Flood hydrology roadmap

Appendices

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We are the Environment Agency. We protect and improve the environment.

We help people and wildlife adapt to climate change and reduce its impacts, including flooding, drought, sea level rise and coastal erosion.

We improve the quality of our water, land and air by tackling pollution. We work with businesses to help them comply with environmental regulations. A healthy and diverse environment enhances people's lives and contributes to economic growth.

We can't do this alone. We work as part of the Defra group (Department for Environment, Food & Rural Affairs), with the rest of government, local councils, businesses, civil society groups and local communities to create a better place for people and wildlife.

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Contents

Executive summary

The flood hydrology roadmap sets out a 25 year vision for flood hydrology in the UK and an action plan to realise that vision. The Environment Agency has led the roadmap project, but the roadmap itself has been developed by and for the UK flood hydrology community.

The roadmap is intended to cover England, Wales, Scotland and Northern Ireland from 2021 to 2046. It considers all sources of inland flooding, including fluvial, pluvial and sewers, groundwater and reservoirs. It also considers the full range of inland flood hydrology activities in the UK, from operational practice to scientific research.

Development of the roadmap has been driven by:

- the scale of investment that flood hydrology data, methods, models and expertise underpin (around £6 billion over the next 6 years)
- the need to support the implementation of flood risk management strategies across the UK
- the need to improve partnership working and collaboration across the UK flood hydrology community
- the need to improve the translation of science into practice
- the need to deal with known limitations and issues in existing operational flood hydrology methods
- the need for flood hydrology to account for and predict the impacts of future environmental change (climate change and land use change)
- the opportunity for flood hydrology to contribute to net zero carbon targets

The flood hydrology roadmap has been developed through multiple phases of consultation with the flood hydrology community in the UK. It is built around a vision for the next 25 years which states 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

This vision will be realised through 31 actions grouped into 4 thematic work areas:

- ways of working
- data
- methods
- scientific understanding

Successfully achieving the vision of the UK flood hydrology roadmap will require strong leadership, and improved partnership working and collaboration across the flood hydrology community. The estimated funding required to implement the roadmap is between £110 million and £165 million over its 25 year lifetime.

Introduction

The document contains the appendices to the flood hydrology roadmap published on GOV.UK.

Appendix A – Questions in the questionnaire

The questions asked in the May 2018 questionnaire were:

Question 1 - Your team/organisation

- how is the work of your team affected by flood hydrology?
- why does it matter to you?

Question 2 - The vision

We will develop a joint vision for flood hydrology 10 to 20 years from now. Please imagine you are in the future and that things are working well. Please describe what flood hydrology work looks like. We're not asking for any suggestions or solutions but rather short descriptions of what the future could provide.

Please write as many future vision statements as you'd like.

Question 3 - The problems today

Respondents were given prompts to help identify specific problems/challenges and opportunities:

- what are the inadequacies in current approaches?
- what are your team's biggest challenges in flood hydrology?
- what do you think are the wider challenges in flood hydrology?
- how urgent are they and how big are the impacts?
- how well known are the problems?

Respondents were asked to score each of the problems/challenges or opportunities they identified for 3 criteria:

1. urgency scale – score from 1 to 5, with 1 being "It will make things better, but there is no inherent urgency" and 5 being "We have already missed a key deadline".
2. impact scale – score from 1 to 5, with 1 being "It has a locally important impact" and 5 being "It affects how we do things fundamentally, impacting everything and almost everyone (forecasting, long-term flood risk, all sources of flooding)".
3. topic maturity – score from 1 to 5, with 1 being "We don't know much about the issue at all" and 5 being "Knowledge of the issue is known and updated, it needs translating into practice".

Question 4 - Prioritisation method

We will receive lots of suggestions of what we can do to improve things. We will need to prioritise these needs/ ideas for projects to know where to concentrate our efforts. Which criteria/questions do you think we could use to decide where to focus our efforts?

Question 5 - Roles

This roadmap/strategy is for everyone in UK flood hydrology to share and deliver and will not be implemented by any one organisation. To improve the way things work, it is helpful to have an understanding of different people's expectations of who does what in flood hydrology. Please note below any ideas you have on who can provide what and how we can work better together.

Ideas were asked for under 2 main headings:

- what is your view on roles and responsibilities in flood hydrology in the UK?
- how could your organisation contribute towards improvements in flood hydrology?

Question 6 – Links with other work

Please highlight other work, technical developments or projects or organisations you think we could usefully link with.

Question 7 – Any other comments

Respondents were simply asked to add any other comments or feedback to the questionnaire.

Appendix B – Vision statements from the Birmingham workshop

Vision statements - Group one

Our vision is that in 25 years all (flood) hydrology is aligned with best available and continuously improving whole system process understanding, underpinned by excellent data and evidence to quantify uncertainty and other characteristics and its sources, tailored to each location, time scales and application in a consistent, sustainable and open way to enable robust decision-making. Recognising that leadership, championing and collaboration are key to delivery of this vision.

Better data

- We have collected the baseline data that allows us to characterise our systems sufficiently.
- We have sufficient funding, knowledge, capability and resources to monitor everything we need, particularly the extremes.
- Data is communicated openly, properly archived and centrally located.
- Data is of sufficient quality for the proposed application and we understand the uncertainties.

Methods

- Whole system integration.
- There will be greater consistency between estimates.
- A consistent, robust, transparent, centralised, and accessible toolkit (data, methods, and outputs) to support long-term planning.
- Joined up methods/approaches
- Methods deal with combined sources of flood risk and there is integration between rainfall hydrological models.
- A catchment based approach to allow natural flood management (NFM) and other measures, not solely flooding.
- Harmonisation in approach and methodology across different areas, for example, around sustainable drainage systems and reservoir safety.
- There is join up between forecasting and long-term flood risk.
- We use all the information we have at the time (data assimilation, historical floods, latest observations, meteorological hindcasts, land use changes, snow depth/melt rate, remote sensing, and citizen science, soil moisture).
- We use more of our hydrological information, rather than only looking at extreme events.

Credibility and plausibility

- Analytical methods for flood hydrology are scientifically up to date, rigorously peer-reviewed tested (international best practice) and openly published.
- Analysis can be easily questioned and validated.
- We can account for future changes in urbanisation or other land use and climate inputs.
- Hydrological methods no longer result in counter intuitive estimates and they represent physical processes and spatial and temporal patterns.

Outputs appropriate to application

- Methods can change to meet changing requirements and can be used flexibly to allow rapid scenario exploration or detailed analysis.
- Realistic, fit for purpose hydrological estimates that give useful outputs considering all end users.
- Our outputs can manage all sources of risk (flooding, channel change) and be used to support managed adaptive approaches.
- We consider the whole life cost of a hydrological approach.
- Hydrology for simple, low risk, studies is ‘easy’ and ‘efficient’ and hydrological ‘effort’ is concentrated on complex, high risk studies.
- Methods are appropriate for catchment/problem.
- We have a robust, consistent, and evidence-based approach to hydrology that covers all the types of catchments and types of problems with which we work (small, urban, permeable, different rainfall mechanisms, joint probability, volumes land management).

Accessible/open source

- Our methods are open access and transparent, robust, up to date, and reproducible.
- There is continual improvement in our methods, taking advantage of scientific and technological developments and availability of information.
- We encourage innovation.

Uncertainty

- Uncertainty is calculated and used.
- We have the ability and tools to present a useable and practical understanding of the uncertainty associated with the estimates of flood hydrology.

More efficient/effective ways of working

- Need a collaborative, representative central group with a unifying overview as a lead voice for hydrology, to create more effective and efficient ways of working.

Vision statements – Group two

In 25 years, through working together society will have the best hydrological information and understanding to manage the impacts of flooding from all sources, at all scales in a changing world.

Better methods/technical approaches

- reliable and trustworthy
- easily accessible
- framework – integrated science, scalable
- balance for flexibility and consistent approach
- better utilisation of uncertainty and communication about uncertainty
- scales from hourly to decades
- including non-stationary environment

Better scientific understanding

- better process understanding in an ‘earth system’ interacting approach at all space-time scales
- evidence based (that is science based) and don’t let methods constrain science (for example, the flood estimation handbook)
- understanding and quantifying uncertainty and knowing how to use a probabilistic approach
- using all data sources from improved hydrometry, radar, satellite, landscape spatial data (knowing that we will never have enough)
- valued and supported long-term catchment scale experiments
- open and honest community of practice (open data and open models)

Appendix C – Potential actions identified at the Birmingham workshop

The following actions to improve UK flood hydrology were identified at the September 2018 workshop in Birmingham.

The 73 actions have been grouped around 16 main headings. The main headings are represented by whole numbers (for example, Action 1 and Action 2). Actions related to the main heading are represented by the main heading number and a sub-heading number separated with a full stop (for example, Action 1.2 and Action 1.2). A short description of each action is also given (taken directly from workshop worksheets).

Action 1 - Develop a decision-making under uncertainty framework.

A consistent framework for quantifying uncertainty and characterising its sources. This should be integrated decision-making under uncertainty to utilise these uncertainty estimates. The framework needs to work across all applications. Also include tiered approach.

Action 1.1 - Evaluating the value of hydrometry and hydrology. Lack of appreciation of hydrometry in quantifying flooding from a planning, forecasting and insurance perspective. Leads to underfunding/resourcing.

Action 1.2- Review and agreement around decision-making approaches, including financial evaluation of hydrology. May include robust decision-making, adaptive management, receptor-based risk rather than source based. Impact based approaches and aggregate up to provide broad area of risk. Cost/benefit analysis on decision making – operational as well as planning.

Action 1.3 - Economic assessment of hydrological techniques.

Carry out robust economic assessment of different hydrological techniques.

Action 1.4 - Ability to use probabilistic information - do we need a code of practice?

Rather than using a single number, being able to understand how to use a range of numbers within the known uncertainties to give better outputs for better decisions. This also requires education among decision makers to know how to best use the information. Need to clarify the nomenclature re probabilistic.

Action 2 - Create a working group to look at monitoring issues holistically.

Level to flow translation. Automated high flow monitoring. Capture enthusiasm and channel it! Sensor tech teams. Know about each other and work collaboratively.

Action 2.1 - Create monitoring team as incident response team to capture high flows and other flood data.

No description.

Action 2.2 - More effective monitoring methods

Resilient approach to collecting useful monitoring data that will provide most benefit.

Action 2.3 - Hydrometry review and improvements (intelligent programme and upgrades).

Target monitoring network upgrades (rainfall, flow, and groundwater). Identify those catchments/processes currently not covered by monitoring network. Review of methods to collect hi-flows, locations and technology. Require solutions that do more for less. Continuous review.

Action 2.4 - Improving small catchment data sets to have significantly improved representation in 25 years.

Especially for small urban catchments and also rural (particular issue in Scotland). Can we make use of international data for urbanised catchments where the specific soil processes may not be limiting translocation? Ditto for permeable catchments. Invest in the network now!

Action 2.5 - Soil moisture monitoring.

Bring together point (for example cosmic-ray soil moisture monitoring network [COSMOS]) and remote sensed satellite soil moisture data sets and make them available for use with real-live flood forecasting models. Extend existing observation networks where required.

Action 2.6 - Develop means to capture pluvial/groundwater flood impact data.

Systems in place but impact data needs to be. Improve understanding of groundwater. Stored centrally and open access. Not just impact data – need to make much better use of 3rd party data across all the observation categories.

Action 2.7 - Implementation of standard quality control methods across measuring authorities, the Met Office and water companies.

Standardised procedures - including hydrological checks and inter site consistency. Including ratings, flow bypassing and out of bank flows.

Action 2.8 - Quantify the value of monitoring to enable decisions around future investments.

No description.

Action 2.9 - Incorporating uncertainties in measurements.

Incorporating uncertainties in measurements (like forecast ensembles) – based on data quality checks. Incorporate uncertainties in data processing.

Action 3 - Better process understanding.

How do numerous small interventions in the catchment affect catchment response? Predictability is poorly known (for flood forecasting particularly). We still don’t predict convection well; weather forecasts need to improve for flash flooding. Better understanding of sediment transport and geomorphology effects on velocity and flow regime. More broadly, how land use affects run-off.

Action 3.1 - Combine catchment specific understanding with standard approaches aimed at ‘average catchment’ scientific understanding.

How to use the process understanding to estimate flood frequencies (Revitalised Flood Hydrograph version 1 (ReFH) is too crude, and the statistical model could also account for more of the specific properties of a catchment. What about catchment types which are not in the calibration data set)?

Action 3.2 - Increase research funding to allow looking at the catchment as a whole.

Need for detailed understanding of process at small scales over whole catchment. Important for many other studies of hydrology too (not just natural flood management) including groundwater.

Action 3.3 - Understanding hydrological processes as part of a combined environmental system.

Hydrology is one part of the global water cycle and needs to be understood within the larger system.

Action 3.4 - Understand better how rivers behave at extreme peak flow – geomorphology.

No understanding of how conveyancing changes during peak flows. Role of erosion/deposition effects on conveyance, for example, during peak flows. Fund research, laboratory and fieldwork to address this.

Action 3.5 - Develop a process-based hydrological framework.

Develop a process-based approach to modelling the hydrological system that starts from the decision to be taken as well as what processes are important and determinant to final decision. Ability to select approaches with the framework depending on processes and open inclusion of scientific development.

Action 3.6 - Improvement of modelling catchment processes in flood risk estimation.

Representing catchment change including natural flood management. Moving from catchment descriptors to distributed process representation. Applying research models for practical flood hydrology problems.

Action 3.7 - Improved methods for combining risk from different flood mechanisms.

Includes improved quantifications of groundwater flood risk.

Action 3.8 - Improvements in flood estimation in permeable and impermeable catchments.

Link to groundwater models. Consideration of complexity of permeable and impermeable (urban drainage networks) catchments and responses.

Action 3.9 - Improved methods for assessing risk by lead local flood authorities on groundwater flooding

No description.

Action 3.10 - Adopt a whole system approach to hydrological risk.

Systems approach to characterising hydrological risk, moving beyond unique 'design events' to consider a wider spectrum of hydrological conditions that create flood risk. This should also incorporate process understanding. Including tiered guidelines appropriate to different stages of analysis.

Action 3.11 - Linking scales in hydrology.

Integrate how we approach hydrology across scales. We can innovate what we do at the local scale in hydrology with advances at the regional/global scale. We can innovate what we can do at the global scale with the detail of the local scale. How can we learn about the hydrology of one place based on hydrology of another place?

Action 3.12 - Develop a method for estimation of flood volumes and time to rise.

Calculated to observed flood volumes and volumes over thresholds.

Action 4 - Developing methods which address climate change implications.

Flood estimation method changes. Stationary to non-stationary methods. Impacts on probable maximum flood. Do we understand enough about flooding mechanism and the mixed distribution that result? Translation of this into flood estimation practice. Making use of existing data sets (for example, future flows).

Action 4.1 - Accounting for non-stationarity.

Accounting for non-linearity (including climate change and land use change).

Action 4.2 - Improved catchment descriptors for characterisation in a changing world.

For example, characterisation of the urban environment. Near surface parameterisation of geology.

Action 5 - New improved methods for reservoir flood estimation.

Probable maximum flood and probable maximum precipitation estimation. Stochastic methods? Impacts of climate change. Modelling catchment response in extreme floods (for example, 10,000 year floods). Method for assessing risk of unprecedented UK rainfall. Ideally integrated with methods for smaller floods or even average/low flows.

Action 5.1 - Physical estimate of probable maximum flood.

No description.

Action 5.2 - Put physics into depth-duration-frequency (DDF) models (especially for high return periods).

No description.

Action 6 - Further research of groundwater flooding.

Recharge with changing climate and land use. Implications of natural flood management on groundwater. Geological controls on groundwater flooding. Improved quantification of groundwater flood risk (with better monitoring network). Impact of greater use of sub surface in urban areas on groundwater flows and flooding. Mobilisation of legacy pollutants with higher groundwater levels.

Action 6.1 - Large Natural Environment Research Council (NERC) programme for flood hydrology.

To include funding, time and resources for translation of research into operational practice (from practitioners).

Action 7 - Removing obstacle to academics working with government bodies and consultancies.

Environment Agency framework agreements and consultancy practices make it difficult to employ and engage with academics (and academic expertise) in practice. Range of placements from day job shadowing to 6 month secondments.

Action 7.1 - Transfer of information between academics and practitioners via secondments.

Lack of transfer of information between bodies. Academia – consultancies – Environment Agency.

Action 7.2 - More effective ways of working - understanding everyone's needs.

Knowing who the users are, what their needs are and how those needs can be met. For example, water utility companies for network design using the same hydrology as Environment Agency and others use.

Action 7.3 - Getting our institutes to buy into this process – to allow people to spend time on it.

Universities, Met Office, Environment Agency and other agencies need to agree, sign off and support their staff to undertake actions.

Action 7.4 - Joint assessment of research needs for future shape of monitoring network.

Look at connection between operations and researchers leading to lack of evidence to prepare new techniques to solve key questions (for example, small clay catchments).

Action 7.5 - Flow of knowledge

Improved communication between academics and practitioners.

Action 8 - Improve access to flood hydrology data.

Data sets can be costly or take a long time to obtain. Develop Information technology (IT) systems that allow ready access to both historical and current data sets. Data sets are affordable.

Action 8.1 - Get all data digitised and made open.

Still plenty of long-term river flow/peak flow data in non-digital archives.

Action 8.2 - Open access to data and information and to use it appropriately.

One archive in the 'Cloud'. Combines measuring authorities, Met Office and water company data. Consistent quality control. Open access codes and procedures.

Action 8.3 - Environment Agency research and development - open access process.

No description.

Action 8.4 - Hydrology library.

Develop a 'repository' for hydrology methodologies, data and outputs. A tool kit which is accessible to all to share work. To include international data where appropriate. Needs to archive but also editable to help capture the latest understanding.

Action 8.5 - Curating (Environment Agency) models and data for everyone to use.

Central repository of models, data and metadata that everyone knows how to use and is easily accessible.

Action 8.6 - Create UK (near real time and historical) hydrometric and meteorological data store and server.

Include regulators, water companies, researchers, public bodies, local authorities. Include flows, not just levels.

Action 8.7 - Data management - continuous data updating.

No description.

Action 8.8 - Collective action plan for coordinating, curating and making data.

Available nationally. Strategic planning to integrate data and provide national leadership. Thinking about technology developments and planning for their implementation.

Action 8.9 - Make hydrology open.

Nationally and publicly funded models and methods should be open.

Action 8.10 - Establish a mechanism for clear and up-to-date practitioner guidance that is open access.

Openly available best practice guidance.

Action 8.11 - Strengthening links between academia and practitioners and risk management authorities.

Strengthen links (working projects, research, and community of practices) between practitioners (measuring authorities and the Met Office), universities and the British Hydrological Society.

Action 8.12 - Closer integration of research and practice.

Despite our best efforts, much research falls at the last hurdle of getting out into industry. Understand and overcome barriers to uptake of research by investigating barriers (commercial and contractual arrangements) to collaboration at all levels, real or perceived.

Action 9 - Improve skills and knowledge of flood hydrology practitioners.

Does the correct 'training course' culture meet industry needs? Improve access to MSc courses through funded places.

Action 9.1 - Training to increase knowledge and capacity within local authorities to make decisions on planning related to flooding.

No description.

Action 9.2 - Developing skills and knowledge in flood hydrology of Environment Agency practitioners.

Training on the job. Incorporating strong flood hydrological training in practitioner training courses. Strong collaboration with teaching establishments (university modules) to ensure graduates have the skills practitioners require. Knowing where to enhance these skills with external expertise. Apprenticeships – specific to flood hydrology. Mid-career continued professional development (for high and low flows). River coastal engineering programme. Joint MSc/MEng programmes.

Action 10 - Quantifying relative uncertainties in our flood hydrology methodologies.

Understanding how to use it better. Uncertainties in the modelling chain (relative). Appreciate the impact that these uncertainties have on justification and funding for schemes.

Action 10.1 - What type of catchments are most important to risk in the UK?

Improve the understanding of how different processes (surface water, groundwater, pluvial, coastal and fluvial) contribute to risk in a particular catchment.

Action 11 - Build a plan of actions based on recommendations of the National Flood Resilience Review.

Collectively come up with a more detailed plan and timeline of how to tackle gaps and recommendations identified in the National Flood Resilience Review.

Action 11.1 - Strategic technical leadership group.

Group to drive the vision forward, act as a forum for discussion and provide leadership to prioritise and deliver the action.

Action 11.2 - Create a partnership (UK measuring authorities and others).

Create a partnership agreement between the main measuring authorities, to agree a common vision and move it forward on a UK basis.

Action 11.3 - Consider other models for strategic leadership around critical issues.

No description.

Action 12 - Review and implement scientific developments to improve real-time forecasting.

Probabilistic forecasting, machine learning, artificial intelligence, integration of meteorological and hydrological models, finer-scale forecasts, prediction of pluvial flooding and distributed models.

Action 13 - Global network and collaboration.

Learning and sharing between countries. What can be learned from other countries?

Action 13.1 - Collaboration – common challenge.

Different scales, local, national and global. Different organisations face common challenges. Break these down and work together.

Action 13.2 – Data.

Characterisation of high flows. Gauging. Channel cross-sections.

Action 14 - Update Flood Estimation Handbook.

Develop a mechanism to update the Flood Estimation Handbook or replace it.

Action 14.1 - Review Flood Estimation Handbook methods in the context of global best practice.

Is the Flood Estimation Handbook suitable? What can we learn from other countries? For example, Australia Monte Carlo sampling of event types. Continuous simulation methods – whether driven by a stochastic weather model or a numerical weather model.

Action 15 - Sediment data monitoring in the UK.

There is no continuous record of suspended sediment or bedload in the UK. Could start with pilot(s) of a small number of gauged sites and catchments.

Action 16 - Training standards for hydrometric data collection and archiving.

Ensure staff have greater understanding of uses of data so metadata is more useful in analysis (skills, knowledge, communication) required.

Appendix D – Work areas in the online survey

Q5. Establish a steering group to own and champion delivery of the flood hydrology roadmap.

The remit of the steering group would include ongoing ownership of the roadmap specifically, identifying funding opportunities, steering delivery of priority work areas, reporting on progress and periodic updates to priority work areas.

Q6. Establish a UK flood hydrology scientific advisory group made up of professionals from across the community.

The scientific advisory group could have a wide remit and could provide technical advice on flood hydrology to measuring authorities, practitioners and others. They may form specialist groups on specific topics such as monitoring.

Q7. Raise the profile of flood hydrology in the UK.

Work to make the hydrological profession more valued and respected. This could include creating a range of promotional materials to communicate and visualise flood hydrology concepts and outputs with non-experts (including schools, the public and the media). These materials could be used to attract funding and encourage graduates to a long-term career in hydrology.

Q8. Build international partnerships to foster greater transfer of knowledge and best practice.

Improve and build upon current partnerships. Identify and establish new international relationships to encourage knowledge exchange, diverse learning opportunities, and skills transfer.

Q9. Improve the transfer of scientific advances in flood hydrology into practice.

Increase the impact of UK Research and Innovation funded programmes and projects through improved translation of science into practice. This work area should encourage practitioners to share information with researchers about current practice, current needs, what does and doesn't work well, and examples where new methods and techniques have been applied in practice.

Q10. Increase integration across the flood hydrology community

Encourage more integrated relationships across the flood hydrology community. This could include ways to enable skill and knowledge sharing between different industry groups (for example, regulators, consultants, academics, water companies and developers) and technical disciplines (for example, high flow and low flood specialists, meteorologists and geomorphologists).

Q11. Review and define roles and institutional responsibilities in UK flood hydrology.

Carry out a review of current and future roles required to achieve effective flood hydrology in the UK. This should include a skills gaps analysis for leading roles.

Q12. Improve hydrological skill and capacity in the UK.

This work area should aim to address any skills gaps identified in the work area above. It could also cover a range of activities, including measures for encouraging more investment in hydrology education and training, establishing cross-community work placement schemes to enable skill sharing.

Q13. Develop, maintain and publish clear guidance on 'industry standard' methods and tools for flood hydrology.

