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Rivers as Natural Capital Assets: A Quick Scoping Review to Assess the Evidence Linking River Asset Condition to Changes in the Flow of Ecosystem Services

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ABSTRACT

River managers are beginning to adopt natural capital approaches in practice. However, while it is crucial for river management, the link between river asset condition and the flow of ecosystem services is poorly understood. In this study, we conducted a Quick Scoping Review (QSR) of the research into river asset condition and ecosystem service delivery to explore the current state of knowledge. The review team developed a PICO (Population, Intervention, Control, Outcome) model to transpose the concepts of the research enquiry into a search strategy for the evidence base and used a Delphi screening exercise to prioritise a subset of literature for the narrative findings. VOSviewer was used to analyse the high-level linguistic themes from the full list of references. This co-designed, collaborative and objective QSR approach allowed us to examine a large body of literature in a reproducible manner while minimising bias, demonstrating best practice for evidence review that should be continuously updated, generating a 'living evidence' knowledge asset. The results of the review demonstrate there is some knowledge of the mechanisms linking the condition of river assets to the delivery of ecosystem services for the majority of the broad range of ecosystem services analysed, with the exception of some of the cultural services, where comparatively fewer studies explore this link. However, a clear understanding of the quantitative evidence of the relationships between condition and ecosystem service delivery is missing for all of the ecosystem services. This gap stems from a lack of standardised methodologies used across the studies and a focus on a narrow range of definitions of condition. The gap needs to be addressed in future research on the topic, and a first step is to adopt more standardised indicators of river asset condition.

1 | Introduction

Human societies depend on nature to survive (Daily et al. 1997), yet habitats are being negatively affected by human impacts, preventing the delivery of those ecosystem services that humanity needs (Zingraff-Hamed et al. 2021). The natural capital concept offers a holistic decision-making approach that balances people's short-term needs with conservation of biodiversity and ecosystem health, to ensure sustainable delivery of ecosystem services in the long term (Costanza and Daly 1992; Daily et al. 2009; Hancock 2010; Özdemiroğlu 2019). Natural capital assets are '…elements of nature that directly or indirectly produce value or benefits to people, including ecosystems, species, freshwater, land, minerals, the air and oceans, as well as natural processes and functions' (Natural Capital Committee 2014). The benefits provided can be material goods such as timber or food, from processes such as crop pollination or flood regulation, or non-material benefits such as recreational opportunities or improved health and well-being. These are 'the contributions that ecosystems make to human well-being' (p. 4) and are collectively defined as Ecosystem Services (Haines-Young and Potschin 2018). How effective ecosystems are at delivering services from which people benefit depends on how extensive they are (quantity), where they are situated in relation to the people who benefit and the wider landscape (location) and how well they function (asset condition, or quality). These three aspects, together, determine the 'state of natural capital'. While quantity and location are fixed attributes of ecosystems, asset condition is measured based on the properties that underpin the service being examined (Schröter et al. 2016).

Practical management of freshwater systems in England still generally relies on monitoring aspects of the habitat such as biodiversity, water quality and water flow to determine near-natural rivers, which are then used as a baseline for restoration for improving habitat condition and the prevention of deterioration. As yet, management is not usually informed by a natural capital approach. The Water Framework Directive (WFD) has been the main legislative framework for the protection of European waters since 2000. It aims to protect the integrity of ecosystems by monitoring and regulating pollutants and assemblages of species so that water bodies do not deteriorate and are able to reach good status, which requires good ecological and chemical conditions (WFD 2000).

Environmental management in England is gradually moving towards a more integrated approach to biodiversity decision-making, focused around considering ecosystem functions closeness to its natural state. Frameworks have been developed to assess and capture key aspects of natural ecosystem function or 'naturalness' in freshwater habitats by characterising the main elements of natural ecosystem function, including hydrological, physical, chemical and biological integrity (Mainstone et al. 2018). For this reason, there is a need to design monitoring networks that measure attributes that tell us about ecosystem function, which determines the flow of ecosystem services they provide.

At present, there are no comprehensive spatial datasets specifically addressing natural capital asset condition for the freshwater environment. If the aim of environmental management is to identify areas most at risk of loss or degradation of ecosystem services, the quality and coverage of natural capital evidence need to be improved.

The Defra 25 Year Environment Plan has committed to adopting a natural capital approach (Defra 2018) to managing the natural environment so that it continues to deliver vital services that support the economy and society. It aims to achieve clean and plentiful water, bringing at least three quarters of England's waters closer to their natural state by reducing excessive water abstraction from rivers and groundwater; reaching or exceeding biodiversity or drinking water objectives for rivers, lakes, coastal and groundwaters that are specially protected; supporting the Water Services Regulation Authority (OFWAT) in minimising the amount of water lost through leakage; and improving water cleanliness, particularly by reducing harmful bacteria in bathing waters (Defra 2018).

Rivers are important habitats for delivering ecosystem services (Smith et al. 2017), but the provision of ecosystem services in aquatic environments is understudied compared to terrestrial systems (Holland et al. 2011). A key barrier to implementing the natural capital approach for river management is the ability to identify and measure the flow of ecosystem services and benefits to society from freshwater habitats, in both temporal and spatial terms. It is also generally understood that habitats in better condition are more capable of delivering a higher level of ecosystem services (Harrison et al. 2014; Pullanikkatil et al. 2016) but the link between river asset condition and the delivery of ecosystem services still represents a large knowledge gap that needs to be explored further. Being able to quantify ecosystem services in relation to condition would enable an understanding of the implications of the deterioration of the asset to biodiversity and society, as well as the effectiveness of interventions to improve asset condition. Quantifying the value of the benefits would enable society to sustainably manage its natural capital asset stock for future generations.

In this study, we are following on from the work of Maskell and Norton (2021) and the Natural Capital Indicators in Environment Agency Monitoring Project, delivered by the UK Environment Agency (EA)[1] under the Natural Capital and Ecosystem Assessment programme (NCEA)[2], which aims at filling these knowledge gaps to bring environmental protection towards a natural capital and ecosystem services approach.

The aims of this study were to conduct a review of the scientific literature to (i) identify the evidence linking different aspects of the condition of river assets to the delivery of a set of riverine ecosystem services, and (ii) establish the nature of the relationship between different aspects of river asset condition and ecosystem services delivery in a qualitative manner. The primary focus of the review was England, as this was commissioned by the EA, whose remit covers England, but the work is still relevant for temperate regions.

2 | Methods

Because of the breadth of the topic considered, we adopted a Quick Scoping Review (QSR, Collins et al. 2015) approach. Quick Scoping Reviews are a form of qualitative evidence synthesis that provides a balanced and weighted overview of research rather than a detailed and critical evaluation. To draw conclusions that are trustworthy and actionable, the QSR should apply the principles of a systematic review by following a process that is reproducible and transparent and ideally involves a competent practitioner in the field of systematic searches (McGowan and Sampson 2005). QSRs are less time-consuming than systematic reviews, yet examine the evidence in a scientific, structured and transparent way. This approach is also deemed most appropriate for meeting policy and practice evidence requirements (Collins et al. 2015).

For the purpose of this review, we selected a sample of published articles from scientific journals and other 'grey' sources that were considered relevant and representative of the overall literature on natural capital and ecosystem services by the review team. To mitigate the risk of bias, a large multidisciplinary research index, Scopus, featuring a sophisticated search interface, was used as the primary source for peer-reviewed research. The QSR process was complemented with insights from VOSviewer (van Eck and Waltman 2010), a software tool for constructing and visualising bibliometric networks for analysing large sets of scientific publications to analyse patterns and trends from the linguistic structure of the overall evidence base.

The natural capital and ecosystem services approach is a holistic approach requiring expertise in a wide breadth of subject areas, from water quality to hydrology, ecology, economics and social science (amongst others). We assembled a review team combining experts in river restoration and catchment management from the River Restoration Centre, with a team specialising in natural capital and ecosystem services assessment as well as biodiversity science (Natural Capital Solutions Ltd). The project was run with the help of a steering group and a wide group of stakeholders with complementary skills through workshops and the review process. Experts from the Environment Agency's team working on Defra's NCEA Programme commissioned, steered and co-delivered the project, providing further evidence and knowledge on river asset condition and the QSR methodology. The QSR followed a collaborative approach between the experts involved throughout.

The QSR sought to identify what relevant evidence is available to indicate how asset condition affects the delivery of ecosystem services from rivers. The approach to the review was developed using a protocol that established the search strategy and evidence screening criteria. The PICO (Population, Intervention, Control, Outcome) approach was used to identify the underlying concepts from the primary research question to form the basis of a search strategy (see Table 1). Originally developed to embed evidence-based practice in healthcare, the PICO formula can be used flexibly to translate a research question into a systematic search strategy that targets the underlying concepts and gives confidence to the findings. The PICO also helped when choosing keywords for the literature search, ensuring focus and clarity of the questions. As part of the protocol, clear limits to the scope of the review were defined (see Table 2), for example, results would be restricted to papers written in English about relevant geographical areas with a focus on England to be applicable to English river management issues. Through the protocol, we also established the rules of the screening strategy applied to the papers that were found as a result of the search strategy (this process is explained in more detail below).

In order to select the ecosystem services on which the review would focus and define key search terms for the QSR, two online workshops were held with 41 experts from across the EA representing the NCEA programme, the Chief Scientist's Group, Fisheries, Biodiversity and Geomorphology, Sustainable Places, Flood Risk Management, Water, Land and Biodiversity, Public Health, Funding, and Agriculture, Operations and Environmental Land Management. Since river asset condition was the primary focus of the review, it was important to capture the range of ways in which it can be understood in the context of rivers and natural capital. Defining what is meant by river asset condition became an important question to put to stakeholders at the workshops (see Supporting Information 1) to ensure that we captured the full range of perspectives in this study. In the first exercise of the workshops, participants were asked to discuss what river asset condition meant to them (see Supporting Information 1). The discussion around condition at the workshops identified key themes and words, which were then used directly to populate the PICO framework and identify the search terms for the review. To ensure that the scope of the study was manageable within the available resources, participants were also asked to answer questions about the type of ecosystem services and assets that should be included (see Supporting Information 1). Ecosystem services were prioritised by workshop participants through a ranking exercise (see Supporting Information 1 for more details). The list was supplemented with services for which the consensus amongst experts was that little information exists for these important services (almost exclusively cultural services). The 10 selected ecosystem services are (in order of importance scored by workshop participants): water for drinking/agriculture/industry; water quality regulation; water flow regulation; characteristics and features of biodiversity that are valued; health and well-being; recreation and tourism; habitat and population maintenance; aesthetic experiences; education, training and investigation; and spiritual and cultural experiences. Selected ecosystem services were defined, categorised and compiled into a table (see Supporting Information 2).

