

The future of flood hydrology in the UK

Article

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1 The future of flood hydrology in the UK

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27

28

29 Abstract

30

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

39

40 Keywords

41

42 Flood, hydrology, research, practice, future, plan

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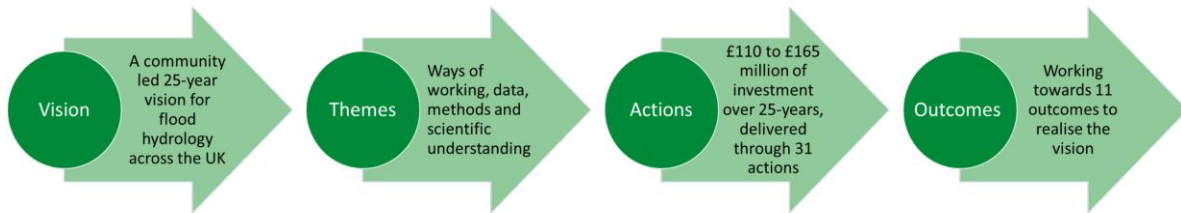
44 Highlights

45

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

52

53 Graphical abstract



54

55

56 Introduction

57

58 Flood risk in the UK

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

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

72 Flood risk EAD in the UK has been projected to reach £2.7-3.0bn annually in the 2080s under a global
 73 warming trajectory of +2°C by 2100, or £3.5-3.9bn under a +4°C trajectory. Inland hydrological risks
 74 will continue to predominate in economic terms, although relative increases in risk will be largest for
 75 surface water (from £587m to £1.2bn in a +4°C future) and coastal (£361m to £1bn) flooding. These

76 projections assume that risk management measures, including land use planning and investment in
77 flood and coastal defences, will continue at rates commensurate with current policy objectives.
78 Enhanced flood management, including increased investment, appears to have the greatest
79 potential to mitigate the projected increases in risk for fluvial flooding, which further highlights the
80 importance of flood hydrology.

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

88

89 [Historical context and drivers for change](#)

90 There is a long tradition of hydrological research and observation in the UK (Rodda and Robinson,
91 2015), dating back at least as far as quantitative experiments by Edmund Halley in the seventeenth
92 century (Deming, 2021), and often intrinsically linked with practical problems in water management
93 (J.S.G. McCulloch, 2007, C. McCulloch, 2022). The water sector today reflects a complex mosaic of
94 public, private and third sector stakeholders. Although the interconnectedness of the hydrological
95 cycle has long been appreciated (Biswas, 1970), a fragmentation of responsibilities (Pitt, 2008) and
96 the generally increasing depth of technical knowledge in science and engineering disciplines mean
97 that methods applied in practice have become increasingly functionally specialised. Many methods
98 routinely used in UK flood hydrology have roots in the 1960s-1990s. For example, the Flood Studies
99 Report (NERC, 1975) paved the way for the Flood Estimation Handbook (FEH, Institute of Hydrology,
100 1999) and its derivatives in current use. The FEH methods are widely used, including in the national
101 risk mapping that underpins the risk assessments cited in the opening paragraphs of this paper. Yet
102 some choices made in the past, for example assumptions of spatial uniformity or temporal
103 stationarity, could be questioned when viewed with a contemporary perceptual understanding of

104 hydrology (Wagener et al. 2021), or when taking account of advances in observations (Beven et al.,
105 2019) or evidence of change in UK flood data (Faulkner et al. 2020, Hannaford et al., 2021).

106 Regionally- and nationally- significant events in Britain (including in 1998, 2000, 2005, 2007, 2009,
107 2013-16, 2019 and 2020) have highlighted the impacts of flooding (Environment Agency, 2018).

108 Meanwhile, an increasing emphasis on whole-system thinking points to a need for integrated
109 models to support improvements in flood resilience (Cabinet Office, 2016). In recent years,
110 transformations in our capacity to share information rapidly through digital communications, an
111 increasing appreciation of the importance of community ownership of risk, and perhaps also an
112 expansion of educational and training opportunities in flood risk management have stimulated a
113 wider range of demands on hydrological data and methods.

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

119

120 [The 25-year roadmap for flood hydrology](#)

121 This paper describes how the evolving demands for hydrological analysis and advances in scientific
122 knowledge have prompted a comprehensive reappraisal of research and innovation in UK flood
123 hydrology, culminating in the publication of a roadmap for the next 25 years (Environment Agency,
124 2022), available from [https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-
125 reports/flood-hydrology-roadmap](https://www.gov.uk/flood-and-coastal-erosion-risk-management-research-reports/flood-hydrology-roadmap).

126 The roadmap is a community initiative, building on a strongly collaborative approach that will be
127 introduced in the following section. We then describe the objectives of the roadmap project, and
128 how it fits with related initiatives both in the UK and internationally. The following sections set out
129 the methodology for development of the roadmap and summarise its contents. We then discuss
130 how the roadmap is being implemented, what is needed to ensure its long-term success, and

131 aspects of its development that may be transferable to other settings. We conclude with an
132 overview of the roadmap project's key outcomes.

133

134 Research, innovation and knowledge-sharing in UK flood risk 135 management

136

137 Flooding and coastal risk management (FCRM) are considered together in UK policy. No recent
138 estimate is available of total spend on research or innovation in flood hydrology, although analysis in
139 2011 found that over the preceding decade there had been annual public spend of between
140 approximately £7m and £14m (£12.5m and £25m at 2021 prices) in FCRM research (Moore and
141 Rees, 2011). The private sector also invests in FCRM research and innovation, but this has not been
142 quantified.

143 An important feature of flood risk management in the UK is the history of cooperation between
144 universities, the public sector and private industry. Collaborative research and development
145 programmes (including those in footnotes^{1,2,3,4}) have helped to promote exchanges of knowledge
146 about the scientific and practical drivers for continuing developments in flood hydrology. Research
147 programmes with a focus on flood risk have included Flood Risk from Extreme Events (FREE,
148 Hardaker and Collier, 2013), the Flood Risk Management Research Consortium (FRMRC,
149 Environment Agency, 2021) and Flooding From Intense Rainfall (FFIR)⁵. This coordination helps
150 support communities of practice, enhanced through knowledge exchange networks including
151 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>

152 more than 900 members, the British Geomorphological Society, and chartership institutions in water
153 management⁶, civil engineering⁷, meteorology⁸, geology⁹ and geography¹⁰.