Technical guidance for practitioners should cover methods for all sources of flooding over a range of spatial and temporal scales. Guidance should be peer-reviewed and have sign-off from an appropriate group (for example, the proposed flood hydrology scientific advisory group). Guidance should be reviewed and updated annually as a minimum to take account of new and updated methods and user feedback.

Q14. The right IT infrastructure.

Regulators and others to review their IT infrastructure needs to enable them to effectively carry out an intelligent client role in flood hydrology, ensure they can replicate results and access the latest software and techniques (for example, machine learning). To include reviewing policies and software architectures (for example, compliance with standards, use of cloud services, accessibility to virtual labs).

Q15. The commissioning process.

Regulators to review their commissioning and quality review processes to ensure flood studies require high quality thorough flood hydrology investigations using latest research and guidance where appropriate.

Q18. Scope the long-term development of an open, online, modular system for flood hydrology that blends statistical methods and rainfall-runoff models.

This modular system could be capable of predicting floods in real time and estimating flood risk from all sources of flooding.

Q19. Review the concept of probable maxima.

Carry out a review of the concept of probable maximum precipitation (PMP) and probable maximum flood (PMF) and current methods for estimating these for reservoir and other critical infrastructure standards. Recommend a revised methodology for estimating very high return period inflows for these applications. This may include updated PMP depth-duration maps.

Q20. Develop guidance to help decision makers quantify, communicate and take account of uncertainty in flood hydrology.

Review and synthesise current knowledge about uncertainty in flood hydrology to provide guidance, allowing end users to better take account of uncertainty in decision-making. This work area should be regularly reviewed to ensure guidance keeps pace with scientific developments.

Q21. Accounting for climate change in flood hydrology.

Develop a long-term strategy for ensuring that flood hydrology methods take account of climate change in a scientifically robust way.

Q22. Review how real-time flood forecasting and longer-term flood risk assessment could be more integrated.

Carry out a review of the current level of integration between flood forecasting and flood estimation methods for all sources of flooding. The review could include a scoping exercise to identify actions that would allow greater integration of flood forecasting and flood estimation methods.

Q23. Investigate how scientific advances in physics/process/conceptual based modelling could be applied in operational flood hydrology.

Review and translate scientific developments into practice, including event-based, continuous simulation and machine learning approaches. This work area should be regularly reviewed to ensure methods keep pace with scientific developments.

Q24. Investigate how scientific advances in statistical modelling could be applied in operational flood hydrology.

Review and translate scientific developments into practice. The review should look beyond extreme value analysis of annual maximum flow data, be applicable to all sources of flooding, and take account of non-stationarity. This work area should be regularly reviewed to ensure methods keep pace with scientific developments.

Q25. Investigate how machine learning and artificial intelligence could benefit flood hydrology.

Carry out a review to define how machine learning and artificial intelligence could be used in flood hydrology and the data sets required. The review should go on to recommend future work areas and projects relevant to the UK.

Q26. Develop methods and guidance for quantifying the hydrological benefits of flood risk management interventions in the catchment.

Carry out a review and develop methods and visualisation tools to help decision makers quantify the hydrological changes (for example, reducing peak flows and changing timings) from management interventions in the catchment, such as natural flood management measures. Methods should be applicable from reach to catchment scale.

Q27. Benchmarking of flood hydrology models.

Establish benchmarking tests for flood forecasting and flood estimation models, assess their quality and compare them. This would include developing data sets from a range of catchments, at a range of scales, and for all sources of flooding. To include establishing quality criteria for inclusion or acceptance of methods/codes.

Q28. Develop methods for identifying, attributing and accounting for non-stationarity in flood hydrology.

Develop end user focused tools and guidance to help decision makers visualise, communicate, identify, attribute and account for non-stationarity in flood extremes. This should cover all sources of hydrological non-stationarity such as climate change, physical changes in catchments and geomorphological channel and flood plain evolution.

Q29. Understand flood hydrology outputs required for current and future needs.

Review information needs of end users of flood studies to ensure flood hydrology methods are able to produce useful outputs for all types of flood studies.

Q32. Establish and maintain a register of data relevant to UK flood hydrology studies.

Collate and publish metadata that can be used in flood hydrology operations and research. The register should be regularly updated and gather metadata from a wide variety of sources.

Q33. Carry out a comprehensive review of existing UK flood hydrology data.

Review data in the flood hydrology data register (previous work area) to define its quality, applicability to particular technical areas, and scope for improvement. This should cover hydrometric data from all sources of flooding, meteorological and spatial data (including flood impacts).

Q34. Investigate future flood hydrology data needs.

Identify ways to improve existing data. Identify data gaps and recommend ways to fill these gaps, particularly by exploiting new technology. This should cover data for operational and research use and include hydrometric data from all sources of flooding, meteorological and spatial data.

Q35. Investigate the use of citizen science data in flood hydrology.

Carry out a review of how citizen science could be used to collect data in flood hydrology. This review could consider how community observations can be integrated with more traditional data collection methods, and how to encourage community groups and volunteers to get involved.

Q36. Develop and maintain open access data archives for all sources of flood hydrology data.

This will include (but not be limited to) a ‘local data’ archive to complement systematic flood hydrology data archives. The local data archive should be able to log and store input from citizen science approaches and also archive historical and palaeoflood data and results from previous hydrological studies and reports.

Q37. High flow gauging during flood incidents.

Measuring authorities encouraged to review and improve high flow gauging during flood events from all sources of flooding. This could also include collecting other event-based data such as flood extent and duration.

Q38. Salvaging historical data.

Digitisation and salvaging historical data (for example, archiving the spatial radar estimates of rainfall, historic flood records, analogue records).

Q39. Investigate new techniques for flood measurement.

Exploration of new technology and methods for capturing flood information for all sources of inland flooding.

Q42. Research on all sources of uncertainty in flood estimation and forecasting.

This work area would identify the relative importance of different sources of uncertainty. It would include understanding the practical limits of prediction, sources of uncertainty and development of new methods to take account of uncertainty in flood hydrology.

Q43. Improving process understanding.

This work could include establishing long-term monitoring in experimental catchments, understanding which processes are important in which catchment types and studying hindcast data to understand the climatic drivers of floods and the natural variability in these drivers. To include improving understanding of surface/groundwater interactions for flooding and understanding whether there is a step-change in process functioning for floods of different magnitudes. To include investigations around the impacts of other processes on flood hydrology (and vice-versa), such as ecological response, erosion, hill-slope river coupling, woody debris, sediment transport and geomorphological change.

Q44. Understanding the spatial, temporal and cumulative impacts of flood risk interventions.

Research to help understand how the cumulative effects of small and large scale flood risk interventions impact on flood risk. This work could include examining the wider impacts of natural flood management measures at various spatial and temporal scales for different magnitude flood events.

Q45. Improving characterisation of rainfall for flood hydrology.

This work could include improving quantitative estimates from weather radar, spatial measurement of rainfall.

Q47. Development of flood estimation science.

Research to drive the development of new methods of flood estimation in a changing world. This could include the development of new physics-based, conceptual and/or statistical models applicable from the site scale to the catchment scale.

Q48. Improving hydrological modelling for flood forecasting.

Research to drive the development of improved methods flood forecasting in a changing world. To include developments in data assimilation.

Q49. Improve evidence for long-term drivers of hydrological variability and change.

Research to understand drivers of hydrological variability and change. To include development of methods for the analysis of non-stationarity.

Appendix E – Current practice tables

Four voluntary groups were established to summarise current practice in flood hydrology for reservoirs, groundwater, surface water and fluvial flood risk for both forecasting and planning perspectives.

Fluvial task group members were:

- Phil Raynor (Jacobs)
- Dr David Mould (The Chartered Institution of Water and Environmental Management (CIWEM) and the Canal and River Trust)
- Dr Mike Vaughan (Environment Agency)
- Dr David Price (Flood Forecasting Centre)

Surface water task group members were:

- Bridget Woods-Ballard (HR Wallingford)
- Dr David Price (Flood Forecasting Centre)
- Richard Robinson (Environment Agency)
- Richard Kellagher (HR Wallingford)
- Richard Body (HR Wallingford)
- Adrian Lee (NWL)
- Mel Harrowsmith (Met Office)
- Duncan Faulkner (Jeremy Benn Associates (JBA) Consulting)
- Dave Smith (Environment Agency)

Groundwater task group members were:

- Dr Mark Whiteman (Environment Agency)
- Dr Geoff Parkin (Newcastle University)
- Dr David MacDonald (British Geological Survey)
- Dr David Price (Flood Forecasting Centre)
- Nigel Hoad (Environment Agency)

Reservoir task group members were:

- Dr Thomas Kjeldsen (University of Bath)
- Dr David Mould (CIWEM and Canal and River Trust)
- Duncan Faulkner (JBA Consulting)
- Alan Brown (Jacobs)
- Alan Warren (Mott MacDonald)
- Peter Ede (British Hydrological Society)
- Tony Deakin (Environment Agency)
- Luke Ballantyne (Arup)

Fluvial

Fluvial flood risk is the most widely studied source of flooding. The Environment Agency's National Flood Risk Assessment (2009) stated that there were approximately 2.4 million properties at risk from fluvial and coastal flooding, with the majority from fluvial flood risk. The expected annual average damage to residential and non-residential properties, including hospitals and schools, from these sources amounts to more than £1 billion. In Scotland, approximately 284,000 properties are at risk from flooding (2018 figures), in Wales the number is approximately 208,500 (2014 figures) and in Northern Ireland it is approximately 46,000 (2016 figures).

There are well developed methods in both forecasting and planning applications but both need improving, especially the methods used in planning which have a number of limitations.

Forecasting

Ways of working

Who is responsible and who does what?

The Environment Agency run a suit of local forecasting models across England to provide forecasts for warning and operations to other teams. The Flood Forecasting Centre provide a 5-day assessment of national flood risk. The model (Grid to Grid [G2G]) is used to provide an assessment of flood risk primarily for days 3 to 5, which is refined through conversations with Environment Agency modelling teams.

The Environment Agency provides flood warnings based on the outputs of probability distributed rainfall-runoff models (PDM) and routing models and coordinating operational response. This is technically not a responsibility, it is a power not a duty.

The process is similar elsewhere, except that in Wales it is National Resources Wales that provides the forecasts. In Scotland, the Scottish Environment Protection Agency provides the national and local forecasts, although it is linked with the Flood Forecasting Centre and the Met Office. The situation in Northern Ireland is unknown.

What are the benefits of this set-up?

- a good improving working relationship between the Flood Forecasting Centre, the Environment Agency, National Resources Wales, Scottish Environment Protection Agency and the Met Office
- good access to expertise in consultancy
- possibly more reliable
- to a point there is a greater consistency in approach – possibly linked to consistency in the interaction between national and local forecasting
- the general view is that the Flood Forecasting Centre has been a big success

What are the known issues with this arrangement?

- capacity in consultancies to cover the work to develop and update new PDMs and routing models
- communication between the UK Centre for Ecology and Hydrology (UKCEH), the Environment Agency and the Flood Forecasting Centre over long-term plans and research
- relatively robust in terms of reliance on out-of-hours staff/software but this is a potential weakness
- lots of links in the chain have their own weaknesses – telemetry, model accuracy, rainfall forecast
- warnings are either given or not – there and then a decision is made by a group of staff on duty at the time - there could be variability in the decision-making process between teams making the decisions and between regulators
- code updates (for example, UKCEH's PDM models) may be infrequent; hydraulic modelling software is often updated more frequently
- forecasting model performance testing is not adequately carried out – at the beginning yes, but not often repeated
- little operational link to groundwater/whole flow range

Data

What data do our methods rely on?

- Environment Agency monitoring data, rainfall, levels and flows
- radar (jointly owned Environment Agency, Met Office, Scottish Environment Protection Agency and utilities)
- Met Office numerical weather prediction (NWP) models
- PDM models are calibrated against Environment Agency rain gauge network and observed flow and level data
- G2G is calibrated on flow and level data and rainfall data
- both (PDM and G2G) use Met Office NWP

What are the benefits of this set-up?

- uses standard national data for calibration
- best available data for forecasting runs

What are the known issues with this?

- NWP is limited in predicting the location of short duration intense rainfall
- PDMs are calibrated against a different data set from that which they are run (forecast NWP verses observed data) - note, observed data is used to drive them in real time, but forecast often more important (depends on how flashy the catchment is)
- no snow observations used – snow model has limited observation
- no soil moisture data is used – little available

- there are more data sources that could be used for both calibration, validation and running of the models
- data record lengths vary and may not have captured many high events in some locations
- routing models – sometimes simplified, less structures and have to run faster so on larger scale the hydraulics perform as well but locally there might be issues
- G2G has similar issues to PDM models
    - routing component is simplified
    - calibration is based on a national calibration approach
    - 1km grid and 12 parameters that control the relationships locally
    - they are set on a national basis
    - locally the model may under or overperform
- spatial representativeness of rainfall inputs (despite radar)

Methods

Which methods are used operationally?

PDMs are used for local models across the country (in England) and connected to routing models and telemetry systems. So, depending on location and timing, forecasts are based either on forecast rainfall put through a hydrological and routing model, observed rainfall put through the models, observed river levels upstream put through a routing model, or used directly. There used to be a varied set of models in different regions, but they have all recently been (or are in the process of being) converted to a single PDM model type to make it easier to maintain systems. The same process applies in Wales (although we are not certain on the standardisation of PDM (could be others)). The Scottish Environment Protection Agency and Northern Ireland are likely to be similar.

G2G models are used for an initial outlook by the Flood Forecasting Centre that feeds into daily flood guidance correspondence. The Environment Agency also feeds into daily flood guidance statements via its models.

PDM models are run every day, regardless of outputs from the Flood Forecasting Centre – depending on location it could be every 3 hours. A future system to replace local PDM is coming out.

There is no direct relationship between the outputs of the G2G and the local forecasting models. G2G covers a wider area, while local model coverage can be incomplete.

What are the benefits of these methods?

- PDM and routing models
    - quick to run
    - account for some physical characteristics of the catchment
- G2G
    - quick to run
    - accounts for catchment wetness

    - national coverage

What are the main assumptions made in these methods and known issues with them?

- assume that behaviour of catchment is adequately captured in model to forecast outside observed extremes
- not easy to make alterations to models over time (following changes in the catchments) without full recalibration
- less reliable forecasts in ‘shoulder’ seasons which is linked to accuracy of soil moisture inputs
- no ability to update the states in the model (with soil moisture information, for example)
    - changing soil moisture through an event is accounted for, however, there is no way to change the soil moisture in the soil store, only some of the routing elements
    - the local models are run in continuous simulation model and can’t change on the fly (one of the main issues)
    - use of real-time updating to adjust the forecast does occur – a mixture of state updating (only PDM, not routing models) and error prediction and error correction
    - looking to move to auto-regression moving average (ARMA), although both have limitations
- there are too many parameters for autocalibration, done by the Environment Agency or consultants
- links between models and configuration of routing models is an Environment Agency role
- poor ability to model snowmelt
    - a snowmelt model does exist in the Environment Agency although it is currently only used in the north-east (to be rolled out elsewhere)
    - little data to calibrate
- poor performance in some areas
    - no model is as good as you’d like but there is some suggestion that it is worse in the south and east and better in the north and west (of England) – linked to soil moisture and, to a degree, geology/permeability
- in the Environment Agency, flooding and low flows are considered separately
    - drought modelling is undertaken – CatchMod or similar and in some basins there is an operational forecast of groundwater, for example, in the Thames, which is undertaken in a flood forecasting system
- not enough validation
- lack of methods for rapidly responding catchments
    - it is a challenge linked to the models
    - for example, rainfall forecast accuracy is a big issue and in PDM models the issue can be availability of data on flow at this scale of catchment
- no explicit treatment of combined surface water/sewer/ coastal and fluvial floods
    - is joint probability forecasting a long-term aspiration?

    - coast is better forecast than fluvial side, as astronomical tide is easier to predict, and surge can be reasonably forecast. Wave/overtopping is less so

Scientific understanding

What scientific knowledge is already out there that could be used to improve methods?

- many different rainfall-runoff models exist - routing models could vary
- machine learning might offer a way of improving forecasts
    - lack of clear evidence currently that it does, but there is always a lag between new technology
    - area of concern is extrapolation issue to more extreme events

What scientific gaps are known?

- ability to predict rainfall and understand the local scale spatial nature of intense rainfall
- ability to model impacts of changing land use and catchment (for example, natural flood management) interventions
- links to the coast or water resources
    - coast is an important boundary condition in many cases
    - catchment models and hydrodynamic models can be used to estimate travel times for pollutants/objects (has been done for Police in the past), could also potentially be used for forecasting low flows if models could be calibrated well enough for both high and low flows
- assimilation of soil moisture observations (for example, satellites, COSMOS network (cosmic-ray soil moisture monitoring network), and possibly others) into forecasting models to improve simulation of soil wetness in the models

Planning (flood estimation)

Ways of working

Who is responsible and who does what?

Organisations involved are the Environment Agency, Natural Resources Wales, the Scottish Environment Protection Agency, the Department for Infrastructure, Northern Ireland, lead local flood authorities, consultants, UKCEH, insurance companies, developers, funders, and public/stakeholders.

Two broad types of work are covered in this section - hydrological studies for flood mapping and/or schemes, and hydrological modelling to provide an evidence base for impact assessment in infrastructure development, including property).

In the case of flood mapping and schemes, within the Environment Agency it is local Planning and Strategic Overview teams that commission studies to alleviate known flooding issues in their areas. These are almost entirely given out to consultants to complete and come into the national Monitoring and Forecasting service in the

Environment Agency for technical input. Large scale projects will go through a technical assurance process for 'Large Projects Review Group'. Monitoring and Forecasting is currently running an Inland Technical Induction Group; a series of training courses and workshops for new starters in monitoring and forecasting. New starters are split into groups of 2 to 4, with each group spending approximately 6 months working together to carry out a small flood risk mapping study, constructing a linked 1D-2D model and calculating hydrology for an Area team. Support is provided by Environment Agency experts via telecons and workshops. The aim is to develop internal Environment Agency skills.

Elsewhere, Natural Resources Wales is likely to have a similar arrangement, where consultants work with internal technical staff to produce modelling and mapping products and to develop flood risk management schemes. In Scotland, the arrangement is slightly different, with consultants working for local authorities to develop schemes, while the Scottish Environment Protection Agency work with consultancies to produce national scale flood mapping. It is also worth noting that at a local scale, for ordinary watercourses for example, consultancies will work with lead local flood authorities and councils to assess and map risk from non-main rivers, which can then be incorporated into local flood risk management strategies, and/or local planning documents. The insurance industry appears to employee consultants to develop its own data sets to inform risk modelling and products offered.

In the case of hydrology to support infrastructure/property development, this is usually carried out by consultees on behalf of the developer, which could include national organisations such as Highways England or Network Rail, through to utility companies and local authorities, down to private developers of housing or commercial sites. There is also a due diligence market. Essentially, the driver is a need to support some form of planning, whether it be via the Town and Country Planning Act under relevant national planning policies (for example, the National Planning Policy Framework in England, the Scottish Planning Policy and Planning Policy Wales) or for larger infrastructure, it could be assessments to inform a Development Consent Order application under relevant national policy statements. The National Infrastructure Commission plays some part in advising government on relevant design standards that are then interpreted via relevant policy and guidance.

In many cases, there may just be a flood risk assessment (or a flood consequences assessment in Wales), but there may also be a wider hydrological input to inform environmental impacts assessments, of which the flood risk assessment would typically form a technical appendix. Other hydrological inputs might also be needed to inform Water Framework Directive Screening and Assessment, plus the design of infrastructure (for example, culverts, bridges, outfalls, weirs) with a hydraulic purpose. In some cases, the development may be water resources related (such as borehole development) or may impact on water resources. As such, there can be an element focused on assessing the impact of the development on the water environment (for example, water availability, water quality and flow rates), but also the risk to the development, such as flood risk or drought.

Where the infrastructure being developed is part of or could influence the canal network, the Canal and River Trust (and others) has expertise to ensure that discharges to canals are safe and appropriate (sustainable drainage systems/water quality related) and also act as a stakeholder.

In most cases, the work carried out to support development, at whatever scale, needs to be agreed by relevant regulators (for example, the Environment Agency, Natural Resources Wales, the Scottish Environment Protection Agency and/or lead local flood authorities), and as such, industry standard assessment methods are generally applied. Consequently, various organisations can influence the process, such as those that commission new research (for example, the Environment Agency), those who undertake the research and method development, and consultants via relevant research projects. The pool of organisations involved in new research can be quite large, as it can often be quite specialist.

What are the benefits of this set-up?

- good access to expertise in consultancy, regulators and the wider industry
- agreed methods and tools nationally, and guidance and legislation
- largely well understood methods (but not always), but expert use still required

What are the known issues with this arrangement?

- there can be skills gaps in various organisations, which link to a variety of wider issues such as availability of STEM (science, technology, engineering and mathematics) graduates, attraction of consultancy versus regulator jobs, influence of procurement mechanisms (frameworks) and cycles in the industry, direction of current research
- national hydrological methods and application are, by definition, not always locally appropriate
- too many methods - reluctance to discard older methods for various reasons, and adopt a consistent contemporary method
- lack of ownership/coordination by a body - who that body should be is uncertain
    - do we need (for example) a council of hydrology that provides this guidance and is prepared to make the judgment call or give direction

Data

What data do our methods rely on?

- Flood estimation handbook (FEH) statistical method
    - historical observed levels and flows, catchment descriptor maps and spatial data sets such as HOST (hydrology of soil types) data (for ungauged sites), catchment descriptors and regression equations
    - method calibrated for a relatively large data set
    - can be influenced by local data and historical records
- ReFH rainfall-runoff methods

    - FEH 2013 DDF (Flood Estimation Handbook 2013 rainfall depth duration frequency) rainfall data set which is based on observed rainfall data up to 2008 only
    - can be calibrated against observed flows but often used as a hydrograph shape and scaled to match statistical outputs of FEH statistical method
    - also relies on catchment descriptors and regression equations derived from analysis of a smaller data set than that for FEH statistical
- continuous simulation methods
    - long stochastically-generated rainfall data sets through a rainfall-runoff model
    - rely on historical rainfall observation data sets
- direct rainfall methods in 2D hydrodynamic models
    - rely on digital terrain model and FEH 2013 DDF data sets (only includes data up until 2008)
- FEH WebService[1] catchment descriptors
- older, now less favoured, methods such as IH124[2] used coarse maps of winter rainfall acceptance potential (WRAP) which defines the SPR (standard percentage run-off) of soils for use alongside other catchment descriptors
- peak flow data set now managed by UKCEH's National River Flow Archive
- observed hydrometric (rainfall, stage and flow) data and ratings (including spot flows) underpins all methods, either directly or indirectly
- potential evaporation data also needed in some cases, but usually taken from Met Office models as observed data not generally available
- historic data, where available and accessible

What are the benefits of this set-up?

- derived from and calibrated against national data set
- AMAX (annual maximum peak flow) data updated relatively frequently

What are the known issues with this?

- there can be lag in data availability meaning assessments are not always using latest observations
- reliant on updates centrally to use more updated data sets
- other sources of catchment information are not being used consistently
- catchment descriptors and other spatial data sets (for example, FEH 2013 DDF) are not publicly (freely) available

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[1] Flood estimation handbook web service [Last accessed 27 September 2021]

[2] Institute of Hydrology. 1994. Flood estimation for small catchments, Wallingford.

- discrepancies between flood peaks in WISKI (system used by the Environment Agency for the management of hydrometric and hydrological measured values) and the National River Flow Archive
- licensing constraints on some software and methods mean limited adoption of methods due to costs and practical considerations
- FEH WebService – costs have restricted hydrologists investigating changes in catchment descriptors across a study area and tend to consider flood estimation points only
- historic flood data (for example, flood marks and newspaper reports) can be difficult to obtain due to no central repository
- some catchment types insufficiently represented in data sets (for example, small catchments, urbanised permeable catchments)
- lack of consistent recording of catchment changes (land-use, schemes)
- high flow measurement problematic (ratings, flood plain velocity measurement)
- homogeneity of time series observations
- quality control of time series data
- lack of long-term planning of gathering data to meet future needs, both strategically and in areas of greatest development pressure
- spatial variation in rainfall not well measured despite radar network
- rainfall measurement not as accurate as required
- much time series data not readily available over the web – has to be requested and supplied manually

Methods

Which methods are used operationally?