The interrogation of Scopus (carried out over the week commencing on the 13th of March 2023) was organised around strings of search terms concatenated using Boolean operators. The Scopus query builder allows the use of proximity operators to broaden the search to account for the different ways in which researchers express key phrases such as 'ecosystem service'. The use of these operators also helped optimise the search string to capture combinations of a terms such as 'water industry' and 'drinking water' within a sentence. The choice of keywords was informed by workshop outputs. Definitions of river condition were used as impact keywords, the definitions of the selected ecosystem services were used as outcome keywords and the review team and

TABLE 1 | PICO table.

PICO model	
Population	River waters and their floodplains
Impact	High quality/good condition
Control	Low quality/poor condition
Outcome	Change in delivery of ecosystem services

TABLE 2 | Limits to the scope of the review.

Scope of the work	Restrictions
Geographical reference	UK > northern Europe > temperate regions
Climatic conditions	Temperate
Language	English
Date restrictions	None
Population restrictions	Rivers and their floodplains

steering group formulated the remaining population keywords. A standard PICO framework normally requires both control and impact keywords. In the case of our study, the conventional use of 'impact' and 'control' was substituted with 'high quality' and 'low quality' to compare against the 'population', rivers and 'outcome', to identify the studied change in ecosystem services.

A preliminary search was conducted selecting papers matching any listed population, impact and outcome keywords (see Table 3). As this yielded 502,341 results (see Figure 1 for overview of the screening process) it was decided that the papers should also make explicit mention of 'ecosystem services' or assets. This would restrict the search to research that had explicitly approached the study of rivers through the lens of ecosystem services. Other terms could have been used to do this, but 'Ecosystem service' is a more established term, widely used for a long time in the scientific literature, yielding a larger pool of research compared to 'ecosystem processes' or 'natural capital', which are of more recent implementation. This cut the number of results to 4550. The search was initially performed using title, abstract and keywords, but some words such as pollut* and fish* (where * allows multiple word endings or starting to be matched) gave a biased sample of the literature when included as keywords in the search; hence, the search was limited to abstract and title.

The final search string used in Scopus returned 3605 papers (journal articles and reviews, conference papers and book chapters):

TITLE-ABS((ecosystem* W/1 (service* OR asset*)) AND (river* OR headwater* OR floodplain* OR riparian* OR bluespace* OR *stream*) AND (value OR naturalness OR perception OR resilience OR *connect* OR *morpholog* OR pollut* OR condition* OR character* OR access OR qualit* OR anthropogenic) AND (water W/1 (drink* OR industr* OR flow OR storage OR supply OR quality)) OR nutrient* OR nitrogen OR phosphorus OR sediment* OR runoff OR flood* OR drought OR biodiversity OR habitat OR society OR *social OR ecology* OR health OR wellbeing OR recreatio* OR touris* OR fish* OR exercis* OR aesthetic OR scen* OR landscape OR cultur* OR experien* OR intrinsic* OR existen* OR option* OR education* OR training OR investigation) AND LANGUAGE (english).

To complement the sensitivity testing of the search strategy, emerging results were also assessed using network visualisation. This enabled the review team to check for unexpected terms from the overall corpus, investigate their source references for relevancy and refine and rerun the searches (see Supporting Information 3).

Grey literature comprises information published outside traditional sources that does not go through a rigorous peer review process like that required for publishing in academic journals. Nonetheless grey literature can provide relevant information and a strategy for targeting this type of evidence was also developed for the review. The following organisation's public databases were searched for published reports: EA, Natural England, NatureScot, Natural Resources Wales (NRW), UK Centre for Ecology and Hydrology (UKCEH) and Natural Environment Research Council (NERC). In addition, internal searches were conducted in the EA and Natural England intranets.

TABLE 3 | Keywords used in the literature search.

Keywords	
Population keywords	river* OR headwater* OR floodplain* OR riparian* OR bluespace* OR *stream*
Impact keywords	value OR naturalness OR perception OR resilience OR *connect* OR *morpholog* OR pollut* OR condition* OR character* OR access OR qualit* OR anthropogenic
Outcome keywords	Water for drinking/agriculture/industry = (water W/1 (drink* OR industr* OR flow OR storage OR supply OR quality OR abstraction)) Water flow regulation = flood* OR drought OR {natural hazard*} OR runoff* Water quality regulation = nutrient* OR nitrogen OR phosphorus OR sediment* OR water qualit* Characteristics and features of biodiversity that are valued = intrinsic* OR existen* OR bequest OR option* Health and well-being = society OR *social OR health OR wellbeing OR crime OR {social benefits} OR {antisocial behaviour} Recreation and tourism = recreatio* OR touris* OR fish* OR exercis* OR {physical activity} Habitat and population maintenance = *diversity OR habitat OR ecology* Aesthetic experiences = aesthetic OR scen* OR landscape OR experien* Education, training and investigation = education* OR training Spiritual and cultural experiences = spiritual* OR cultural
Other keywords	ecosystem* W/1 (service* OR asset*)

Once the search strategy had been refined as described above, the number of papers was narrowed down in two phases (Figure 1). A first screening phase was completed by a single reviewer by removing those titles that were not relevant (not explicitly mentioning rivers, watersheds, freshwater). Through this process, 794 papers were selected.

We used VOSviewer for the scientometric analysis of the list of screened references from the Scopus search (see Figures 2 and 3).

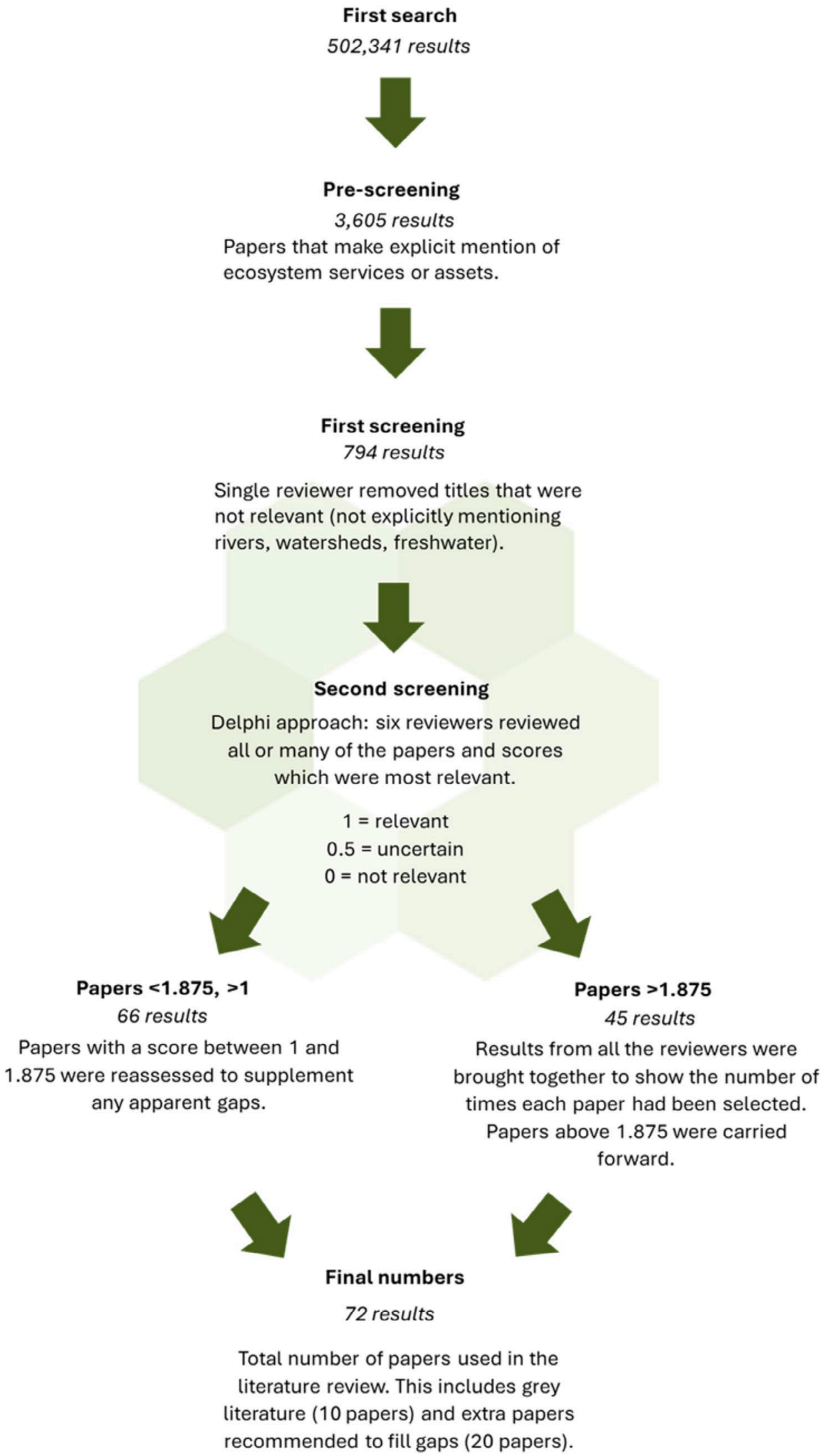

FIGURE 1 | Overview of the entire screening process. [Color figure can be viewed at wileyonlinelibrary.com]

VOSviewer (van Eck and Waltman 2010) is a software tool for constructing and visualising bibliometric networks from the most statistically relevant terms out of a large set of scientific publications. The software uses a mapping technique called VOS (visualisation of similarities) and Natural Language Processing algorithms to identify patterns, trends and relationships from the title and

