The future of flood hydrology in the UK

Article

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The future of flood hydrology in the UK

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Abstract

A "roadmap" for the future of UK flood hydrology over the next 25 years has been published, based on a wide-ranging and inclusive co-creation process involving more than 270 individuals and 50 organisations from different sectors and disciplines. This paper highlights key features of the roadmap and its development as a community-owned initiative. The roadmap's relationship with hydrological research and practice is discussed, as is its context within the wider flood risk management innovation landscape, including funding. Whilst the paper has a focus on UK flood hydrology, reflecting the scope of the roadmap, it is also considered in the context of advances in hydrology internationally.

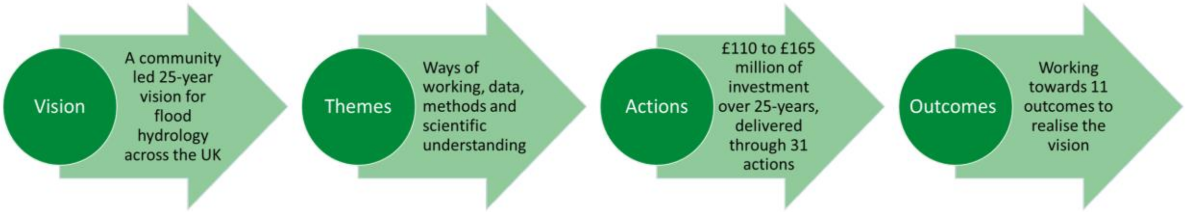
Keywords

Flood, hydrology, research, practice, future, plan

Highlights

- We describe a roadmap for flood hydrology in the UK over the next 25 years
- The roadmap has been published on behalf of the flood hydrology community
- More than 270 individuals and 50 organisations contributed to the roadmap's development
- The roadmap will inform many flood risk management activities to strengthen community, infrastructure and climate resilience
- The roadmap spans science, practice and the evolution of the professional community

Graphical abstract



Introduction

Flood risk in the UK

Floods have devastating effects on lives, communities and livelihoods, and the averaged economic risk of flooding in the UK is estimated (Sayers et al., 2020) to be £2.1bn per annum. In its National Risk Register, the UK government has judged only pandemic disease and nuclear or biochemical attacks to have greater potential impacts (Cabinet Office, 2020).

Rivers are the biggest source of flood risk, with £1.1bn in expected annual damages (EAD). Surface water (pluvial) flood risk is £0.6bn EAD, coastal risk £0.4bn, and groundwater £0.05bn. Hydrology is therefore an essential foundation for evidence-based decisions about managing economic risks of at least an estimated £1.7bn EAD. Alongside the economic assessment, 1.9 million people have more than an estimated 1/75 annual chance of being flooded, with the risk falling disproportionately in the most socially vulnerable neighbourhoods. Flood risk is assessed separately by the responsible authorities in each of the UK's nations. Here, and in what follows, UK-wide baseline data and future projections have been aggregated from the Third UK Climate Change Risk Assessment (CCRA3, Sayers et al., 2020).

Flood risk EAD in the UK has been projected to reach £2.7-3.0bn annually in the 2080s under a global warming trajectory of +2°C by 2100, or £3.5-3.9bn under a +4°C trajectory. Inland hydrological risks will continue to predominate in economic terms, although relative increases in risk will be largest for surface water (from £587m to £1.2bn in a +4°C future) and coastal (£361m to £1bn) flooding. These projections assume that risk management measures, including land use planning and investment in flood and coastal defences, will continue at rates commensurate with current policy objectives. Enhanced flood management, including increased investment, appears to have the greatest potential to mitigate the projected increases in risk for fluvial flooding, which further highlights the importance of flood hydrology.

The risk-based approach to flood management in the UK (Hall, 2014) demands scientifically robust analysis to prioritise resources where they will deliver best value for society (HM Treasury, 2022). Economic projections (Environment Agency, 2019; JBA and Sayers, 2018) suggest that investments to mitigate the increasing risk are both feasible and economically justified, but with substantial residual risks that will be difficult to plan for, particularly in relation to surface water flooding, which may occur suddenly. The risk and investment projections are built on detailed modelling carried out for national flood management agencies, ultimately driven by hydrological analysis.

Historical context and drivers for change

There is a long tradition of hydrological research and observation in the UK (Rodda and Robinson, 2015), dating back at least as far as quantitative experiments by Edmund Halley in the seventeenth century (Deming, 2021), and often intrinsically linked with practical problems in water management (J.S.G. McCulloch, 2007, C. McCulloch, 2022). The water sector today reflects a complex mosaic of public, private and third sector stakeholders. Although the interconnectedness of the hydrological cycle has long been appreciated (Biswas, 1970), a fragmentation of responsibilities (Pitt, 2008) and the generally increasing depth of technical knowledge in science and engineering disciplines mean that methods applied in practice have become increasingly functionally specialised. Many methods routinely used in UK flood hydrology have roots in the 1960s-1990s. For example, the Flood Studies Report (NERC, 1975) paved the way for the Flood Estimation Handbook (FEH, Institute of Hydrology, 1999) and its derivatives in current use. The FEH methods are widely used, including in the national risk mapping that underpins the risk assessments cited in the opening paragraphs of this paper. Yet some choices made in the past, for example assumptions of spatial uniformity or temporal stationarity, could be questioned when viewed with a contemporary perceptual understanding of hydrology (Wagener et al. 2021), or when taking account of advances in observations (Beven et al., 2019) or evidence of change in UK flood data (Faulkner at al. 2020, Hannaford et al., 2021).

Regionally- and nationally- significant events in Britain (including in 1998, 2000, 2005, 2007, 2009, 2013-16, 2019 and 2020) have highlighted the impacts of flooding (Environment Agency, 2018). Meanwhile, an increasing emphasis on whole-system thinking points to a need for integrated models to support improvements in flood resilience (Cabinet Office, 2016). In recent years, transformations in our capacity to share information rapidly through digital communications, an increasing appreciation of the importance of community ownership of risk, and perhaps also an expansion of educational and training opportunities in flood risk management have stimulated a wider range of demands on hydrological data and methods.

Those demands stem from many areas of flood management, including: the design and maintenance of flood defences, flood risk mapping, risk assessments for investment or development planning, the design and operation of forecasting and warning systems, reservoir safety, sustainable drainage systems, the evaluation of nature-based flood management, and understanding of the impact of environmental change on flood risk.

The 25-year roadmap for flood hydrology

This paper describes how the evolving demands for hydrological analysis and advances in scientific knowledge have prompted a comprehensive reappraisal of research and innovation in UK flood hydrology, culminating in the publication of a roadmap for the next 25 years (Environment Agency, 2022), available from https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/flood-hydrology-roadmap.

The roadmap is a community initiative, building on a strongly collaborative approach that will be introduced in the following section. We then describe the objectives of the roadmap project, and how it fits with related initiatives both in the UK and internationally. The following sections set out the methodology for development of the roadmap and summarise its contents. We then discuss how the roadmap is being implemented, what is needed to ensure its long-term success, and aspects of its development that may be transferable to other settings. We conclude with an overview of the roadmap project's key outcomes.

Research, innovation and knowledge-sharing in UK flood risk management

Flooding and coastal risk management (FCRM) are considered together in UK policy. No recent estimate is available of total spend on research or innovation in flood hydrology, although analysis in 2011 found that over the preceding decade there had been annual public spend of between approximately £7m and £14m (£12.5m and £25m at 2021 prices) in FCRM research (Moores and Rees, 2011). The private sector also invests in FCRM research and innovation, but this has not been quantified.

An important feature of flood risk management in the UK is the history of cooperation between universities, the public sector and private industry. Collaborative research and development programmes (including those in footnotes[1,2,3,4]) have helped to promote exchanges of knowledge about the scientific and practical drivers for continuing developments in flood hydrology. Research programmes with a focus on flood risk have included Flood Risk from Extreme Events (FREE, Hardaker and Collier, 2013), the Flood Risk Management Research Consortium (FRMRC, Environment Agency, 2021) and Flooding From Intense Rainfall (FFIR)[5]. This coordination helps support communities of practice, enhanced through knowledge exchange networks including professional societies, notably the British Hydrological Society (BHS), a volunteer organisation with

[1] https://www.gov.uk/government/organisations/flood-and-coastal-erosion-risk-management-research-and-development-programme
[2] https://www.sniffer.org.uk/
[3] https://ukwir.org/
[4] https://www.ciria.org/
[5] http://blogs.reading.ac.uk/flooding/files/2013/11/Flooding-From-Intense-Rainfall-Summaries.pdf

more than 900 members, the British Geomorphological Society, and chartership institutions in water management[6], civil engineering[7], meteorology[8] , geology[9] and geography[10].