- FEH statistical method and local data
- ReFH rainfall-runoff methods
- continuous simulation methods
- direct rainfall methods in 2D hydrodynamic models
- small catchment methods, for example, IH124 plus others
- Devon hydrology strategy methods
- rainfall-runoff method
- Flood Studies Report (FSR) method (NERC, 1975)
- all linked to 1d and 2d hydrodynamic models

There are others elsewhere globally (the above is not an exhaustive list).

What are the benefits of these methods?

- uses standard national data for calibration
- relatively simple
- quick to do, pressing a few buttons
- can get an estimate for anywhere (can also be a drawback)

What are the known limitations issues with this?

- FEH statistical method
    - independence of flood events at different sites across the country
    - historical info is good indicator of future
- ReFH rainfall-runoff methods
    - time to peak does not vary with scale of the event
    - maintenance of volumes in Revitalised Flood Hydrograph version 1 (ReFH) ReFH and the Revitalised Flood Hydrograph version 2 solution (ReFH2)
    - different approach in Scotland
- continuous simulation methods
    - do the historical observed rainfall data sets contain enough information about extremes to cover future extremes
    - assumptions inherent in the chosen rainfall-runoff model
    - requirement to calibrate 2 models; a rainfall model and a rainfall-runoff model
- direct rainfall methods in 2D hydrodynamic models
    - all flow is overland excess flow
    - is a rainfall return period equivalent to a run-off return period?
    - no guidance on direct rainfall methods, for example, return period assumption, infiltration rates, overland flow
    - calibration of outputs to estimates produced through other methods is highly problematic, both practically and conceptually
- unable to consider joint probability of tributaries as methods focus on estimates at a single point
- unable to easily model impacts of natural flood management interventions – direct run-off can partially attempt this
- all methods produce results with uncomfortably large uncertainties
- unable to provide rigorous uncertainty estimates with values
- doesn’t take into account changes in the catchment or climate (non-stationarity)
- outputs can be difficult to communicate to the layman (not at all visual)
- in some cases, it is difficult to investigate results and see what led to the outputs (very black box)
- some methods only produce frequency estimates of flood peak
    - we need to characterise rate of rise, volume and duration of flooding too
        - hybrid method allows this - hydrograph from ReFH, with peak scaled, however, there’s no evidence that this is the ‘right’ way to do it
        - little to no analysis of observed volume return periods except perhaps on a project specific basis, which is needed
- design flood estimates do not effectively account for variation in antecedent conditions
- too often studies are recycled and updated, but flood mapping hydrology needs can often differ to that needed for schemes and flood risk assessments
- some catchment types inadequately represented (for example, small catchments, urbanised permeable catchments)
- not all methods are freely available

Scientific understanding

What scientific knowledge is already out there that could be used to improve methods?

- methods could be expanded to account for variability in input parameters, especially antecedent conditions, which could improve understanding of variability in outcomes and inform probabilistic estimates
- many different rainfall-runoff models exist - not specifically designed to be used for extreme events like ReFH - more for continuous simulation
- no other generalised methods suitable to apply nationally
- insurance industry uses continuous simulation models to base its financial forecasts on

What scientific gaps are known?

- lack of evidence of efficacy of natural flood management interventions and difficulty in application through existing methods and/or poorly linked to existing methods
- lack of our ability to model flood risk in small, rapidly responding catchments for which we have little data
- lack of robust methods suitable for permeable catchments
- lack of robust methods that deal specifically with urban catchments
- run-off generation processes in UK catchments not fully understood, limiting modelling ability, particularly where the spatio-temporal variations in run-off are important (for example, natural flood management)

Links to the coast or water resources?

- coast is an important boundary condition in many cases
- no current link to water resources but could have a model that looked at catchment more holistically in future

Surface water

- Pluvial flood risk prediction capability has developed with the widespread implementation of shallow water equation 2D modelling and linked 1D – 2D modelling of flooding resulting from drainage system capacity.
- Studies to date using this technique tend to have been constrained to urban areas subject to specific flooding risks - model run speeds tend to be slow.
- The use of machine learning models is likely to be an option for improving forecast prediction speeds into the future.
- Principal limitations are associated with the lack of ability to forecast localised rainfall events accurately enough with longer than an hour or two's lead time.
- Sewer model forecasting is also limited by a number of factors that determine and influence the performance of the sewer system and which are difficult to predict and therefore model (for example, sewer blockages).
- Data analytical and statistical tools are being used (albeit limited) and which use both historical and nowcast data.
- The Flood Forecasting Centre (FFC) uses the Surface Water Flooding Decision Support Tool (SWFDST) to provide an objective assessment of surface water flood risk at a county/unitary authority scale.
- The FFC will be implementing the Surface Water Flooding Hazard Impact Model (SWFHIM) when funding is available; a novel approach to modelling surface water impacts which has been developed under the Natural Hazards Partnership.
- Many sewerage companies have tested proof of concept integrated catchment modelling (ICM) live sewer flood forecasting systems, and some (for example, Thames) have now rolled these out across their entire region.

Forecasting

Ways of working

Who is responsible and who does what?

- The Flood Forecasting Centre (a Met Office/Environment Agency partnership) provides flood guidance information for 5 days ahead that highlights the risk for all types of flooding — river, groundwater, tidal/coastal and surface water flooding as a flood guidance statement
    - this information is available to Category 1 and 2 responders only
- on a commercial basis, the Met Office can provide nowcast forecasts that map the current weather and then (by estimating its speed and direction of movement) a forecast for a short period (up to 6 hours) ahead
- nowcast updates can be issued every 15 minutes
    - to predict the likely path and progress of heavy rainfall, Short-Term Ensemble Prediction System (STEPS) data is applied across the UK at a 2km resolution
    - water and sewerage companies are starting to forecast likely sewer performance using nowcast data from the Met Office (and other weather

service providers), but only for their business use (rather than providing warnings to the public)

What are the benefits of this set-up?

- flood risk warning
- water quality warning
- active catchment management – pollution prevention and smart infrastructure, for example

What are the known issues with this arrangement?

- urban area surface water flood forecasting would require close cooperation with water and sewerage companies in terms of access to and use of their hydraulic models
- requirements for very rapid alert systems (for example, SMS messaging) to provide high speed warnings to the public
- access to sewer data (and other drainage infrastructure such as highway assets) potentially has intellectual property rights (IPR) and issues of commercial sensitivity
    - development of effective procedures for forecasting in an urban environment would require this issue to be addressed

Data

What data do our methods rely on?

Generic:

- radar and telemetered rain gauge information
- surface type and soil information
- ground surface level
- hydraulic control features above and below ground (not evident from ground level information)
- drainage infrastructure data and operational knowledge, which may include manually adjusted systems that are not necessarily readily known

Specific system needs:

- the Flood Forecasting Centre's SWFDST relies on (i) the Met Office rainfall ensemble data - Met Office Global and Regional Ensemble Prediction System (MOGREPS-UK), (ii) county median soil moisture deficit values and the Updated Flood Map for Surface Water, or the 'blue square map'
- the SWFHIM relies on MOGREPS-UK, Nowcast ensemble, the G2G model, the Risk of Flooding from Surface Water Maps, the National Population database and the National Receptor data set
- the Rainfall Nomogram relies on forecasts of probable worst case as well as sufficient meteorological data to ascertain if the forecast summer convection is slow moving and triggered from the surface

What are the benefits of this set-up?

- ground wetness can reasonably be assessed from historic rainfall and temperature data
- accuracy of ground level information is largely sufficient nationwide
- established data sets/databases and data is readily available

What are the known issues with this?

- for the SWFDST, there are limitations with both the SMD data and the use of the 'blue squares' approach
- the SWFHIM uses a number of models and data sets which have associated errors and uncertainties - these are covered elsewhere

Methods

Which methods are used operationally?

The Flood Forecasting Centre uses the SWFDST to provide an objective assessment of surface water flood risk at a county/unitary authority scale.

The Flood Forecasting Centre is currently working to implement the SWFHIM operationally – when funding is available. The SWFHIM is a novel approach to modelling surface water impacts which has been developed under the Natural Hazards Partnership.

The Flood Forecasting Centre uses a Rainfall Nomogram, which is a graph-based lookup tool developed using an empirical approach to ascertain a relationship between precipitable water content and hourly rainfall accumulation in cases of slow moving surface based convection. A 5-day forecast of precipitable water content allows for a quick assessment of potential hourly accumulations if meteorological conditions are similar to the 20 case study events used to develop the tool.

What are the benefits of these methods?

Generic benefits:

- probabilistic approach and some accounting for the uncertainty in forecasting rainfall, especially convective events
- worst-case scenarios derived and used for planning purposes
- very rapid processing time
- provides an objective assessment of surface water flood risk

Benefits of existing systems:

- the SWFDST is driven by the Met Office MOGREPS-UK ensemble data - this is the best available data (in terms of spatial resolution and model parameterisation) for capturing rainfall detail, and especially convective rainfall which typically leads to surface water flood events
- MOGREPS-UK data also allow a probabilistic approach

- MOGREPS-UK data are analysed to determine the probability of exceeding main depth-duration thresholds (and linked to surface water flooding) for all counties/unitary authorities in England and Wales
- the SWFDST also accounts (in a basic fashion) for antecedent conditions (soil moisture deficit) and the level of urbanisation within each county/unitary authority – these are included in the calculation of surface water flood risk
- the SWFDST allows rapid assessment of surface water flood risk at a county/unitary authority scale – this is available in seconds following the availability of the MOGREPS-UK data
- the SWFHIM uses the Met Office MOGREPS-UK ensemble and the Nowcast ensemble
- ensemble data is input into the G2G distributed hydrological model to generate a SWF Hazard Footprint – a 'map' of all $1km^2$ modelled cells where surface run-off exceeds pre-defined thresholds
- the SWFHIM accounts for the main hydrological processes involved in surface water generation and flooding (through use of the G2G)
- SWFHIM uses the concept of an impact library, determined offline using the Environment Agency's Risk of Flooding from Surface Water maps and pre-calculated impact information for different hazard scenarios
- using the impact library means that the majority of the processing is done offline resulting in rapid run times when used operationally
- the SWFHIM provides a more objective assessment of surface water risk in real time
- the Rainfall Nomogram is based on actual data and can provide a quick and easy sense check of potential hourly rainfall accumulations in slow moving surface based convection type events

What are the main assumptions made in these methods and known issues with them?

Generic issues:

- the speed at which detailed hydraulic sewer models (high resolution, 2D deterministic models) can be simulated is a limiting factor
- machine learning, interpretation and analysis of sewerage systems is still in its infancy with respect to how inputs (hydrology, dry weather flow (DWF), external influences) all interact
- differing design standards for pluvial and fluvial infrastructure
- critical duration and interaction between pluvial and fluvial infrastructure
- very short lead time – limited benefits from a warning perspective
- assumptions used in assessing the proportion of run-off from pervious areas (loss modelling to determine net rainfall) are currently quite approximate
- accurately predicting run-off and speed of run-off, particularly slow response from pervious surfaces and ground infiltration
- calibration of run-off models within hydraulic modelling software

- radar rainfall data accuracy can be problematic for events that cause pluvial flooding
    - real time linkage and processing of combined radar and raingauge data is feasible but yet to happen on an automated basis
- risk of 'cry wolf' as accuracy is very variable
- a sensitivity analysis needs to be carried out to establish which assumptions in terms of run-off assessment are the most problematic
- the limitations of the shallow water equation with respect to gradient is an important aspect which should be considered in any procedure involving flood depth prediction
- lack of uncertainty representation/probabilistic forecasting capability
- lack of verification (rainfall, routing, impacts)
- integrated modelling needs where multiple drivers for sewer flooding (for example, coastal, fluvial, groundwater interactions)
- inclusion of sewer blockage hazards
- some ICM live models (for example, those developed by Thames Water) use real time river level as a proxy for groundwater level to drive the sewer infiltration input module in the ICM system

Issues with existing systems:

- the Flood Forecasting Centre's SWFDST is driven by MOGREPS-UK data and is therefore dependent on the quality of the rainfall forecast – NWP models can demonstrate poor spatial and temporal accuracy, particularly during convective events
- delays associated with transfer of MOGREPS data may reduce its suitability for rapidly evolving situations
- the SWFDST uses a 'blue squares' map as a proxy for the amount of urbanisation
    - this map was originally developed using an older version of the flood map for surface water
    - however, the percentage 'blue square' coverage values per county and basic methods used by the tool to account for urbanisation would probably not see much change in its output if the latest flood map for surface water were used to recalculate the percentage blue squares
    - a 'blue square' indicates where at least 200 people, 20 business or one critical service might be flooded to a depth of 0.3 metres by a 1 in 200-year rainfall event using the Environment Agency and Natural Resources Wales' Flood Map for Surface Water
- the SWFDST is 'calibrated' on summer convective events, therefore is not tuned to other meteorological set-ups
- there are a number of potential limitations with the MOGREPS-UK data, it is likely to be underspread and, in the early stages, is unlikely to have had sufficient time to adequately 'spin-up'
- the SWFHIM also uses probablistic rainfall forecasts (MOGREPS-UK and Nowcast ensemble) and is subject to their associated limitations

- the SWFHIM uses the G2G distributed hydrological model and is subject to limitations arising from process representation, parameterisation and the temporal and spatial scales used
- the SWFHIM assumes that G2G surface run-off reasonably equates to the ‘effective rainfall’ used as input into the Risk of Flooding from Surface Water Maps
- the SWFHIM uses the National Population Database and the National Receptor Dataset; these are subject to a degree of error
- there are assumptions associated with the pre-calculated impact libraries for different impact types and severities, as well as assumptions when upscaling 1km gridded impacts to county level
- the Rainfall Nomogram is only useful in specific cases of slow moving, surface based summer convection type events
    - the graph assumes best fit lines that are trying to represent widespread, localised, isolated and extreme hourly accumulations
    - the isolated and extreme accumulations in particular are only based on a limited data set

Scientific understanding

What scientific knowledge is already out there that could be used to improve methods?

- the SWFHIM offers a new mechanism for operational forecasting for surface water flooding, one that builds on existing models, data and tools
- UKWIR (UK Water Industry Research) projects
- academia
- water and sewerage company data

What scientific gaps are known?

- local scale spatial prediction of intense rainfall
- integration of gauge data with radar in real time for auto-correction of rainfall intensity
- ability to model, particularly in real time, the complex processes that control surface water flooding, especially run-off generation on vegetated surfaces
- limitations of NWP models’ forecasts – most evident during convective rainfall events
- limitations of current ensemble data sets (we need a lot more ensemble members; the ensemble may lie outside of the envelope, especially if extreme; forecasting extreme rainfall which is rarely experienced is a big challenge for both models and humans)
- NWP model parameterisation, including process representation and temporal and spatial scale inaccuracies
- hydrological model limitations, including process representation and temporal and spatial scale

Links to the coast, water resources, fluvial, groundwater?

- integration with any linked real time tidal or tidally influenced boundary conditions for sewerage modelling
- fluvial boundary conditions are main impact on sewerage flooding
- groundwater levels can be important influence on surface water flooding

Planning (flood estimation)

Ways of working

Who is responsible and who does what?

- the Environment Agency has the strategic overview; it commissions national-scale surface water flood risk mapping
- local authorities are responsible for local flood risk management
- water and sewerage companies are responsible for sewerage flooding
- the development sector is responsible for the design of surface water drainage systems for new development sites

What are the benefits of this set-up?

- appropriate level of representation, knowledge and ability to successfully manage catchment issues (in theory)

What are the known issues with this arrangement?

- multiple stakeholders, confused division of responsibilities, lack of formal sustainable drainage systems adoption bodies, sewerage undertakers not statutory consultees to the planning process, automatic right to connect to a public sewer
- General Data Protection Regulation
- alignment of funding opportunities
- resources
- differing design standards - design return periods
- back-to-back rainfall events - multiple smaller storms leading to disproportionate catchment responses or removal of assumed storage

Data

What data do our methods rely on?

- FEH2013 rainfall data set
- ground level accuracy for 2D modelling
- soil properties
- land use for roughness

What are the benefits of this set-up?

- nationally available data and methods

What assumptions are made?

- all surface water flooding is generated by overland flow
- losses element of a river flow prediction model like ReFH can be applied to calculate overland flow, even though we know most river flood flow in temperate climates is generated via interflow
- return period of rainfall equals return period of surface water flood impact

What are the known issues with this?

- specific site planning is usually on generic criteria applied at a site basis, leading to little understanding of the general catchment response in relation to the development area
- as no single authority has oversight, this can lead to some issues – for example, a water company may allow an unrestrained discharge to sewer that then flows to a watercourse, but lead local flood authorities may not be aware

Methods

Which methods are used operationally?

Surface water flood modelling:

- design rainfall model (FEH13)
- run-off /loss models including losses component of fluvial rainfall run-off models (for example, ReFH, ReFH2), infiltration models (for example, Horton, Green-Ampt) and simpler approaches (fixed % runoff, initial and continuing loss models)
- 2D ‘direct rainfall’ models that represent overland flow (for example, JFlow, TUFLOW, ISIS 2D [hydraulic modelling software])
- integrated models that represent both overland flow and also 1D pipe/channel networks (for example InfoWorks ICM)
- MicroDrainage and small scale development assessment tools

Sewer design methods:

- design rainfall model (FEH13 best but many still using earlier versions)
- time series rainfall from stochastic models
- various run-off models for percentage run-off, including old/new UK models and UKWIR
- pipe models
- modified rational method for simple calculations

What are the benefits of these methods?

- established standard methods

What are the known limitations issues with this?

- drainage network performance not explicitly represented (a simple rainfall loss model is generally applied)
- accuracy of rainfall-runoff loss model
- applicability of infiltration models and ability to provide them with meaningful parameters that represent local soil conditions
- applicability of losses components of rainfall-runoff models, which do not make any assumption about the pathway followed by rapid run-off
- applicability of overland flow models to represent generation of surface water flooding: the flow process may not be overland, for example, if interflow emerges from the ground it becomes surface water flooding before it enters a stream
- determining the correct soil wetness value for extreme flood event analysis
- need to capture rainfall and wetness joint probability
- impacts of climate non-stationarity on input rainfall data sets
- cross compatibility of various model, modelling packages and modelling techniques

Scientific understanding

What scientific knowledge is already out there that could be used to improve methods?

- use of continuous simulation would capture joint probability issues - this would require a synthetic 200-year rainfall time series, plus equivalent for soil moisture, evapotranspiration
- for large catchments, there is a need for the ability to develop spatial rainfall models able to produce 200-year series
- alternative rainfall-runoff models such as Dynamic TOPMODEL have some ability to represent sub-surface flow processes as well as overland flow

What scientific gaps are known?

- more effective rainfall-runoff loss models for pervious catchments
- finding a model that can represent the partition between overland flow and subsurface flow without needing to get seriously physics-based, which can be data-hungry and slow to run

Groundwater

Forecasting

Ways of working

Who is responsible and who does what?

The **Environment Agency** has responsibility for managing flood risk from main rivers and the sea, and also has a strategic overview for all sources of flooding, including from groundwater. The Environment Agency provides operational groundwater flood alerts and warnings across England for known areas of groundwater flood risk.

Lead local flood authorities have responsibilities for local flood risk, including groundwater under the Flood and Water Management Act 2010, and are responsible for management of groundwater flooding, including operational response.

The **Flood Forecasting Centre** and consultants GeoSmart operate a groundwater flood warning system producing daily forecasts available online to provide an initial estimate of risk nationally to inform the 5-day Flood Guidance Statement.

The **Hydrological Outlook partners** (Environment Agency, UKCEH, British Geological Survey and the Met Office) prepare summary information on groundwater levels across the UK looking 1 to 3 months ahead.

Environment Agency Area Groundwater and Contaminated Land teams working with Area Flood Resilience teams monitor specific locations for threshold crossings indicating risk of groundwater flooding. Area teams also run a forecasting spreadsheet tool in some Areas (for example, Wessex).

Data

What data do our methods rely on?

Data requirements for Catchmod, Aquimod, GeoSmart and Wessex forecasting models are summarised in the report 'Groundwater Flood Forecasting Scoping Study' (RAB Consultants, September 2016). The approach of all 4 models is similar in that they are based on calibrating observation boreholes, which are then mapped across catchments/geographic areas; they use recent borehole levels, recorded rainfall and forecast ensemble rainfall (either historic or a predictive ensemble) to a varying degree; and can go out to 30+ days.

- the forecasting models rely on logged/telemetered groundwater levels
- Aquimod data requirements are groundwater levels, rainfall and evaporation data
    - it uses forecast data and can be used for short term (1 to 5 days), medium term (1 to 3 months) and has been used in both long-term hindcast and forecast models for climate change modelling using ensemble data

    - within the Hydrological Outlook forecasts are based on data provided by the Met Office
- Catchmod uses daily rainfall and potential evapotranspiration data for input at sub-catchments represented in the model
- GeoSmart forecasts require telemetered groundwater levels delivered via the Environment Agency's API (Application Programming Interface) or equivalent from external providers (for example, Shoothill)
    - the model is initialised using the most recent telemetered groundwater level at a borehole, recent rainfall data from the Environment Agency real time API together with a 15-day ensemble rainfall forecast (via the National Centers for Environmental Prediction Global Ensemble Forecast System atmospheric model)
    - the groundwater model is then run using each realisation of 15-day rainfall to produce a probabilistic ensemble forecast of groundwater levels for each borehole
    - the model also produces a forecast over a 30-day period, using historical daily rainfall data weighted with the 15-day Global Ensemble Forecast System control rainfall forecast
- Environment Agency Area Groundwater and Contaminated Land teams use a mixture of manual groundwater level observations (for example, monthly dips), logged and telemetered groundwater levels
- the Wessex Area spreadsheet uses real time borehole data, recent historic rainfall and the Met Office 5-day forecast

Methods

Which methods are used operationally?

Catchmod is a rainfall-runoff model developed in the 1970s and used by the Environment Agency for water resource planning and abstraction licence allocation in England and Wales. It is based on a series of simple modelled stores to represent the soil, unsaturated zone and saturated zone. The groundwater level is calculated from the river discharge by an empirical relationship; dual calibrations are implemented where significant changes in aquifer properties occur at high or low levels.

Aquimod (previously RGroundwater) is a lumped parameter computer model developed by the British Geological Survey (BGS) to simulate groundwater level time-series at observation boreholes in aquifers by linking simple hydrological algorithms that model soil drainage, the transfer of water through the unsaturated zone and groundwater flow. Aquimod is used at 42 locations as the basis for making forecasts on groundwater status for the Hydrological Outlook.

GeoSmart runs its own in-house lumped-parameter model to provide a national scale flood risk guidance for groundwater flooding tailored to meet the needs of the Flood Forecasting Centre. The model is a lumped-parameter water balance model, which includes a soil zone, unsaturated zone and groundwater stores (slow and fast). The model predicts groundwater levels at key indicator boreholes. Forecast groundwater levels in each indicator borehole are used to evaluate groundwater flood risk in catchments associated with that borehole. For each of those catchments, the ensemble of modelled groundwater levels in the borehole are compared to a specific threshold groundwater level to provide information on the probability and expected severity of groundwater flooding over the forecast period.

Wessex Area (Environment Agency) uses a bespoke forecasting spreadsheet developed by Amec consultants (now Wood) as a simple alternative to Catchmod. The model uses a linear relationship calibrated for each borehole to give a flood warning for 23 communities. The Wessex Area has a water resources groundwater model for the chalk aquifer and the conceptualisation and understanding gained through the development of this model was used to develop the spreadsheet approach.

Manual observation of observed/telemetered groundwater levels by Environment Agency Area Groundwater and Contaminated Land teams.

Groundwater flood alerts and warnings on telemetry.

What are the main assumptions made in these methods and known issues with them?