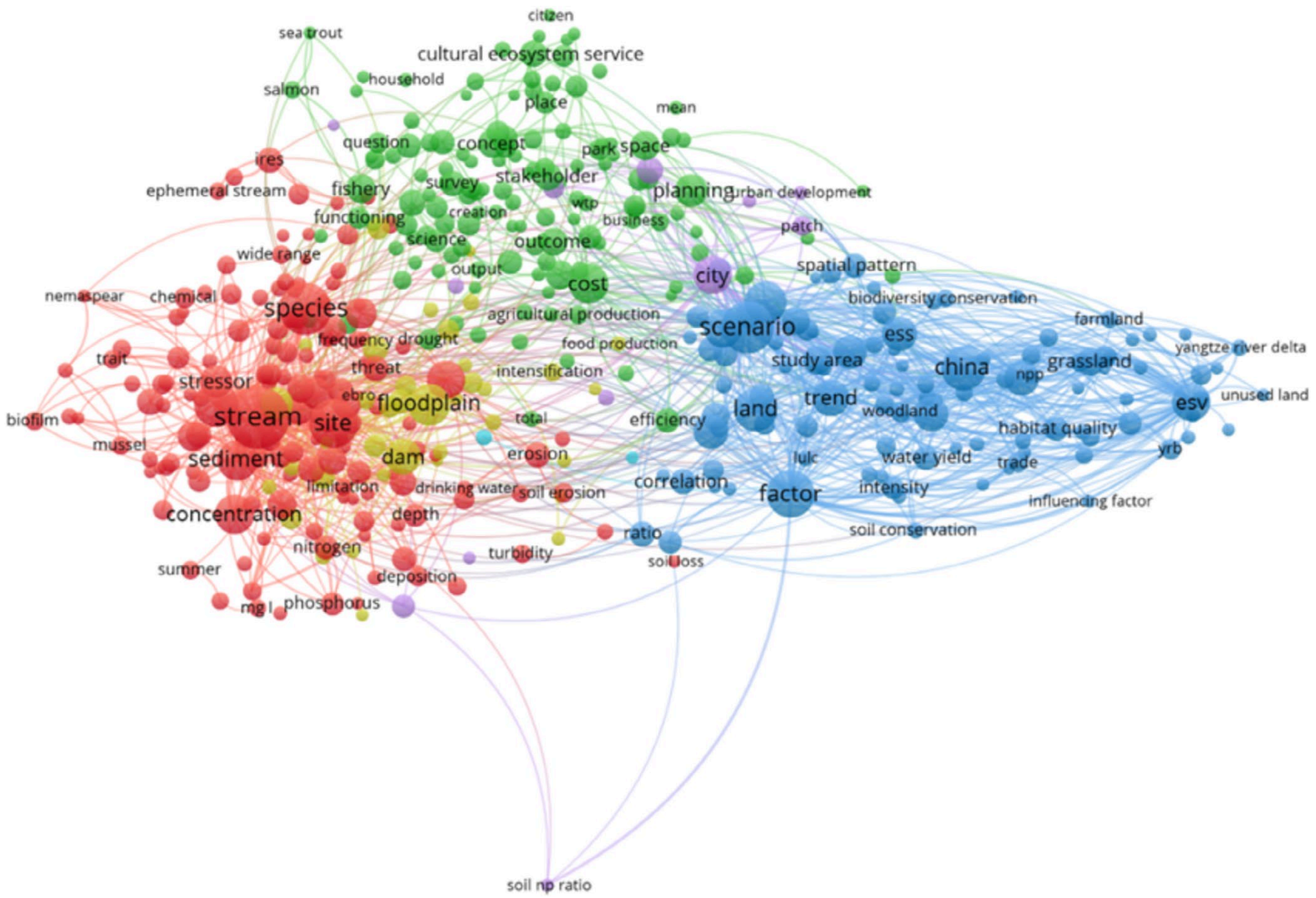

FIGURE 2 | Network visualisation of results remaining after the first screening phase selecting 794 papers. [Color figure can be viewed at wileyonlinelibrary.com]

abstract fields of a large corpora of bibliographic information (van Eck and Waltman 2010). The maps arrange this information into coherent clusters, which can help to identify emerging or established research topics or interdisciplinary research areas. This is known as a term co-occurrence map and indicates major research topics in articles and reviews indexed by Scopus. Each term occurs in at least 10 publications, and in the 60% most frequently occurring terms are visualised. The size of the circles in the visualisations relates to the number of times the word or phrase appears across all the articles. Related terms are grouped into the same colour. Lines between terms indicate where terms are used together, and the distance between terms indicates how often they co-occur; the smaller the distance, the larger the number of co-occurrences, and the stronger the terms are related to each other.

Three main clusters emerged (Figure 2): the red cluster identifies more of the physical entities (see 'stream', 'species' and 'sediment'), while the blue cluster identifies more of the mechanisms and potential stressors due to interventions, 'land use change', as well as 'China' since this is where a significant proportion of the research on natural capital and ecosystem services of rivers originates. The green cluster identifies themes more related to people where it is possible to see 'citizen', 'household', 'stakeholder', 'cultural ecosystem service'. Overall, the maps highlight the degree to which rivers are contested spaces with multiple pressures affecting their condition, and the need to manage the supply and demand of ecosystem services. This trend is further emphasised by the 'overlay visualisation' showing how terms evolve from 'state' related biotic indicators such as 'fish', towards abiotic indicators like 'precipitation' and 'water yield' which may reflect a transition of rivers towards increasingly unstable and unpredictable systems.

The overlay visualisation (Figure 3), where blue indicates older papers and red is used for more recent publications, shows how academia has shifted its focus over time from more traditional papers focusing on species and habitats (note the blue-shaded 'floodplain', 'species', 'salmon') towards a holistic view of rivers focusing on ecosystem services and their value (not visible but in the background) 'esv', and increasingly towards including social sciences and cultural ecosystem services compared to the greater focus on provisioning services of previous years. It is also evident how China is becoming a leading country in this field of research, showing in a lighter shade of red on the left-hand side of the figure, suggesting the country is mentioned very often in more recent papers.

Once papers that mentioned rivers were selected, a second screening phase (a Delphi approach) was adopted to further narrow the number of papers. This was adopted to reach consensus between experts using a multi-round assessment.

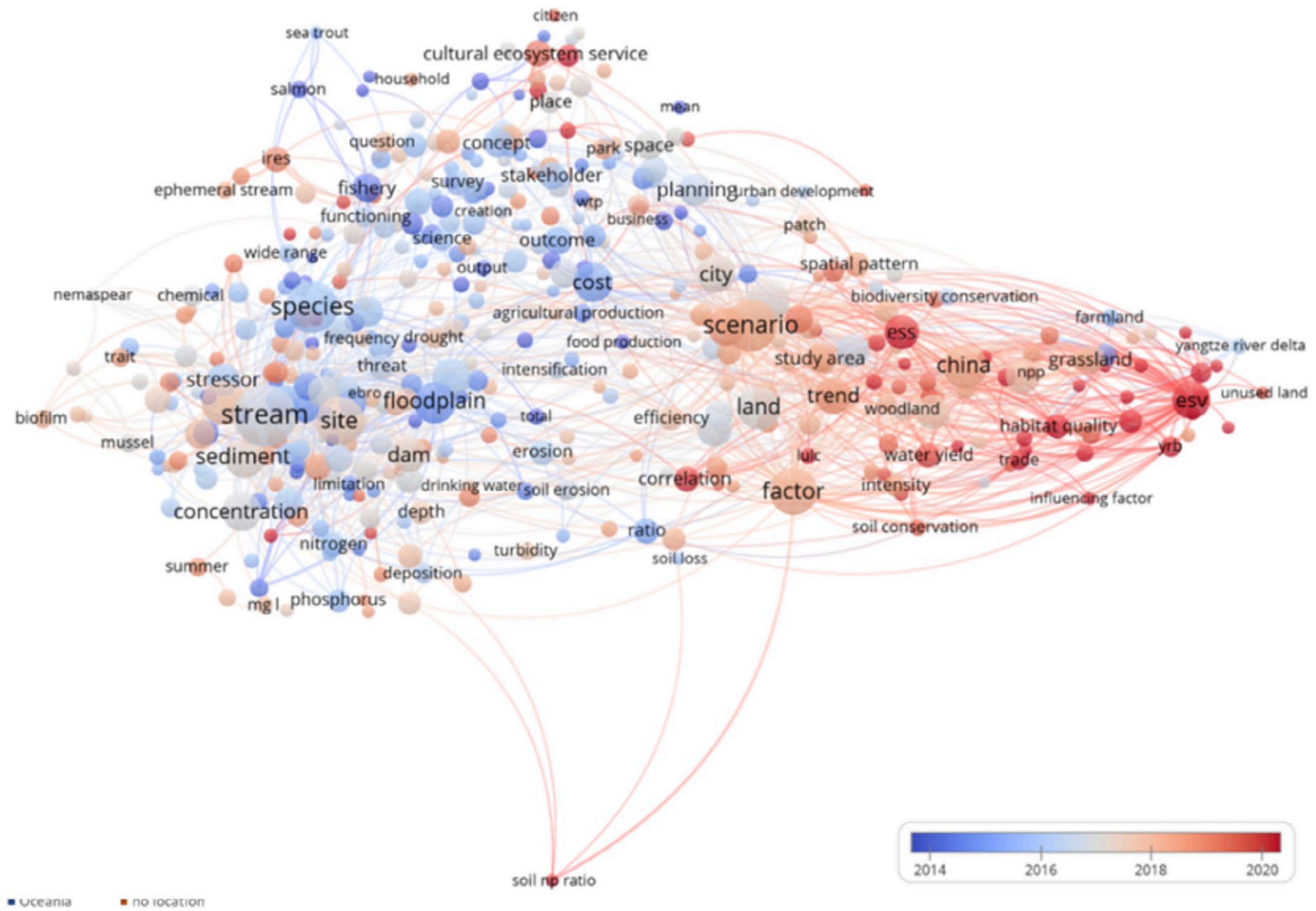

FIGURE 3 | Overlay visualisation of results remaining after the first screening phase selecting 794 papers. [Color figure can be viewed at wileyonlinelibrary.com]

In our case, six reviewers reviewed some (or in some cases all) of the identified papers to determine which ones are relevant for answering the research questions, in order to minimise single-person bias. The review team found that it was usually necessary to read whole abstracts to determine whether papers were relevant. Reviewers started the screening process at different places on the list to ensure that all papers were reviewed by more than one person. Each reviewer gave a score of ‘1’ to relevant papers and ‘0’ to non-relevant ones. Each reviewer also used question marks (which were later assigned a score of 0.5) where a paper sounded less relevant but worth examining briefly, or where there was uncertainty (see Supporting Information 5).

Relevance was based on three criteria:

- Does the paper explicitly address a change in the delivery of one or more ecosystem services?
- Is this related/due to a change in condition?
- Is the study geographically relevant? Although note that this criterion was applied less strictly as it was considered that a paper from a different climate zone might still be relevant for some cultural services, where fewer papers were expected.

Results from all the participants were brought together. In total:

- 533 papers were screened by three different reviewers.
- 261 papers were screened by four different reviewers.

Records screened by four reviewers were given a weighting of 0.75, so that all scores were equalised and out of a total of three. A weighted score showing the number of times each paper was selected was calculated, with the number of records given a different set of scores. Papers with a score of 1.875 ($n=45$, see Table 4) and above were carried forward and used in the knowledge mapping. A score of 1.875 and above indicates that at least two reviewers have deemed the paper relevant. Papers achieving a score greater than 1 (indicating that more than one reviewer found the papers to be relevant) were used to supplement the initial list (papers scoring 1.875) where gaps were apparent in the knowledge map. This provided an additional 66 papers to consider.

In the knowledge mapping step, key information was extracted from each paper selected by the aforementioned screenings (see Supporting Information 5). In particular: geographic location, asset type (river, freshwater, entire watershed, etc.) and study type (observational, review, qualitative, experimental) were recorded to provide a more detailed characterisation

TABLE 4 | Number of records and cumulative records of scores assigned to the 794 papers by six reviewers. In bold are the values we refer to in the text.

Weighted score	Number of records	Cumulative records
3	8	8
2.5	2	10
2.25	5	15
2	21	36
1.875	**9**	**45**
1.5	45	90
1.125	**21**	**111**
1	154	265
> 0 and < 1	221	486
0	308	794

of the literature. For each ecosystem service reviewed, the aspects of condition affecting the ecosystem service and the relation to the ecosystem service (whether a certain aspect of condition would negatively or positively affect the delivery) were also recorded.