Governance and objectives of the flood hydrology roadmap

Recognising the broad drivers for change discussed above and the long-term (~10 to ~100 years) influence of flood hydrology on infrastructure and land use plans, the flood hydrology roadmap was initiated in 2018 through a research and development programme[1] run jointly by public risk management authorities and government departments in England and Wales. First, a project board was established to take overall responsibility. The board was supported by, and worked closely with, a steering group drawn from the regulatory, academic and non-profit organisations. For brevity the board and steering group will be referred to in this paper as the "project team".

Broad initial objectives were set by the project team, framed as ambitions that the roadmap should:

- take a 25-year view
- be inclusive and community-owned
- combine scientific credibility and practical utility
- consider inland flood hydrology (flood risk from rivers, surface water, groundwater and reservoirs)
- consider both forecasting the near future and longer-term risk
- enable and drive change (for example in research, guidance, data or organisations).

[6] https://www.ciwem.org/
[7] https://www.ice.org.uk/
[8] https://www.rmets.org/
[9] https://www.geolsoc.org.uk/
[10] https://www.rgs.org/

Related initiatives

Recently there have been several important consensus statements about challenges in hydrology. A landmark study is the international “Twenty-three unsolved problems in hydrology” (23 UPH) initiative (Blöschl et al., 2019) to identify major scientific problems, motivated by a need for stronger harmonisation of research efforts. The 23 UPH project did not have a specific focus on flooding, but, like the roadmap, it involved iterative co-creation through a blend of digital channels, in-person meetings and working groups.

Three of the UPH relate specifically to hydrological extremes, either droughts or floods, and one relates exclusively to exceptional runoff produced by rain-on-snow events. The 23 UPH in general reflect fundamental questions about variability, scaling, process interactions, empiricism, modelling and the role of water in society. Hence there are connections with flood hydrology embedded within many of the remaining 20 UPH. Blöschl et al. (2019) concluded that hydrological applications and fundamental research reinforce each other. They viewed the UPH as proof of concept that a broad consultation process was feasible and welcomed by the hydrology community. Both findings also characterise the roadmap. The 23 UPH coincided with the International Association of Hydrological Sciences (IAHS) scientific decade 2013 – 2022 denoted “Panta Rhei – Everything Flows” (Montanari et al., 2013), which has been dedicated to research about changes in hydrology systems and their relationships with a rapidly changing society.

In the UK, a working group was formed in 2018, under the auspices of the BHS, to debate and make recommendations about the future of UK hydrology, leading to two journal papers (Beven et al., 2020, Wagener et al., 2021). Most individuals who participated in the BHS working group also contributed to the roadmap. Additionally, the roadmap team examined the working group’s outputs to understand areas of strong or weak alignment with the emerging roadmap, a process that informed the final action plan.

Another source of advice that informed the roadmap was a UK flood resilience review (Cabinet Office, 2016), which made the case for integrated modelling, encompassing both physics-based and statistical approaches, regular updating of risk assessments and tests of resilience based on extreme event scenarios. An earlier report commissioned by the Government Office for Science (Royal Society, 2015) highlighted the need for improved observations of natural hazards, including flooding, to increase the UK's resilience. This prompted a study (from 2020 to 2022) to establish the requirements for national Floods and Droughts Research Infrastructure (FDRI). The aim of the FDRI is to transform research capability to improve flood and drought forecasting, planning, incident response and management. The FDRI study engaged with a broad range of stakeholders from public, private and non-profit sectors, using similar methods to the flood hydrology roadmap, and producing several proposed investment options, which are being taken forward into a business case for funding at the time of writing. The Reservoir Safety Research Strategy (Environment Agency, 2016) also highlighted needs for research on extreme rainfall and runoff, which have informed the roadmap.

The timing of the initiatives discussed above is summarised in Figure 1. All the initiatives can be expected to have continuing long-term influence. A notable feature of the roadmap and the UK FDRI is that both include costed plans for implementation and have led to the development of business cases for funding.

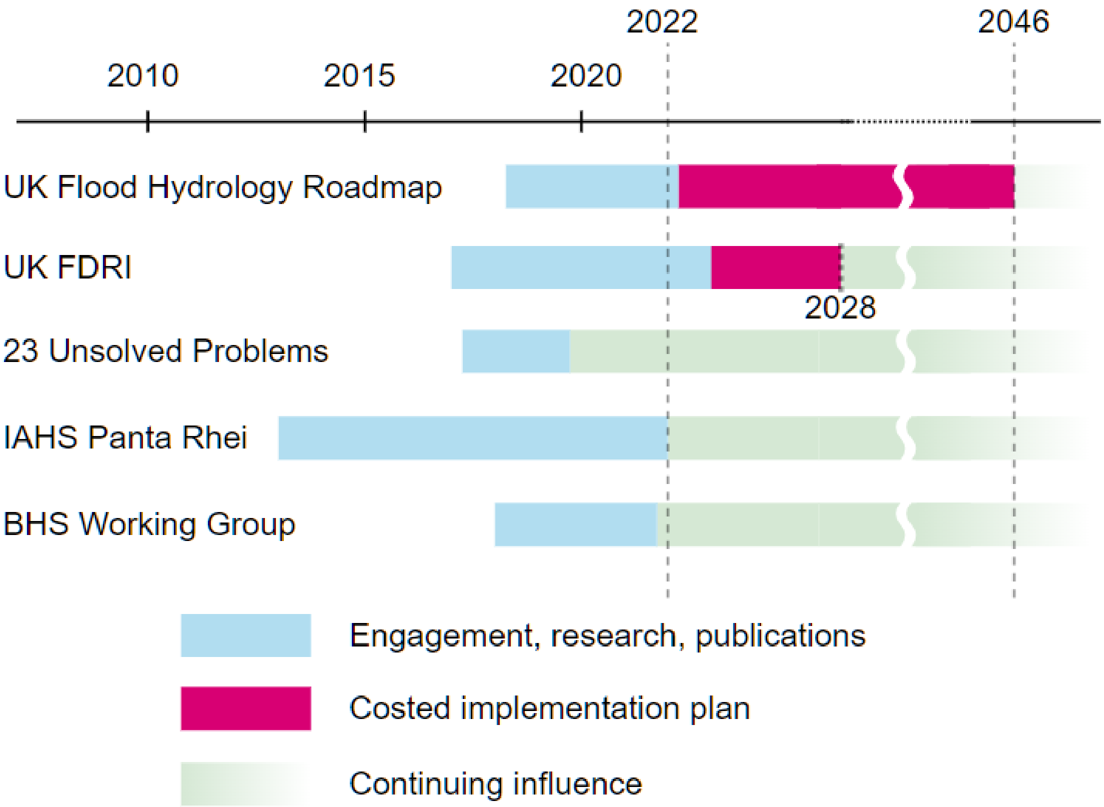


Figure 1. Timeline of UK and international research and innovation scoping initiatives. FDRI – Floods and Droughts Research Infrastructure, IAHS – International Association of Hydrological Sciences, FDRI – Floods and Droughts Research Initiative, BHS – British Hydrological Society.

Methodology

Overview

The roadmap developed as an iterative co-creation process. Figure 2 shows its evolution, highlighting stakeholder engagements and the progressive refinement of ideas. Table 1 details interactions with the stakeholder community. In total, there were >1,000 points of engagement (comprising responses to surveys, attendances at meetings, webinar participation and written inputs) involving >270 individuals. Different modes of engagement were used to maximise the opportunities for participants to get involved, and to reduce the scope for inadvertent biases that might have occurred had there been only one way to contribute. Written questionnaires, in-person and online workshops, online survey, specialist task groups and public webinars were all deployed. A stakeholder "map" was created and maintained throughout to monitor the makeup of the community participating in the roadmap's development (see discussion of Figures 6 and 7 below) and ensure that a spread of disciplines, types of organisation and interests were represented.

The initial consultation questionnaire represented a form of purposive sampling. Subsequent stages of engagement were designed to achieve greater depth and breadth, with a larger pool of participants being encouraged through promotion in professional newsletters, email lists, meetings and webinars. No fixed target was set for the number of respondents; instead, the aim was to ensure that anyone with an interest in hydrology and flood risk management in the UK had the opportunity to contribute through at least one of the engagement processes.