Assumptions:

- the approach of all 4 models is similar in that they are based on calibrating observation boreholes, which are then mapped across catchments/geographic areas
- Aquimod assumes the indicator boreholes are representative of the groundwater response over large areas - the models are calibrated on the historical record, so assume forecast conditions are within the historical range
- Catchmod - the model is developed using data for known areas subject to groundwater flooding
- GeoSmart - each catchment is associated with its nearest indicator borehole, under the assumption that groundwater levels in that indicator borehole are representative of conditions in the catchment
    - this assumption is justified by the process of initially selecting the indicator boreholes to be representative of groundwater conditions in surrounding areas, by ensuring that they are not influenced by artificial abstractions, and that their groundwater level records are correlated with those of nearby boreholes
- Wessex spreadsheet - the simple spreadsheet approach would not lend itself easily to using a complex data ensemble approach

Known issues:

It is important that the modelling methods used for groundwater flood forecasting are published by the various model developers, to demonstrate that the models have been validated and calibrated and are accepted by the wider technical community.

- Aquimod is least efficient at capturing the flashy hydrograph of a heterogeneous, fractured Limestone aquifer
    - thresholds for flood warning purposes would need to be obtained from local sources (Environment Agency and local government)
- Catchmod is generally overly simplistic, for example, the simplicity of current rainfall and evaporation models
    - the model is dependent on calibration of the empirical relationship to derive groundwater level. It is indicative of groundwater levels only, not emergence.
- GeoSmart - further discussion is required between the Flood Forecasting Centre, and local Flood Resilience and Groundwater teams in the Environment Agency to build communication of the GeoSmart forecasts into operational incident response practice

The model is subject to ongoing improvements in response to feedback from the operational team at the Flood Forecasting Centre. Issues and improvements implemented since the initial pilot study in 2015/16 and the review by RAB (2016) include the following. The extent of use of the model is limited to aquifers at highest risk of groundwater flooding and locations where telemetered groundwater level data is available. Coverage is gradually being extended and now includes models in the Chalk (Southern England, Lincolnshire and Yorkshire), Cotswold Limestone and Lincolnshire Limestone. Additional borehole models will be phased in over the next 3 years. Better representation of the slow passage of infiltrated rainwater through the unsaturated zone was implemented in the model in spring 2018. The model is dependent on calibration of the empirical relationship to derive groundwater level. Each model is specific to the borehole and the results are assumed representative of a wider catchment area. Thresholds for flood forecasting purposes were derived from Environment Agency Area teams, where available, in summer 2018 as part of the new service contract. However, implementation of future changes to threshold levels would depend on communication with the Environment Agency and local government. Additional improvements should be considered to model specific boreholes susceptible to a rapid response to summer convective rainfall and in locations where explicit representation of groundwater-surface water interaction is required.

Scientific understanding

What scientific knowledge is already out there that could be used to improve methods?

Our knowledge of the hydrogeology of groundwater flood-prone settings, in particular the Chalk, has improved with more detailed geological mapping and the development of 3D geological models.

There have been advances in understanding groundwater recharge processes that haven't been incorporated in recharge components of Chalk aquifers models.

What scientific gaps are known?

The limitation is more on the availability of data to drive models, for example, the number of monitoring points and the design and location of the network; and the parameterisation of models. Greater resource to build more smaller scale models, in addition to better data, would improve forecasts.

We really don’t understand the aquifer characteristics of the zone ordinarily unsaturated, but saturated at times of extremely high groundwater levels. How do these zones behave when recharge of X occurs (given certain antecedent conditions)?

Planning (flood estimation)

Ways of working

Who is responsible and who does what?

Planning work, including estimating groundwater flood risk, is carried out by developers (for example, property developers), lead local flood authorities and major infrastructure providers (for example, water companies, national rail, national grid).

Lead local flood authorities have responsibilities for local flood risk, including groundwater under the Flood and Water Management Act 2010. This Act gives lead local flood authorities duties to prepare local flood risk management strategies and to co-operate with other risk management authorities, as well as powers to carry out local flood risk management.

The Environment Agency has responsibility for managing flood risk from main rivers and the sea. It also has a strategic overview for all sources of flooding, including from groundwater. This means supporting lead local flood authorities in the development of local flood risk management strategies by providing advice and data. The Environment Agency is continuing to develop more understanding of groundwater flood risk on a national scale as part of its strategic overview, and supporting the development of tools and approaches to understand these risks. The Environment Agency will work with lead local flood authorities on solutions to manage groundwater flood risk when it interacts with flooding from rivers and the sea and when there is an economic case to do so.

Data

What data do our methods rely on?

The British Geological Survey groundwater flood susceptibility data set uses the following data: bedrock and superficial geology maps at 1:50k scale; rock permeability index data set; groundwater level maps based on river level and historic groundwater level data. Susceptibility is converted into risk using analysis of groundwater and river level time series from the Environment Agency monitoring network. Note, it is important that methods used to do this are published by the various model developers.

Methods

Which methods are used operationally?

There are a number of commercial groundwater flood susceptibility/risk mapping products from consultancies that are used in planning, including JBA Consulting, GeoSmart/Ambiental. These products build on a groundwater flood susceptibility data set developed by the British Geological Survey.

The Environment Agency provided the lead local flood authorities with maps based on a combination of this and the pluvial flooding risk data set as input to preliminary flood risk assessments.

What are the main assumptions made in these methods and known issues with them?

Assumptions:

In 2015/16, the Environment Agency started a research and innovation project to compare the methodologies used by the main products showing groundwater vulnerability/flood risk from JBA Consulting, British Geological Survey, ESI (now GeoSmart) and Jacobs. However, this report was never published as the intention was to carry the results forward into a wider Defra-led project in 2017 (which the author understands never started). Also, the preliminary work did not really explore the underlying methodologies used to convert the BGS source data set (groundwater flood susceptibility data set) into groundwater risk maps.

So, the assumptions made in each of the commercially available groundwater flood vulnerability/risk maps is a research question that still needs to be addressed before each of these can be used with confidence and knowledge of their limitations.

Known issues:

It is important that the modelling methods used for groundwater flood risk estimation are published by the various model developers, to demonstrate that the models have been validated and calibrated and are accepted by the wider technical community.

Current operational methods are dependent on information on historical flooding, and on monitored groundwater levels at a set of observation boreholes. Issues related to this information include:

- lack of consistent, national, publicly available information on historical groundwater flood events (including a methodology for building an ongoing national database of events)
- insufficient geographic coverage of observation boreholes, including for potentially at-risk areas not yet monitored, and appropriate locations of boreholes to be representative of groundwater response in at-risk areas

Existing methods focus on areas at highest known risk of groundwater flooding, particularly from Chalk aquifers. There are many other locations which individually may involve fewer at-risk properties; these may be included in national susceptibility mapping, but are not covered by risk assessments or groundwater flood forecasts (the number of sites affected is unknown – this is similar to the situation about a decade ago when focus on fluvial flooding did not cover the large number of geographically spread people and properties at risk from pluvial flooding). Examples include urban areas at risk of rising groundwater levels, for example, from reduced abstractions, and areas close to locations of groundwater emergence in lithologies other than chalk (for example, in karstic aquifers); many anecdotal examples exist of these examples, but a more comprehensive assessment of the extent of these is not yet available.

Existing modelling approaches do not fully take account of interacting groundwater-surface water systems, including mechanisms of water movement such as the role of urban drainage systems, and multi-source flood risk (for example, rainfall onto high groundwater level and/or already groundwater flooded areas).

Scientific understanding

What scientific knowledge is already out there that could be used to improve methods?

One of the most valuable additions to knowledge would be through a systematic methodology for recording information on groundwater flooding – valuable information is already available through, for example, Section 19 Flood Investigation Reports, but a) it is sometimes difficult to identify flood water sources for individual events (a more systematic recording approach may help in interpretation), and b) this information is dispersed in lead local flood authorities and other repositories and not always readily available. It is understood that much of this type of information may have been collated by GeoSmart, but it is not known if this is more widely available.

Development of 3D digital geological models for other applications may be repurposed to support understanding of groundwater flood mechanisms and models. Also, integration with more open data sources (for example, for infrastructure networks, through buried asset registers), as these become more widely available.

Improvements in integration of high-resolution hydrodynamic surface and subsurface flood models, including infrastructure networks is rapidly advancing, but not yet at an operation-ready state. These may find increasing use in flood protection design.

New gridded rainfall data products for hourly rainfall are in development that could be used for improved risk assessment particularly for summer convective events, and for understanding very rapid groundwater rise in fissured/karstic aquifers.

What scientific gaps are known?

Little work has been carried out into multi-source flood risk, including national scale integration of flood risk mapping (some advances have been made towards integration of susceptibility maps, and presentation of flood risk from individual sources). Groundwater flooding differs significantly from other sources of flooding in its need to characterise rate of rise, flood volumes and durations, as well as flood peak levels. Note, there is a PhD study currently in progress at Newcastle focusing on this issue.

Understanding of the role of near-surface superficial deposits (for example, alluvial gravels) and infrastructure systems (for example, urban drainage) on the extent and dynamics of groundwater flooding, including for areas which may be at risk, but have limited historical evidence of flooding.

Measures should be provided to disseminate current knowledge to flood practitioners through guidance notes and training courses, particularly in lead local flood authorities where personnel from a range of educational backgrounds may be involved in flood risk assessments and reporting.

Reservoirs

There are around 2,000 reservoirs in England which come under reservoir safety legislation. These have a wide variety of uses, including water supply, hydropower, amenity, agriculture and flood storage. The average age of these reservoirs is now 120 years, with an average dam height of 7m and a maximum height of 70m. Approximately one-third of incidents and dam failures in UK history relate to flood events, and currently 2.3 million people are living in areas at risk of flooding from reservoir failure. Flood safety is therefore a critical part of all dam safety evaluations.

The reservoir owner is responsible for ensuring that the reservoir is compliant with any mandatory recommendations made in periodic (typically 10-yearly) Section 10 safety inspections by panel engineers under the provisions of the Reservoirs Act 1975. For floods, these responsibilities normally relate to the capacity of the spillway to pass floods safely over the dam. These inspections apply guidance issued by the Institution of Civil Engineers and test adequacy of the dam against the standards current at the time of the inspection.

As failure of the dam and release of the reservoir contents could result in multiple fatalities (250 people were killed in Sheffield in the Dale Dike disaster in 1864), dams are required to be safe against very extreme floods, assessed through reservoir flood studies. The highest consequence (Category A) dams are against the probable maximum flood (PMF), and the 1 in 10,000 probability per year floods. Lower consequence dams, Category B and C, are required to be safe against the 1 in 10,000 and 1 in 1,000 probability per year floods, respectively. The methods to estimate these high-return period and PMF design floods for reservoir flood risk are outlined in Floods and Reservoir Safety (ICE, 2015).

Most reservoirs have had 2 or more phases of increasing spillway capacity, following the Flood Studies Report (NERC, 1975) and the Flood Estimation Handbook (Institute of Hydrology, 1999). Spillway improvements can occur as a result of changes in flood estimation tools, engineering guidance on use of the tools, or due to site-specific circumstances (for example, a change in a dam's consequence class). Costs associated with spillway upgrades could be reduced by introducing changes in flood estimation tools/guidance in an integrated manner rather than rolling out improvements as and when they become available.

Changes to the Reservoirs Act 1975 made in 2013 included a requirement for reservoir owners to develop an on-site flood risk plan setting out procedures to take actions 'on site' to reduce the risk of flooding in an emergency. This provision has not yet been brought into force but it is considered good practice (voluntary) and the majority of reservoirs have such a plan. 'Off-site' plans setting out actions that would be taken on land not owned by the reservoir owner are the responsibility of the lead local authority under the 2004 Civil Contingencies Act.

Reservoir flood maps that show the impact that an uncontrolled release of water could have if a dam or reservoir failed are prepared by the Environment Agency at a national screening level as part of the requirements of the European Floods Directive. For very high consequence dams some water companies have commissioned more detailed reservoir flood maps for use in emergency planning.

The reservoir flood studies and reservoir flood mapping process both require the derivation of the PMF and other high magnitude floods. The PMF hydrological method has only been subject to minor updates since the release of the Flood Studies Report in 1975; in particular, its rainfall component, the probable maximum precipitation (PMP) has not been updated, and is known to have been exceeded on a number of occasions. This data set, which is central to the evaluation of dam safety at all high-consequence reservoirs in England, is known to be unfit for purpose.

Forecasting

Ways of working

Who is responsible and who does what?

- Reservoir owners are responsible for operation of their reservoirs, but ‘high risk dams’ are subject to independent review by panel engineers.
- Reservoir operation does not rely on short-term forecasting except in the case of most flood storage reservoirs and some reservoirs with large gated spillways.
- Longer term forecasting is useful for the Environment Agency and water companies when deciding how to balance the use of reservoirs versus river abstraction versus groundwater and when to implement drought plans.
- Short-term forecasting of floods may be required during construction works on dams, when they may be vulnerable to floods, for example, if the spillway is being enlarged or a new spillway is being added.
- Some flood storage reservoirs have ‘active controls’ which require collaboration between local Environment Agency forecasting teams and reservoir owners, but in most cases, the owner is the Environment Agency.
- Generally, there are no legal drivers for reservoir owners to provide flood storage.

Data

What data do our methods rely on?

- Met Office numerical weather prediction (NWP) models
- monitoring data – rainfall, reservoir levels and river flows and levels

Methods

Which methods are used operationally?

There are examples of regional collaboration between local Environment Agency teams and reservoir owners (utilities). For example, the Environment Agency Midlands region and Severn Trent Water collaborate closely on the use of forecast tools to operate reservoirs (early release), but most other regions have no formal collaboration.

The extent to which water utilities operate in-situ flood warning systems for their own reservoirs is unclear.

What are the known issues with them?

- operating reservoirs for dual purpose of water supply and flood storage (multipurpose reservoirs)
- uncertainty in rainfall forecast if adapting existing reservoirs for flood storage operation

Scientific understanding

What scientific knowledge is already out there that could be used to improve methods?

- Environment Agency/Met office already has complex operational forecasting systems in all regions which could provide flood forecasts

Planning (flood estimation)

Ways of working

Who is responsible and who does what?

- Reservoir owners are responsible for spillways being able to accommodate design floods of a rarity according to risk category of reservoir.
- Panel engineers provide an independent audit on the safety of dams
    - this may include a requirement that a flood study be carried out within a specified time period

Data

What data do our methods rely on?

- FEH 2013
- Monitoring data – rainfall, levels and flows
- FEH Catchment descriptors
- snowmelt depths and snowmelt rates – based on Hough and Hillis (1997)
    - underlying data from 16 stations for the UK
- 1975 methodology and data for estimation of probable maximum precipitation

Methods

Which methods are used operationally?

Reservoir flood studies

- Methods are described in Floods and Reservoir Safety (ICE, 2015) (FRS4) - these rely on a rainfall run-off models combined with design rainfall estimates.

- For the highest consequence dams (Category A) the guidance recommends that they are capable of passing the probable maximum flood (PMF)
    - for derivation of the PMF, these rely on the FSR/ FEH rainfall-runoff models (with some modifications particular to consideration of the PMF) combined with FSR design rainfall estimates
- for lower consequence dams (for example, where there is risk of inundation of a few houses only) the guidance recommends evaluation of dam safety in the 1 in 1,000, or 1 in 10,000 chance per year floods
    - the calculation of these floods uses combinations of the flood estimation handbook 2013 rainfall depth duration frequency (FEH13 DDF) with ReFH2 or the FSR/FEH rainfall-runoff model
- where reservoirs fall short in flood capacity against the guidance the Panel Engineer may apply a risk-based approach in considering appropriate actions

Reservoir flood maps

- The design floods described above for reservoir flood studies are also used to derive reservoir flood maps.

Other

- The extreme magnitudes of events used for reservoir flood studies are such that the same underlying hydrological methods are also used in industries with an interest in extreme events (for example, the nuclear industry).

What are the main assumptions made in these methods and known issues with them?

Assumptions:

- multiple assumptions are made when using current design flood estimation tools to calculate design events for very extreme rainfall and flood events
- the vast majority of flood events used in the development of the FSR/FEH (and ReFH) models had a return period of less than 25 years, but the methods are being extrapolated to return periods of 10,000 or even PMF for the purpose of reservoir safety
- the time to peak is reduced by 1/3 for the PMF but not for less severe events such as the 10,000-year event
- the analysis of snow depth and melt rates is assessed through a number of coarsely defined methods for data transfer from 16 stations UK wide
- frozen ground adjustment to percentage run-off is only considered for PMF
- climate change is not accounted for in reservoir flood estimation, including PMP calculations

Issues:

- PMP data is from the Flood Studies Report (1975) and has not been updated

    - PMP has been exceeded on a number of occasions and therefore the data set is known to be unfit for purpose
    - areal reduction factors (to translate point rainfall to catchment area rainfall) also require re-evaluation
    - improvements are also required to the rainfall-runoff models for extreme flood estimation
- to better facilitate application of risk based methods the PMF must be assigned a probability, otherwise the probability of dam failure cannot be quantified and combined with the potential consequences to quantify risk
    - a nominal 1 in 400,000 is suggested in FRS4 but this needs more research to provide a more reliable estimate
- PMF time-to-peak arbitrarily reduced by 1/3 (FSR rule)
    - studies suggest times to peak have been observed to decrease markedly with rainfall intensity on some catchments, and this may be leading to underestimation of peak flows in long return period floods (not necessarily as extreme as the PMF)
- uncertainty in antecedent rainfall for extreme floods
- rainfall-runoff methods to estimate dam safety floods (1 in 1,000 to 1 in 400,000 chance per year) often give peak flows 2 to 5 times larger than the pooling group method or than the newer ReFH2 rainfall-runoff model
- multiple storm events not accounted for in FSR method
    - there is a need for better guidance on specification of design rainfall for reservoirs with long critical storm durations, for which the FSR unimodal storm profile is inappropriate
    - these can be lower reservoirs in cascades, for instance
- estimation of run-off volume on low SPR catchments, in particular HOST class 4
- effect of frozen ground on run-off characteristics not well understood
- rates of snowmelt often not correctly accounted for due to misunderstanding of guidance (for example, applying the 5-year return period when the 100-year melt rate is recommended, or failing to increase melt rates to allow for energy due to incoming rainfall)

Scientific understanding

What scientific knowledge is already out there that could be used to improve methods?

- estimation of PMP has been updated across the world over the past 50 years since the current UK estimates were produced - high scope for revising UK PMP estimates
- the Australians have assigned probability to PMP (although their weather systems are different from UK)
- a significant study of PMP for Colorado and New Mexico states has recently been published

What scientific gaps are known?

- how high return period rainfall events vary with probability - is there genuinely a plateau of maximum rainfall which cannot be exceeded, or does potential rainfall continue to increase in magnitude with increasing rarity?
- effects of climate change on high return period rainfall events
- behaviour of catchment response (volume and run-off timing) during very extreme events
- effect of catchment delineation on resulting design flood (using a lumped versus spatially distributed run-off model)
- levels of uncertainty associated with high return period design events
- joint probability of extreme rainfall, snowmelt and frozen ground

Appendix F – Initiatives

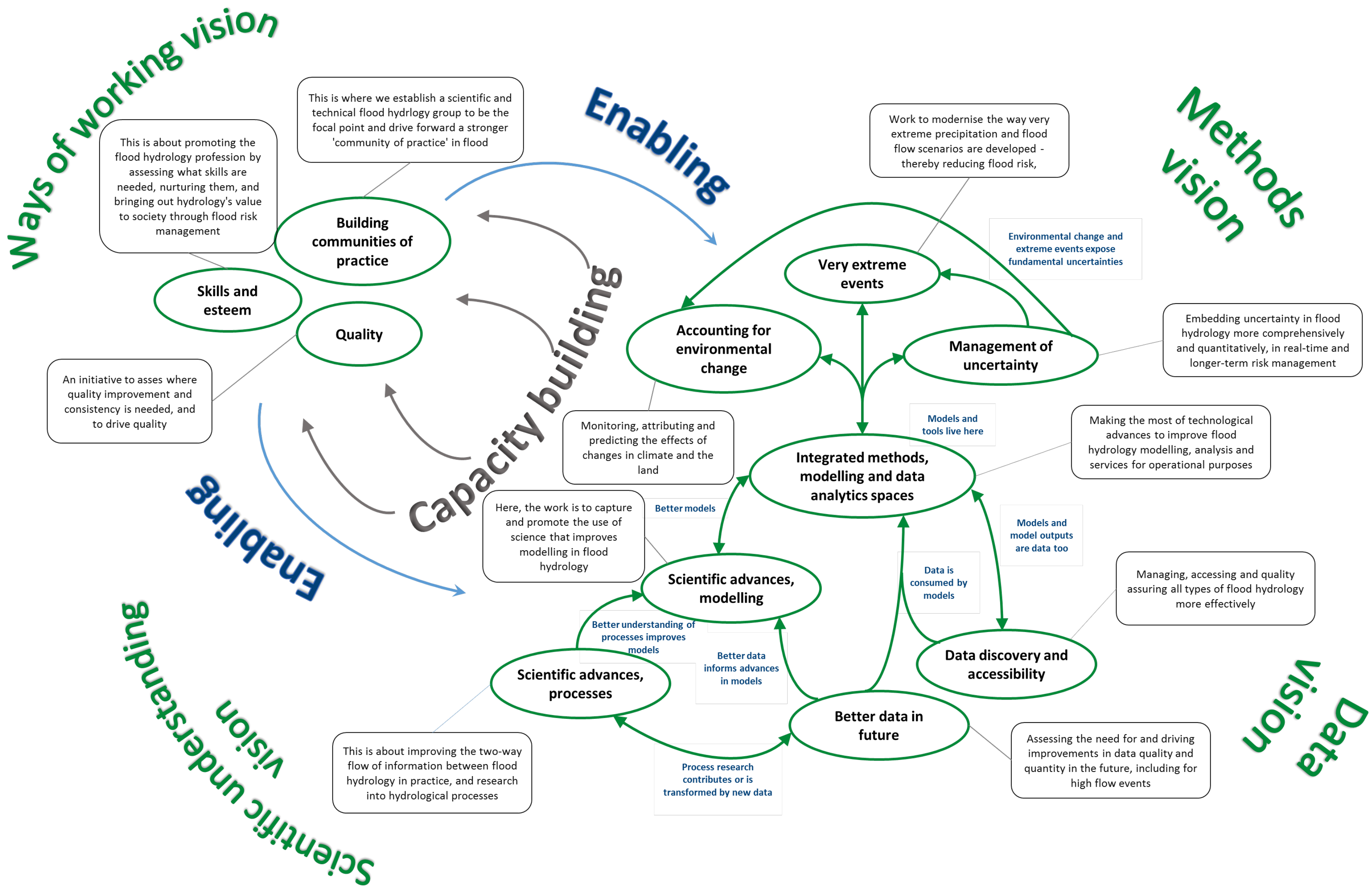
Section **Error! Reference source not found.** describes the development of the 11 initiatives presented below. These initiatives were developed by JBA Consulting (principally, Rob Lamb and Murray Dale). This work was initiated by the Project Board.

The 11 initiatives are:

1. better data in future
2. building communities of practice
3. data discovery and accessibility
4. integrated methods, modelling and data analytics spaces
5. management of uncertainty
6. monitoring, attributing and predicting the effects of environmental change
7. quality assurance
8. scientific advances in modelling
9. scientific advances in process understanding
10. skills, esteem and value
11. very extreme events

Figure F-1 shows the relationships between individual initiatives, and the following sections describe each initiative in detail.

Figure F-1 – Summary of initiatives and relationships between them



Better data in future

Primary theme(s)

- Flood forecasting and flood estimation

Cross cutting area(s)

Score 1 to 3 for relevance to cutting area, where 1 is most relevant and 3 least relevant:

- Data – 1
- Methods – 2
- Ways of working – 3
- Scientific understanding – 2

Executive summary of initiative

Looking to the future, the flood hydrology community has an increasing need for high quality data. This initiative will assess and quantify the need for improved hydrometric data capture in the future during periods of high flow/flooding. It will assess the technologies available for obtaining high flow gauging on rivers, acquiring citizen-based data of flood periods to enhance and enrich the flood hydrology database, and improved use of weather radar data. It will also examine the opportunities for new and evolving data to support flood hydrology from a range of technologies. The initiative will consider prior work in this area and how to build from this. It will also consider how newly acquired data from new technologies should be stored, managed and made available. There are links between this initiative and other initiatives in the Flood Hydrology Road Map (data discovery and accessibility, monitoring, attributing and predicting the effects of environmental change, quality assurance and skills, esteem and value).

