



Riverine Natural Capital Condition and Ecosystem Service Mapping Project: project report

Chief Scientist's Group report

May 2026

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Email: research@environment-agency.gov.uk



Project Team:

Environment Agency

Alice Crouch, Chris Cooper, Rachel Goodwin, Sarah Rustage, Emma Warner, Jed Nicholson and Ruth Jones

Natural Capital Solutions

Valentina Zini, Jim Rouquette, Chris Osborne and Malori Richards

River Restoration Centre

Marc Naura and Josh Anthony

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Research contractors:

Natural Capital Solutions, Towcester, Northamptonshire, NN12 8AX. +44 (0)7790 105375

River Restoration Centre, Cranfield, Bedfordshire, MK43 0AL. +44 (0)1234 752979

Environment Agency's Project Lead: Alice Crouch, Chief Scientist's Group

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Research at the Environment Agency

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This report is the result of research commissioned by the Environment Agency's Chief Scientist's Group.

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If you have any comments or questions about this report or the Environment Agency's other scientific work, please contact research@environment-agency.gov.uk.

Dr Robert Bradburne
Chief Scientist

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Executive Summary

The Riverine Natural Capital Condition and Ecosystem Service Mapping Project created the Ecosystem Service Map Explorer (ESME). ESME uses evidence on the condition of the water environment (initially rivers) to model and map ecosystem service capacity (i.e. the potential to provide key ecosystem services). Ten ecosystem services are currently included: Provisioning services (Water supply), Regulating services (Water quality regulation; Water flow regulation; Habitat and species population maintenance), and Cultural services (Aesthetic and amenity Experience; Recreation; Physical / mental health and wellbeing; Education and investigation; Spiritual, cultural and religious experiences; and Intrinsic value of nature). The data can be explored at 3 spatial scales: management catchment, river water body and river reach. **ESME is currently being released as a Beta version innovation product, and we welcome all feedback.**

ESME was developed over multiple phases. It began with a quick scoping review to understand the links between natural asset condition and the provision of ecosystem services in rivers. This was accompanied by the development of conceptual frameworks and the identification of evidence gaps. Next began the development of a set of indicators, prototype mapping methods and the testing of mapping options. This was followed by a process of refinement and review, that included the development of new baseline river reaches and a new approach for combining indicators using decision trees. A draft national mapping tool was developed using the ArcGIS Experience Builder application available on ArcGIS Online, with features and functionality designed and refined based on user input and feedback. The project was completed by a period of further refinement and testing, and preparation for publication.

An important component of the project development in all phases was that it was designed to be collaborative with Environment Agency staff, who were fully involved in shaping the project through workshops and surveys, and by active participation in the review team. Wider partner feedback was also sought and considered. The project was commissioned by the Environment Agency's Natural Capital Team and delivered by Natural Capital Solutions Ltd, in conjunction with the River Restoration Centre. It was funded by Defra's Natural Capital and Ecosystem Assessment (NCEA) Programme.

This report describes the background to the project, an assessment of existing ecosystem service mapping tools, the process followed to create the evidence presented in ESME, the key decisions made, and how to use and interpret the outputs. It also provides information on level of confidence in the outputs, and provides a series of recommendations. There are a number of accompanying documents that explore further aspects, including a **Methodology Report**, a short report detailing **Applications and Limitations**, a **User Guide**, **Case Studies** of potential uses, a **Dataset and Indicators library**, and a **Project Summary**.

ESME can be accessed from this [link](#).

1. Introduction

The Riverine Natural Capital Condition and Ecosystem Service Mapping Project aimed to develop, trial and publish national riverine natural capital condition and ecosystem service maps to support operational and strategic user needs and offer a framework to support national Natural Capital and Ecosystem Assessment (NCEA) baseline assessment. The key output has been the creation of a mapping tool called the Ecosystem Service Map Explorer (ESME), underpinned by an extensive evidence base and the development of a series of indicators, baselines and conceptual frameworks.

ESME is a first-of-its-kind open and transparent tool. It uses evidence on the condition of the water environment to model and map ecosystem service capacity (i.e. the potential to provide key ecosystem services). In doing so, ESME can advance the environmental sector's ability to map and understand natural capital. **ESME is currently being released as a Beta version innovation product, and we welcome all feedback**, which can be sent to NaturalCapital@environment-agency.gov.uk.

The **ecosystem service capacity** is the potential of a natural asset to provide a specific service under current conditions, regardless of whether that service is being used by beneficiaries.

The tool currently covers natural and modified freshwater rivers across England. The data can be explored at 3 spatial scales: management catchment, river water body and river reach.

The tool can be used to view the underlying natural asset condition indicators and relative ecosystem service capacity in an area of interest, in map and chart form. Ten ecosystem services are currently included:

- Provisioning services (Water supply)
- Regulating services (Water quality regulation; Water flow regulation; Habitat and species population maintenance)
- Cultural services (Aesthetic and amenity experience; Recreation; Physical / mental health and wellbeing; Education and Investigation; Spiritual, cultural and religious Experiences; and Intrinsic value of nature)

The results can be exported and used in analysis, stakeholder engagement, business cases or project planning. ESME reports a 2025 baseline assessment of condition and ecosystem service capacity based on data from 2013 to 2025, which was the most suitable national evidence available in 2025. It should be considered a starting point for understanding ecosystem service capacity in a place, and interpretation should be supplemented with local data and knowledge. It is important to understand limitations and confidence in results and scale - for further information please refer to the ESME Applications and Limitations guidance.

This report describes the background to the project, the process followed to create the tool, the key decisions made, and how to use and interpret the outputs.

ESME can be accessed from this [link](#).

1.1 Context

The Environment Agency aims to improve and increase the quality, consistency, accessibility, and use of natural capital evidence. A Natural Capital workstream was established as part of the Environment Agency's contribution to Defra's terrestrial [Natural Capital and Ecosystem Assessment \(NCEA\) Programme](#)¹. The NCEA is Defra's largest research and development programme and will produce a baseline of our natural assets by 2029; enabling a natural capital approach to policy and decision-making. The Environment Agency's natural capital workstream is assessing the need for, and where necessary, developing new and/or improved natural capital indicators, metrics and maps to support a wider understanding of the ecosystem services that are derived from natural capital assets. A review of user needs identified three interlinked geospatial evidence gaps that have been prioritised: mapping a) the natural capital asset baseline, b) condition of natural assets, and c) ecosystem services.

The project focuses on rivers, although this may be expanded in follow-on work. Rivers are important habitats for delivering ecosystem services (Smith *et al.*, 2017), for example water supply, climate regulation (Wong *et al.*, 2017) and recreation (Natural England, 2019). However, the provision of ecosystem services in aquatic environments is understudied compared to terrestrial systems (Holland *et al.*, 2011).

The provision of ecosystem services is at risk from habitat degradation and loss of natural capital stocks, and the State of Natural Capital Report for England (Lusardi *et al.*, 2024) outlines that all natural assets and almost all the benefits they provide are at a high or medium-to-high risk. This needs to be urgently addressed to ensure sustainable long-term human wellbeing. Natural capital geospatial evidence is patchy with many gaps, particularly in relation to condition. There is a need to improve the quality of natural capital evidence to identify areas most at risk of loss or degradation of ecosystem services.

It is generally understood that habitats in better condition are more capable of delivering ecosystem services (Harrison *et al.*, 2014; Pullanikkatil *et al.*, 2016). However, the link between condition and delivery is a crucial knowledge element that needs to be explored further.

The Riverine Natural Capital Condition and Ecosystem Service Mapping Project was set up to explore the links between river asset condition and the provision of ecosystem services, to create indicators that mapped a range of ecosystem services based on those links, and to produce a mapping tool with England-wide coverage to display the results in a user-friendly platform. The mapping tool was named the Ecosystem Services Map Explorer, or ESME.

The NCEA is collecting national data on the health of England's rivers. The River Surveillance Network (RSN) and Small Streams Network (SSN) are statistically designed national monitoring networks consisting of an unbiased and representative set of monitoring sites across English rivers and small streams. They monitor a wide

¹ Natural Capital and Ecosystem Assessment Programme - GOV.UK (www.gov.uk)

range of parameters, supporting long-term measurement and detection of change following a five-year panel design that balances temporal and spatial coverage. When fully implemented, the RSN will provide a nationally representative dataset to support robust national insights. From late 2025 the Environment Agency started to release early outputs from these networks and is currently exploring the feasibility of integrating this data with ESME data to enable ecosystem service reporting at different scales. This work will inform future updates to ESME.

1.2 Project overview

The key steps taken to deliver the project are outlined in Figure 1 (overleaf).

The [first phase of this project](#) (Zini *et al.*, 2023) was commissioned to review the links between the condition of rivers and the ecosystem services they provide, to determine if existing data could be used to map asset condition, to review approaches to mapping, and to identify evidence gaps. Phase 1 ran from January to July 2023, with key outcomes shown in Box 1 and summarised in Figure 1.

Box 1. The key outcomes of Phase 1:

- Reviewed the links between natural capital asset condition and the provision of ecosystem services. An academic paper was published from this review:
- Zini *et al.* (2025) 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. River Research and Applications.
<https://doi.org/10.1002/rra.4439>
- Developed flow diagrams linking asset condition to ecosystem services.
- Identified where existing data, evidence and methods are robust and where there are evidence and data gaps or issues.
- Made recommendations on evidence gaps and on the data and indicators appropriate for mapping condition in the next phase.

Ecosystem Service Map Explorer (ESME): Project overview and key steps

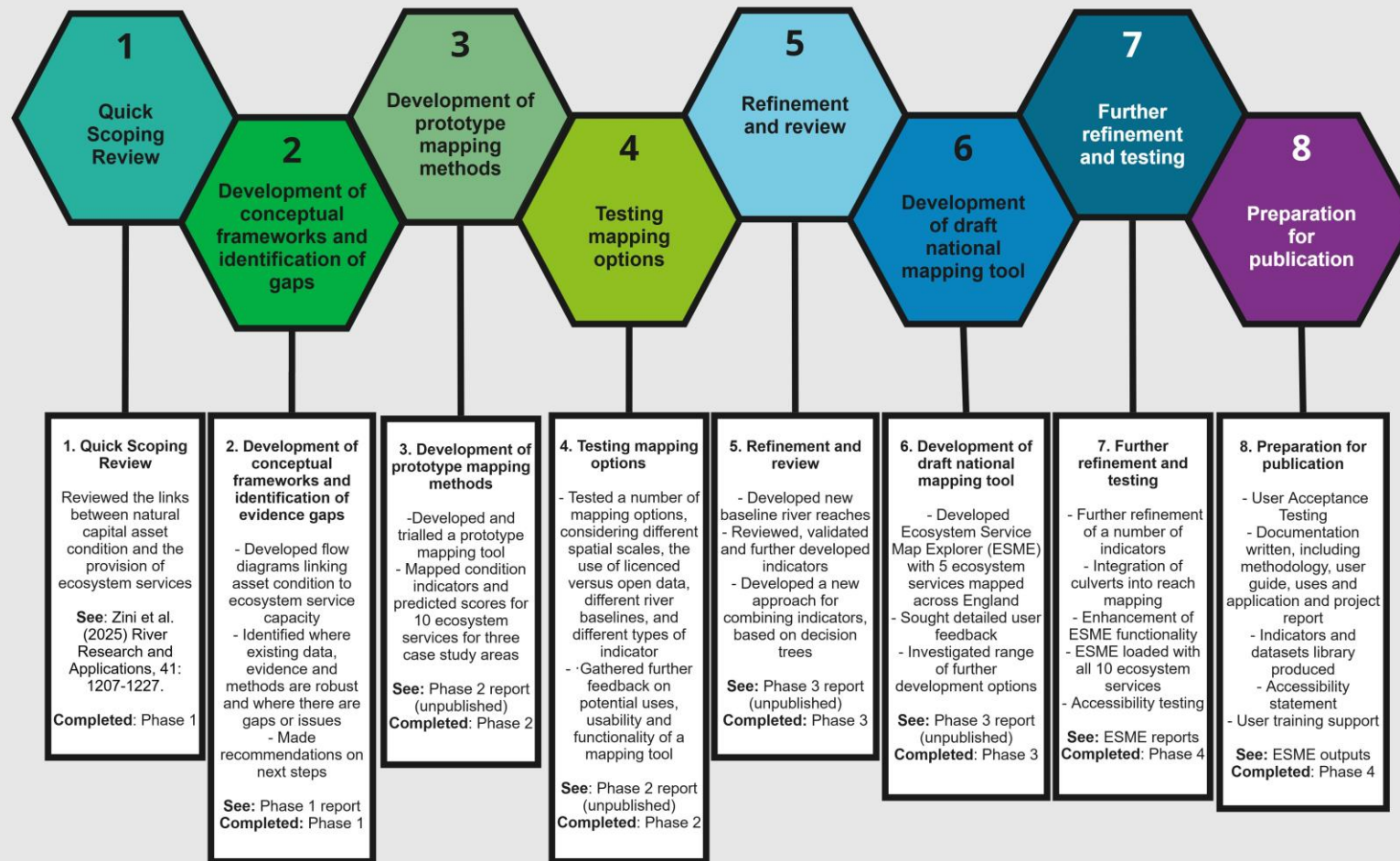


Figure 1: Project overview and key steps

Based on the findings of Phase 1, a second phase of the project was undertaken to trial a number of approaches to condition and ecosystem service mapping identified in Phase 1. This phase ran from November 2023 to the end of March 2024, with the key outcomes shown in Box 2, and further details presented in the project report (Zini *et al.*, 2024). Note this is an interim project report and is not published externally.

Box 2. The key outcomes of Phase 2:

- Developed and trialled prototype riverine natural capital condition and ecosystem service mapping methodologies and products, building on the approaches, evidence and indicators identified in Phase 1.
- Mapped condition indicators and predicted scores for 10 ecosystem services for three case study areas representing a range of catchment features.
- Produced a prototype mapping tool to display results and gain feedback.
- Tested a number of mapping options, considering different spatial scales, the use of open versus licensed data, different river baselines, and different types of indicators.
- Gathered further feedback on potential uses, as well as usability and functionality of a mapping tool.
- Presented a series of recommendations on taking the work further and producing a mapping tool with national coverage.

Based on the findings of Phase 2, a third phase of the project was then developed to take the project forward and start to produce mapping at the national scale. The main aim of Phase 3 was to refine, scale up and progress towards publishing national riverine natural capital condition and ecosystem service maps to support local and national level decisions about environmental planning and investment. The key outcomes are shown in Box 3 (summarised in Figure 1). This phase ran from September 2024 to the end of March 2025, and further details are presented in the project report (Rouquette *et.al.*, 2025). Note this is an interim project report and is not published externally.

Box 3. The key outcomes of Phase 3:

- Created new baseline river reaches by developing a more scientifically rigorous approach to river segmentation.
- Reviewed, validated and further developed indicators.
- Developed a new approach for combining indicators, based on decision trees, and validated our approach for scaling indicators.
- Developed the Ecosystem Service Map Explorer (ESME) in draft version, with 5 ecosystem services mapped across England at three different scales.
- Sought detailed user feedback.
- Briefly investigated a range of further development options.

The key aim of Phase 4 of the project was to publish ESME so it can support environmental planning and decision making. This involved a period of further refinement and testing, followed by preparation for publication (Figure 1). There were four main objectives:

- Finish developing a set of 10 national riverine natural capital condition and ecosystem service maps, accessed via a fully functional Ecosystem Service Map Explorer.
- Undertake user acceptance testing, develop case studies and produce guidance and training materials.
- Publish openly accessible England-wide map outputs via ESME, accompanied by user guidance.
- Base the approach on scientifically robust principles, apply common data standards, ensure accessibility to all users, and interoperability with other natural assets (e.g., estuaries) and data products.

This phase of the project ran from July 2025 to March 2026 as part of the NCEA programme.

An important component of the project in all phases was that it was designed to be collaborative with Environment Agency staff, who were fully involved in shaping the project through workshops and surveys, and by active participation in the review team. Wider partner feedback was also sought and considered, including from other NCEA partners (e.g. Defra and Natural England), water companies and local Rivers Trusts. The project was commissioned by the Environment Agency's Natural Capital Team and delivered by Natural Capital Solutions Ltd, in conjunction with the River Restoration Centre.

This report presents the key background to the Ecosystem Service Map Explorer, or ESME, and how it was produced. It includes decisions made in previous phases of the project, so can be read as a stand-alone document.

1.3 Report structure

Much of the background and key definitions for this project were established in Phase 1, but it is important that these are reiterated here. Section 2 of this report therefore sets out this background and key definitions, including for ecosystem services, assets, and condition.

Section 3 briefly outlines other ecosystem service mapping tools that are available and what they do and do not cover. This therefore sets out the need for the bespoke mapping tool that has been created here.

Section 4 describes the validation process, the key decisions that have been taken and the reasons. This includes the spatial scales taken forward, whether the data and outputs should be open, consideration of artificial watercourses, and key user needs around functionality of the tool.

A key recommendation from an earlier phase was to develop new baseline river reaches (a river asset baseline) that were more appropriate for the mapping of condition and ecosystem services, and the process that we went through to deliver this is described in Section 5.

Our approach to indicator development and the principles for mapping ecosystem services used in ESME is set out in Section 6. We then describe how indicators were scaled and how they were combined together to produce ecosystem service scores, a key process when producing the mapping (Section 7).

The development of ESME is described in Section 8. This includes a description of how it was set up, a summary of the key features and limitations, as well as reporting on a workshop and user testing and the feedback received.

Section 9 then describes how to use and interpret the mapped outputs in ESME. This includes what the maps show and how to interpret them, how ecosystem service capacity (scores) could be improved, how the different scales of mapping should be used, the importance of spatial scale for different ecosystem services, and links to benefits and values.

Finally, the report ends with conclusions and recommendations (Section 10), including an assessment of confidence in the outputs, limitations and caveats, a discussion of suitable frequency of updating, and a series of recommendations.

There are a number of accompanying documents that explore different aspects of the project and the ESME mapping tool, which are outlined here:

- **Methodology Report** – presents the methodology used to develop evidence presented in the ESME tool. It outlines the approach to indicator development, provides technical details on how the reaches, indicators and decision trees were developed, and for each ecosystem service presents the indicators and the logic behind each decision tree. It also describes how the ESME tool was created.
- **Applications and Limitations Report** – short report detailing uses and applications of ESME, relationship with the Water Framework Directive (WFD), information on how to use the outputs, and it draws together all the limitations and caveats.
- **User Guide** – annotated guide on how to use each part of the ESME tool.
- **Case Studies** – brief description of some examples of where ESME has been used. The case studies document will be expanded over time, once ESME has been published and starts to be used more widely.
- **ESME Dataset and Indicators Library** – an Excel spreadsheet providing comprehensive information on, and a full assessment of each dataset and indicator used in ESME, as well as datasets not taken forward.
- **Project Summary** – provides a technical summary of each of the key aspects of the project.

2. Background and key definitions

Phase 1 of the project developed key definitions for use in all later stages and gathered the evidence to support the development of indicators and mapping that was the subject of later phases of the work. Definitions and scope were developed through a combination of an assessment of literature and co-design with Environment Agency staff, who determined the areas of interest to be taken forward. Key definitions and decisions are set out below, with full details provided in the Phase 1 report (Zini *et al.*, 2023).

2.1 Natural capital and ecosystem services

Natural Capital is defined as:

“...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).

It is the stock of natural assets (e.g., soils, water, species) that produces a wide range of ecosystem services that provide benefits to people. These benefits include food production, regulation of flooding and climate, pollination of crops, and cultural benefits such as aesthetic experiences and recreational opportunities. Different types of ecosystem service are shown in Figure 2.

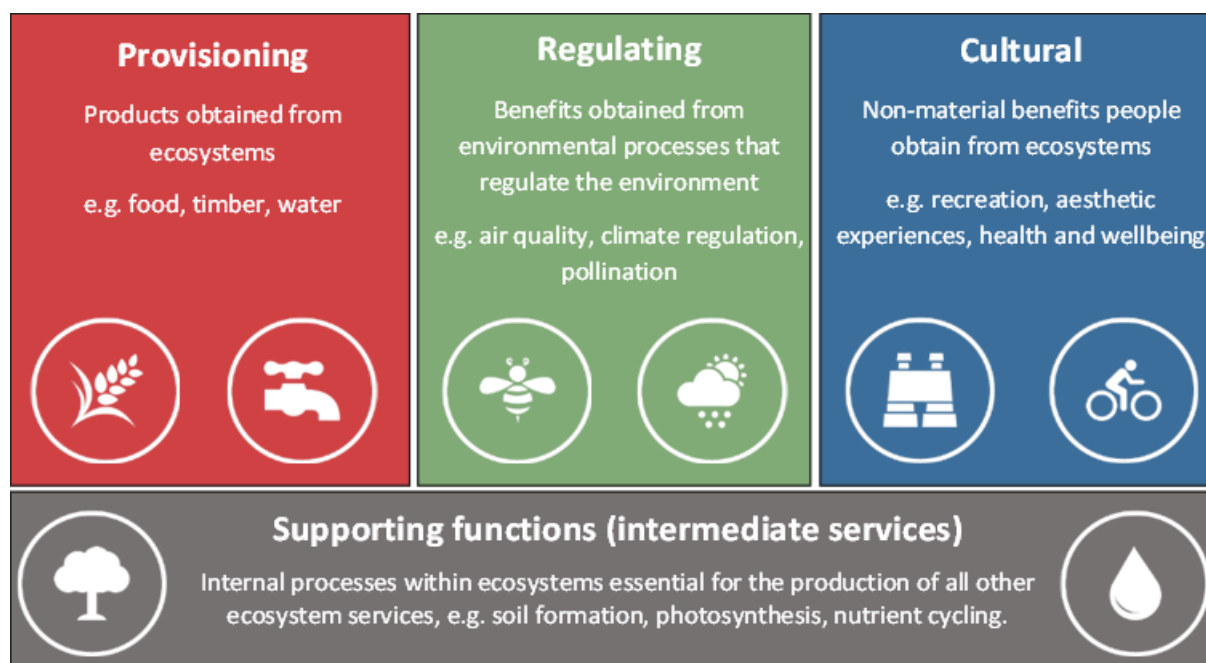


Figure 2: Key types of ecosystem services (based on Millennium Ecosystem Assessment (2005) and CICES (Haines-Young & Potschin, 2018)). Note that supporting or intermediate services are now categorised as ecological functions (Haines-Young & Potschin, 2018), and are the underpinning structures and processes that give rise to ecosystem services.

Ecosystem services are thus defined by the Common International Classification of Ecosystem Services (CICES) as “*the contributions that ecosystems make to human wellbeing*”. Using Millennium Ecosystem Assessment (MA) and CICES V5.1, and recent literature surrounding ecosystem services provided by rivers, a table was compiled containing the main services for consideration in this project. These were focused on ecosystem services that could be provided by rivers. This merged a number of CICES categories (e.g., 12 different categories of cultivated plants and reared animals merged into one category), and used some older names and definitions from MA (2005), where these were more intuitive. It is acknowledged that although internationally agreed terminology and definitions of ecosystem services have been in place for some time (i.e., CICES), these are not always the most meaningful and are not fully incorporated across the sector, including within the Environment Agency, where a slightly different set of terms have been in use.

The full list of ecosystem services was presented to Environment Agency staff at two workshops in Phase 1 and 40 polls were completed to determine which should be taken forward within this project. Each were assessed against importance to the Environment Agency, and which contained the greatest data gaps, and a combined score was compiled. The decision was taken to focus on the first seven services in order of importance, supplemented by those receiving the highest combined importance and data gaps score. A full list of the assessed ecosystem services and their scores is provided in Table 1. The final ten ecosystem services taken forward are highlighted in the table.

In 2024 the Environment Agency reviewed the names and descriptions of ecosystem services used across the organisation and created a Natural Capital Glossary. These names and descriptions have now been adopted for this project. Table 2 shows the old names used in Phases 1 and 2, and the new name and definition used from this phase onwards, and Appendix A gives a more complete table showing old descriptions and old Environment Agency names to enable a full comparison.

Table 1: Ratings of different ecosystem services, listed in order of importance. Importance (5 = most important) and data gaps (5 = most data gaps) were rated on a scale of 1-5 and the average is reported here (n = 40). Score is calculated as the sum of importance and data gaps. The services with highest scores in this column are in bold and were additional priorities for study. The final set of ten ecosystem services that were taken forward in the rest of the project are highlighted in green.

Ecosystem services	Importance	Data gaps	Score
Water supply (drinking/ agriculture/ industry)	4.55	0.41	4.96
Water quality regulation	4.50	0.91	5.41
Water flow regulation	4.23	0.87	5.10
Intrinsic value of nature*	4.08	2.15	6.23
Physical / mental health and wellbeing	3.90	2.71	6.61
Recreation	3.85	2.03	5.88
Habitat and species population maintenance	3.75	1.78	5.53
Waste removal	3.64	1.41	5.05
Aesthetic and amenity experiences	3.62	2.60	6.22
Erosion control	3.58	2.18	5.76
Carbon sequestration and storage	3.55	2.48	6.03
Education and investigation	3.53	2.74	6.27
Spiritual, cultural and religious experiences	3.43	3.14	6.57
Pest and disease control	3.23	2.82	6.05
Local climate temperature regulation	3.13	2.36	5.49
Fire protection	3.03	3.00	6.03
Cultivated plants and reared animals	2.95	1.61	4.56
Pollination and seed dispersal	2.95	3.00	5.95
Hydropower	2.83	0.87	3.70
Wild produce	2.44	2.92	5.36

Source: Zini et al. (2023)

* At the time of the workshops this was referred to as “Characteristics and features of biodiversity that are valued”. There have been small changes to other names since then as well, as shown in Table 2.

Table 2: The ten ecosystem services (ES) that are assessed as part of this project, showing the names used in Phases 1 and 2, along with the new names and descriptions adopted for later phases and used in ESME.

Category	Ecosystem service name used in Phases 1 & 2	New EA NCEA ES terminology*	New EA NCEA ecosystem service description, as used in ESME*
Provisioning	Water (for drinking /agriculture /industry)	Water supply (drinking/ agriculture/ industry)	Water abstracted from surface and below-ground* sources that can be used for drinking, agriculture and industry (such as material or for cooling). * ESME does not currently consider groundwater abstraction
Regulating	Water quality regulation	Water quality regulation	How biotic (animals, plants, bacteria, fungi, and algae) and abiotic features and processes of the ecosystem regulate the chemical condition of freshwaters. This includes both the maintenance of baseline abiotic conditions such as nutrient balance and pH, and the remediation, dilution, and removal of anthropogenic pollutants.
	Water flow regulation	Water flow regulation	The biotic and abiotic features of an ecosystem that regulate water flow, as well as ecosystem structures and characteristics that help mitigate or prevent potential damage from drought and from flood and storm surges to the environment, human use of the environment or human health and safety. For example, the capacity of ecosystems (e.g., vegetation, soil) to retain water and release it slowly.
	Habitat and population maintenance	Habitat and species population maintenance	The ecological conditions necessary for supporting sustaining populations of species throughout their lifecycle. This includes breeding grounds, feeding grounds, refugia, and wildlife corridors.

Category	Ecosystem service name used in Phases 1 & 2	New EA NCEA ES terminology*	New EA NCEA ecosystem service description, as used in ESME*
Cultural	Recreation and tourism	Recreation	The contribution and opportunity provided by the environment for recreational uses. Natural ecosystems used as places for the active enjoyment of recreation, including walking, hiking, camping, cycling, boating, fishing, watersports, and nature viewing.
	Health and well-being	Physical / mental health and wellbeing	The role of natural landscapes and urban green and blue space for maintaining mental and physical health. Natural environments can offer places and opportunities for informal physical activity, and to use nature and the outdoors to destress and socialise.
	Aesthetic experiences	Aesthetic and amenity experiences	The passive enjoyment of being in and around natural scenery, landscapes, and cultural spaces; the beauty of nature. This provides human enjoyment, and it can also have economic importance by influencing property prices and commercial activity.
	Education, training and investigation	Education and investigation	The contribution and opportunity provided by the environment towards study, education, and research.
	Spiritual and cultural experiences	Spiritual, cultural and religious experiences	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 for people. Nature is a common element of all major religions. Natural landscapes also form local identity and a sense of belonging.

Category	Ecosystem service name used in Phases 1 & 2	New EA NCEA ES terminology*	New EA NCEA ecosystem service description, as used in ESME*
	Characteristics and features of biodiversity that are valued	Intrinsic value of nature	The things in nature that we think should be conserved because of their non-utilitarian qualities (existence value). The things in nature that we want future generations to enjoy or use for whatever reason (option or bequest value). Things in nature that are used to inspire art, books, or films.

*Source: Environment Agency NCEA ecosystem service names and descriptions come from the Environment Agency's Natural Asset and Ecosystem Service Indicators and Metrics project.

2.1.1 Natural capital logic chain

The natural capital logic chain (Haines-Young & Potschin, 2010) shown in

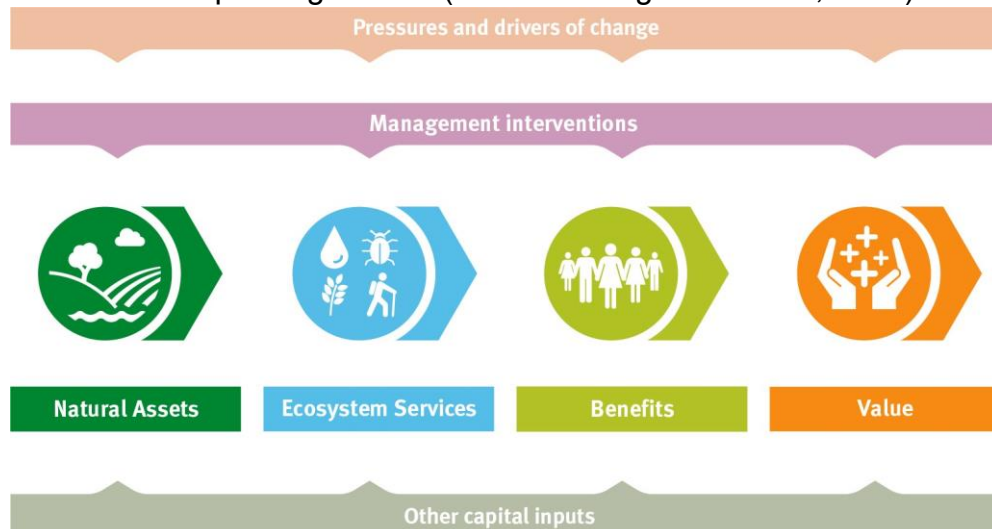


Figure , illustrates the links between natural capital assets, the ecosystem services that flow from those assets, the benefits that these provide, and the values that these benefits are given. It also shows that pressures and drivers of change influence management interventions, which in turn affect these connections. As society changes how we value different benefits this can also have a feedback effect on the system, driving change.

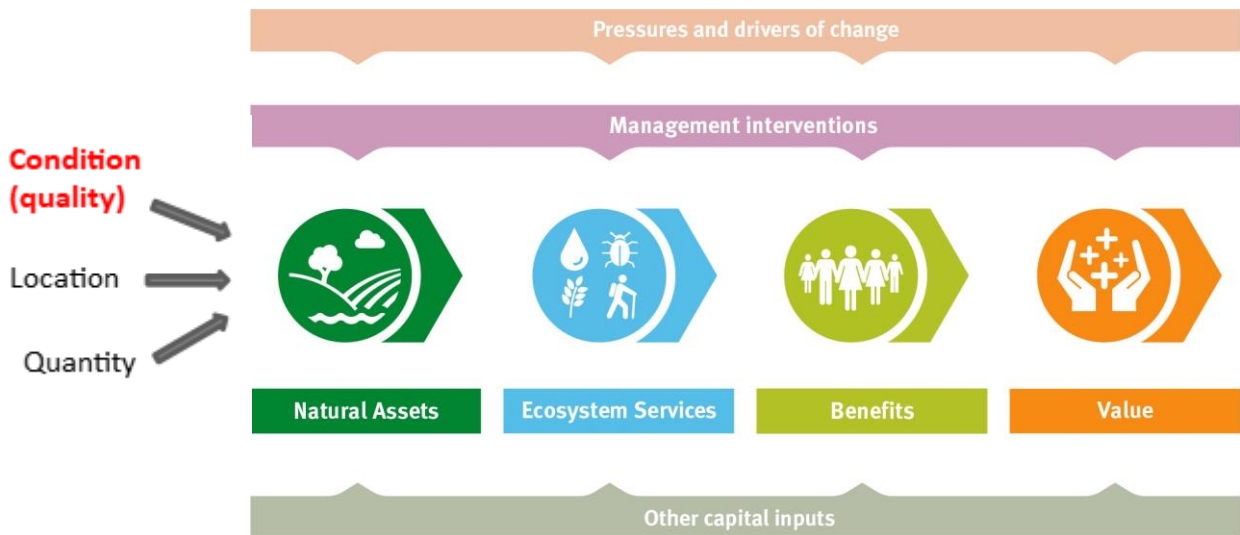


Figure 3: The natural capital logic chain, (adapted from Haines-Young & Potschin, 2010). Note that ecosystem function (or intermediate/supporting services) from Figure 2, sits between natural assets and ecosystem services in many versions of this logic chain.

In this project we are focussing on the first two steps of the logic chain; natural capital assets and the ecosystem services that flow from those assets. In particular, the condition of assets and the links between asset condition and ecosystem service flow. We are not directly considering benefits or values, although the potential benefits provided by ecosystem services to people, society, organisations and business are included at a high level as supporting narrative in ESME.

Natural capital assets can generally be assessed for three properties. Information on the location and quantity of assets is relatively well studied, whereas information on the condition (also referred to as quality) of assets (shown in red in

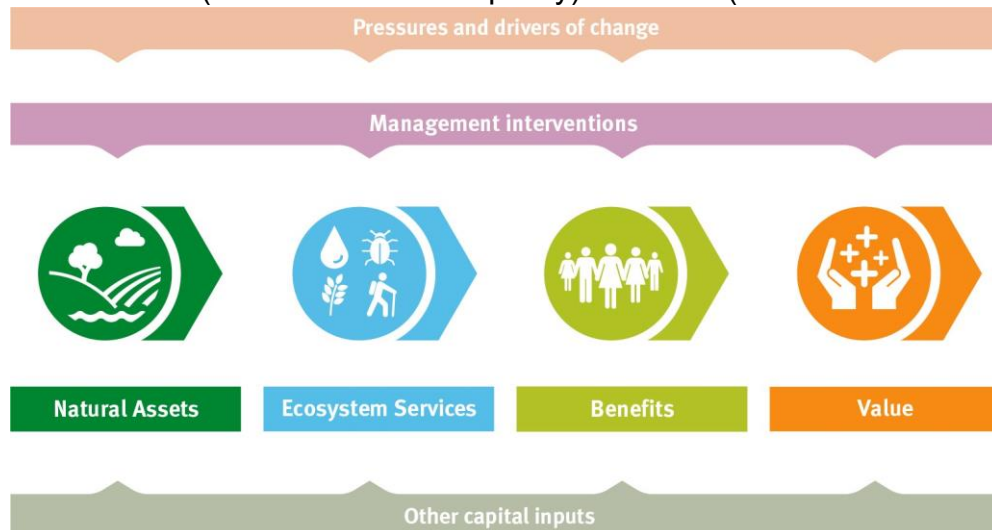


Figure) is much less well understood. This is the focus of the current project, but assets and condition first need to be defined.

2.2 Defining assets

The focus of this project is on freshwater rivers, although there is the potential to broaden this scope in the future. Within the river asset class, and following workshop feedback and discussion during Phase 1, we decided to initially use two categories of rivers: natural and artificial, rather than using any further subcategories like upland/lowland.

Note that artificial waterbodies are no longer being taken forward in this phase of the project (see Section 4.5 for more details), hence we focus entirely on natural rivers.

Natural rivers are defined as:

'surface water bodies that are naturally occurring within the landscape and originally formed by natural processes' (Water Framework Directive).

It is important to note that anthropogenically modified rivers are classed as 'natural' within this context, as they were present prior to alteration. Hence rivers classified as Heavily Modified Water Bodies (HMWB) under the Water Framework Directive (WFD) are included in this type.

2.3 Defining condition (quality)

Based on a review and workshop feedback in Phase 1 (see Zini *et al.*, 2023 for further details), we can state the following:

- There is no one single way of measuring natural capital asset condition (also referred to as quality), as it varies depending on the ecosystem service under consideration.
- For the purpose of this project, we are therefore defining good condition as the state of the asset that enables high provision of the ecosystem service being assessed.
- Condition is most commonly associated with various aspects of naturalness, resilience, connectivity, and access, and crucially, it is strongly influenced by perception and value judgements, particularly for cultural ecosystem services.

3. Ecosystem service mapping tools

3.1 Introduction

A wide range of ecosystem service assessment tools exist; each designed with slightly different purposes and strengths. Some rely on simple models that require minimal technical expertise, limited data, and short analysis times. Others use detailed biophysical or economic modelling, demand extensive datasets, advanced technical skills, and longer processing periods. The methods used to estimate multiple ecosystem services vary across tools; while some rely on empirical equations or lookup tables, others follow more spatially explicit processes.

While many of these tools offer valuable approaches, this assessment focuses on a selected group that most closely align with ESME for a high-level comparison. This approach helps clarify how ESME fits within the broader landscape of ecosystem service tools, provides guidance on its application, and highlights opportunities for ESME to complement other tools where their functions intersect. We briefly outline some of the most relevant ecosystem service tools in Table 3 and assess six in more depth, alongside ESME. Note that a wide range of other tools are also available and Table 3 is in no way comprehensive. The six tools assessed in more depth are: InVest, Environmental Benefits from Nature tool, England Green Infrastructure Mapping Database, Natural Environment Valuation Online, EcoServR and Co\$ting Nature.

3.2 Tool assessment

For each of the six tools in turn (and ESME), we describe the key features of the most recent version available of the tool and the main strengths and limitations of each. We outline these alongside ESME to enable comparison. Table 4 provides key information on each tool including the authors, the version assessed, whether it is open source, the frequency of update, the model approach, whether there is guidance and support, and the overall usability of the tool. Table 5 provides a further assessment on the robustness, the input data required, whether the tool is spatially explicit, the transparency, scale, whether it includes valuation, whether it explicitly considers rivers, whether condition is considered, and the output type. Finally, Tables 6-8 provide a list of the regulating, provisioning and cultural ecosystem services included in the ecosystem services tools and some brief information on the type of model.