154

155 Governance and objectives of the flood hydrology roadmap

156

157 Recognising the broad drivers for change discussed above and the long-term (~10 to ~100 years)
158 influence of flood hydrology on infrastructure and land use plans, the flood hydrology roadmap was
159 initiated in 2018 through a research and development programme¹ run jointly by public risk
160 management authorities and government departments in England and Wales. First, a project board
161 was established to take overall responsibility. The board was supported by, and worked closely with,
162 a steering group drawn from the regulatory, academic and non-profit organisations. For brevity the
163 board and steering group will be referred to in this paper as the “project team”.

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

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

172

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/>

173 Related initiatives

174

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

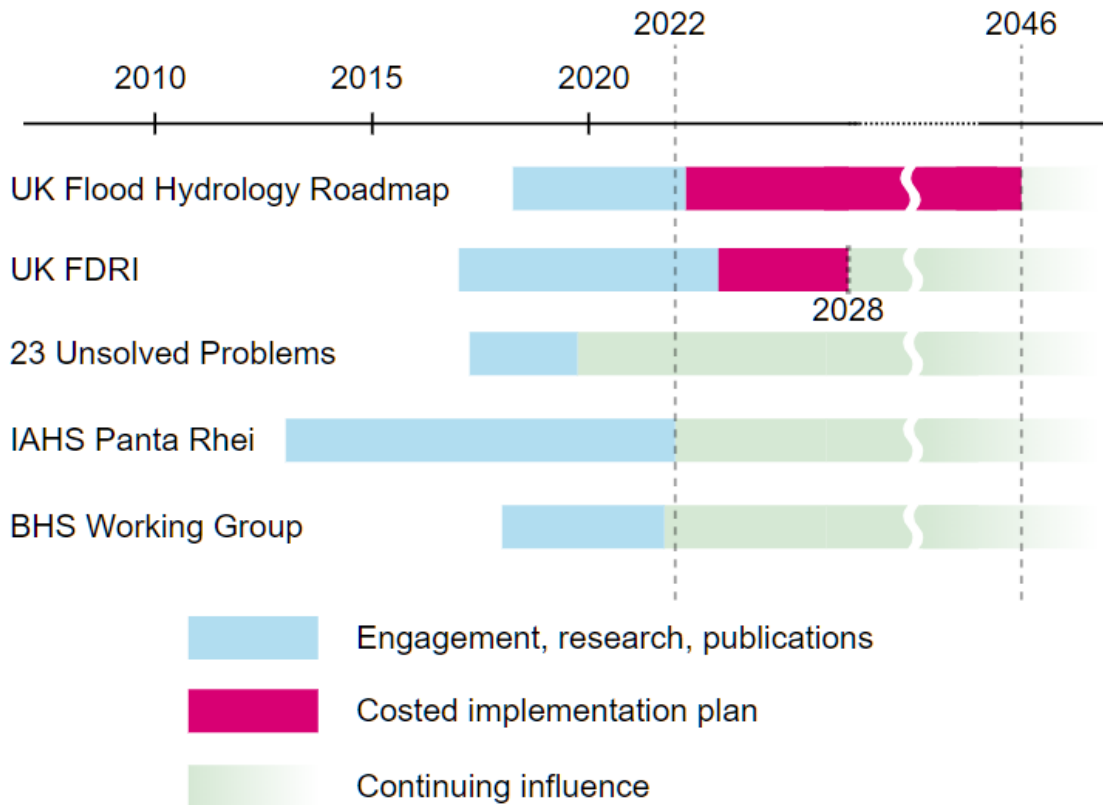
181 Three of the UPH relate specifically to hydrological extremes, either droughts or floods, and one
182 relates exclusively to exceptional runoff produced by rain-on-snow events. The 23 UPH in general
183 reflect fundamental questions about variability, scaling, process interactions, empiricism, modelling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

192 In the UK, a working group was formed in 2018, under the auspices of the BHS, to debate and make
193 recommendations about the future of UK hydrology, leading to two journal papers (Beven et al.,
194 2020, Wagener et al., 2021). Most individuals who participated in the BHS working group also
195 contributed to the roadmap. Additionally, the roadmap team examined the working group’s outputs
196 to understand areas of strong or weak alignment with the emerging roadmap, a process that
197 informed the final action plan.

198 Another source of advice that informed the roadmap was a UK flood resilience review (Cabinet
199 Office, 2016), which made the case for integrated modelling, encompassing both physics-based and
200 statistical approaches, regular updating of risk assessments and tests of resilience based on extreme

201 event scenarios. An earlier report commissioned by the Government Office for Science (Royal
202 Society, 2015) highlighted the need for improved observations of natural hazards, including flooding,
203 to increase the UK's resilience. This prompted a study (from 2020 to 2022) to establish the
204 requirements for national Floods and Droughts Research Infrastructure (FDRI). The aim of the FDRI is
205 to transform research capability to improve flood and drought forecasting, planning, incident
206 response and management. The FDRI study engaged with a broad range of stakeholders from public,
207 private and non-profit sectors, using similar methods to the flood hydrology roadmap, and
208 producing several proposed investment options, which are being taken forward into a business case
209 for funding at the time of writing. The Reservoir Safety Research Strategy (Environment Agency,
210 2016) also highlighted needs for research on extreme rainfall and runoff, which have informed the
211 roadmap.