Context of initiative

High quality hydrometric data are needed for a wide range of research and flood hydrology activities. Hydrological models in the future will permit, and in some cases require, greater volumes of data and at higher spatial and temporal resolution. The increased understanding and more complex modelling of the hydrological cycle places increased emphasis on the need for hydrometric data.

Hydrometric data form a vital foundation for our understanding of flooding, whether in real time or when considering the risk of flooding in the future. It is common for the largest floods on record to be highly uncertain as a result of a lack of accurate high flow gaugings. This uncertainty can feed through into bias in forecasting or modelling of flood risk. Increasing the sophistication of models is not expected to provide a way round this difficulty because all models ultimately rely on measurements. In order for regulators to be able to make improvements in their flood risk activities they need to capture peak flow rates/peak flow volumes during floods. This is imperative to:

- the successful management of flood incidents
- developing accurate flood models
- designing appropriate flood risk management measures and interventions (including capital schemes)
- ultimately helping ensure people and businesses are more resilient to the impacts of flooding

As well as the traditional sources of data in flood hydrology, there are opportunities for examining new or evolving sources of data, such as for estimating soil moisture, evaporation, snow. There are also spatial, soils, geology, catchment descriptor type data which can be improved in the future, potentially with new technologies becoming available. Data for process understanding (subsurface flows, chemical tracers) may also evolve and improve.

The high-flow gauging element of this initiative links to the Environment Agency's 2020 project proposal 'Improving Flood Flow Measurements in Flood and coastal erosion risk management (FCERM)' (FRS18193). This identifies:

"The Hydrometry and Telemetry [H&T] service needs to adapt if we are to meet the requirements and standards being set out in FCERM's new Commission for H&T and realise our aspirations for flood measurements. Our updated requirements and standards ask for:

- more resilient monitoring sites, capable of returning continuous, accurate measurements throughout a larger range of flood events (0.5% probability)
- more agile, flexible and rapidly deployable measurements to meet temporary, project-related and incident management needs
- more measurements in ungauged locations and in locations and situations where existing sites and technologies aren't suitable, available, or perform well, including for flood plains and overland flows and in rapidly responding watercourses
- safe, accurate, cost effective methods for ad hoc, spot flow measurements"

New technologies can allow new data types to be collected to add to the richness of hydrological data. For example, 'citizen science' data can be collected by members of the public during flood or high flow periods and new technologies can allow for safe gauging of rivers and watercourses at high/flood flow periods.

Weather radar data are used in flood hydrology, although much more use could be made of radar data to examine spatial variability in flood-producing rainfall events. There is now a large body of radar data from flood-rich years available for analysis. There has been ongoing research in this area, such as Ochoa-Rodriguez and others (2019) - [A review of radar-rain gauge data merging methods]

The roadmap's vision for flood hydrology data is as follows:

'Funding, knowledge, capability and resources exist to monitor the UK hydrological environment, particularly extremes.

New and historical data are communicated and shared openly, properly archived and centrally located to support all flood hydrology studies. Data are freely available for all carrying out flood hydrology studies.

Data are of sufficient quantity and quality for each application; uncertainties are understood and communicated effectively.'

The roadmap's vision for scientific understanding is as follows:

'We continually improve our understanding of the processes governing all areas of flooding risk (fluvial, fluvio-tidal, surface water, reservoir and groundwater) with state-of-the-art science. This science and knowledge is transferred into practical improvements in the efficiency and effectiveness of methods, ways of working and data.'

This scope aligns with the British Hydrological Society (BHS) Working Group (BHS WG) on the future of hydrological research, which published a paper on observational methods (Developing observational methods to drive future hydrological science) and was (June 2020) considering modelling and theory. The BHS WG identified strands of observational technology research that are reflected in the Phase 2 objectives of this scope, and noted the potential of spatial mapping measurement of river flows, transit and residence times, which would not necessarily require entirely new technology. Important links were identified with modelling and uncertainty to help justify and guide new measurement strategies.

This initiative links to the following work areas developed at earlier stages in the roadmap:

Q34. Investigate future flood hydrology data needs. Identify ways to improve existing data. Identify data gaps and recommend ways to fill these gaps, particularly by exploiting new technology. This should cover data for operational and research use and include hydrometric data from all sources of flooding, meteorological and spatial data.

Q35. Investigate the use of citizen science data in flood hydrology. Carry out a review of how citizen science could be used to collect data in flood hydrology. This review could consider how community observations can be integrated with more traditional data collection methods, and how to encourage community groups and volunteers to get involved.

Q37. High flow gauging during flood incidents. Measuring authorities encouraged to review and improve high flow gauging during flood events from all sources of flooding. This could also include collecting other event-based data such as flood extent and duration.

Q39. Investigate new techniques for flood measurement. Exploration of new technology and methods for capturing flood information for all sources of inland flooding.

Q45. Improving characterisation of rainfall for flood hydrology. This work could include improving quantitative estimates from weather radar, spatial measurement of rainfall.

Objectives of initiative

Phase 1 – Needs assessment

1. Assess where there are gaps in the UK hydrometric data set – this task should learn from (or might possibly be combined with) the data discovery and accessibility initiative scope Part B – Data quality and quantity.
2. Assess and evaluate the need for improved high flow gauging (this can build from the Environment Agency project proposal 'Improving Flood Flow Measurements in FCERM' (FRS18193)).

Phase 2 – Technologies assessment

1. Examine new technologies for high flow gauging that could enable safe collection of reliable flow estimates at main sites during periods of high flow/flood.
    a. this aligns with the Environment Agency project 'Improving Flood Flow Measurements in FCERM' (FRS18193) proposal Phase 1: Phase 1 will review and evaluate current and emerging technologies and methodologies to accurately measure flood flows in excess of QMED and low flows
    b. part of the initial evaluation will identify if particular techniques are more appropriate to capture multiple parameters (for example, sediment) and multiple flow regimes (for example, the median annual maximum flood (QMED), low flows, Q95))
2. Propose technical solutions for high flow gauging following step 1.
    a. for the Environment Agency, this may follow Improving Flood Flow Measurements in FCERM (FRS18193) Phase 2: Phase 2 will deliver a minimum specification for those techniques which are identified in Phase 1 as having potential benefit to us
    b. this will include site trials, evaluation of operational deployment (cost, ease of use, safety, efficiency, resources)
3. Examine new technologies for citizen science data collection, storage and management.
4. Prior research exists in this area and should be reviewed/built upon, for example
    - integrated Twitter urban real-time flood model [last accessed 18 November 2021]
    - assessing the utility of social media as a data source for flood risk management [last accessed 18 November 2021]
    - validating city-scale surface water flood modelling using crowd-sourced data [last accessed 18 November 2021]
5. Examine opportunities for improving understanding of characterisation of rainfall from weather radar, and the spatial measurement of rainfall, focusing on flood-producing rainfall events – this needs to link to prior and ongoing work to improve the quality and coverage of radar data and its data archive.

6. Examine opportunities for other data types to support flood hydrology: for example, for estimating soil moisture, evaporation, snow, geo-spatial data, soils, geology, catchment descriptor type data and data for process understanding (for example, subsurface flows, chemical tracers)

Carry out a benefit-cost options assessment of these technologies.

Phase 3 – Implementation

1. Based on outcomes of Phase 2, step 5 benefit-cost assessment, and appropriate funding, undertake implementation of new high flow gauging technologies across the UK.
2. Establish links with data discovery and accessibility initiative to define where the high flow data will be stored and how it will be made accessible.
3. Implement citizen science data collection, storage and management, based on outcomes of the Phase 2, step 5 benefit-cost assessment.
4. Implement any additional radar data improvement activities not otherwise underway in other research and project activities, based on justification from Phase 2, step 5 benefit-cost-accessibility to radar and rain-gauge data is covered within the data discovery and accessibility initiative.

Expected benefit and outputs of initiative

1. Improved understanding of how new technology can improve data quality and capture, especially in high flow/flood situations.
2. Step change in the quantity of high flow/flood event flow data collected to improve:
    a. the successful management of flood incidents
    b. development of accurate flood models
    c. design of appropriate flood risk management measures and interventions (including capital schemes)
    d. helping to ensure people and businesses are more resilient to the impacts of flooding
3. Increased involvement of the public in providing citizen based data, thereby gaining a much increased picture of flood impact for post-event analysis and real-time flood management, as well as increasing the public’s involvement that increases the profile of flood hydrology and flood risk management activities (link to skills and esteem initiative).
4. Increased use of radar and rain gauge data for flood hydrology research and activities/projects, including use for real-time incident management.

Drivers for this initiative

1. A lack of gaugings carried out at high flows/flood periods leading to weakened data sets that exclude important high flow estimates.
2. As detailed in the Environment Agency proposal ‘Improving Flood Flow Measurements in FCERM’ (FRS18193))

    a. “due to the broad range of functions the network needs to support Hydrometry Gauging Stations that are not always located in an optimum location to capture flood flows
    b. sometimes floods happen in ungauged catchments
    c. H&T staff are not always available to carry out high flow spot measurements
    d. it is not always safe to deploy H&T staff during an incident to undertake validation measurements for our stations with the existing technology that we are working with
    e. a review of our essential sites for flood forecasting purposes found that our high flow capability is not currently meeting our needs, we have insufficient resilience to major floods and as such we need major improvement.”
3. Climate change and land use practice are driving increasing flood flows (higher events, more frequent events), making high-flow gauging more important than ever (for example, highest flows on record on various rivers in 2020, 2019, 2015, 2009).
4. The degree of uncertainty/error introduced by uncertainty over ratings, for example, AMAX series with outliers – errors can be very large
    a. for example, the Sept 1968 flood’s apparent magnitude is 2 or 3 times the next highest on record at some gauges – can we trust it?
5. A recognition of the need to make more of spatial rainfall information from radar archive data to better understand spatial characteristics of flood producing rainfall – this is particularly important for urban environments and sewer system modelling.

Risk(s) associated with not carrying out this initiative

1. Nearly all gauges use ratings to calculate flow, so without sound high-flow ratings, the foundations of the whole fluvial flood risk management sector are undermined: so much depends on knowing what the flows are – for example, Nafra2, cost-benefit analysis of schemes, flood forecasting, planning, development control, natural flood management.
2. Without reliable data for flood model calibration outputs (on which very costly schemes are based) can be misleading and highly inaccurate
    a. the risk can be a huge under- or overspend due to poor quality model output
    b. this also affects residual risk and the messaging related to the level of service provided by flood schemes
3. The trend of reduced personnel and resources for carrying out high low gauging could continue and the collection of future high flow gaugings reduce further as a result.
4. Reduced quantity of this highly important data are collected and the benefits and outputs described above would not be realised.
5. Missed opportunity to gather citizen-based flood data, building on prior research in this area.
6. Reduced focus on radar data use for flood hydrology; missing the opportunity to understand spatial variation in rainfall from radar data.

Building communities of practice

Primary theme(s)

- Flood forecasting and flood estimation

Cross cutting area(s)

Score 1 to 3 for relevance to cutting area, where 1 is most relevant and 3 least relevant:

- Data – 2
- Methods – 2
- Ways of working – 1
- Scientific understanding – 2

Executive summary of initiative

This is where we establish a scientific and technical flood hydrology group to be the focal point and drive forward a stronger 'community of practice' in flood hydrology.

Many of the initiatives proposed within the roadmap aspire to achieve knowledge exchange, collectivism and sustained, regular updating. Yet flood hydrology lacks an obvious mechanism or champion to achieve these aspirations. This initiative proposes to establish a scientific and technical group, specific to flood hydrology that can take up the mantle of the roadmap in the long term and provide the nucleus of a community of practice.

Context of initiative

The roadmap’s vision for ways of working is as follows:

There is a representative UK group with a unifying overview as a lead voice for flood hydrology, to create more effective and efficient ways of working.

In the flood hydrology community, we work together with skilled teams and stakeholders, communicate clearly and use excellent, consistent technical guidance.

We engage across the UK and internationally, embracing and encouraging scientific and technological developments to continually improve efficiency and innovation in our field.

Six work areas that have emerged through the roadmap process explicitly address perceived needs for improved partnership, knowledge sharing and institutional cohesion within hydrology, and flood hydrology specifically. All 6 feature within the ways of working theme. Collectively, the 6 work areas concern the strengthening of a community of practice around flood hydrology (where ‘practice’ is understood to encompass research and science, as well as applications of hydrology).

The call for improvement in the transfer of scientific advances from research into practice scored 3rd-highest of all work areas surveyed in the 2019 online consultation, while the establishment of a UK flood hydrology scientific advisory group and better integration across different sectors and disciplines within flood hydrology were also highly ranked (13th and 17th respectively).

It is notable that similar concerns have been identified by the BHS Working Group (WG) on the Future of UK Hydrological Research, which, in its first meeting, commented that "We need to break down organisational/institutional barriers both within the hydrological community and with other related disciplines" (BHS Working Group on the Future of UK Hydrological Research) [last accessed 18 November 2021]. Citing the example of large projects in space exploration or physics as analogies, the WG expressed an aspiration for the hydrological research community to become more proactive by coming together to formulate ideas that are longer and more intensely collaborative (including deeper international partnerships) than the usual funding programmes in hydrology. This process might be described as 'work together to think big'. In this context, the growth of a community of practice, as an outcome of the roadmap, could be seen as an important stimulus. It would help to ensure that future, ambitious research programmes are matched by, and closely connected to, strong partnerships across industry.

This initiative links to the following work areas developed at earlier stages in the roadmap:

Q5. Establish a steering group to own and champion implementation of the flood hydrology roadmap. The remit of the steering group would include ongoing ownership of the roadmap specifically, identifying funding opportunities, steering implementation of priority work areas, reporting on progress and periodic updates to priority work areas.

Q6. Establish a UK flood hydrology scientific advisory group made up of professionals from across the community. The scientific advisory group could have a wide remit and could provide technical advice on flood hydrology to measuring authorities, practitioners and others. It may form specialist groups on specific topics such as monitoring.

Q8. Build international partnerships to foster greater transfer of knowledge and best practice. Improve and build upon current partnerships. Identify and establish new international relationships to encourage knowledge exchange, diverse learning opportunities, and skills transfer.

Q9. Improve the transfer of scientific advances in flood hydrology into practice. Increase the impact of UK Research and Innovation funded programmes and projects through improved translation of science into practice. This work area should encourage practitioners to share information with researchers about current practice, current needs, what does and doesn't work well, and examples where new methods and techniques have been applied in practice.

Q10. Increase integration across the flood hydrology community. Encourage more integrated relationships across the flood hydrology community. This could include ways to enable skill and knowledge sharing between different industry groups (for example, regulators, consultants, academics, water companies and developers) and technical disciplines (for example, high flow and low flood specialists, meteorologists and geomorphologists).

Q11. Review and define roles and institutional responsibilities in UK flood hydrology. Carry out a review of current and future roles required to achieve effective flood hydrology in UK. This should include a skills gaps analysis for important roles.

Objectives of initiative

1. Create an interim Scientific and Technical Advisory Group (STAG) for UK flood hydrology, charged with generating a rapid proposal for:
    a. a permanent body of the same name
    b. its terms of reference
    c. its modus operandi and business plan (resources required, secretariat)

    The STAG could work through a voluntary process, as with the BHS science WG, but may benefit from being driven for the initial planning phase by a sponsor.

2. Establish a 25 year plan for a community of practice in flood hydrology, drawing on a review of the institutional landscape, roles, skills and resourcing needs.

Expected benefit and outputs of initiative

1. Flood hydrology has a higher profile, linked to more coherent, powerful institutional representation in influencing policy and lobbying for resources.
2. Hydrological skills are more valued and professional esteem raised (link to skills and esteem initiative).
3. Research initiatives are better targeted at meeting the needs of practitioners, and their findings are more readily implemented.
4. Practitioners are more aware of and better equipped to implement scientific advances.

Drivers for this initiative

1. We need to get better at working together to answer the complex challenges posed by environmental and social change.
2. Increasing depth and range of specialisms in science and engineering, combined with the costs of advancing science, mean that we need to be able to ‘scale up’ partnerships, knowledge sharing and advocacy within hydrology.

Risk(s) associated with not carrying out this initiative

1. Without a group to champion flood hydrology over the long term, there is a risk that progress made in the flood hydrology roadmap will not be sustained.

Data discovery and accessibility

Primary theme(s)

- Flood forecasting and flood estimation

Cross cutting area(s)

Score 1 to 3 for relevance to cutting area, where 1 is most relevant and 3 least relevant:

- Data – 1
- Methods – 2
- Ways of working – 2
- Scientific understanding – 3

Executive summary of initiative

This initiative aims to manage, access and quality assure all types of flood hydrology data more effectively.

Access to high quality flood hydrology data is important for all the flood hydrology community and impacts the quality of flood risk management activities. This initiative will identify the status of data accessibility in the UK and will set out options for improving accessibility. It will also examine options for improving flood data quality and quantity (the 'richness' of data). Implementation of the options will follow these investigations, further to gateway review by the commissioning body.

Context of initiative

The roadmap's vision for flood hydrology data is as follows:

Funding, knowledge, capability and resources exist to monitor the UK hydrological environment, particularly extremes.

New and historical data are communicated and shared openly, properly archived and centrally located to support all flood hydrology studies. Data are freely available for all carrying out flood hydrology studies.

Data are of sufficient quantity and quality for each application; uncertainties are understood and communicated effectively.

Data are the 'raw material' for flood hydrology. High quality and ambitious flood hydrology research and activities need access to data that meet the needs of practitioners and researchers in terms of quality and quantity of data. Access to data is an important concern for many; this initiative seeks to address issues of data accessibility. Centralised storing of data and data quality assurance and data volumes are separate but related aspects that affect the UK flood hydrology community and are also covered in this initiative.

This initiative has links to the better data in future initiative that focuses on future data needs.

The BHS Working Group (BHS WG) on future hydrological research has, in its publication on observational methods (Developing observational methods to drive future hydrological science) (last accessed 18 November 2021], highlighted the importance of multiple forms of observations, some of which may involve new technologies or observation strategies. These strategies may include more 'agile' approaches to field measurement than fixed infrastructure. The BHS WG also called for the hydrological community to coalesce around joint initiatives. If flood hydrology is to evolve in the above directions, then the management, discovery, and accessibility of data will all be important.

This initiative links to the following work areas developed at earlier stages in the roadmap:

Q32. Establish and maintain a register of data relevant to UK flood hydrology studies. Collate and publish metadata that can be used in flood hydrology operations and research. The register should be regularly updated and gather metadata from a wide variety of sources.

Q33. Carry out a comprehensive review of existing UK flood hydrology data. Review data in the flood hydrology data register (previous work area) to define its quality, applicability to particular technical areas, and scope for improvement. This should cover hydrometric data from all sources of flooding, meteorological and spatial data (including catchment properties and flood impacts).

Q36. Develop and maintain open access data archives for all sources of flood hydrology data. This will include, but not be limited to, a 'local data' archive to complement systematic flood hydrology data archives. The local data archive should be able to log and store input from citizen science approaches and also archive historical and palaeoflood data and results from previous hydrological studies and reports.

Q38. Salvaging historical data. Digitisation and salvaging historical data (for example, archiving the spatial radar estimates of rainfall, historic flood records, analogue records).

Objectives of initiative

Part A – Data accessibility

1. Carry out a review of all sources of data relevant to flood hydrology in the UK, identifying:
    a. what these data sources are (should include spatial data sets that support flood hydrology as well as hydrometric data) and what further data sources would be desirable, for example, data related to:
        i. extreme value analysis

    ii. multivariate/joint probability
    iii. spatial statistics (for example, spatial coherence)
    iv. precipitation
    v. evaporation
    vi. snowmelt
    vii. run-off/soils
    viii. groundwater
    ix. sediment
    x. surface water/sewers
    xi. water quality
    xii. ecology
  b. who manages the data and who owns the data
  c. what licensing arrangements exist for use of the data
  d. which data are freely available to all, which are freely available to some, and which are not freely available
  e. what data quality assurance is carried out on the data in these separate sources, noting how this varies and compares
  f. what the arrangements are for updating the data
2. Produce a report on the findings of the investigation in phase (1).
3. Develop a series of options for the future of UK flood hydrology data - these options should consider:
  a. developing discoverable portal or portals for all UK flood hydrology data
  b. proposals for funding and licensing of data (ownership, management and quality assurance) such that quality controlled data are 'freely available to all'
  c. examining international data availability approaches such as those of the USA and other European countries to identify learning points for the UK, answering, among other things, 'how do freely available flood hydrology data benefit society, the economy and the environment?'
  d. options should be costed and ordered in the form of a cost-benefit approach that makes option testing and assessment easier
4. Engage with funding bodies and relevant UK government departments to discuss cost models developed in stage 3, setting out the benefits of the preferred options.
5. Subject to passing gateway review, engage in implementation of preferred option.

Part B – data quantity and quality (could be carried out in parallel with Part A)

1. Carry out a comprehensive review of existing UK flood hydrology data
  a. review data in the flood hydrology data register to define its quality, applicability to particular technical areas, and scope for improvement
  b. this should cover hydrometric data from all sources of flooding, meteorological and spatial data (including flood impacts)
2. Examine opportunities for salvaging historical, non-digitised data and for digitising this
  a. define the extent of data this concerns, cost-effective approaches for digitisation (minimising manual conversion), and effort levels required

3. Develop plans for improving UK flood hydrology data quantity and quality, addressing findings from steps 1 and 2.
4. Implementation of plans (following gateway review).

Expected benefit and outputs of initiative

1. A comprehensive assessment of need for improved data accessibility and data quality control – this leads to better decision-making in implementing options developed.
2. Development of realistic options for improving data accessibility, leading to improved data accessibility.
3. Greater data accessibility increases research potential and can fuel more ambitious and more useful research and development in flood hydrology, with knock-on benefits in reducing flood risk.
4. Increased delivery efficiency of operational projects through better data.
5. Development of plans to improve data quality and quality assurance, making flood hydrology data better, more extensive and more accurate – this will benefit many flood hydrology activities and have knock-on benefits in reducing flood risk.

Drivers for this initiative

1. There is an appreciation of the high value flood hydrology data have in all aspects of UK flood hydrology and the need to focus on its availability, quality and quantity.
2. Currently, data are held in multiple locations with different owners.
3. Free, open access to data does not exist in all cases and, even when present, is not always straightforward, meaning many practitioners or researchers cannot use data easily without acquiring licenses.
4. Cost models used for data platforms are prohibiting use and access to data that could be used for research or consultancy purposes.
5. Reduced access to data impedes progress in flood hydrology research and impacts many projects aiming to reduce flood risk – inaccessibility is regarded as a problem for many in the flood hydrology community today.
6. The UK has an opportunity to follow the example of other countries where data are made freely and readily available.
7. Flood hydrology data quality is known to be of variable quality and, in some cases, reducing in quantity – there is a need to understand the severity of this issue and develop plans to improve data quality and quantity where needed.
8. Data updates could be made with greater regularity across all data types if the data were held in one database/source.

Risk(s) associated with not carrying out this initiative

1. Important and useful data are not used because of the financial constraints and licensing arrangements or because they are not known about or not easily or quickly enough accessible.

2. Flood risk increases (property, lives, cost) because data cannot be widely used.
3. Flood risk management is held back because innovation from academia and other practitioners is constrained by a lack of data access.
4. Reputationally, the UK lags behind other countries who make data freely available – could result in a ‘brain drain’ away from the UK.
5. Access to flood hydrology data continues to be fragmented and subject to cost models that are regarded as impeding research and the ability of practitioners to use data most effectively on flood hydrology projects.
6. The future access to flood hydrology could be subject to greater restrictions than we have today if the issue of data accessibility is not reviewed.
7. Flood hydrology data quality and quantity could ‘stagnate’ and there could be no pan-UK programme for seeking continual improvement in UK flood hydrology data quality and quantity.

Integrated methods, modelling and data analytics spaces

Primary theme(s)

- Flood forecasting and flood estimation

Cross cutting area(s)

Score 1 to 3 for relevance to cutting area, where 1 is most relevant and 3 least relevant:

- Data – 2
- Methods – 1
- Ways of working – 2
- Scientific understanding – 2

Executive summary of initiative

This initiative aims to make the most of technological advances to improve flood hydrology modelling, analysis and services for operational purposes.