Table 3: Natural capital tools most relevant for comparing with ESME.

Tool	Description	Link
InVest	<p>InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) is a suite of free, open-source software models developed by the Stanford University Natural Capital Project. It helps users quantify, map, and value ecosystem services. InVEST models are designed to inform decision-making by evaluating trade-offs associated with the use of natural resources. The tool addresses issues such as water quality, biodiversity, coastal protection, and carbon storage, among others, making it useful for governments, NGOs, and private-sector organizations involved in environmental planning and management.</p>	<p>InVEST Natural Capital Project</p>
EVAST	<p>The EVAST (Ecosystem Valuation and Scenario Tool), being developed by the UK Centre for Ecology and Hydrology (UKCEH) and Defra, is a tool designed to assess the economic value of ecosystem services and evaluate different land use scenarios. It allows users to model how changes in land use or management practices impact ecosystems and their services, such as carbon storage, water quality, and biodiversity. The tool supports decision-making in land and resource management by providing quantitative insights into the trade-offs between ecological benefits and economic development. Note this is still in development and it was not possible to access it to consider it in our assessment of tools.</p>	<p>Environmental Value Assessment Scenario Tool (EVAST) - UKCEH Science Infrastructure Catalogue</p>
Environmental Benefits of Nature (EBN) tool	<p>The EBN tool is designed to help deliver wider benefits for people and nature from land use change. It works with Biodiversity Net Gain and alongside the Green Infrastructure Framework to provide integrated support for users looking to maximise multifunctional land use and deliver service gains that match local needs. It aims to help users better understand the impact of proposed land use change on the services nature provides within their project area. It encourages positive change through improved consideration of nature-based services in project design and may be used to start a broader conversation (about local needs, impacts, priorities and opportunities) to help deliver the right gains in the right places. The tool highlights the projected impact of proposed changes across 18 different ecosystem services (ranging from flood management, to cooling and shading, air quality and recreation) and displays impact over a 30-year period, highlighting the benefits that can be achieved as new habitats establish.</p>	<p>The Environmental Benefits from Nature Tool - Beta Test Version - JP038</p>

Tool	Description	Link
The NATURE tool	The NATURE Tool (Nature Assessment Tool for Urban and Rural Environments) was developed to enable built environment professionals throughout the UK to objectively assess and measure to what extent new plans or developments achieve net gains. It assesses the impact of land-use and management changes on natural capital performance.	https://nature-tool.com/
ciriabest (previously called B&ST)	ciriabest online is used to assess and monetise many of the wider benefits of blue-green infrastructure. The results enable users to understand and quantify the wider value of drainage and natural flood management measures. This can support investment decisions. Benefits can be used to identify stakeholders and potential funding routes. The online tool provides direct access to projects linked in a spatial format.	https://www.ciriabest.com/
England Green Infrastructure Mapping Database	<p>The England Green Infrastructure Mapping Database is designed to provide technical evidence on the Green Infrastructure of England as an open data product under Open Government License (OGL) conditions. The England Green Infrastructure Mapping Database aims to be:</p> <ul style="list-style-type: none"> • A publicly accessible data, analysis and mapping resource. • A resource providing a nationally consistent approach to Green Infrastructure spatial evidence. • A resource capable of providing information at multiple scales from England wide, Upper and Lower Tier Local Authority, Middle Super Output Area (MSOA) and Lower Super Output Area (LSOA). • A resource that can be used to provide evidence to inform a variety of national to local planning, strategy and targeting exercises involving Green Infrastructure. • A baseline evidence resource providing a consistent level of data and analysis across England capable of being adapted and/or supplemented with additional and/or local data as required by the end user. • This tool can be used in conjunction with the EBN tool described above. 	Green Infrastructure Map
Natural Capital	This spatial dataset shows variation in ecosystem service flow for habitats across England, based on indicators identified by Natural England in the 2018 Natural Capital Indicators	Natural Capital County Atlas Mapping (England)

Tool	Description	Link
County Atlas Mapping	project. The dataset comprises a hexagonal grid which summarises indicator values across the country (each unit = 5km ²).	
EcoServ-GIS	EcoServ-GIS is a Geographic Information System (GIS) toolkit for mapping ecosystem services at a county or regional scale. It uses input GIS/map data to generate fine-scale maps that illustrate human need or demand for ecosystem services as well as the capacity of the natural environment to provide them.	https://drive.google.com/drive/folders/0B_v9QO2jyC4eNIVUbzY1UUstZU0?resourcekey=0-g3hPoyz8iUX70u4LqxAoiQ
EcoservR	EcoservR is a tool for mapping natural capital assets and ecosystem services. It is an updated version of Ecoserv-GIS, a toolkit for mapping habitats and ecosystem services in the UK using widely available national datasets. The toolkit generates an environmental baseline classifying over 200 habitat types, and uses spatial models to map their capacity to provide a range of ecosystem services, as well as the demand for them.	https://ecoservr.github.io/EcoservR/
ARIES	ARIES (ARTificial Intelligence for Environment and Sustainability) is a collaborative and open-source platform for interoperable models and data, based on the Knowledge Laboratory (k.LAB) technology: an AI-powered and digital software for rapid ecosystem service assessment and valuation. It gives equal emphasis to ecosystem service supply, demand and flow to quantify actual service provision and use by society (as opposed to quantifying potential service benefits). It aims to provide a suite of models that support science-based decision-making where nature counts. Besides ecosystem services, ARIES also tackles natural capital accounting, food security, marine spatial planning, and renewable energy.	ARIES - ARTificial Intelligence for Environment & Sustainability
TESSA	The TESSA toolkit is an easy-to-use workbook that leads the user through the steps needed to assess the ecosystem services provided at a particular site. It is built around a comparison of the site in two alternative states, e.g. before and after restoration or conversion, and encourages a high level of stakeholder engagement. The toolkit was initially developed for conservation practitioners but can be used by anyone, including the private sector and those with no prior knowledge of ecosystem services. It includes an introduction to the concepts of ecosystem services and natural capital, guidance on how to	Tessa Tools - BirdLife International

Tool	Description	Link
	<p>conduct a preliminary scoping appraisal to identify important services and beneficiaries, decision trees to identify the best methods to use for each service, and links to a set of simple low-cost methods for measuring ecosystem services either qualitatively or quantitatively. Worked examples are provided, as well as instructions for collecting site-specific data where appropriate (including field surveys and stakeholder input). There is also guidance on how to communicate results to decision-makers.</p>	
<p>Natural Environment Valuation Online (NEVO)</p>	<p>NEVO is a freely accessible online tool that allows users to select an area anywhere in England or Wales, from the scale of a county or catchment down to a 2km grid cell, and then view estimates of the value of that area for delivering a range of ecosystem services (agricultural production, timber production, greenhouse gas emissions reduction and sequestration, recreation, water quantity and water quality) and its value for biodiversity (estimated number of species present).</p>	<p>Enhancing access to NEVO – the Natural Environment Valuation Online Tool - SWEEP</p>
<p>Co\$ting Nature</p>	<p>Co\$ting Nature V3 is a web-based policy-support tool for natural capital accounting and analysis of the ecosystem services provided by natural environments. The focus is on costing nature (understanding the resource, e.g. the land area, and the opportunity cost of protecting nature to produce ecosystem services) as opposed to valuing nature (i.e. how much someone is willing to pay for it), though the tool does support economic valuation and has the necessary tools for this. The tool estimates the current provision of 18 ecosystem services including: Timber (softwood, hardwood), Fuelwood (softwood, hardwood), Grazing/fodder, non-wood forest products, water provisioning (quantity, quality), fish catch, carbon, natural hazard mitigation (flood, drought, landslide, coastal inundation), culture-based tourism, nature-based tourism services, environmental and aesthetic quality services, wildlife services (pollination, pest control), wildlife dis-services (crop raiding, pests) and identifies the beneficiaries. It then analyses current human pressures on the land, future threats and levels of biodiversity. It derives conservation priority from these factors. Users can then apply scenarios for land-use or land management change, and examine the impacts on ecosystem services and the implications for beneficiaries. The tool can be used to assess the impacts of human</p>	<p>policysupport.org - Co\$tingNature</p>

Tool	Description	Link
	interventions for conservation prioritisation and planning. It also calculated Nature's contributions to the Sustainable Development Goals (SDGs).	
Natural Capital Register and Account Tool (NCRAT)	Developed by the Environment Agency, NCRAT is a publicly accessible, excel-based natural capital accounting tool. It helps users establish a baseline of the natural assets in a place and the services they provide. A natural capital register and account presents the value, quantity, and quality of natural resources in a place. NCRAT enables users to create an account themselves by collecting and entering data on natural assets to estimate natural capital value for a place. It complements other, more conventional, business case models to help stakeholders make more sustainable place-based decisions. It automatically generates results that stakeholders can use to support decision-making by showing the links between the natural environment, the economy and society, and it provides a view of the irreplaceable services that nature provides us.	Natural capital register and account tool - GOV.UK

InVest

InVEST is an open-source suite of spatially explicit models designed to quantify the biophysical supply, spatial distribution, and in some cases the economic value of ecosystem services. Developed by the Natural Capital Project (a partnership between Stanford University, World Wildlife Fund, The Nature Conservancy, and the University of Minnesota), InVEST is widely used in conservation planning, land-use scenario analysis, natural capital assessments, and policy decision-support, and is applicable worldwide.

Each model is GIS-based, using spatial inputs such as land cover, climate, soil, topography, and hydrology to generate service production maps and, where available, maps of beneficiaries. Users can evaluate how alternative land-use or management options affect ecosystem service outcomes, although this requires the user to do separate runs of the same model and then compare outputs. Some models include economic valuation (e.g., carbon, coastal protection, hydropower), linking biophysical outputs to monetary values or avoided damages.

InVEST often employs a production function approach to quantifying and valuing ecosystem services. A production function specifies the output of ecosystem services provided by the environment given its processes. Once a production function is specified, we can quantify the impact of, for example, land-use changes on ecosystem service provision.

InVEST does consider rivers, but only as spatial features and just like other habitats, condition needs to be supplied by the user by differentiating the scores assigned to rivers with different conditions. The tool is this capable of incorporating habitat condition, but only if users supply a dataset representing it.

InVEST is built on published ecological and environmental models, and the methods have been documented extensively in the scientific literature. Hundreds of peer-reviewed papers have used InVEST models making this one of the largest evidence bases for an ecosystem service modelling tool. Multiple InVEST models have undergone formal validation studies comparing outputs against observed data. Validation is strongest for models that use empirical spatial data and well-established process relationships.

Strengths

InVEST's strengths lie in its biophysical modelling, supported by extensive scientific literature and validation carried out on these models, giving confidence in the outputs. Unlike simple scoring approaches, InVEST uses equations of biophysical units to estimate service supply with the spatial resolution of the outputs being user dependent. By running alternative scenarios users can test how alternative land-use or management change ecosystem service outcomes. Several models include economic valuation (e.g., carbon sequestration, coastal protection, hydropower), enabling integration into cost-benefit assessments. Anyone can download and adapt

the models, and they work across different countries. Results are usually spatial (can be mapped).

Limitations

Models typically rely on land-cover maps, not ecological condition, meaning degraded and high-quality habitats may be treated similarly unless the user customises inputs. Hydrological models use relatively simple water-balance or routing approaches and do not simulate detailed river condition, channel morphology, in-stream ecology, or water quality dynamics. Reliable outputs require good-quality spatial data (Digital Elevation Model, soils, rainfall, land cover), which may not be available at appropriate resolution. Although user-friendly compared to some other modelling tools, it still requires considerable GIS skills, careful preprocessing of inputs, and understanding of the underlying assumptions. Learning how to use InVEST models and setting them up for the first time takes a lot of time. Some models include monetisation, and users can customise parameters, which means results can vary significantly based on assumptions. InVEST is a tool for experienced modellers to run their own models, and there is no website or tool currently available that displays the results of InVEST modelling across England.

EcoservR

EcoservR is a re-write of Ecoserv-GIS and was initially developed and tested at Liverpool John Moores University in collaboration with Natural Capital Solutions, Forest Research, and the Cheshire Wildlife Trust. NatureScot have recently released a prototype Natural Capital Tool, which is a free, easy-to-use decision support tool built using EcoservR. Some Environment Agency projects have used EcoservR to develop local mapped outputs (e.g., the North West Opportunity Toolkit and Eastern Hub Natural Capital Mapping project). It is an R-based ecosystem services mapping tool designed for use by local authorities, ecological consultants, conservation bodies, and researchers in the UK. EcoservR automates and standardises the production of ecosystem-service maps using UK-specific datasets. It runs as an R package where each model runs by linking habitat types to scores as well as being subject to spatial modifiers (e.g. slope, proximity to features). This produces scores (usually on a 0-100 scale), not physical units, generating ecosystem service capacity, demand and opportunity maps.

EcoservR does consider rivers, but only as spatial features and just like other habitats, condition needs to be supplied by the user by differentiating the scores assigned to rivers with different conditions. The tool is thus capable of incorporating habitat condition, but only if users supply a dataset representing it.

Rivers influence flood regulation scores, water quality, local climate regulation, recreation and connectivity. While the models in EcoservR are all based on strong evidence of relationships between habitats and ecosystem service capacity and demand, the tool hasn't been through formal validation of the outputs.

Strengths

Fine grained assessments can be carried out making the tool suitable for local mapping of ecosystem services. Each service has a clearly documented scoring matrix with values assigned to land-cover types and refined using contextual modifiers (e.g., slope, distance to sensitive receptors, urban extent, waterbodies). The tool is flexible and resolution is defined by user input data, but is usually at high resolution (10m or better). Methodology is transparent, and rule based matrices are published. It is good at mapping urban ecosystem services. It is flexible with data sources since users can add both high and low resolution datasets. Maintained and developed by a small team and is the basis of a user-friendly tool covering the whole of Scotland.

Limitations

No biophysical modelling is carried out, with ecosystem service scores based on land-cover proxies rather than measured processes. This means results are semi-quantitative, not absolute values. Accuracy depends heavily on input data. Not validated through peer-reviewed studies, it has limited formal validation. The tool cannot be used worldwide, it is UK-tailored. Although rivers are included in some models, it is largely a tool for assessing ecosystem services delivered by terrestrial habitats and it does not comprehensively consider condition.

Environmental Benefits from Nature (EBN) tool

The Environmental Benefits from Nature (EBN) tool is a spreadsheet-based assessment tool designed by Natural England and the University of Oxford to help users evaluate how changes in land use, habitat type, and habitat condition affect the relative provision of multiple ecosystem services. The tool focuses on 18 ecosystem services spanning regulating, cultural, and provisioning benefits, and provides a 0–10 relative scoring system based on a literature review of over 700 papers and further developed by an extensive panel of experts. The tool compares how different habitats perform in delivering each service. The tool is simple, transparent and accessible, making it suitable for early-stage planning and option appraisal. It is intended to support decision-making around land-use planning, nature recovery projects, green infrastructure design, and biodiversity-net-gain proposals. It is designed to be fully compatible with the Biodiversity Metric, extending assessment of Biodiversity Net Gain (BNG) to Environmental Net Gain (ENG).

A defining feature of the tool is its explicit use of around 40 habitat condition and spatial indicators (in line with the Biodiversity Metric approach of using condition categories) as key modifiers of ecosystem service provision. This means that two areas with the same habitat type but different condition will receive different relative scores for their ecosystem service contributions, allowing the tool to capture ecological quality in a way most other tools aren't able to do. Users can enter habitat

type, area, condition and spatial indicators, and the tool calculates relative service scores to compare “before and after” scores for proposed interventions.

The EBN Tool does not produce biophysical quantities (e.g., tonnes of carbon sequestered) or monetary valuation; it provides qualitative comparison across habitats supported by a literature review and expert consultation. While it should not replace detailed modelling, the EBN Tool fills an important gap by linking habitat type and condition directly to ecosystem service delivery.

The tool isn't highly robust since the underlying approach is score-based, not process-based. The scores rely heavily on broad land-cover classes and local ecological variation is only represented by the condition and spatial indicators. There also isn't a formal, peer-reviewed validation of the EBN tool. It has not been subject to published scientific validation studies or compared against field data or process models. This might be because it is not designed to produce biophysical quantities. Some form of informal evaluation exists, as Defra and Natural England testing was carried out.

Strengths

The EBN tool is one of the few ecosystem service tools that explicitly integrates habitat condition (using around 40 indicators) into service provision scores. The tool is a simple, easy to use spreadsheet, suitable for non-specialists since it doesn't require complex modelling or coding skills. All scoring logic is documented so that users can understand how each habitat contributes to each ecosystem service, with a transparent scoring system. Scenario comparisons are very easy to achieve; while other tools require users to model a before and after scenario and calculate a metric to quantify differences, the tool has a built in “before and after” assessment. The tool has a broad coverage of services including 18 ecosystem services across regulating, cultural, and provisioning categories. It aligns with UK policy and uses habitat classifications and condition assessments consistent with the Biodiversity Metric and Natural England frameworks. Good for early-stage decision-making, supporting screening and prioritisation where detailed modelling is not feasible.

Limitations

The tool provides relative values with outputs scoring 0–10 scores, not biophysical quantities and does not calculate economic values. Static and rule-based, it relies on fixed lookup tables and scoring, and is unable to model spatio-temporal dynamics. For this reason, it is not intended as a substitute for hydrological modelling as it does not model flow dynamics, floodplain processes, or other in-channel ecosystem services. It provides essentially a non-spatial assessment, although it does consider spatial aspects as modifiers of the scores. The evidence base is still evolving; the tool is currently in Beta release (v1.1), meaning some ecosystem service–habitat relationships are still being revised.

Natural Environment Valuation Online (NEVO)

NEVO is a web-based decision-support tool developed by the Land, Environment, Economics and Policy Institute (LEEP) at the University of Exeter, with support from Defra and NERC. It is designed to help users explore, quantify, and predict the benefits derived from existing or modified land use across England and Wales. NEVO uses spatial data to run ecosystem service models, and assigns an economic value to the services. Within the tool users can view baseline conditions which report habitat types for a given area and the flow and value of multiple ecosystem services. Spatial resolution ranges from 2 km grid cell up to large administrative units, catchments, or the entire country. Users can alter land use within the given study area and test how changes in land use affect the flow of ecosystem services and their value. A useful function is 'optimise' which selects where land-use changes would maximize a given objective (e.g. maximize biodiversity, timber profit, carbon sequestration, or a combination of ecosystem services) for user-defined changes. It is useful for early-stage appraisal of proposed land-use or policy changes to compare ecosystem service changes in economic terms.

NEVO does not incorporate habitat condition and considers rivers only as spatial features, not as part of a hydrological model.

NEVO brings together a variety of detailed models that are robust and evidence based. Its agricultural model is calibrated on empirical data, the recreational model uses OrVal which is considered the most robust tool to assess recreation value in England, and SWAT is used for hydrological modelling. In contrast, the biodiversity module isn't robust and consists of a simplified biodiversity assessment.

Strengths of NEVO

The integrated valuation across multiple ecosystem services without requiring user data input is a major strength of this tool. It has national, consistent coverage. Scenario and optimisation analysis that can identify where land-use changes could maximise a chosen objective is also a unique feature of this tool. It is easy to use despite the complexity of the calculations performed and incorporates climate-change projections. Overall it is excellent for broad, strategic natural-capital valuation and exploring how land-use change affects multiple ecosystem services at catchment to national scales.

Limitations of NEVO

Coarse spatial resolution (2 km grid) is probably its most important limitation. A 2 km grid is too coarse for site-specific river management. It does not map habitat condition and rivers are represented indirectly, not with physical models. NEVO's water-related outputs are catchment-scale indicators, not fine-scale hydrological models. Biodiversity estimates are highly simplified, based on expected species richness from land cover. Not suitable for fine-scale assessments. Only a subset of services (e.g., agriculture, timber, carbon, recreation) is monetised. Many important

river and habitat functions remain non-quantified or non-valued. Overall, it lacks the fine resolution and ecological detail required to assess habitat condition or river health.

England Green Infrastructure Mapping Database

The portal is part of the Green Infrastructure Framework developed under the UK 25 Year Environment Plan. It was launched by Natural England and Defra. It is aimed at planners, local authorities, developers, researchers, NGOs, and broader stakeholders to support planning and decision-making relating to green infrastructure, access to nature, biodiversity, urban planning, and ecosystem service provision. The portal allows data to be viewed at different spatial scales: from nationwide, down to lower-area units such as Local Authorities, Middle Layer Super Output Areas (MSOAs)/ Lower Layer Super Output Area (LSOAs) (census output areas). A combined Green and Blue Infrastructure assets layer aggregating multiple source datasets is the core of the tool; a series of layers showing the level of access throughout England based on different access standards has been built around this. Other layers are available including urban habitat mapping (detailed version only available with OS MasterMap licence), sports facility provision, urban habitat naturalness and a series of preliminary, broad-scale ecosystem-service proxies:

- Urban cooling assessment (heat-mitigation potential).
- Air-pollution mitigation (PM_{2.5} removal potential in urban green spaces), using underlying green infrastructure data, along with pollution and demographic data.
- Local food provision which maps the need for local food and the opportunity for local food production.

The portal includes water bodies (blue infrastructure) among its mapped assets and a waterside access layer which identifies “likely accessible waterside” – i.e. rivers, streams, lakes, canals etc. that are probably reachable by the public through rights-of-way, public paths, or are adjacent to accessible Green Infrastructure. Other than for the accessible nature services, ecosystem services delivered by rivers are not explicitly mapped.

The tool does not consider condition, it reports a “naturalness” score for each mapped urban vegetation polygon which can also be interpreted as a condition assessment, however the score is calculated using data from the Detailed Urban Habitat mapping plus accessible Green Infrastructure polygons, roughly representing how “nature-rich” or “least-managed” a space appears, as a proxy for habitat condition / ecological quality. The naturalness score is not considered when calculating the ecosystem service proxy layers.

The Green and Blue Infrastructure Assets layer combines data from many authoritative sources (e.g. OS Open Greenspace, OS Open Map Local, Local Nature Reserves, etc.), giving a solid map of publicly accessible green/blue spaces. The

mapping of supply and demand of accessible Green Infrastructure is thus fairly robust. The local climate mitigation is assessed using the InVest model which is robust, but the input data is coarse (250m grid). Cooling demand is estimated combining social vulnerability data with a measure of heat hazard-exposure which are both published and considered fairly robust. The air pollution mitigation model is moderately robust: a spatial accounting approach that applies published pollutant-removal factors to mapped habitat classes to estimate PM_{2.5} removal at LSOA scale. The urban food production is moderately robust: a spatial, evidence-driven estimation that uses mapped allotment extents, empirically derived cultivation factors and socio-economic indices to infer provision, need and opportunity.

Strengths

Provides a single, nationally consistent database of green and blue infrastructure across England (scalable from national down to LSOA/MSOA/local authority). This makes comparisons and reporting straightforward. Combines terrestrial Green Infrastructure with blue infrastructure and provides analysis for accessible greenspace per population and accessibility standards as calculated outputs, not modules to run. Includes urban habitat mapping and a naturalness score which is a proxy for habitat-quality. Data and mapping are publicly accessible.

Limitations

The portal provides mapped assets and proxies (naturalness, water-quality classes) rather than models of service flows (e.g. pollutant transport, sediment routing, hydrodynamics). Blue infrastructure features are included and WFD status layers exist, but the portal lacks detailed aquatic habitat structure (channel morphology, in-stream habitat suitability) and it relies on monitored water bodies (so smaller/unmonitored streams may be absent). Scenario modelling is not available. Condition is not measured other than with naturalness of the site. The naturalness rating is a proxy and does not necessarily capture all dimensions of habitat quality (biodiversity, species richness, ecological connectivity, habitat fragmentation, micro-habitats). Naturalness in this assessment is concerned with the degree to which people using the greenspace might consider the level of management the space is subject to. The three ecosystem service models under development are currently only available for one location (Manchester). The urban habitat mapping is only available for some cities and requires an OS Mastermap licence.

Co\$ting Nature

Co\$ting Nature is a web-based ecosystem services and conservation prioritisation tool developed by King's College London (KCL), AmbioTEK, and partners. It is designed to support global to regional analyses of natural capital, ecosystem service provision, biodiversity importance, and human pressures. Co\$tingNature incorporates ecosystem service provision and benefits information into conservation prioritisation and planning by mapping 16 ecosystem services. It then combines them with analysis of current pressure, future threats, biodiversity and conservation priority

to produce an assessment of priority areas for conservation and careful (sustainable) management on the basis of all of these factors. This is done first using baseline datasets representative of the current situation. These are mapped globally using a combination of global remote-sensing products, climate, hydrological data, land-use datasets and protected area data. Users may then apply scenarios for land use or valuation and examine the impacts and implications for beneficiaries. By default, all outputs are expressed in normalised biophysical units in relative terms as indices from 0-1 locally within the study area. Users may carry out economic valuation of 22 potential and 22 realised ecosystem service values.

Two spin-off tools are available: Co\$tingNature for Sustainable Development which is aimed at assessing nature conservation and restoration investment priorities and Co\$tingNature for nature-related financial risk disclosure (TNFD).

Co\$ting Nature includes hydrological modelling, making it stronger than rule-based tools and more similar to InVEST in its treatment of water processes, but its hydrology is derived from global datasets, so scale is quite coarse.

Co\$ting Nature does not include habitat condition, however it features a current pressure on nature index as the combination of relative population, relative fire frequency, relative grazing intensity, relative agricultural intensity, relative dam density and relative infrastructural density, which is a proxy for habitat condition, though this is evaluated at a broad scale.

Co\$ting Nature has a strong scientific grounding and is described in numerous peer-reviewed publications.

Strengths

One of the few tools with complete global data, ready to use with no local datasets required. Integrates modelling of supply and beneficiaries and in particular can model where services are produced, where benefits are delivered and who receives them. Compared to other tools it features a more holistic approach combining ecosystem services, beneficiaries and monetary valuation, biodiversity, threats and conservation priorities. The hydrological modelling performed is robust given this is a tool with global coverage.

Limitations

The tool has a coarse spatial resolution (1ha or 1km). Even when users input their own data, customisation is limited given that global datasets are being used with possibly coarser spatial resolution. Users must work within set resolutions and set areas (tiles, basins, countries). The tool uses process models, but these are simplified algorithms that should not be used for detailed hydrodynamic modelling or nutrient modelling. Despite the name, it doesn't provide monetary valuation, it focuses on relative scores. Peer-reviewed validation is limited, but more has been

published compared to EBN or EcoServR. The interface is more technical and can be a barrier compared to other easier to use tools.

Ecosystem Service Map Explorer (ESME)

ESME (as described in more detail through this report) is an open-source and transparent mapping tool created to visualise and explore spatially explicit ecosystem service model outputs. Outputs have been modelled using expert-designed decision trees and the R package. ESME was developed as part of the Riverine Natural Capital Condition and Ecosystem Service Mapping project funded by Defra's NCEA programme. The underlying evidence and tool was developed as a collaborative approach between the Environment Agency, Natural Capital Solutions, and River Restoration Centre over multiple phases and reviewed by a wide panel of experts.

It uses environmental and socio-economic evidence on the condition of the water environment and surrounding catchment to model and map ecosystem service capacity (i.e. the potential to provide key ecosystem services). Users can view the underlying natural asset condition indicators and relative ecosystem service capacity in their area of interest, in map and chart form. The tool currently covers natural and modified freshwater rivers across England. Ten ecosystem services are currently included, and data can be explored at 3 spatial scales: management catchment, river waterbody and river reach.

Users can export the results to use in analysis, stakeholder engagement, business cases or project planning. ESME provides a snapshot in time using the most suitable national evidence available in 2025. It should be considered a starting point for understanding ecosystem service capacity in a place, and interpretation should be supplemented with local data and knowledge. It has been released as a Beta innovation product and will use user feedback to inform future improvements.

Strengths

Provides a single, ready to use, nationally consistent database of blue infrastructure (for freshwater rivers) across England, scalable from river reaches to WFD river waterbody catchments to WFD management catchments (from fine to broad spatial scale). It is based on robust evidence and co-designed with subject matter experts. It uses river condition to more accurately capture variability in ecosystem service capacity. It has a user-friendly interface, co-designed with users, and integrated user guidance, and does not require expert modelling or GIS skills to use it. Comparisons and reporting at different scales are straightforward. The tool provides analysis of the ten ecosystem services as calculated outputs and user-friendly ready to use maps, not modules to run, making this accessible to everyone, i.e. a user does not need to input data in order to obtain outputs. A user can load their own data to view alongside outputs if they wish and they can easily export data to use in their own systems. Map and chart outputs can also be exported. Data and mapping are open and publicly accessible. ESME has been reviewed by experts.

Limitations

This is a desk-based mapping tool based partially on national scale datasets, so spatial accuracy is not always high or coverage comprehensive for all indicators. The tool provides mapping for river reaches across England, but smaller streams may be absent. Artificial watercourses and tidal rivers are not currently assessed and mapped. Scenario modelling is not available. Economic valuation is not included. While the tool and outputs are open source, some underlying datasets have been used under license or with permission. The tool focuses on natural and modified freshwater river reaches; however, it does not include hydrological modelling to simulate river flows, water levels, or connectivity. As a result, ecosystem services associated with these reaches are assessed using simplified, static assumptions rather than being derived from process-based hydrological models, meaning that flow-dependent services (such as flood regulation or water availability) are not explicitly modelled. Service delivery is not based on modelled biophysical units, but on a scoring system that relies on indicators. It uses a mix of scoring approaches so should be seen as providing relative ecosystem service capacity scores. Model outputs have not been validated on the ground.

3.3 Conclusions

In reviewing a suite of tools for mapping ecosystem services including, InVEST, EcoServR, the EBN Tool, NEVO, the England Green Infrastructure Mapping Database, Co\$ting Nature and ESME it becomes clear that each offers useful but distinct capabilities. Of all the tools assessed, the EBN tool and ESME explicitly incorporate habitat condition into their assessment frameworks allowing it to influence the delivery of services, although within EBN Tool this is largely non-spatial. By contrast, Co\$ting Nature, InVEST, EcoServR, NEVO, and the England Green Infrastructure Mapping Database primarily rely on land-cover categories or modelled biophysical processes without directly integrating habitat condition. Apart from ESME, none of the tools explicitly assess river condition or in-channel ecological quality in a meaningful way. While Co\$ting Nature and NEVO offer hands-off mapping and ready to use outputs, EcoServR and InVEST provide a GIS-based approach for more detailed mapping, while EBN allows non-specialists to assess ecosystem service delivery. ESME offers all of the above features.

Together, the comparison highlights that although the six external tools collectively provide strong spatial and analytical foundations, there was a clear gap in capabilities. There was a need for a tool that focusses on rivers and one that integrates both habitat and river condition to more accurately capture changes in ecosystem service capacity. A further need was for a tool that provides ready to use and user-friendly mapped outputs, rather than requiring the user to carry out modelling, and does so at a fine spatial scale. The Ecosystem Service Map Explorer (ESME) has been designed to meet a number of these needs and how this has been

achieved is set out in the remainder of this report. ESME is the only user-friendly open mapping tool that uses evidence on the condition of rivers to model and map ecosystem service capacity.

Table 4: Details of the ecosystem services tools assessed. ESME is included at the bottom for comparison.

Tool	Authors	Version assessed	Open source	Frequency of update	Tool format / approach	Guidance and support	Usability (level of expertise required to use, time commitment)
InVEST	Stanford University.	3.17.1	Yes	Update every 3 months.	Consists of spatially explicit models the user runs on their own computer. Biophysical units are modelled.	Extensive documentation available, user guidance, tutorials, worked examples with sample data. Provides information on data sources and potential parameter values. Extensive virtual training options also available. Guidance informs interpretation. A dedicated forum is available to ask questions about ecosystem service models.	Requires GIS expertise and careful preprocessing of inputs.
EcoservR	Liverpool John Moores University in collaboration with Natural Capital Solutions, Forest Research, and the Cheshire	Beta testing.	Yes, but reliant on non-open data.	Unknown	Consists of spatially explicit models the user runs on their own computer.	Little guidance and support are available for this tool.	Tool is not easy to use given little guidance is provided for installations. No tutorial is available. GIS skills and good computer skills are required to install and run the R package, view outputs and pre-process data, although coding skills are not strictly required.

Tool	Authors	Version assessed	Open source	Frequency of update	Tool format / approach	Guidance and support	Usability (level of expertise required to use, time commitment)
	Wildlife Trust.						
Environmental Benefits from Nature (EBN) tool	Natural England.	Beta Release v1.1	Yes	Unknown	Excel sheet which needs input data from user.	User guide, data catalogue, and evidence base describing the scoring rationale as well as quick start videos and case studies.	Tool is relatively easy to use, no spatial data expertise needed. EBN module on GI mapping portal links with EBN tool. Habitat and contextual information are needed for the EBN tool which can now be found on the GI website.
NEVO	Land, Environment, Economics and Policy Institute (LEEP), University of Exeter.	Version not clear (accessed Dec 2025)	Yes	Unknown	Consists of a portal where data can be viewed, scenarios can be tested online without input data and results downloaded.	Technical reports, video tutorial and case studies are available.	Tool is very easy to use, no spatial data expertise needed.

Tool	Authors	Version assessed	Open source	Frequency of update	Tool format / approach	Guidance and support	Usability (level of expertise required to use, time commitment)
England Green Infrastructure Mapping Database	Natural England and Defra.	2.2	Yes, (mostly)	Regularly	Consists of a portal where data can be viewed online and downloaded.	Documentation available as well as introductory videos.	User guide provides information on data sources and data processing of the available outputs. Given no data processing is required by the user the tool is highly usable.
Co\$ting Nature	King's college London, AmbioTEK, UNEP-WCMC.	3	Not free for commercial use, free for non commercial use.	Regularly updated.	Consists of a portal where data can be viewed, scenarios can be tested online without input data (though it is possible to add own data) and results downloaded.	User guide and video tutorials available.	Tool interface less easy to use compared to others but still user friendly. No spatial data expertise needed, unless using own data.
ESME	Environment Agency, Natural Capital Solutions, River Restoration Centre	Beta 1.0	Yes	Not yet determined.	Consists of a portal where data can be viewed online and downloaded.	Extensive documentation available including project and methodology reports, a user guide, video tutorial, applications and limitations guidance, case studies, and a dataset and indicators library.	No data processing is required by the user, and it has a user-friendly interface, so the tool is highly usable. No spatial data expertise needed.

Table 5: Further details of the ecosystem services tools assessed. ESME is included at the bottom for comparison.

Tool	Robustness	Data input required	Is the tool spatially explicit?	Transparency	Scale	Valuation	Does it explicitly consider rivers	Is condition considered	Output type
InVEST	Very robust. Results have been validated in a lot of instances.	Yes	Yes	Medium - Users can understand underlying processes by reading the documentation, but given it is a process based model it won't be straightforward.	Resolution is user dependent.	Uses a production function which relates to the spatial output.	Not a river focussed tool.	Does not model detailed in-river processes. It treats rivers mostly as flow paths for sediment, water, and nutrients.	Results consist of spatial data generated on user's own computer.
EcoservR	Moderate robustness, but evidence-based models are used.	Yes	Yes	Medium - Users can understand underlying processes by reading the EcoServ-GIS documentation, but given it is a process based model it won't be straightforward.	Resolution is user dependent, but generally fine scale (c. 10m ²).	Not provided.	Not a river focussed tool.	No	Spatial maps showing relative ecosystem service demand and capacity through indices.
Environmental Benefits from Nature (EBN) tool	Moderate robustness. Little to no validation.	Yes	No. Spatial information can be used to modify scores within the excel sheet, but this	High - Habitats and condition assigned values based on lookup tables make it very easy to	Resolution is user dependent.	Not provided.	Not a river focussed tool.	Yes	Tabular output (and charts).

Tool	Robustness	Data input required	Is the tool spatially explicit?	Transparency	Scale	Valuation	Does it explicitly consider rivers	Is condition considered	Output type
			is very different from spatially explicit mapping of ecosystem services.	understand the process.					
NEVO	Robust	No	Yes	Medium - Users can understand underlying processes by reading the documentation, but given it is a process based model it won't be straightforward.	2 km grid cell up to large administrative units, catchments, or the entire country.	Provided	Not a river focussed tool.	No	Spatial maps and charts showing ecosystem service flows and values at different scales (grid, catchment, administrative area). Projections over decades accounting for climate-change scenarios.
England Green Infrastructure Mapping Database	Variable, none of the outputs are very robust.	No	Yes	High - Simple calculations made to generate outputs make outputs straightforward to understand.	Variable, data often aggregated at LSOA	Not provided.	Not a river focussed tool, but provides	Does not consider condition of rivers or other asset classes.	Results consist of spatial data that can either be viewed on

Tool	Robustness	Data input required	Is the tool spatially explicit?	Transparency	Scale	Valuation	Does it explicitly consider rivers	Is condition considered	Output type
					level or 250m grid.		accessible watersides dataset.		website or downloaded.
Co\$sting nature	Variable, but overall moderate robustness.	No, but can add own data.	Yes	Medium - Users can understand underlying processes by reading the documentation, but given it is a process based model it won't be straightforward.	1ha – 1km ²	Provided	Not a river focussed tool.	No	Spatial maps and charts showing ecosystem service flows and values as well as tabular outputs for economic valuation where applicable.
ESME	Variable, depending on ecosystem service model. Overall moderate robustness as expert derived models are	No	Yes	High – users can understand scoring system by reading the documentation.	River reach scale up to catchment scale.	Not provided.	Yes	Yes	Results consist of relative ecosystem service capacity spatial maps and charts that can either be viewed on website or downloaded,

Tool	Robustness	Data input required	Is the tool spatially explicit?	Transparency	Scale	Valuation	Does it explicitly consider rivers	Is condition considered	Output type
	used. Results have not yet been validated on the ground.								at different scales.

Table 6: Review of the list of regulating ecosystem services included in the selected ecosystem services tools and ESME.