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



216

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

220

221

222 Methodology

223

224 Overview

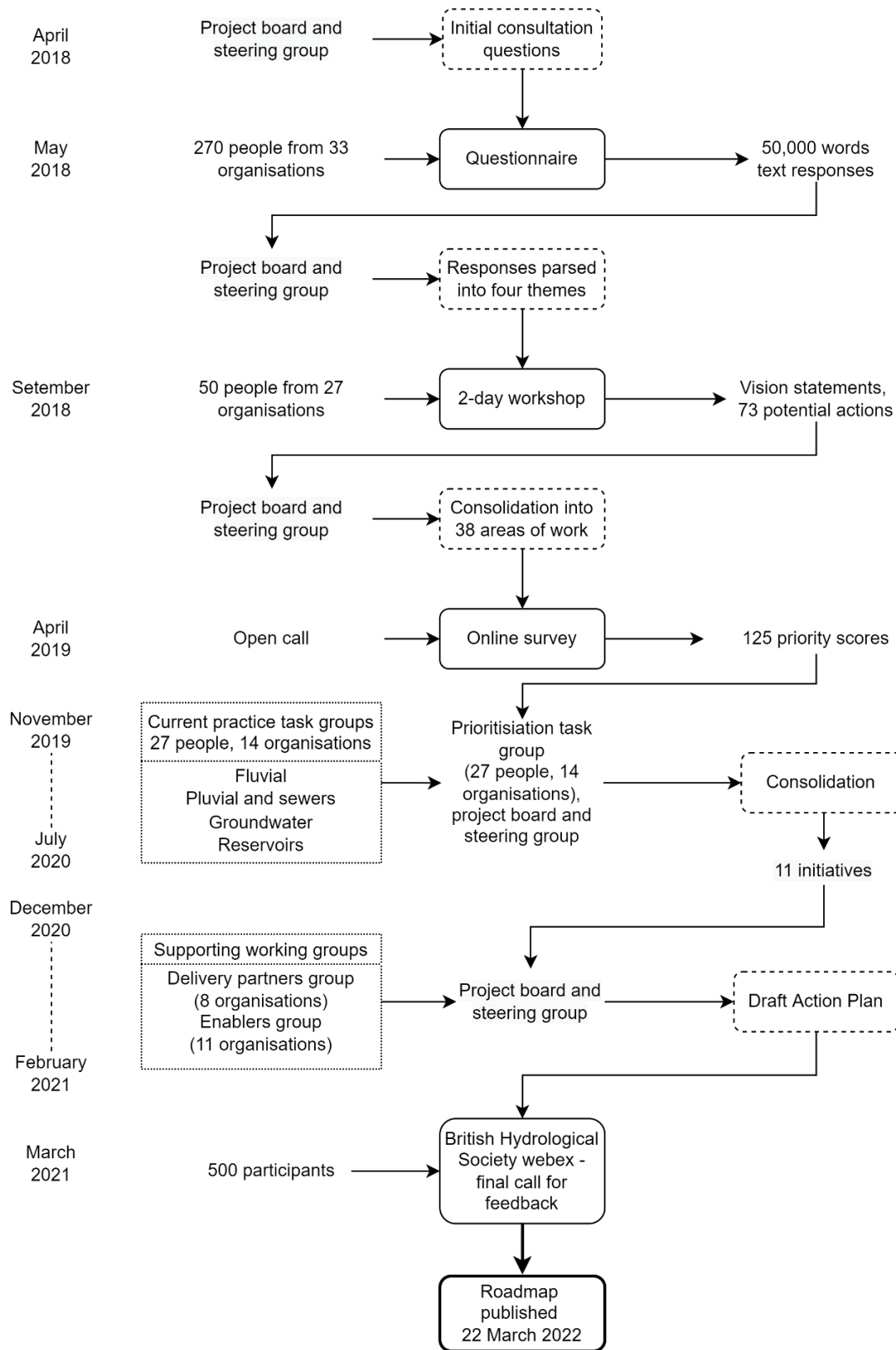
225 The roadmap developed as an iterative co-creation process. Figure 2 shows its evolution,
 226 highlighting stakeholder engagements and the progressive refinement of ideas. Table 1 details
 227 interactions with the stakeholder community. In total, there were >1,000 points of engagement
 228 (comprising responses to surveys, attendances at meetings, webinar participation and written

229 inputs) involving >270 individuals. Different modes of engagement were used to maximise the
230 opportunities for participants to get involved, and to reduce the scope for inadvertent biases that
231 might have occurred had there been only one way to contribute. Written questionnaires, in-person
232 and online workshops, online survey, specialist task groups and public webinars were all deployed. A
233 stakeholder “map” was created and maintained throughout to monitor the makeup of the
234 community participating in the roadmap’s development (see discussion of Figures 6 and 7 below)
235 and ensure that a spread of disciplines, types of organisation and interests were represented.

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

242

243



244

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

246 and processes).

247

248 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

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253 Questionnaire

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

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

271

272

273 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.

274

275

276 [Workshop](#)

277 The workshop aimed to build ownership of the roadmap among influential stakeholders, and to start

278 creating its content in terms of a vision for the future, analysis of perceived needs, and the actions

279 required to meet those needs. Over two days, 50 individuals from 27 organisations generated draft

280 vision statements and 73 potential actions grouped into 16 clusters. For example, one cluster of

281 actions was "Improve access to flood hydrology data"; see Environment Agency (2022, Appendix C)

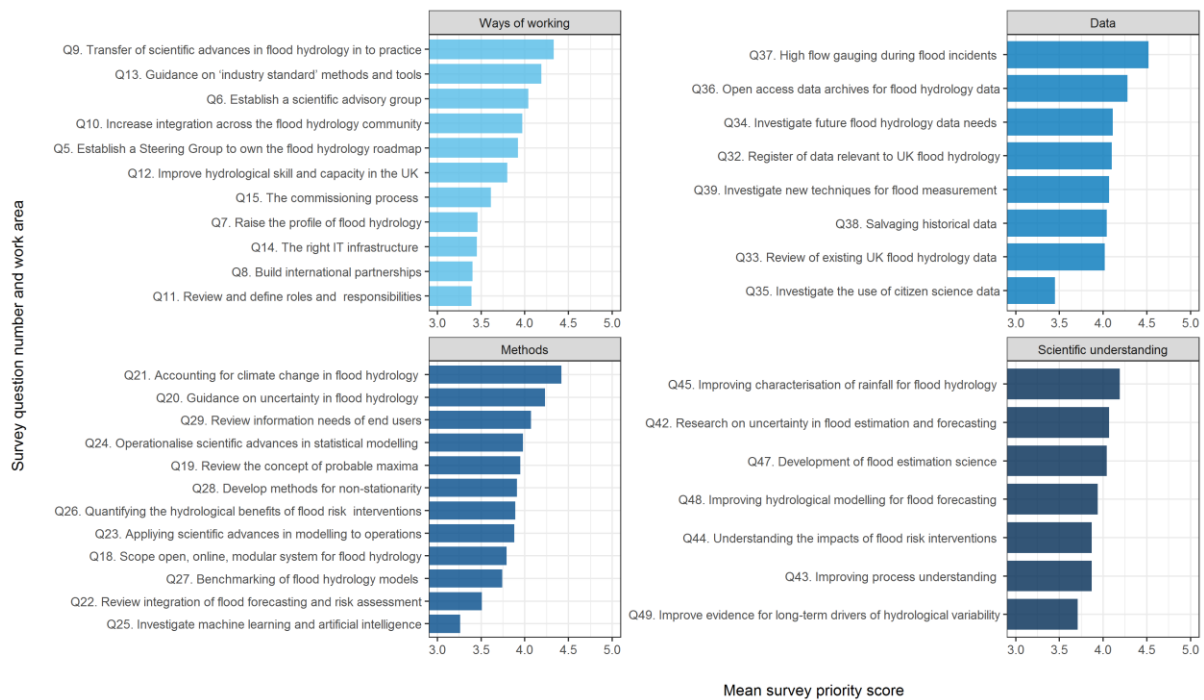
282 for a comprehensive account. The 73 actions were further consolidated by the project team into 38
 283 potential areas for future work, which formed the basis of the next step, an online survey.