After the initial review of the top 45 papers and grey literature, knowledge mapping revealed that for some of the services very few papers were found and that some key evidence may not have been captured by our search strategy (see Supporting Information 5). A gap-filling exercise was then carried out by examining the next 66 papers that had received scores between 1.125 and 1.5, along with a few additional papers recommended by members of the review team. This exercise was focused on those ecosystem services with fewer results, but key papers for other services were also added. In total, 20 extra papers were added (see 'Extra papers' tab in spreadsheet, Supporting Information 5) to our review.

Following the production of the knowledge map, the evidence from the selected literature (72 studies in total) was synthesized into a narrative summary. It is worth noting that the summary presented below cites other studies that were not part of the 72 analyzed. These other studies have been added to support general statements and are not fully described in the text like the ones identified by the QSR methodology. For each ecosystem service, we present the evidence to answer the primary research question: how does asset condition affect the delivery of ecosystem services from rivers?

This work was then internally reviewed by nine members of the study team comprising natural capital and evidence synthesis experts from the EA, as well as ecosystem service, natural capital and river specialists. It was then subject to further interdisciplinary review with an additional 13 EA reviewers with expertise in natural capital, social science, water environment research and evidence, geomorphology, Water Framework Directive, 25 Year Environment Plan Indicators, freshwater ecosystem restoration, river monitoring design, water strategy and NCEA. An independent expert from the University of Oxford's Environmental Change Institute also peer-reviewed the work.

3 | Results

3.1 | Distribution of Evidence

A total of 72 papers linking river asset condition to changes in ecosystem service provision met the criteria for inclusion following the screening of the search results. This included papers selected from the Scopus search, grey literature and extra papers suggested to fill the gaps. The data gathered through the knowledge mapping process is summarised in Figure 4.

Most of the studies selected came from Europe, and within this group the United Kingdom was the most represented country (19 studies), while many studies came from the United States (8), and some were global studies (6). The largest number of studies were observational, some were reviews and others were experimental or modelling, while only one qualitative study was selected. Regarding the temporal distribution of the papers selected, only one predated 2000, 15 papers were published between 2000 and 2010 and 50 were published from 2011 to 2023. The ecosystem services for which very little evidence was gathered (each ecosystem service only had two relevant results between papers and grey literature) were 'water for drinking/agriculture/industry' and 'characteristics and features of biodiversity that are valued', closely followed by 'spiritual and cultural experience' and 'education training and investigation' (five and six, respectively). 'Aesthetic experience', 'health and well-being', 'water flow regulation' and 'water quality regulation' were addressed in 15 or more papers (15, 16, 17 and 20 respectively) and lastly 'recreation and tourism' and 'habitat and population maintenance' had the greatest number of papers (26 and 33, respectively).

The grey literature selected was almost entirely from the United Kingdom (with only one EU-wide study) and largely took the form of reviews (with two observational studies). 'Water flow regulation', 'water quality regulation' and 'habitat population and maintenance' were the ecosystem services most represented (six, five and five grey literature items), followed by 'recreation and tourism' with three items and 'health and well-being' with one item.

The QSR revealed that the amount of evidence for river asset condition and its impacts on ecosystem service and benefits provision available in the scientific literature varied greatly, depending on the type of ecosystem service (see Table 5 where a RAG rating is used to show the relative strength of evidence assessed through expert opinion and amount of papers found for each ES). The ecosystem services for which the most evidence was found were habitat population and maintenance, aesthetic experience, health and well-being and recreation and tourism. For water for drinking, water flow regulation and water quality regulation, a smaller amount of evidence was found, and very little was found for all the remaining services. Findings of our review are presented below, individually, for each ecosystem service, although there is inevitably some overlap between these, particularly within the regulatory services and within the cultural services. Findings are also presented in knowledge map

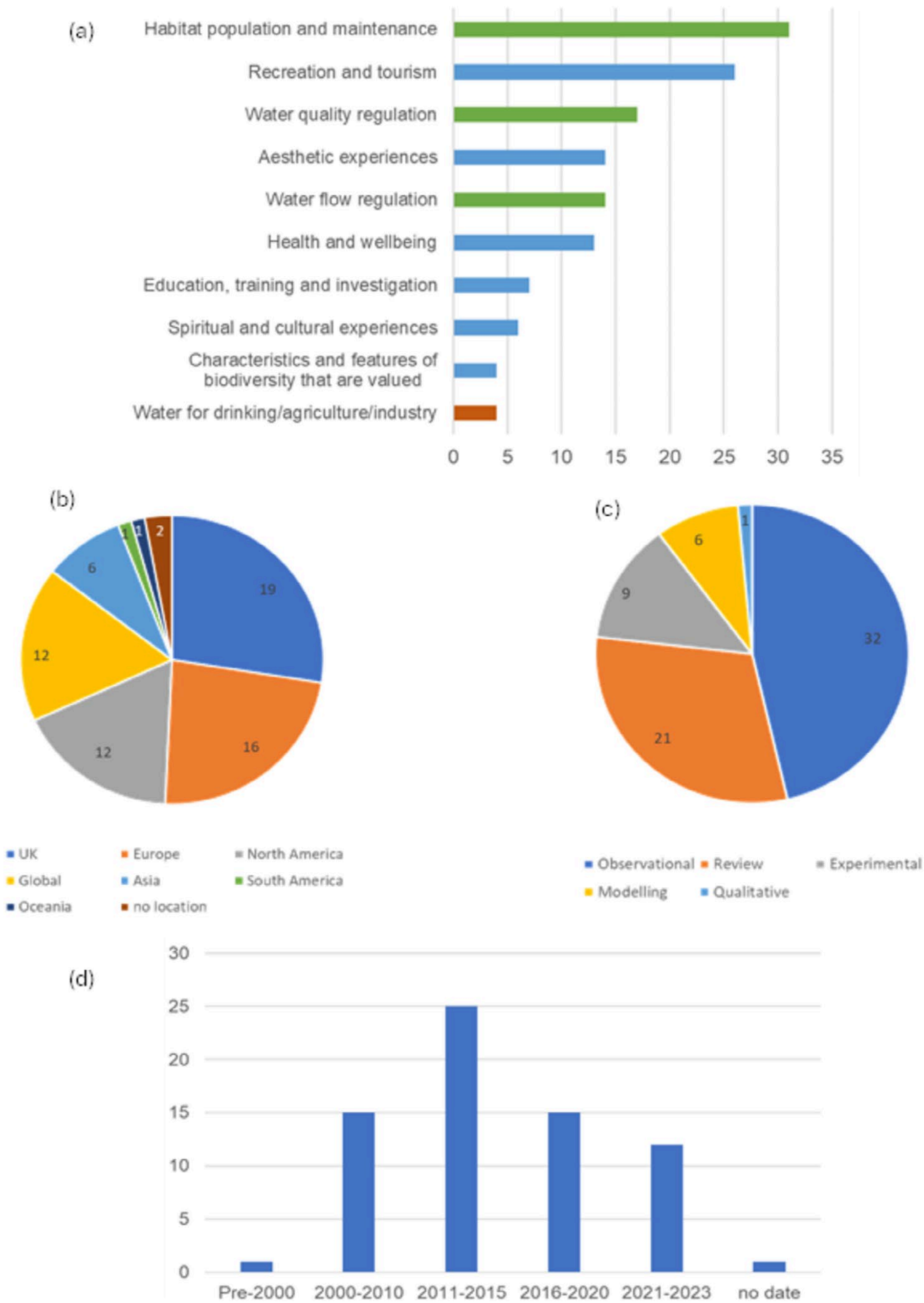

FIGURE 4 | Summary of the knowledge map. Number of studies by ecosystem services (a) where green indicates regulating services, orange for provisioning and blue for cultural services, geography (b), type of study (c) and year published (d). [Color figure can be viewed at wileyonlinelibrary.com]

summary tables (see Supporting Information 5), showing the aspect of condition considered and the relationship identified with ecosystem service provision.

3.2 | Provisioning Services

3.2.1 | Water for Drinking, Agriculture and Industry

Water abstraction is the process of taking water from a natural source for human use. In the context of this service, it is important to recognise that while the condition of a river itself may influence the amount of water a river can provide for abstraction, the condition of the whole catchment system, climate and weather patterns will have a more significant impact on it. The process of water abstraction can have a significant impact on a river's ecosystem and condition, especially when performed excessively or without proper regulation. Experts rate interventions related to infrastructure and intensive land use as having negative effects on the availability of water for agricultural, industrial use or for human consumption (except for dyke relocation) and consider that restoration of lateral connectivity to the floodplain and renaturalisation of banks and vegetation can improve water availability

TABLE 5 | Summary RAG rating (Red = low, Amber = medium, Green = high) showing the strength of evidence found in the QSR, evaluated through expert assessment.

Ecosystem service	Strength of evidence
Water for drinking, agriculture and industry	Red
Water flow regulation	Amber
Water quality regulation	Amber
Habitat and population maintenance	Green
Characteristics and features of biodiversity that are valued	Red
Aesthetic experiences	Green
Health and well-being	Green
Recreation and tourism	Green
Education, training and investigation	Red
Spiritual and cultural experiences	Red

(Schindler et al. 2014). The hydrogeomorphological state of a river also affects the water availability: water storage is high in anastomosing (type of river with multiple, interconnected, coexisting channel belts on alluvial plains), medium in meandering and low in leveed, constricted and braided rivers (Thorp et al. 2010).

3.3 | Regulating Services

3.3.1 | Water Flow Regulation

The water flow regulation service refers to the hydrological cycle, regulating water flow (including flood control, and coastal protection) and the capacity of ecosystems (e.g., vegetation, soil) to retain water and release it slowly. Regulating the flow of water is often artificially achieved through the construction of dams, reservoirs, weirs, locks, levees and other infrastructure that alter natural flow patterns (Lian et al. 2012). Dams, for example, can reduce the natural flow variability of a river, causing downstream areas to experience lower flows during dry periods and higher flows during wet periods (Mohamoud et al. 2009), and vice versa can reduce flow during wet periods; this is desirable as it can provide benefits such as flood control, irrigation and hydroelectric power, but it can also have negative impacts on the ecosystems and communities upstream, changing sediment regimes and acting as a barrier to fish passage.