Tool	Local atmospheric regulation (air quality)	Water quality regulation	Soil health	Climate regulation	Global atmospheric regulation	Habitat and Species Population Maintenance	Pollination and seed dispersal	Water flow regulation	Erosion control	Protection from coastal erosion	Protection from coastal inundation	Nuisance mitigation
InVEST	/	Index of nutrient retention which can be converted into biophysical units.	/	Biophysical model and valuation.	Biophysical model and valuation and specific model available on blue carbon and forest edge effect.	Available, no valuation.	Creates an index of pollinators value to agricultural production.	Biophysical model and valuation.	Biophysical model.	Qualitative map of coastal erosion risk.	qualitative map of coastal flood risk.	/
EcoservR	Mapped index, no valuation.	Mapped index, no valuation.	/	Mapped index, no valuation.	Mapped index, no valuation.	/	Mapped index, no valuation.	/	/	/	/	Mapped index, no valuation.
EBN	Score	Score	/	Score	Score	Score	Score	Score	Score	/	/	Score
NEVO	/	Map of biophysical units. No valuation.	/	/	Biophysical model and monetary valuation.	Available, no valuation.	/	Map of biophysical units. No valuation.	Unclear	/	/	/
GI mapping database	Mapped index, no valuation.	/	/	Mapped index, no valuation.	/	/	/	/	/	/	/	/
Co\$ting Nature	/	Biophysical model and monetary valuation.	/	/	Biophysical model and monetary valuation.	Mapped indirect use value of all species in study area	Biophysical model and monetary valuation.	/	Biophysical model and monetary valuation.	/	/	/

Tool	Local atmospheric regulation (air quality)	Water quality regulation	Soil health	Climate regulation	Global atmospheric regulation	Habitat and Species Population Maintenance and monetary valuation.	Pollination and seed dispersal	Water flow regulation	Erosion control	Protection from coastal erosion	Protection from coastal inundation	Nuisance mitigation
ESME	/	Score	/	/	/	Score	/	Score	/	/	/	/

Table 7: Review of the list of provisioning ecosystem services included in the selected ecosystem services tools and ESME.

Tool	Cultivated plants and reared animals. (Plants)	Cultivated plants and reared animals. (Acquaculture)	Renewable energy (hydro/geothermal)	Timber provision	Fuel wood production	Water supply (drinking/ agriculture/ industry)	Food from fisheries
InVEST	Crop yield map.	/	Biophysical model and valuation.	/	/	/	/
EcoservR	/	/	/	/	/	/	/
EBN	Score	/	/	Score	/	Score	Score
NEVO	Biophysical model of yields and production responses. Monetary valuation.	/	/	Biophysical model and monetary valuation.	/	Map of biophysical units. No valuation.	/

Tool	Cultivated plants and reared animals. (Plants)	Cultivated plants and reared animals. (Aquaculture)	Renewable energy (hydro/geothermal)	Timber provision	Fuel wood production	Water supply (drinking/ agriculture/ industry)	Food from fisheries
GI mapping database	Mapped index, no valuation.	/	/	/	/	/	/
Co\$ting Nature	Biophysical model and monetary valuation.	Biophysical model and monetary valuation.	/	Biophysical model and monetary valuation.	Biophysical model and monetary valuation.	Biophysical model and monetary valuation.	Biophysical model and monetary valuation.
ESME	/	/	/	/	/	Score	/

Table 8: Review of the list of cultural ecosystem services included in the selected ecosystem services tools and ESME.

Tool	Aesthetic and amenity experiences	Spiritual, cultural and religious experiences	Education and investigation	Recreation	Physical / Mental Health and Wellbeing	Open space proximity	Green travel	Intrinsic value of nature
InVEST	Produces maps of impacts of infrastructure on views of marine and	/	/	Visitation rate available, no valuation.	/	Amount of natural space per capita and	/	/

Tool	Aesthetic and amenity experiences	Spiritual, cultural and religious experiences	Education and investigation	Recreation	Physical / Mental Health and Wellbeing	Open space proximity	Green travel	Intrinsic value of nature
	coastal seascapes. No valuation.					demand. No valuation.		
EcoservR	/	/	/	/	/	Mapped index of accessible nature capacity and demand, no valuation.	/	/
EBN	Score	Score	Score	Score	Score	/	/	/
NEVO	/	/	/	Provides visits and monetary valuation.	/	/	Provides visits and monetary valuation.	/
GI mapping database	/	/	/	/	/	Yes, value of ha of open space per capita and other metrics available, no valuation.	Yes, linear access mapped, no valuation.	/
Co\$ting Nature	Hedonic value mapped and	Mapped annual spend of all culture-based		Mapped annual spend of all nature-	/	/	/	/

Tool	Aesthetic and amenity experiences	Spiritual, cultural and religious experiences	Education and investigation	Recreation	Physical / Mental Health and Wellbeing	Open space proximity	Green travel	Intrinsic value of nature
	monetary valuation.	tourists in the study area and monetary valuation.		based tourists in the study area and monetary valuation.				
ESME	Score	Score	Score	Score	Score	/	/	Score

4. Validation process and key decisions

A key part of developing a national riverine natural capital condition and ecosystem service mapping tool is to ensure a robust process of testing, feedback and validation. Here we outline this process (Section 4.1) and how the tool was validated (Section 4.2). When developing the tool, a number of options were developed and presented, and feedback sought. Decisions on these options, which were then taken forward, and the justifications for why these were taken, is shown Sections 4.3 to 4.6.

4.1 Reviewing and gathering feedback

An important component of the project was that it was designed to be collaborative with Environment Agency staff, who were fully involved in shaping the project through workshops and surveys, and by active participation in the review team. It was also subject to an extensive review process. Wider partner feedback was also sought and considered, including from other NCEA partners (e.g. Defra and Natural England), water companies and local Rivers Trusts. An outline of the steps taken to ensure review of the project is thorough and feedback is integrated appropriately is shown here:

- Phase 1: Series of workshops held to define scope and parameters of project, and to determine key ecosystem services to be included. Quick Scoping Review (QSR) of scientific literature, followed by extensive peer review by Environment Agency staff and externals. The QSR has also now been published in the scientific literature, so was subject to further external peer review.
- Phase 2: Prototype mapping tool developed. Internal Environment Agency and external peer review of tool and methods. Feedback from workshops and questionnaires was collated and analysed, and recommendations compiled. Additional feedback was also collected by the Environment Agency team after Phase 2 had completed and these suggestions have also been integrated.
- User Stories: Between Phases 2 and 3, 17 focus groups were interviewed to gather information on potential uses of the mapping tool and to collate user requirements and feedback.
- Phase 3: Workshop held on river reach design, and another on scaling and combining indicators, to shape the methods taken forward. New tool developed (ESME) and demonstrated during stakeholder workshop session. ESME was provided to Environment Agency staff for testing, with feedback via questionnaire. Methods also subject to extensive Environment Agency review.
- Phase 4: Decision trees and indicators went through a further round of Environment Agency review, and specific internal and external subject

experts were also approached for comments on particular outstanding questions. Beta version of ESME subject to detailed quality assurance by the project team and a User Acceptance Testing programme by a group of 20 Environment Agency staff. All documentation subject to internal and external review.

4.2 Validation

Validating the output of ESME is an important but difficult task. It is vital that the outputs make sense and appear reasonable so that users can have confidence in the results, but it is difficult to achieve this as there is little to compare results to. All aspects of ESME have been subject to extensive review and testing (as outlined above) and this process can continue on publication. We are releasing ESME as a Beta version innovation product and welcome all feedback. To provide feedback please contact NaturalCapital@environment-agency.gov.uk.

Here we list the approach to validation already taken and further steps that can be taken.

4.2.1 User review and testing

This has been the main process used so far to validate the methods and results. As described in Section 4.1, all phases of the project have been developed and co-designed in close conjunction with the Environment Agency steering group and with large numbers of reviewers involved in checking all aspects of the work. This provides increased confidence in the results, as subject experts have thoroughly reviewed the methods developed, datasets chosen and so on, and means that many users will have also had some input and exposure to the tool before launch. Smaller groups of technical experts were also closely involved in developing some of the more technical aspects of the work, such as designing the reaches and deciding the best approach for combining indicators. User Acceptance Testing has focussed on testing the tool itself for usability, reliability and bug identification.

As the tool is released publicly, we welcome further feedback from a wider range of audiences. Local users are likely to have a good feel for their catchments and how the results should look and hence will be able to identify obvious discrepancies. In addition, publication means that the tool will be available to a wider range of people, who may bring different perspectives and have different uses for the tool, which may throw up additional points.

4.2.2 Adding own datasets

One process that has been built into ESME that will help with validation is the ability for users to import their own or additional datasets. In particular, if users have local datasets that provide data on an aspect of condition that is not available nationally, this can be imported into the tool and viewed alongside the national coverage data. This can be used both to inform/validate how well the national tool is working or to

provide additional nuance and detail. Where relevant, users can feed back this information back to the Environment Agency so adjustments can be considered in future iterations.

4.3 Which spatial scale should be presented?

A key option tested in an early phase of the project concerned the spatial scale at which the mapping should be presented. Three options were presented: river reach, WFD waterbody catchment, and WFD management catchment. In questionnaires and polling, virtually all participants favoured retaining more than one scale (97%, Figure 4 top). The majority of responses favoured using all scales available (60%) (Figure 4 bottom). The second most popular option (29%) was to use river sections and waterbody catchments, but not management catchments.

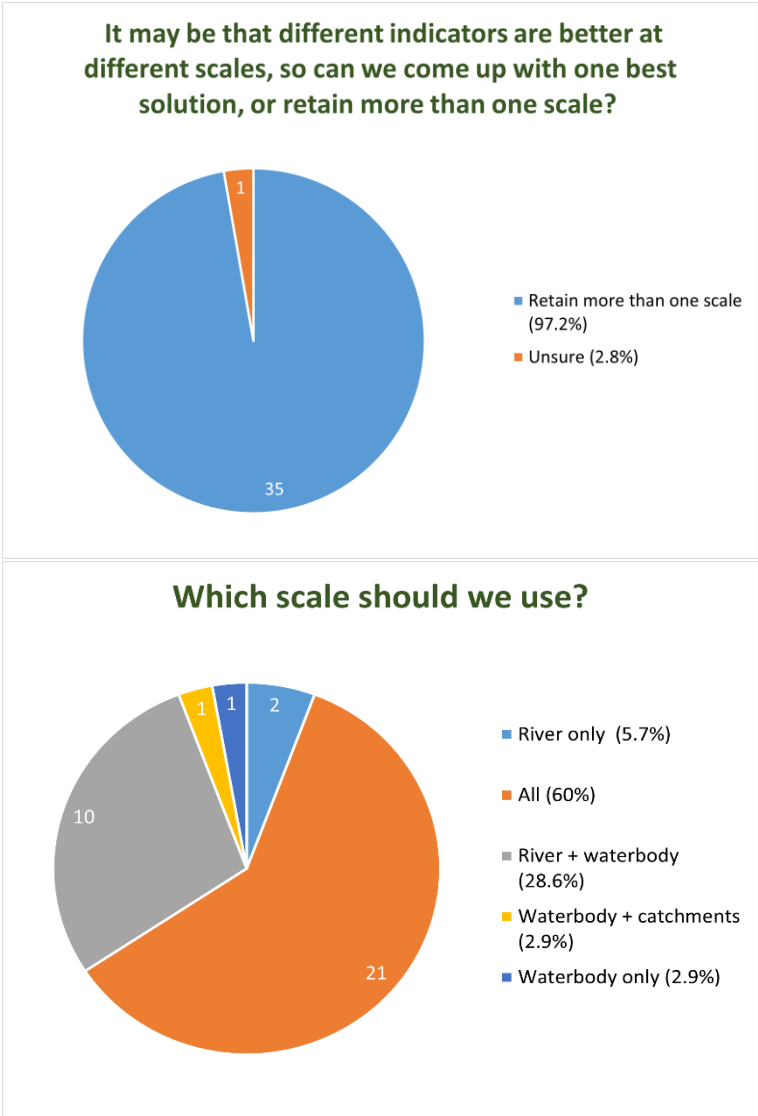


Figure 4: Preference for one best scale or retaining more than one (top, n = 36), and preferred scale (more than one scale could be selected, bottom, n = 35). Data collected from questionnaires in Phase 2 (further detailed in interim Phase 2 report (Zini et al., 2024) although note this has not been published).

This question was asked again during the User Stories focus groups. The preferred user output scales from the 17 groups were as follows:

- River reach: 88%
- Water body: 82%
- Management Catchment: 71%

Response: There was a clear preference expressed across all user testing for all three scales. **We have therefore retained all three scales in the national tool.**

4.4 Should the product use open source or licenced data?

We tested whether it would be possible to use only open source data for the mapping tool by developing two prototype versions: one using only open data and the other using some licenced data (where it was felt this might offer richer evidence). In both versions almost all the data used for the indicators was open source, although we did use a limited number of licenced datasets for the licenced product. The main areas where open source data was not available or of significantly lower quality was for species data (most data is under licence from National Biodiversity Network) and some water resources datasets.

Differences were most significant, however, in the river baselines that underly the mapping at reach scale. For open source data, we used the Open Rivers Network (ORN) combined with open data on canals, whereas for the licenced version we were able to use the Ordnance Survey Water Network (OSWN), which forms the basis of the NCEA Analysis Ready Water Network (ARWN). The latter is much more detailed, including the spatial location of very small channels, and details such as culverted sections.

Feedback on which product to use was initially mixed, with many suggesting that an open data product would be preferable, particularly to enable sharing with external partners, but others preferring the accuracy of the OSWN and the links to other Environment Agency licenced mapping products. However, there was also acknowledgement that the OSWN was too detailed, and provided river reaches that were much too short for ecosystem service mapping (see Section 5 for further detail on reaches).

Between Phases 2 and 3, the Environment Agency project team undertook an in-house analysis of the open versus licenced outputs. The overall finding was that the use of open versus licenced outputs did not result in significant differences in the ecosystem service outputs, with the recommendation to pursue only using open data as the product was further developed.

The use of open versus licenced data was further addressed in the User Stories focus groups. The preferences expressed by the 17 groups were as follows:

- Open data essential: 100%

- Licenced data use acceptable: 41%

The User Stories also considered sharing requirements for the tool and outputs. Sharing with external partners was considered an important requirement, with 18 different user groups identified. The top 3 partners identified by multiple groups were:

- Catchment partnerships (identified by 71% of groups).
- Spatial planners and combined or local authorities (65%).
- Water companies (59%).

Sharing with partners would require an open product with no licence restrictions (although public sector bodies can access OS data under the Public Sector Geospatial Agreement).

A further assessment of the potential use of restricted data has shown that there appears to be little advantage in using restricted data for the river baselines. Using entirely open data (or 3rd party data where we have express permission to use it to derive open outputs) within ESME also adequately captures the vast majority of important datasets, enabling us to map indicators and ecosystem services with relatively high confidence (see Section 10 for more on confidence). The only significant enhancement that could be gained from using restricted (licenced) datasets that we could identify would be the use of species data for the Intrinsic value of nature and possibly in other ecosystem services scores.

Response: Due to the only small difference in outputs under the two approaches and the requirement to share outputs with external partners, there was a clear **preference for the tool to be fully open.**

4.5 Artificial watercourses

During an earlier phase of the project, the prototype mapping tool included indicators and ecosystem services for artificial watercourses (see Box 4), but we found few asset-specific indicators, and maps were largely created by excluding the river indicators that were not applicable to artificial watercourses. However, these watercourses are quite different to natural rivers and confidence in the results was generally low, due to a lack of specific data for these assets. It was recommended that further work should be completed on these watercourses by engaging the Canal and River Trust (CRT) to provide data and artificial watercourse expertise.

Box 4. Artificial watercourses

Artificial watercourses are defined as:

'a surface water body which has been created in a location where no water body existed and which has not been created by the direct physical alteration or movement or realignment of an existing water body' (European Commission, 2003).

Artificial waterbodies include completely artificial dug canals, water diversions, leats and reservoir feeders (Environment Agency, 2009). It includes channels classified as Artificial Waterbodies under the Water Framework Directive.

A meeting was therefore held with CRT. However, it was not possible to take this arrangement further. They acknowledge ecosystem service evidence for artificial watercourses is lacking which is why they've embarked on a plan to develop benefit valuation information over the next few years. They are collecting detailed data on visitor numbers and ecology on parts of their network to support this. The Environment Agency will continue to explore avenues to improve the evidence base, and would like to include artificial watercourses in future iterations of ESME when suitable evidence with national coverage becomes openly available.

Response: Due to the lack of data and therefore confidence in the outputs, it was decided that the **mapping of artificial watercourses would not be completed** and these watercourses would not be included in the mapping tool. They could be added at a future date, once suitable data and expertise becomes available.

4.6 Mapping tool platform and functionality

Initially the prototype mapping tool was created on the Environment Agency's Esri ArcGIS Online (AGOL) platform as an "Instant App". Extensive feedback was collected on desired functionality, and this drove the development of the next version of the tool (the Beta national version).

Feedback was also collected as part of the User Stories. Generally, respondents felt that:

- The tool was intuitive and easy to use.
- More information and guidance would benefit users.
- Ecosystem service scores are best left separate (not combined).

There was a strong preference in the broader feedback to continue using a tool within AGOL, rather than a customised application, predominantly to ensure that the tool could be maintained and updated by Environment Agency in-house. The new Beta version therefore continues to use an Esri product, but it has now been built using Experience Builder within AGOL, which gives better performance and a wider range of options for the look and functionality of the tool. Processes have been built in to enhance rendering performance at different scales, and a completely new layout was developed based on extensive feedback (see Figure 5).

A range of new functionality has now been built in, including graphics, import, export, additional reference data layers, guidance videos, and documentation. These are described in more detail in Section 8, and user guidance is available within the tool itself and in a stand-alone User Guide.

A number of suggestions for future improvements were also made as part of the User Stories focus groups. Many of these suggestions have been addressed. The suggestions and our responses are listed in Table 9.

Response: A brand new mapping tool has been developed with an improved look and much greater functionality. The Beta national tool is now called the Ecosystem Service Map Explorer (or ESME).

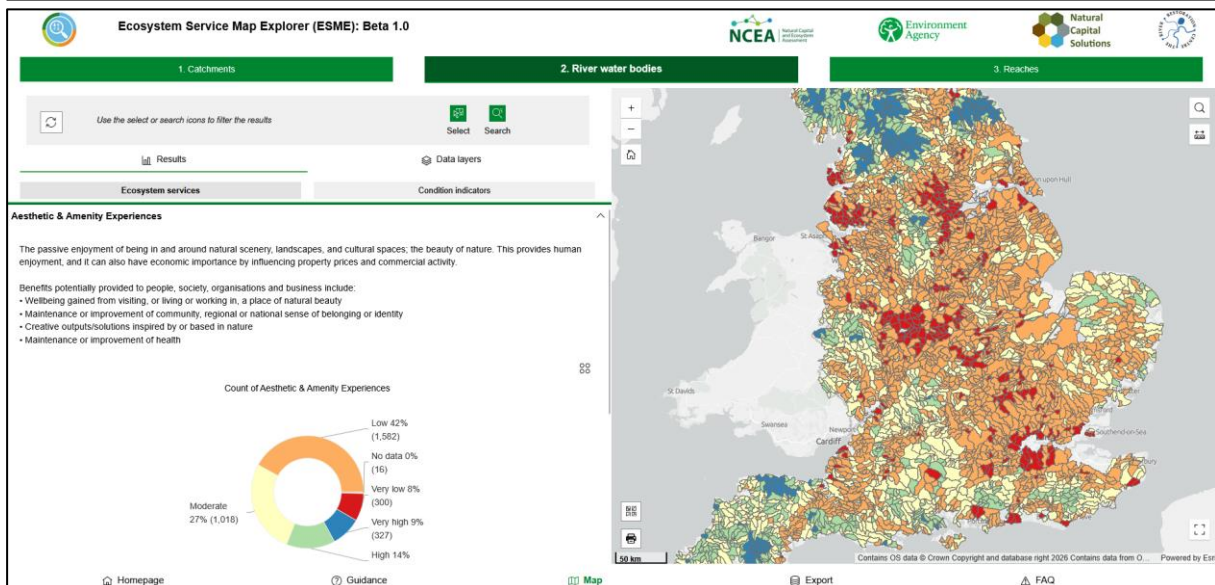
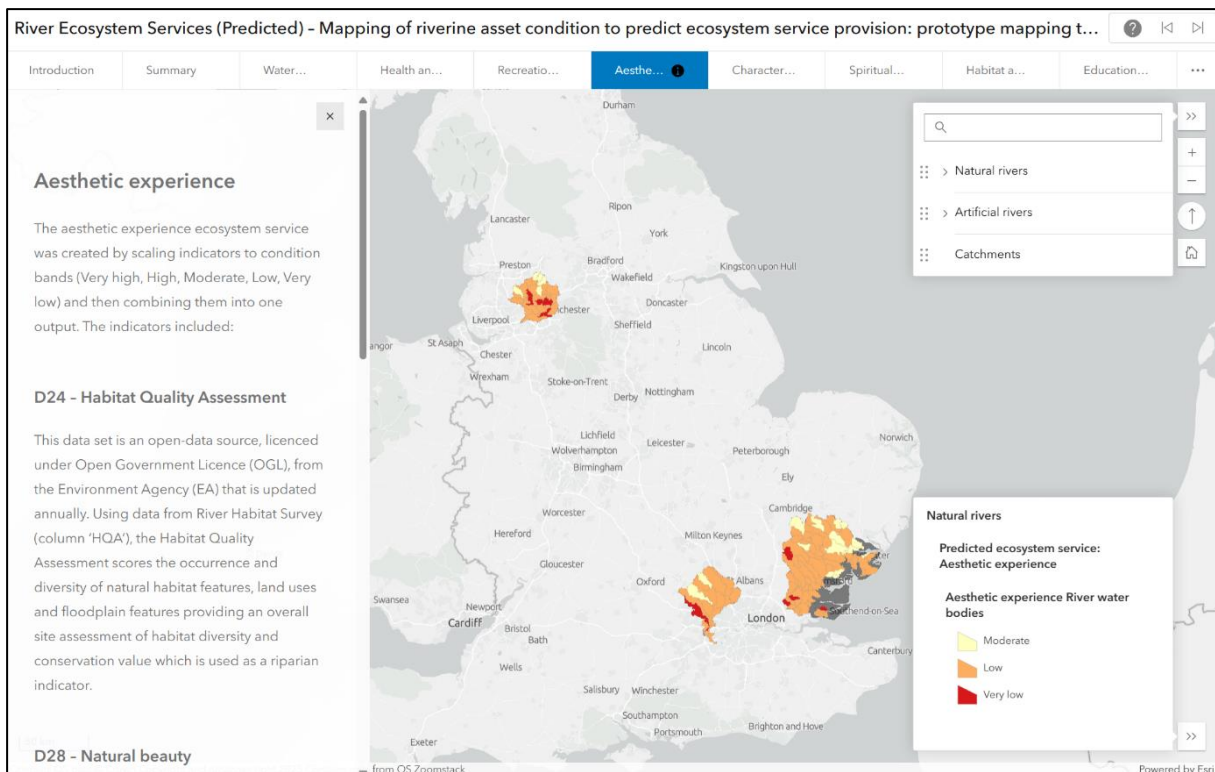


Figure 5: Screenshots showing the look of the prototype tool developed in Phase 2 (top), and the Ecosystem Service Map Explorer (ESME) Beta version (bottom).

Table 9: Further improvements suggested by the User Stories focus groups and the project response. Part A shows all suggestions made by at least two group, part B.) shows selected suggestions made by one group only.

Suggested improvements	% Users	Response
A.) Main suggestions		
Tracking of change to ecosystem services over time	88.2	Future development could address this (once we have a time series of data against the 2025 baseline)
Add reference datasets	70.6	ü Included
Option to generate a pdf map and/or summary report	58.8	ü Included, but scope to enhance further in the future
Add own layers	47.1	ü Included
Link to benefits/beneficiaries and valuation	41.2	ü High-level benefit narrative included, but scope to expand in future
Guidance on scoring criteria	17.6	ü Included
Clear training and guidance on use	17.6	ü Included
Options for map transparency	11.8	ü Included
B.) Other suggestions:		
Ability to export reach level data for use in BNG / condition impact assessment	5.9	ü Included
Different basemap options	5.9	ü Included
Include transitional and coastal water bodies and coastal areas	5.9	Identified in ESME. Option to include full assessment in the future
Inclusion of artificial water bodies, i.e. canals	5.9	Future development could address this
Consider future demands for ecosystem services	5.9	Future development could address this
Create a super user network	5.9	Future development could address this

N.B. % Users shows the percentage of Focus Groups (not individuals) where the suggestion was made (there were 17 groups in total).

5. Reaches

5.1 Introduction

A reach can be defined in either “operational” or “functional” terms which reflect the needs to balance management and practical restrictions with the changes in environmental conditions, such as hydrology, morphology and habitat structure (Parker et al., 2012). A functional reach can be defined as a “section of river along which boundary conditions are sufficiently uniform that the river maintains a near consistent internal set of process-form interactions” (Gurnell et al., 2014). It can be defined by a change in:

- Lateral confinement (channel width:floodplain width ratio)
- Valley gradient (energy conditions; dams/weirs)
- Catchment area (water supply; tributaries)
- Sediment supply (debris flows, landslides)
- Sediment calibre

Reach delineation divides a catchment into manageable units, that can be used as a basis for assessment at different scales to achieve catchment-scale objectives. Phase 2 of the project delineated reaches based on digitised segments of polylines in the ORN within its pilot mapping. As such, the reach lengths and groupings of river segments were arbitrary and did not represent environmental or hydrological properties that would affect ecosystem service provision. However, incorporating these components into a method that produces more homogeneous reaches has to be balanced with the practical need to tie-in with standard Environment Agency networks and management practices.

Further reach development work in subsequent phases offers a more scientifically rigorous approach to river segmentation by aiming to maximise the similarity in hydromorphological conditions within reaches and the differences between adjacent reaches. It also divides rivers by key administrative boundaries in the WFD, including water body ID, and is constrained by criteria that match the needs of users. To reach consensus on reach delineation, an expert workshop was designed to determine what should represent a good reach, what it should be used for and by whom, and the delineation criteria and method. The results of the workshop are summarised below and have been used to inform the method for river segmentation. An overview of possible approaches to segmentation and the one taken forward is provided here, with full methodological details provided in the accompanying Methodology report.

Expert Workshop

An expert workshop was conducted on the 16th October 2024, involving 16 attendees with expertise in a range of related disciplines including water quality research, freshwater ecology, fisheries science, geomorphology, hydromorphology, river

networks and lakes. Attendees participated in a guided mind-mapping session and discussion aimed in three key areas:

1. What should a reach represent?
2. What should it be used for, and by whom?
3. What should be the delineation criteria and method?

5.2 Results

The results of the workshop are illustrated in Figures 6 and 7, together with a summary of what was agreed for each of the three discussion points.

5.2.1 What should a reach represent?

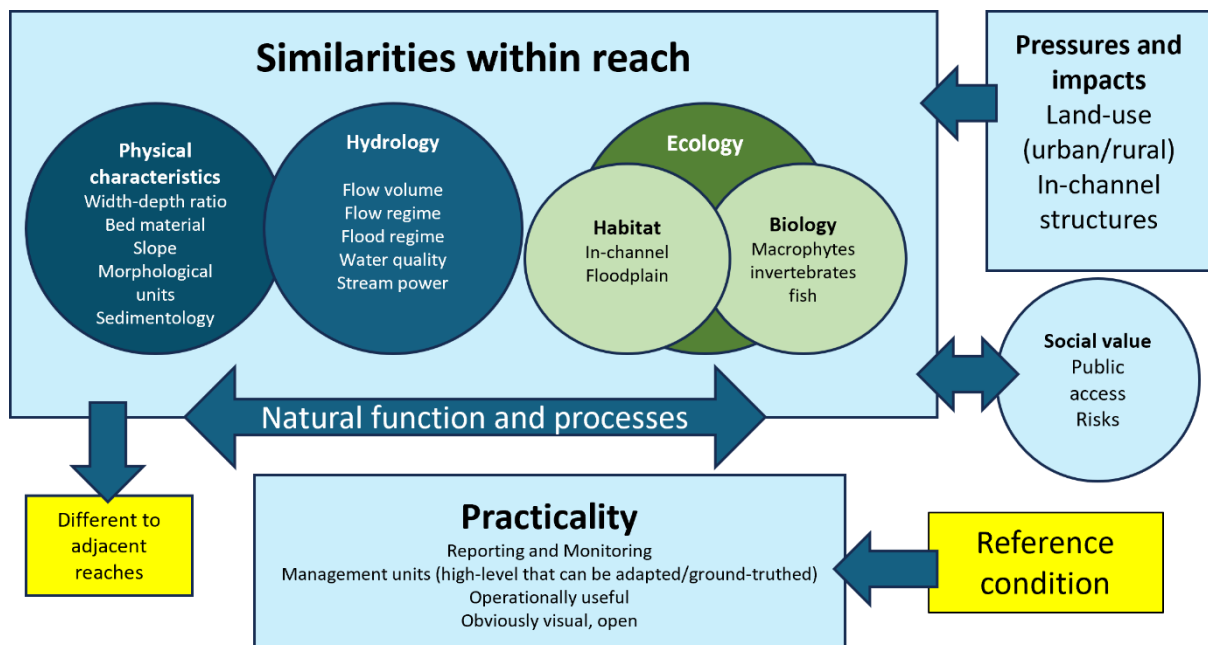


Figure 6: Summary of results from workshop session: "What should a reach represent?"

A range of parameters for representing a reach were identified, including its physical characteristics, hydrology, and ecology (habitat, biology, etc.); pressures and impacts along the river and floodplain; and practical and management units. It was recommended that the parameters should be similar within the reach and different to the adjacent reaches.

In summary, a reach should:

- Represent a distinct unit consistent in:
 - space - in terms of its hydromorphology (habitat), hydrology, morphology, processes, and forms; and

- time - reaches boundaries should not fluctuate in time and should represent distinct reference condition units.
- Be useful for the purposes of monitoring and reporting, regulation, and planning.

5.2.2 What should it be used for, and by whom?

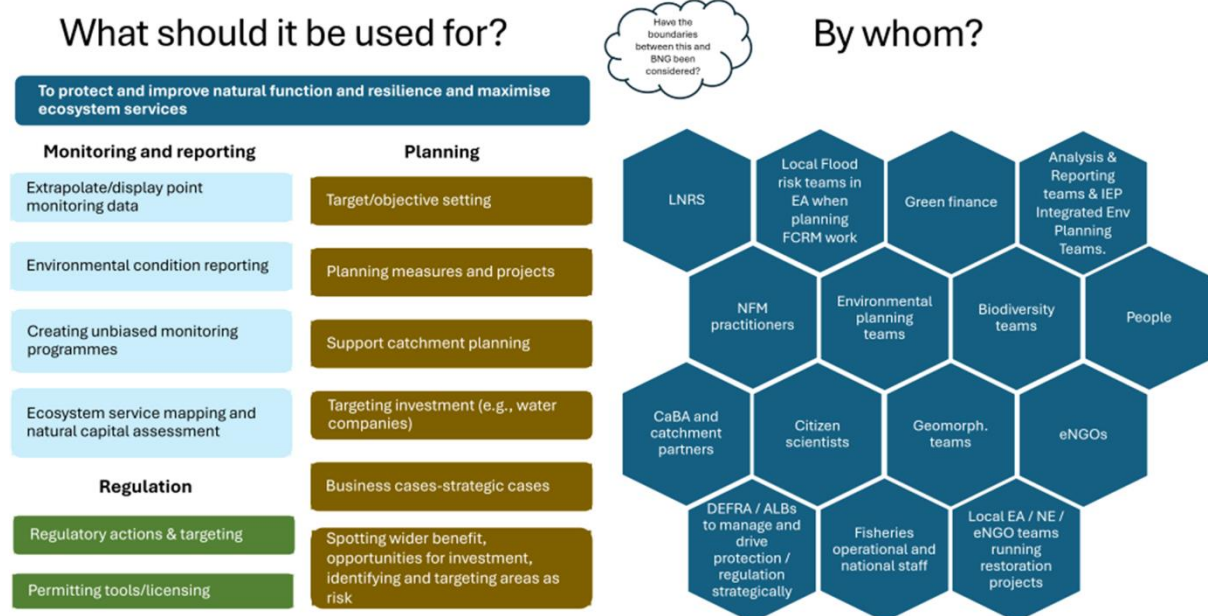


Figure 7: Summary of results from workshop session: "What should a reach be used for, and by whom?"

The workshop results suggest that a reach should be useful for a range of purposes including monitoring and reporting, regulation, and planning purposes. It additionally should be useful for operational staff (flood risk, fisheries, etc.), planners (environmental planning, Local Nature Recovery Strategies, etc.) and third-sector and local authorities (CaBA, eNGOS, etc.).

5.2.3 What should be the delineation criteria and method?

The discussion of delineation criteria highlighted the importance of having a minimum length, for example "smaller than WFD bodies for it to provide additional detail", or simply a 1 km minimum. A maximum reach length was shown to be less of a concern in the workshop, as long as the conditions within a reach are similar. Additional comments about the method for reach delineation are given in Figure 8.

In summary, a reach should be defined by the following delineation criteria:

- 1 km minimum length
- Waterbody (WFD boundaries)
- Changes in drivers and processes
- Changes in forms and habitats

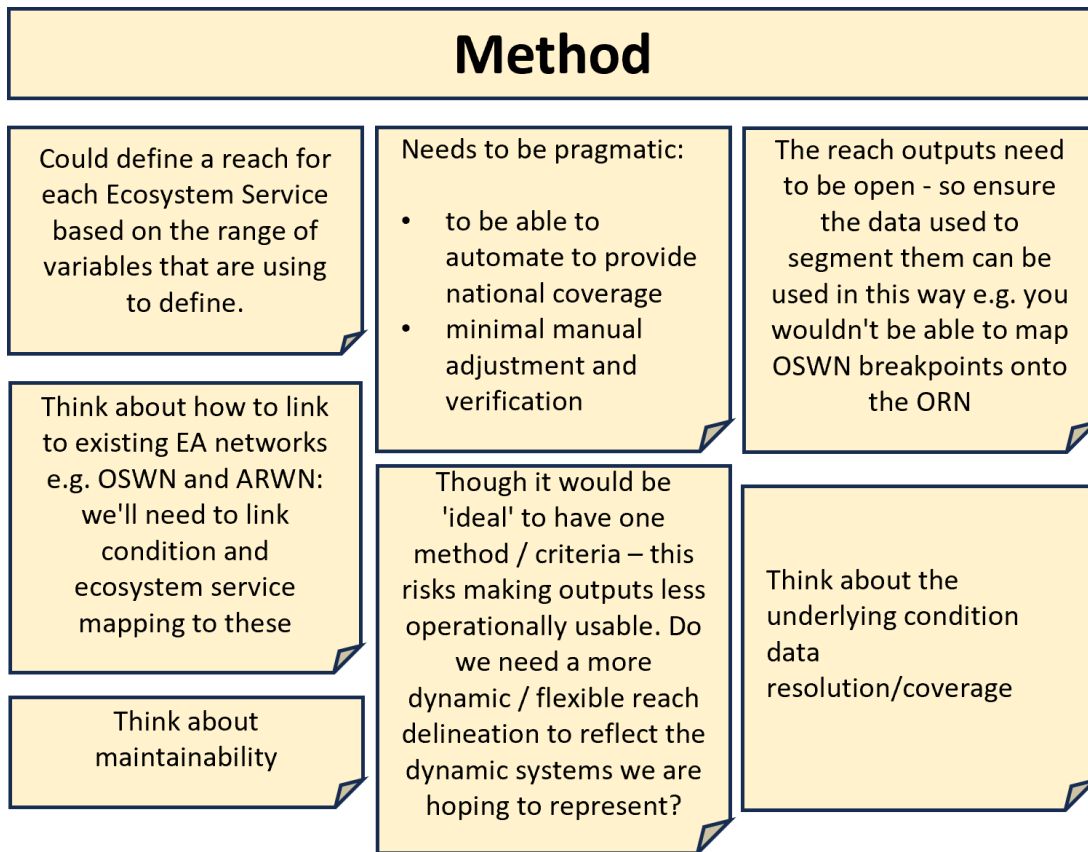


Figure 8: Suggestions from workshop attendees for the segmentation method.

5.3 Options moving forward

Following the workshop, several options for the delineation of reaches were designed that could be implemented across the ORN network. The three options are given below:

1. Building blocks of segmentation
2. Adaptation of existing segmentation (CatchmentLife)
3. Simplified approach assuming that habitat is defined by energy

5.3.1 Option 1: Building blocks of segmentation

Option 1 was designed so that reaches could be created or combined based on specific uses or requirements. It would enable users to identify reaches and break points for individual criteria such as:

- a. Management
 - i. Waterbody ID
- b. Drivers and processes
 - i. Strahler order
 - ii. Specific stream power

- iii. Land-use
 - iv. Flow (discharge, flow regime, groundwater)
 - v. Ratio valley/channel width
 - vi. Sediment supply
- c. Forms and habitats
- i. In-channel habitats
 - ii. Floodplain habitats

This approach was not deemed pragmatic at this point in the project due to the available resources and time but could be explored further in future iterations.

5.3.2 Option 2: Adaptation of existing segmentation (CatchmentLife and ToolHab)

Option 2 builds upon an existing method designed and validated by the River Restoration Centre (RRC) for the [CatchmentLife](#) project. The CatchmentLife method builds on a previous method derived as part of a Decision Support System called ToolHab that was developed for the Environment Agency in 2013 (Naura, 2013 and 2014). The ToolHab and CatchmentLife methods used data derived and predicted at 500m points along the UKCEH river network to identify river segments with similar characteristics and distinct from neighbouring segments. The delineation for ToolHab included 8 attributes representing known hydromorphological dimensions (channel substrate, flow-types, channel vegetation and geomorphic activity) as observable and in semi-natural conditions. For the CatchmentLife delineation, additional attributes were included in the analyses such as Strahler stream order, water bodies and land use. CatchmentLife delineation also assumed a minimum reach length of 2 km based on an analysis of hydromorphological conditions variation using RHS data nationally which showed that there are no statistical differences between RHS site habitats and pressures within 2 km distance (Marc Naura, personal communication). To be applicable to the natural capital assessment, the minimum reach size would have to be set at 1 km instead of 2 km and the UKCEH points would have to be snapped to the ORN network. The orange boxes in Figure 9 show which parameters the CatchmentLife method contributes towards. The data and data points from the UKCEH river network points are only used for deriving river reach boundaries and will not be published as part of the final outputs, therefore, there are no restrictions on the publication and public use of the reach boundaries.