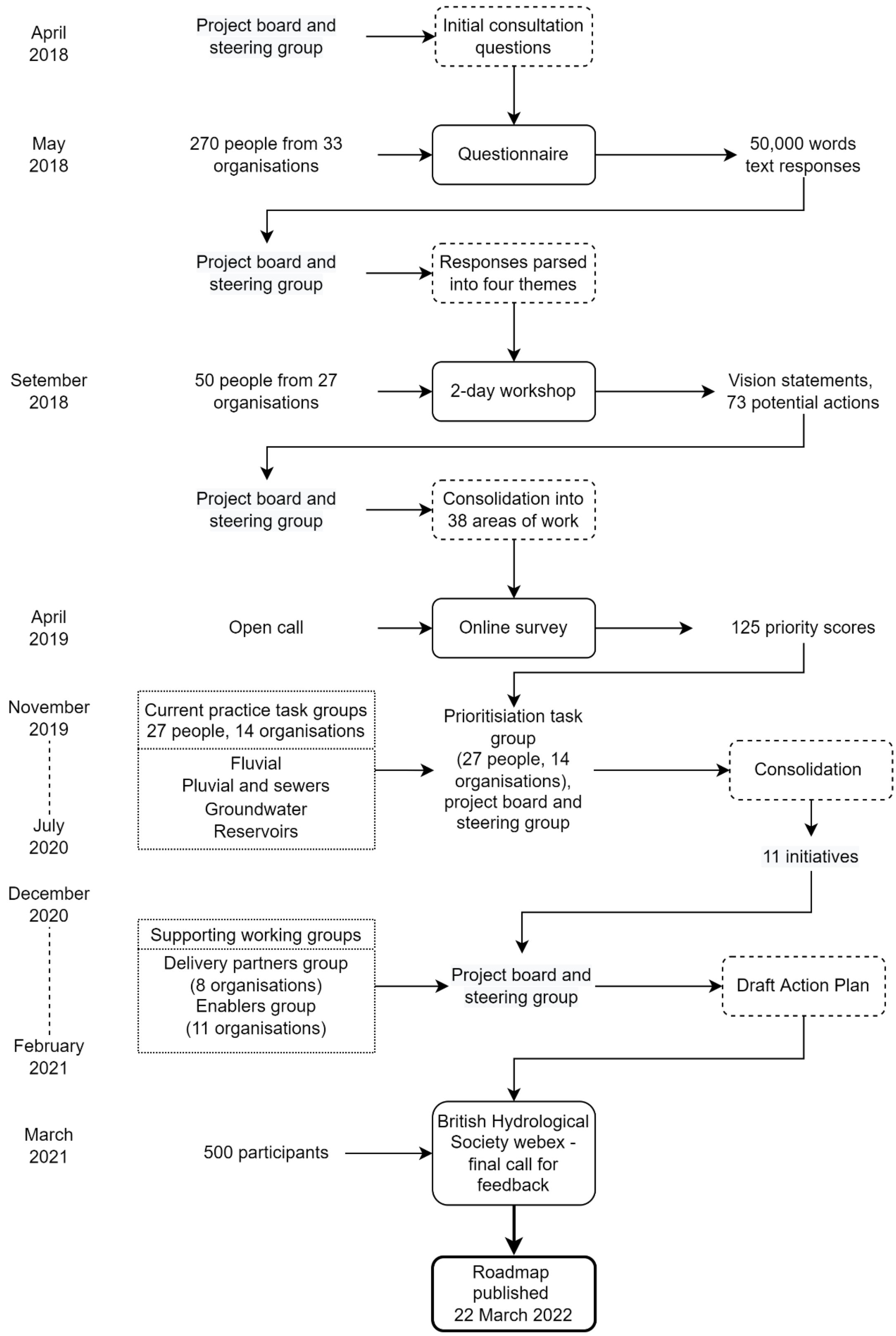


Figure 2. Evolution of the flood hydrology roadmap (see Table 1 for further details of stakeholders and processes).

Table 1. Summary of stakeholder community engagement during development of the roadmap.

Engagement actions and groups	**Description and outputs**	**Number of engagements**
Project board and steering group	Ten individuals from six organisations responsible for direction and delivery of the roadmap.	20 meetings
Professional community	A broad and open community of stakeholders with interests in UK flood hydrology, including, practitioners, academic researchers, regulators and individuals with backgrounds in multiple disciplines.	As detailed in rows below.
Questionnaire	Initial evidence gathering through written answers to seven open questions. Produced evidence base about needs and priorities in flood hydrology to inform discussion at workshop.	270 people contributed representing 33 organisations
Workshop	Two-day event with professional facilitation. Produced vision statements and 73 potential actions for the future of flood hydrology in the UK.	50 participants representing 27 organisations
Online survey	Consolidated the potential actions generated by the workshop into 38 potential work areas. Gathered feedback on draft vision statements and work areas using a priority scoring scheme.	125 responses received
Current Practice Task Groups	Four groups produced baseline summaries of current UK practice in the sub-topics: fluvial, pluvial and sewers, groundwater, reservoirs.	27 individuals from 14 organisations
Prioritisation Task Group	Reviewed the 38 potential work areas, which were further consolidated into 11 linked	27 individuals from 19 organisations (not

	initiatives, identifying objectives and dependencies to form the final action plan.	identical to the Current Practice Task Groups)
Enablers Group	Advised on how which organisations could contribute to delivery of the roadmap action plan and how that could be achieved, taking account of dependencies.	11 organisations represented
Delivery Partners Group	Advised on the content, prioritisation, funding requirements and delivery opportunities within the roadmap action plan.	8 organisations represented
British Hydrological Society Webinar	Progress update and final call for comment on draft roadmap.	500 participants

Questionnaire

An initial questionnaire was formulated by the project team. Its structure is shown in Table 2, which details the motivation for each section. The questionnaire was sent to 52 individuals or groups, selected in line with the Environment Agency's internal guidance on engagement. Responses, totalling more than 50,000 words, were submitted in free text format. To avoid constraining the solution space too soon, the questionnaire was intentionally directed towards mapping the stakeholder community and identifying problems, needs or opportunities, rather than identifying specific actions or solutions. It was designed to inform a wider discussion at the subsequent workshop, enabling the refinement of problem areas and the co-creation of proposed solutions and actions.

The project team parsed the raw questionnaire responses, collating them the into four themes: “ways of working”, “data”, “methods” and “scientific understanding”, which provided a foundation for the workshop. Alongside this subjective process, a machine learning approach was applied to the questionnaire responses to seek out topics with distinctive meanings as groups of key words, in this case the 10 most frequent words associated with each of four putative topics. The word groups discovered using machine learning aligned well with the themes chosen by the project team (Environment Agency, 2022, Appendix I), giving some assurance that the choices were evidence-based and not strongly biased by the backgrounds of the project team.

Table 2. Structure of initial questionnaire.

Section	Motivation
Respondent information	Establish identities of respondents and why flood hydrology is relevant to them.
Vision	Inform debate about ambitions and vision for the future of UK flood hydrology.
Today's problems	Identify general and specific challenges for present-day flood hydrology, including inadequacies in knowledge, methods, data or ways of working, and with scoring of urgency and potential importance of each problem statement.
Prioritisation approaches	Gather evidence about how the stakeholder community understands the relative importance of problems and needs in flood hydrology
Roles and expectations	Evidence the community's near-term expectations about flood hydrology services and products provided by others.
Links	Capture connections with technical developments, projects, or organisations potentially relevant to the roadmap.
Open comments	Allow contributions additional to the above topics.

Workshop

The workshop aimed to build ownership of the roadmap among influential stakeholders, and to start creating its content in terms of a vision for the future, analysis of perceived needs, and the actions required to meet those needs. Over two days, 50 individuals from 27 organisations generated draft vision statements and 73 potential actions grouped into 16 clusters. For example, one cluster of actions was "Improve access to flood hydrology data"; see Environment Agency (2022, Appendix C) for a comprehensive account. The 73 actions were further consolidated by the project team into 38 potential areas for future work, which formed the basis of the next step, an online survey.

Online survey

The survey was carried out in April 2019 to test the vision statements and the work areas emerging from the questionnaire and workshop. Engagement with the stakeholder community was expanded by use of the online survey format, with 125 responses being received in the form of priority scores for each of the 38 potential work areas (Figure 3).