Flood hydrology relies heavily on data and software systems. Yet the development of methods, analytical tools, software and supporting IT infrastructure within the profession has generally been ad hoc, driven by a mix of research funding and private sector competition. Significant scientific and technological changes are gathering pace around us, many already familiar in day-to-day life. Calls (reflected in the roadmap) for advances in modelling and data will lead to greater technological demands. The roadmap offers a timely opportunity to bring together the professional community to innovate the software and IT that will be the platform for the future of flood hydrology.

Context of initiative

Integrated modelling and data analytics (virtual) spaces are the combinations of underlying technological infrastructure (both physical and in terms of 'platform' software such as cloud-based resources) and hydrology-specific software that enable flood hydrology models, tools, data analysis and services to exist.

The availability of data and analytical tools for science and engineering applications have been increasing dramatically in recent years. Flood risk management (FRM) and flood hydrology are, along with all other sectors, moving towards an era of big data. Specific challenges in flood hydrology and FRM are that relevant models and data sources exist at a variety of scales, and can be very heterogeneous (that is, involving a mix of different types of model or data from different sources, with some data being highly structured, such as hydrometric databases, and other data more unstructured, such as written reports of historical flood events).

Models and data used in flood hydrology have developed alongside a changing technological landscape, which has evolved from the mainframe computers of the 1970s, through the era of the personal computer or workstation (1980s to 2000s), the emergence of the internet and world wide web in the 1990s, and the period 2007 to around 2012, when the landscape was dominated by grid computing technologies. Over this time, the computational power available to hydrologists grew significantly. Since then, the technological landscape has changed through 3 significant areas of innovation:

- cloud computing (which promotes a view of ‘everything as a service’)
- data science (a fundamentally cross-disciplinary area of science analysing and making sense of very large and/or highly complex data sets)
- mobile technologies (including communications, sensors, Internet of Things, and novel types of user/machine interfaces such as voice recognition)

These technologies have created opportunities for significant, and beneficial, changes in the way that models and data can be developed and applied. Specifically, tools for collaborative working are far more powerful than before. This is already becoming apparent in rapid spread of non-technical ‘Office’ tools, such as Office365, GSuite or MS Teams. In data science, similar technologies are emerging (for example, ‘Jupyter notebooks’ and ‘virtual labs’). An important feature of the Cloud is its elasticity, meaning that data storage and processing power can flex and, in principle, enable users to access resources that would previously have been unaffordable because of high capital costs. It is possible to envisage computationally-demanding models, or analysis of very large data sets, becoming accessible to many users when previously they would have been exclusive to well-funded research institutions or technology centres.

The new technology landscape also presents challenges, including access to requisite skills and the need to navigate technologies and tools of differing levels of maturity (and the inevitable churn associated with rapid innovation). There is also an important change in the way that new technologies may cause us to rethink approaches to ownership, funding and trust (much in the same way that many people now rent digital entertainment media, rather than own it, and social media has transformed our ability to inform, but also to misinform).

Against this background of radical change, 3 work areas have emerged through the roadmap consultation, dealing with IT infrastructure and software architectures. Good service design of the ‘right infrastructure and software’ is implied in one of the work areas, which is motivated by a need for the profession to enable regulators and others to be intelligent clients. There are also scientific and technical drivers expressed in 2 other work areas, which together proposed greater integration (though software and technology) of statistical and rainfall run-off models, and greater integration of models applied for real time forecasting and for long-term risk analysis. Additionally, a driver for openness was expressed. These 3 work areas were classified under the themes of methods and ways of working.

Q14. The right IT infrastructure. Regulators and others review their IT infrastructure needs to enable them to effectively carry out an intelligent client role in flood hydrology, ensure they can replicate results and access the latest software and techniques (for example, machine learning). To include reviewing policies and software architectures (for example, compliance with standards, use of Cloud services, accessibility to virtual labs).

Q18. Scope the long-term development of an open, online, modular system for flood hydrology that blends statistical methods and rainfall-runoff models. This modular system could be capable of predicting floods in real time and estimating flood risk from all sources of flooding.

Q22. Review how real-time flood forecasting and longer-term flood risk assessment could be more integrated. Carry out a review of the current level of integration between flood forecasting and flood estimation methods for all sources of flooding. The review could include a scoping exercise to identify actions that would allow greater integration of flood forecasting and flood estimation methods.

Objectives of initiative

1. To create a service design for flood hydrology system technology requirements:
    a. understand who benefits from and values flood hydrology models and data
    b. understand what their realised (explicit) needs are
    c. construct hypotheses for their unrealised needs
    d. create hypotheses for what the technology and software solution would be for them (in terms of experience and value proposition)
    e. rapidly iterate outline plans for software and IT infrastructure based on those hypotheses to gain confidence in the required solution
2. To produce a business case for subsequent development of the required systems and technologies.
3. Assess where there are gaps in the current UK operational methods
    a. this would include the following parameters/outcomes as a minimum:
        i. precipitation
        ii. evaporation
        iii. snowmelt
        iv. run-off
        v. throughflow
        vi. soil moisture
        vii. groundwater
        viii. sediments
        ix. peak flows
        x. food volumes
        xi. hydrographs
        xii. rate of rise
        xiii. flood durations over threshold
    b. this aligns with the data, quality and scientific advances in modelling initiatives

The objectives are not specified in greater detail here because a service design methodology involves iterative identification and evolution of specific needs and solutions based on the process 1(a)-1(e). This approach is suggested in view of the numerous stakeholders and rapidly-evolving technological context. Although the approach is purposefully open and iterative, it should be informed by specific aspirations that have emerged through the flood hydrology roadmap process, including improved integration of forecasting and flood risk estimation methods (as noted in items Q18 and Q22 in the online consultation study of 2019, which have been in the context section of this document).

Expected benefit and outputs of initiative

1. A plan that has wide community buy-in for the systems, including software and technology infrastructure, needed to support flood hydrology services (both commercial and non-commercial).
2. Clarity over the benefits of the proposed systems and the values embedded within their design.
3. A business case that will enable funding to be secured (and by whom).

Drivers for this initiative

1. Growing requirements to take a systems-of-systems view of flooding, which is needed to:
    a. improve understanding of all sources of flood risk
    b. achieve consistency at all spatial scales, from local to national
    c. achieve consistency between different sources of flooding
    d. achieve consistency at all time scales from real-time to long-term
2. Challenges and opportunities associated with rapid technology innovation (within and beyond FRM) and ‘big data’.

Risk(s) associated with not carrying out this initiative

1. Flood hydrology, as a discipline, may struggle to meet the needs of stakeholders who are increasingly likely to demand more sophisticated analytical services.
2. Competing ad hoc systems may emerge that lack compatibility, leading to inefficiencies.

Management of uncertainty

Primary theme(s)

- Flood forecasting and flood estimation

Cross cutting area(s)

Score 1 to 3 for relevance to cutting area, where 1 is most relevant and 3 least relevant:

- Data – 3
- Methods – 1
- Ways of working – 3
- Scientific understanding – 2

Executive summary of initiative

This initiative aims to embed uncertainty in flood hydrology more comprehensively and quantitatively, in real-time and longer-term risk management.

This initiative aims to make management of uncertainty central to flood hydrology, rather than a ‘bolt-on’ to existing methods. It will clarify the value of taking a coherent approach to uncertainty, identify where guidance is needed and provide working examples of method and guidance statements, addressing:

- flood forecasting and warning
- long-term risk management (planning and climate adaptation)

Context of initiative

Uncertainty has been an explicit and perennial topic within hydrological research for at least 40 years. Flood risk management itself is fundamentally a response to uncertainty. The need to consider the concept of risk stems from unpredictability and imperfect knowledge.

Uncertainty is a very broad topic, encompassing the natural and mathematical sciences, engineering and social science. Numerous technical methods have been proposed in the scientific literature to describe, quantify and model uncertainties in hydrology, and some have been applied in practice. But many are complex and may be difficult or expensive to apply in conjunction with industry-standard analytical methods. Communication of uncertainty is also recognised to be a challenge, both to stakeholders and within the FRM profession.

International standards already exist for some applications (for example, in the International Organization for Standardization (ISO) Hydrometric Uncertainty Guidance) and for generic aspects of measurement (the ISO Guide to the Expression of Uncertainty in Measurement). These inevitably have a relatively narrow and specific focus. Some attempts have been made to develop broader, systematic and structured approaches to the management of uncertainty (for example, during the Flood Risk Management Research Consortium (FRMRC) projects in the first decade of the 2000s), but with limited uptake in practice. Elsewhere in the fields of natural hazards, adaptation and resilience, there are large initiatives such as the World Bank ‘Understanding Risk’ forum that could potentially inform practice in FRM and flood hydrology.

To date, within flood hydrology, there is no consensus set of standards or guidelines on methods for the quantification and communication of uncertainty in general, or for its recognition within FRM decisions that are informed by hydrology. It is not even clear whether a ‘standard’ set of methods would be appropriate, or whether it may be more realistic to establish some principles and demonstrators (simplified but realistic reference cases and tools), around which methods can evolve to reflect advances in scientific understanding and tools.

Fortunately, relevant basic concepts appear to be widely acknowledged in the hydrological profession. These include the routine application of probabilistic analysis (through models based on statistical distributions or stochastic simulation), the classification of sources of uncertainty (in particular, the distinction between aleatory and epistemic, or ‘randomness’ and ‘knowledge’ uncertainties), and the use of non-probabilistic scenarios or storylines. Against this background, there is considerable scope for innovation and knowledge transfer between research and practice to enable hydrologists to tackle the management of uncertainty with greater confidence. This initiative is, in a general sense, a reflection of the inexact nature of hydrological science, as noted by the BHS working group on the future of UK hydrological research, and also the potential for reductions in uncertainty to be an important motivation

Objectives of initiative

1. Review the rationale and motivation for the management of uncertainty in flood hydrology, clarifying the associated value (economic or otherwise) within FRM - in other words, establish clear answers to the questions:
    a. why is uncertainty management important?
    b. (why) is it worth spending resources to do it well?
    c. under what circumstances would it be beneficial to spend more effort to move beyond a baseline approach of using judgement and tolerating the resulting residual risk?
2. Define the scope of new guidance for the management of uncertainty in flood hydrology:
    a. what kind of guidance is needed?
    b. what is scientifically valid?
    c. what is practical for different applications in flood hydrology?
    d. how would new observations help to constrain uncertainties in hydrological knowledge and predictions?
3. Review state-of-the-art in scientific research and in practice.

4. Establish draft guidance and methods or demonstrators for specific applications:
    a. one of which should focus on forecasting and warning
    b. one of which should focus on long-term risk management, for example, planning, climate adaptation
5. Define a process to enable the ongoing evolution of guidance and methods.

Further detailed objectives require additional scoping to decide on the appropriate level of resourcing for objectives 1 and 2, and the appropriate level of depth and rigour for (3) and (4).

Objectives (3) and (4) are envisaged here as parallel activities, with the guidance and demonstrators in (4) initially drawing on methods already known at proof-of-concept or from applied research studies to provide relatively quick, useable outputs, while testing the analysis of needs and justification explored in (1) and (2) above. The state-of-art review (objective 3) would then position the community to update those initial guidance and demonstration outputs should better science and methods be identified. An alternative would be to wait until the science review completes (objective 3) before starting work on the guidance and demonstrators (4), but this would delay practical outcomes.

Expected benefit and outputs of initiative

The main benefits will be to:

- enable hydrologists to tackle the management of uncertainty with greater confidence
- improve the robustness of FRM decisions, and communication of flood risk
- support the further integration of statistical and physically-based approaches as envisaged by the National Flood Resilience Review (NFRR)

Drivers for this initiative

Work areas on uncertainty scored highly in the roadmap 2019 online consultation (5th- and 12th-ranked), underlining the importance of the topic. Uncertainty is also a cross-cutting issue, reflected in the fact that proposed work areas appear in both the methods and scientific understanding themes (with the development of novel methodology being included in the latter). Although this work area (as consulted on in 2019) did not mention the uncertainty, it essentially deals with making informed and rational decisions about the most extreme possible hydrological events, which are, by definition, those we can be least certain about.

Q20. Develop guidance to help decision makers quantify, communicate and take account of uncertainty in flood hydrology. Review and synthesise current knowledge about uncertainty in flood hydrology to provide guidance, allowing end users to better take account of uncertainty in decision-making. This work area should be regularly reviewed to ensure guidance keeps pace with scientific developments.

Q42. Research on all sources of uncertainty in flood estimation and forecasting. This work area would identify the relative importance of different sources of uncertainty. It would include understanding the practical limits of prediction, sources of uncertainty and development of new methods to take account of uncertainty in flood hydrology.

Risk(s) associated with not carrying out this initiative

Uncertainty will be treated as an ‘add-on’ to hydrological analysis, rather than recognising that it is the fundamental driver for most risk management. This will discourage the appropriate allocation of resources to the management of uncertainty, resulting in poorly tested and documented ‘short-cut’ methods gaining traction.

Flood hydrology could drift out of step with more sophisticated approaches to risk management that may emerge from the science of climate adaptation, disaster risk reduction and decision analysis.

Monitoring, attributing and predicting the effects of environmental change

Primary theme(s)

- Flood estimation

Cross cutting area(s)

Score 1 to 3 for relevance to cutting area, where 1 is most relevant and 3 least relevant:

- Data – no score
- Methods – 1
- Ways of working – no score
- Scientific understanding – 2

Executive summary of initiative

This initiative is about monitoring, attributing and predicting the effects of changes in climate and the land.

Environmental change is fundamental both as a driver of flood risk and a source of uncertainty in flood hydrology. It poses challenges for flood hydrology in dealing with:

- uncertainties about how the future will unfold, which depend both on nature and on human actions
- the implications of historical and ongoing changes, some of which may not be easily or fully understood

This initiative amalgamates 3 work areas identified within the flood hydrology roadmap that concern aspects of climate and land use change. It considers both scientific understanding of the causes of change, analytical methods to account for change, and the practical guidance and methods. It will enable flood hydrology professionals to inform flood risk management decisions through better projections of the long-term future impacts of change, and better analysis of the implications of changes already happening.

Context of initiative

A work area on 'Accounting for climate change in flood hydrology' was ranked 3rd highest in the flood hydrology roadmap online consultation in 2019. This work area (tagged under methods) suggested the development of a long-term strategy for ensuring that flood hydrology methods take account of climate change in a scientifically robust way.

Climate change is central to risk management authorities' strategies for FCERM. There are also other types of environmental change that can be important, including physical changes in catchments and geomorphological changes in channels and flood plains.

These issues have been identified in the roadmap in a suggested work area to 'Develop methods for identifying, attributing and accounting for non-stationarity in flood hydrology'. This work area suggested tools and guidance to help decision makers visualise, communicate, identify, attribute and account for non-stationarity in flood extremes. Two prominent focal points for analysis of catchment changes are urbanisation (or development plans more generally) and other land management changes, especially natural flood management.

This proposal also draws on a suggested work area, tagged under the scientific understanding theme, to 'Improve evidence for long-term drivers of hydrological variability and change' and develop 'methods for the analysis of non-stationarity'.

During the development of the roadmap, hydrologists have identified confusion[3] over how national climate change guidance should be interpreted. Specific concerns relate to the incorporation of new climate projections into practical guidance, which varies in different contexts (including differences between England, Wales and Scotland), and dealing with the transitional period during the present decade when climate change has already been shown to have an influence on major flood events (through event attribution science), but natural variability is still predominant (NFRR).

There are multiple other activities that form the scientific and technical backdrop for this initiative, notably:

- new interim national guidance on non-stationary fluvial flood frequency estimation (Environment Agency/Defra flood and coastal erosion risk management research and development programme)
- rapid evidence assessment on non-stationarity in flood hazards (Environment Agency/Defra flood and coastal erosion risk management research and development programme)
- UK Climate Projections 2018 (UKCP18) regional and local (high resolution) climate projections (Met Office)
- updated projections for river flows based on UKCP18 (UKCEH, Environment Agency/Defra flood and coastal erosion risk management research and development programme[4]) and analysis of UKCP18 local projections for intense rainfall (NERC research and knowledge exchange)

[3] "Climate change confuses matters because we change how we deal with it. Admittedly, this is probably because our understanding of it changes too, but more consistency would help." "As far as I can tell, we don't exactly know how to quantify the impact of climate change on a catchment level. So, till we know that, it will be hard to account for the changes." - 2019 survey responses.

[4]The Environment Agency funded the sea level projections to 2300, and we are funding some of the peak flows published this year.

- analysis of catchment susceptibility to intense rainfall (NERC flooding from intense rainfall programme)
- NERC natural flood management research programme (Q-NFM, Protect-NFM and LANDWISE)
- NERC capital programme on flood and drought resilience (long-term observation networks)
- continuing fundamental academic research on climate and landscape change (processes, modelling and future scenarios), on extreme event attribution, and on statistical analysis of change (non-stationarity)

The new interim England and Wales guidance on non-stationary fluvial flood frequency estimation found that:

- two-thirds of peak flow series in England and Wales have upward trends
- a range of statistical methods for modelling non-stationarity can be applied using specialist tools
- estimates of flood probabilities based on these methods can differ from those derived using conventional methods
- attribution of observed trends is an essential ingredient for understanding future trends, suggesting a need to bring together the statistical analysis of past flood and rainfall data with the physics-based modelling of future changes (which also aligns with recommendations made within the NFRR)

A related challenge is the need to assess changes in rainfall, to inform flood studies that use statistical estimates of rainfall extremes to drive rainfall-runoff models, which encompass applications to some rivers, to reservoirs and all surface water flooding investigations.

Overall, this work should take account of existing knowledge and address the following knowledge gaps:

Existing knowledge:

- There is evidence that environmental change can influence, and already has influenced, inland flood risk.
- Models and model outputs exist for baseline and projected future climates.
- Evidence, data and models for the hydrological impacts of other forms of environmental change are evolving as research progresses.

Knowledge gaps:

- The scale and nature of the influence is uncertain - specialist tools and expertise are needed to assess it, and its influence, with tools and guidance for hydrologists only recently emerging.
- Translation of those models and model outputs to address specific hydrological requirements is constantly evolving, raising questions about interpretation of guidance.

- Methods applied in practice may have to adapt, or not be capable of adapting, to keep up with new scientific evidence.

This initiative links to the following work areas developed at earlier stages in the roadmap:

Q21. Accounting for climate change in flood hydrology. Develop a long-term strategy for ensuring that flood hydrology methods take account of climate change in a scientifically robust way.

Q28. Develop methods for identifying, attributing and accounting for non-stationarity in flood hydrology. Develop end-user focused tools and guidance to help decision makers visualise, communicate, identify, attribute and account for non-stationarity in flood extremes. This should cover all sources of hydrological non-stationarity such as climate change, physical changes in catchments and geomorphological channel and flood plain evolution.

Q49. Improve evidence for long-term drivers of hydrological variability and change. Research to understand drivers of hydrological variability and change. To include development of methods for the analysis of non-stationarity.

Q26. Develop methods and guidance for quantifying the hydrological benefits of flood risk management interventions in the catchment. Carry out a review and develop methods and visualisation tools to help decision makers quantify the hydrological changes (for example, reducing peak flows and changing timings) from management interventions in the catchment, such as natural flood management measures. Methods should be applicable from reach to catchment scale.

Objectives of initiative

Develop improved and scientifically robust methods and guidance to account for the impacts of environmental change, both past and future, on all sources of inland flooding. Objective (1) will help to steer the subsequent work and add detail to the objectives (2) to (5).

Specific objectives (subject to confirmation during an in-depth inception phase) are to:

1. provide a short synthesis of existing evidence and knowledge reviews to establish and summarise the gaps between current methods in practice and scientific knowledge about environmental change
    a. the main question to be answered by this synthesis is ‘In what ways do government policy and risk management authority strategic ambitions require new knowledge and methods to account for environmental change?”
2. produce an approach for ongoing detection and attribution of trends in high river flows and rainfall (with identification of covariates that can explain changes in distributions of relevant variables)
    a. review theoretical basis
    b. recommend suitable method or classes of methods

    c. develop guidance on implementation
3. further develop and test methods for modelling flows and rainfall as non-stationary data to enable interim guidance to transition into a more mature analytical approach, feeding into (1) above
4. develop seamless approach for past and future climate change impacts, taking account of both statistical hydrology approaches and physically-based climate or land use change modelling
5. translate model results into guidance and data that can be used for estimating future river flow and rainfall scenarios to improve FRM decisions, and to assess the robustness of existing analyses that have been based on stationarity assumptions
    a. assess the implications of past and contemporary change for flood hydrology with respect to:
        i. robustness, performance and maintenance of forecasting models
        ii. robustness of hydrological inputs to risk assessments

Expected benefit and outputs of initiative

Outputs:

1. Technical guidance to offer hydrologists a menu of tested and appropriate analytical methods.
2. An open-access 'virtual lab' or similar toolkit and data resource, with a programme of periodic updates, to continue testing for and seeking to explain changes in relevant indicator variables (for example, peak flows for selected benchmark catchments).
3. More integrated and coherent guidance and rationale for assessing the transition from historical to future climates.

Benefits:

1. Clarity for hydrologists and FRM decision makers about the influence of environmental change, appropriate methods to assess it, and the associated uncertainties - a scientifically robust basis for current and future FRM decisions.

Drivers for this initiative

To ensure that hydrological analysis supplies the robust answers required to make sound FCERM decisions now and for the future:

1. widespread requirement for this from public sector, private sector and academia
2. research needs identified through the non-stationarity guidance and rapid evidence assessment projects
3. lack of ability to extend non-stationary models of flood frequency into the future or to merge them with climate change allowances
4. lack of clarity on how climate change allowance guidance should be used
5. guidance (in England and Wales) not including latest research output using convective-permitting climate models

6. need for non-stationarity and trends to be accounted for in managing risk of flooding from surface water, reservoirs, lowland catchments and rivers at ungauged locations

Risk(s) associated with not carrying out this initiative

1. Climate change is not properly allowed for (for example, wrongly assuming that past trends mean future allowances can be reduced, or that all climate change is yet to come) – leads to under-adaptation, over-adaptation or maladaptation.
2. Emerging science about catchment change is not integrated with other forms of non-stationarity.

Quality assurance

Primary theme(s)

- Flood forecasting and flood estimation

Cross cutting area(s)

Score 1 to 3 for relevance to cutting area, where 1 is most relevant and 3 least relevant:

- Data – 2
- Methods – 2
- Ways of working – 1
- Scientific understanding – 3

Executive summary of initiative

This is an initiative to assess where quality improvement and consistency is needed, and to drive quality improvements.

Quality assurance (QA) in flood hydrology is recognised as highly important. Its absence, or lack of full application, can have implications on safety of human life, economics, and societal and environmental impacts. The quality of inputs to flood hydrology are also important - data quality is addressed in the data discovery and accessibility scope.

This initiative aims to examine where quality assurance may be lacking or inconsistent in UK flood hydrology activities and the reasons for this. It will look for examples of 'good practice' and highlight these. It will pay particular attention to quality assurance of flood hydrology models (real-time and flood estimation) and in applying QA in the commissioning of flood hydrology projects.

Recommendations will be made for improving QA in flood hydrology across the UK and the initiative will develop consistent QA standards for application to address inconsistencies identified. This will also be an opportunity to develop world-leading standards that drive a continual improvement in quality in flood hydrology projects, research and operational activities.

Context of initiative

The field of flood hydrology in 2020 uses a wide range of tools, technologies and guidance to help ensure it is providing high quality outputs, recommendations and engineering designs. Frequently, these outputs have a major bearing on public safety and in reducing substantial economic, societal and environmental damage in flood risk management activities. Therefore, a high degree of rigour and quality control is required to make sure outputs, recommendations and engineering designs from flood hydrology activities meet required standards.

Many quality standards and procedures currently exist in the flood hydrology community to enhance quality assurance. However, existing QA and standards in flood hydrology may be less formalised than in sectors such as engineering design processes, for example.

This initiative is designed to strengthen quality assurance across all flood hydrology activities. It is meeting a perceived need to address areas where quality assurance may be less than desired, and to develop a single set of standards and guidance that are applicable across all sectors, organisations and locations.