5.3.3 Option 3: Simplified approach assuming that habitat is defined by energy

Option 3 was designed as a simpler alternative that would build the reaches from scratch using the following criteria:

- a. Waterbody ID
- b. Energy, using
 1. Stream power map from Environment Agency or

The CatchmentLife method uses a hierarchy of segmentation break causes that are implemented in the following order (see Methodology report for more details):

1. WFD Waterbody ID
2. WFD Lake ID
3. Strahler stream order (derived from UKCEH 50k network using RivEX)
4. Changes in the semi-natural Principal Component Analysis (PCA) score
5. Changes in the modelled (observed) PCA score
6. Land-use (10 m raster dataset from UKCEH Land Cover Map): Urban and suburban land-use class considered collectively as urban.

The reach delineation technique uses statistical aggregation of modelled hydromorphology indices representing habitat form that were originally derived at 500m intervals along the UKCEH 50k network (Naura, 2013 and 2014; Naura *et al.*, 2016). For the purposes of delineating reaches for the current project, the points were snapped to the recently updated ORN (Hornby *et al.*, 2023) and the segmentation method applied on that network at the 500m points.

A new 1 km minimum reach criterion was applied to the method, which would increase the number of smaller reaches by enabling more break points to be included (where they were previously excluded if within 2 km of an existing break point). The initial results produced a maximum reach length of 32.8 km. This was considered too long, as cultural service provision can vary considerably over much shorter lengths. Furthermore, the median distance that people will travel to visit green and blue spaces is around 3 km according to Natural England's People and Nature Survey (PANS) and other data, with the vast majority traveling less than 10 km. Therefore, a maximum length of 7.2 km was introduced, which was the 95th percentile of reach lengths, and fits with the travel distance to sites for the vast majority of visitors.

A large number of very small reaches also existed in the dataset, which consisted of very small tributaries, side channels and segments cut-off from the main channel by the ORN mapping process. These are not relevant for the mapping of ecosystem services, and most will not have any data associated with them. Therefore, all reaches less than 500m were deleted from the dataset.

The river reaches obtained through the process described above left a few gaps that needed to be addressed, since a few WFD river water bodies did not have any reaches in them. For those river water bodies, we filled in the gaps by stitching in missing river stretches from the Environment Agency's WFD Rivers Canals Surface Water Transfers Waterbody classifications polyline layer. We only used stretches that were not classified as artificial and split them where they were significantly longer than 7.2 km.

As a final step, all reaches were reshaped to exclude areas that overlapped with existing lakes (which removed online lake features) or had culverted sections (see Methodology document for further details). After removing culverts and lakes some reaches were significantly smaller and reaches shorter than 100m were removed from our calculations.

The final reach statistics are summarised in Table 10. Further details on the segmentation process and the steps to create the final dataset are provided in the Methodology report.

Table 10: Statistics for final reaches.

Statistics	Mean	Median	Min*	Max*	No. of reaches
Value	2.3 km	1.8 km	0.1 km	8.7 km	29,062

* Final minimum length <500m and maximum length >7.2km due to removal of online lakes and culverts and addition of missing stretches at final step.

The mean reach length and number of reaches per river varies by river length (Figures 10 and 11). The mean reach length peaks at 5.1 km.

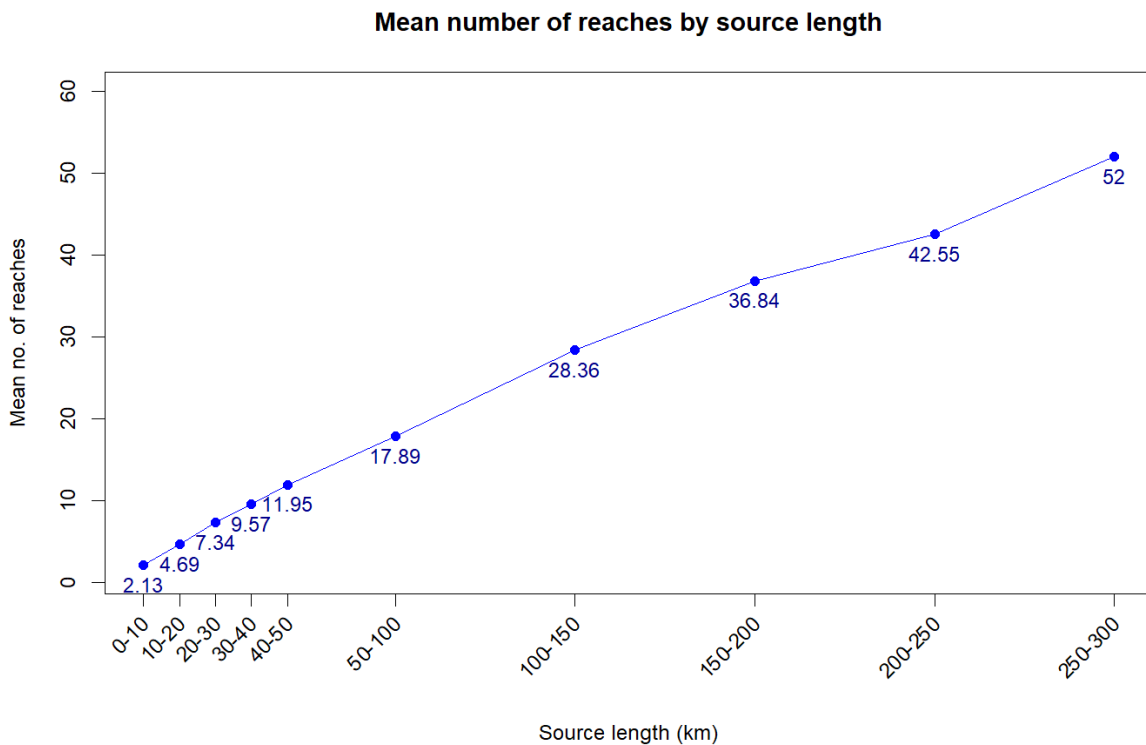


Figure 10: Graph showing the mean number of reaches per its source channel length.

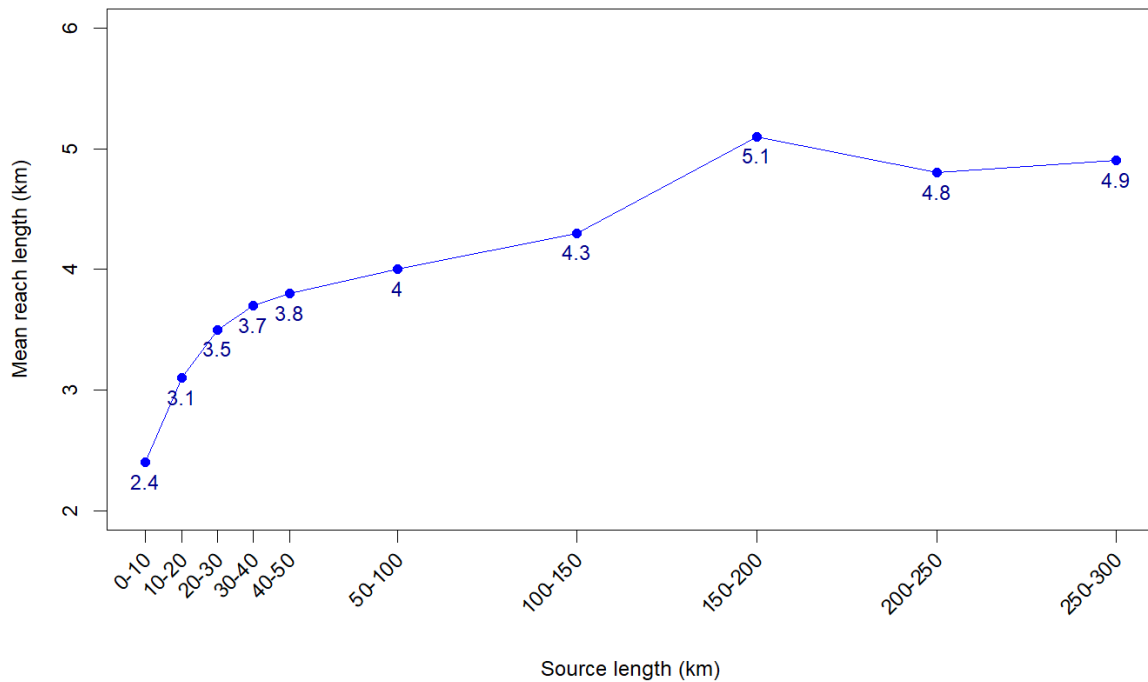


Figure 11. Graph of mean reach lengths according to length of its source channel.

5.5 Future updates and linking to OSWN or ARWN

The river reaches may be updated in the future to reflect changes in land use or water body boundaries. This potential requirement needs to be carefully considered as it will impact on the data structure and indicator computation. Some of the indicators are calculated using basic statistical averaging at reach or water body scale, but others require more specific procedures such as weighted averages. If it is forecasted that reach boundaries may change in the future, it is important that any indicator calculation at reach or water body scale is performed on the fly using code when displaying the data, and are not stored in a database table. Storage in tables may be considered if there are database triggers that will automatically recalculate indicators at reach and water body scale following any update in underlying point or reach data. The structure of the data, the triggers and events and work flows associated with the production of statistics therefore need to be carefully considered before future versions of the dataset and tool are implemented.

The ORN dataset on which the reaches are based could be linked to the NCEA Analysis Ready Water Network (ARWN) or Ordnance Survey Water Network (OSWN), provided that these were split in equivalent river reaches with identical reach id. This cannot be done on the fly and reach boundaries would have to be snapped on both networks to identify equivalent river reaches. Snapping quality will have to be checked manually as the ORN, as opposed to the ARWN and OSWN, is a

single channel network and many reach boundaries are likely to fall on tributaries or branches of an anabranching network such as for the river Test or Itchen. The two river networks are also likely to be longer than the ORN and contain more tributaries and small drains. Some of the water quality, RHS and other data will relate to parts of these networks that are not represented in the ORN. To include them, we would need to process the OSWN and ARWN to derive additional river reaches. That could be done using the UKCEH points and would extend the network of river reaches quite significantly, although not in its entirety as the UKCEH river network is significantly smaller than the OSWN.

An alternative would be to process the OSWN and ARWN from scratch. That would involve deriving 500m points on the networks and re-iterating predictive models for hydromorphological indices. Although this may appear to be significantly more work (5-6 weeks required to re-derive the indices and process for the OSWN), problems with snapping UKCEH river points on the right channels and quality controlling the outputs may also require significant amounts of time that are not fully predictable but likely to take several weeks. The outputs, altogether, would be more accurate using recent data.

5.5.1 Potential further development of river reach segmentation

Reach segmentation used in ESME uses a combination of hydromorphological and management/practicality components to delineate reaches along the river network. Changes in hydromorphological conditions are based solely on univariate analysis of two variables derived from principal component analysis of the eight hydromorphological indices. Future work could consider implementing a multivariate technique (e.g., similarly to the VAST algorithm employed in ToolHab, Naura 2014), which would allow for multiple hydromorphological parameters to be considered simultaneously.

The reaches produced here would benefit from validation by field surveying a selection of case studies to determine if the modelled changes in hydromorphological conditions are accurate and observable on the ground. Reaches defined by management and practical considerations (land cover, WFD boundaries) would benefit from an assessment of their usefulness and appropriateness by users of the network.

The updated ORN network is a single channel network that has removed braids and anabranches by identifying a main single channel. Greater hydromorphological detail could be achieved by developing a method that utilised multi-channel connected systems. This is possible with the VAST algorithm, although its capability for managing large networks has not been tested.

In project discussions of methods, a valley confinement parameter had been suggested for the model as an indicator of sediment supply, planform development and river-floodplain interaction. This is also outlined as one of the components of reach delineation in the REFORM typology (Gurnell *et al.*, 2014). The initial stages of a valley bottom model were quality controlled in the River Ribble catchment, to assess its suitability for determining valley confinement.

The valley bottom model provides a basis from which to derive a valley width along the river. For much of the ORN in the River Ribble catchment it has successfully identified a valley floor that can be validated against LiDAR elevation data. However, it may struggle to identify the valley bottom for small tributaries. For example, on a tributary with stream order 1 in the upper reaches of the Ribble catchment (Figure 12), where the valley floor is not easily identified visually using LiDAR data, the valley bottom model is disconnected along the small tributary. There are also many examples where the valley bottom model overlaps with the ORN, which would need to be corrected in order to calculate a valley width value.

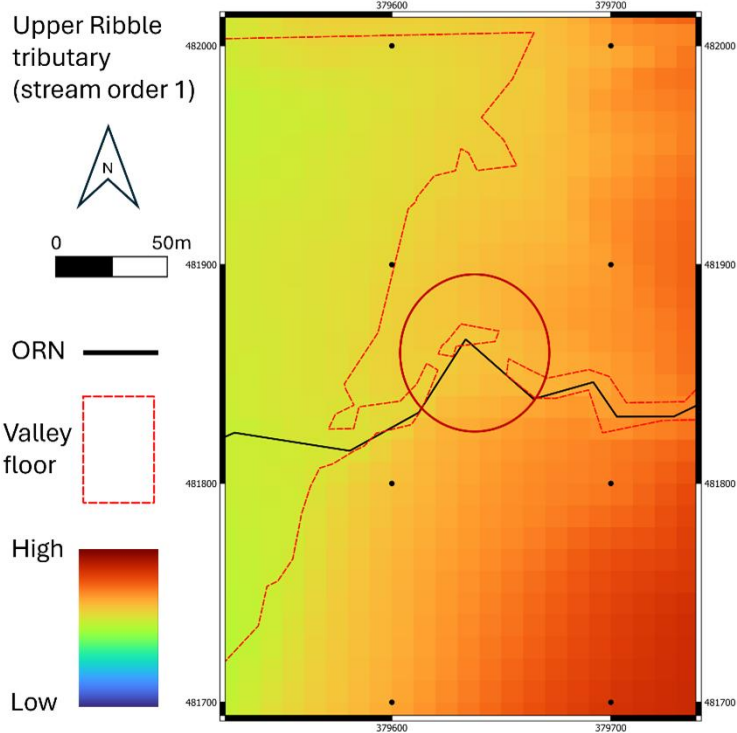


Figure 12: Upper Ribble tributary

Some valley floor contours were difficult to validate with LiDAR and satellite imagery. For example, as shown in the inset of Figure 13 the valley floor around the Ribble is initially contained within a narrow contour that then opens up to the wider floodplain. Incorporating a valley width component in reach delineation at this point could artificially segment the river due to the sudden change in the valley bottom contour.

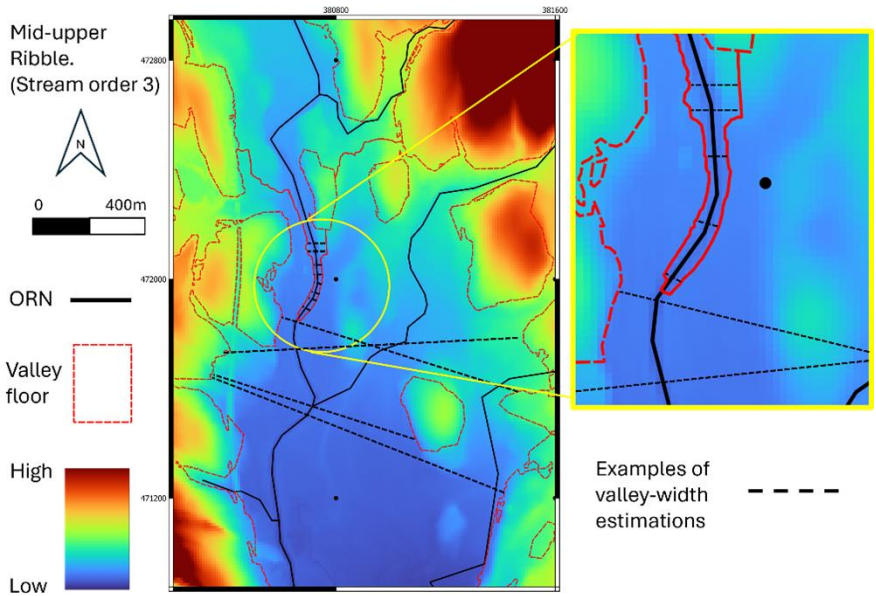


Figure 13: Upper-mid Ribble catchment. Inset is a magnified section of the river illustrating the change in the valley floor contour along the Ribble.

Automating an estimation of valley width could be challenging using the valley bottom model. For example, isolated hills or knolls within the floodplain form contours within the valley bottom model that could be intercepted by the cross-section of a valley-width estimation (Figure 13). Depending on the angle of the cross-section across the floodplain, the valley width could vary widely around knoll-like features. This could be particularly problematic on meandering rivers where the angle of cross-section changes along the meander bend (Figure 14, inset).

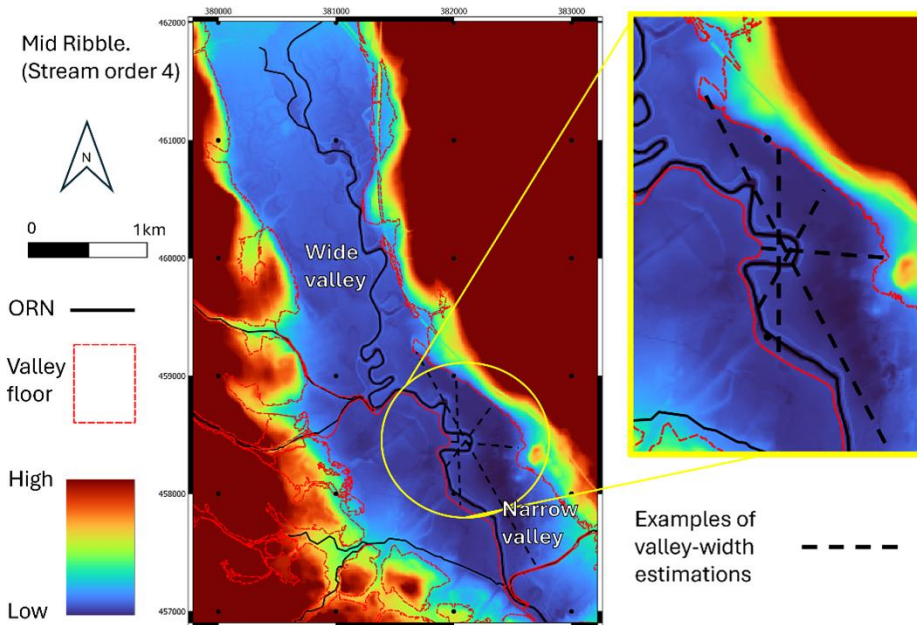


Figure 14: Middle reach of River Ribble in a wide valley. The valley bottom is defined differently upstream and downstream of the tributary joining from the west.

Tributaries may additionally complicate the calculation of valley width. For example, in Figure 14, the northern section of the river has a wide valley bottom, while downstream of a tributary joining from the west the valley bottom is modelled as narrower with the main channel abutting the contour of the valley bottom on its west. The issue is further illustrated in the lower reaches of the Ribble in Figure 15.

In its current stage of development, the valley bottom model may not be suitable for deriving a valley confinement parameter through automation. Although in most cases it presents a model of the valley bottom which is verifiable with LiDAR data, the methodological issue of defining a valley width remains. Some corrections are additionally needed to align it more accurately with the ORN.

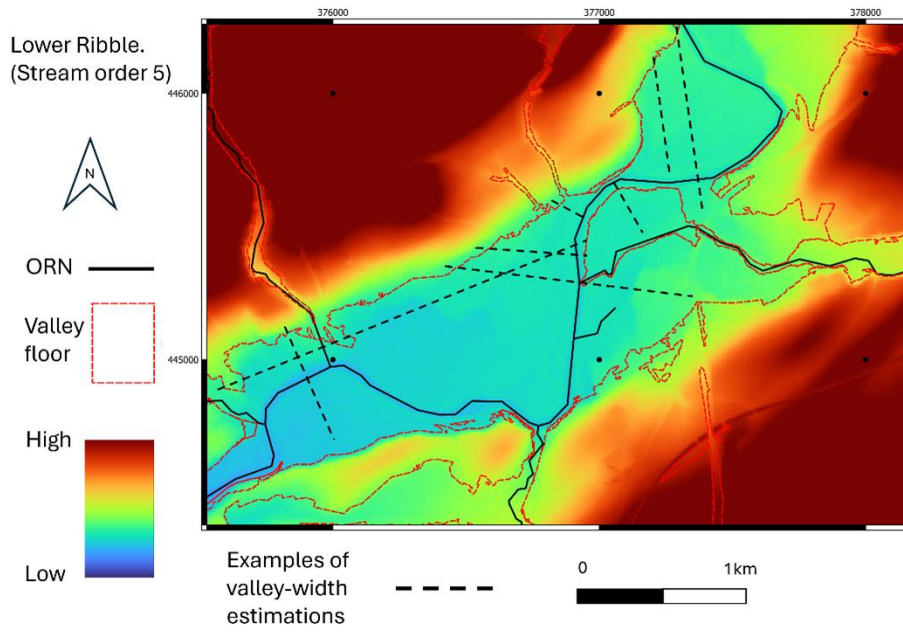


Figure 15: Lower Ribble illustrating options for valley width calculations based on Valley Floor model.

6. Indicator method, approach and principles for ecosystem services mapping in ESME

The ESME framework has been developed through several phases, each involving methodological choices and adaptations. In constructing and combining indicators the team has applied different approaches depending on data availability, context, and stakeholder needs. It is not possible to use the same type of indicator for each ecosystem service, but it is important that the different types are identified. Here we clarify the assumptions and decisions embedded in the methodology. The key terms set out here are used when describing each indicator in ESME and in the Methodology document (where this introduction is repeated as it is fundamental to the indicator methodology) and are also shown in the accompanying dataset and indicators library.

6.1. Principles and definitions

The natural capital approach requires understanding the benefits that nature provides. A key aspect of this approach is the ability to assess and indicate the capacity of natural assets to provide ecosystem services. Ideally, we would like to directly measure the capacity (or even the flow) of these ecosystem services, however this often is not technically feasible or practically possible. To overcome this challenge, we adopt a natural asset led approach to understanding the capacity for ecosystem service provision. This means that instead of directly measuring the flow of ecosystem services, we assess the state (quality, quantity and location) of the asset that provides the service, and use this information to infer the capacity (or potential) of the asset to provide the ecosystem service, regardless of whether that ecosystem service is realised.

Ecosystem service capacity

The ecosystem service capacity is the potential of a natural asset to provide a specific service under current conditions, regardless of whether that service is being used by beneficiaries.

Ecosystem service capacity is determined by the state of the natural asset, a combination of its condition (often referred to as quality), quantity and location. This is also affected by ecological attributes like biodiversity, structure, and functioning of the asset.

For example, a healthy river with steady and abundant flow has the capacity to provide water for abstraction, even if no one is currently drawing water from the river. If no water is abstracted from the river, there is no actual flow of the ecosystem service, despite having the capacity. The capacity (potential provision) remains the same, but without utilisation, the actual flow of the service can be zero. This

distinction between capacity and actual flow is critical when describing ecosystem services, as other forms of capital - such as manufactured, social and human capital - play a significant role in enabling the delivery of ecosystem services.

Ecosystem service demand

Demand is the potential or actual human need or desire for a specific ecosystem service in a particular place and time.

Ecosystem service demand reflects socio-economic and cultural needs and can vary spatially and temporally. It is normally measured by a combination of population density and consumption rate. For regulating services this is expressed as the amount of natural regulation provided by a natural asset to reach the desired condition.

For example, an urban area might have a high demand for recreational green or blue space due to high population density, irrespective of the number of available parks and rivers to walk along. Or, for instance, there may be a very high demand for water supply within a region with water scarcity, but the flow of the service may be low for that region if not much water is taken due to rivers being protected.

Ecosystem service flow

Flow is the actual use or uptake of an ecosystem service by people.

It occurs where ecosystem service capacity meets human demand. While ecosystem service capacity is site-specific, ecosystem service flow is not necessarily limited to the site of production (e.g. upstream soil or nutrient retention provides the ecosystem service of clean water to people downstream). The area where benefits can be experienced is the benefit zone, while the people benefitting are the beneficiaries.

For example, when people visit rivers for recreation, or when a city uses water purified by the riparian vegetation upstream, that is the flow of the ecosystem service.

6.2. Background to natural capital indicators

The core aim of ESME is to understand the condition of natural assets, so that we can reliably understand their capacity to provide ecosystem services. A natural capital indicator is defined as a specific characteristic of the environment or people, from which we can infer a more general understanding of the state or trend of change in natural capital. Natural capital indicators can tell us about any aspect of the logic chain - asset, service, benefits or value.

Different ecosystem services require different types of information to understand and predict them, and therefore require different indicators. We use a wide range of datasets - biological, physical, socio-economic etc. - all used and interpreted for the same purpose of assessing ecosystem service capacity. Different types of ecosystem service also require different approaches. In particular, cultural ecosystem services need to be assessed differently to regulating and provisioning services, with further details provided in Section 6.2.4.

A natural capital metric is defined as a standardised, quantitative system of measurement of some aspect of natural capital, including units of measurement. Within ESME a few indicators are derived from measured units and could, in principle, be interpreted as metrics. However, because all indicators are subsequently transformed into categorical classes, we refer to them collectively as indicators rather than metrics.

6.2.1 Limitations in data on the “state” of assets

There is a significant amount of data available on the state of natural assets, such as information gathered through River Habitat Surveys (RHS) and other environmental assessments. Despite the wealth of available data, there is often not enough information with appropriate coverage, resolution and accuracy, to comprehensively quantify and measure the state of a natural asset with respect to its ecosystem service capacity. As a result, we have explored and made use of alternative datasets that can act as proxies for understanding the state of natural assets. A proxy is an indirect measure used to represent a condition or process that is difficult to observe or quantify directly, relying on a related variable that provides a reasonable approximation. This is justified based on logical and evidence-based links to ecosystem functions. Proxy indicators also carry limitations since they may only partially capture the phenomenon of interest.

We utilise a variety of indicator types within ESME: capacity, demand, flow, ecological pressure, and vulnerability indicators.

Capacity indicators directly relate to the level of potential provision of the service (e.g. presence of riparian vegetation that will help purify water).

Demand indicators relate to the demand for a given ecosystem service in specific areas (e.g. population density in a given area gives an indication of the demand for accessible green and blue spaces).

Flow indicators relate to the utilisation of the service. For example, we may use data on how much water is abstracted from a river as a direct measure of ecosystem service flow. However, we can also use it as a proxy for the state of the asset, as high water abstraction can indicate there is a high capacity for the provision of the ecosystem service - hence why we are abstracting from that location. Over-utilisation can also lead to a pressure (see below).

Ecological pressure indicators capture the anthropogenic and natural stressors that affect capacity, such as changes in land and sea use, direct exploitation (e.g. overfishing, logging), climate change, pollution, and invasive alien species. The data on pressure is used as a proxy to assume the state of the asset. Pressure indicators focus on what is happening to the ecosystem, regardless of whether it leads to actual ecosystem service loss. Pressure can degrade the state of assets, resulting in them having a reduced ability to provide the ecosystem service. For example, this can be related to overuse (e.g. overfishing or over-abstraction), or from trade-offs with other ecosystem service capacities (e.g. increased nutrients in rivers due to increasing agricultural production). As an example, we use the presence of storm overflows as an indicator that tells us about the expected pressure on a river. While storm

overflows are not a direct measure of the asset, they can be used as a proxy to understand the asset's water quality, as we have high confidence that if there are storm overflows the water quality is likely to be worse. In this way, pressure-based datasets help us infer the condition of an asset when direct biophysical measurements are unavailable.

Vulnerability indicators refer to measures that capture the sensitivity, exposure, and adaptive capacity of ecosystems to potential disturbances or pressures. These indicators highlight how fragile or resilient the supply of ecosystem services might be under different conditions. These integrate both the state of the ecosystem and the pressures/stresses it faces, along with its adaptive capacity or resilience.

6.2.2 Using built infrastructure as indicators

Ecosystem services are fundamentally underpinned by the quantity, quality and location of natural capital assets. However, human, social, and built (or manufactured) capital play critical roles in influencing how ecosystem services are accessed and delivered. Therefore, comprehensive ecosystem services mapping must go beyond a purely biophysical approach and consider the broader socio-economic and infrastructural context. This integrated perspective ensures a more realistic assessment of ecosystem service capacity.

For cultural services, we can conceptually consider some built infrastructure as indicators of asset quality and location (Lusardi *et al.*, 2018). For example, accessibility networks along rivers (e.g. paths and trails) will enhance or inhibit the delivery of recreation services. The proximity of those accessibility networks to where people live will also influence the capacity of the river to deliver recreation services.

Built infrastructure used as indicators, such as accessibility networks, may be linked to a river's natural beauty and ecological richness, but may also be significantly influenced by external factors such as urban planning decisions (e.g. footpaths created for accessibility rather than for asset significance or quality); proximity to other infrastructure (e.g. a well-maintained car park or visitor centre); or historical or cultural factors (e.g. the presence of heritage trails). There are also potential trade-offs with increased public access, e.g. high access can lead to litter and pollution, wildlife disturbance by dogs, or damage to bankside vegetation.

For provisioning services, water abstraction locations are a form of built infrastructure, and have been used to assess the capacity of rivers for Water supply, (along with indicators of abstraction volume and sustainability). Similarly to the above, the built infrastructure used as indicators may be influenced by other external factors that don't necessarily reflect a river's suitability for water supply, such as land ownership, proximity to treatment works, population pressures, or planning constraints.

As a result, while built infrastructure may be applicable as indicators, these should be used mindfully and with care in environmental planning.

6.2.3 Relative vs actual capacity

Ecosystem service capacity can be measured in absolute terms (based on a measured physical quantity at that location) or relative to other locations. As outlined above, within ESME a few indicators are derived from measured units and so could provide a measure of actual or absolute capacity, but in most cases it is either not possible or not desirable to do so. As outlined in Section 3, condition is strongly influenced by perception and value judgements, particularly for cultural ecosystem services, and this precludes a fully quantitative approach.

To provide an indication of relative capacity, many of our indicators have been scaled using a quintile-based approach. A quintile is one of five values that divides a range of data into five equal parts, each being one fifth (20%) of the data (see Section 5.3 of the Methodology report). Using quintiles emphasises the relative capacity of ecosystem services across the landscape, highlighting where capacity is higher or lower compared to other areas, rather than showing absolute magnitudes. While maps based on actual values preserve the true measurement differences, they can obscure spatial patterns when data are highly skewed or when indicators are not directly comparable. In contrast, quintile scaling makes patterns more interpretable and comparable across indicators, but it does so by sacrificing information about absolute values and the magnitude of differences.

6.2.4 Cultural ecosystem service indicators

Assessing cultural ecosystem services brings an additional set of challenges in addition to those outlined above. The indicators used in ESME were examined and aligned to fit with the Fish *et al.* (2016) conceptualisation of cultural ecosystem services (Figure 16). This conceptual framework builds upon the linear logic chain approach to cultural ecosystem services used by the UK National Ecosystem Assessment follow on (UK NEA 2014). It emphasises the importance of non-linear relationships between people and nature in the delivery of cultural benefits. This framework is the first to recognise the importance of distinguishing between ecosystem services (which comprise of geographical contexts where people interact with nature, and activities that relate people to each other and the natural world) and the benefits derived from them (characterised by dimensions of wellbeing in the form of identities (e.g. belonging), experiences (e.g. tranquillity) and capabilities (e.g. health)). For instance, kayaking along a river is a recreation service (influenced by a host of cultural factors), and the feelings of tranquillity, or improved physical fitness are the benefits.

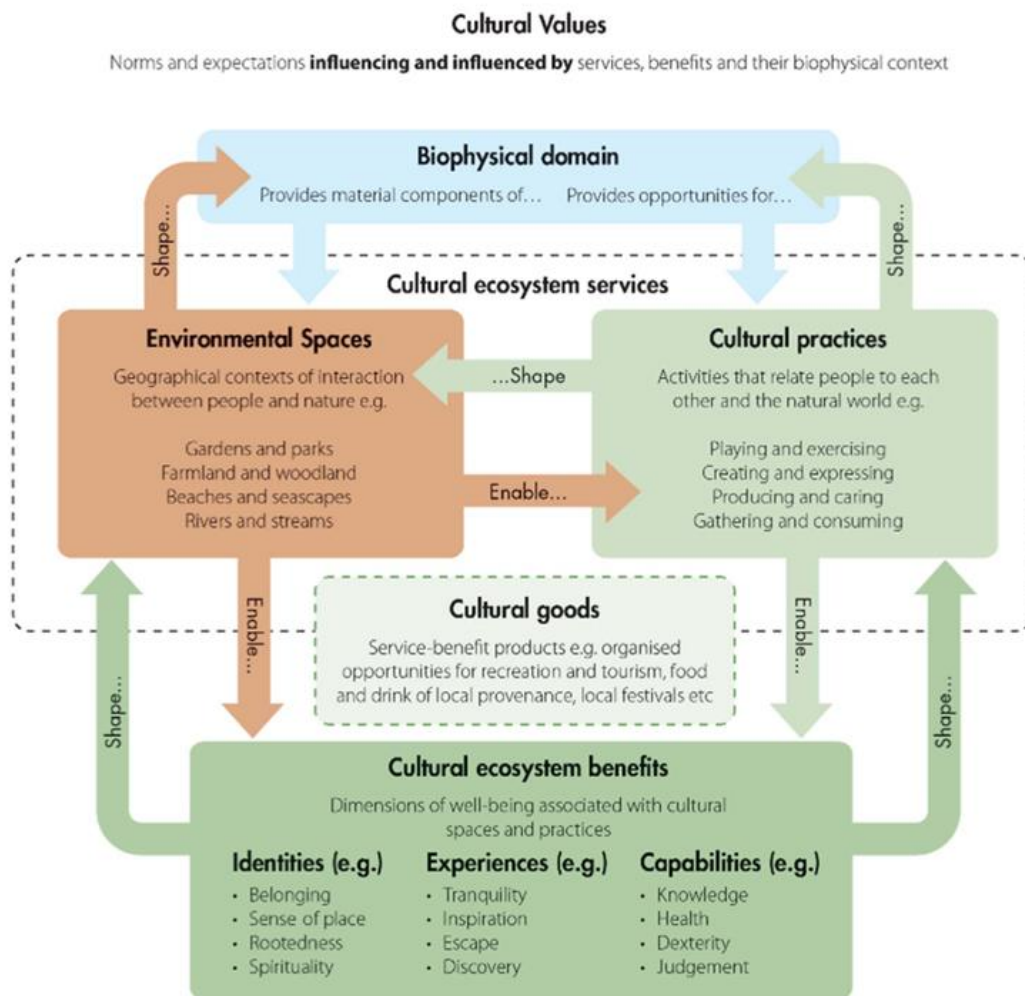


Figure 16: Conceptual framework for cultural ecosystem services (source: Fish et al. 2016).

ESME is concerned with the top half of this conceptual framework: how the condition of the biophysical domain (the natural capital) and environmental spaces interact with cultural practices to deliver cultural goods and services. The cultural ecosystem benefits (dimensions of wellbeing) are not assessed here.

In order to align the cultural ecosystem services indicators used in this project with the cultural ecosystem services conceptual framework, each indicator was examined individually and organised into their respective component of the framework. The indicators used in ESME fall into a number of different categories. Some indicators provided information on the condition of the biophysical domain and environmental places, for example river habitat quality and water quality, and others considered cultural practices, such as the recreational hotspots and local access indicators. It is important to note that some indicators could be used for multiple components of the cultural ecosystem services conceptual framework.

6.2.5 Conclusion

ESME is underpinned by an extensive literature review and the development of conceptual frameworks (flow diagrams) for each ecosystem service that explored the link between asset condition and ecosystem service capacity and the components that influence each ecosystem service in turn. Based on this knowledge, and using best available data, ESME brings together a range of different types of indicators, including capacity, demand, flow, ecological pressure, and vulnerability indicators, and we use a mixture of metrics, proxies and indicators. In addition, we use some indicators of actual capacity, but many present capacity in relation to other locations across England. Assessing cultural services adds further complexity as we need to consider public access and built infrastructure for some ecosystem services, and use a mixture of indicators that assess different aspects of natural assets, environmental spaces and cultural practices.

Despite this range of indicator types, and the use of proxies, the indicators are all being used to achieve the same overall aim of mapping the river's ecosystem service capacity in a location. In an ideal world, our indicators would all be measures of the biophysical state of the rivers, however this type of data is limited, and so proxies are required. This would also not capture the nuances of assessing cultural ecosystem services.

In summary, ESME is a tool that predicts the relative capacity of rivers to deliver 10 different ecosystem services, based on the underlying condition of the river and its wider catchment.

7. Scaling and combining indicators

A challenging aspect of this project concerns how to scale the indicators appropriately and how to combine indicators into an overall predicted ecosystem service score. In the initial prototype mapping developed in an earlier phase of the project, some condition indicators were scaled following the literature, but in many cases, quintiles were calculated across the three test catchments being used at the time. This means that the quintiles were based only on the values that occurred in the test catchments, rather than the full range of values that occurs across England. Note that a quintile is a statistical method of dividing a range of data into five equal parts, each being one fifth (20%) of the data, but can be calculated in different ways. Please see section 5.3 of the Methodology report for more detail on quintile calculation.

Individual indicator scores were then combined without additional weighing to give the overall ecosystem service score, which was therefore an average of all of the indicators. However, some indicators are inevitably more important than others and this was considered to be a weakness of these early outputs.

A number of recommendations were made at the end of that phase, in particular:

- A key area of additional work was required around how to combine indicators to produce the final scores. This needed to consider weightings and thresholds, as well as the scaling of both the individual indicators and the final scores.
- Ecosystem service scores should be calculated relative to England as a whole.
- The use of quintiles as an appropriate way of scaling indicators, should be explored further.

These issues were explored as part of the next phase of the project and are described in this section. Our approach was to hold a workshop with technical experts to build a consensus of the best approaches to take and then to implement these ideas.

The workshop was held on 22nd November 2024, with 16 attendees (excluding Natural Capital Solutions), representing technical experts in various disciplines within the Environment Agency (e.g. indicator development, statistics, ecology, water quality, flood risk management, natural capital and so on), as well as external natural capital expertise from the University of Oxford. Following introductory presentations, a series of discussions were held on each major topic, together with a Miro board and polling to gather feedback. The three main areas of discussion and outcomes are described below.