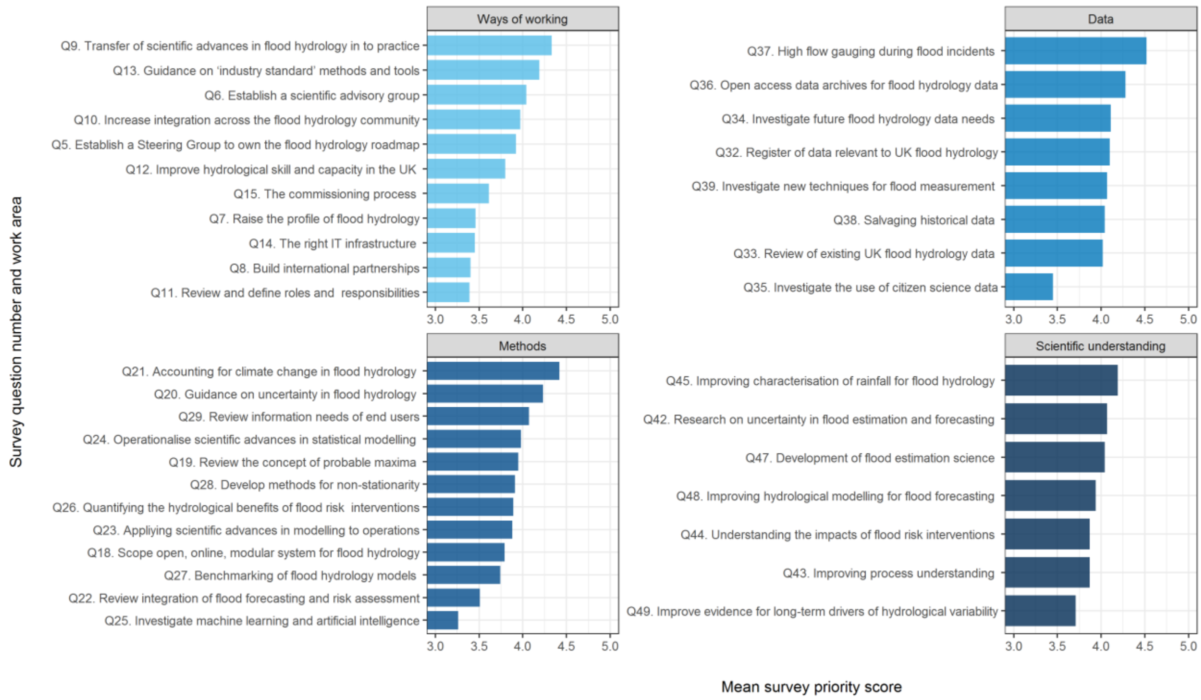


Figure 3. Prioritisation scores returned by the online survey (1 = low, 5 = high) for 38 potential work areas, each labelled as a survey question (prefix "Q") and classified by theme.

Current practice and prioritisation task groups

Four task groups were established in March 2019 to summarise the current state of knowledge with respect to reservoirs, groundwater, surface water and fluvial flood risk, considering both forecasting and flood risk management planning perspectives. The groups comprised volunteers with expertise in each topic from academic, government and non-government organisations. Their reports (Environment Agency, 2022, Appendix E) helped to consolidate the evidence gathered during the questionnaire and workshop and were used by the project team as baselines in developing proposals for future improvements.

A prioritisation task group with 27 members was also established following the April 2019 online survey. Its remit was to help shape the survey responses into a draft action plan. The group included people with a mix of regulatory, private sector and academic backgrounds, with interests and expertise spanning the same topics as the current practice groups. The terms of reference included 13 prioritisation criteria, encompassing judgements about economic and social benefits, technical outcomes, affordability and project management risks or opportunities. The resulting matrix of 13 criteria and 38 potential work areas, many of them co-dependent, was too complex to support a straightforward ranking. To help constrain the process, the 38 work areas were refactored into 11 inter-linked “initiatives”, shown in Figure 4, which identifies the relationships between the initiatives and the four thematic visions. Each initiative was presented as a short proposal setting out its context, drivers, objectives, outputs and expected benefits, along with the risks of not carrying out the work (Environment Agency, 2022, Appendix F).

With input from the prioritisation task group about the relative importance and scheduling of the 11 initiatives, the project team developed a draft action plan during 2020.

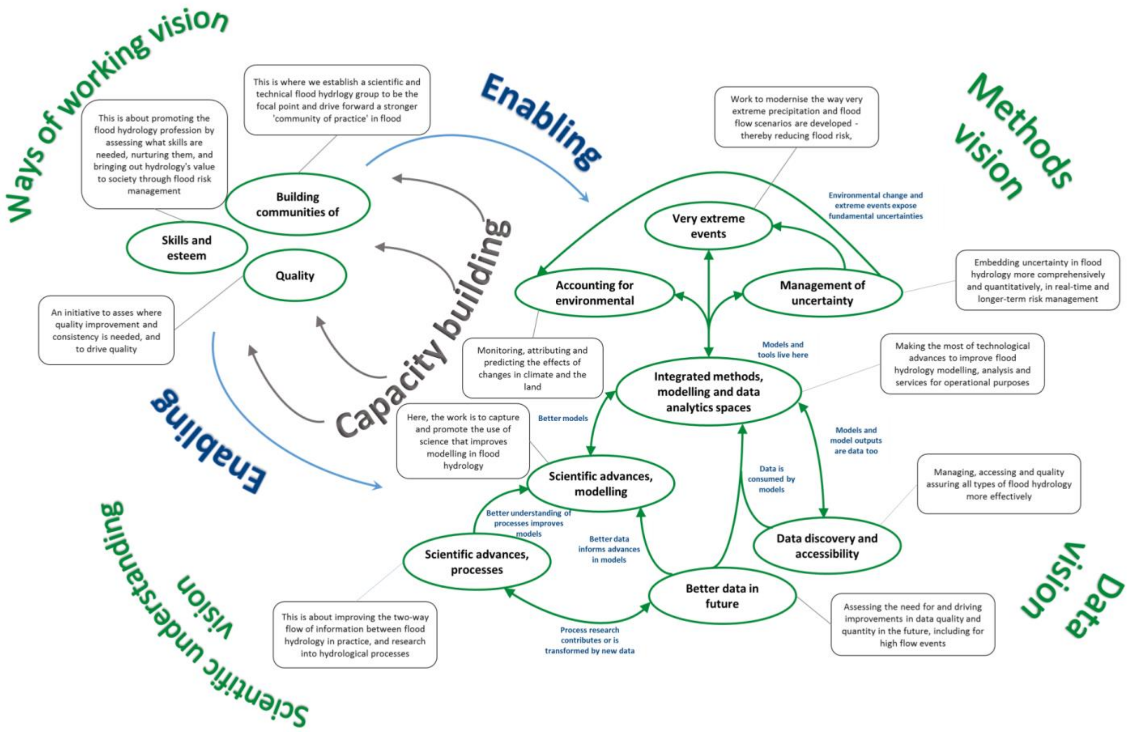


Figure 4. Eleven initiatives (green ovals) developed during work plan prioritisation. Each initiative reflects the influence of the four thematic visions (located as "attractors" at the corners of the image). Dependencies and synergies are identified by arrows. The rectangular boxes summarise each of the initiatives.

Delivery plan

Two further task groups were established in parallel to help finalise the roadmap; a "delivery partners" group advised on the timing of actions and who could fund them, whilst an "enablers" group advised on how contributions could be made in other ways. Advice from the two groups was gathered during four workshops in early 2021 and supported the project team in drafting a final roadmap action plan including estimated costs.

Webinar

The development process and draft action plan were previewed through a public webinar hosted by the BHS in March 2021 and attended by nearly 500 people. Following this webinar, the draft plan was made available on request and eight sets of comments were received to feed into the final roadmap.

The flood hydrology roadmap

The UK flood hydrology roadmap was published in March 2022 (Environment Agency, 2022). The roadmap includes details of 31 actions, shown in Figure 5, spanning 25 years. The actions were formulated in response to issues raised throughout the engagement process, integrating across the four themes. This means that some topics span broadly across the roadmap (for example, climate change, one of the highest-scoring work areas in the online survey, is embedded in multiple actions in the Methods and Scientific Understanding themes). Appendix G of the roadmap sets out a programme and budgets for the 31 actions, reflecting a synthesis of the inputs described earlier. Here, we outline key findings that emerged during development of the roadmap.