284

285 **Online survey**

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

290



291

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

294

295

296 **Current practice and prioritisation task groups**

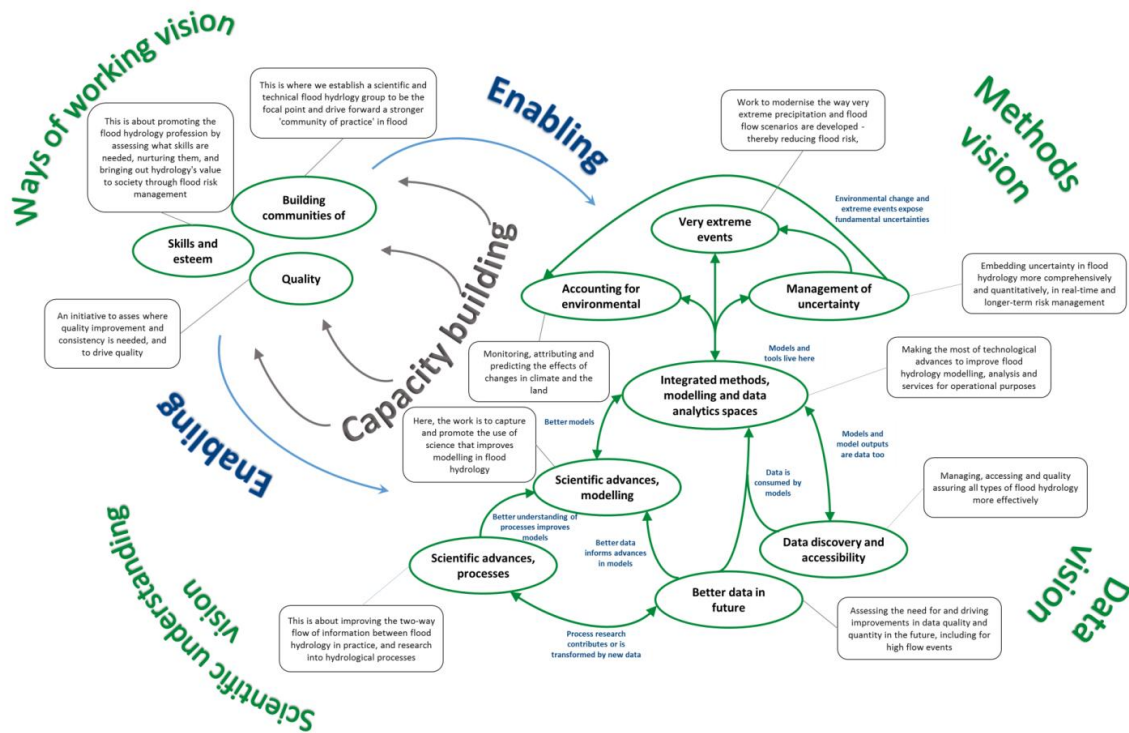
297 Four task groups were established in March 2019 to summarise the current state of knowledge with
298 respect to reservoirs, groundwater, surface water and fluvial flood risk, considering both forecasting
299 and flood risk management planning perspectives. The groups comprised volunteers with expertise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

304 A prioritisation task group with 27 members was also established following the April 2019 online
305 survey. Its remit was to help shape the survey responses into a draft action plan. The group included
306 people with a mix of regulatory, private sector and academic backgrounds, with interests and
307 expertise spanning the same topics as the current practice groups. The terms of reference included
308 13 prioritisation criteria, encompassing judgements about economic and social benefits, technical
309 outcomes, affordability and project management risks or opportunities. The resulting matrix of 13
310 criteria and 38 potential work areas, many of them co-dependent, was too complex to support a
311 straightforward ranking. To help constrain the process, the 38 work areas were refactored into 11
312 inter-linked “initiatives”, shown in Figure 4, which identifies the relationships between the initiatives
313 and the four thematic visions. Each initiative was presented as a short proposal setting out its
314 context, drivers, objectives, outputs and expected benefits, along with the risks of not carrying out
315 the work (Environment Agency, 2022, Appendix F).