7.1 Scaling indicators

The project team described how they had scaled indicators in the prototype, with three main approaches used, depending on the data:

- Quintiles (calculated across the whole river network)
- Pre-determined (if available in the literature)
- Presence-absence

The project team pointed out that if using quintiles, the bottom 20% will always be deemed very low and top 20% will always be deemed very high. In other words, the scores will inevitably be relative to the current situation, rather than absolute. We also asked if quintiles should be calculated based on stretch length or based on value. Stretch length would mean that if the total length of river reaches was summed, 20% of the total length would fall into each band, whereas based on value means that the length of each section is not considered but the values are divided into five equal categories. In the former you would end up with an uneven number of reaches in each category, but an equal length of river and vice versa.

Workshop discussion

Lots of interesting discussion ensued. Key points are shown in the bullet points below:

- The final usage of the tool should be driving the way the tool is structured. The user guidance will need to clearly state that it is a relative picture of ecosystem service capacity. A main limitation of relative scores is related to the ability of attaching monetary values to these services.
- As minimum and maximum values will be changing over time and the aim is that of showing improving condition, setting the boundary of the quintiles in this first baseline assessment would allow meaningful comparisons over time, but historical data could also be used in setting minimum and maximum values. Quintiles should always be manually checked and adjusted, including fixing boundaries so everything is already in either the top or bottom quintile if necessary.
- It has also been suggested that each of the sub-indicators needs to be scaled based on the 'ideal' condition, and then scaling either side of that so we can see where we are falling short of the standard, and equally we can see where we are exceeding. For example, WFD biological quality elements are based on the ratio of quality to reference quality, it may be possible to use a similar measure, but this depends on how these measures will be used and whether we wanted to value every river equally.
- An approach for presence/absence indicators is to assign presence/absence scores either side of the acceptable boundary instead of the extremes. E.g. if acceptable is 4 or more, present would be 4, absent would be 3, so it would have less impact when averaged up.
- Different river systems across England have different magnitudes of benefit and value because of population and use - the Thames probably being the most valuable in terms of high demand from the population. Although note that this is only relevant to indicators based on demand, or ecosystem service flow, rather than capacity, and remote rivers will have higher value in respect of naturalness and other factors. A benefit of using quintiles is that it might help

us to complement WFD classification by also considering measures of ecosystem service and natural capital, which are measured economically. WFD is about ensuring good qualitative and quantitative status and preventing deterioration of the water environment. To do this, an integrated approach to water management is needed, prioritising where we need to undertake measures to achieve objectives, usually good status, which provides the most sustainable balance of cost and benefits.

- Another possibility is that of using quarters or thirds etc. as quintiles might overlap with WFD understanding.
- It has also been suggested to use a scale from 0 to 1 where 0 = ecosystem services could be present (but are not) and 1 = all ecosystem services are present that could be.
- A suggestion is that of investigating the correlation between numerical indicators using multivariate techniques.
- Climate change resilience is not being accounted for in the tool, but it could be incorporated using the underlying data to create an indicator of climate change resilience. For example, if a river reach is laterally constrained or disconnected from the floodplain, it is likely to have less resilience to future climate change.
- It would be important to highlight areas where there is the most potential to increase ecosystem service delivery (e.g. land use choice modelling tools).

Polling

Following group discussion, we carried out two polls, with results shown in Figure 17.

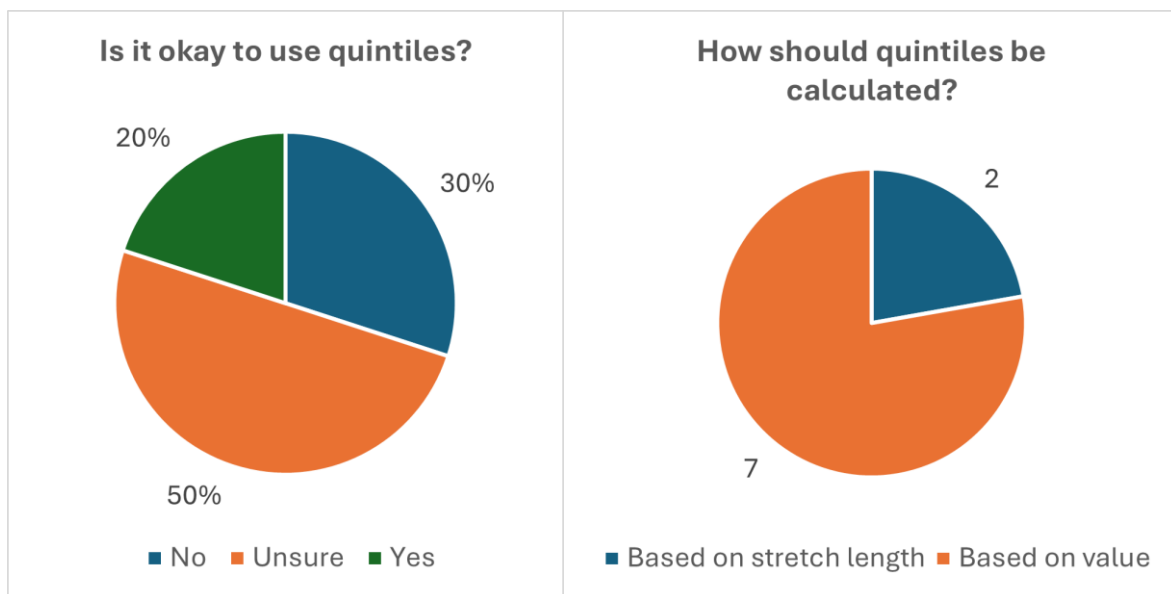


Figure 17: Results of polling carried out at the workshop on the use of quintiles for scaling indicators.

Outcome

There was a lot of uncertainty around using quintiles, with the majority being unsure in the polling. However, following further discussion within the project team, it was decided that we would use the quintile approach. There is little viable alternative, as it is not possible to determine alternative meaningful ways to sub-divide indicators for each dataset, as this would require a national scale study of each indicator in turn and how it would score under reference (natural) conditions. This is available for some indicators (such as biological water quality) and where available these categories are used.

It is important that we highlight that the ecosystem service scores provided in the tool are in most cases relative scores, rather than absolute. This should be seen as a characteristic of the tool, rather than a limitation, and will be made clear in the guidance.

There was more agreement on the question of how quintiles should be calculated. Calculating quintiles based on value was therefore the approach that has been taken forward (see section 5.3 of Methodology report for more details on quintiles).

7.2 Combining indicators

The project team described how they had combined indicators to produce the final ecosystem service scores in the prototype tool, which had simply been the average of the scaled indicators. Four options were presented for how this could be taken forward:

- 1.) Equal weights for each indicator (prototype approach)
- 2.) Different weights for each indicator
- 3.) Formula based (including decision trees)
- 4.) Lowest scoring indicator determines the overall ecosystem service score (e.g. like WFD) or thresholds are used.

We also highlighted how the approach would have to deal with different types of indicators, for example negative indicators, presence-absence indicators, those with a threshold effect, or modifiers that changed the score of another indicator, as well as more standard indicators scaled on a 1-5 scale. We asked the participants to discuss which is the best approach and should it be the same for each ecosystem service?

Workshop discussion

As above, lots of interesting discussion ensued, with key points in the bullets below:

- Some support was raised for the formula or weighted average way of combining indicators, but confidence in setting weights is lacking and questions were raised over if there is enough evidence to do this. Weights are going to be difficult to assign as people won't easily agree on how important each indicator is. In the Environmental Benefits from Nature (EBN) tool²,

² See <https://publications.naturalengland.org.uk/publication/6414097026646016>

multiple condition indicators were combined for each ecosystem service but these were not weighted; instead they were set using a conservative approach of adjusting the basic habitat-specific scores slightly up or down (typically by 10-15%).

- If weightings are used, they must be transparent and clearly documented so people understand them.
- The one-out all-out approach (where the lowest ranking from multiple indicators is used) didn't receive any support. This approach hides changes over time in the ecosystem service.
- More support was shown for multivariate analysis and decision trees. It was pointed out that decision trees are very effective and are best to reflect expert judgment of ecosystem service quality. Decision trees would also allow the flexibility of being able to change approach based on the ecosystem service (which was considered important).
- Concerns were raised that a combined indicator would not necessarily answer user needs, as a lot of information can be lost once indicators are combined. There is also a risk of error propagation once indicators are combined. Giving users more choice might answer user needs better as we are combining very different categories of data. It may be possible to give users a choice of what approach to use, and/or present a suite of maximum, minimum, and average scores. Other approaches suggested are spider graphs, radar diagrams and other ways of representing status that don't have to be a single number.
- It is appropriate to consider how the outputs would be used in catchment planning. If the aim is to drive improvements in ecosystem services, then decisions that affect ecosystem services (e.g. river restoration) are almost always the result of local catchment priorities. A system allowing to 'switch on / off' ecosystem service indicators to reflect local priority would be most helpful. An excellent output could then be a layer indicating that 'based on the choices made, these are the missed ecosystem service opportunities perhaps as a list with scale from Low to High'.
- Could consider Eutrophication Weight of Evidence risk tool as one relatively simple approach to combine often contradictory data into a single decision.
- It has also been suggested to ask other experts across the world. The payment for ecosystem services developed for Australia could be explored in its approach, similarly RESI could also be explored (<https://www.resi-project.info/en/>).
- Invasive non-native species (INNS) need to be reconsidered in a wider sense as species and context are important. e.g., INNS are a pressure and not a measure of quality. Invasive species are not the same as other non-native species, which can have positive value (parks and gardens).

Polling

Following group discussion, we carried out a poll to rank the order in which the different approaches were preferred. Results are shown in Table 11 and show broad agreement amongst participants. Using decision trees (formula-based) was by far the preferred choice, being the first choice of 64% of participants and the second choice of a further 18%. The clear second choice was for different weights for each indicator; equal weights for each indicator was the third choice, and the lowest scoring indicator driving the overall score was the overwhelming least preferred option.

Table 11: Percentage of participants picking each approach as their first, second, third and fourth choice for how indicators should be combined to form ecosystem service scores.

Approach	First choice	Second choice	Third choice	Fourth choice
Equal weights for each indicator	9	9	73	9
Different weights for each indicator	27	64	0	9
Formula based / decision trees	64	18	9	9
Lowest scoring indicator driving the overall score (e.g. like WFD) or use thresholds	0	9	18	73

Outcome

Given the overwhelming consensus, we chose to take forward the approach of combining indicators using decision trees. Draft decision trees were developed for each ecosystem service by four of the project team and then reviewed by a large number of Environment Agency and external reviewers. This provides a more robust and transparent approach than used previously, based on expert opinion and evidence. The process of modelling and mapping ecosystem service capacity based on condition indicators and decision tree logic was undertaken using R software. More background information on decision trees is provided in Box 5, with full details of the methodology for each ecosystem service provided in the accompanying methodology document.

The individual indicators that make up each ecosystem service are also retained and mapped within the ESME tool, so anyone with a particular interest in certain aspects can still view and download those particular indicators. This helps to answer one of the issues raised above about meeting user needs.

Box 5. What is a decision tree?

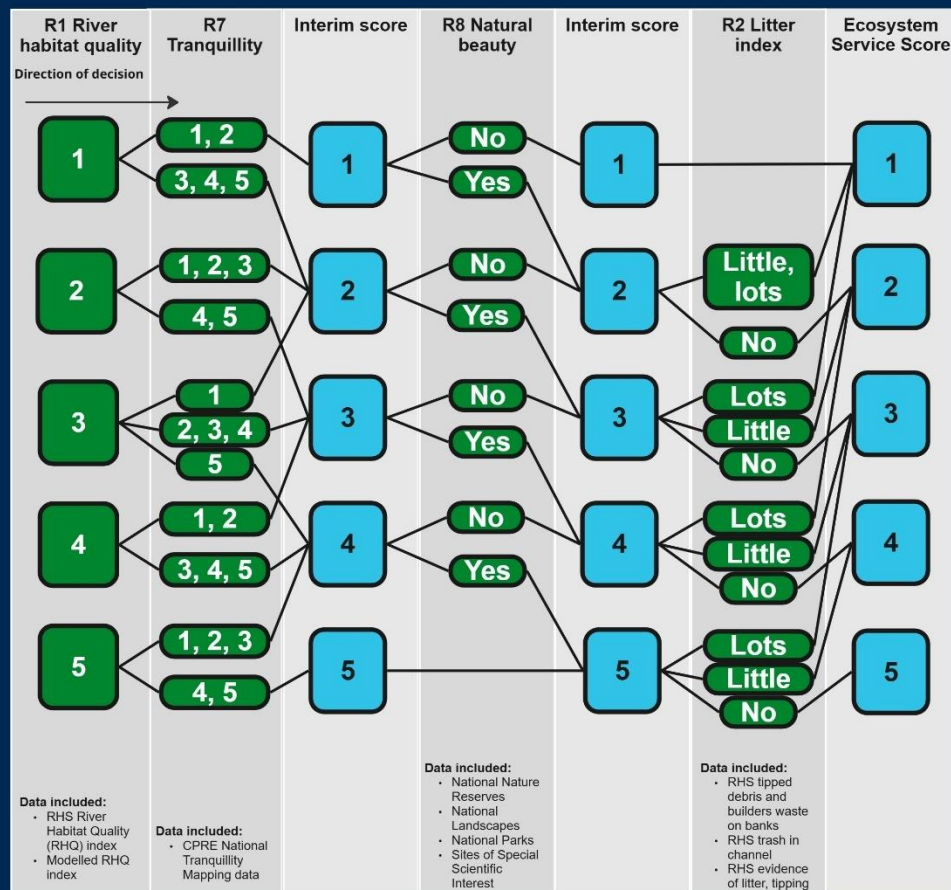
A decision tree is a specific type of flowchart used to visualise the decision-making process by mapping out different courses of action.

A set of general principles are determined, and decisions are then made about the impact of each indicator in turn.

An example decision tree for Aesthetic and amenity experiences is shown below. Full details of the decision trees for each ecosystem service mapped in this project, including the general principles applied, the indicators that were incorporated, how the indicators were scaled, and the justification for how they were combined into the decision trees, is provided in the accompanying methodology document, which can also be accessed directly within ESME.

Ecosystem service - Aesthetic and amenity experiences

Scores: 1 = very low 2 = low 3 = moderate 4 = high 5 = very high



Source: Ecosystem Service Map Explorer, Environment Agency

7.3 Scaling up from river reaches to waterbodies and catchments

The final part of the workshop considered how to scale up the results for both indicators and ecosystem services from river reaches (stretches) to waterbodies and catchments. All indicators will be initially calculated at the reach scale. In the prototype tool, indicators were separately calculated at the three scales, but in a number of cases this caused discrepancies between the results at the different scales, which led to some confusion. For example, if the indicator is supposed to map the number of monitoring stations in each river reach this will result in a range of values, for example 0 - 15. If we are to report this raw number for each river water body this will have a different range of values, for example 50 - 200 and a similar issue would happen for catchments. When we assign categories for condition scores to these numbers the breaks created for the distribution of values calculated across the river reaches (values 0 - 15) will be meaningless when applied to river water bodies (values 50 - 200) or catchments.

Going forward, it was decided that the scores at the broader scales will be based on those at the reach scale, but there remained options over the best approach. The participants discussed two main options:

- Weighted averages of the reaches. A weighted average calculates an average where each data point contributes differently based on its "weight" or importance. In this case we would give more weight to longer river reaches compared to shorter ones.
- Worst scoring reach will define the value at the broader scale.

There was also a discussion of how to deal with presence/absence indicators when scaling up and how to report at the management catchment scale.

Workshop discussion

Key discussion points are shown below:

- Given so many possible uses and users of the data at varying spatial scales it has been suggested to focus on having a strong reporting and analysis interface (data visualisation) for the map to allow different questions to be asked. The data will be mapped once at reach scale, but the interface will facilitate this being reported in different ways.
- Scaling up will be necessary for the NCEA programme, with a preference for a weighted average approach, and this was repeated by other participants.
- Some attendees questioned whether it is necessary to scale up in the first place. If this is really necessary, it could be done visually looking at the river reaches. River managers will then decide how to aggregate the information. Scaling up would also introduce another layer of complexity and uncertainty including carrying through biases in the coverage of the data. Different indicators provide ecosystem services at different scales, so rare species with

small populations may need to be mapped at a very large scale, whereas some geomorphological processes such as natural sinuosity, which provides flood attenuation and control of sediment movement, act at a catchment scale. It isn't possible to see some of these morphological features at reach scale, so scaling up from reach would automatically ignore them.

- On the other hand, some people wanted a snapshot overview to help them think about their catchment more holistically. River basin scale and national scale might also be required.
- Little support was found for the WFD approach (one-out all-out approach) overall, though weighted averages would be useful for some purposes and worst scoring is useful for other purposes. If the purpose is to identify where investigation is needed then the WFD approach can be used, otherwise weighted averages might be more appropriate.

Polling

Two polls were conducted after discussions, with results shown in Figure 18.

Results were decisive, with the 80% of participants preferring a weighted average of the reaches (stretches) and all participants preferring a proportional breakdown when reporting for management catchments. Note that as there were no votes for a single condition score, this does not show up on Figure 18.

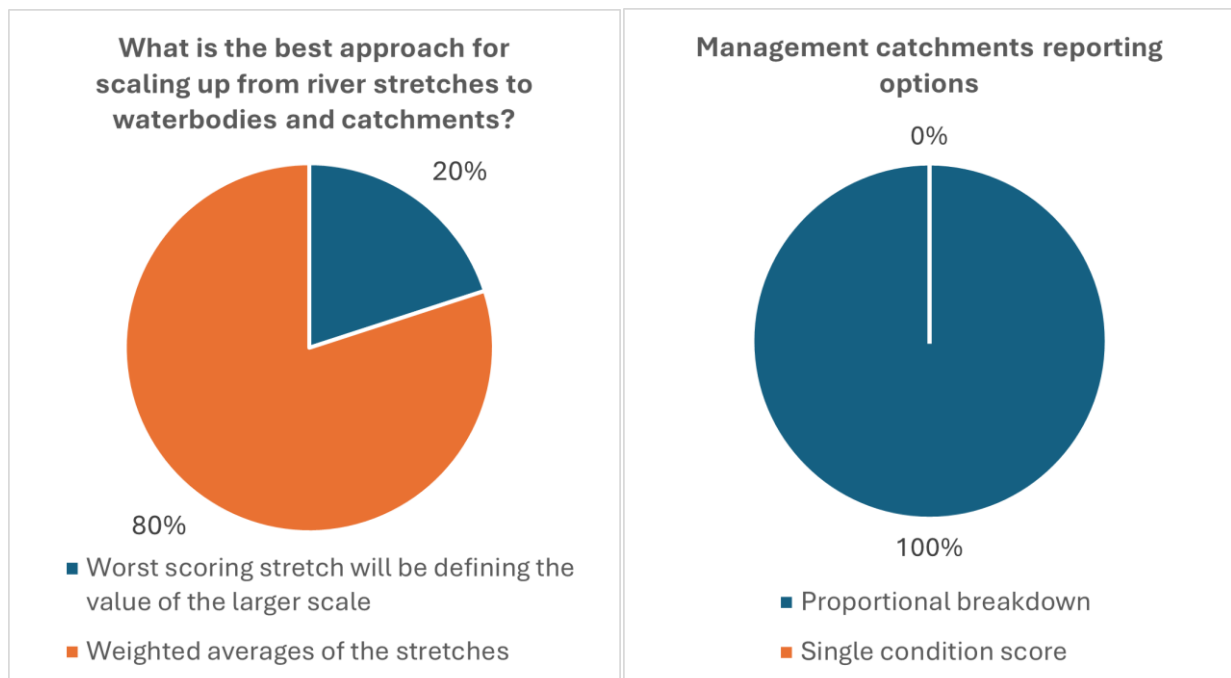


Figure 18: Results of polling carried out at the workshop on scaling up.

Outcome

Although not all participants were keen on scaling up, overall there is a strong user demand for this and it is considered a necessary output of the ESME tool. Therefore, we decided to scale up using the weighted average approach. This also addressed an issue identified in the prototype tool concerning discrepancies when calculating results independently at the different scales.

To address the preference for a proportional breakdown when presenting results at broader scales, especially at the management catchment scale, we have added graphics into ESME that show the breakdown of results within each catchment. Given the desire for the results to be displayed in different ways for different users and uses, we have built in flexibility into ESME so that the breakdown of results can be displayed for any area of interest, but also mapping is available that shows a single score for each waterbody or management catchment where this is preferred.

8. Developing the Ecosystem Service Map Explorer (ESME)

This section outlines the Ecosystem Service Map Explorer, known as ESME, which visualises the evidence developed during the project. Feedback relating to the prototype web application highlighted a need for a more user-friendly structure, one that was formatted in a more accessible style, and one with clearer guidance signposted throughout.

Improvements on functionality were also requested, which included: options for importing/exporting data; structured around scale filters to improve rendering performance; search functions and filters to help identify locations/features; additional reference datasets such as boundaries and environmental data; user selections that link between multiple map tabs; and printing functionalities.

An outline of how ESME was set up, key features and functionality, limitations, user workshop, and user testing and feedback are described below. How to use the tool is described separately in the User Guidance document and guidance information is also available directly in ESME.

8.1 How it was set up

The ESME tool was created using Esri's ArcGIS Experience Builder application available on ArcGIS Online (AGOL). Compared to the Instant App application used in the prototype tool, Experience Builder offers greater choice for formatting the application's structure, more options for user interactions (such as feature selections), easier integration of data visualisations (e.g. graphs and charts), and more flexibility around including non-map pages (such as introduction and guidance pages). Considering the earlier feedback and improvement requests, ArcGIS Experience Builder was capable of meeting these requirements. Experience Builder is also available through the Environment Agency's ArcGIS Online account meaning ESME can be internally maintained in the future.

Experience Builder can utilise web maps created in ArcGIS Online, and three web maps (one for each scale) were created. The web maps included feature layers for the scale's ecosystem service and condition indicator outputs. A series of static reference datasets were also included, and these were chosen to provide users with additional contextual datasets that may assist their interpretation of the ESME tool's results.

The ESME tool was separated into five pages:

- *Homepage*: which outlines the ESME tool's functionalities and purpose.
- *Guidance*: which includes steps to help the user understand and interact with the ESME tool.

- Map: which includes the web maps for each scale alongside charts and summary text for each ecosystem service, and descriptions for each condition indicator. Functionality for users to import their own data is also included.
- Export: which includes tables that allow users to export the resulting datasets at three scales.
- FAQs: which includes a list of frequently asked questions around the tool and its use.

Dynamic interactions between each of the three web maps, the charts and map content were possible using ‘message action’ triggers (a core feature of Experience Builder) which allows for elements within the application to react to the user’s interactions. For example, if a user selected features within the map (using the Select widget), the charts for the ecosystem services would update to only show the results for the features selected by the user.

8.2 Summary of key features and functionality

The key features included in the ESME tool are as follows:

- A landing page which includes information on what the tool is, how to use the tool, who to contact for more information about the tool, and additional information relating to the NCEA programme.
- Integrated guidance page which provides a step-by-step guide for users on how to navigate and interact with the tool. This page also includes short, animated screenshares to further guide users, and options to download more detailed guidance as well as the technical methodology.
- A series of maps for each scale that interact with one another. For example, selecting a management catchment will filter the river water bodies and reaches map to show features within the selected management catchment.
- Charts that show a summary of the ecosystem service results, effectively allowing a user to query and report on ecosystem service provision within an area of interest.
- Select and search widgets that allow the user to filter the results on the maps and charts based on a location or collection of scale features.
- A large list of reference datasets that users can add to the maps to provide contextual information. For example, local authority boundaries, national designations (such as Sites of Special Scientific Interest (SSSIs)).
- The ability for users to import their own datasets, either from their ArcGIS Online account, via a URL (such as a WMS), or from file (such as a CSV, SHP).
- The ability for users to export the results to file for their own analysis. Export formats include CSV for tabular outputs and GeoJSON and Shapefile for spatial outputs.

- Options to print the map view and the current screen view of the tool.
- An FAQ (frequently asked questions) page that provides users with further guidance on using the tool.

8.2.1 Accessibility and branding

ArcGIS Online's Experience Builder application platform mostly conforms with accessibility standards and guidelines. Full details can be found in the [ArcGIS Experience Builder Accessibility Report](#). Throughout the development of the ESME tool, accessibility has been tested using the WAVE plugin. The WAVE plugin is a web accessibility evaluation tool developed by WebAIM.org. It provides visual feedback and reports on the accessibility of web content and outlines whether an element fails accessibility checks. The design of the ESME tool has focussed on maximising text legibility, by using a common font (Arial) and ensuring high contrast between the text colour and the background colour.

A brief accessibility audit was carried out by Defra. The audit identified a number of accessibility issues within ESME, which included inconsistencies with keyboard focus ordering and the inability to view ESME with JavaScript disabled. These issues were not resolvable, as they are caused by the Experience Builder platform. Other accessibility issues identified were resolved where it was technically feasible to do so, and advice followed. Where issues could not be resolved workarounds have been identified and a roadmap of accessibility improvements has been developed to make improvements as technological improvements within the ArcGIS Online platform allow. Full details can be found in the accessibility statement within ESME. All external documents linked within the ESME tool (e.g. the user guidance) were created in Microsoft Word and passed the built-in Microsoft accessibility checker before being exported to PDF format. The Methodology report and this Project report (and other outputs) have also been tested for accessibility and were compiled using the Environment Agency report template, including Environment Agency colours, fonts and branding.

The ESME tool uses the Environment Agency's organisation theme within Experience Builder, to ensure that the organisation's colours and font styles are used throughout the tool. Logos and branding guidance were provided by the Environment Agency at the start of this phase, and the ESME tool has been developed in line with the provided guidance.

8.3 Limitations

As outlined in Section 6.1, the ESME tool uses 'message action' triggers in order to filter the map features and charts to features that have been selected by the user via the select or search widget. During Phase 3, it was discovered that these triggers would stop working when data within the maps was adjusted (for example, the styling of a reference dataset). Through discussions with Esri, it was found that this is a known issue on Esri's side. Considering the future maintainability of the ESME tool, it

was deemed not practical or sustainable for the tool to include dozens of the triggers that could break when updates were made to the data. As a result, only the map layers for the scale features (management catchments, river water bodies, reaches) have a trigger that filters themselves based on a user selection. This meant that ecosystem service outputs and condition indicator map layers were not filtered by the user selection. Corresponding chart data was linked to the scale features that included a trigger, allowing the charts to update based on a user selection. However, triggers were not created for a selected chart segment/bar that would show its location on the map.

During Phase 3, the draft ESME tool suffered from slow load times due to the high number of charts (c. 162 in total) shown in the map page. In Phase 4, the decision was made to remove the condition indicator charts (reducing the total number of charts to 30). The removal of the condition indicator charts improved the load times significantly.

It is not possible to print a 'report like' format of the ESME tool within Experience Builder. To achieve this, a separate Esri application is required, known as Report Builder. This application could be utilised in future phases (see Recommendations).

The Phase 2 feedback on the pilot web app asked for the use of hybrid tiles and feature layers to improve the rendering of datasets with large and/or complex geometries – particularly the reaches dataset. At the time of this project, the combining of tile and feature layers (known as Vector Tile Layers in the Esri platform) was not implemented by Esri for use in web maps. This meant that for datasets with large and/or complex geometries, their scale visibility had to be adjusted so that they only rendered on the map when the user zoomed in to a closer scale. This has been improved for the Beta version of ESME so that it currently only affects some of the reference datasets.

8.4 User workshop

On the 6th February 2025, a workshop was held with the title “*Introducing ESME: the Ecosystem Service Map Explorer – workshop and demo*”. The workshop consisted of a presentation on the background to the project, a second presentation on progress and changes since Phase 2, a live demo of the tool with discussion, a Q&A session, and a brief outline of next steps. During the workshop two polls were conducted to gather information on the attendees and their first impressions of the tool. Key results are shown below.

The workshop was attended by approximately 70 people (including the project team), with 49 completing the first poll. In total, 44 of those completing the poll were from the Environment Agency, with two people from Natural England (NE), two from Defra and one person from the University of Oxford. The vast majority of the Environment Agency staff (34) were from the National Environment and Business Directorate, with six from Local Operations, and two each from National FCRM and National Strategy, Transformation and Assurance. The National Environment and Business staff represented a range of teams, including biodiversity, natural capital, research, nature

recovery, Operations Catchment Service, Statutory Assessment and Reporting, Strategic Evidence Assessment and Design, water monitoring, water resources and others.

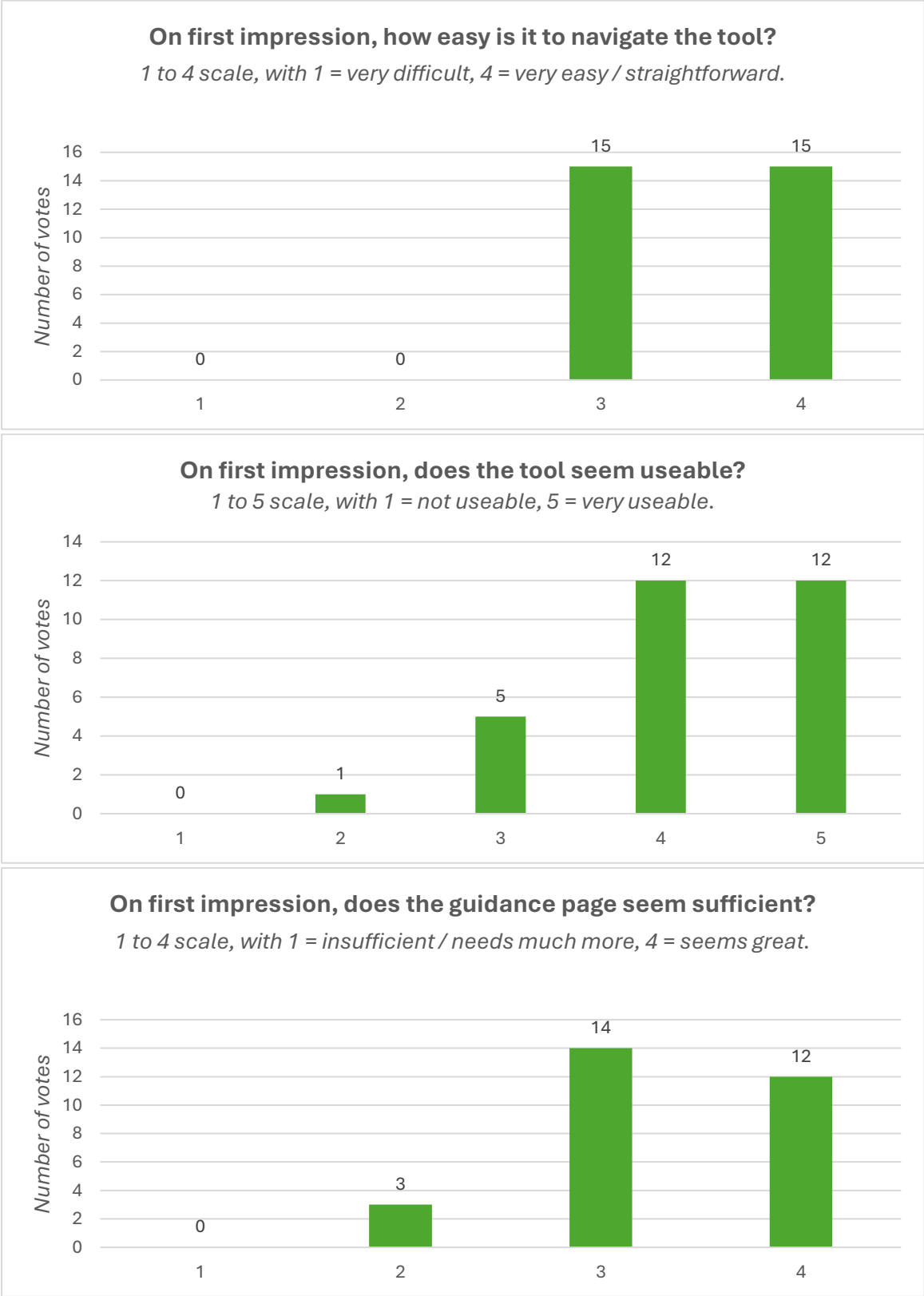


Figure 19: Scores for navigation (top), usability (middle) and guidance (bottom) as given by workshop participants.

Attendees were reasonably knowledgeable about the concept of natural capital and ecosystem services, with a self-assessed mean score of 2.86 out of 4. A similar score of 2.76 out of 4 was given when asked about assessing the condition of rivers for water quality / water flow / ecology, whereas attendees were markedly less knowledgeable about assessing the condition of rivers for cultural services, with a mean score of 1.94 out of 4. All of these scores were extremely similar to those given by workshop attendees in Phase 2.

Following the demo, attendees were asked to give their first impressions of the tool and 30 people filled in these polls. They were asked “*on first impression, how easy is it to navigate the tool?*”. We used a 1 to 4 scale, with 1 = very difficult, 4 = very easy / straightforward. There was an even spread amongst the two highest categories (Figure 19 top), with all participants answering either 3 or 4, and a mean response of 3.5, suggesting that the tool was considered easy to navigate on first impression.

Workshop participants were also asked “*on first impression, does the tool seem useable?*”. Here we accidentally used a 5 point scale (Figure 19, middle), but most participants answered in the top two categories (4 or 5), although there were a few lower scores. The mean score was 4.17, which is equivalent of 3.33 when converted to a 4-point scale. The final question of this type asked, “*on first impression, does the guidance page seem sufficient?*” and again almost everyone answered in the top 2 categories (Figure 19 bottom), with a mean score of 3.31 out of 4.

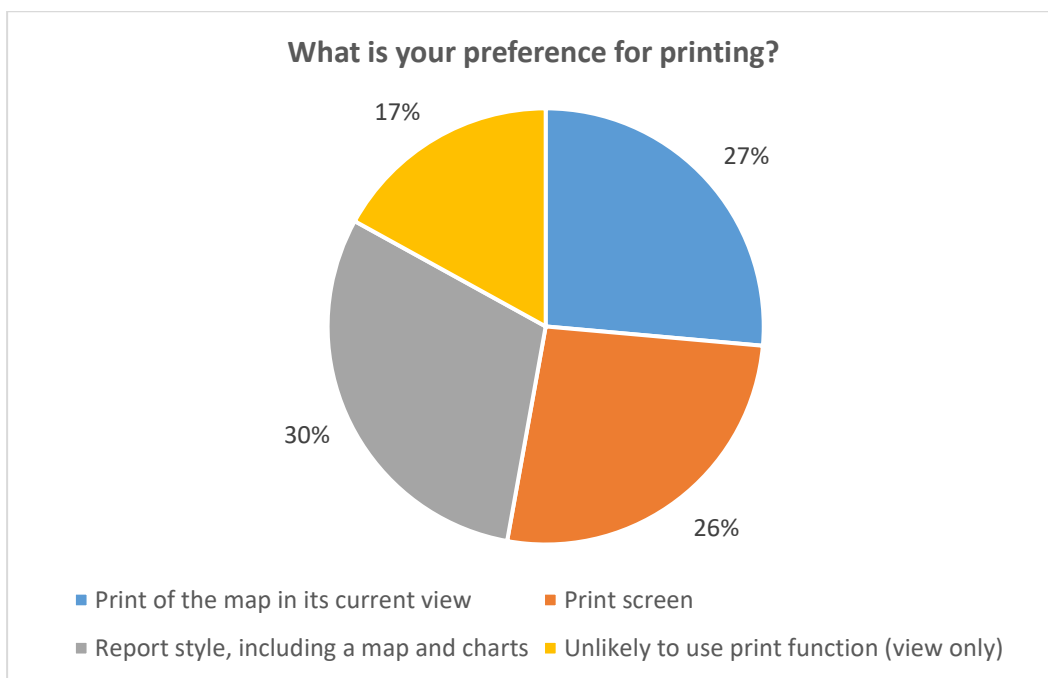


Figure 20: Printing preferences expressed at the workshop.

Workshop attendees were asked if functionality seemed useful and if anything obvious was missing, with mostly positive responses given. They were also asked about printing preferences. Two options within ESME were demonstrated (printing

the map, or printing the screen), with a third option to produce a report discussed, but not available at this stage. Poll results (Figure 20 and Table 12) showed that there was a fairly even spread of preferences for the different printing options, with slightly more people choosing the report option.

Additional comments were also collected, which were collated with other comments (see below).

Table 12: Printing preferences according to the workshop and the user testing questionnaire.

Printing preferences	Workshop	Questionnaire
Print of the map in its current view	14	4
Print screen	14	6
Report style, including a map and charts	16	4
Unlikely to use print function (view only)	9	0

N.B. People were allowed to pick as many options as they liked, hence there are more answers than people. Number of people answering was 30 for the workshop and 9 for the questionnaire.

8.5 User testing, questionnaire and actions taken

After the workshop, a 2-week testing period took place where users could access the tool itself. At this stage, 3 ecosystem services and all their indicators were available on the tool, and the tool was working with full functionality, with the exception that the export data functions were disabled. During this time, users provided feedback on the ESME tool via a questionnaire, which was an expanded version of the polls answered during the workshop.

In total, nine responses were received at this stage. Seven were from the Environment Agency, with one each from Natural England and the River Restoration Centre. Most (7) of these respondents had also attended the workshop, so to avoid double counting we have not amalgamated the answers with those from Section 6.4.

When asked about ease of navigation, usability, and if the guidance was sufficient, the mean scores were 3.22, 3.22, and 3.25 respectively (out of 4), indicating generally high scores across the board. More detailed comments were also collected as participants had had more time to properly use the tool and test it for themselves. When asked about printing preferences, there was again a spread of answers across the three printing options, but with slightly more choosing the print screen option on

this occasion. Results are shown in Table 12, for comparison with the answers from the workshop.

Further comments were collected on functionality, presentation of the maps, background datasets, and other comments. Information on potential applications and update frequency was also collected and is reported on in Sections 8.2 and 8.3 respectively.

As well as the feedback via the questionnaire, more detailed user testing was carried out by four further individuals from the natural capital team and detailed feedback received. All outputs were also reviewed by an external expert from the Environmental Change Institute, University of Oxford. All of the feedback that suggested actions or ideas for ESME, from the workshop polls, questionnaire, and detailed separate feedback was collated together.

Feedback that was actioned included (but were not limited to): placing the guidance steps, FAQ steps and ecosystem service results into 'accordion' elements (dropdowns) to provide a more focussed layout view; additional reference datasets; additional guidance steps and tooltips; consolidating print options into one button; minor text changes; and formatting changes, particularly for smaller screen sizes.