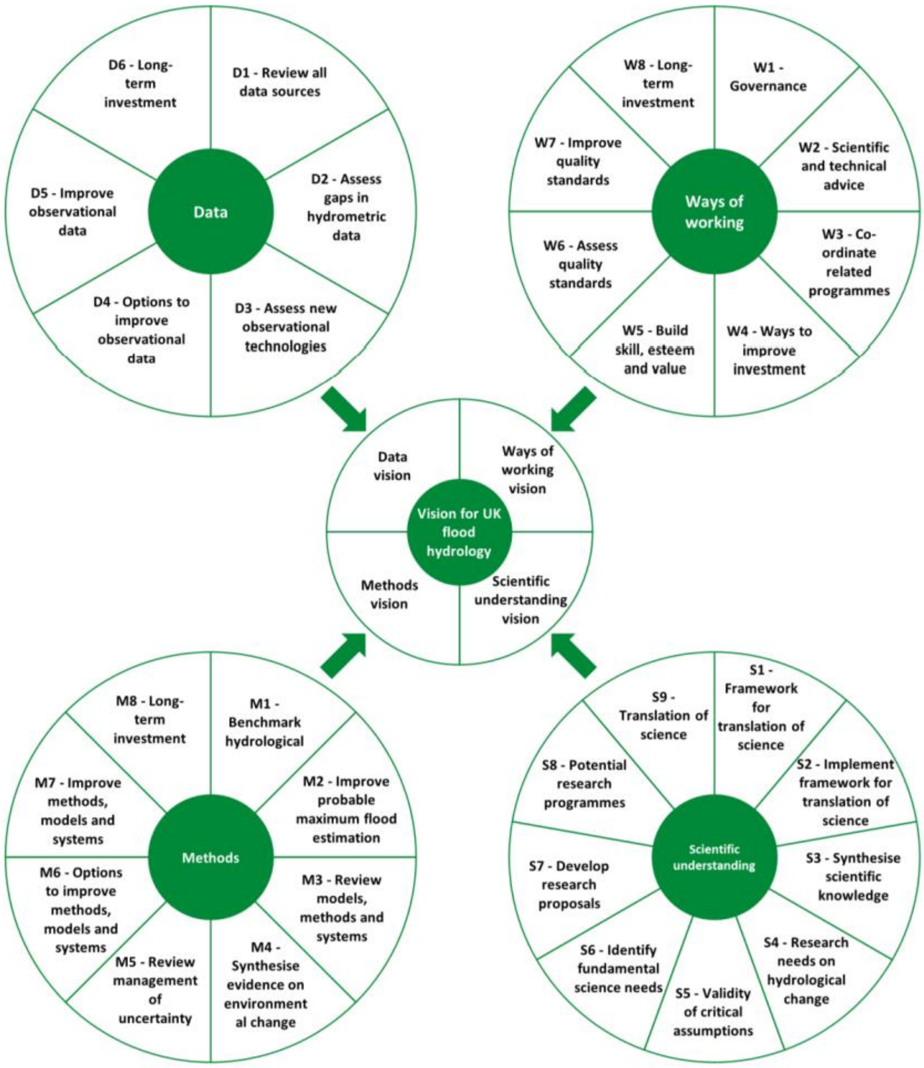


Figure 5. The 31 actions developed within the 25-year UK flood hydrology roadmap, grouped by theme.

Composition of the UK flood hydrology community

The roadmap has highlighted the breadth and depth of the stakeholder community involved with flood hydrology in the UK. Figure 6 shows the distribution by sector of organisations represented throughout the entire co-creation process. Nearly half (45%) of engagements were with public sector organisations, reflecting the regulatory and policy landscape. Private industry and academia were the next largest groups, representing 28% and 23% of engagements, respectively, and providing reassurance about the representation of both the research community and practitioner stakeholders.

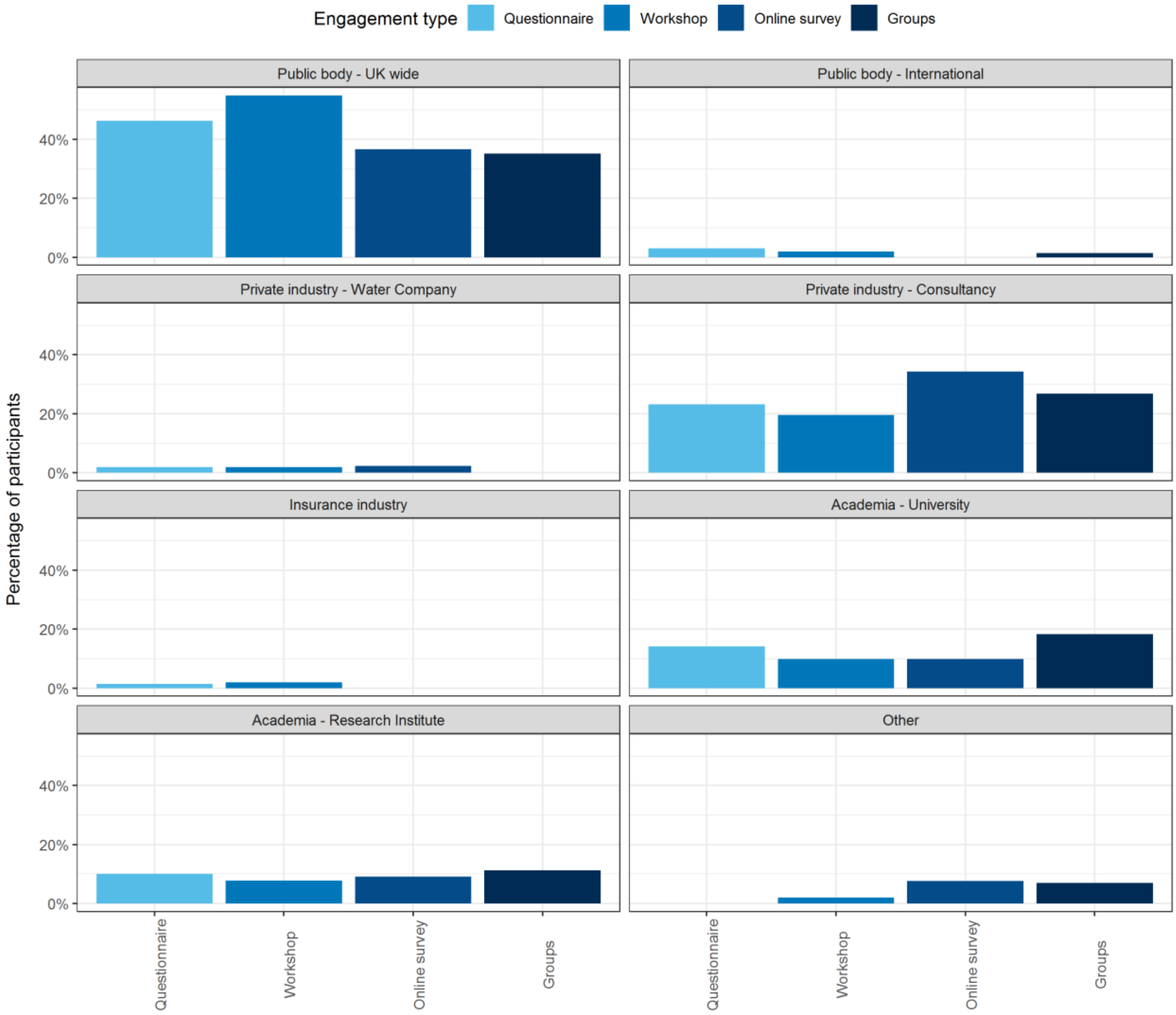


Figure 6. Sectoral distribution of the stakeholder community engaged throughout co-creation of the roadmap, grouped by organisation type (separate panels) and mode of engagement (shaded bars). “Groups” refers to the multiple working groups involved in the latter stages of the roadmap.

Figure 7 shows the distribution of technical interests amongst those engaged during creation of the roadmap. Both long-term analysis of river flood flows (“flood estimation”) and near-future prediction (“forecasting”) were important areas of technical interest. Whilst fluvial hydrology was the most common primary interest, surface water, reservoirs and groundwater were all strongly represented.

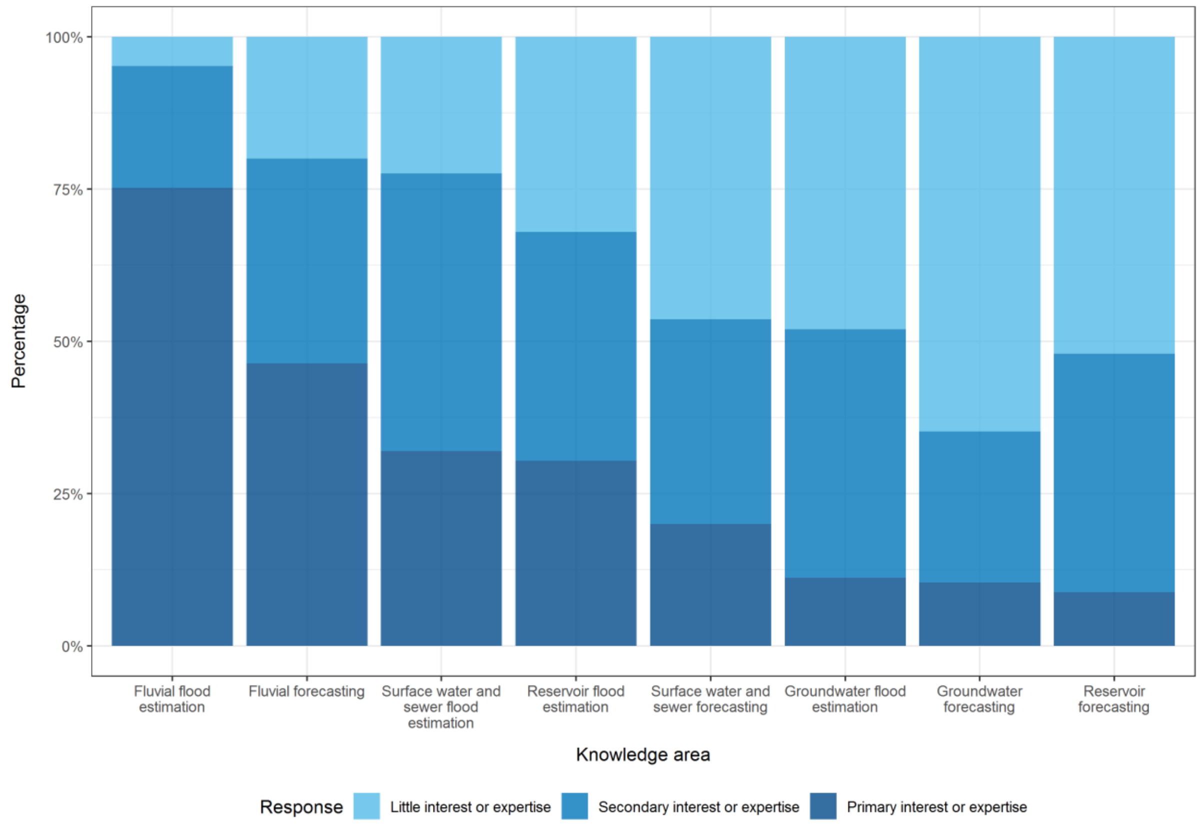


Figure 7. Distribution of areas of technical interest, responsibility and/or expertise within the stakeholder community engaged throughout co-creation of the roadmap.

