of studies for high flows (though they are more frequent in absolute terms). A higher proportion of high flow studies modeled (39%) or inferred (21%) impacts on extreme flows compared to low flows (28% modeled and 16% inferred, respectively). This indicates that while the evidence base for low flows is smaller, there is a greater emphasis on direct measurement of flow magnitude or timing. In contrast, while the evidence base is larger for high flows, it is more common for impacts on hydrological extremes to be either modeled or inferred than it is for them to be directly measured.

To synthesize the main outcomes of the papers, Figure 7 presents heatmaps to show the frequency of papers for each outcome category for high and low flows, plotted according to the evidence type. For flood flows, 80% of sources

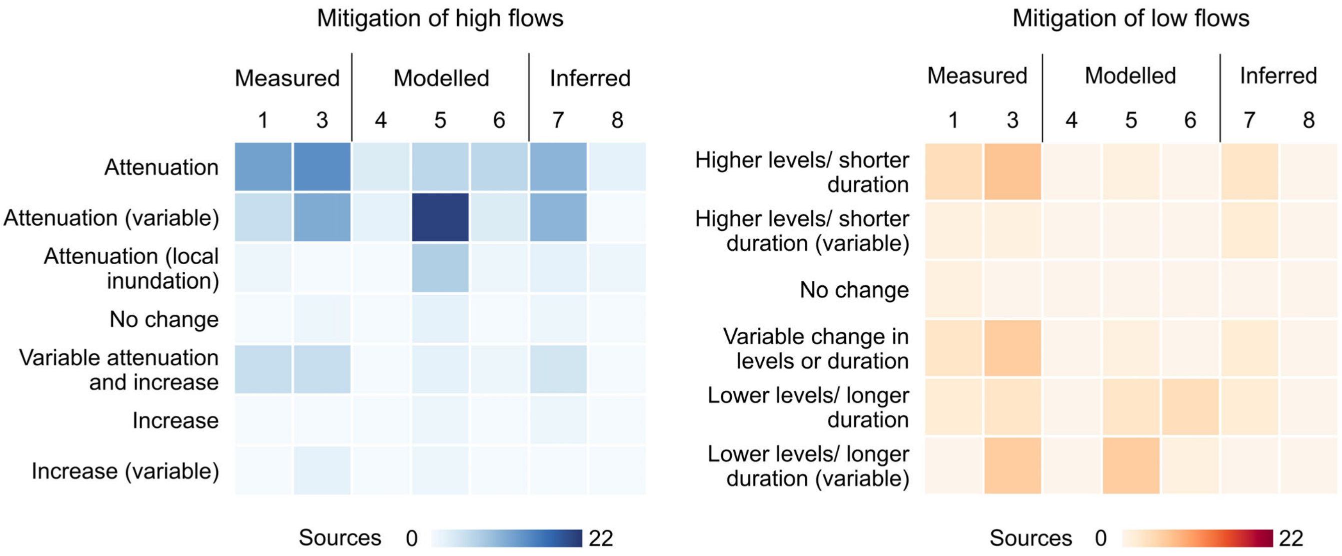


FIGURE 7 Heatmaps showing the frequency of studies that indicate attenuating or increasing effects on high flows (left, blue shading) and low flows (right, orange shading) for rewilding-relevant trajectories, according to each evidence type.

identified a mitigating effect associated with the rewilding-relevant trajectory, some of which note variable magnitude of the effect(s) (29% of studies). These variations reflect the moderating influence of factors such as event magnitude (e.g., Garcia-Ruiz et al., 2010; Cruise et al., 2010) the scale of landscape change or intervention (e.g., Škute et al., 2008; Ward et al., 2008), vegetation characteristics (e.g., species; Fahey & Jackson, 1997; Murphy et al., 2021 and maturity; Viola et al., 2014), antecedent conditions such as soil moisture (e.g., Ghimire et al., 2013; Hughes et al., 2020), catchment size (e.g., Deutscher and Kupec, 2014) and legacy effects associated with the landscape history (e.g., Ahiablame et al., 2019). Only 3% of high flow studies showed no change or negligible change, attributed to physical characteristics at the catchment scale (O'Donnell et al., 2011) and site or valley scale (Worley et al., 2022). Interactions between multiple environmental factors created a combination of increases and decreases in flood risk for some publications: 11% reported variable outcomes spanning attenuation and increased peak flows within the same study. For example, increasing forest vegetation cover may mitigate lower magnitude floods, but ditching networks associated with forested catchments can increase peak flows relative to grassland (Bathurst et al., 2020). Likewise, interactions between the structural configuration of wood jams and groundwater-surface water interactions may lead to either attenuation or increases in flow peaks (Munir and Westbrook, 2020). Several studies reported local increases in high flows that could generate attenuation effects downstream, for example, local inundation around wood jams (Keys et al., 2018) or arising from embankment removal (Clilverd et al., 2013), highlighting the importance of considering the nature of receptors in the landscape. Increases in high flows were generally associated with management practices including spatial variations in stocking densities (Meijles et al., 2014) and forest harvesting and regeneration cycles (Yu et al., 2019). There was no obvious systematic variation in outcomes with evidence type for high flows.