8.6 Developing and testing the Beta version of ESME

The Beta version of ESME was developed in Autumn 2025. This version includes indicators and ecosystem service maps for all ten ecosystem services. It also brings together all changes requested during earlier feedback. Key changes and enhancements include:

- Inclusion of the decision tree diagrams for each of the ecosystem services
- A link to a document outlining use case studies for ESME
- An initial 'splash screen' that appears when a user first loads ESME. The splash screen includes an Open Government Licence statement, accessibility statement and an optional registration form
- Formatting changes to improve the experience on smaller, laptop screen sizes
- Formatting changes to enhance the accessibility of ESME
- The removal of condition indicator charts to improve the overall performance of ESME
- Data formatting improvements, specifically within the export tab tables

8.6.1 User Acceptance Testing (UAT)

The Beta version of ESME was subject to User Acceptance Testing by approximately 20 Environment Agency staff, as well as more general testing by the project team. The UAT testers were provided with a script setting out each element within ESME for testing.

UAT comprised of eight tests:

Test 1 Homepage

Testers were asked to review the legibility of all text and logos on the homepage, test each tab along the bottom of ESME and check that the links to the use cases worked correctly.

There were no fails for this test, only minor suggestions, such as text changes.

Test 2 Guidance

Testers were asked to download each document available in the guidance tab, review each guidance step, and test whether the content was legible.

One fail was reported for this test, which involved text overlaps when scrolling down to the accordion section.

Test 3 Map Catchments

Testers were asked to test the functionality of the select and search widgets; map functionalities (zoom, full screen, measure, address search); print functionalities; data layer visibility and reordering; map layer popups and transparency; import data functionalities; legibility of ecosystem service text and charts; legibility of condition indicator descriptions; ecosystem chart data exports; and decision tree appearance for the catchment scale within the map tab.

Testers reported some fails for this test. Fails included: no basemap options for 2 testers; the cursor changing to a 'grab hand' preventing 3 testers from navigating through ESME; the clear selection not resetting the map to full extent for 4 testers; the print output failing for 1 tester; chart labels overlapping for 1 tester.

Test 4 Map River water bodies

Testers were asked to repeat the tests from Test 3, but to test the River water bodies scale rather than the catchments.

Testers reported some fails for this test. Fails included: no basemap options for 2 testers; the cursor changing to a 'grab hand' preventing 3 testers from navigating through ESME; chart labels overlapping for 1 tester; two print windows appearing instead of one for 1 tester.

Test 5 Map Reaches

Testers were asked to repeat the tests from Test 3, but to test the Reach scale rather than the catchments.

Testers reported some fails for this test. Fails included: no basemap options for 2 testers; the cursor changing to a 'grab hand' preventing 3 testers from navigating through ESME; the clear selection not resetting the map to full extent for 4 testers; the print output failing for 1 tester; chart labels overlapping for 1 tester; the print functionality not working for 14 testers.

Test 6 Map filtering

Testers were asked to test the map filtering from other scales (for example, a catchment selection filtering the river water bodies results).

3 testers reported a fail for this test, caused by the 'grab hand' they had first experienced in test 3; 2 testers reported a fail for the filtering of river water bodies and reaches, however this was a result of a misunderstanding of the filtering functionality.

Test 7 Export

Testers were asked to test each scale tab within the export table in ESME's export tab and download each format for each scale; download and view the data schema; and test whether a selection of scale features in the map tab subsets the export table.

5 testers reported a fail for this test, where they were unable to see the data download (a result of their browser website popup restrictions).

Test 8 FAQ

Testers were asked to review each FAQ and test whether the content was legible, and, where a link was included in the FAQ, test whether the link redirected to the correct location.

3 testers reported a fail for this test, where one of the FAQ links was incorrect.

Test 9 General comments

The final test was for any general comments that had not been captured in the previous eight tests.

Changes were made to ESME post UAT to address all issues raised. The majority of issues raised were resolvable. For example, 14 testers found that the reaches print map did not function correctly, and this was resolved by fixing the link to the print widget within Experience Builder. Additionally, it was found that multiple issues raised were related to a user's browser blocking pop-ups by default (such as the issue some testers had when attempting to download data). The resolution for these issues involved expanding the guidance text within ESME and the user guide to advise users to check their browser settings if the issue occurs. Some issues were not resolvable however, and many of these related to the limitations of ESME's platform, Experience Builder (such as a group within the map layers not automatically checking when a layer within the group is selected). Full details on the issues raised in UAT and the resolutions taken are outlined in a separate UAT report (unpublished).

9. Using and interpreting the mapping outputs in ESME

In this section we describe the mapping outputs shown in ESME. This includes what the maps show and how to interpret them, how ecosystem service capacity (scores) could be improved, how the different scales of mapping should be used, the importance of spatial scale for different ecosystem services, and links to benefits and values.

Information on potential applications and uses is provided in the separate document – ESME Applications and Limitations.

9.1 Interpreting the maps

9.1.1 Aesthetic and amenity experiences

The ecosystem service of Aesthetic and amenity experiences considers people's perceptions of the landscape, with higher scoring areas being those with greater levels of perceived naturalness. It combines local scale indicators of condition, including River Habitat Quality and litter, with landscape indicators, including tranquillity and natural beauty. The latter do not directly describe the river asset itself but are included because the wider landscape context strongly influences how people perceive and enjoy a river.

The maps show that many areas of lowland England have relatively low scores for River Habitat Quality, largely due to the fact that the vast majority of rivers are modified in some way. Tranquillity clearly shows the urban-rural divide, although note that this indicator captures broad patterns and does not pick up local patches of tranquillity, such as quiet stretches of river in the middle of an urban area. The dataset is also quite old (2007), so will not pick up recent changes. Natural beauty picks up the national parks and uplands, as well as large areas of national landscapes (previously called Areas of Outstanding Natural Beauty) in the south. Litter is clearly under-recorded, but the index does pick up some areas of litter, particularly in more heavily urbanised areas.

The overall Aesthetic and amenity experiences map (Figure 21) tells a relatively simple story and shows that the national parks and wilder areas, especially in the north and west, score highly (when looking at the scale of reaches or waterbodies), and locations with high populations and intense land use tend to score badly. Note that the maps do not consider the influence of the natural environment on property prices, which would be higher in urban areas.

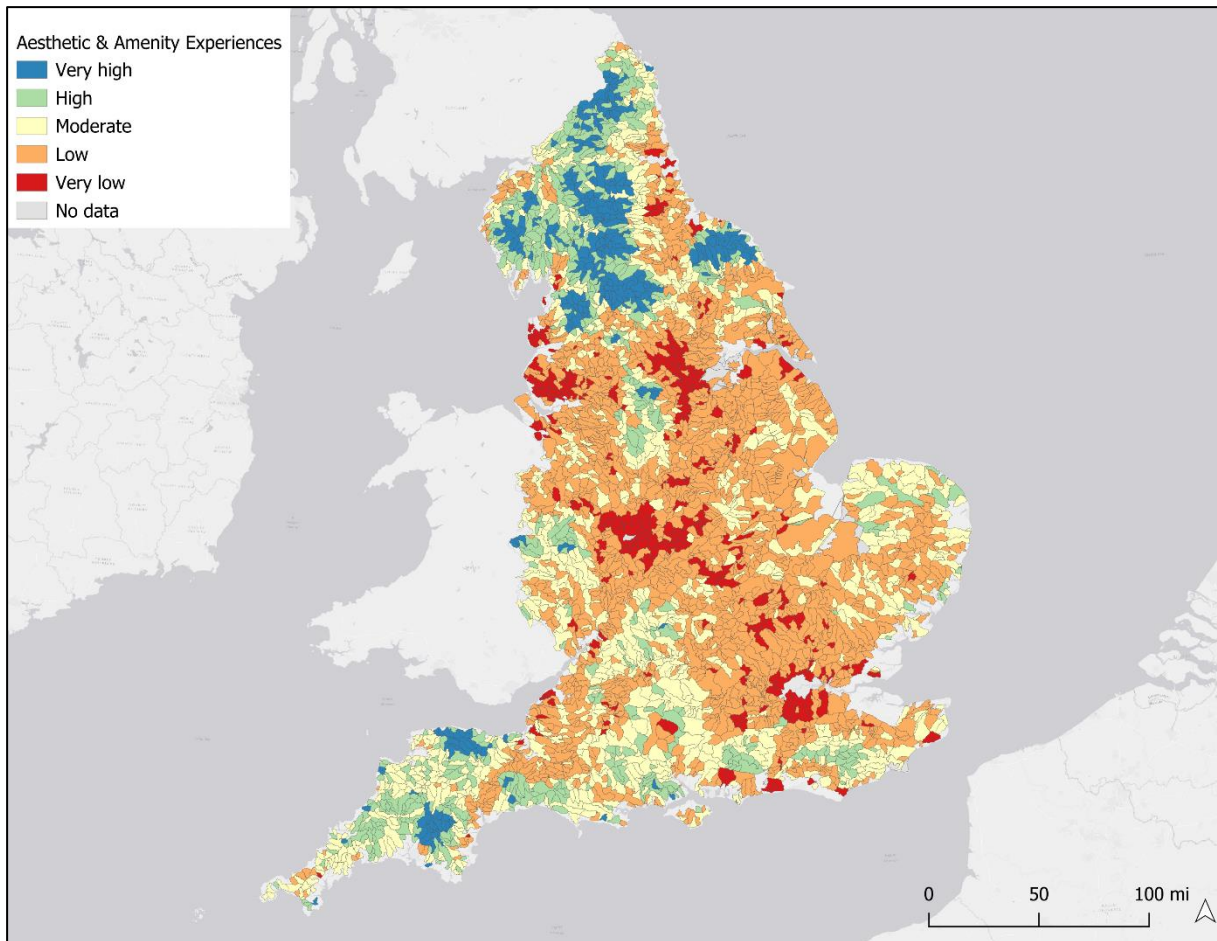


Figure 21: The overall capacity of each river waterbody to deliver the ecosystem service of Aesthetic and amenity experiences.

9.1.2 Education and investigation

This ecosystem service considers the contribution and opportunity provided by the environment towards study, education, and research. As it is difficult to know objectively what enables a river to have a high capacity for education or research, we have mostly relied on using data identifying rivers that have already been designated as important (scientific interest) or where monitoring activity is already taking place (monitoring stations) as a proxy. The logic is that if there is a lot of education or monitoring happening in a place, there must be something about that site that gives it high capacity for this ecosystem service.

The evidence to support the pupils access indicator is weak, as there is no direct recording of school trips to rivers, so we have had to base this indicator on typical school trip distance and information on accessible riversides and school locations. Nevertheless, this does give a broad indication of the number of pupils who could potentially visit a stretch of river. As the average journey length of school trips in England is relatively long, the pattern seen in the mapping is driven by overall population density.

On the overall map (for reaches and waterbodies), the chalk streams are shown as generally having a very high capacity for this ecosystem service, which appears to be a reflection of where there is active study and public interest (Figure 22). Few other major patterns in the data are apparent.

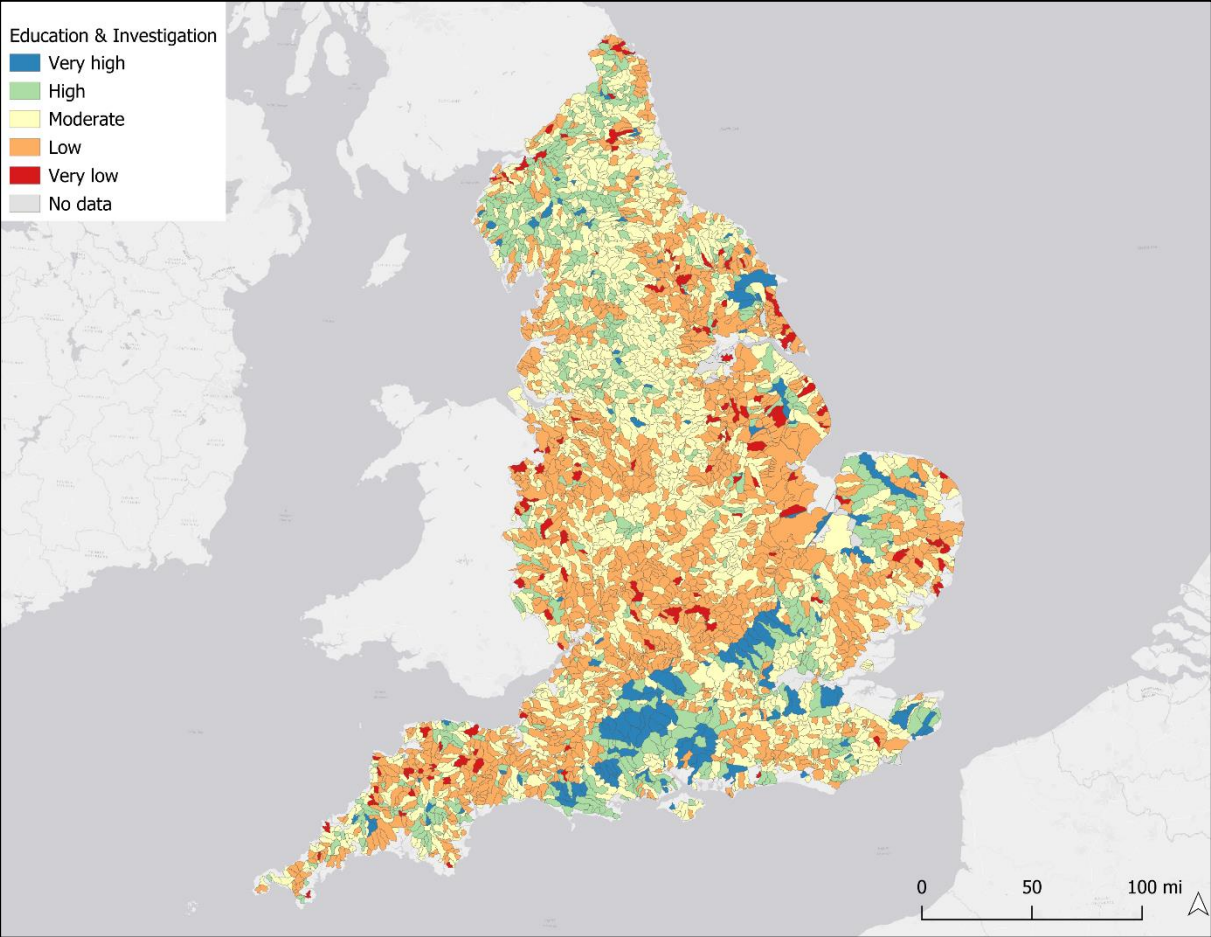


Figure 22: The overall capacity of each river waterbody to deliver the ecosystem service of Education and investigation.

9.1.3 Habitat and species population maintenance

This ecosystem service considers the ecological conditions necessary for sustaining populations of species throughout their lifecycle. As this has been the focus of much scientific research and monitoring, we have much better and relevant data for this service, and therefore a stronger understanding of the ecological conditions needed. As a result, the scores are based on absolute capacity (based on measured physical quantities at locations) rather than comparisons between rivers (relative capacity).

This makes the overall ecosystem service map look different compared to the other ecosystem services maps as there are far more lower scoring rivers and less of an even spread across the full range of scores. This is justified because we have robust data and clear thresholds, so we can map it absolutely with higher confidence. The decision tree also looks different and is structured much more like a WFD classification. However, although it includes most of the elements that are used within

a WFD classification, it provides a greater depth of information than WFD ecological status, as it also includes (amongst other differences) an assessment of the naturalness and diversity of the river channel and bankside, and an assessment of longitudinal, vertical and lateral connectivity.

The overall ecosystem service map (Figure 23) reflects a generally low capacity for this ecosystem service overall, with all rivers scoring from moderate to very low at catchment scale, and only a few rivers in the north and south-west scoring better than this at reach and waterbody scales. This is driven by River Habitat Quality, which is the most influential indicator for this ecosystem service and scores poorly, as almost all rivers in England have been modified in some way. This was selected as the most influential indicator, and therefore placed first in the decision tree, based on the evidence review undertaken at the start of the project and confirmed by expert input at workshops and review feedback. The connectivity indicator shows a good spread of scores, and hydrological condition is good in many rivers. The water quality indicator shows a mixed picture, with the vast majority of rivers scoring moderate or poor.

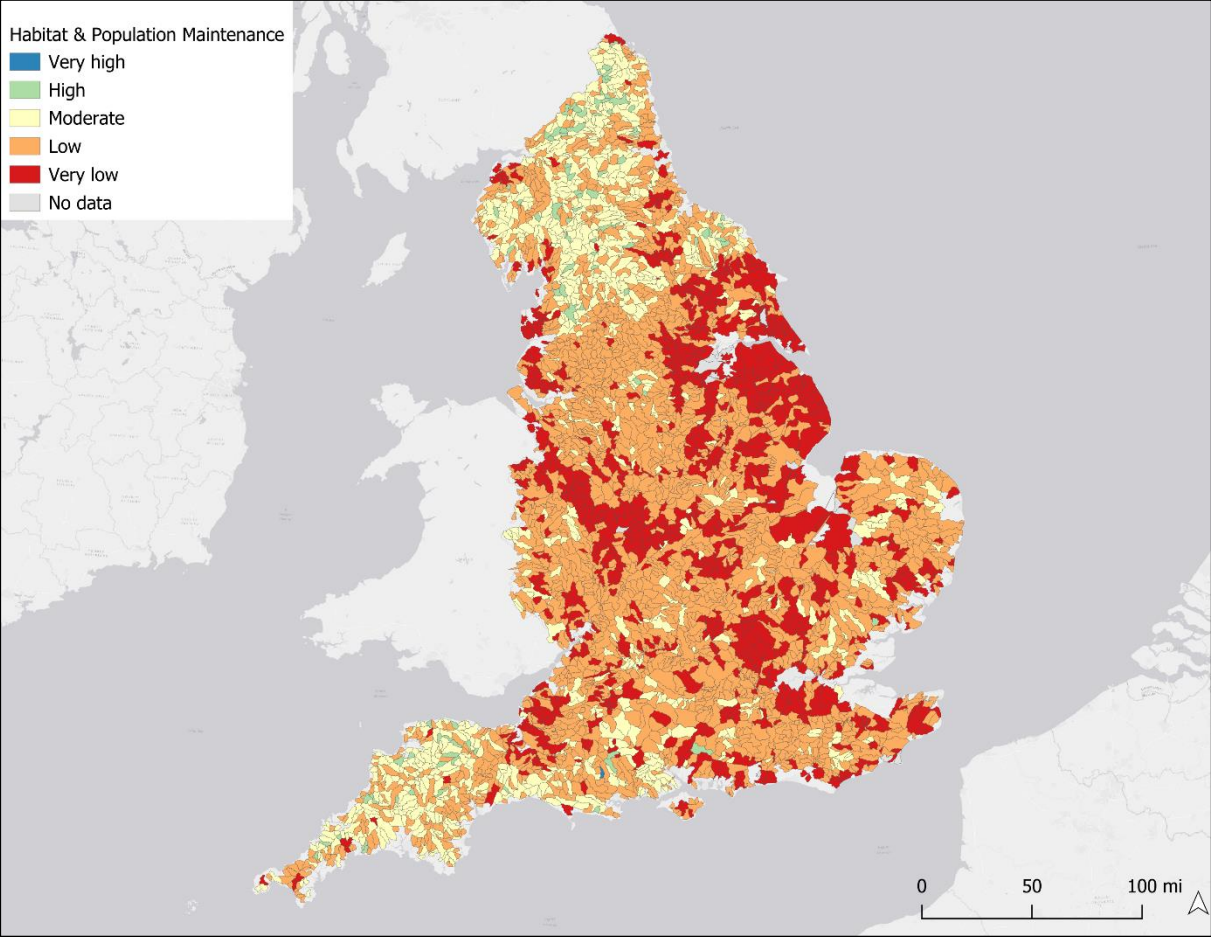


Figure 23: The overall capacity of each river waterbody to deliver the ecosystem service of Habitat and species population maintenance.

9.1.4 Physical / mental health and wellbeing

This ecosystem service considers the role of natural landscapes, including in urban areas, for maintaining mental and physical health. It combines a large number of different datasets within indicators of different typologies.

The recreational hotspots map shows that there is a good spread of rivers providing high recreational use and hence providing health and wellbeing benefits. The highest scoring reaches tend to be on larger rivers and in rivers in national parks and other well visited destinations. On the other hand, the local access indicator reflects much more local use and is concentrated on rivers that flow through urban areas. In both cases we assume that high use indicates a high level of service capacity.

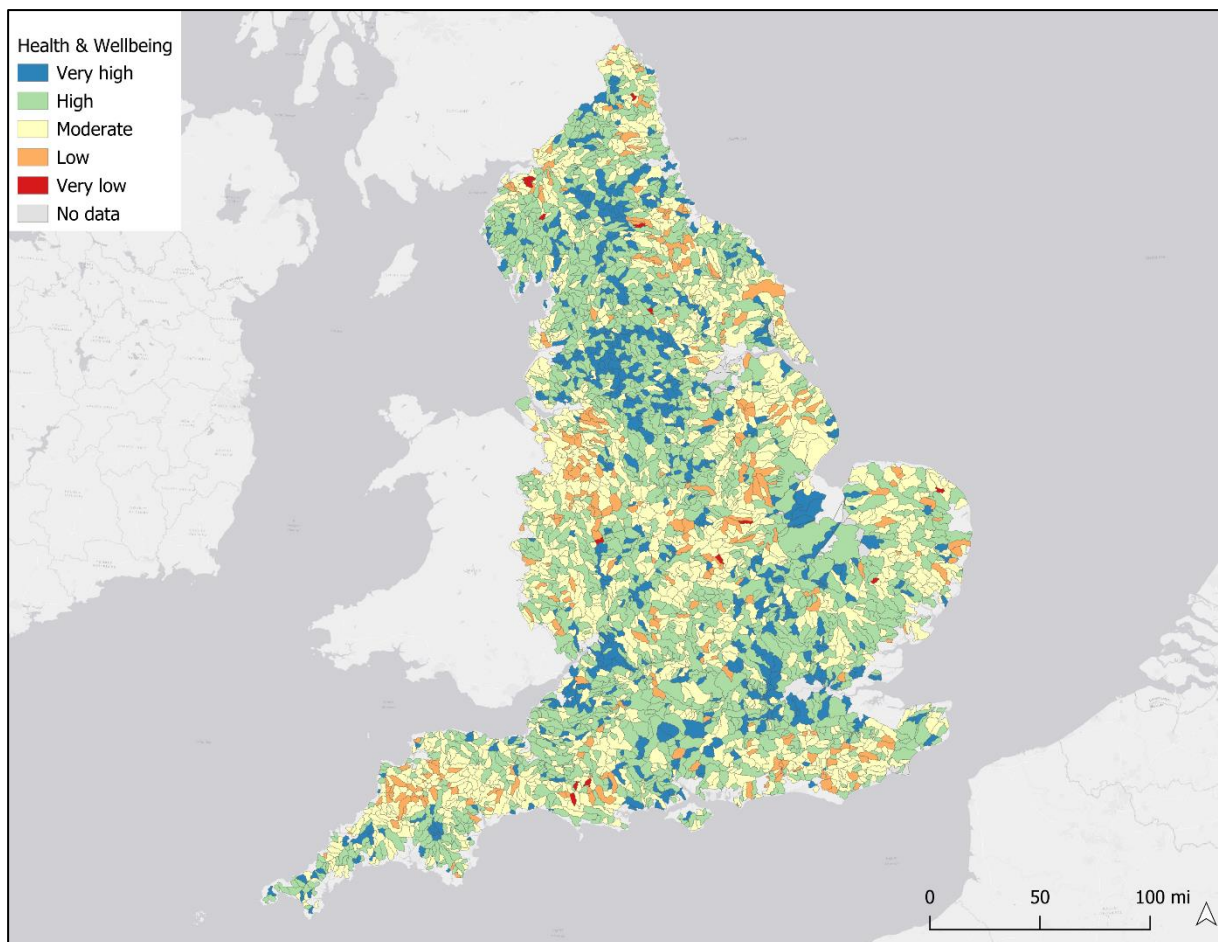


Figure 24: The overall capacity of each river waterbody to deliver the ecosystem service of Physical / mental health and wellbeing.

The most potentially confusing indicator is health deprivation by access. This is a culturally specific indicator, as it reflects the increased value that the service provides depending on the people it benefits. Hence the highest scoring areas are those where there is high deprivation but also access to a river as these populations will most benefit from that service. This tends to be focused in many northern towns and cities as well as coastal communities across England. Much of central lowland England scores poorly for this indicator as it is relatively affluent and has fewer areas

of deprivation. Note that this indicator is based on the 2019 version of the Indicators of Multiple Deprivation, as the 2025 update was published too late for inclusion in this version of ESME (although the pattern of the 2025 data appears to be very similar). The recreational hotspot and local access indicators are modified by the water quality indicator and the latter also by health deprivation by access, before combining and modifying by tranquillity to produce the final score. The resulting final map (Figure 24) performs well overall, particularly in highlighting national parks and other protected and important natural areas, but also highlighting rivers that flow through and close to major urban centres. Note that the flow of the ecosystem service (the amount actually used) is likely to be highest where people live, but the capacity (as mapped in ESME) is not directly linked to usage, although there is some inevitable crossover between the two concepts in our mapping.

9.1.5 Intrinsic value of nature

Intrinsic value of nature considers the things in nature that should be conserved because of their existence, option, bequest and inspirational value. We have mapped it based on the conservation value of the reach, the presence of iconic species (positive) or invasive non-native species (INNS, negative), the quality and naturalness of the local habitat, and the scientific value of the river or landscape through which the river flows.

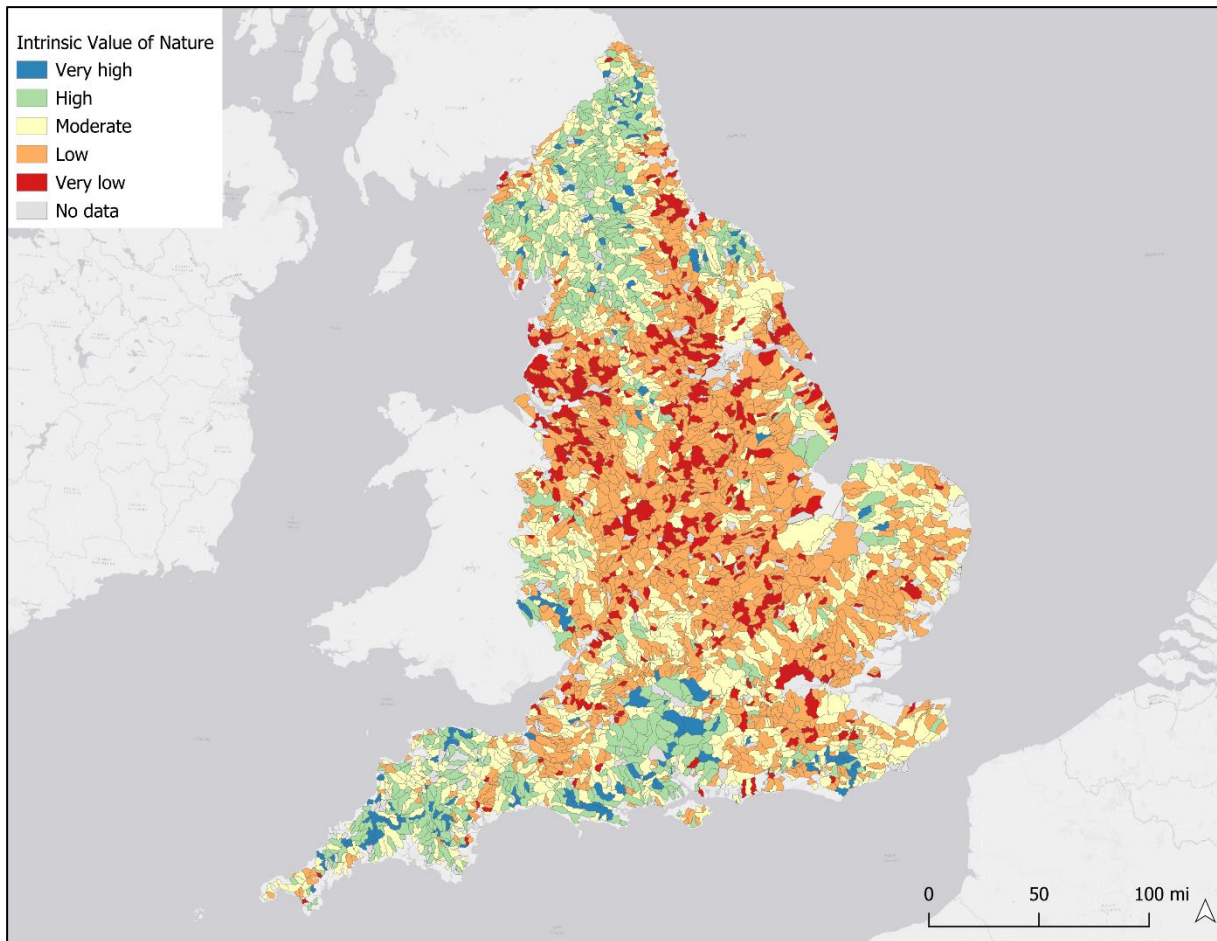


Figure 25: The overall capacity of each river waterbody to deliver the ecosystem service of Intrinsic value of nature.

This is effective at capturing different aspects of the value of the river. However, the data on iconic species and INNS is limited as we were restricted to the use of open data and most species records are licenced. As a result, those two maps should be treated with caution as there will be many reaches containing species that have not been captured in them. Furthermore, species reporting data mostly comes from citizen science schemes and studies have shown that participation in citizen science is higher in more affluent areas. There may be a pattern showing more species in these areas simply due to greater survey effort, which may have an influence on the patterns shown in the maps.

The remaining indicators are not based on citizen science and are likely to be more representative. The final ecosystem service map (Figure 25) appears to be functioning well, showing high intrinsic value in areas which are known to be valued, such as the chalk streams and more natural areas of England, with low intrinsic value in post-industrial and densely populated areas.

9.1.6 Recreation

The ecosystem service of recreation considers the contribution and opportunity provided by the environment for recreational uses. It is important to be clear that this

is not just where people carry out recreational activities. The latter depends on lots of non-natural-capital factors, such as infrastructure and where people live. We do capture these elements of use through indicators such as the recreational hotspots indicator, but this is only a part of the overall mapping. The overall map can be described as capturing recreational opportunity (capacity), rather than realised use.

A number of the indicators for recreation are the same as for Physical / mental health and wellbeing and so show the same patterns. Hence the highest scoring reaches for recreational hotspots tend to be on larger rivers and in rivers in national parks and other well visited destinations, whereas the local access indicator maps much more local use and high scores are concentrated on rivers that flow through urban areas. However, there are some different indicators in recreation compared to health and wellbeing and we have combined them together in slightly different ways to reflect the differences in the two ecosystem services. For example, Physical / mental health and wellbeing includes an indicator on health deprivation by access, an indicator on tranquillity, and poor water quality has a greater impact on the score. Recreation does not include the first two but does include a natural beauty indicator instead.

The overall map (Figure 26) shows that many rivers deliver high or very high recreation ecosystem service capacity. This does highlight the importance of rivers for recreation, both in “destination” locations such as national parks, but also in and around towns and cities throughout England.

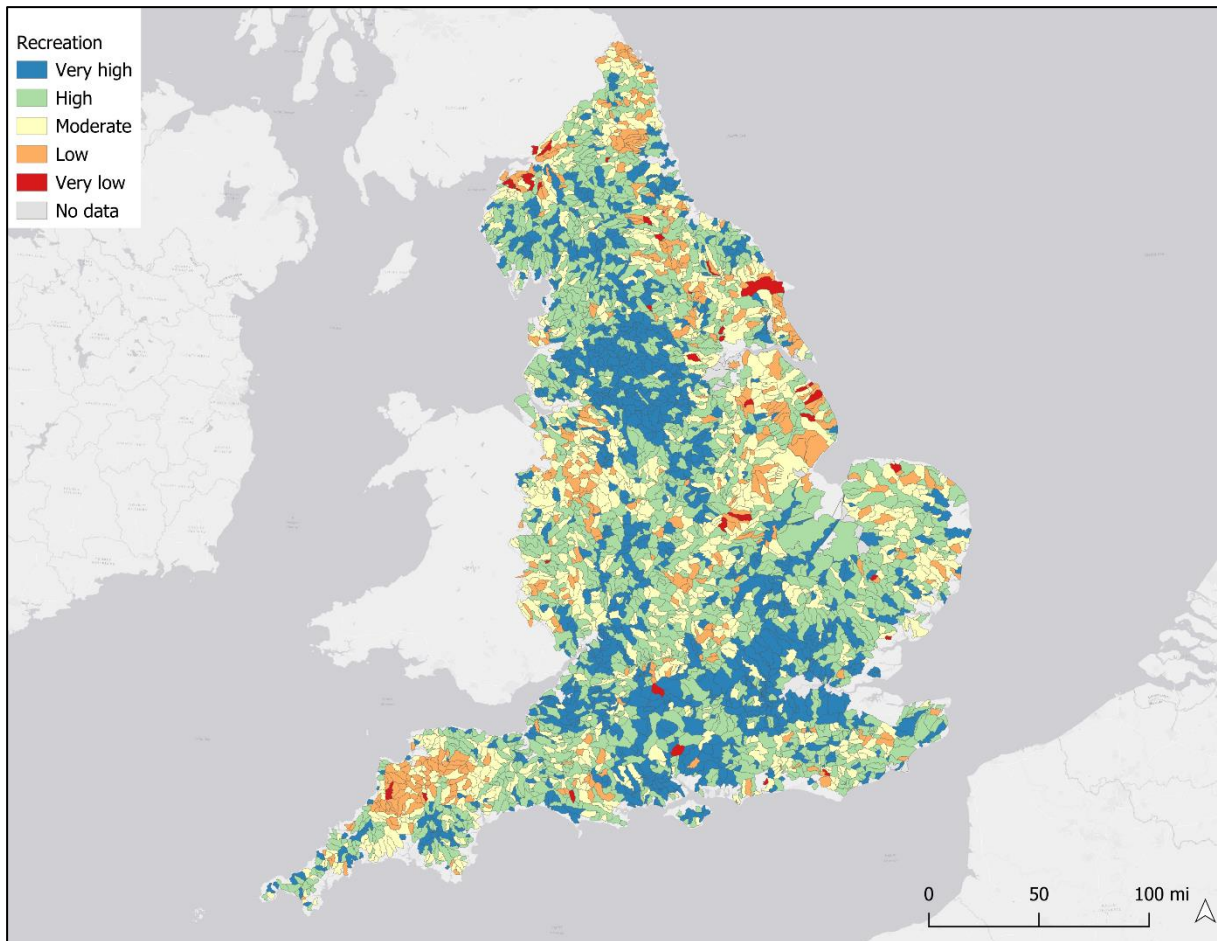


Figure 26: The overall capacity of each river waterbody to deliver the ecosystem service of Recreation.

9.1.7 Spiritual, cultural and religious experiences

This ecosystem service considers 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 for people.

As noted in the limitations, the mapping does not consider the full range of spiritual/cultural/religious experiences facilitated by rivers as it would be very difficult to capture all the reasons why a place has particular spiritual, cultural or religious meaning or value. However, we do attempt to capture a number of factors.

The presence and condition of heritage features is the starting indicator and therefore the most influential. We attempt to only consider heritage features that are either directly associated with the river, or their setting is influenced by the river, by only capturing features that are within 50m of a river. However, we acknowledge that not all of these historic features will be necessarily linked to the river itself, so there may be some false positives.

Alongside this, we've used the National Character Areas (NCA) to build the sense of place / history indicator. In many cases the assessment in the NCA will not directly relate to rivers, however, it does still provide information on the broader landscape

context of the area as a whole, which will have a bearing on Spiritual, cultural and religious experiences.

The overall map (Figure 27) highlights the important role of rivers for cultural values. Rivers in inspirational landscapes such as the Lake District score particularly well, as would be expected.

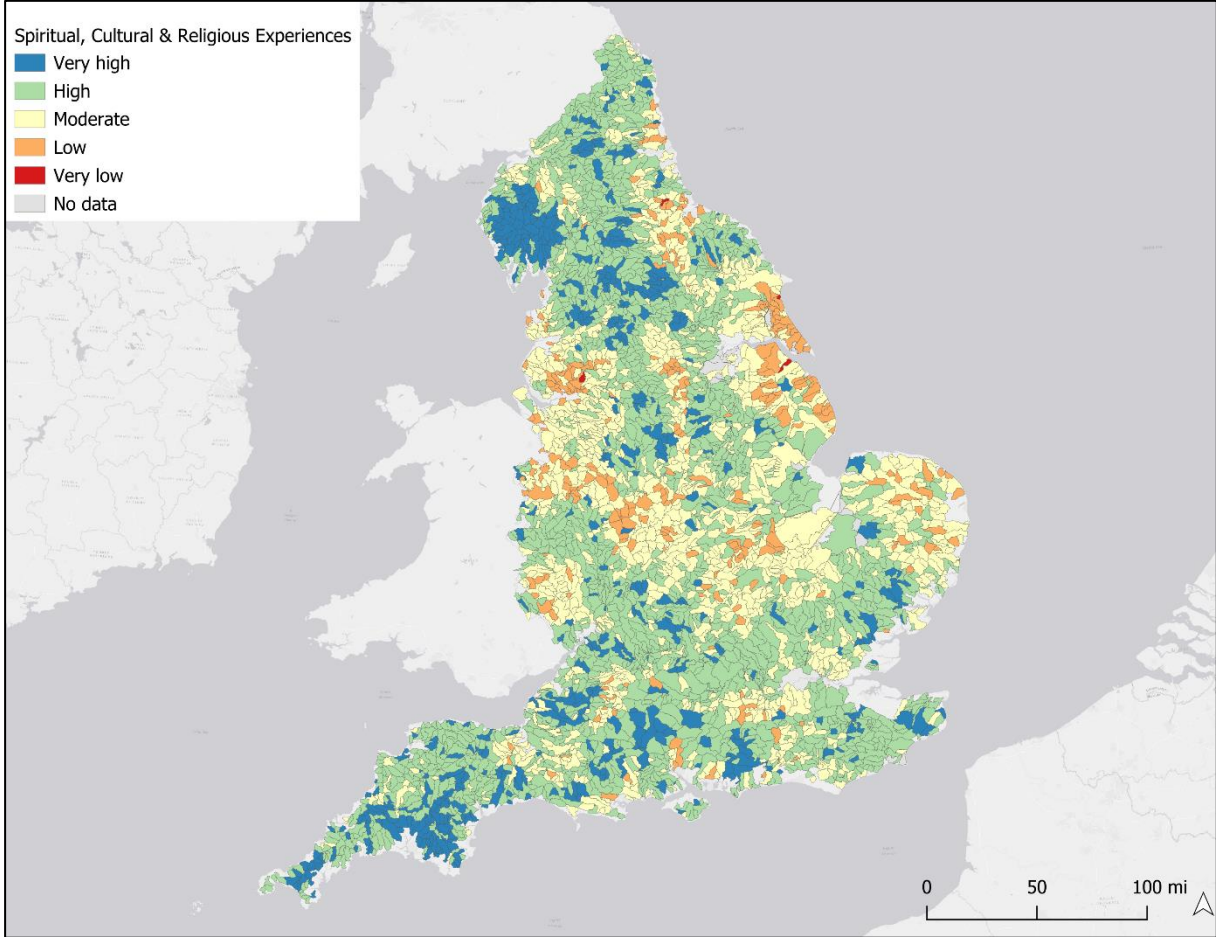


Figure 27: The overall capacity of each river waterbody to deliver the ecosystem service of Spiritual, cultural and religious experiences.