25-year vision statement

The community's overall vision for the future of UK flood hydrology is that:

- during the next 25 years society will have improved hydrological information and understanding to manage flood hazard in a changing world
- flood hydrology and whole-system process understanding will be underpinned by excellent evidence with quantified uncertainty
- leadership and collaboration are crucial to achieving this vision.

The vision embodies the different dimensions of the roadmap, encompassing the importance both of science and applications. Specific references are made to uncertainty and holistic systems-based thinking, which is reflected throughout the action plan at the interfaces between flood hydrology and related environmental, physical and social systems.

The final part of the vision highlights the importance of leadership and partnerships, which reflects both the community ownership of the roadmap, achieved through the co-creation process, and the development of the ways of working theme. Early priorities within this theme include the establishment of a governance structure and a scientific and technical advisory group to identify funding opportunities, to promote the delivery of projects and to review progress against the roadmap action plan.

Funding and delivery

The roadmap has an estimated budget requirement of £110m (present value, PV, of £74m) over 25 years. Adjustments to account for optimism bias in cost and timing have been calculated using methods detailed in Environment Agency (2022, Section 4.2), giving upper estimates of £165m (PV £111) costs and a 37.5-year programme. The best estimate average annual funding requirement is £4.4m, with a peak in 2032 in the range £9.9m to £14.9m (after optimism bias adjustment), and will need to be met by, and coordinated across, multiple funding bodies. Already, the Environment Agency in England has preliminarily allocated £6.9 million of funding over six years, from April 2021, to begin implementing the roadmap. Additional funding for science, and its translation into practice and policy, will be required to deliver the roadmap in full.

It is very difficult to construct a full economic appraisal of the roadmap *a priori* because the benefits of investments in flood hydrology are varied, and are embedded deeply within many facets of flood risk management, and across related aspects of environmental and socioeconomic planning. It is likewise difficult to evaluate the benefits of flood management holistically (Defra, 2008). Instead, the roadmap includes a mapping between its outcomes and the ultimate flood management benefits for people and communities. The roadmap will contribute directly (as outlined in Figure 8) to 11 of the 13 flood risk management outputs in the FCRM strategy for England (Environment Agency, 2020), which are prerequisites for the strategy's desired outcome, "a nation ready for, and resilient to, flooding". Further details of outcomes and benefits can be found in the roadmap, which includes comprehensive mapping between the roadmap's flood hydrology actions and the higher-level flood management outputs that are shown in Figure 8.

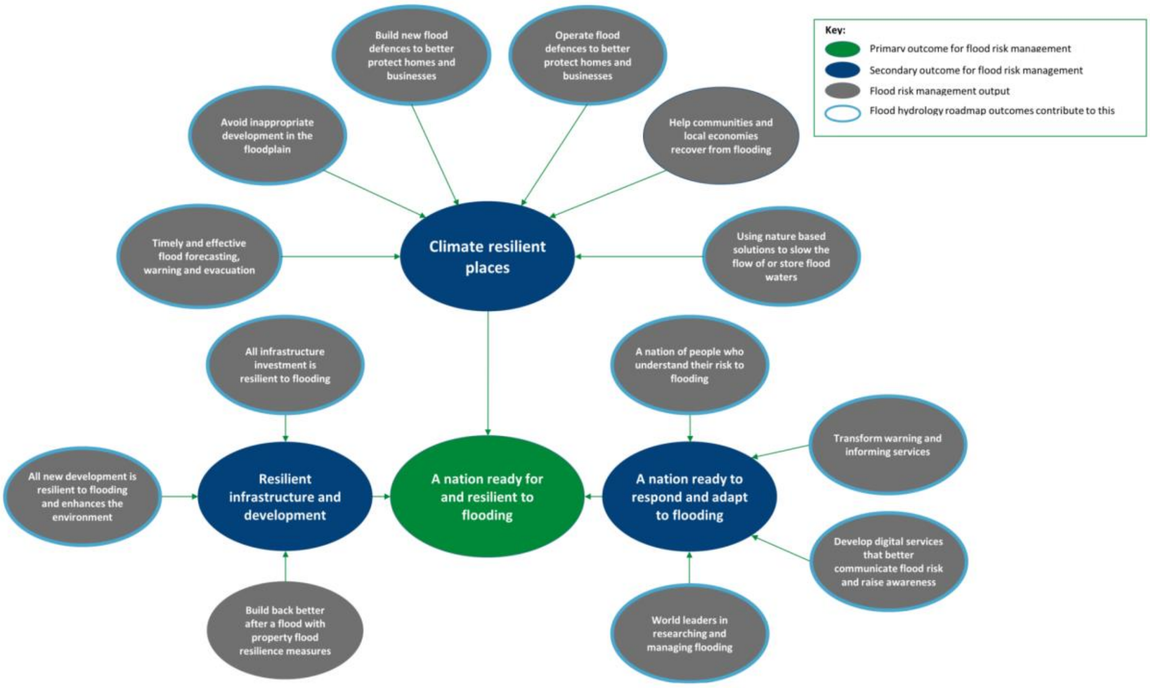


Figure 8. High level mapping between outcomes of the flood hydrology roadmap and outcomes of the flood risk management strategy for England (reproduced from Figure 8 in Environment Agency, 2022).

There are few estimates of the economic value of flood hydrology, or, specifically, research and innovation in flood hydrology. The annual economic benefits of the Flood Estimation Handbook (Institute of Hydrology, 1999) were estimated in 2006 (CEH, 2020) to be between £8.3 million and £31.3 million (£11.2m and £42.2m at 2021 prices), whilst the reduction in damages from flood early warning systems, including both meteorological and hydrological components, was estimated by NERC (2015) at between £76 million and £127 million (£86m and £145m at 2021 prices). The above assessments are not comprehensive evaluations of all the benefits of flood hydrology, which may be larger. Even so, the figures demonstrate the potential for the roadmap action plan to deliver benefits that considerably exceed its costs. An action within the roadmap ("W4: Identify ways to improve investment in flood hydrology") will address in detail the business case for further investment in flood hydrology by quantifying the contributions of hydrology and hydrometric data to flood risk management outcomes, while other actions will explore the value of the (flood) hydrology skills base and provide for evaluation of the benefits realised through the roadmap.

Discussion

Outcomes

Individual actions and their outcomes are detailed comprehensively within the published roadmap. Rather than duplicate the details, we will discuss the key characteristics below.

Flood hydrology is often described in terms of physical domains (e.g., surface water, rivers, urban), scales (e.g. long-term risk, real-time forecasting, small catchments), or sectors (e.g. regulatory, academic, private). The four themes that emerged through the roadmap's co-creation process (ways of working, data, methods and scientific understanding) instead provided a useful and parsimonious architecture of flood hydrology, both as a technical discipline and profession, that helped enable the roadmap to develop along multi-disciplinary and multi-sectoral lines.

As expected, the roadmap includes strong emphases on observations, data and modelling. Data from past events cannot be changed (unless systematic measurement errors are discovered and corrected), but it may be possible to assess uncertainties better to help decide on priorities for future observations, either to improve current estimates or to commission new types of measurement. It is notable that uncertainty features in the roadmap as a fundamental topic, along with an open philosophy with respect to data, methods and models. Future environmental change is a primary example of how knowledge uncertainties may influence decisions that shape flood resilience.

Funding is inevitably a critical challenge for any programme as ambitious as the roadmap. The allocation of funds by the EA (see above) marks a significant early outcome. Further sources in future could include other UK regulatory or public sector bodies, UKRI, European and other international programmes, private industry and charities. By combining scientific research and applied needs in a coherent package, the roadmap will help to inform and substantiate the pathways to impact through which future research funding will deliver wider benefits. A critical element of this is likely to be continued efforts to understand, quantify and reduce uncertainties.