This requirement cuts across all sectors working in UK flood hydrology (academia, regulators, science bodies and consultants), although it has particular importance for sectors working directly to reduce flood risk to people, economy, society and the environment. Any standards developed should avoid stifling innovation and be focused on making flood hydrology analysis better.

This initiative links to the following work areas developed at earlier stages in the roadmap:

Q13. Develop, maintain and publish clear guidance on ‘industry standard’ methods and tools for flood hydrology. Technical guidance for practitioners should cover methods for all sources of flooding over a range of spatial and temporal scales. Guidance should be peer-reviewed and have sign-off from an appropriate group (for example, the proposed flood hydrology scientific advisory group). Guidance should be reviewed and updated annually as a minimum to take account of new and updated methods and user feedback.

Q15. The commissioning process. Regulators to review their commissioning and quality review processes to ensure flood studies require high quality thorough flood hydrology investigations using latest research and guidance where appropriate.

Q27. Benchmarking of flood hydrology models. Establish benchmarking tests for flood forecasting and flood estimation models assess their quality and compare them. This would include developing data sets from a range of catchments, at a range of scales, and for all sources of flooding. To include establishing quality criteria for inclusion or acceptance of methods/codes.

Q29. Understand flood hydrology outputs required for current and future needs. Review information needs of end users of flood studies to ensure flood hydrology methods are able to produce useful outputs for all types of flood studies.

Objectives of initiative

1. Assess existing quality assurance (QA) in flood hydrology, determining how this differs across different parts of the UK.
2. Identify where there are:
    a. recognised shortfalls in quality assurance being applied
    b. examples of ‘good practice’ in flood hydrology quality assurance being used (could include ISO standards)

   c. reasons for quality standards/procedures not being adhered to (for example, is this due to time or budget constraints on projects, lack of understanding of how to apply QA protocols, or lack of appropriate senior experienced staff making QA reviews)
3. Paying specific attention to flood hydrology models (flood estimation and forecasting), assess what model QA is required across the UK by commissioning agencies, how appropriate this is and how rigorously it is being applied
   a. in England, the Environment Agency's flood forecasting model performance guidelines exist for real-time models QA
   b. this activity can allow model benchmarking to be carried out
4. Examine the way in which QA is embedded in project scopes/terms of reference from commissioning bodies
   a. is the wording used clear, appropriate and (for competitive tenders) is sufficient focus in the evaluation of proposals put on proposal responders' treatment of QA in their responses?
5. Make recommendations for standards in QA of flood hydrology activities, including models, that build from examples of 'good practice' and seek to provide consistency in QA across the UK (if all regulatory bodies desire this) for all bodies commissioning flood hydrology work.
6. Review information needs of end users of flood studies to ensure flood hydrology methods are able to produce useful outputs for all types of flood studies.
7. Upon approval of 5, develop these standards.
8. Establish an owner for the new QA standards who is responsible for:
   a. hosting the standards in an online environment
   b. communicating the standards and gaining accreditation for these from relevant institutions (for example, Institution of Civil Engineers (ICE), CIWEM, BHS)
   c. updating the standards periodically or when improvements are sought

Expected benefit and outputs of initiative

1. Developing consistent quality assurance across all flood hydrology activities, applicable, where appropriate, across all of the UK. Consistent quality adds confidence to flood risk management activities (for example, flood defence schemes, real-time flood forecasting) and reduces the risk of incorrect calculations or flawed recommendations.
2. Flood hydrology models (real-time and flood estimation) are tested with required rigour and quality assurance procedures in a more holistic, nationwide way, increasing the consistency of high quality models being used for operational purposes or design of (often costly) flood defence measures.
3. Encourages fair competition that maximises value through innovation and quality rather than pricing, in other words, helps to avoid race-to-the-bottom.

Drivers for this initiative

1. A perceived inconsistency in application of suitably rigorous quality assurance (QA) procedures across all flood hydrology activities, including flood hydrology models.
2. A recognised need to drive quality upwards in all areas of flood hydrology – striving to the highest quality and continuing the UK's long history of being global experts in hydrology standards and procedures.

Risk(s) associated with not carrying out this initiative

1. Quality assurance in flood hydrology is variable across organisations and countries in the UK and lacks consistency.
2. Quality in flood hydrology activities is compromised due to pressures of time, budget, skill shortages and/or inconsistency of requirement for QA in project scopes.
3. Real time and flood estimation models are produced without consistent QA being applied resulting in models of unacceptable quality being used to inform judgments, which may be flawed as a result.
4. The above issues lead to lower than desirable quality in flood hydrology activities that lead to mistakes or other issues in flood risk management activities and other flood hydrology research.

Scientific advances in modelling

Primary theme(s)

- Flood forecasting and flood estimation

Cross cutting area(s)

Score 1 to 3 for relevance to cutting area, where 1 is most relevant and 3 least relevant:

- Data – 3
- Methods – 1
- Ways of working – 3
- Scientific understanding – 1

Executive summary of initiative

This initiative is about capturing and promoting the use of science that improves modelling in flood hydrology.

This initiative is designed to capture scientific advances that will benefit flood hydrology through a process of concept validation. It covers advances in statistics, dynamic (process-based) modelling, methods and new areas of data science. The proposed work is translatory R&D, to proof-of-concept stage, to support other projects that have a more explicit focus on the methods and guidance applied in practice (links to integrated modelling and data analytics).

Context of initiative

The roadmap's vision for methods is as follows:

Flood hydrology methods for real-time, design and planning deal with all sources of flood risk. Methods are open-source, effective and regularly updated.

Methods allow use of all information available and employ appropriate, best available tools that are consistent, accessible and peer reviewed.

Impacts of future change and the calculation of uncertainty are included in decision-making as standard.

Five work areas have emerged in the flood hydrology roadmap around the topic of scientific advances in modelling. Some are directly dependent on observations and may benefit from improvements in hydrological data. Others relate to advances in process-based (physics or conceptual) models.

The context for this initiative therefore includes both the wider background state of knowledge in science, and the scopes relating to scientific advances in processes, and to better data in future.

There is no unique, authoritative entity that maintains an up-to-date and comprehensive synthesis of the state of knowledge in hydrological science (in contrast with, say, climate science, where the Intergovernmental Panel on Climate Change (IPCC) has this role internationally).

In 2019, an initiative began under the auspices of the BHS to form a working group (BHS WG) on the future of hydrological research. The BHS WG has to date published a report[5] and a journal paper, on observational methods[6]. Further BHS WG papers on theory and modelling are underway.

Although it is impossible to predict where and when scientific advances will emerge, some areas that may be focal points for research include:

- better observations of basic variables of the catchment water balance, space-time variability of hydrological responses and variables linked to water flow and transport - new observations may involve advances in geophysical methods to gain insights about water storage, more use of earth observations (satellite), and citizen science observations
- synthesis studies to assess knowledge and knowledge gaps across different types of research and different environments
- use of modelling to help target observational requirements (where would best added value be realised?)
- more complete integration of physical systems in models, allowing additional constraints to be placed on uncertainties - for example, solving for both energy balance and water balance might constrain the parameterisation (calibration) of a model when comparing it with observations of mass and energy fluxes

From a theory perspective, an emphasis on identification of knowledge gaps and the specificity of models is more realistic than a generalised ‘grand unified theory’. This may entail more effort to develop enhanced perceptual (that is, descriptive) models of hydrological processes that are specific to different types of physical environment.

Clearly it is very difficult to ensure that scientific advances are operationalised without being clear about the state of scientific knowledge. This points to the need for an accessible synthesis of that knowledge. The aspirations driving this scope of work lend support and motivation to efforts to create, and regularly update, a synthesis of scientific

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[5] http://www.hydrology.org.uk/bhs-working-group-future.php

[6] https://onlinelibrary.wiley.com/doi/full/10.1002/hyp.13622

knowledge relevant to UK flood hydrology. This should be sent as a clear message to research funders.

The aspiration for flood hydrology to keep pace with advances in science should also motivate activities within the building communities of practice scope of work, through establishing and maintaining a scientific and technical advisory group that can act as a forum to filter new science and capture advances that are important in keeping flood hydrology methods up to date.

This initiative links to the following work areas developed at earlier stages in the roadmap:

Q23. Investigate how scientific advances in physics/process/conceptual based modelling could be applied in operational flood hydrology. Review and translate scientific developments into practice, including event-based, continuous simulation and machine learning approaches. This work area should be regularly reviewed to ensure methods keep pace with scientific developments.

Q24. Investigate how scientific advances in statistical modelling could be applied in operational flood hydrology. Review and translate scientific developments into practice. The review should look beyond extreme value analysis of annual maximum flow data, be applicable to all sources of flooding, and take account of non-stationarity. This work area should be regularly reviewed to ensure methods keep pace with scientific developments.

Q25. Investigate how machine learning and artificial intelligence could benefit flood hydrology. Carry out a review to define how machine learning and artificial intelligence could be used in flood hydrology and the data sets required. The review should go on to recommend future work areas and projects relevant to the UK.

Q47. Development of flood estimation science. Research to drive the development of new methods for flood estimation in a changing world. This could include the development of new physics-based, conceptual and/or statistical models applicable from the site scale to the catchment scale.

Q48. Improving hydrological modelling for flood forecasting. Research to drive the development of improved methods for flood forecasting in a changing world. To include developments in data assimilation.

Objectives of initiative:

1. Establish a sustainable process to ensure regular knowledge exchange between researchers and those engaged with applications of hydrological science (links with communities of practice project initiative).
2. Refocus efforts to look beyond annual maximum data in statistical flood hydrology - allied with the initiative on better data in the future, this will enable 2 important areas to progress:
    a. more flexible analysis of joint probabilities, to improve assessments of flooding from all sources and at multiple scales (as spatially and temporally

coherent events) and other complex cases (for example, joint analysis of volumes and peak flows, long durations, sequences of events)
   b. greater flexibility in the assessment of non-stationarity with models that include covariates
3. Extend and generalise work on the accounting for environmental change initiative to model change as it affects both present-day and near-future assessments of risk, as well as longer-term projections or historical trends, taking advantage of:
   a. scientific advances in methods for modelling non-stationarity statistically
   b. greater use of dynamic, process-based models, for example, to assess event probabilities through ensemble simulations or to improve our understanding of the plausibility of extreme event scenarios (learning from meteorological research to inform PMP)
4. Assess the role of data-driven methods based on machine learning and artificial intelligence to augment or improve on hydrological methods and models
5. Assess the scope for improvements to data assimilation methods applied in flood forecasting, and potentially for updating and uncertainty analysis in long-term risk models.

For objectives 2 to 5, work instigated within this initiative should be in the form of proof-of-concept and/or benefit assessment studies involving demonstrator experiments or applications.

Expected benefit and outputs of initiative

1. A strategic approach to knowledge exchange between researchers and those engaged in applied flood hydrology, so that the communication of relevant scientific advances and of applied needs is less ad hoc than previously.
2. Evidence to inform the uptake of new ideas into practice and investments in new or updated methods, guidance and tools.

Drivers for this initiative

1. A realisation that there are rapid and potentially relevant developments occurring in areas of science beyond the traditional foundations of flood hydrology - examples include data science, earth observation, statistics, and earth system modelling.
2. The broad interdisciplinary nature of flood hydrology, combined with ever increasing specialisation in science, means that knowledge exchange is best approached as a collective effort.

Risk(s) associated with not carrying out this initiative

1. Decisions informed by flood hydrology may be called into question if the methods used to carry out hydrological analysis are criticised as being inconsistent with the latest science.

2. Opportunities for flood hydrology specialists or end users to influence scientific thinking and research plans may be missed - the value of the advisory group proposed in the communities of practice project scope would not be fully realised.
3. The value and benefits of regular scientific synthesis work may not be fully appreciated by research funders.

Scientific advances in process understanding

Primary theme(s)

- Flood forecasting and flood estimation

Cross cutting area(s)

Score 1 to 3 for relevance to cutting area, where 1 is most relevant and 3 least relevant:

- Data – 2
- Methods – 2
- Ways of working – 3
- Scientific understanding – 1

Executive summary of initiative

This initiative is about improving the two-way flow of information between flood hydrology in practice, and research into hydrological processes.

Our understanding of hydrological processes continues to evolve as new research and new methods and modelling techniques are developed. Understanding of processes is particularly important where there is a lack of data or likely changes in flood risk levels due to environmental change.

This initiative will provide a better understanding of the physical processes governing flood generation, in particular run-off generation, including in surface water flooding, interactions with groundwater and extreme events. It will also improve understanding of interactions between hydrological processes and other physical processes; what processes are driving hydrological change; and how this is expected to alter in the future. It will result in improvements in methods and models that can be applied by practitioners, leading to improved flood risk management.

Context of initiative

The roadmap's vision for scientific understanding is as follows:

We continually improve our understanding of the processes governing all areas of flooding risk (fluvial, fluvio-tidal, surface water, reservoir and groundwater) with state-of-the-art science. This science and knowledge is transferred into practical improvements in the efficiency and effectiveness of methods, ways of working and data.

Without improving understanding of such processes, there is a risk that models and techniques used in flood risk management (whether real-time or for planning and design) give incorrect or misleading results because they are based on incorrect assumptions about the governing processes. Understanding of processes is particularly important in areas of flood hydrology that either lack data or where environmental change means that decisions about future risk cannot necessarily be made solely from empirical analysis of past data. Examples include:

- the need to better understand distributed phenomena such as surface water flooding and the effects of land management on flood risk
- the need to plan for exceptional floods which are well outside the typical observed range (extrapolation)
- the challenge of generalising predictive models from places with observations, where they can be calibrated and tested, to places that lack observations (transferability)

The context for this initiative also includes both the need to translate scientific advances into useful tools and the desire for better data: refer to the initiatives relating to scientific advances in modelling, and better data in future.

There is no unique, authoritative entity that maintains an up-to-date and comprehensive synthesis of the state of knowledge in hydrological science (in contrast with, say, climate science, where the IPCC has this role internationally). In 2019, an initiative began under the auspices of the BHS to form a working group (BHS WG) on the future of hydrological research. The BHS WG has to date published a report[7] and a journal paper on observational methods[8]. Further BHS WG papers on theory and modelling are underway.

Some responses to the 2019 online survey suggested that there is already enough scientific understanding of fundamental processes and the challenge is instead incorporating such process understanding into hydrological tools and procedures that are used by practitioners. The BHS WG is identifying significant knowledge gaps, while a recent international initiative involving 230 scientists identified 'Twenty-three unsolved problems in hydrology'[9] that "remain focused on the process-based understanding of hydrological variability and causality at all space and time scales".

This initiative links to the following work areas developed at earlier stages in the roadmap:

Q43. Improving process understanding. This work could include the establishment of long-term monitoring in experimental catchments, understanding which processes are important in which catchment types and studying hindcast data to understand the climatic drivers of floods and the natural variability in these drivers. It could include improving understanding of surface/groundwater interactions for flooding and understanding whether

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[7] BHS working group on the future of UK hydrological research

[8] Developing observational methods to drive future hydrological science

[9] IAHS 23 unsolved problems in hydrology

there is a step-change in process functioning for floods of different magnitudes. It could also include investigations around the impacts of other processes on flood hydrology (and vice-versa), such as ecological response, erosion, hill-slope river coupling, woody debris, sediment transport and geomorphological change.

Q44. Understanding the spatial, temporal and cumulative impacts of flood risk interventions. Research to help understand how the cumulative effects of small and large scale flood risk interventions impact on flood risk. This work could include examining the wider impacts of natural flood management measures at various spatial and temporal scales for different magnitude flood events.

Objectives of initiative

1. Issue a call for evidence (structured around the BHS WG on theory and a sub-set of the International Association of Hydrological Sciences (IAHS) 23 unsolved problems in hydrology), aimed at encouraging submissions and research proposals on the topic of understanding of the physical processes governing flood generation and driving hydrological change
    a. this should focus in particular on the interactions between flood hydrology and other processes, including ecological responses, water quality, hill-slope river coupling, woody debris, sediment transport, geomorphological change and SuDS
    b. a review of physical process linkages could also be framed as a rapid evidence assessment
2. Implement a project to capture critical assumptions made in current practice and design (conceptually) a set of experiments that would test those assumptions
    a. an example may be the structure of rainfall-runoff models, tested against evidence from observations, including both intensive field campaigns and remote sensing
    b. outputs would be a report and ideally peer-reviewed paper describing the motivations, design and expected outcomes of the proposed experiments
3. Investigate funding sources and mechanisms for incorporating the experiments into other research proposals, to be published as a report designed to influence research funding organisations such as UK Research and Innovation (UKRI).
4. Establish a framework for filtering and synthesising research findings and using them to develop, for example:
    a. improvements in model structure
    b. guidance on representing processes
    c. techniques for altering standard methods to take account of catchment or flood types where processes are expected to alter

    The intention is to create a clear pathway towards practical application of improvements in knowledge - links with activities within the communities of practice initiative and externally BHS working group on future of hydrological research, if continued.

Expected benefit and outputs of initiative

The ultimate aspiration is that improved understanding will lead to better management of flood risk. This could be achieved by improvements to the accuracy, realism and applicability of techniques used by hydrologists, along with improvements to associated data sets.

The exact nature of the benefits will depend on the discoveries made during the research, since this topic is focused more on fundamental understanding than on improvement to any particular procedure.

Drivers for this initiative

1. Need to better understand distributed phenomena such as surface water flooding, which arises from distributed run-off processes that are rarely measured and may be fundamentally misrepresented using simplified conceptual models.
2. Continuing need to better understand the effects of land management on flood risk.
3. Need to plan for exceptional floods which are well outside the typical observed range and may arise from processes that are not currently well understood.
4. Need to understand what processes are driving observed hydrological change and how these might evolve.

Risk(s) associated with not carrying out this initiative

1. Models and techniques used in flood risk management (whether real-time or for planning and design) give incorrect or misleading results because they are based on incorrect assumptions about the governing processes.

Skills, esteem and value

Primary theme(s)

- Flood forecasting and flood estimation

Cross cutting area(s)

Score 1 to 3 for relevance to cutting area, where 1 is most relevant and 3 least relevant:

- Data – 2
- Methods – 2
- Ways of working – 1
- Scientific understanding – 2

Executive summary of initiative

This initiative is about promoting the flood hydrology profession by assessing what skills are needed, nurturing them, and bringing out hydrology’s value to society through flood risk management.

This initiative will assess the current and future need for flood hydrology skills, experience and staff numbers in the UK and develop a framework for nurturing and growing the number of flood hydrology professionals, and their skills and knowledge.

Skills and knowledge in flood hydrology and supporting disciplines are vital for the UK to maintain its current activities and important for the future of flood risk activities.

Starting with an assessment of the status of the flood hydrology resource base and its skills at the current time, the initiative will identify where gaps lie and how these should best be addressed. A framework for development of skills and experience will be developed and will include practical tools and approaches for increasing the profile of flood hydrology in the UK, developing new flood hydrology skills and nurturing existing skills, and addressing the need for new hydrologists entering the profession/research area and how this can be encouraged.

Valuing the benefits to society from flood hydrology investigations will further enhance the value of flood hydrology - the objectives of the initiative include methods to quantify these benefits.

The initiative includes considering maintaining the benefits over the long term, through periodic monitoring of defined progress measures. The governance of this initiative is linked to the communities of practice initiative.

Context of initiative

The future of flood hydrology in the UK will depend as much on its development of tools, techniques and leading science, including observations, as on its human resources. The UK will need young hydrologists to become the leading thinkers and activists in this area in the future. For the UK to remain in its strong position in global hydrology, we will need to excite, enthuse, train and nurture the UK-based hydrologists of the future. This needs both the profile of hydrology, especially flood hydrology, to be raised, and a programme or framework for the development and continual improvement of flood hydrology skills.

Skills also need to include 'inputs' (for example, hydrometric data collection) and applications of outputs (for example, hydrodynamic modelling).

This requirement cuts across all sectors working in UK flood hydrology: academia, regulators, science bodies and consultants.

The value of the benefits brought by flood hydrology can further support its esteem and skilled resource base. Quantification of the value that flood hydrology brings to the economy, society and environment will help demonstrate its importance to the public, government and UK plc.

The ambition of the BHS working groups on future hydrological research implies a continuing need for advanced research skills across a wide range of scientific and technical disciplines, while investments in new observations may in part be justified by the value they unlock in terms of hydrological applications.

This initiative links to the following work areas developed at earlier stages in the roadmap:

Q7. Raise the profile of flood hydrology in the UK. Work to make the hydrological profession more valued and respected. This could include creating a range of promotional materials to communicate and visualise flood hydrology concepts and outputs with non-experts (including schools, the public and the media). These materials could be used to attract funding and encourage graduates to a long-term career in hydrology.

Q12. Improve hydrological skill and capacity in the UK. This work area should aim to address any skills gaps identified in the work area above. It could also cover a range of activities, including measures for encouraging more investment in hydrology education and training, and establishing cross-community work placement schemes to enable skill sharing.

Q26. Develop methods and guidance for quantifying the hydrological benefits of flood risk management interventions in the catchment. Carry out a review and develop methods and visualisation tools to help decision makers quantify the hydrological changes (for example, reducing peak flows and changing timings) from management interventions in the catchment, such as natural flood management measures. Methods should be applicable from reach to catchment scale.

Objectives of initiative

1. Assessing the landscape: quantify the flood hydrology 'workforce' in the UK working in the various sectors (academia, regulators, science bodies and consultants)
    a. Include metrics such as:
        i. level of hydrological education/training
        ii. knowledge/skills in particular areas
        iii. proportion of working time spent on hydrology
        iv. some measure of degree of influence on the sector and analyse data
    b. Include a future projection, derived from information such as:
        i. academic courses available
        ii. projected changes in course numbers
        iii. mentoring and training arrangements in large organisations (for example, the Environment Agency)
2. Establish a programme/framework for the development and continual improvement of flood hydrology skills - this needs to cover:
    a. an assessment of resource need against current resources and future resources projection – resource numbers per sector
    b. an understanding of the skills 'gap' now and at 5-year intervals in the future by sector, looking at 'pinch points' in the skills and experience profiles
    c. developing skills development ideas and tools that organisations can use to demonstrate how they are assessing, tracking and enhancing flood hydrology skills in their personnel (for example, competency frameworks applicable to the different sectors)
    d. (could be done in collaboration with CIWEM and BHS) development of required competences for flood hydrologists carrying out basic flood hydrology tasks – could be applicable across all sectors (academia, regulators, science bodies and consultants)
        i. development of required or mandatory competences for flood hydrologists carrying out specialist/sector-specific tasks/research - (note - the subject of establishing an accreditation scheme specifically for hydrologists has been an ongoing discussion within the BHS and CIWEM for 15+ years – the group responsible for this initiative should consider the current status of these discussions in light of this step)
    e. promotion/profile-raising of flood hydrology in the UK to increase funding and talent pool
        i. needs to consider how this should be done most effectively and efficiently - ideas include:
            1. creating a range of promotional materials to communicate and visualise flood hydrology concepts and outputs with non-experts (including schools, the public and the media)
        ii. promotion should also target the funding agencies (for example, UKRI, Joint Programme, UKWIR) so that funders are aware of the importance of flood hydrology and its human resource need, as well as the efforts being made to monitor progress in addressing shortages and knowledge gaps

    f. develop methods for boosting understanding of hydrology among linked disciplines and enhancing ability of hydrologists to work with others
3. Assess the value to the economy, society and the environment of flood hydrology activities in reducing flood risk. This could involve some element of benefit-cost analysis as well as a broader evaluation of the role of flood hydrology, and the value added by continued investments in hydrological research and observations.
4. Measuring progress: develop metrics to measure progress in addressing resources and knowledge gaps - monitor using these metrics on a periodic basis (for example, annually) and publicise the findings as widely as possible.

Expected benefit and outputs of initiative

1. The maintenance of a strong, continually improving resource base in flood hydrology to provide improved flood risk management services across the UK as well as globally, thereby increasing our ability to save lives and reduce the harmful societal, economic and environmental impacts of flooding. The UK has the potential to show global leadership and develop/promote skills that can be of benefit elsewhere.
2. Understanding the importance of flood hydrology resources (numbers of), experience and skills at the present time.
3. Quantitative evidence of the value of flood hydrology in reducing flood risk.
4. A structured framework for growing and nurturing flood hydrology skills in each sector (academia, regulators, science bodies and consultants), designed to address knowledge and skills gaps now and in the future.
5. Ongoing tracking of progress of the framework to assess its impact and allow for new ideas/concepts to be used that improve its effectiveness.