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

318

319



320

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

325

326

327 **Delivery plan**

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

333

334 Webinar

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

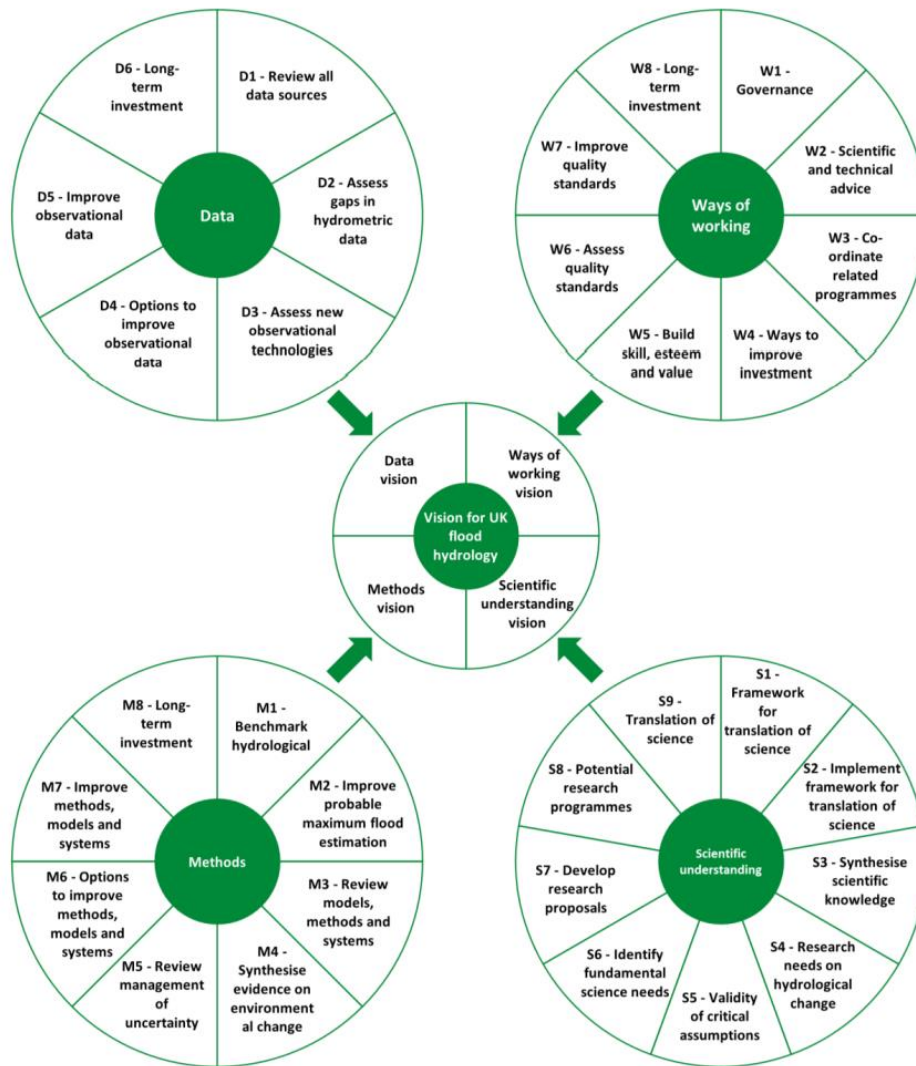
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340 The flood hydrology roadmap

341

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

350



351

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

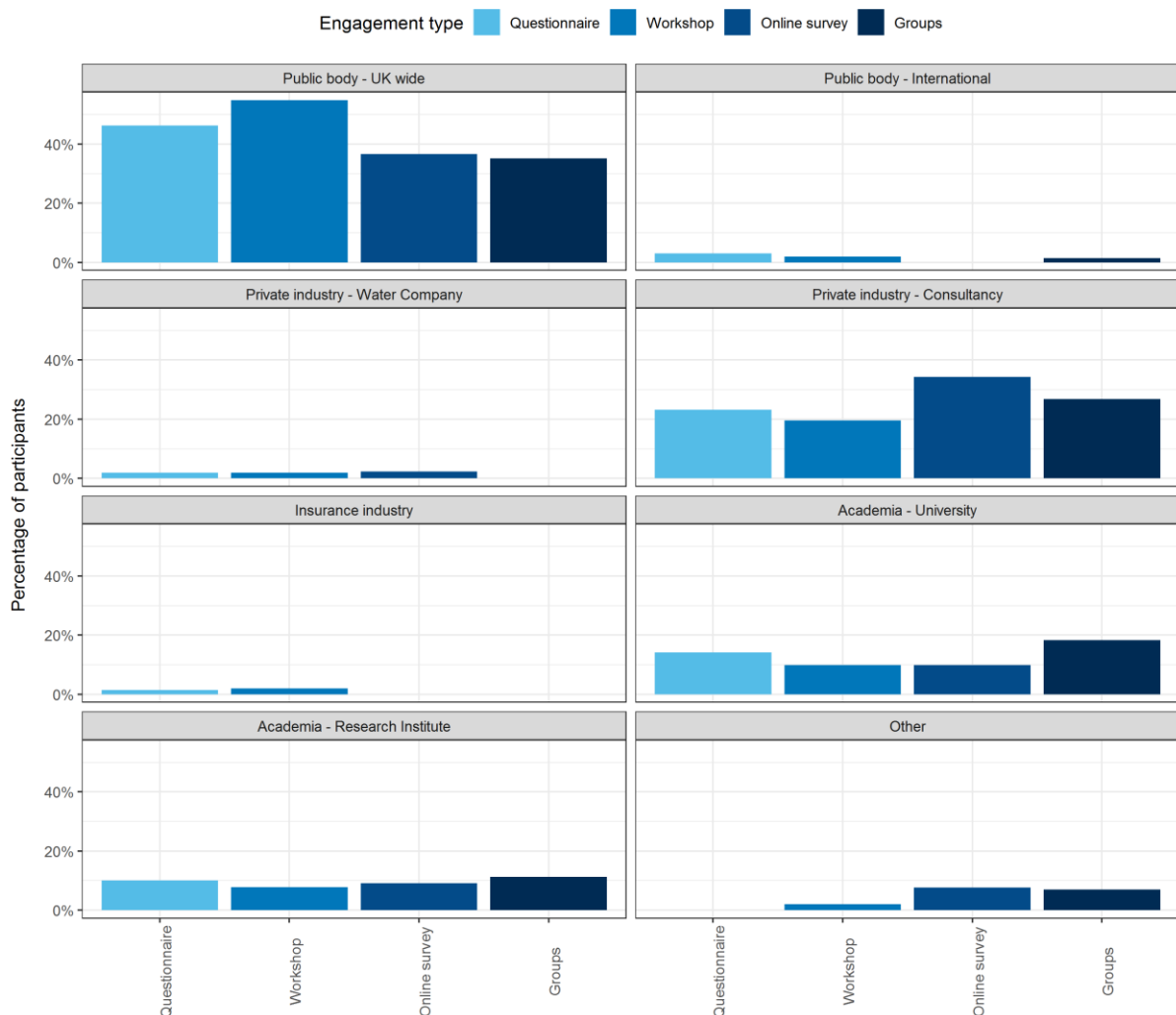
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355

356 [Composition of the UK flood hydrology community](#)

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

362 providing reassurance about the representation of both the research community and practitioner
 363 stakeholders.