The outcomes are more complex for low flows, albeit based on a much smaller absolute number of sources. For low flows, 29% of studies show evidence of reduced low flow stress that is, higher water levels under low flow conditions and/or shorter durations of low flow periods. These responses tend to be associated with change trajectories such as beaver dams (Nyssen et al., 2011; Puttock et al., 2021) and other wood jams (Wenzel et al., 2014; Norbury et al., 2021), peatland restoration (Wilson et al., 2011; Bathurst et al., 2018) and lake, wetland and floodplain restoration (Carling et al., 2020; Quin & Destouni, 2018). Compared to high flows, a higher proportion of studies (19%) reported no change or negligible change for low flows while just over half of studies (51%) indicate potential for increased low flow stress associated with reduced water levels and/or longer duration of low flow periods. Increases in vegetation cover, and in particular forest cover, accounted for a lot of instances of increased potential for water stress, reflecting increased evapotranspiration (e.g., Willaarts, 2012; Adelana et al., 2014; Tian et al., 2017; Vicente-Serrano et al., 2021). Such studies, however, often focus on established forests and there is a lack of research into the scrub, shrubland and wood pasture habitats characteristic of earlier stages of natural vegetation regeneration in lowland temperate environments. Although based on a small sample size, low flow outcomes raise the possibility that some rewilding-related landscape change trajectories could lead to increased water stress. As for high flows, this also depends on the nature of receptors in the landscape and interaction with other risks, for instance retaining water upstream could exacerbate low flow risks downstream but could mitigate on-site risks such as wildfire. Further research statistically analyzing the magnitude of these effects and causal factors for different rewilding trajectories is an important next step. Studies exploring the impacts of combinations of rewilding trajectories on hydrological processes are also urgently required to help identify whether potential increases in hydrological risks are mitigated by the interactions between multiple rewilding actions and outcomes, and establish the significance of positive and negative feedbacks. For example, increased water use associated with terrestrial vegetation regeneration may occur alongside beaver reintroductions and other forms of instream large wood that can help sustain baseflows.

6 | CONCLUSION AND RECOMMENDATIONS

The evidence base for rewilding impacts on hydrological processes and mitigation of hydrological extremes is young and narrow in focus but is rapidly developing. There remains a significant lack of published data on rewilding-driven changes to hydrological processes, but analogue landcover change trajectories can, with caution, provide indicators of the expected nature and magnitude of effects. More emphasis should also be given to researching the impact of rewilding actions within freshwater systems as well as the rewilding of terrestrial landscapes. Most studies employ spatial comparisons through control-impact research design, enabling quantitative comparison of degraded versus restored or natural settings relevant to rewilding. The focus on space-for-time substitution and lack of before-after comparisons limits full understanding of the nature of change through time, and the influence of legacy effects from previous land use on potential rewilding outcomes.

There are over twice as many studies focusing on high flow effects compared to low flows, and less than a third of studies address high and low flows simultaneously. This creates a significant knowledge gap since rewilding-style landcover changes can be associated with mutually beneficial—or contrasting—effects across high and low flows depending on the nature of change, the scale, and the receptor in question. Flow magnitude variables are represented more frequently than flow timing variables for both high and low flows. This represents an important gap since both magnitude and timing together influence the potential for mitigation of flow extremes. Overall, impacts on extremes are more commonly modeled or inferred for high flows, rather than directly measured, while the reverse is true for low flows, albeit with fewer low flow studies overall. The evidence for high flows suggests a mitigating effect across the majority of studies, although with some exceptions and with variability in the magnitude of effect reflecting moderating factors including event magnitude. The nature of change for low flows is more complex and suggests a higher potential for increased risks of low flow events associated with certain trajectories but is based on a very narrow evidence base. Further, quantitative research is required to establish the magnitude of effects associated with different trajectories, the relationship with causal factors, and the interacting effects of multiple rewilding actions and change trajectories on both floods and low flows concurrently.