A consistent finding in the literature is that greater naturalness of the riparian habitat and the absence of artificial structures (for mineral resource extraction, navigational infrastructure or built-up areas) greatly helps in achieving flood regulation without harming downstream ecosystems, compared to infrastructure-based methods for water retention. While increasing naturalness is the optimal solution for water flow regulation, this is constrained by locations of human settlements and space available, meaning infrastructure based approaches are necessary to protect humans and property. Expert-based assessments suggest building of infrastructure or hard surfaces and intensive land use are bad for water flow regulation capacity of rivers, while restoration and rehabilitation measures increase the service (Schindler et al. 2014). A lot of evidence has been collected around the concept of ‘working with natural processes’ (Burgess-Gamble et al. 2018), but it is beyond the scope of this QSR to review this. However, other examples support this concept. One study (Hanczaruk and Kompała-Bąba 2019) demonstrated how the concreting of the banks, urban development and the removal of riparian forest, in anthropogenic sections of a Polish river, increased average annual flow by twofold (mean annual flow from 3.0 to 6.41 m^3/s), compared to semi-natural river sections. Increasing riparian vegetation has been shown to have positive effects on water flow regulation, slowing the flow of water as it moves towards the river (Natural England 2015). Simulation studies also show lower flow speeds and flood peaks in restoration scenarios (Burek et al. 2012).

The amount of sediment moving within a river system can impact water flow. Sediment from agriculture and urban land uses reduces river conveyance, which can, in turn, increase flood risk (Stone and Shanahan 2011). In the United Kingdom, data have been collected on hydrology, river habitats, invertebrates, geomorphology and sediment across five river sites (Bettess et al. 2011), showing sediment maintenance can modify water flow, with different impacts recorded across sites. For example, dredging reduced flow type diversity (e.g., patterns on the water surface, velocity, flow direction and influence of river bed substrate), artificial riffle creation increased flow type diversity and vegetation maintenance modifies flow condition (Bettess et al. 2011).

The phase of development of a river determines its capacity for flood alleviation. In anastomosing rivers, water is diffused over the floodplain; thus, flood peaks are maximally attenuated. A reduced ability for flood attenuation is found in sinuous, single thread and laterally active rivers where flood and drought refugia are reduced but still present. In channelised and quasi-equilibrium stages of river evolution, flood and drought refugia are limited; thus, the capacity for flood attenuation is minimal. The intermediate stages of the river evolution model (degrading, arrested degradation, degradation and widening, renewed incision and aggrading and widening) do not seem to provide significant flood alleviation benefits (Cluer and Thorne 2014).

Restoration and rehabilitation projects generally improve water flow regulation capacity (Schindler et al. 2014), especially those reconnecting rivers and floodplains. Restoration work comprising improved habitat, opening of obstructions, removal of a spillway and deculverting in the River Glaven (United Kingdom) gave the river a more natural hydrology, improving water flow regulation. For example, a modelling study comparing a near nature-state floodplain with a scenario where the riverbed is straightened, floodplain terrain is flattened and surrounding land use changed to arable reveals the scenario had a 36% reduction in water retention volume compared to a near nature-state (Pithart et al. 2010).

Beaver reintroduction has also been shown to be an important tool for flood amelioration (Nature Scot 2017). Beaver dams impound flow by increasing open water extent from which all the other impacts follow; these include increased surface and subsurface water storage, altered flow hydrology and geomorphic heterogeneity (Larsen et al. 2021). In England, Beaver dams were monitored, and during storms, the flow of water was reduced and the lag time between rainfall peak and flow peak was increased, indicating flow attenuation; even more impressive was the effect recorded during the largest storms, showing average flood flows were reduced by 60% (Puttock et al. 2021). A similar effect is achieved with riparian woodland, which, through the production of woody debris, decreases water velocity, increasing the travel time of water across the catchment (Mott 2006).

3.3.2 | Water Quality Regulation

A lot of research has been carried out on factors affecting water quality regulation, which is defined as the regulation of the chemical condition of fresh waters by plant or animal species that enable human use or health. Widely understood are the problems related to the microorganisms present in human and animal waste products (particularly for drinking water quality), eutrophication due to excess nitrogen and phosphorus from agriculture and urban areas and the presence of toxic heavy metals that is made worse by acidification (Lundqvist and Falkenmark 2000). However, these relate to the causes of poor water quality and not the ecosystem service of water quality regulation delivered by plants and animals in or close to the river. Hence, these types of study are not reviewed in depth here.

These water quality issues are made worse by human interventions related to extraction, infrastructure and intensive land use (Schindler et al. 2014). Water abstraction, for example, can cause changes in the concentration of dissolved minerals, nutrients and pollutants, and the higher the abstraction ratio, the less water remains in the stream, reducing the dilution effect and the self-purification capacity (Lundqvist and Falkenmark 2000). A study investigated the treatment cost per unit of wastewater by a sewage treatment plant to quantify the impact of hydropower facilities and revealed that an extra 3,550,000 yuan (c. £400,000) was needed to pay for extra treatment costs related to increased water pollution at one of the sites (G. Wang et al. 2010).

Organisms naturally present in rivers are capable of maintaining water quality, and generally, water quality is positively related to biodiversity (Ricketts et al. 2016). For example, though other pathways to nitrogen loss exist, respiratory denitrification by bacteria is thought to be the main nitrogen loss mechanism in freshwater ecosystems (Heathwaite 2010). Excess nitrates from fertilisers and human and animal waste constitute a threat to the safety of our river waters. Rivers that have more agriculture in the catchment have more nitrogen in water, while those catchments where forest is more abundant have lower nitrogen levels (Yao et al. 2016), although again this is driven by processes in the catchment rather than in the channel or riparian zone.

Restoration and rehabilitation projects generally have positive effects on water quality (Schindler et al. 2014) and while these interventions may alter the delivery of the ecosystem service, often they can reduce the pressure and need for this ecosystem service. Urban stream restoration, using reedbed creation in Mayesbrook Park (London, UK), for example, has been shown to improve water quality (Everard and Moggridge 2012). A high-level review of existing evidence reports that excluding livestock, reducing canalisation and increasing planting of riparian vegetation have positive effects on water quality (Natural England 2015). The addition of riparian trees, for example, can improve water quality by removing added phosphorus and nitrates before they enter the water and acting as a physical barrier to prevent pesticides from reaching watercourses (Woodland Trust 2016). While the beneficial effect of riparian woodland on water quality is understood, a better quality riparian woodland does not necessarily provide additional benefits to water quality; other factors such as the habitat adjacent to the riparian woodland strip and the habitat composition within the catchment are more important factors affecting service delivery than riparian woodland quality (Terrado et al. 2015).

High-level synthesis of studies of woody debris in rivers reveals that woody debris can have a positive impact on water quality via the removal of fine silt from the water system (Mott 2006). The addition of dead wood to increase the complexity of a river showed that restored parts of the stream had a greater ability to retain coarse benthic organic matter which, in turn, positively affected water quality, while coarse particulate organic matter breakdown rates were not affected. The longer water residence time caused by the slower flow enhanced the uptake of NH_4 (ammonium) and PO_4 (phosphate) (Acuña et al. 2013). A qualitative assessment of beaver introduction to the River Leven and River Forth catchments in Scotland suggests water quality is improved after beaver translocation; through dam creation that in turn leads to wetland creation, runoff is reduced causing fewer contaminants to reach the water body (Nature Scot 2017).

Other types of restoration projects that do not directly impact rivers can still affect freshwaters. A comparison of drained peatland, recently blocked drains and intact peatland streams shows changes in physicochemical variables such as higher concentrations of fine particulate organic matter (FPOM), nitrogen trioxide (NO_3) and suspended sediment concentration (SSC) in drained sites compared to intact peatland; intact and drain-blocked sites have overall higher water quality (Ramchunder et al. 2012).

The changes a river goes through during its evolution profoundly affect its ability to purify water. Anastomosing/anabranching rivers forming network channels are considered to have a high capacity to cycle nutrients and store sediments, producing high water clarity; the large amount of vegetation around network channels also keeps water temperature low. In sinuous single-thread and laterally active rivers, sediment storage and nutrient cycling are reduced compared to anastomosing rivers, but while vegetation is still present to provide shading (Cluer and Thorne 2014). Channelised rivers have limited capacity for nutrient cycling given the simplification of the channel, and lower water clarity, hyporheic exchanges (exchanges in transitional areas where groundwater and surface water meet) and temperature amelioration compared to the previous river evolutionary stage (Cluer and Thorne 2014). General improvement in water quality related to sedimentation of particulate matter and biological water quality (based on macroinvertebrate counts) is greater in non-channelised watercourses; heavy-metals concentration is the only aspect that does not differ between channelised and non-channelised rivers (Lundy and Wade 2011). In the degrading phase of a stream evolution, nutrient cycling is further reduced and becomes ineffective in arrested degradation phases. Nutrient cycling then becomes dysfunctional in degraded and widening rivers with further reductions in renewed incision phases. In further phases such as aggrading and widening rivers, the capacity to deliver the service improves again due to features such as bars developing and vegetation emerging. The clarity of the water further improves in quasi-equilibrium stages while nutrient cycling remains weak; laterally active rivers, instead, have moderate water clarity and increased nutrient cycling (Cluer and Thorne 2014).

Water quality, sedimentation and water temperature regulation are linked. Hydromodification (alteration of the natural flow of water through a landscape) has been associated with general water quality degradation, as it increases water temperature and sedimentation (Mohamoud et al. 2009). Agriculture and urban land use also affect water quality through increased sediments, which decrease dissolved oxygen content (Stone and Shanahan 2011). Everard (2010a, 2010b) describes the effects of restoration work on the River Avon in Wiltshire (where the river was placed at the centre of the floodplain and secondary channels created) and on the River Glaven in North Norfolk (reconnecting interrupted reaches through naturalising the river channel); ecosystem service delivery was assessed, and both catchments saw a positive effect of restoration on water quality through increased sediment capture.

3.3.3 | Habitat Population and Maintenance

This service is defined as the presence of ecological conditions (usually habitats) necessary for sustaining populations of species that people use or enjoy, and the ability of rivers to function as wildlife corridors, enhancing connectivity and resilience of populations. A lot of papers were found for this ecosystem service. Restoration and rehabilitation projects benefit river habitats (Griffiths et al. 2008; Schindler et al. 2014); this is achieved in several ways, but often it happens by increasing habitat diversity and revegetation (Everard 2010b). Restoration projects, however, sometimes come with infrastructure for recreation which may not be beneficial to riparian ecosystems (Schindler et al. 2014), allowing visitors to impact habitats and disturb wildlife. It has been suggested that in restored river sites that see increased visitor numbers, a reduction in hours or days the site is accessible would not affect recreation but would help flora and fauna; areas with dense vegetation would also discourage visitors from accessing that part of the site, creating wildlife refugia (Kaiser et al. 2021).

Riparian vegetation is important in supporting riparian habitats; factsheets from Natural England provide evidence on how excluding livestock and reducing canalisation are strongly associated with greater riparian ecosystem health (Natural England 2015). Riparian woodland, in particular, plays a crucial role in river ecosystem health. Riparian trees positively affect habitat and population maintenance as these provide structural complexity and may connect areas of woodland, creating wildlife corridors (Woodland Trust 2016). Fish sampling in Brazil revealed the functional and taxonomic composition of species to be greater in restored rivers: specialised and intolerant fish species have been found to occupy forested areas (preserved areas) and to be less abundant in areas with intermediate conditions; degraded areas were instead mostly occupied by detritivores, tolerant and small-sized species (Casatti et al. 2012). Riparian woodland is also a source of woody debris which creates niche habitats with differing temperatures and water flow, providing shelter for fish and invertebrates as well as larger species like otters (Mott 2006). In a restoration project, the addition of dead wood to a stream channel increased fish biomass (Acuña et al. 2013). For similar reasons, beaver translocation in Scotland has been suggested to have positive effects as this species acts as a catalyst for woodland creation (Nature Scot 2017).