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365

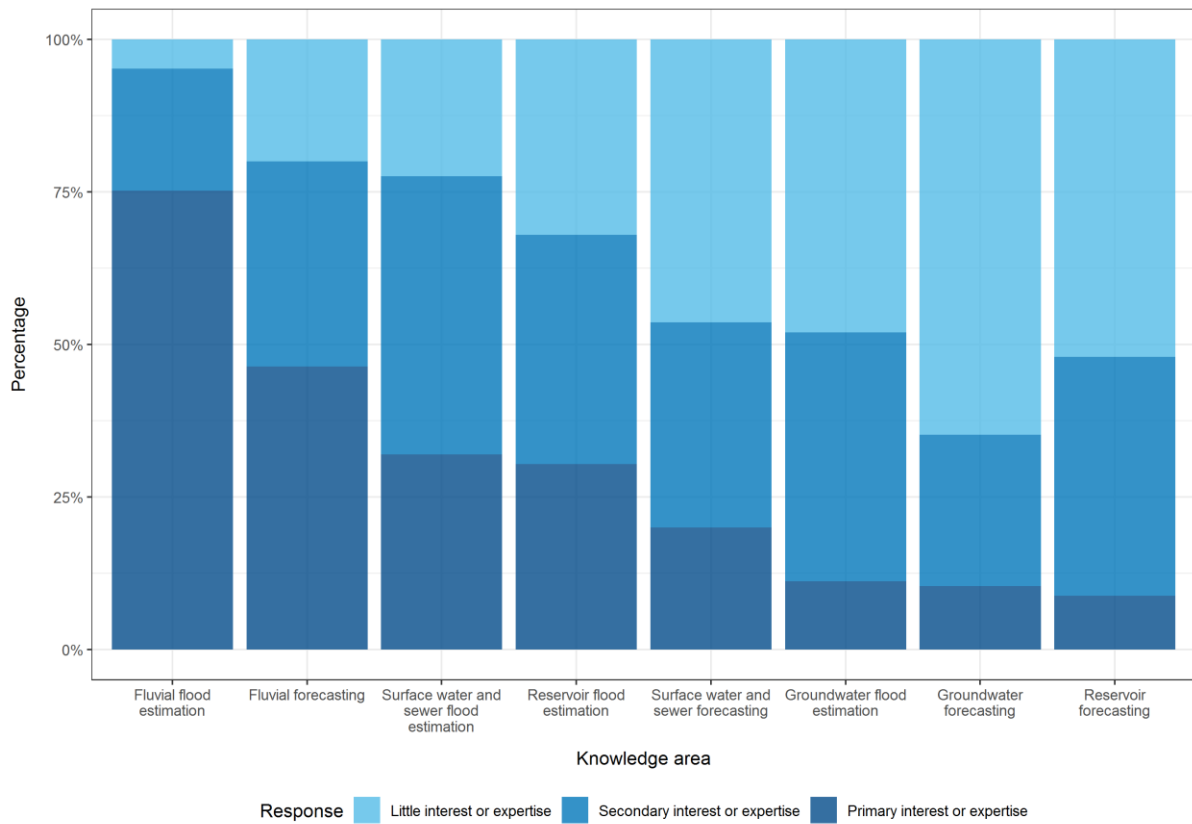
366 Figure 6. Sectoral distribution of the stakeholder community engaged throughout co-creation of the
 367 roadmap, grouped by organisation type (separate panels) and mode of engagement (shaded bars).
 368 “Groups” refers to the multiple working groups involved in the latter stages of the roadmap.

369

370

371 Figure 7 shows the distribution of technical interests amongst those engaged during creation of the
 372 roadmap. Both long-term analysis of river flood flows (“flood estimation”) and near-future
 373 prediction (“forecasting”) were important areas of technical interest. Whilst fluvial hydrology was

374 the most common primary interest, surface water, reservoirs and groundwater were all strongly
 375 represented.



376

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

379

380 [25-year vision statement](#)