This review also highlights the potential for land managers developing and implementing rewilding projects to consider hydrological impacts and ecosystem benefits of their projects. Although some rewilding projects are focused on floodplain and wetlands systems, the literature shows that more terrestrial projects have the potential to mitigate flood risk and potentially low flow effects. Any project which leads to more structurally diverse vegetation cover and better structured soils has the potential to provide water management-related ecosystem benefits.

Figure 8 summarizes key research approaches and methodological considerations arising from our review to guide future work. As well as examining high flow and low impacts concurrently, and addressing changes in the timing of flows alongside magnitude, there is also a need to develop novel monitoring approaches to provide field evidence (e.g., low-cost sensor networks, Internet of Things), experimental approaches to generate process understanding of how water moves through the landscape (e.g., flow tracers including environmental DNA, plot-scale field experimentation, exclusion and inclusion, laboratory-based physical modeling experiments) and predictive hydraulic and hydrological modeling approaches, particularly in relation to understanding impacts on high severity events, the net effects of interacting trajectories of change, and variability of responses under future climate scenarios. As well as employing before-after-control-impact designs where appropriate and feasible, the relative low frequency and uncertainty in the timing of flood and low flow events generates a pressing need for more long-term field monitoring in conjunction with modeling of hydrological extremes.

REWILDING AND HYDROLOGICAL EXTREMES: RESEARCH RECOMMENDATIONS

RESEARCH AND ANALYSIS APPROACHES

Aim high, and low

Extremes can be influenced in different and sometimes contrasting ways. **Assess low and high flows** in field and modelling approaches

How much and when?

Both the **magnitude and timing** of water flows are important when considering impacts on floods and low flow stresses

Changing hydrological processes

Novel monitoring, experimental and modelling approaches required to understand how changes in vegetation cover and animal species alter how water moves through the landscape

METHODOLOGICAL CONSIDERATIONS

Comparative approach

Integrate 'before-after' comparisons into monitoring design to enable full understanding of the nature of change, using 'before-after-control-impact' where possible

Longer-term data

The relative low-frequency nature of floods and droughts means that demonstrating the effects on flood peaks or low flows requires long-term river flow data as well as modelling approaches

FIGURE 8 Infographic providing a summary of the research recommendations for future studies arising from this review.

Given the rapid expansion of rewilding projects, there are many opportunities to capture these effects, but modeling and field monitoring efforts are urgently required to capture baseline data, temporal dynamics and develop a full understanding of the nature of change in different rewilding contexts. We recommend that future research in this area simultaneously captures effects at high and low flow extremes, considers both magnitude and timing properties for both high and low flows, and adopts a full BACI design where possible (Figure 8). Since rewilding is a low control process and nature recovery can advance in a variety of directions, hydrological monitoring must take place alongside monitoring of nature recovery trajectories to help understand the drivers of hydrological change and potential feedbacks.

AUTHOR CONTRIBUTIONS

Gemma L. Harvey: Conceptualization (lead); data curation (supporting); formal analysis (supporting); funding acquisition (lead); investigation (lead); methodology (lead); project administration (lead); visualization (lead); writing – original draft (lead); writing – review and editing (lead). **Adam T. Hartley:** Data curation (lead); formal analysis (lead); methodology (supporting); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Alexander J. Henshaw:** Conceptualization (supporting); data curation (supporting); formal analysis (supporting); funding acquisition (supporting); investigation (supporting); methodology (supporting); project administration (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Zareena Khan:** Data curation (supporting); formal analysis (supporting); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Stewart J. Clarke:** Conceptualization (supporting); funding acquisition (supporting); investigation (supporting); methodology (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Christopher J. Sandom:** Conceptualization (supporting); funding acquisition (supporting); investigation (supporting); methodology (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Judy England:** Conceptualization (supporting); funding acquisition (supporting); investigation (supporting); methodology (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Sara King:** Conceptualization (supporting); funding acquisition (supporting); investigation (supporting); methodology (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Orlando Venn:** Conceptualization (supporting); funding acquisition (supporting); investigation (supporting); methodology (supporting); writing – original draft (supporting); writing – review and editing (supporting).

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CONFLICT OF INTEREST STATEMENT

Stewart Clarke (National Trust), Sara King (Rewilding Britain) and Orlando Venn (Wildfowl and Wetlands Trust) are employed by registered charities. Judy England is employed by the Environment Agency of England. Chris Sandom is a Director of Wild Business Ltd. The views expressed within this paper are those of the authors and do not necessarily represent the views of their respective employer organisations.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

RELATED WIREs ARTICLES

Natural flood management
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Rewilding and the water cycle

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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