The roadmap recognises the importance of sustaining the flood hydrology community if the 25-year vision is to be realised. It represents a coalition of interests from across hydrology, flood management and allied disciplines. The roadmap offers a focal point for this community; its future evolution is likely to depend in part on funding, combined with continued voluntary activities of societies such as the British Hydrological Society, which has agreed to support the implementation of the roadmap through engagement activities. The vision is not static; rather, continuing review and opportunities for updating of the roadmap are foreseen through the “ways of working” theme.

Returning to comparisons with international perspectives, in Supplementary Information 1 we present a text-mining analysis to map between the 23 UPH and the UK flood hydrology roadmap actions. This shows strong alignment across many topics. The analysis indicates that the international perspective perhaps places more explicit emphasis on links and feedbacks between social and physical systems (see, for example, Di Baldassarre et al., 2015). This may in part reflect the fact that the roadmap was from the start embedded within the wider practice of flood risk management within the UK, which is, fundamentally, concerned with interfaces between physical and social systems. Two of the three key pillars for progress in hydrology identified in the 23 UPH were “generalisation and open data/models”, and “activities organised around integrated questions”; the UK flood hydrology roadmap is aligned with both. Blöschl et al. (2019) gave equal importance to the substance of the 23 unsolved problems and to the process of community-level learning involved in their development, and they advocated for similar consultations to be carried out in future. This finding is perhaps echoed in the roadmap’s “ways of working” theme, which aims to sustain a community of science and practice in flood hydrology. However, it is interesting to reflect on differences in framing of this concept; the roadmap process is perhaps more oriented towards outputs and applications, rooted in scientific progress, whereas the 23 UPH is framed in terms of collective learning. In taking the roadmap forward, it may be beneficial to identify explicitly the opportunities for community-level learning.

The third key pillar of the 23 UPH initiative may offer a useful challenge in the future implementation of the UK roadmap. It relates to risk and reward. The roadmap has been developed with explicit consideration of opportunity costs, delivery risks and optimism bias. Perhaps reflecting similar considerations, the 23 UPH project recognised that progress is often incremental and most of the UPH might not be "solved conclusively but can likely be realistically advanced in the next couple of decades" (Blöschl et al., section 4.2.1). However, the authors also gave explicit consideration of high-risk/high-gain activities, noting that apparently "outrageous" scientific hypotheses (difficult as they are to define) can turn out to be true. A hydrological case in point may be the existence of preferential flows in soils (Beven, 2018), perhaps as an element of a fundamental reconsideration of the natural hysteresis in hydrological systems (Beven, 2019). The 23 UPH could prompt a useful debate about where the balance should lie between such apparently riskier ideas, and a professional culture that tends to favour "solid, proven methodologies".

Limitations

We noted earlier that a stakeholder analysis was maintained throughout the roadmap's development to help reduce the scope for bias. This was done to ensure representation within the roadmap across different technical disciplines and from different categories of stakeholder, including by sector (e.g. public, private), function (e.g. service user, service provider, regulator), geography (representation across UK regions, international) and impact or influence (e.g. directly affected, indirectly affected, able to affect the work).

Equality, diversity and inclusion (EDI) emerged amongst the principles to be embedded within the roadmap. This is reflected in the emphasis given to EDI within roadmap actions, such as in the establishment of a technical advisory group for UK flood hydrology (Action W2). Future stakeholder engagement could include an explicit EDI plan, and usefully gather information about the characteristics of the community.

It is a challenge to understand the professional community around flood hydrology because it is varied and does not necessarily speak with one voice (as evidenced by the many different priorities identified in the roadmap). The inter-disciplinary nature of hydrology means that the boundaries between flood hydrology and related disciplines are difficult to draw. The roadmap engagement was framed as a practical exercise rather than as a research project. Resources were not available to fund research about the engagement process itself, but this perhaps missed an opportunity to gain additional insights. An initial review of the representation of different disciplines and groups within similar national or international initiatives (not only in hydrology) might help steer the initial consultation in future scoping exercises.

Stakeholders were not asked to identify their backgrounds with fixed disciplinary categories precisely because of an awareness of the inter-disciplinary nature of flood risk management and the consequent risk of reductionism. However, their backgrounds spanned multiple disciplines including, in alphabetical order: climate science, ecology, economics, engineering, geology, geomorphology, meteorology, policy and social sciences. Input from the meteorology and climate science communities was strong with participation from the Met Office (UK), incorporating perspectives on integrated environmental modelling from the wider Unified Model Partnership[11], from the Bureau of Meteorology (Australia), and from the European Centre for Medium-Range Weather Forecasts (ECMWF). Better integration across different sectors and disciplines was ranked 17th most important out of 38 potential work areas in the online survey, and inter-disciplinary issues feature explicitly in Actions W5 (Build hydrological skill, esteem and value), D3 (Assess the potential of new observational technologies to improve flood hydrology), S7 (Develop proposals for research programmes) and S8 (Potential research programmes).

[11] https://www.metoffice.gov.uk/research/approach/collaboration/unified-model/partnership

Conclusions

The flood hydrology roadmap is a significant step in the evolution of hydrology within the UK, both as a scientific and an applied profession. It has brought together different sectors and disciplines to produce a costed, long-term plan with shared ownership and a clear vision. Its origins reflect a diverse need for applications of hydrology in flood risk management and related activities, and an engaged research community.

The roadmap captures the energy and ambitions of a large, representative coalition of individuals and public-, private-, academic- and third-sector organisations. Although its original stimulus came in large part from an applied perspective, it recognises the importance both of scientific progress and of practical drivers. Comparisons with other national and international hydrological scoping initiatives show much commonality with the roadmap, whilst suggesting it may be useful to explore further the interfaces between flood hydrology and water quality, health and social science. The roadmap includes mechanisms to enable its action plan to adapt and evolve to address any scientific gaps or changes in context that become apparent.

In total, the roadmap embodies a substantial, coordinated intellectual effort by more than 270 people over 47 months. It has been developed using multiple modes of engagement, an approach that has succeeded in galvanising and bringing together a community of differing interests. The multi-modal approach to engagement was particularly important in enabling the roadmap to continue its development despite disruptions caused by the Covid-19 pandemic. The roadmap presents an ambitious, 25-year, programme that has already helped to enable significant new investment into the improvement of flood hydrology within the UK. By publishing this commentary in Hydrology Research, an international journal, we hope to have placed the roadmap in context, to have highlighted insights from the headline report and its appendices, and to encourage further exchange and learning between the UK flood hydrology community and international communities of practice.

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Supplementary information, S1

We visualise a mapping of topics between the roadmap and 23 UPH in Figure S1. First, we associated each of the 23 UPH with a set of descriptive single or muti-word expressions, which we call key words (Table S1). We then searched for occurrences of the key words within the detailed action plan published in Appendix G of the roadmap. We sense-checked the results to remove spurious matches caused by words appearing in unrelated contexts; for example, we rejected matches between the key word “scale” associated with UPH 6 (“What are the hydrologic laws at the catchment scale and how do they change with scale?”) and the word “timescales” that appears in Appendix G in a project management context. The results of the topic mapping are, of course, a reflection of our choice of key words, which is inherently subjective, and our decision to search for matches within the roadmap actions, as opposed, say, to the entire roadmap text. We chose to base the analysis exclusively on the roadmap actions in order to focus on future activities.

The visualisation does not imply dependencies between the roadmap and the 23 UPH; the mapping merely indicates an association of topics between the two publications based on common occurrences of the chosen key words. The association appears to be stronger for the roadmap’s “data”, “methods” and “scientific understanding” themes than for the “ways of working” theme. This should be expected, given that the ways of working theme is less directly concerned with the underlying scientific issues than the other themes.

The results suggest that most of the UPHs are relevant to the roadmap. However, there were no key word associations found between the roadmap actions and UPHs 2, 3, 8, 15 and 23. Of these, UPH 2 and UPH 3, relate specifically to cold and (semi-)arid regions, which are not dominant in the UK (although both climates may be relevant to UK hydrology, especially when considering climate change). UPH 8 is about the distribution of response and water transit times in catchments, which are relevant to the hydrological processes that explain and control hydrological extremes. The roadmap action plan places significant emphasis on process understanding and research, but specific research questions about transit times are perhaps implicit within the broader ambition to improve scientific understanding rather than being articulated explicitly in the actions. UPH 15 is about contaminants and pathogens. Although these key words are not mentioned explicitly in the roadmap actions, action S4 (“Identify research needs to improve understanding of flood generation processes and drivers of hydrological change”) includes a call to treat the science of flood hydrology holistically, including consideration of water quality. The lack of a match with UPH 15 is perhaps suggestive of a gap that could be explored further in terms of interfaces between flood hydrology and pollution or health issues. We also found no key word matched with UPH 23, which relates to the role of water in the dynamics of human civilisations. Although the FHRM is fundamentally about the interaction between human and natural systems, this interaction was framed in the context of established institutional and legislative structures, rather than as a research topic.