9.1.8 Water flow regulation

Water flow regulation ecosystem service considers the biotic and abiotic features and processes of the ecosystem that regulate both peak flows (flood) and low flows (drought). As such it is relatively difficult to map as a river could be potentially good at mitigating floods but poor in drought conditions, or vice versa, although a number of natural processes can help with both aspects. Results should be interpreted with that in mind. It should also be noted that over-straightened and channelised rivers are technically very effective at moving water away quickly during floods, but as we consider this service in the context of resilient and sustainably managed catchments rather than an individual section, this element is penalised in the decision tree.

Similar to many of the other ecosystem services, the indicators combine site level indicators, such as lateral connectivity (connections between river and floodplain) and vertical connectivity (infiltration of surface water into groundwater), with landscape and catchment scale indicators, such as runoff (based on the mix of habitat types in the catchment) and infiltration (based on geology), and abstraction licencing strategy (indicating water availability). The runoff and infiltration indicator tells us more about the condition of the wider catchment than the river asset itself, but this is important as rivers need to be understood as part of their broader landscape. Water flow regulation is heavily influenced by catchment geology and land use, with very different conditions in, for example, a chalk catchment compared to a clay catchment.

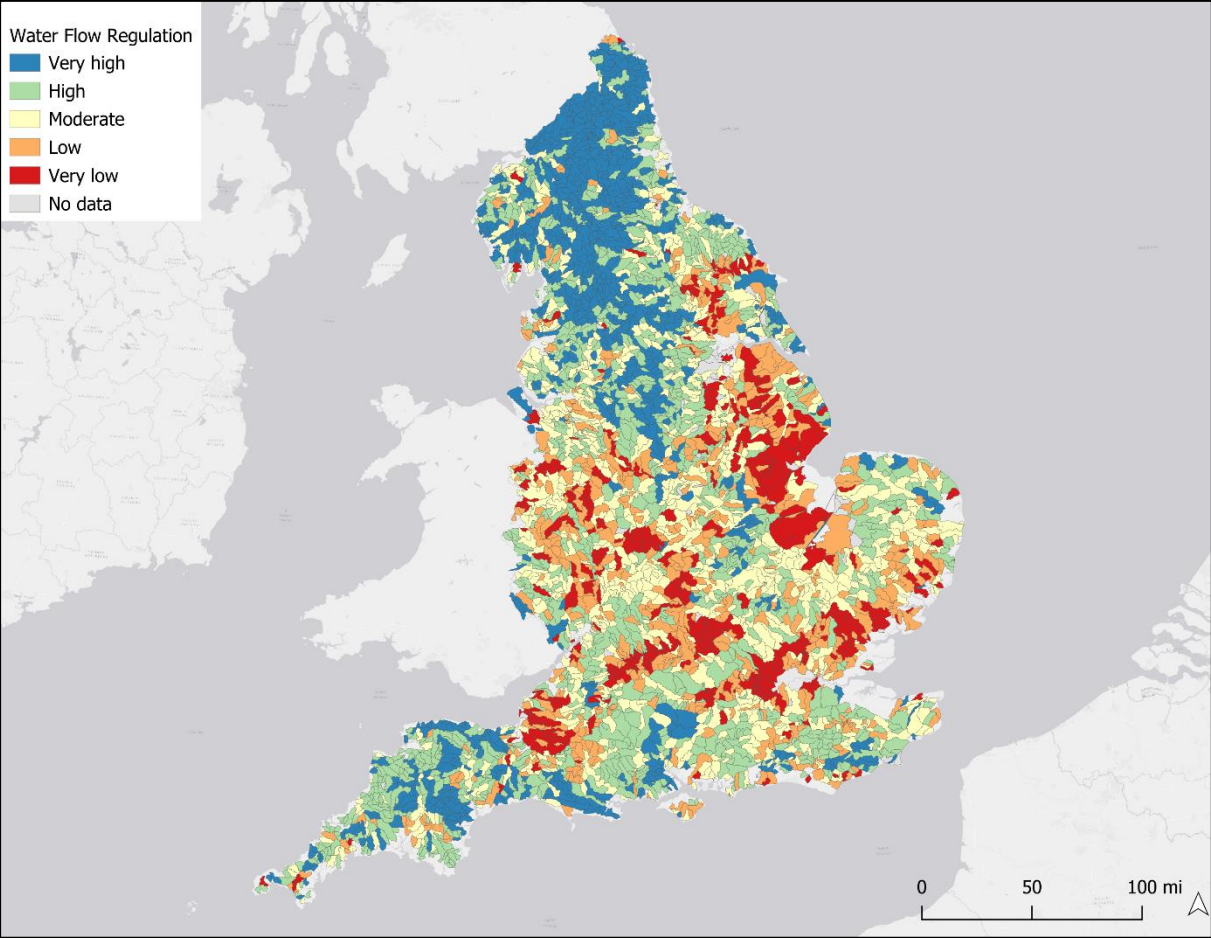


Figure 28: The overall capacity of each river waterbody to deliver the ecosystem service of Water flow regulation.

A number of patterns emerge on the maps. Lateral connectivity is generally lower in the Midlands and the East of England in rivers that are more modified and regulated. On the other hand, vertical connectivity is quite high scoring in the majority of rivers across the country, indicating that bed reinforcement and similar features are not too widespread and much less common than bankside alterations (that impact lateral connectivity). Runoff and infiltration follows the pattern of geology, with chalk and limestone catchments generally performing better (as expected), although a number

of the chalk streams (and many others) show restricted or no water is available for abstraction.

The overall Water flow regulation map (Figure 28) shows that many of the highly regulated rivers (where flow and levels are artificially controlled by man-made structures) in the east have very low capacity, although there are rivers with low or very low capacity in other parts of the country as well. Many of the rivers with very high capacity occur in more upland areas. Chalk streams have the potential to have very high capacity but often perform slightly less well due to land use and abstraction practices that bring the capacity score down by one or two categories.

9.1.9 Water supply

The Water supply ecosystem service considers how important a river is for surface water abstraction. The abstraction amount reflects that importance, but this is considered in the context of the sustainability of abstraction so that a high capacity of this ecosystem service is not conflated with just maximal volume of abstraction.

This was a difficult ecosystem service capacity to map. One of the challenges is that “water supply” is a very broad ecosystem service. Water can be abstracted for a lot of different reasons, and each of those has different data associated with it. For instance, we had a few potentially useful datasets that would work well if the water was being abstracted for drinking (e.g. drinking water safeguard zones), but those same datasets are not applicable if the water was being taken for industrial use (e.g. cooling). Because of that, we had to exclude or adapt several datasets.

The most influential indicator in this service is the surface water abstraction amount. Where more water is abstracted, the score is higher, based on the assumption that abstraction locations in England are already optimised, so if water is being abstracted from a river, it is likely because the river has the capacity to support it (although see section below on the sustainability indicator where this may not be the case). In other words, we are using the flow of the service as a proxy for its capacity. Whilst not perfect, in the absence of other data, this was considered the best approach to use.

The downside of that logic is that abstraction locations are influenced by other factors that don't necessarily reflect river suitability – for example, land ownership, proximity to treatment works, population pressures, or planning constraints. Those factors can skew where abstraction happens, which might in turn distort the ecosystem service scores.

To avoid simply mapping where the biggest rivers or highest populations are, we built in an abstraction sustainability indicator, which reflects how sustainable or resilient abstraction is in the long term. This combines the Abstraction licensing strategy indicator, showing the water available in the catchment as a whole, with Hydrology of Flow Compliance data which shows whether abstraction is having an impact on the river ecosystem.

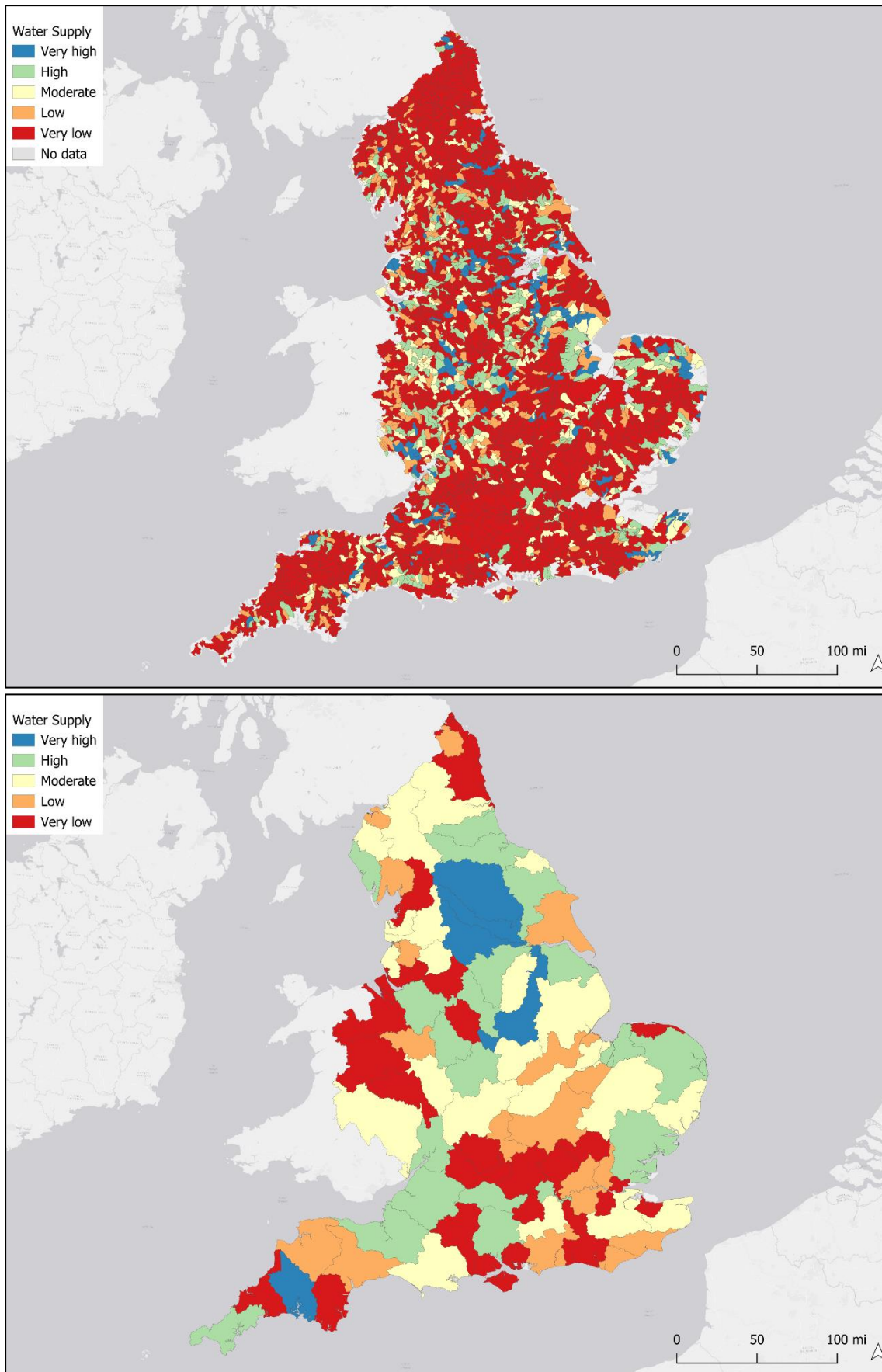


Figure 29: The overall capacity of each river waterbody (top) and management catchment (bottom) to deliver the ecosystem service of Water supply.

Finally, one other nuance – if a river has high abstraction upstream, we might not abstract further downstream simply because the water has already been taken. That means a downstream reach or waterbody could get a lower ecosystem service score, even though it might have just as much potential capacity to provide the service. This should be borne in mind when considering the results at reach and waterbody scale. Note also that surface water abstraction volume is only available at the waterbody scale, so all reaches within a waterbody will receive the same score for this indicator.

Due to the pattern of abstraction just noted, we have calculated the catchment scale indicator of surface water abstraction amount in a different way to the other indicators in ESME. We sum the total abstraction volume across the catchment as a whole, rather than taking a weighted average, as this will provide a more realistic picture at catchment scale. However, this does mean that the pattern of results at this scale look quite different from the results at waterbody scale (Figure 29).

The overall Water supply ecosystem service maps (Figure 29) shows that there are large differences in capacity across the country, with very high capacity in some areas and very low in many others where there is no surface water abstraction (in addition to the differences in neighbouring waterbodies noted above). For example, Water supply capacity is particularly high in many parts of the Humber river basin, but much lower in the Thames, which relies more on groundwater resources. Capacity is reduced in a number of locations as abstraction is not fully sustainable. Note that this ecosystem service is mapping surface water abstraction only and there are a number of catchments that are marked as very low capacity that are very important for water supply through groundwater abstraction. ESME currently focuses on river assets, but ecosystem service capacity from groundwaters could be mapped in a future extension.

9.1.10 Water quality regulation

Water quality regulation considers regulation of the chemical condition of freshwaters by biotic and abiotic processes. It is not about “water quality” itself, as an absolute measure, rather the active process of water purification. It is also challenging because the asset we’re assessing is the river, not the wider catchment. We do include a land use pressure indicator, which is more of an indicator for terrestrial habitats rather than the river, but we are using this as a proxy for pressure on the river, and therefore an indicator of its likely state.

Riparian quality is a key indicator as the riparian area is considered to be a part of the river itself, providing water quality regulation through the trapping and filtration of pollutants. This is a local site-based indicator, along with river shade. Note that a caveat with the use of the river shade indicator is that a river can be over-shaded, which we can’t currently capture, as our model assumes shading is always good for water quality regulation. It also means that areas like the Fens, where there are few riverside trees but there may be plenty of reeds or wetland vegetation, end up being penalised and the method doesn’t currently correct for this.

The overall Water quality regulation map (Figure 30) presents a fairly nuanced picture. Rivers in national parks tend to have high or very high capacity and those in

the East of England tend to have low or very low capacity, but the pattern across other rivers is mixed and there is often wide variation across reaches within the same waterbody or catchment, due to local site level differences.

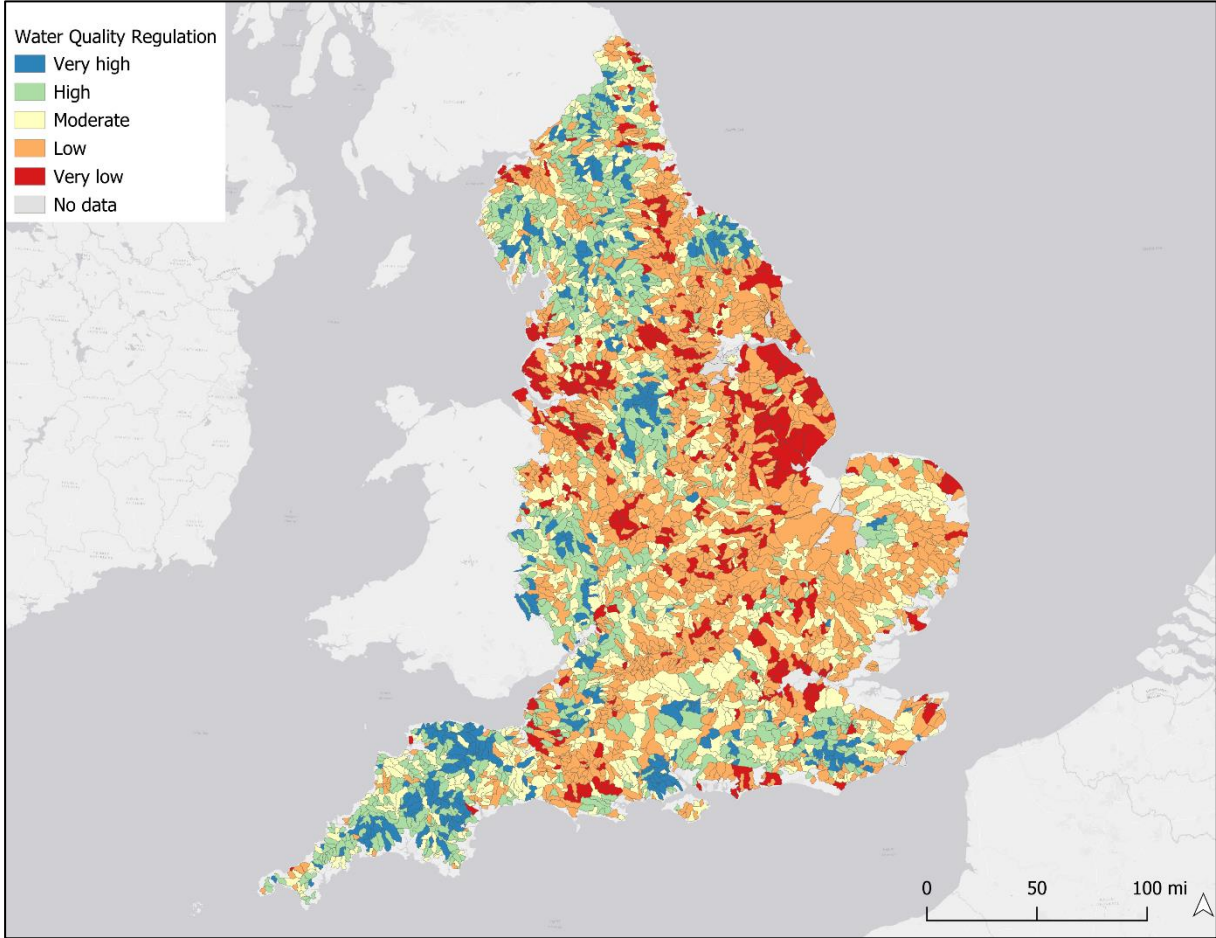


Figure 30: The overall capacity of each river waterbody to deliver the ecosystem service of Water quality regulation.

9.2 How can ecosystem service capacity be improved?

There is interest from users in understanding the sensitivity of the ecosystem service scores to change. In particular, which indicators are driving scores, which should be targeted first to enable the score to improve, and how much change would be required to shift a score into a better category. This can be used to help identify interventions to bring about a change and how to use reporting based on ESME to incentivise the delivery of those actions.

Below we make general comments on key indicators for each ecosystem service and whether changes to them are actionable. It would also be possible to explicitly map the key reason for low scores for each reach, as a future project.

This information would need to be considered in the wider context of the opportunities and constraints in a place; and also whether there are trade-offs between ecosystem services.

9.2.1 Key indicators

The ecosystem service scores are calculated based on decision trees and, due to the nature of decision trees, this means that the most influential indicator for each ecosystem service is placed at the start. That first indicator is used to derive the initial score that is then modified up and down by subsequent indicators. This was expert-derived as being the key indicator for each ecosystem service and was often a local indicator that allowed differentiation of scores for each reach, rather than landscape indicators which do not allow that, and may be less prone to change.

This means that it is relatively straightforward to identify the most influential indicators and therefore the ones that would be best to target to drive an improvement in score. Table 13 shows the most influential indicator for each ecosystem service. In most cases, this is one indicator, but in a few cases, we have listed two, if a second indicator also has a major effect on the scores. We also indicate whether these indicators are realistically actionable by Environment Agency teams or local partners, in other words how easy they would be to change through targeted interventions. More information is provided in the text below.

Table 13: The most influential indicator(s) for each ecosystem service, which will have the greatest effect on the overall score, and whether these indicators are realistically actionable by EA teams or local partners.

H = high (possible to change), M = medium (more difficult, but could be changed), L = low (difficult to change).

Ecosystem service	Most influential indicator(s)	Actionable
Aesthetic and amenity experiences	R1 - River Habitat Quality	H
Water quality regulation	R3 - Riparian Quality Index	H
Habitat and species population maintenance	R1 - River Habitat Quality	H
Physical / mental health and wellbeing	R13 - Recreational hotspots R12 - Local access	M M
Recreation	R13 - Recreational hotspots R12 - Local access	M M
Intrinsic value of nature	R15 - Community Conservation Index	M
Spiritual, cultural and religious experiences	R18 - Heritage features R1 - River Habitat Quality	L H
Education and investigation	R30 - Scientific interest	L

Ecosystem service	Most influential indicator(s)	Actionable
Water supply	R26 - Surface water abstraction amount	L
	R27 Abstraction sustainability	M
Water flow regulation	R5 - Lateral connectivity	H
	R6 - Vertical connectivity	H

In half of the ecosystem services, the key indicator is one derived from the River Habitat Survey and in three cases this is the River Habitat Quality (RHQ_{reach}) index. This captures multiple aspects of a site but is most often driven by habitat modification or engineering pressure such as culverts, bridges, outfalls and deflectors, bank and bed reinforcement, bank and bed re-sectioning, berms and embankments, weirs, dams and sluices. Reaches that undergo a re-naturalisation addressing the aforementioned aspects would significantly improve their condition and is an intervention that is realistically actionable by Environment Agency teams and project partners.

The Riparian Quality Index is most influential for Water quality regulation and can be improved by enhancing the complexity, naturalness and continuity of the riparian zone (the bank and a 5m buffer), so is also something that can be changed.

Water flow regulation is most impacted by the Lateral and Vertical connectivity indicators, which could be enhanced by improving the naturalness of the channel and banksides, particularly if it is possible to remove embankments and channel and bank re-sectioning.

For Recreation and Physical / mental health and wellbeing the key indicators are the Recreational hotspots indicator and the Local access indicator. To drive an increase in these scores, the most effective action would be to try to enhance public access, with bankside access increasing the local access score, but a further increase in score if fishing, boating or swimming were enabled. Changing these aspects is likely to be more difficult, as it may require significant funding, but is still possible, so we have scored these as being medium in terms of ease of delivery.

The service of Spiritual, cultural and religious experiences is most heavily influenced by Heritage features and River Habitat Quality. While it would be very unlikely that new heritage features could be identified, it would be possible to increase the score by enhancing river habitat quality (as outlined above).

The Community Conservation Index has the greatest impact on the Intrinsic value of nature, so improving river habitat condition in general or specific actions to enhance habitat for species of conservation interest would be the best way to enhance the score for this ecosystem service. This would be moderately challenging to deliver, as may involve addressing multiple components that are currently degrading a river.

For Education and investigation, the scientific interest has greatest effect. This score is based on the designation of reaches as priority rivers, priority headwaters, NNRs (National Nature Reserves), SSSIs or chalk streams. Increasing this score would require a range of actions, from increasing the number of designations, a societal

shift to undertake more education and investigation visits, and / or a significant change in river environments driving demand for more investigation, so would be difficult to deliver.

The Water supply ecosystem service is different to the others, as it is largely influenced by the total volume of surface water abstraction, which would increase with increased abstraction. However, it is modified by the Abstraction sustainability indicator, which is derived from flow compliance and abstraction licencing strategy. The most desirable way to increase the score would be to improve the sustainability of abstraction, rather than to increase total volume of abstraction. Hence surface water abstraction amount has been scored as low for ease of action, and sustainability of abstraction has been scored as medium.

9.3 Which scale of mapping should I use?

The indicator and ecosystem service capacity maps are presented at three different scales in ESME – reaches, WFD water bodies and WFD management catchments. Each scale has advantages, disadvantages and caveats, which are described below.

9.3.1 River reach scale

In total 20 of the 29 unique indicators used in ESME were developed at the reach scale (finest scale), hence this is the base unit of mapping upon which the results at other scales are presented. In some way this means that this is the best and most accurate scale to use, based on the available data, and also presents the most detailed results. However, there are some caveats.

A number of datasets are only available at waterbody scale, which means that the eight indicators derived from these datasets can only be built at waterbody scale. This includes those derived from WFD data such as R11 Water quality, R19 Water quality including specific metal pollutants, R21 Hydrological condition and R25 Naturalness of the flow regime; those based on abstraction data such as R26 Surface water abstraction amount and R28 Abstraction licencing strategy; and landscape measures mapped to waterbody catchments such as R9 Land use pressure and R24 Runoff and Infiltration.

There is also one indicator (R20 sense of place / history) that covers wider landscape areas (Landscape Character Areas) which may cover several waterbodies. There are also a few datasets at other spatial scales that are used within indicators, such as people accessing rivers (D56a, Local Authority scale), which is used within R12 Local access, meaning that there will not be reach scale variation across the indicator for that aspect, although the indicator as a whole is mapped at reach scale.

Where these 9 indicators have been developed at broader spatial scales, all reaches within the waterbody are given the same score. This means that using them at reach scale in these circumstances may give a false sense of accuracy and should be treated with caution if used as individual indicators at this scale.

This issue is reduced when considering the overall ecosystem services scores. In all cases, apart from Water supply, the most influential indicator that is driving the score is one that can be differentiated at reach level and generally those that have a strong effect on the score are also reach scale indicators. Waterbody scale indicators have usually been used to modify scores by only one point and are seen as providing useful landscape context.

Another point to bear in mind when using reach scale outputs is that data was not available for all reaches for all indicators. In some cases, we have extrapolated results for a reach either by applying the average score from the upstream and downstream reaches or the average across the whole waterbody. These reaches are marked with an asterisk within ESME for transparency. In cases where extrapolation was not possible, or desirable, the reach is marked as “no data”.

Results at reach scale can also be spuriously variable in some cases, for example R15 Community Conservation Index, where there can be big changes in score across neighbouring reaches, simply due to sampling variability.

A further important consideration is the scale over which an ecosystem service operates, or the importance of spatial configuration in predicting ecosystem service capacity. This is described in Section 9.4 (below). It highlights that spatial considerations are highly important for many of the cultural services and for Habitat and species population maintenance but are generally less important for the other regulating and provisioning services. For ecosystem services like Aesthetic and amenity experiences, Recreation, and Physical / mental health and wellbeing, there can be dramatic shifts in ecosystem service capacity over short distances. In this context, examining results at the reach scale is far more informative than at broader scales.

9.3.2 WFD waterbody scale

The waterbody scale is the middle scale used in ESME. An advantage is that all indicators except for one (R20 Sense of place / history) have been developed at waterbody or finer scale, hence the mapping output matches the scale at which the input data is available. It also means that even if there is data missing at reach scale, it is almost certain that there will be data available at waterbody scale, hence the results may be more complete.

Waterbody scale also matches the scale at which the Environment Agency usually presents results, for example for WFD reporting. It is therefore a scale that is familiar and can be used to compare with other outputs and is compatible with the Catchment Data Explorer tool.

On the other hand, for 20 of the 29 unique indicators, results at waterbody scale have simply been averaged from the results at reach scale. This means that the waterbody results are more likely to obscure high or low results that are different from other results from the waterbody and actual range will inevitably be obscured. This may mean that an important location for an ecosystem service (or a reach that is performing particularly poorly) is overlooked. On the other hand, this can also reduce

spurious variation which can be useful, such as in the example of R15 Community Conservation Index, where there are big changes in score across neighbouring reaches, simply due to sampling variability. In general, the results at waterbody scale do tend to show good variation across the full range of scores.

R2 Litter index, R16 Iconic species and R17 Invasive non-native species present particular issues when mapping results at waterbody scale. In all cases, data were sparse and were presented on a 3-point nominal scale (no / little / lots for R2, and no / one / two or more for R16 and R17), so we could not simply present weighted averages from the reach scale data. We had to apply arbitrary thresholds and the results at waterbody scale are not as meaningful or intuitive as at reach scale.

Finally, the scale over which an ecosystem service operates is again important (Section 9.4). Many of the cultural ecosystem services would benefit from assessment at fine scale (reach), but some such as the Intrinsic value of nature, and Education and Investigation, together with the regulating services, such as Water quality regulation and Water flow regulation, and provisioning services like Water supply, operate over broader scales and so may benefit from assessment at waterbody scale, especially as a number of the datasets used for these services are provided at this scale.

9.3.3 WFD management catchment scale

The broadest scale used within ESME is the WFD management catchment scale. These can cover large areas (typically 1,000-4,000 km²), often incorporating more than one river catchment. The main use of this scale is for broader scale reporting and to highlight regional trends. This can match reporting scales in other business areas of the Environment Agency, such as for River Basin Management Plans.

The disadvantages stated for the waterbody scale apply again only to a much greater extent. In almost all cases the scores at this scale are simply an average of the finer scale results meaning that a lot of variation is lost. This is apparent in the results, where most management catchments achieve middle scores within the range and very low and very high scores are rare.

The points above are illustrated in Figure 31, which shows the overall national result for Aesthetic and amenity experiences at the three different scales. At the reach scale there is a broad spread of data, with the most common class being “low” which occurs in 34% of reaches, but there are also 6% of reaches with no data. At the waterbody scale the spread of data is broadly similar, although slightly more constricted, with 42% of waterbodies in the largest “low” category, and slightly less in the “very high” category, but there are now very few showing no data (0.4%). At the management catchment scale, the reduction in range is much more pronounced, as there are now very few scoring “very high” or “very low”, with 44% now in the most common category (low) and a large number now also in the “moderate” category (41%).

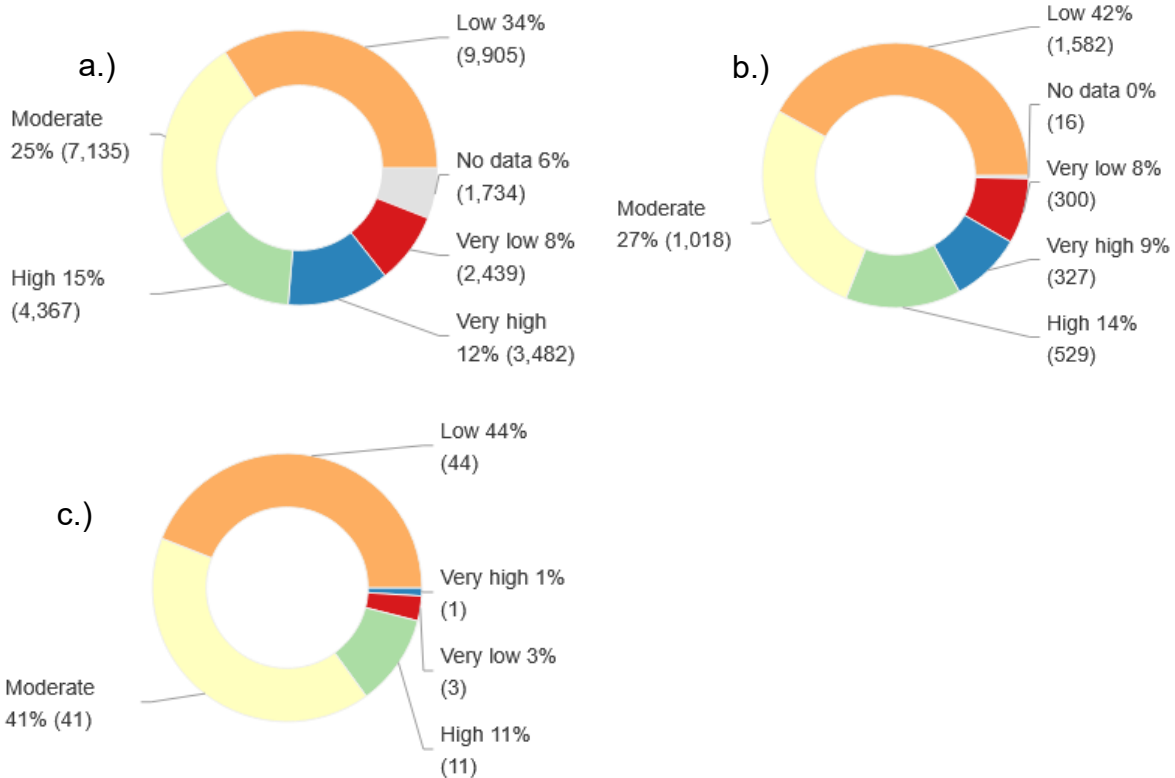


Figure 31: National results for Aesthetic and amenity experiences ecosystem service at the three different scales, showing a.) reaches, b.) waterbodies, and c.) management catchments.

As for waterbodies, R2 Litter index, R16 Iconic species and R17 Invasive non-native species are difficult to scale up to management catchment scale (see the Methodology document for details), so the results become somewhat arbitrary.

R26 Surface water abstraction volume is the only other indicator that is not scaled up by taking a weighted average but instead uses the cumulative total across the whole catchment. This may give more meaningful results for this indicator, where the amount of water abstracted within a catchment is more important than where it was abstracted from, although it will not match the pattern of results at other scales.

When considering the scale over which an ecosystem service operates, it is clear that most should not be assessed at such a broad scale. One exception is Water supply, as mentioned above, where abstraction over a catchment does provide some useful information (alongside the information provided at waterbody scale). However, it is not helpful that management catchments sometimes include multiple individual river catchments, as discrete catchments cannot always be assessed independently. With the exception of R20 Sense of place / history, indicators and ecosystem services are not assessed at management catchment scale, but rather at reach and sometimes waterbody scale. Hence, the outputs at management catchment scale are not a single assessment at the broad scale but an average of ecosystem service capacity across the catchment.

9.3.4 Conclusion

ESME is best used at reach and waterbody scales, with the best scales for each ecosystem service indicated in Table 15 and summarised below:

- **Reach scale** provides the most detailed results and is best for assessing many of the cultural services, especially, Aesthetic and amenity experiences, Recreation, and Physical / mental health and wellbeing. But it should be noted that not all datasets and indicators could be assessed at that level of detail so there may be a false sense of accuracy, or missing data in some cases, especially for the regulating services, and spurious levels of variation in some indicators that are recorded at reach scale.
- **Waterbody scale** provides a good compromise between providing enough detail to make the results useful and not giving a false sense of accuracy. The results are broadly similar to those reported at reach scale, but with some of the potentially spurious variation removed. It is a particularly good scale for assessing the results of the regulating services and some of the cultural services such as Intrinsic value of nature, and Education and investigation. It also matches the scale of other reporting published by the Environment Agency, such as for WFD.
- **Management catchment scale** is considered much less useful operationally as most results are broad averages, removing much of the variation and nuance in the outputs. But user feedback indicates it may be useful for strategic reporting, comparing broad patterns across regions, and it provides some additional useful information for Water supply.

9.4 The importance of spatial configuration for different ecosystem services

In this section we consider the impact of spatial configuration in ecosystem service capacity, linking with consideration of scale reported in Section 9.3. We also consider if any potential improvements could be made to the indicators used in ESME.

In Table 14, we have listed the importance of spatial considerations for each ecosystem service, the spatial resolution of the indicators and data currently used, and the potential to make improvements to the spatial aspects of the indicators.

In general, spatial considerations are more important for cultural services than for regulating or provisioning services. In particular, spatial considerations were considered to be highly important for Aesthetic and amenity experiences, Physical / mental health and wellbeing, and Recreation. For these ecosystem services, the provision of the service can vary considerably across small distances as they are heavily dependent on access and local conditions, hence it is important that the data used in indicators is also spatially precise.

Many of the data and indicators used in ESME for these ecosystem services are spatially accurate, but there are improvements that could be made, such as for the tranquillity indicator (to improve resolution).

Table 14: The importance of spatial considerations, the spatial resolution of the indicators and data currently used, and potential improvements, shown for each ecosystem service.