Interventions that stop peatland drainage have been shown to benefit riparian and in-stream organisms as well. A study in northern England found that undrained sites have higher benthic macroinvertebrate taxon richness compared to drained sites; the abundance of pioneer species such as Ephemeroptera is similar in drain-blocked and intact sites, while the abundance of Plecoptera and Tricoptera is still different between intact and drain-blocked sites, suggesting a lasting impact of drainage has not yet allowed the drain-blocked sites to recover (Ramchunder et al. 2012).

Biodiversity and the functional groups supported by rivers change with river evolutionary stages. By changing the extent of open water area, changes in species assemblages are induced and primary productivity is affected (Larsen et al. 2021). Biodiversity and the proportion of native biota are thought to be greater in anastomosing river sections (Thorp et al. 2010), as these support high primary productivity (Cluer and Thorne 2014); sinuous single-thread channels have reduced morphological complexity and bank length (compared to anastomosing rivers) and see a reduction in biodiversity and productivity, while the floodplain vegetation communities change from wetland to more terrestrial ones. In the following evolutionary stage, species are unable to adapt to the disturbance caused by the channelisation, so trophic diversity and species richness decrease dramatically together with productivity; floodplain vegetation that is disconnected from the channel will further shift towards terrestrial. In the degradation phase, benthos is destroyed, species richness and productivity decrease further, and a lower water table negatively affects floodplain vegetation. In the arrested degradation phase, some riparian plant communities are able to start early succession, and while productivity and species richness remain low, some species will colonise the channel; a similar scenario continues in the degrading and widening phase. Plant communities are dysfunctional in the renewed incision phase as the cycle of incision prevents recovery of habitats, the proportion of native biota is still low and productivity collapses. Productivity recovers in aggrading and widening rivers, which also see a return of aquatic, emergent and riparian plants; further increase in productivity is seen in quasi-equilibrium stages which also see a small improvement in biodiversity and establishment of aquatic, emergent and riparian plant communities. Finally, laterally active rivers see an improvement in biodiversity, moderate productivity and increased extent of riparian and floodplain plant communities (Cluer and Thorne 2014).

Urbanisation imposes enormous changes on the form and function of the riverine landscape (Gurnell et al. 2007). Increased proportions of impervious surfaces in the surrounding land, stormwater drainage systems, pollution and channel modifications alter catchment hydrology, flows, sediment regimes, water quality and lateral connectivity (Gurnell et al. 2007; Paul and Meyer 2008; Walsh et al. 2005). These in turn impact on the ecology and biodiversity of urban river systems, which commonly display reduced biotic richness, and increased dominance of the species tolerant of such conditions. This set of environmental stressors and the resulting biological impoverishment has been referred to as the 'urban stream syndrome' (Walsh et al. 2005), and these effects extend into the riparian zone through impacts on hydrology, soils and vegetation (Groffman et al. 2003). Hydromodification accompanying urbanisation causes water quality degradation (higher water temperature, lower dissolved oxygen, increased sedimentation) that in turn affects aquatic habitat structure causing loss of aquatic populations (Mohamoud et al. 2009). A comparison of Polish river sections shows plant communities are richer in seminatural sections compared to anthropogenic ones (Hanczaruk and Kompała-Bąba 2019). Intense management of streamside vegetation, such as removal of trees and bushes to allow construction projects along the river, alters the community structure, for example, in Rekolanoja, Finland, the proportion of bird species inhabiting lush vegetation and deciduous forests had declined, and the proportion of species common in urban habitats had increased (Yli-Pelkonen et al. 2006). In some cases, urban rivers are channelised and the high flow velocity does not allow the establishment of permanent vegetation which in turn does not contribute to primary productivity (Lundy and Wade 2011).

Diffuse pollution from agriculture also badly affects river flora and fauna, but in some instances, interventions related to urbanisation can improve river habitats. The effects of anthropogenic land use change from agriculture to suburban on a headwater stream in Poland over 44 years were examined and found an increased habitat and population diversity as sewage systems were improved as a result of urbanisation and reduced agricultural pressure (Bylak et al. 2022).

Agriculture and urbanisation place some of the greatest pressures on river ecosystems. Note that these pressures, although not a direct measure of river condition, can be used as indicators of condition; hence, the evidence linking these pressures to habitat population and maintenance is reviewed further below. These pressures operate at a catchment scale; as discussed earlier, rivers are profoundly affected by their catchments, and although the review is focusing on river condition and ecosystem services, it is not possible to consider the condition of a river in isolation from its catchment (Aitken 2003).

Nitrogen and phosphorus enrichment is the main issue arising from agriculture in the river catchment as these are the main drivers of primary productivity in aquatic habitats. Nitrogen-fixing cyanobacteria seem to meet some seasonal limitations, and the focus of control measures has so far been on phosphorus from point and diffuse pollution, which induces excessive algal growth leading to shading and thus reducing the growth of other plants (Heathwaite 2010), leading to de-oxygenation on decomposition, which negatively impacts the animal community. It is not clear whether urban or arable land use is impacting more on river ecological status; in West Virginia, analysis of bacterial community richness in rivers across differing land uses reports a higher resilience to agriculture than urban land use (Martin et al. 2021), but these effects can be highly context-dependent.

Excess sediment also has a negative impact on riparian communities. Negative impacts of sediment from agriculture and urban land use affect a variety of ecological groups, including fish, aquatic plants and macroinvertebrates; large amounts of fine sediments can damage fish gills, reduce food availability and reduce dissolved oxygen content (Stone and Shanahan 2011). A four-factor experiment across 64 stream mesocosms in China was carried out to assess the effects of sedimentation, flow velocity and nutrient enrichment on invertebrate communities. Results indicated that invertebrate abundance decreases with increased sediment and that, while flow velocity and nutrient enrichment affect community composition, the main factor shaping communities was sediment (Juvigny-Khenafou et al. 2021).

Human interventions in rivers that are related to extraction, infrastructure and intensive land use have negative effects (with the exception of fishery-intensive interventions and dyke relocations; Schindler et al. 2014). One of the main effects of water abstraction on rivers, for example, is the reduction of water flow, which can lead to the drying up of the riverbed. This can have devastating effects on the river's ecosystem, affecting the fish population, plant life and other aquatic species that depend on the river's water flow to survive. Furthermore, the artificial structures required for water abstraction act as a barrier for species, altering connectivity (Lundqvist and Falkenmark 2000).

Greater diversity indicates greater ecosystem productivity, and this is affected by toxic pressure. A study estimated the economic impacts of polluted sediments based on the average ecosystem service value provided by estuarine or freshwater ecosystems. The differences in total ecosystem service value among biomes could generally be explained by the differences in productivity, with higher productivity resulting in higher ecosystem service values (J. Wang et al. 2021).

Sand mining negatively affects the ecological communities of rivers (Ekka et al. 2020). Mining contaminates water and negatively affects fish assemblages (notable are histopathological lesions on trout), fisheries production and reduces the diversity of the benthic community as a whole (Jordan and Benson 2015).

Pollutants such as heavy metals from industry and other sources are damaging to aquatic life (e.g., chromium, copper, silver and zinc), and the problem is exacerbated by acidification (Lundqvist and Falkenmark 2000). In upland freshwaters, acidification is the most significant factor affecting ecological health, reducing species richness and causing the loss of acid-sensitive organisms across all trophic levels as it affects some species directly (via a change in the water chemistry) or indirectly (changing food availability or habitat) (Allott 2009).

Invasive species represent a different kind of threat to the river habitat. Field surveys of Scottish rivers found, for instance, invasive plant species to have a high negative effect on macroinvertebrates (Seeney 2019).

3.4 | Cultural Services

3.4.1 | Characteristics and Features of Biodiversity That Are Valued

This service refers to the things in nature that we think should be conserved because of their non-utilitarian qualities (existence value) and those things that we want future generations to enjoy or use for whatever reason (option or bequest value). Limited evidence was found linking river condition to this ecosystem service, but what was found is that streams are areas where people are in contact with nature and are valued highly (Yli-Pelkonen et al. 2006). A questionnaire administered in England and Wales found people are willing to pay to improve freshwater condition; local improvements were valued much more than national improvements and the improvement from medium to high condition was valued more than poor to medium condition (Metcalfe et al. 2012).

3.4.2 | Health and Well-Being

This ecosystem service refers to the role of natural landscapes and urban green and blue space in maintaining mental and physical health. Our physical and mental health are inextricably linked to our environment, and greater exposure to blue spaces promotes physical activity and improves general health and well-being (Gascon et al. 2017). Rivers, more than other green spaces, have been shown to improve mental well-being (Bergou et al. 2022). Interviews with residents in southern Finland revealed that streams are desirable environments offering silence (in otherwise noisy and stressful urban environments), relaxation and the water moving in the stream is considered pleasing (Yli-Pelkonen et al. 2006). In the United States, salivary cortisol measures combined with GPS data and surveys of hikers revealed that visitors to riparian areas that were more biodiverse and had higher aesthetic value had decreased cortisol and improved well-being compared to visitors to other habitats. Wildlife presence was not related to lower cortisol, but hikers attributed higher aesthetic quality to areas with high biodiversity. The authors suggest that since biodiversity is a proxy for ecological function, hikers gain more well-being benefits when the habitat has a 'natural feel' (Opdahl et al. 2021). Interestingly, biodiversity surveys and questionnaires administered to the public in the United Kingdom show that in ecologically complex habitats such as riparian areas, the public is ill-equipped to judge species richness (with the exception of birds); thus, while a positive relationship between well-being and perceived biodiversity was revealed, the study did not find a relationship between well-being and species richness (Dallimer et al. 2012). These studies show that people gain greater health and well-being benefits from places that they perceive to be more natural, more aesthetically pleasing or more biodiverse, but this is not necessarily related to measured biodiversity.

The changing flow of water can impact the accessibility of rivers and their banks, preventing people from using the space for exercising or enjoying the mental health effects of the river. In India, the increased flow of water in the monsoon season has been shown to affect health and well-being as access to the River Beas is limited during that period (Ncube et al. 2021). Evidence also shows flood risk to be linked to psychological effects such as anxiety when it rains, flashbacks to past flood events, anxiety about future flood events and long-term physical effects like heart conditions (Miller et al. 2012). To reduce these impacts, strengthening of flood defences (though we have already seen that nature-based techniques can be better than hard flood defences, which have trade-offs for other benefits), flood resistance and resilience and the communication of these interventions to the public are key (Miller et al. 2012).