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

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

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

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

397

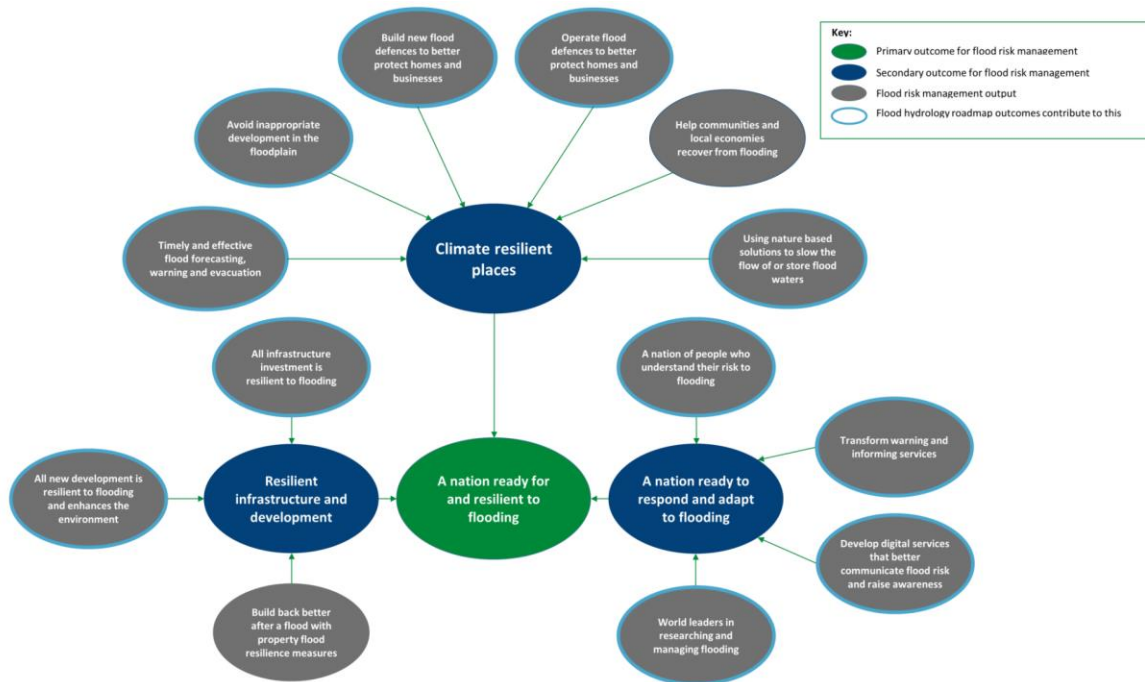
398 Funding and delivery

399 The roadmap has an estimated budget requirement of £110m (present value, PV, of £74m) over 25
400 years. Adjustments to account for optimism bias in cost and timing have been calculated using
401 methods detailed in Environment Agency (2022, Section 4.2), giving upper estimates of £165m (PV
402 £111) costs and a 37.5-year programme. The best estimate average annual funding requirement is
403 £4.4m, with a peak in 2032 in the range £9.9m to £14.9m (after optimism bias adjustment), and will
404 need to be met by, and coordinated across, multiple funding bodies. Already, the Environment
405 Agency in England has preliminarily allocated £6.9 million of funding over six years, from April 2021,
406 to begin implementing the roadmap. Additional funding for science, and its translation into practice
407 and policy, will be required to deliver the roadmap in full.

408 It is very difficult to construct a full economic appraisal of the roadmap *a priori* because the benefits
409 of investments in flood hydrology are varied, and are embedded deeply within many facets of flood
410 risk management, and across related aspects of environmental and socioeconomic planning. It is
411 likewise difficult to evaluate the benefits of flood management holistically (Defra, 2008). Instead, the
412 roadmap includes a mapping between its outcomes and the ultimate flood management benefits for
413 people and communities. The roadmap will contribute directly (as outlined in Figure 8) to 11 of the
414 13 flood risk management outputs in the FCRM strategy for England (Environment Agency, 2020),

415 which are prerequisites for the strategy’s desired outcome, “a nation ready for, and resilient to,
 416 flooding”. Further details of outcomes and benefits can be found in the roadmap, which includes
 417 comprehensive mapping between the roadmap’s flood hydrology actions and the higher-level flood
 418 management outputs that are shown in Figure 8.

419



420

421 Figure 8. High level mapping between outcomes of the flood hydrology roadmap and outcomes of
 422 the flood risk management strategy for England (reproduced from Figure 8 in Environment Agency,
 423 2022).

424

425

426 There are few estimates of the economic value of flood hydrology, or, specifically, research and
 427 innovation in flood hydrology. The annual economic benefits of the Flood Estimation Handbook
 428 (Institute of Hydrology, 1999) were estimated in 2006 (CEH, 2020) to be between £8.3 million and
 429 £31.3 million (£11.2m and £42.2m at 2021 prices), whilst the reduction in damages from flood early
 430 warning systems, including both meteorological and hydrological components, was estimated by
 431 NERC (2015) at between £76 million and £127 million (£86m and £145m at 2021 prices). The above

432 assessments are not comprehensive evaluations of all the benefits of flood hydrology, which may be
433 larger. Even so, the figures demonstrate the potential for the roadmap action plan to deliver benefits
434 that considerably exceed its costs. An action within the roadmap (“W4: Identify ways to improve
435 investment in flood hydrology”) will address in detail the business case for further investment in
436 flood hydrology by quantifying the contributions of hydrology and hydrometric data to flood risk
437 management outcomes, while other actions will explore the value of the (flood) hydrology skills base
438 and provide for evaluation of the benefits realised through the roadmap.

439

440 Discussion

441 Outcomes

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

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

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

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

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

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

487 towards outputs and applications, rooted in scientific progress, whereas the 23 UPH is framed in
488 terms of collective learning. In taking the roadmap forward, it may be beneficial to identify explicitly
489 the opportunities for community-level learning.

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

502

503 [Limitations](#)

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

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

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

524 Stakeholders were not asked to identify their backgrounds with fixed disciplinary categories
525 precisely because of an awareness of the inter-disciplinary nature of flood risk management and the
526 consequent risk of reductionism. However, their backgrounds spanned multiple disciplines including,
527 in alphabetical order: climate science, ecology, economics, engineering, geology, geomorphology,
528 meteorology, policy and social sciences. Input from the meteorology and climate science
529 communities was strong with participation from the Met Office (UK), incorporating perspectives on
530 integrated environmental modelling from the wider Unified Model Partnership¹¹, from the Bureau of
531 Meteorology (Australia), and from the European Centre for Medium-Range Weather Forecasts
532 (ECMWF). Better integration across different sectors and disciplines was ranked 17th most
533 important out of 38 potential work areas in the online survey, and inter-disciplinary issues feature
534 explicitly in Actions W5 (Build hydrological skill, esteem and value), D3 (Assess the potential of new
535 observational technologies to improve flood hydrology), S7 (Develop proposals for research
536 programmes) and S8 (Potential research programmes).

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

537

538 Conclusions

539

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

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

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

564

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566

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571

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573

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682 Supplementary information, S1