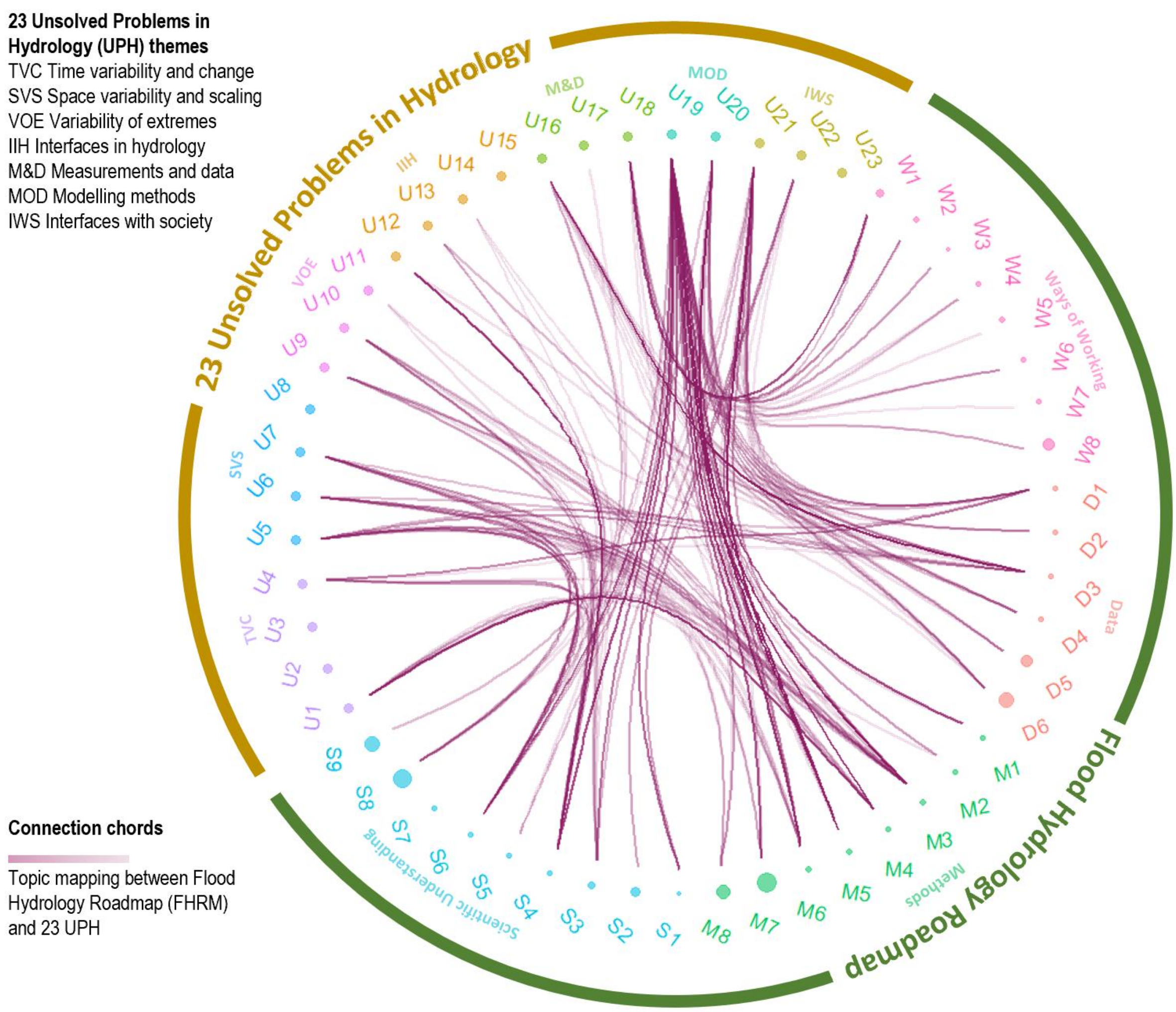

Figure S1. Topic mapping between actions in the UK Flood Hydrology Roadmap and the IAHS 23 Unsolved Problems in Hydrology, based on co-occurrence of key words listed in Table S1. Nodes around the circumference represent the roadmap actions (labelled by theme: W*n*, D*n*, M*n*, S*n*, and scaled in proportion to their indicative costs) and the 23 UPHs (labelled U*n*). Each chord represents one key word match.

Table S1. Key word search terms associated with the 23 Unsolved Problems in Hydrology (UPHs) for topic matching with the Flood Hydrology Roadmap actions.

UPH	**Key Words**
1. Is the hydrological cycle regionally accelerating/decelerating under climate and environmental change, and are there tipping points (irreversible changes)?	climate change, environmental change, tipping points, variability
2. How will cold region runoff and groundwater change in a warmer climate (e.g. with glacier melt and permafrost thaw)?	cold region
3. What are the mechanisms by which climate change and water use alter ephemeral rivers and groundwater in (semi-) arid regions?	ephemeral, arid, semi-arid, water use
4. What are the impacts of land cover change and soil disturbances on water and energy fluxes at the land surface, and on the resulting groundwater recharge?	land cover change, land use change, land management, soil, groundwater, energy fluxes, fluxes, land surface, recharge
5. What causes spatial heterogeneity and homogeneity in runoff, evaporation, subsurface water and material fluxes (carbon and other nutrients, sediments), and in their sensitivity to their controls (e.g. snow fall regime, aridity, reaction coefficients)?	reaction coefficients, spatial patterns, heterogeneity, evaporation, nutrient, sediment, sensitivity, homogeneity, carbon flux, carbon cycle, nutrient cycle, morphology, scaling, scale, spatially coherent
6. What are the hydrologic laws at the catchment scale and how do they change with scale?	hydrological laws, theories, scale, scaling, spatially coherent
7. Why is most flow preferential across multiple scales and how does such behaviour co-evolve with the critical zone?	preferential flow, scaling, critical zone, scale, macropore
8. Why do streams respond so quickly to precipitation inputs when storm flow is so old, and what is the transit time distribution of water in the terrestrial water cycle?	rapid response, transit time, wave speed, celerity, flash, attenuation, time constant
9. How do flood-rich and drought-rich periods arise, are they changing, and if so why?	flood-rich, drought-rich, temporal variability, cluster, flood rich, flood poor, variability, decadal, interannual
10. Why are runoff extremes in some catchments more sensitive to land-use/cover and geomorphic change than in others?	runoff extremes, sensitivity, land use, land management, morphological change, variability

11. Why, how and when do rain-on-snow events produce exceptional runoff?	rain-on-snow, extreme events
12. What are the processes that control hillslope-riparian-stream-groundwater interactions and when do the compartments connect?	hillslope, processes, interactions, riparian, compartments, connectivity
13. What are the processes controlling the fluxes of groundwater across boundaries (e.g. groundwater recharge, inter-catchment fluxes and discharge to oceans)?	groundwater, recharge, inter-catchment, inter-basin, ocean, marine, boundary, boundaries
14. What factors contribute to the long-term persistence of sources responsible for the degradation of water quality?	persistence, water quality, pollution, degradation, WFD, heavily modified, failing, chemical, chemistry
15. What are the extent, fate and impact of contaminants of emerging concern and how are microbial pathogens removed or inactivated in the subsurface?	pathogens, microbial, contaminants, fate
16. How can we use innovative technologies to measure surface and subsurface properties, states and fluxes at a range of spatial and temporal scales?	innovation, observations, measurement, technology, technologies, states
17. What is the relative value of traditional hydrological observations vs soft data (qualitative observations from lay persons, data mining etc.), and under what conditions can we substitute space for time?	qualitative, data mining, media, anecdotal, unstructured data
18. How can we extract information from available data on human and water systems in order to inform the building process of socio-hydrological models and conceptualisations?	human, socio-, governance, industry, social
19. How can hydrological models be adapted to be able to extrapolate to changing conditions, including changing vegetation dynamics?	vegetation, models, change, extrapolate, extrapolation
20. How can we disentangle and reduce model structural/parameter/input uncertainty in hydrological prediction?	uncertainty, model structure, model input, parameter, confidence
21. How can the (un)certainty in hydrological predictions be communicated to decision makers and the general public?	communication, decision, public, uncertainty
22. What are the synergies and tradeoffs between societal goals related to water management (e.g. water-environment-energy-food-health)?	societal goals, society, water management, health, policy, regulation, food
23. What is the role of water in migration, urbanisation and the dynamics of human civilisations, and what are the implications for contemporary water management?	migration, urbanisation, human, civilisation