When river waters are polluted, these can lead to various health problems. More than 100,000 chemicals, including persistent pollutants, are present everywhere in the environment and are found in human and animal tissue samples (Lundqvist and Falkenmark 2000). Heavy metals extracted and produced for industrial, agricultural and other purposes have severe adverse health effects, which are exacerbated by acidification that makes them more bioaccessible (Lundqvist and Falkenmark 2000). Mining-related contaminants such as cadmium, arsenic and radon in river waters have been associated with higher rates of cancer (Jordan and Benson 2015). Diffuse pollution from agriculture and livestock increases nitrogen and phosphorus concentrations, which affect the quality of drinking water (Heathwaite 2010); nitrates have also been reported to be especially dangerous for infants (Lundqvist and Falkenmark 2000). The health effects of pollution are also worsened by intense water abstraction, making pollutants more concentrated (Lundqvist and Falkenmark 2000). Polluted water can also affect the quality of food, as fish and other aquatic species absorb harmful pollutants that can accumulate in their tissues (Geng et al. 2019; Maurya et al. 2019).

Waterborne diseases and pests are also a big threat to public health. In the United Kingdom, surfers and wild swimmers reported sewage pollution and dry spills to have caused vomiting, sickness and Leptospirosis after swimming (Slack et al. 2022), in rivers as well as in coastal areas. The presence of riparian woodland has the potential to regulate water temperature, in turn reducing the proliferation of some organisms causing diseases such as *E. coli* (Mokondoko et al. 2016). Excluding livestock from riparian areas has also been shown to reduce the abundance of *E. coli* in waters (Natural England 2015).

3.4.3 | Aesthetic Experiences

This service refers to the value people place on the beauty of nature. Urban rivers have high aesthetic value compared to other types of urban habitats despite being impacted by human activities (Yli-Pelkonen et al. 2006).

The literature analysed shows that features of rivers that are man-made and give a non-natural feel decrease the aesthetic experience. Expert assessments report interventions related to extraction, infrastructure and intensive land use (e.g., water and mineral resource extraction, traffic and navigational infrastructure, energy conversion) reduce landscape aesthetics, with the exception of fishery extensive management and dyke relocations (Schindler et al. 2014). An observational study in southeast China using a monetary valuation method where the cost of travel to a tourist spot near a hydropower facility is used as a proxy for the aesthetic value of the site (G. Wang et al. 2010) shows landscape aesthetics to be negatively affected by hydropower. The presence of man-made infrastructure that allows access to a site is instead perceived positively when the naturalness of the site is low (Junker and Buchecker 2008).

The majority of restoration and rehabilitation projects reported beneficial outcomes in relation to river aesthetics, with the following exceptions: the removal of topsoil, recreational infrastructure, removal of dams and weirs and lowering of the floodplain (Schindler et al. 2014). Analysis of social media content reveals that restored river sites are more appreciated by the public, especially where more open landscapes are present (Kaiser et al. 2021). Channelised urban rivers are viewed as less aesthetically pleasing (Lundy and Wade 2011), while meanders are more attractive. The addition of meanders and increased opportunity for wildlife sightings (especially birds) in the River Skerne in England increased its 'natural feel' making it more attractive to the public after rehabilitation (Åberg and Tapsell 2013). Similarly, semi-structured interviews with locals revealed scenic beauty to be increased after the restoration scheme in the River Dearne (England) due to the environment being cleaner, increased morphological diversity and enhanced habitat quality for flora and fauna (Westling et al. 2014). The scale of the restoration efforts also seems to play a role in the aesthetic experience, with larger-scale projects being more positively viewed compared to smaller restoration projects (Poledniková and Galia 2021).

There is consensus that more ecologically valuable rivers are considered more aesthetically pleasing; however, public perceptions are strongly context-dependent and are informed by the cultural background of the individual, and visual preferences often do not reflect changes in ecological condition (Arsénio et al. 2020). A photo questionnaire of braided rivers with variable amounts of water and gravel revealed a gap in perceptions between scientists and civil servants and the wider public. Scientists and civil servants were aware of the value of the functional processes occurring in braided rivers, while the wider public did not seem to appreciate it, seeing large amounts of gravel in riverscapes as not aesthetically pleasing, almost considering it an 'alien' element in need of management actions (Le Lay et al. 2013). Studies suggest this perception gap can be closed when the public has the opportunity to learn, for example, wood reintroduction in rivers for restoration is considered dangerous and not aesthetically pleasing in those countries where this restoration approach has not been used, while in countries where the public has already experienced the approach, perceptions are more positive (Piégay et al. 2005). People are able to detect small iimprovements in eco-morphological quality when these happen in rivers changing from channelised with narrow banks to more meandered with larger banks (Junker and Buchecker 2008), but other types of improvements may not be as obvious to the general public.

Water levels also affect people's aesthetic perceptions. Ncube et al. (2021) found that river provision of aesthetic experience is highest at higher water levels (during and post-monsoon) in India and decreased over time with increased water abstraction and pollution. It is possible that people in the United Kingdom also find lower water tables to be less attractive, but there is little evidence to confirm this, and winterbournes in their dry phases still provide some aesthetic experience (Datry et al. 2018). Sediment has also been reported to impact river aesthetics, with sites with more fine sediment and high suspended loads in the river attracting fewer visitors (Stone and Shanahan 2011) showing people prefer clear waters.

3.4.4 | Education, Training and Investigation

Natural areas provide numerous opportunities for study, education and research, as well as references for monitoring environmental change.

Rivers are an important part of the local environment for teachers and pupils to learn about nature (Yli-Pelkonen et al. 2006), for anglers to learn about aquatic life (Snyder 2007) and for the wider public to learn about nature.

Given the chance to choose outdoor settings to educate pupils, teachers prefer rivers more than other types of urban nature, although rivers are also seen as more hazardous (Simmons 1998), measures improving safe access to rivers would be beneficial for this ecosystem service. An expert-based assessment found positive effects of the following interventions on education and training: sediment addition onto the river bed, removal of bank fixations, lateral floodplain reconnection, channel oxbow and pond creation, creating natural habitat from forest, agro-land or extraction sites, control of invasive species, creation of gravel banks, land use extensification, recreational infrastructure, dyke relocation and extensive fisheries (Schindler et al. 2014), confirming local schools derive great benefits from local stream restoration work (Everard and Moggridge 2012). Management options considered to have negative effects were also identified in: bank or bed stabilisation, channel corrections, intensive fishery, agriculture and forestry practices, navigational infrastructure, settlement and traffic infrastructure (Schindler et al. 2014).

As regard the influence of water flow level, Ncube et al. (2021) found that the provision of formal and informal learning opportunities in India does not change with water levels over the year and has instead decreased over time with increased water abstraction and pollution.

3.4.5 | Recreation and Tourism

Rivers are important areas for recreation and physical activity (Yli-Pelkonen et al. 2006). Rivers where perceived naturalness is high are used more frequently for recreational purposes. A study mapping recreation along rivers shows the delivery of the service is positively related to naturalness, water clarity and water flow (Kerr and Swaffield 2012).

Through increased landscape attractiveness, restored river sites see more recreational activity (Everard and Moggridge 2012; Kaiser et al. 2021; Schindler et al. 2014). Poledniková and

Galia (2021), for example, found an increase in perceived recreational function from photo-simulated river restoration scenarios. Conversely, when landscape attractiveness is decreased through the addition of artificial structures, fewer visitors are expected (Schindler et al. 2014). In southeast China, travel-cost methods reveal the value of recreational activity to be lower in sites close to hydropower facilities (G. Wang et al. 2010) and channelised rivers have been shown to have low potential for recreation compared to natural rivers (Lundy and Wade 2011; Natural England 2015). However, artificial structures that improve access to the river enhance the delivery of recreation and tourism (Åberg and Tapsell 2013).

Surveys of public perception of before and after rehabilitation of the River Skerne in England show the visitation rate increased after river rehabilitation, mostly due to the opportunity for wildlife watching. The addition of footpaths, bridges and the availability of a circular path increased walking, cycling and jogging, and despite being artificial, these features were considered crucial for the enjoyment of the river (Åberg and Tapsell 2013).

Another aspect of access to a site is closeness to large settlements; rivers that are closer to big cities receive more visitors (Doi et al. 2013). A national scale study across England and Wales revealed that the effect of closeness to populations has a bigger effect on recreational use than site-specific, more local factors (such as Environmental Quality Index, taxon richness, freshwater biodiversity); these factors indicate that regional patterns in visitation are driven by population and distance, whereas high river quality is more important at the local scale (Holland et al. 2011).

Relationships between river condition and recreational use also differ depending on the type of activity. In Japan, lower biodiversity and ecosystem health (across 109 sites) were related to low recreational use, but fish diversity, habitat structure and water quality were the factors affecting fishing and playing in rivers, while the number of people walking and engaging in sports was related to water quality and the size of the surrounding population (Doi et al. 2013).

In the United Kingdom, water quality data from WFD were combined with surveys of walking, boating, fishing and swimming activities. Analysis shows walking to be strongly associated with good and high water quality status (despite being the activity having the least contact with water), while the other activities were not predicted by WFD. However, some of the indicators used in assessing WFD status may not be relevant to recreation; while the presence of litter may discourage swimmers, this has little impact on the WFD status, and what is considered a good water temperature (for WFD standards) may not be ideal for swimming. Similarly, poor water clarity (not appreciated by swimmers, as they prefer clear water; see Miller et al. 2012) is not always an indicator of poor (or good) ecological health. The authors argue that the wider public is ill-equipped to distinguish between WFD status and that it is easier to distinguish between poor and medium WFD status than between good and high status, making the relationship between WFD status and recreation non-linear. For sports such as swimming, boating and angling, the presence of infrastructure allowing the sport to take place appears to be the most important factor rather than water condition, while walkers can be more responsive to WFD status given the lack of such constraints (Ziv et al. 2016).

Angling is closely associated with the presence and abundance of the species or functional group of interest rather than habitat structure (Smith et al. 2017), but it tends to be higher when river waters are clearer (Miller et al. 2012). Fish populations are affected by water quality (Lundqvist and Falkenmark 2000) and available habitat for reproduction. A modelling study comparing a near-nature state floodplain with a simulation where the riverbed was straightened, floodplain terrain flattened and land use changed to arable resulted in the scenario having a 50% reduction in fish catch due to a lack of suitable habitat for fish reproduction (Pithart et al. 2010). The addition of dead wood to restore the complexity of a stream channel, forming dams and deflectors, has instead been shown to increase opportunities for angling (Acuña et al. 2013). Fish catches have also been shown to be negatively affected by fine sediment deposition and high suspended loads from human sources (agriculture and urban land use; Stone and Shanahan 2011).

Some river restoration projects target the recovery of fish populations and are assumed to also affect biodiversity and improve other types of recreational activities, but this is not always the case; the type of restoration intervention carried out is crucial in determining the outcome for the delivery of ecosystem services. In Finland, habitat condition for salmonids was improved mostly by increasing channel width, and while this increased fishing opportunities, only slight improvements in naturalness and access were achieved, yielding small changes in other recreational activities (Marttila et al. 2016).