<p>Aesthetic and amenity experiences</p>	<p><u>Importance of spatial considerations:</u> High</p> <p><u>Spatial resolution of indicators / data:</u> R1 River Habitat Quality and R2 Litter index are based on high resolution data, but R7 Tranquillity and R8 Natural beauty are less spatially accurate.</p> <p><u>Potential improvements:</u> Tranquillity and natural beauty can vary over short distances, for example, a tranquil stretch on an urban river in an otherwise untranquil area. This could be addressed by developing a more spatially resolved indicator of tranquillity that could capture these fine scale variations.</p>
<p>Water quality regulation</p>	<p><u>Importance of spatial considerations:</u> Medium</p> <p><u>Spatial resolution of indicators / data:</u> R3 Riparian quality index and R10 River shade are based on high resolution data, but the R11 Water quality indicator and R9 Land use risk indicator are at lower resolution.</p> <p><u>Potential improvements:</u> Land use risk is currently captured at waterbody scale but could be captured for the sub-catchment for each reach. Water quality regulation will be influenced by a mixture of point sources of pollution, river corridor pressures and wider catchment processes. There is potential to capture some of these (especially point source and corridor factors) at higher resolution.</p>
<p>Habitat and species population maintenance</p>	<p><u>Importance of spatial considerations:</u> High-medium</p> <p><u>Spatial resolution of indicators / data:</u> The R1 River Habitat Quality and R4 Connectivity indicators are at high resolution, but the R19 Water quality including metals and R21 Hydrological condition indicators are at lower resolution (waterbody scale). The longitudinal connectivity sub-indicator (part of R4) is based on a simple count of river obstacles within a reach.</p> <p><u>Potential improvements:</u> The longitudinal connectivity indicator could be improved as it only considers the number of barriers, with no consideration of their size or impact, which can lead to significant spatial variation.</p>
<p>Physical / mental health and wellbeing</p>	<p><u>Importance of spatial considerations:</u> High</p> <p><u>Spatial resolution of indicators / data:</u> R14 Recreational hotspots, R12 Local access and R13 Health deprivation by access indicators are based on high resolution data, but the R11 Water quality and R7 Tranquillity indicators have only moderate resolution.</p>

	<p><u>Potential improvements:</u> Tranquillity data could be improved, to be more spatially detailed to pick up more spatial variation and nuance. It is also old (2007), so updating will improve spatial accuracy caused by land use change.</p>
Recreation	<p><u>Importance of spatial considerations:</u> High</p> <p><u>Spatial resolution of indicators / data:</u> Similar to above, R14 Recreational hotspots and R12 Local access are captured at high resolution, but R11 Water quality indicator and R8 Natural beauty are at lower spatial resolution.</p> <p><u>Potential improvements:</u> Limited, although improvements to underlying datasets could always be made.</p>
Intrinsic value of nature	<p><u>Importance of spatial considerations:</u> Medium</p> <p><u>Spatial resolution of indicators / data:</u> R15 Community Conservation Index, R16 Iconic species, R17 Invasive non-native species (INNS) and R3 Riparian quality are captured at quite high resolution, however, the completeness and quality of R16 and R17 is not very good. R30 Scientific interest is captured at moderate resolution.</p> <p><u>Potential improvements:</u> The accuracy of the R16 Iconic species and R17 INNS indicators would be improved considerably by including data from other sources (e.g. Nature Biodiversity Network licenced data, Local Records Centres), which would ultimately improve the spatial accuracy of the results.</p>
Spiritual, cultural and religious experiences	<p><u>Importance of spatial considerations:</u> High-medium</p> <p><u>Spatial resolution of indicators / data:</u> The R18 heritage features, R1 River Habitat Quality and R12 Local access indicators are high resolution indicators, whereas R7 Tranquillity is medium resolution, and the R20 Sense of place / history indicator is low resolution.</p> <p><u>Potential improvements:</u> As previously, it would be possible to improve the tranquillity indicator by creating a new version at higher resolution, which would also better represent current land-uses. The sense of place / history indicator would be hard to improve in its current form, which is based on national character areas, but it may be possible to create an equivalent indicator using different data in conjunction with heritage experts.</p>
Education and investigation	<p><u>Importance of spatial considerations:</u> Medium</p> <p><u>Spatial resolution of indicators / data:</u> The R22 Monitoring stations and R23 Pupil access indicators are high resolution (although the latter makes a major assumption about educational use and uses national average distances, so is not considered accurate). R30 Scientific interest is at moderately high resolution.</p> <p><u>Potential improvements:</u> There is a severe lack of data on the use of rivers for educational purposes, so this is an area that</p>

	could be enhanced in the future if new data were to be collected.
Water supply	<p><u>Importance of spatial considerations:</u> Low</p> <p><u>Spatial resolution of indicators / data:</u> R26 Surface water abstraction amount is reported at waterbody scale, so at medium resolution. The abstraction licensing strategy sub-indicator reports at the whole catchment scale, but this is modified by the flow compliance sub-indicator at higher resolution, so overall R27 Abstraction sustainability is medium resolution as well.</p> <p><u>Potential improvements:</u> No major improvements in resolution are required. Additional data could be added by water companies.</p>
Water flow regulation	<p><u>Importance of spatial considerations:</u> Medium-low</p> <p><u>Spatial resolution of indicators / data:</u> The R5 Lateral and R6 Vertical connectivity indicators are based on high resolution data, whereas R25 Naturalness of flow regime and the R24 Runoff and infiltration indicator are based on medium resolution (waterbody scale) data. R28 Abstraction licencing strategy is fairly low resolution.</p> <p><u>Potential improvements:</u> Similarly to Water quality regulation, the Runoff and infiltration indicator could be captured for the sub-catchment for each reach, but as the ecosystem service is inherently influenced by wider catchment processes, this may not be worthwhile.</p>

Spatial considerations are judged to be of moderate to high importance for Habitat and species population maintenance and Spiritual, cultural and religious experiences, and again the datasets and indicators have high spatial resolution, but some suggestions for improvements are shown in Table 14. Intrinsic value of nature, and Education and investigation are both assessed as medium for the importance of spatial considerations, although the assessment of both of these ecosystem services could be improved with additional data.

Spatial considerations are thought to be of less importance for Water quality regulation, Water flow regulation, and particularly for Water supply, as these are all heavily influenced by wider catchment processes. There are ways that data could be developed at higher resolution, but the improvements may not be necessary given the reduced importance of such detailed spatial aspects.

9.5 Linking with benefits and values

The ESME tool maps the first part of the natural capital logic chain shown in Figure 3: the link between natural capital asset condition and the provision of ecosystem services. These ecosystem services provide benefits for people and these benefits have value, as is shown in the remainder of the logic chain. In addition, ecosystem

service delivery and the benefits and value that they provide, is influenced by demand, which can be determined in part through an understanding of the beneficiaries who would receive the benefits provided. Opportunities can also be objectively identified, where natural assets (or the condition of natural assets) can be enhanced to greatest effect to deliver increased benefits to people.

The potential **benefits** provided by ecosystem services to people, society, organisations and business are included as high level supporting narrative in ESME and expanded upon in Annex 2 of the ESME Application and Limitations guidance document. In addition, there is the potential to add further case studies into the tool that describe these aspects (e.g. benefits, values, beneficiaries and opportunities), especially where the links between them had been established and quantified.

The mapping of ecosystem services and indicators cannot be linked directly to **monetary value** as most of the indicators used could not be valued directly. Methods for monetary valuation are much more limited and are poorly developed for riverine systems. For place-based valuation of benefits, the Environment Agency has developed the [Natural Capital Register and Account Tool](#) (NCRAT). Unfortunately, it is not possible to embed the NCRAT functionality into ESME to directly provide values. NCRAT is focused primarily on terrestrial habitats rather than rivers, some of the data used in NCRAT requires input from local users, it does not provide values for all of the ecosystem services included in ESME, and where there is overlap (e.g. Recreation, Physical health, Education, Water supply, and Water quality) values have been calculated based on different factors, meaning that results may follow different patterns compared to the mapped ecosystem service scores, which may well lead to confusion. For all these reasons, NCRAT and ESME have been kept separate, but linking the respective evidence bases in the future could be considered.

National **opportunity mapping** does already exist for certain aspects, such as for natural flood management and working with natural processes. It would be possible to either link to these or potentially add directly into ESME. It may be possible to identify other opportunity mapping that would also be directly compatible, and this could be investigated further.

To learn more about the Environment Agency's work on natural capital benefits and valuation please contact NaturalCapital@environment-agency.gov.uk.

10. Conclusions and recommendations

The project has created ESME (the Ecosystem Service Map Explorer) which is a mapping tool that estimates the relative capacity of a river to deliver 10 different ecosystem services, based on the underlying condition of the river and its wider catchment. The project to develop ESME has:

- Carried out an extensive literature review and developed conceptual frameworks (flow diagrams) for each ecosystem service that explored the link between asset condition and ecosystem service capacity, and the components that influence each ecosystem service in turn.
- Developed a scientifically rigorous approach to river segmentation by maximising use of similarities in hydromorphological conditions within river reaches (stretches) to create lengths that are more useful for the mapping of condition and ecosystem services.
- Developed a series of indicators based on the literature review and flow diagrams and using best available open data or data licenced for open use. Many of these indicators have been specially developed or enhanced for this project.
- Developed a much-improved approach (compared to the prototype) to combining indicators into ecosystem service scores, using a decision tree approach, which is considered more accurate than simply averaging across indicators, but is also transparent.
- Created a new mapping tool (ESME), which includes much enhanced functionality in a more visually compelling and user-friendly structure, compared to the original prototype. The tool uses mostly open data, alongside some data under licence, to derive open outputs that are being published openly and can be shared with partners.
- Mapped ten ecosystem services with national coverage, at three different scales: river reach, WFD waterbody, and WFD management catchment.
- Worked collaboratively throughout, with the Environment Agency project team and with a wide range of Environment Agency and external experts, to ensure that the approaches and mapping tool are co-designed, expert driven, transparent, and meet user needs. User testing and feedback has been integrated throughout.
- Presented extensive additional resources, including extensive guidance within ESME itself, a stand-alone user guide, case studies on potential uses, a document outlining applications and limitations, a detailed methodology document, and a database of datasets and indicators used.

This is the first tool of its kind available openly in the UK that links asset condition to ecosystem service capacity. It brings together a broad range of ecosystem services,

including regulating, provisioning and cultural services, it focuses on the riverine environment, and it allows mapping at a range of scales, including down to detailed river reaches. It assesses multiple aspects of the condition of natural capital assets to determine the provision of each ecosystem service, with a detailed conceptual framework underpinning each assessment.

10.1 Level of confidence in the outputs

Table 15 reports the overall confidence in and limitations / caveats of the predicted ecosystem services that have been mapped, using a RAG rating:

- red identifies services that had little to no data available for mapping and were therefore left out (no confidence).
- amber indicates services that require more indicators because some aspects of condition have not been mapped (low confidence).
- yellow is for those services that have been predicted using the appropriate condition indicators, but the indicators would benefit from improvement, or it would be difficult to improve these models further, but some uncertainties or gaps remain (moderate confidence).
- green identifies those services which have been mapped using the best open data available to map the service and most aspects of condition have been captured (high confidence).

Note that there are no red or amber boxes in the table below, although earlier iterations of (and this table) did include these colours.

All ecosystem services are now assessed to be yellow or green, indicating that we have at least moderate confidence in all the ecosystem service outputs. The main change in RAG rating compared to earlier phases of the project is for Water quality regulation, Water flow regulation, and Water supply, which have all moved from amber to yellow. These were the ones in which we had least confidence previously, so we have focused on improving these, which has been achieved through consultation with subject experts at the Environment Agency and the identification of additional indicators. Recreation has also improved from yellow to green as we had previously identified a number of issues with some of the indicators when mapping at a national scale, particularly around identifying accessible watersides correctly and in the completeness of the recreational hotspots indicator. This has now been rectified, with the incorporation of new datasets and new analyses for both the recreational hotspots and local access indicators. The main reasons for the other ecosystem services achieving yellow rather than green status is summarised in the Limitations and caveats column in Table 15.

In later phases of the project, we have materially increased confidence in all the ecosystem services, due to the use of more appropriate reaches and a more scientifically accurate way of combining indicators into the final ecosystem service score, although these improvements are not captured in the RAG ratings.

Table 15 also indicates the scale considered the best for examining the outputs, summarising the information presented in Sections 9.3 and 9.4. Reach scale is considered to be the best scale for Habitat and species population maintenance, Physical / mental health and wellbeing, and Recreation, and equally good for Aesthetic and amenity experiences, and Spiritual, cultural and religious experiences. Waterbody scale is considered to be best for Education and investigation, Intrinsic value of nature, Water flow regulation, and Water quality regulation, and equally good for Aesthetic and amenity experiences, Spiritual, cultural and religious experiences, and Water supply. Management catchment is only considered to be equally suitable for Water supply, and otherwise provides only a very broadscale picture of ecosystem service capacity (which has limitations)

Table 15: RAG rating showing overall confidence in the outputs for each ecosystem service mapped in ESME, the scale considered best for examining the outputs, and notes on limitations and caveats. The confidence of ecosystem service scores varies according to availability and/or certainty of the data covering aspects of condition. This is derived using expert judgement. Red = no confidence; Amber = low confidence; Yellow = moderate confidence; Green = high confidence. Best scale: R = reach, W = WFD waterbody, C = WFD management catchment, () = suitable scale but may not be optimum.

Overall confidence	Best scale	Limitations and caveats
Aesthetic and amenity Experiences	R, W	Does not pick up very fine scale changes in tranquillity and this dataset is old (2007). Does not consider impact on house prices
Education and investigation	W	No comprehensive data available on school / educational visits to watersides.
Intrinsic value of nature	(R), W	High confidence in decision tree and key factors, but data on iconic species and INNS is severely limited due to licencing restrictions on relevant data.
Habitat and species population maintenance	R, (W)	Decision tree constructed in a different way. Unlike other ecosystem services, final map is closer to an absolute score, rather than a relative score of ecosystem service capacity.
Physical / mental health and wellbeing	R, (W)	Data on local swimming spots and continuous discharges could be further improved. Does not pick up very fine scale changes in tranquillity and this dataset is old (2007).
Recreation	R, (W)	Considered to work well. Data on local swimming spots and continuous discharges could be further improved. This map does not necessarily indicate that the river is suitable for immersive watersports.

Overall confidence	Best scale	Limitations and caveats
Spiritual, cultural and religious experiences	R, W	<p>Some identified heritage features are not directly relevant to the river.</p> <p>Sense of place / history is very broad scale and may have nothing to do with the river.</p> <p>Difficult to capture all aspects of this ecosystem service.</p>
Water flow regulation	W	<p>Considers how natural processes of rivers regulate both peak flows (flood) and low flows (drought) so difficult to map the ecosystem service.</p> <p>This map is not suitable for assessing flood or drought risk.</p> <p>Data/proxies for baseflow contribution (groundwater input) could be further improved.</p> <p>This ecosystem service should not be conflated with regulation of flows and levels by man-made structures.</p>
Water quality regulation	W	<p>Concerned with the regulation of water quality, not water quality itself.</p> <p>Difficult to map as data on the former is lacking and we have to rely on proxy indicators.</p> <p>This ecosystem service should not be conflated with regulation of water quality by permitting.</p>
Water supply (drinking/ agriculture/ industry)	W, C	<p>Does not consider groundwater abstraction.</p> <p>Abstraction in one waterbody likely to be influenced by upstream abstractions and water level management.</p> <p>This map is not suitable to support water abstraction permit applications.</p>

10.2 Limitations and caveats

The tool is released as a Beta version innovation product, so we would welcome all feedback. Feedback can be sent to NaturalCapital@environment-agency.gov.uk. It has been through a considerable period of development and review, but there are still limitations to be aware of. General limitations and caveats are listed here, along with key ones for each ecosystem service. A more comprehensive list of limitations is provided in the document *ESME Applications and limitations*.

- This is a desk-based mapping tool based partially on national scale open datasets, so spatial accuracy is not always high or coverage comprehensive for all indicators. While ESME can inform decision making across a range of uses, **decisions ultimately need to be considered alongside data and evidence collected on the ground and local knowledge.**
- In several indicators, quintiles have been used to determine the range of condition scores, which provide relative scores across England, meaning that a proportion of sites will always score well or badly. It was not possible to assign absolute scores for many indicators, although some indicators are based on absolute scores. The tool therefore uses a mix of scoring approaches. Overall, it should be seen more as providing **relative ecosystem service scores.**
- Linked to the above, when the tool is updated in the future to show changes over time, it is important that the same breakpoints identified now are used in the future, rather than generating new quintiles. This will enable change to be shown compared to the 2025 baseline, with the baseline being established as the scores in the current version.
- The indicators are not all strictly “condition” or “capacity” indicators, with some indicators of demand, flow, ecological pressure, and vulnerability, but **in all cases used as a proxy of condition and ecosystem service capacity.**
- The indicators used within ESME were developed at the finest spatial scale suitable for each dataset, which was nearly always either reach or waterbody scale. These were then extrapolated or averaged to other scales. This means that in some cases reach scale values are the same across a waterbody. It also means that management catchment scale results are almost always simply an average (normally a weighted average) of results at finer scales so will be more likely to present intermediate values.
- The WFD data used in ESME dates from the period 2013-2019 (forming the statutory basis of Cycle 3 River Basin Management Plans), so it is important to bear in mind that there may have been changes since that time. More recent comprehensive classification data for the Cycle 4 River Basin Management Plans, expected to be released in phases over 2026 and 2027, is not yet available (see Section 10.2 below). A number of datasets used in ESME are more recent (and tranquillity dates from 2007), so there may be a slight temporal mismatch.
- Although the focus is on ecosystem service capacity based on the condition of natural capital assets, it is inevitable that there is some interdependency with built assets, especially around public access, which is a requirement to deliver some of the cultural services. It is not possible, or desirable, to disentangle the capacity of ecosystem services delivered by these different types of asset.
- The mapping of ecosystem services and indicators cannot be linked directly to monetary value as most of the indicators used could not be valued directly. Methods for monetary valuation are much more limited and are poorly

developed for riverine systems, although a separate tool (NCRAT) is available (see Section 9.5).

- Specific data for artificial rivers was unavailable. We were unable to secure expert canal knowledge and evidence. Therefore, **artificial watercourses / waterbodies are not currently included in the tool**, although could be included in the future.
- Although Defra colleagues were consulted as part of the project's expert panel their opinions do not represent Defra official stance.

Limitations and caveats for each specific ecosystem service are listed below:

- The **Aesthetic and amenity experiences** ecosystem service captures broad scale patterns but cannot pick up fine scale difference, such as a tranquil or attractive stretch of river in an otherwise heavily industrialised or urbanised area. It also does not consider the impact of rivers on property prices. There may be overriding contextual factors that might impact significantly the realisation of this ecosystem service (as opposed to the potential ecosystem service). For example, there may be limitations to visibility of the location, planning restrictions on property development or business activities, localised antisocial behaviour etc., which aren't being captured by our indicators.
- For **Education and investigation**, there are no comprehensive data available on school / educational visits to watersides.
- **Habitat and species population maintenance** does not capture historical/heritage landscape features (where there may be relic, protected, heritage infrastructure that supports wildlife and provides unique habitat such as old millstreams and redundant wharf backwaters), or artificially created waterways that provide a unique habitat and support species, such as overwintering migrant birds. These features, on the contrary, would potentially score low on naturalness, connectivity, hydromorphological pressures, etc.
- The **Intrinsic value of nature** ecosystem service is missing an important element of the social context that leads to people having an attachment to a place beyond the ecological framing of the presence/absence of particular species. Furthermore, some data from the National Biodiversity Network Atlas is open under the Open Government Licence (OGL), but much is not. We have only used OGL data to maintain openness of the outputs, but this does mean that the data that we are able to show is partial.
- For the **Recreation** ecosystem service, a caveat that needs to be considered for the realisation of, as opposed to the capacity for this ecosystem service, is that the majority of visits will be bankside (next to the water), rather than in or on the water. It is important to remember this only applies to publicly accessible rivers (i.e. statutory navigations) and the majority of rivers in England are not statutory navigations which means the 'in' and 'on the water' activities are severely restricted by the riparian owner (e.g. bankside Public

Rights of Ways are much reduced). In this tool we also ignore the seasonality to recreation that is more pronounced for the 'on' and 'in the water' categories and that there are often de facto closures at certain times of the year. Data on local swimming spots and continuous discharges could be further improved. The Recreation ecosystem service map shows the potential for the provision of this ecosystem service and does not necessarily indicate that the river is suitable for immersive watersports. For advice on swimming in rivers, lakes or coastal waters, please see this guidance on how to swim healthy: www.gov.uk/government/publications/swim-healthy-leaflet.

- The **Physical/mental health and wellbeing** ecosystem service does not pick up very fine scale changes in tranquillity. It could also benefit from improved data on local swimming spots and continuous discharges. The most potentially confusing indicator within it is health deprivation by access. This is a culturally specific indicator, as it reflects the increased value that the service provides depending on the people it benefits. Hence the highest scoring areas are those where there is high deprivation but also access to a river as these populations will most benefit from that service.
- The **Spiritual, cultural and religious experiences** mapping does not consider the full range of spiritual/cultural/religious experiences facilitated by rivers. It would be very difficult to capture all the reasons why a place has particular spiritual or religious meaning or value.
- The **Water quality regulation** service is affected by fine scale anthropogenic factors significantly influencing this service which aren't being captured here. However, this is not considered a major limitation as we are assessing water quality regulation not water quality itself. This makes it quite difficult to map as data on the natural regulation of water quality is lacking and we have to rely on proxy indicators. This ecosystem service should not be conflated with regulation of water quality by permitting.
- The **Water supply** ecosystem service does not currently consider groundwater abstraction (as we have initially focused on the ecosystem service capacity of rivers). It is also noted that abstraction in one waterbody is likely to be influenced by upstream abstractions and water level management. For this reason, we have calculated the catchment scale indicator of surface water abstraction amount in a different way to the other indicators in ESME. We sum the total abstraction volume across the catchment as a whole, rather than taking a weighted average, as this will provide a more realistic picture at catchment scale. However, this does mean that the pattern of results at this scale looks quite different from the results at waterbody scale. Note that the Water supply ecosystem service map is not suitable to support water abstraction permit applications. The relevant [abstraction licensing strategy documents](#) available on GOV.UK give more detail on how the Environment Agency manages abstraction within each catchment.

- The **Water flow regulation** ecosystem service considers how natural processes of rivers regulate both peak flows (flood) and low flows (drought) and as such it is relatively difficult to map as a river could be potentially good at mitigating floods but poor in drought conditions, or vice versa, although a number of natural processes can help with both aspects. Results should, however, be interpreted with that in mind. Data/proxies for baseflow contribution (groundwater input) could be further improved. This ecosystem service should not be conflated with regulation of flows and levels by man-made structures. This map is not suitable for assessing flood or drought risk.

10.3 Frequency of updating

Testers of ESME were asked how frequently they thought that the tool should be updated. A wide range of answers were provided, ranging from annually to every 4-5 years, although no one suggested 6 years or more. The most common answer and mean was for the 2-3 year period, with users keen on fairly frequent updating. However, the frequency of update will also depend on the frequency by which the underlying datasets are updated. This varies by dataset, with further information provided in the indicators and dataset library (Appendix B), but key patterns are:

- River Habitat Survey (RHS) data is the most used data in the tool and although continuously updated, the rate at which surveys are repeated at any one location is slow and will remain that way unless there is change to the wider programme of surveying.
- Data collected as part of WFD reporting is also widely used in the tool and this is updated approximately every 3 years, although complete updates occur on a 6-year cycle (see below).
- Some datasets that are important for assessing condition will change more rapidly, such as storm overflows, but many others will change at a much slower rate, such as the landscape scale indicators like land use risk and natural beauty, and indicators like local access.
- There are some indicators that we may be able to improve or add in the near future and this would warrant an update more quickly, although there would then be challenges when comparing with the baseline.

Currently, ESME uses WFD classification data reported over the period of 2013 to 2018, with data published in 2019 that forms the statutory baseline for Cycle 3 River Basin Planning. Some classification data was published in 2022, but this data was not fully comprehensive and not entirely compatible with the 2019 data. The advice that we received from Environment Agency experts was that we should use the 2019 data in its entirety and not try to mix in data from 2022, or use 2022 data and backfill with 2019. WFD classifications are being re-run across 2025 to 2026 to use in the Cycle 4 River Basin Management Plans (due to be published in 2027). However, as these were not available within ESME's development or publication timeframes, the 2019 results were used in indicators as the latest and most complete set of

classifications openly available at the time. The Environment Agency will assess the impact of updated classification data on ESME once the new classification data is available and plan when best to incorporate it into updated ESME outputs.

From late 2025 the Environment Agency also started to release national River Surveillance Network (RSN) and Small Streams Network (SSN) Analysis Ready Data collected through the NCEA programme. The Environment Agency is currently exploring the feasibility of integrating this data with ESME data to enable ecosystem service reporting at different scales and this work could also inform the next ESME update.

Given the time period of the WFD data used, we also matched other data sources to a similar time period. Hence River Habitat Survey data, Community Conservation Index and species data for iconic and invasive non-native species was used with a cutoff (start date) of 2013, although we did include more recent data as well.

Overall, frequency of update is a balance between funding, user desires, data updates, and access to new and improved data sources. It would make sense to **update ESME once comprehensive classification data has been published for Cycle 4 River Basin Management Plans** (from 2027). At that stage, the cutoff (oldest date) used for other data sources, especially RHS and species data could also be moved forward to 2019 so that all data matches as much as possible and a moving reporting window is established. In addition, ESME has been released as a Beta version, and an early update would enable us to address any issues discovered following public release so that **ESME could be published as a final, stable release Alpha version**.

After an initial update to capture Cycle 4 data, and to address any issues with the Beta version, it is probably not worthwhile updating in less than 3 years, given the relatively slow rate at which input data is updated and that change in asset conditions occurs, although new datasets could be added in this period to improve the outputs. **A full update would probably be most relevant over a 3-6 year cycle**, with perhaps an interim update every 3 years and a full update to fit with the WFD reporting cycle occurring every 6 years.

10.4 Recommendations

Key recommendations to improve and update ESME

1. **Report functionality.** It is currently possible to print particular maps or screens within ESME. However, there was interest expressed by workshop attendees in developing a user generated report function. This would allow users to create reports ranging from simple, one-page factsheets to complex, multi-page area profiles. Dynamic text, charts, media and maps can be included in an interactive report that provides users with clear information and summaries on particular themes or regions of interest. This could be created using either Esri Report Builder or the third party VertiGIS Studio Reporting application.

2. **Updating and reporting change.** It would be worthwhile running an initial update of ESME once comprehensive WFD classification has been published for the Cycle 4 River Basin Management Plans. This would also enable us to make any changes in response to feedback following public release of the Beta version and to release ESME as a final stable Alpha release version. As reported in the section above, once that has been done it is recommended that ESME should be re-run every 3-6 years to highlight changes and trends over time. When re-running, new data should be converted into condition scores based on the break points used in the current version wherever possible, to show change from the 2025 baseline.
3. **Map reasons for low scores.** It would be possible to map the key reasons for low scores for each reach and hence highlight the best ways to improve ecosystem service delivery, e.g., through targeted interventions. This would explicitly draw out indicators that are low scoring, but with the capacity to be changed through alterations in management, river restoration and so on. It would probably work best as an additional layer per ecosystem service, but could also be combined into one overall layer, depending on what would be most useful.
4. **Data triggers.** Due to concerns over the future maintainability of the ESME tool, some functionalities that relate to data triggers were not implemented within ESME. These include:
 - the filtering of ecosystem service and condition indicator layers within the map to the features selected or searched for in the filter widgets (currently, only the scale layer in the map filters to the user's selection).
 - highlighting the corresponding features within the map when a chart segment is selected (e.g. showing all features labelled 'Moderate' for an ecosystem service)

If future updates of Esri's Experience Builder provide better organisation options for data triggers (such as grouping common data triggers, renaming data triggers to describe their functions), and more stability in trigger permanence after map updates, then the functionalities relating to data triggers that have not been implemented in ESME currently could be implemented in the future.

5. **Other potential features and functions.** Feedback during the testing phase of the EMSE tool included a number of requests that could be explored further (assuming they are possible in the Esri ArcGIS Online suite). These include:
 - Provide the ability to export a report of a boundary of choice (e.g. uploading a shapefile and exporting information from within it).
 - A compare function that compares the ecosystem services in one feature to another, with the ability to print the comparison result.
6. **Further develop case studies.** Case studies that illustrate potential uses of ESME have been added into the tool. The number of case studies included at present is limited, but there are plans to expand this considerably over time.

7. **National reporting.** Produce a State of Riverine Natural Capital report (SoNC Rivers) or similar, which could form a companion to Natural England's SoNC report. This would provide information on the condition and delivery of ecosystem services across the whole river network, as well as an analysis of results, key patterns and areas for improvement. The Environment Agency are piloting the delivery of national-scale assessments of ecosystem service from rivers using data from the NCEA River Surveillance Network (RSN) alongside ESME data. RSN is designed to be unbiased and nationally representative, so combining the ESME methodology and indicators with RSN data will test the feasibility of creating an unbiased, nationally representative assessment of ecosystem services from rivers – suitable for national scale reporting.
8. **Add more ecosystem services.** As previously recommended, users have suggested that more ecosystem services should be added, with particular reference to carbon sequestration (although data is severely limited for rivers), temperature (climate) regulation, and potentially some others. Methods already developed in earlier phases of this project could be repeated relatively quickly.
9. **Add additional assets.** The approach developed here could be rolled out across other asset types, for example estuarine and coastal waters, artificial water bodies, lakes, groundwaters, wetlands etc. If we were to map artificial watercourses we would need data and expertise from relevant experts.

Enhancing specific indicators

10. **Iconic species and invasive non-native species.** The most significant area where the use of restricted (licenced) data would improve the mapping would be the use of better species data for these two indicators for the Intrinsic value of nature ecosystem service. This would improve confidence in the ecosystem service outputs. The Environment Agency does have a licence for the use of National Biodiversity Network (NBN) data, but for internal use only. It is recommended that NBN are approached about extending this licence to allow publicly displaying indicators derived from their data (as there is no need to display the actual species data). It may also be possible to obtain data from other sources such as Local Records Centres, although making indicators derived from such data publicly viewable is likely to remain an issue, and collating and unifying data from multiple sources and potentially in multiple formats would be difficult.
11. **Litter.** This is currently captured from RHS data, but is under-recorded. It could be improved by adding litter data collected as part of Bathing Water monitoring (recorded in the Bathing Water Explorer). At present, data is collected for a limited number of inland sites, but if this was increased in the future this would provide really valuable information. Data collection is much more comprehensive in coastal bathing water sites, so the use of this dataset could also be repeated if rolling ESME out to estuary and coastal assets.

12. **Tranquillity.** This is a dataset that is provided externally and was created using a large number of sub-indicators. However, it is old and relatively broad scale (500m resolution). This means that it will not capture fine scale patterns, cannot be replicated exactly, and it may not be possible to re-run to show the impact of changes in the future. Therefore, we would recommend developing a new tranquillity indicator, inspired by the current one, but that is more spatially accurate and could be updated in-house.
13. **Property price uplift.** The definition of Aesthetic and amenity experiences also includes influence on property prices and commercial activity. This is currently not captured in the ecosystem service, which focusses entirely on aspects of naturalness and beauty, which are typically greater in rural areas. An indicator could be developed to show the relative impact on property prices, using an established Office for National Statistics method. This would also have the advantage of potentially linking to monetary valuation for this service. It would be most represented in highly populated, urbanised areas, although this would present challenges when reconciling with the other rural focussed indicators.
14. **Longitudinal connectivity.** The indicator is currently based on density of obstacles calculated at reach scale, but does not include the impact footprint of the structures. A short reach with a low weir (or series of weirs) may be classified as high impact (poor) whereas a longer one with a high weir will be classified as lower impact. It may be better to assess longitudinal connectivity at river or catchment scale, then each structure could be given a score based on its contribution to overall connectivity. The index would then represent the impact of each individual obstacle on overall river/catchment connectivity. However, it is not clear if there is adequate data available on weir size/impact to be able to do this.
15. **Longitudinal connectivity.** Alternatively, this index could be derived from RHS data, where available. Data on major structures such as weirs, bridges and culverts could be assessed using recorded information and photographic evidence (since 2003, RHS surveyors have been asked to take photographs of any major structures). A composite score assessing the impacts of structures could thus be created by relating obstacle size and footprint to reach length and/or catchment hydromorphology.
16. **Lateral connectivity.** As an alternative to the current indicator, a map-based indicator could be produced for embankments using the Asset Information Management System (AIMS) database by identifying the embankment length around river reaches and relating it to river reach bank length. The new Surveillance of Embankment Assets using LiDAR (SEAL) artificial objects dataset could also be considered. Digital layers have been generated to describe and measure earth embankment flood defences in England using 1m LiDAR data. Data is only available for internal use and a timeline for this product to be available is still unknown, but could be considered for future iterations of ESME.
17. **Lateral connectivity for Water flow regulation.** The index describes the potential disconnection of the river floodplain system and could be greatly

improved for that purpose by the collection of data on existing and historic floodplain boundaries so that an assessment of flood retention volumes could be done pre- and post-modification. This would enable a more accurate assessment of the impacts of flood protection measures on flood retention. There are a series of ways to derive historic floodplain boundaries including modelling, photographic and historical evidence and a hydro-geomorphological method. Note, however, that completing this work across the country would be a very significant undertaking, so may not be very cost-effective.

18. **Vertical connectivity.** This index assesses the connection to groundwater and the hyporheic zone, an important habitat for invertebrates and other species. A major impact on connectivity is the presence of artificial reinforcement and over-deepening (dredging). We have no continuous artificial bed and bank reinforcement datasets for this indicator since the indicator is based on survey points, leaving a lot of data gaps. Such a dataset could potentially be developed using RHS and geostatistical models as for the re-sectioning dataset.

Further work

19. **Validate river reaches.** As outlined in Section 5.5, the river reaches created for this project have not been validated in the field and it would be useful to do so by selecting some case study areas for validation. This could be used to determine if the modelled changes in hydromorphological conditions are accurate and observable on the ground.
20. **Enhance river reach segmentation.** River reach segmentation could be enhanced by bringing in a valley confinement parameter, currently being developed in the Environment Agency (see Section 5.5). This would require further development and testing as indicated before. A multi-parameter algorithm could also be developed that would enable the processing of hydromorphological indices data simultaneously. Additional attributes describing sediment supply could also be investigated.
21. **River Habitat Survey development.** Data from RHS is the most used data source for ESME and is particularly important as it provides site level information that can be used to distinguish reaches. Additional RHS surveys or alternatives would significantly enhance the accuracy of ESME and enable reporting of changes over time.

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Appendix A: Ecosystem services typology and descriptions

This appendix shows the names and descriptions of ecosystem services used in Phases 1 and 2 of the project, the previous Environment Agency terminology, and the updated names and descriptions that were taken forward from Phase 3 onwards and published in ESME.

Table 1A: Ecosystem services terminology and descriptions

Category	Ecosystem service name used in Phase 1 and 2	Previous EA terminology	Definition used in Phase 1 and 2	New EA NCEA ES terminology*	New EA NCEA ES descriptions* used in ESME
Provisioning	Water (for drinking /agriculture /industry)	Water supply (Public water supply; Industrial/ agricultural use; Cooling/energy generation; Other)	The natural storage, retention and supply of freshwater. Fresh water abstracted (or potential for abstraction) for human uses.	Water supply (drinking/ agriculture/ industry)	Water abstracted from surface and below-ground* sources that can be used for drinking, agriculture and industry (such as material or for cooling). * ESME does not currently consider groundwater abstraction
	Water quality regulation	Water quality regulation (Pollution dilution; Water purification - filtration by habitats)	Regulation of the chemical condition of fresh waters by plant, animal, bacteria, fungi or algae, that enables human use or health.	Water quality regulation	How biotic (animals, plants, bacteria, fungi, and algae) and abiotic features and processes of the ecosystem regulate the chemical condition of freshwaters. This includes both the maintenance of baseline abiotic conditions such as nutrient balance and pH, and the remediation, dilution, and removal of anthropogenic pollutants.

Category	Ecosystem service name used in Phase 1 and 2	Previous EA terminology	Definition used in Phase 1 and 2	New EA NCEA ES terminology*	New EA NCEA ES descriptions* used in ESME
Regulating	Water flow regulation	Water flow regulation	Hydrological cycle and water flow regulation (including flood control, and coastal protection). The capacity of ecosystems (e.g., vegetation, soil) to retain water and release it slowly. Buffering of the impacts of natural hazards and disruptions. Structure and storage capacity of vegetation can reduce the effects of storms, floods and droughts.	Water flow regulation	The biotic and abiotic features of an ecosystem that regulate water flow, as well as ecosystem structures and characteristics that help mitigate or prevent potential damage from drought and from flood and storm surges to the environment, human use of the environment or human health and safety. For example, the capacity of ecosystems (e.g., vegetation, soil) to retain water and release it slowly.
	Habitat and species population maintenance	Habitats	The presence of ecological conditions (usually habitats) necessary for sustaining populations of species that people use or enjoy. Rivers as wildlife corridors, enhancing connectivity and resilience of populations.	Habitat and species population maintenance	The ecological conditions necessary for supporting sustainable populations of species throughout their lifecycle. This includes breeding grounds, feeding grounds, refugia, and wildlife corridors.

Category	Ecosystem service name used in Phase 1 and 2	Previous EA terminology	Definition used in Phase 1 and 2	New EA NCEA ES terminology*	New EA NCEA ES descriptions* used in ESME
Cultural	Recreation and tourism	Recreation	Human values derived from recreational uses of ecosystems, including their often substantial tourism potential. Natural ecosystems are often used as places for relaxation and recreation, including hiking, camping, fishing, and nature viewing.	Recreation**	The contribution and opportunity provided by the environment for recreational uses. Natural ecosystems used as places for the active enjoyment of recreation, including walking, hiking, camping, cycling, boating, fishing, watersports, and nature viewing.
	Health and well-being	Physical health and Mental health	The role of natural landscapes and urban green space for maintaining mental and physical health is increasingly being recognised. Using nature to destress.	Physical / mental health and wellbeing	The role of natural landscapes and urban green and blue space for maintaining mental and physical health. Natural environments can offer places and opportunities for informal physical activity, and to use nature and the outdoors to destress and socialise.
	Aesthetic experiences	Cultural heritage (Aesthetic value and sense of place)	Most people enjoy natural scenery and landscapes; the beauty of nature. This is important not just for human enjoyment but can also have economic importance by influencing property prices.	Aesthetic and amenity experiences	The passive enjoyment of being in and around natural scenery, landscapes, and cultural spaces; the beauty of nature. This provides human enjoyment, and it can also have economic importance by influencing property prices and commercial activity.

Category	Ecosystem service name used in Phase 1 and 2	Previous EA terminology	Definition used in Phase 1 and 2	New EA NCEA ES terminology*	New EA NCEA ES descriptions* used in ESME
	Education, training and investigation	Education	Natural areas provide numerous opportunities for study, education, and research, as well as references for monitoring environmental change.	Education and investigation	The contribution and opportunity provided by the environment towards study, education, and research.
	Spiritual and cultural experiences	Cultural heritage (Cultural heritage; Spiritual and religious value)	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 for people. Nature is a common element of all major religions. Natural landscapes also form local identity and sense of belonging.	Spiritual, cultural and religious experiences	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 for people. Nature is a common element of all major religions. Natural landscapes also form local identity and a sense of belonging.
	Characteristics and features of biodiversity that are valued	Cultural heritage	The things in nature that we think should be conserved because of their non-utilitarian qualities (existence value). The things in nature that we want future generations to enjoy or use for whatever reason (option or bequest value).	Intrinsic value of nature	The things in nature that we think should be conserved because of their non-utilitarian qualities (existence value). The things in nature that we want future generations to enjoy or use for whatever reason (option or bequest value). Things in nature that are used to inspire art, books, or films.

*Source: Environment Agency NCEA ecosystem service names and descriptions come from Environment Agency Natural Asset and Ecosystem Service Indicators and Metrics project.

**Tourism taken out as considered more a benefit than a service - and could occur for many different reasons and services (cultural heritage, wildlife watching, recreation) which require different environments

Appendix B: ESME Dataset and Indicators Library

An assessment of the datasets and indicators used in the Ecosystem Service Mapping Explorer (ESME) tool.

Available as a separate stand-alone Excel spreadsheet:

'ESME Dataset and indicators library.xlsx'

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