683

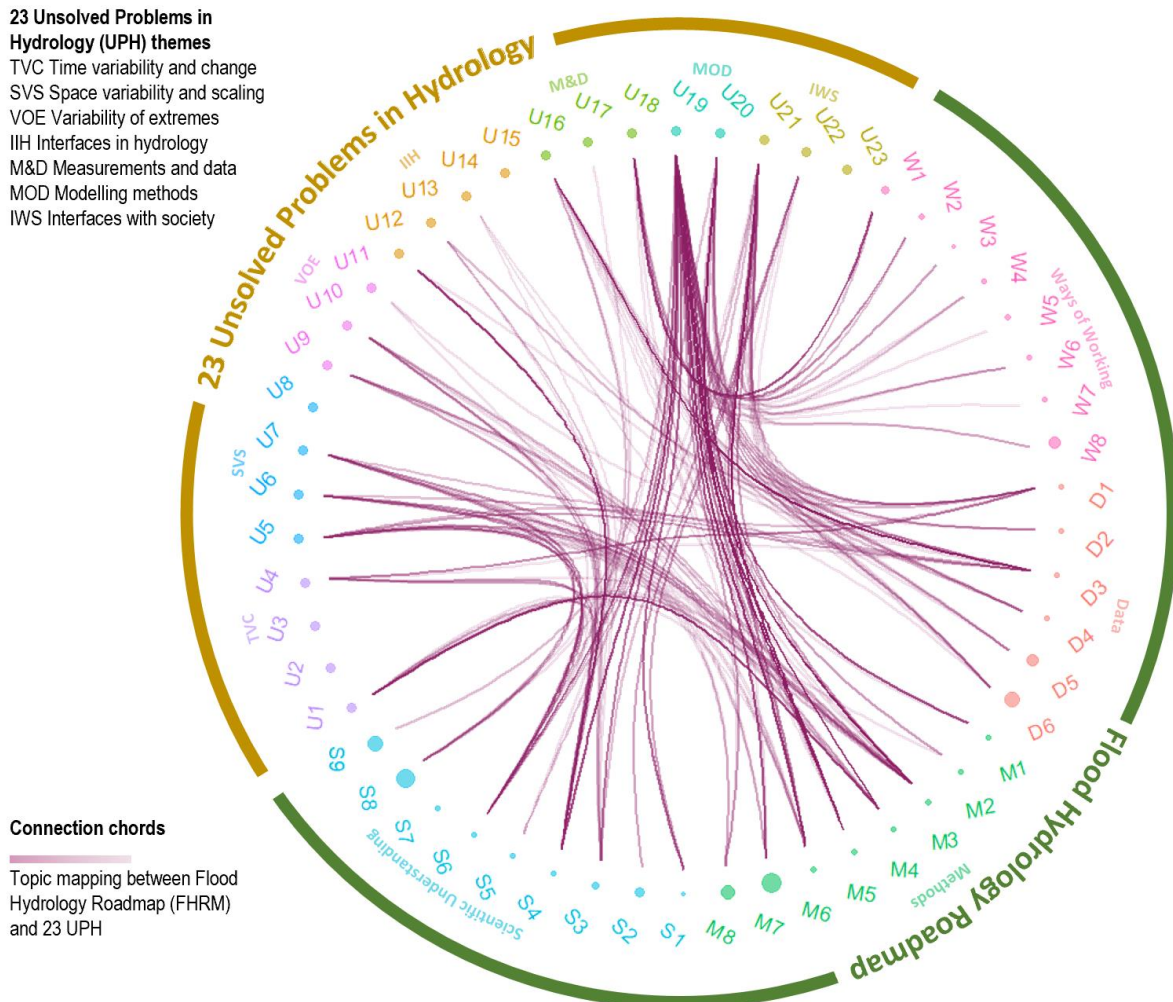
684 We visualise a mapping of topics between the roadmap and 23 UPH in Figure S1. First, we associated
685 each of the 23 UPH with a set of descriptive single or multi-word expressions, which we call key
686 words (Table S1). We then searched for occurrences of the key words within the detailed action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

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

701 The results suggest that most of the UPHs are relevant to the roadmap. However, there were no key
702 word associations found between the roadmap actions and UPHs 2, 3, 8, 15 and 23. Of these, UPH 2
703 and UPH 3, relate specifically to cold and (semi-)arid regions, which are not dominant in the UK
704 (although both climates may be relevant to UK hydrology, especially when considering climate
705 change). UPH 8 is about the distribution of response and water transit times in catchments, which
706 are relevant to the hydrological processes that explain and control hydrological extremes. The
707 roadmap action plan places significant emphasis on process understanding and research, but specific
708 research questions about transit times are perhaps implicit within the broader ambition to improve
709 scientific understanding rather than being articulated explicitly in the actions. UPH 15 is about

710 contaminants and pathogens. Although these key words are not mentioned explicitly in the roadmap
 711 actions, action S4 (“Identify research needs to improve understanding of flood generation processes
 712 and drivers of hydrological change”) includes a call to treat the science of flood hydrology
 713 holistically, including consideration of water quality. The lack of a match with UPH 15 is perhaps
 714 suggestive of a gap that could be explored further in terms of interfaces between flood hydrology
 715 and pollution or health issues. We also found no key word matched with UPH 23, which relates to
 716 the role of water in the dynamics of human civilisations. Although the FHRM is fundamentally about
 717 the interaction between human and natural systems, this interaction was framed in the context of
 718 established institutional and legislative structures, rather than as a research topic.

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721 Figure S1. Topic mapping between actions in the UK Flood Hydrology Roadmap and the IAHS 23
 722 Unsolved Problems in Hydrology, based on co-occurrence of key words listed in Table S1. Nodes

723 around the circumference represent the roadmap actions (labelled by theme: *Wn, Dn, Mn, Sn*, and
 724 scaled in proportion to their indicative costs) and the 23 UPHs (labelled *Un*). Each chord represents
 725 one key word match.

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

UPH

1. Is the hydrological cycle regionally accelerating/decelerating under climate and environmental change, and are there tipping points (irreversible changes)?
2. How will cold region runoff and groundwater change in a warmer climate (e.g. with glacier melt and permafrost thaw)?
3. What are the mechanisms by which climate change and water use alter ephemeral rivers and groundwater in (semi-) arid regions?
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?
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)?
6. What are the hydrologic laws at the catchment scale and how do they change with scale?
7. Why is most flow preferential across multiple scales and how does such behaviour co-evolve with the critical zone?
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?
9. How do flood-rich and drought-rich periods arise, are they changing, and if so why?
10. Why are runoff extremes in some catchments more sensitive to land-use/cover and geomorphic change than in others?

Key Words

- climate change, environmental change, tipping points, variability
- cold region
- ephemeral, arid, semi-arid, water use
- land cover change, land use change, land management, soil, groundwater, energy fluxes, fluxes, land surface, recharge
- reaction coefficients, spatial patterns, heterogeneity, evaporation, nutrient, sediment, sensitivity, homogeneity, carbon flux, carbon cycle, nutrient cycle, morphology, scaling, scale, spatially coherent
- hydrological laws, theories, scale, scaling, spatially coherent
- preferential flow, scaling, critical zone, scale, macropore
- rapid response, transit time, wave speed, celerity, flash, attenuation, time constant
- flood-rich, drought-rich, temporal variability, cluster, flood rich, flood poor, variability, decadal, interannual 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

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