Everard (2010a, 2010b) described the positive effects of river restoration work on recreation and tourism. On the Bristol Avon and River Glaven, fish stocks were enhanced by improving spawning and nursery habitats, which led to an increase in angling, but further tourism benefits were seen from enhanced wildlife, promoting birdwatching, photography and informal recreation as well as increased wildfowl stocks potentially available for shooting. Note, however, there may be potential trade-offs between shooting and other forms of activities. The rehabilitation of the River Pajakkajoki (Finland) was aimed at enhancing the attractiveness of natural areas along the river by improving accessibility (adding parking spots, nature trails with benches and provisions for disabled people) and fish spawning conditions through the restoration of rapids, natural spawning and fry sites, as well as basins for adult fish. A survey of residents and non-residents stated that the improvement was high for both fishing and other recreation, and visitors were willing to pay for the fish habitat, although the amount was very low (< 10 euro per year; Polizzi et al. 2015).

Little evidence is available on the relationship between hydrogeomorphological condition and recreation, but recreation is assumed to be high in anastomosing, medium to low in constricted and meandering and low in leveed and braided rivers (Thorp et al. 2010). As the amount of water changes at different evolutionary stages of the river, or a riverbed becomes dry, recreational activities will be affected. In the United Kingdom, a number of paths adjacent to rivers become flooded at high water levels, thereby impacting access and recreation. Evidence of this has also been found in India; recreation and tourism have been reported to be at the highest capacity at lower water levels (when riverbanks are accessible, before the monsoon season) and the provision has decreased over time due to water abstraction and pollution (Ncube et al. 2021). Dry phases can, however, offer unique opportunities for other types of recreation such as visiting parts of subterranean rivers (Stubbington et al. 2020).

3.4.6 | Spiritual and Cultural Experiences

This ecosystem service refers to the things in nature that help people identify with the history or culture of where they live or come from or that have spiritual importance, form local identity and sense of belonging (Fish et al. 2016).

Cultural ecosystem services are often intangible and difficult to quantify, but they are vital for creating a sense of community, identity and belonging, as they contribute to social cohesion, sense of place and resilience. Spirituality is an essential aspect of human life, and it is deeply connected to nature. Many cultures around the world have traditional beliefs and practices that link them to rivers, which they consider sacred (Porta and Wolf 2021). In India, for example, the River Beas is of crucial importance in the local culture and spiritual ceremonies, but the changing levels of water due to the monsoon season and upstream abstraction do not seem to affect the provision of this service, which is high at any water level (Ncube et al. 2021). Similarly, a review of ecosystem services provided by dry and temporary riverbeds outlined the importance of dry riverbeds in spiritual and cultural heritage, particularly in stories from indigenous people, showing this ecosystem service is not significantly impacted by changing water levels (Steward et al. 2012).

In Western countries, rivers are more associated with local culture, shaping the local identity (Yli-Pelkonen et al. 2006) and are referenced in popular culture and literature. Festivals connected to rivers occur all over the United Kingdom, highlighting the importance of rivers to cultural experience, but there is a lack of evidence on the impact of river conditions on these cultural experiences, although it is likely that a minimum, perhaps moderate, condition would be required. Fly-fishing seems to be one of the few exceptions, as this sport, widely practiced in Western countries, has spiritual and quasi-religious connotations, a ‘lived religion’ according to Snyder (2007), that has produced a lot of literature. The understanding of the natural world required by this activity drives fly-fishers closer to nature, to which they start feeling more connected (Snyder 2007). Even in this case, it can only be assumed that the river condition should be acceptable for a fish population to be present for the activity to take place, although game fish generally require rivers to be in better condition than coarse fish (Kemp et al. 2011).

Expert-based assessment revealed that interventions related to extraction, infrastructure and intensive land use have negative effects on spiritual and cultural experiences, except for fishery extensive interventions and dyke relocations. On the other hand, restoration and rehabilitation programmes increase the delivery of this ecosystem service, as well as projects that improve recreational infrastructure (Schindler et al. 2014).

4 | Conclusions

The variability of the evidence across different ecosystem services highlights the degree of uncertainty regarding their overall relationship with river condition and indicates a need for further research and/or detailed investigations beyond the scope of this review.

During the workshop it was highlighted that condition can be viewed in a variety of ways. The literature review showed that there is no one single way of measuring condition since it varies depending on the ecosystem service under consideration. For example, the presence of access facilities improves the delivery of cultural ecosystem services but reduces the naturalness of the site, which may negatively affect the delivery of other ecosystem services, such as that of supporting and maintaining habitats. Condition is most commonly associated with naturalness, level of pollution, resilience, connectivity and access, and, crucially, it is strongly influenced by perception and value judgements, particularly for cultural ecosystem services. Since our aim is to understand the ability of rivers to provide ecosystem services, good condition is best defined as the state of the asset that enables high provision of the ecosystem service being assessed. We acknowledge that it was necessary to sometimes consider pressures as a proxy of condition where there was limited direct evidence on the condition element itself, as long as they enhance the ability to predict ecosystem service provision.

For many of the services analysed here, there are multiple studies that show how river asset condition is linked to ecosystem service provision, although for some river types, such as winterbournes and intermittent rivers, evidence is poor. An understanding of the factors driving the ‘characteristics and features of biodiversity that are valued’ is also extremely poor, with little evidence available for ‘spiritual and cultural experiences’ and for ‘education, training and investigation’. This is to be expected for these less tangible ecosystem services that are much harder to measure than other ecosystem services and for which additional research using more interdisciplinary approaches, including branches of social sciences, would be required. It would be possible, for example, to further investigate the use of ‘willingness to pay’ studies demonstrating how the public values features of the environment but the data is currently limited.

This review focused on 10 different ecosystem services, but a number of other ecosystem services could be of interest. Our focus was on rivers, but similar work could be extended to consider other habitats using the same methodological approach developed here.

Even when the relationship between asset condition and ecosystem service provision has been demonstrated and is reasonably well understood, the effect size related to this correlation is not. This is largely due to differences in measuring the delivery of the ecosystem service, which could be overcome by introducing standardised methods of measurement. Time delays between changing conditions and outcomes should also be factored in. Furthermore, studies very often focus on a relatively small spectrum of river types (e.g., different types of conditions measured only in urban rivers) or a range of conditions. This could be addressed by larger, more representative, landscape-scale studies.

Although evidence of links between condition and ecosystem services was generally available, there is much less evidence concerning the nature of the relationship between them (the response curve). Although a linear response is often assumed (i.e., as condition improves, delivery of the ecosystem service will also continue to improve in a similar way), this may well not be the case. The majority of the studies included in this review report either linear relationships or no relationships. It is known that relationships in nature are complex, mostly non-linear, or reach stasis or pass thresholds at some point. For example, there is some evidence that people can distinguish quite well between a river in poor condition compared to moderate condition, but are less able to distinguish between improvements beyond that. Likewise, certain activities may not be advisable when rivers are in a poor condition (e.g., fishing, swimming), but may occur once condition reaches a certain threshold. In a lot of instances when these relationships are analysed, it is normally only possible to analyse part of the range of existing conditions, as analysing the whole possible spectrum of values would require larger studies. It is then possible for some studies to find no relation between two variables, which may not mean that there is no relation between the variables, but rather that the plateau part of the relationship is being analysed, where stasis has been reached. Better modelling of these response curves might also help to identify threshold values useful for practical management.

For future research, a set of indicators for each ecosystem service should be agreed upon, standardised and measured in landscape-scale studies encompassing a variety of river types and conditions. Further investigation is needed to provide standardised indicators and measures. The standardised definitions of condition and ecosystem services are not always used in the literature, and more consistency is needed in this regard to facilitate evidence search in a methodological way.

Operational activities already make use of existing evidence to improve waterbody status, but in order to enforce environmental policies, a clear understanding of how ecosystem service delivery changes based on river condition is imperative. To achieve this, the evidence gaps highlighted in this study need to be filled so that decision makers can follow evidence-based approaches in managing rivers for ecosystem service delivery. Another key issue for river environment management is the lack of data on river asset condition. To support the spatial mapping of river condition and ecosystem services, and to guide and prioritise data collection, the Environment Agency Natural Capital Condition Indicator Mapping Phase 1 Evidence Review (Zini et al. 2023) developed a framework to identify potential indicators of river asset condition. For each ecosystem service, a series of data flow charts describing supporting processes, condition assessment methods and indicators were produced, and these were accompanied by an indicators database. These indicators are being further refined and trialled through subsequent river condition and ecosystem service map development. They provide a useful resource that highlights where there is usable data, but also highlights where there are large gaps in condition datasets, which would benefit from targeted monitoring and data collection.

A key additional outcome of the study has been the development of a logical framework and objective method to examine conditions in relation to ecosystem services. The use of synonyms and Boolean operators in our search strategy minimised the risk of bias in the search terms, which in turn increased confidence that the evidence base was providing a balanced and weighted overview of the research and a more genuine reflection of the level of congruity, heterogeneity and amount of evidence. Strength of evidence was summarised through expert opinion by the team, which evaluated the breadth, depth and significance of the evidence for each service (see Table 5). A caveat of this approach is that the quality of the evidence identified through the literature review was not fully assessed (e.g., no formal investigation in the robustness of study method or meta-analysis). The approach was co-designed by the consultancy team and the EA steering group and aimed to be transparent, reproducible and objective, offering a best-practice example of how to conduct a review of this nature. This enabled us to take a huge subject area and identify a representative sample of academic papers (supplemented by a grey literature search) to deliver meaningful results over a relatively limited review period. Co-design was an important element of this study; the review was conducted as a collaboration between the consultancy team and the EA's steering and stakeholder groups, further embedding the co-design principles and enhancing the usefulness and reliability of the outputs. It is hoped that the processes and methods developed and demonstrated for this study, and the co-design practices used, provide an exemplar for projects of this nature going forward.

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Data Availability Statement

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

Endnotes

[1] The Environment Agency (EA) is tasked with protecting and improving the environment within England and focuses on regulating major industry and waste, treatment of contaminated land, water quality and resources, fisheries, inland river, estuary and harbour navigations, conservation, ecology and managing flood risk.

[2] Natural Capital and Ecosystem Assessment (NCEA) is a science innovation and transformation programme overseen by the UK Department for Environment, Food and Rural Affairs (Defra), which spans across land and water environments. It has been set up to collect data on the extent, condition and change over time of England's ecosystems and natural capital and the benefits to society. The Environment Agency is leading NCEA delivery for freshwater, estuaries and coastal waters

(Natural Capital and Ecosystem Assessment Programme—GOV.UK, www.gov.uk).

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Supporting Information

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

Rivers as natural capital assets: a quick scoping review to assess the evidence linking river asset condition to changes in the flow of ecosystem services

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