Drivers for this initiative

1. Concern that flood hydrology requires high quality human resources to maintain its current suite of activities, and that a low profile in flood hydrology and lack of comprehensive programme for training and nurturing skills will impact this in future (and is arguably influencing it now).
2. Concern that a reduction in high quality human resources in the future will diminish the UK's ability to improve existing technologies and approaches, and develop future technologies and approaches in flood hydrology.
3. A perception that hydrology is undervalued and under respected as a profession in the UK (for example, accreditation for hydrologists can be seen as 'falling between the two stools' of CIWEM and ICE).
4. A lack of quantitative evidence on the value flood hydrology brings to reducing the harmful effects of flooding.

Risk(s) associated with not carrying out this initiative

1. The UK risks having a depleted number of flood hydrologists or practitioners working in flood hydrology in the future (because of fewer students taking hydrology courses, reductions in investment in training and support from government, reduced knowledge sharing opportunities, lack of mentoring, the relatively 'low' profile of flood hydrology).
2. A reduced or low profile of flood hydrology will reduce its focus as a subject to be allocated research funding and could reduce its funding within organisations undertaking operational and regulatory activities.
3. Reductions in flood hydrology human resources for the reasons given above reduces:
    a. our capacity to undertake necessary flood hydrology investigations/regulatory flood hydrology duties
    b. the quality and quantity of good flood hydrology research
    c. the development of new flood hydrology tools and applications to continually improve our ability to carry out flood hydrology activities efficiently and to a very high standard
    d. capacity in consultancy firms to support regulators and other public bodies to carry out high quality programmes of work in flood hydrology cost effectively
4. The impacts in 2 will ultimately affect the UK's ability to carry out effective flood risk management, saving lives, and reducing the societal and economic impact of flooding.
5. Evidence of the value of flood hydrology in reducing flood risk remains unquantified and the promotion of this evidence is not possible.
6. Misses an opportunity to offer global leadership: If the UK does not take a lead, other countries will.

Very extreme events

Primary theme(s)

- Flood estimation

Cross cutting area(s)

Score 1 to 3 for relevance to cutting area, where 1 is most relevant and 3 least relevant:

- Data – 3
- Methods – 1
- Ways of working – 3
- Scientific understanding – 2

Executive summary of initiative

This initiative is about working to modernise the way that very extreme precipitation and flood flow scenarios are developed, thereby reducing flood risk, especially risk to life.

This initiative relates to hydrological analysis carried out as part of reservoir safety inspections and other investigations that need to consider ‘high-end’ hydrological extremes of precipitation and flooding for locations of critical importance.

The safety of Category A dams is checked using the probable maximum precipitation (PMP) and probable maximum flood (PMF). Methods and data used to derive PMP and PMF in the UK have not been significantly updated since 1975. This initiative aims to address what improvements can be made to the existing approaches. Of relevance is an Environment Agency project running during 2020 to 2021 (in its first phase): FRS19222, ‘Improving probable maximum precipitation and probable maximum flood estimation for reservoir safety in the UK’.

Also covered in this initiative, but not in FRS19222, is estimation of floods with a defined, very low probability, such as the 0.01% annual exceedance probability (AEP), which is used as the design flood for Category A dams, the safety check for Category B dams, and is also specified in Office for Nuclear Regulation (ONR) guidance for the development of safety cases for nuclear facilities.

Context of initiative

The Environment Agency is shortly (in 2022) to be launching a project to address issues related to PMP and PMF (FRS19222). The background to this project is reproduced below. Improved methods of estimating PMP and PMF will be beneficial to the safety of reservoirs, the definition of which includes flood storage areas and other areas where water can be stored above ground level, whether temporarily or permanently.

Defra's reservoir safety research strategy was updated in 2016 to "refresh research requirements to reflect current priorities for reservoir safety research in the UK". This took into account "new challenges presented to reservoir managers and operators through severe weather events and in the face of climate change."

Extreme flood estimation is a concern not just for reservoirs but also for other high-risk infrastructure, including nuclear power stations and other facilities that store and process nuclear material. In addition, there is value in planning for extreme events more widely, and initiatives such as Nafra2 require estimates of floods with annual probabilities as low as 0.01%. The 0.01% AEP flood is used as the design flood for Category A dams, the safety check for Category B dams, and is also specified in ONR guidance for the development of safety cases for nuclear facilities. Updated methods for estimating extreme rainfall (FEH2013) were released in 2015, based on work carried out around 2008 to 2013. Current practice in estimating the 0.01% AEP flood is to combine a rainfall depth from FEH2013 with the FSR rainfall-runoff model, dating back to the 1970s. There is a need to examine and improve the procedures used for rainfall-runoff modelling of extreme floods. FRS19222 will address this in regard to the PMF but not in relation to extreme floods of a defined probability.

This initiative links to the following work area developed at earlier stages in the roadmap:

Q19. Review the concept of probable maxima. Carry out a review of the concept of probable maximum precipitation (PMP) and probable maximum flood (PMF) and current methods for estimating these for reservoir and other critical infrastructure standards.

Text from **Project terms of reference released May 2020** (FRS19222, Improving probable maximum precipitation and probable maximum flood estimation for reservoir safety in the UK):

The Probable Maximum Flood (PMF) is used to check the safety of Category A dams, where a breach of the dam could endanger lives in downstream communities. Current guidance requires that Category A dam spillways are able to discharge the flow of the PMF event without endangering the safety of the dam. The PMF is calculated from a theoretical Probable Maximum Precipitation (PMP). PMP is defined as "the (theoretical) greatest depth of precipitation for a given duration meteorologically possible for a given basin at a particular time of year. It includes rain, sleet, snow and hail as it occurs, but not snow cover left from previous storms." (ICE, 2015, 63) PMF is defined as "the flood hydrograph resulting from PMP and, where applicable, snowmelt, coupled with the worst flood-producing catchment conditions that can be realistically expected in the prevailing meteorological conditions." (ICE, 2015, 64)

Methods and data used to derive PMP and PMF have not been significantly updated since publication of the Flood Studies Report (NERC, 1975). However, several rainfall and catastrophic flow events have been observed exceeding existing PMP and PMF estimates respectively (for example, Acreman 1989s; Stewart and others, 2010) which raises concerns about the reliability of the existing methods. Category A dams (where a breach could endanger lives in a community) are routinely assessed for safety under PMF *conditions, and should not be based on outdated methods which may no longer be fit for purpose. Furthermore, the possible impact of climate change on extreme flood estimates must be considered.*

Objectives of initiative

- Follow the objectives set out in the Environment Agency project to be run during 2020 to 2021 (in its first phase): FRS19222, 'Improving probable maximum precipitation and probable maximum flood estimation for reservoir safety in the UK.
- Embed the results of the FRS19222 project in new guidance for PMP and PMF analysis, including any alternative approaches to managing extreme precipitation/floods that deviate from the PMP/PMF concept.
- Monitor the application of the new guidance.
- Communicate the guidance such that it can be applied for assessments outside the reservoirs environment for other very high vulnerability cases, that is, maximising the benefit of the research output.
- Carry out a research project looking into methods for estimating low-probability floods, incorporating relevant findings from FRS19222 and examining issues such as joint probability of rainfall, snowmelt and frozen ground.

Expected benefit and outputs of initiative

The main benefits will be:

1. increased understanding of hazards faced by UK dams and reservoirs due to extreme precipitation and flow events.
2. More robust flood risk assessments of reservoirs and other critical locations exposed to extreme precipitation and flow.
3. Reduced flood risk (to life and economy particularly).
4. Outputs that the UK can share internationally to benefit other countries, while also having learnt from approaches in other countries.

Drivers for this initiative

1. Outdated technical approaches being applied in very high risk environments.
2. Scientific advancements since 1975, especially in meteorology, have not been accounted for in current guidance.
3. Several rainfall and catastrophic flow events have been observed exceeding existing PMP and PMF estimates respectively.
4. No account is made for climate change impact on precipitation and flow in the current methods for deriving PMP and PMF.
5. The issue affects water utilities that manage reservoirs for water supply and hydropower, as well as flood risk authorities.

Risk(s) associated with not carrying out this initiative

1. Heightened flood risk at locations downstream of reservoirs and other critical locations.
2. Unacceptable uncertainty in the flood risk at reservoirs and other critical locations continues.
3. The UK is ‘behind’ other countries in its risk management of this issue.

Appendix G – Action plan for thematic work areas

This appendix describes the actions outlined in section **Error! Reference source not found.** in more detail.

Each action has a standard format which comprises:

1. graphic to identify the action - a circular graphic showing which theme of the roadmap the action belongs to
2. objective of the action
3. outline scope for the action
4. intended outputs of the action
5. intended outcomes of the action (this is taken from the outcome mapping described in Appendix H)
6. estimated spend profile and duration – note that a range of cost estimates are presented for each action between the best estimate (based on experience of similar work) and an optimism bias[10] estimate which take account of an optimism bias factor (of 50%, see section 4.2 on the main roadmap report)
7. figure showing the relevant outcome map for the action
8. figure showing the estimated spend profile for the action
9. figure showing the estimated duration of the action

The actions are summarised below, by theme, and then described individually in detail.

Ways of working theme actions

- W1 - Governance of the flood hydrology roadmap
- W2 - Scientific and technical advice for the roadmap
- W3 - Co-ordination of related hydrological programmes and initiatives
- W4 - Identify ways to improve investment in flood hydrology
- W5 - Build hydrological skill, esteem and value
- W6 - Assess quality standards in applied flood hydrology
- W7 - Implement recommendations on improving quality standards in applied flood hydrology
- W8 - Long-term investment in ways of working

[10] Optimism bias is the systematic tendency to be over optimistic about the early assessment of key parameters of a project or strategy, such as costs, timescales, and benefits.

Data theme actions

- D1 - Review of all data sources relevant to flood hydrology
- D2 - Assess gaps in hydrometric data for flood hydrology
- D3 - Assess the potential of new observational technologies to improve flood hydrology
- D4 - Develop options for improving observational data in flood hydrology
- D5 - Implement recommendations for improving observational data in flood hydrology
- D6 - Long-term investment in data

Methods theme actions

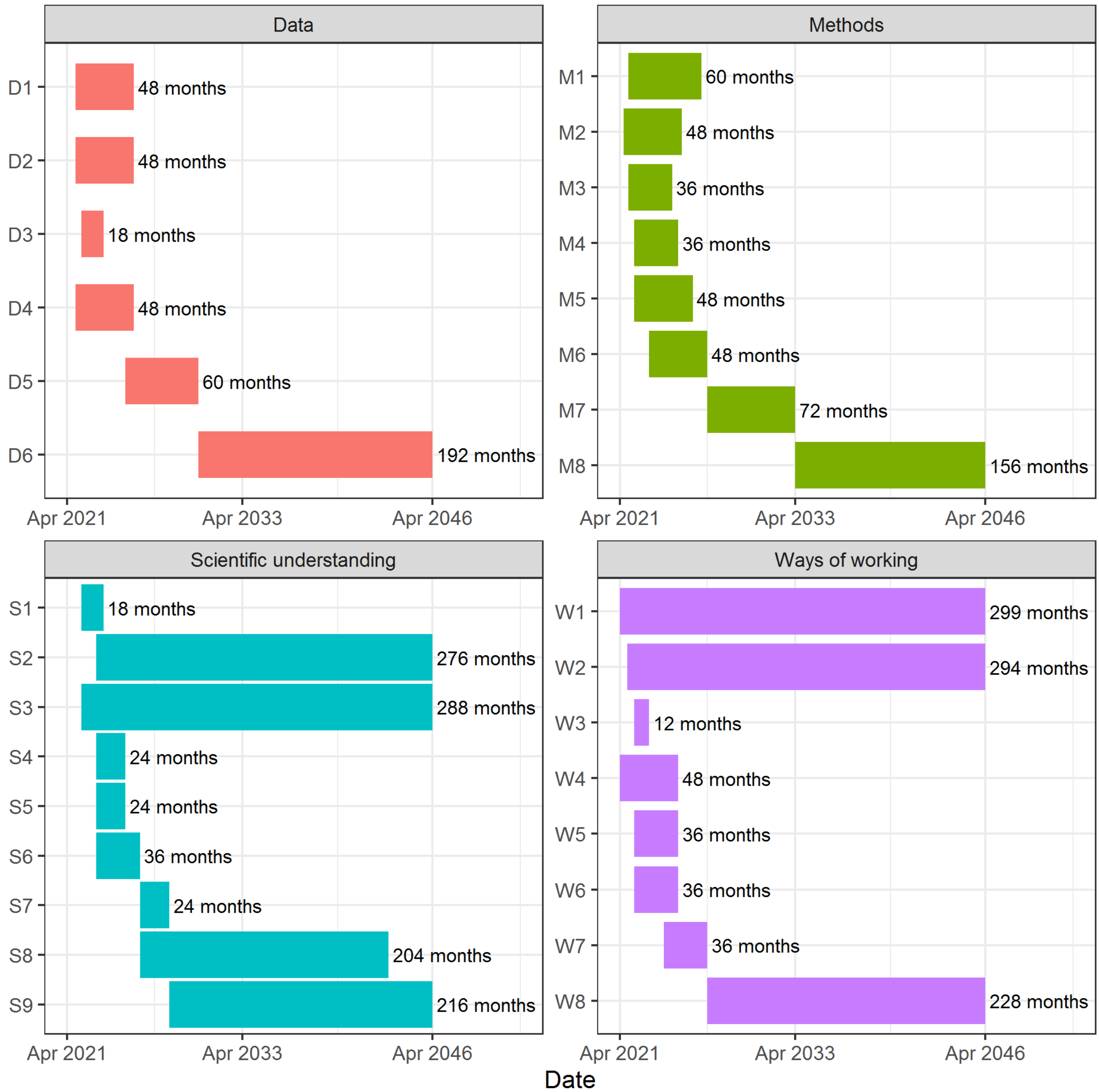
- M1 - Benchmark hydrological models
- M2 - Improve probable maximum precipitation and probable maximum flood estimation
- M3 - Review of strategic and operational flood hydrology models, methods and systems
- M4 - Synthesise evidence on environmental change related to flood hydrology
- M5 - Review the management of uncertainty in flood hydrology
- M6 - Develop options to improve flood hydrology knowledge, methods, models and systems
- M7 - Implement recommendations for improving knowledge, methods, models and systems
- M8 - Long-term investment in methods

Scientific understanding theme actions

- S1 - Develop a framework to improve the rapid translation of new science into policy and practice
- S2 - Implement the framework to improve the rapid translation of new science into policy and practice
- S3 - Synthesis of scientific knowledge in flood hydrology
- S4 - Identify research needs to improve understanding of flood generation processes and drivers of hydrological change
- S5 - Investigate the validity of critical assumptions made in operational flood hydrology
- S6 - Identify fundamental science needs in flood hydrology
- S7 - Develop proposals for research programmes
- S8 - Potential research programmes
- S9 - Translation of science from research programmes into practice

Figure G-1 shows the estimated timescales for each roadmap action. The x-axis shows a 25 year period starting in April 2021 and ending in March 2046. This information is also presented for each action individually in the detailed description of actions below.

Figure G-1 – Outline programme for flood hydrology roadmap actions



Action W1: Governance of the flood hydrology roadmap

Objective

Establish a long-term governance board that owns the flood hydrology roadmap and is responsible for its implementation.

Outline scope

This action will establish a governance board for the flood hydrology roadmap. The board will own the roadmap, be responsible for its implementation and remain in place for the lifetime of the roadmap (around 25 years).

It is likely that the initial members of the board will comprise potential funding organisations and the British Hydrological Society to represent the wider flood hydrology community:

- British Hydrological Society
- Environment Agency, England
- Scottish Environment Protection Agency
- Natural Resources Wales
- Department for Infrastructure, Northern Ireland

In the initial start-up phase (first 6 months) the board will:

1. agree a formal name for the governance board
2. agree ways of working for the board, for example, leadership (chair) of the board could be rotated around member organisations for a fixed period
3. develop terms of reference for the board
4. expand membership of the board as appropriate (for example, to UK Research and Innovation (UKRI) for longer-term scientific actions)
5. develop a costed business plan for the ongoing operation of the governance board
6. establish a scientific and technical advisory group (STAG) which will provide scientific and technical advice to the board to guide implementation of the roadmap (action W2)

Long-term (ongoing) responsibilities of the board are likely to include:

1. securing funding for the governance board business plan
2. development of a communications and engagement plan to encourage participation and investment in the roadmap and its action plan, and to report on progress implementing the roadmap within the wider community
3. identification of funding opportunities to help implement the flood hydrology roadmap
4. regular (annual) progress reviews of the flood hydrology roadmap action plans, with a formal published report on progress at least once every 3 years - these reviews should result in a refresh of the roadmap and action plan at appropriate intervals
5. ensuring that the roadmap is implemented using low carbon solutions and demonstrating the roadmap's contribution to net zero targets across the UK
6. championing the principles of equality, diversity and inclusion (EDI) in all aspect of the roadmap

Intended outputs

1. terms of reference for the governance board
2. a costed business plan for ongoing operation of the governance board
3. a plan to establish a scientific and technical advisory group (STAG) [see action W2]
4. a communication and engagement plan to encourage participation and investment in the roadmap
5. regular progress reviews of the flood hydrology roadmap to enable periodic refresh of the roadmap and its actions

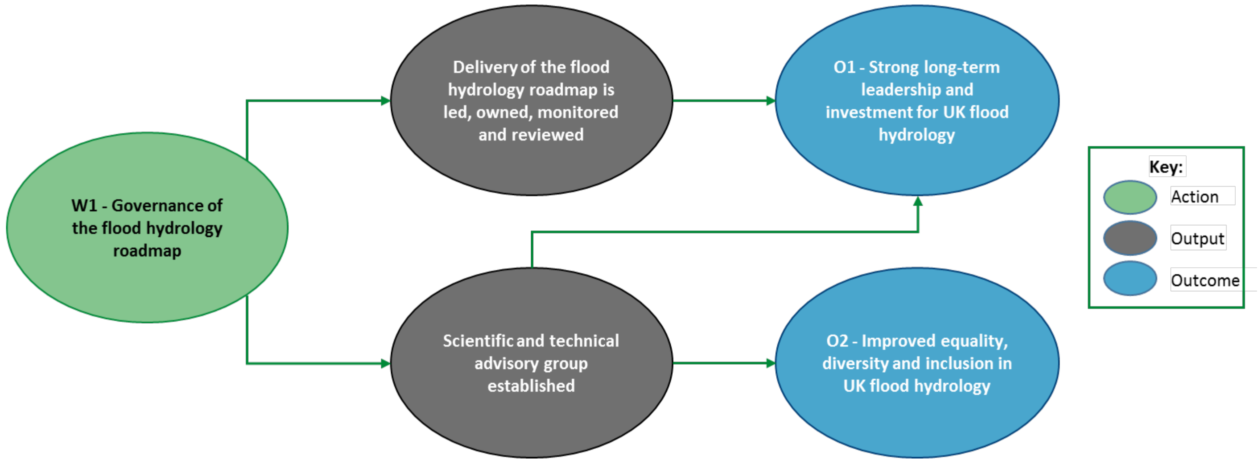
Intended outcomes

This action contributes to 2 outcomes:

- outcome 1 - strong long-term leadership and investment for UK flood hydrology
- outcome 2 - improved equality, diversity and inclusion in UK flood hydrology

The outcome map for this action is shown in Figure G-2.

Figure G-2 – Outcome map for action W1



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-3. The costs comprise £50,000 to £70,000 in year 1 (Apr 2021 to Mar 2022) to establish the board followed by an annual sum of £30,000 to £45,000 for the lifetime of the roadmap (increasing by 2% annually to account for inflation) to cover meeting costs and general expenses incurred by the board. There is also provision of £150,000 to £225,000 for refreshing the roadmap and reporting on progress every 3 years from year 4 (starting in April 2024).

It is anticipated that initial start-up of the governance board with take around 6 months (of year 1) to establish. The board will then continue for the lifetime of the roadmap.

The total estimated cost of this action for the lifetime of the roadmap is between £1.96 million and £2.95 million. The duration of this action is for the lifetime of the roadmap and is shown in Figure G-4.

Figure G-3 – Estimated spend profile for action W1

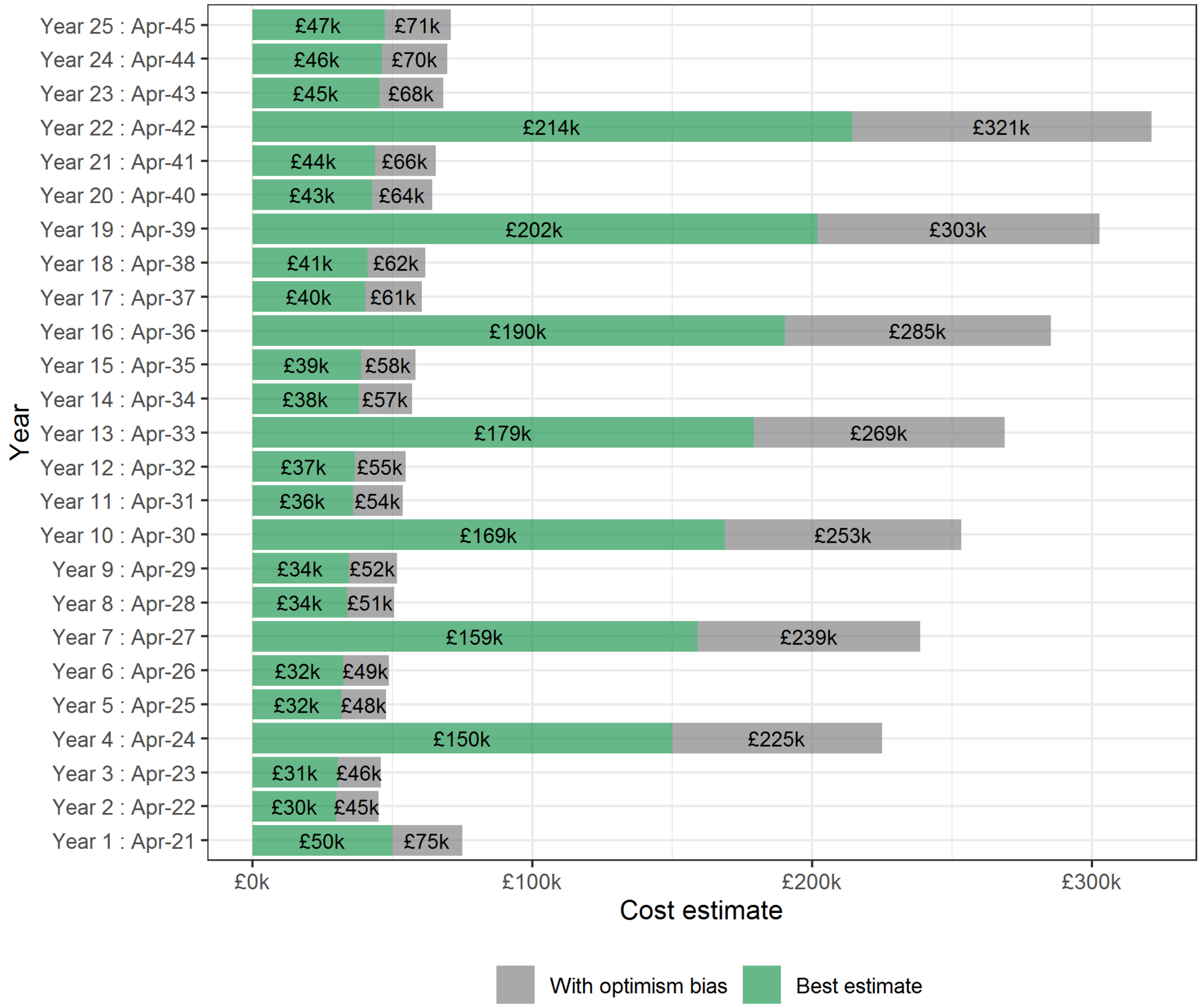
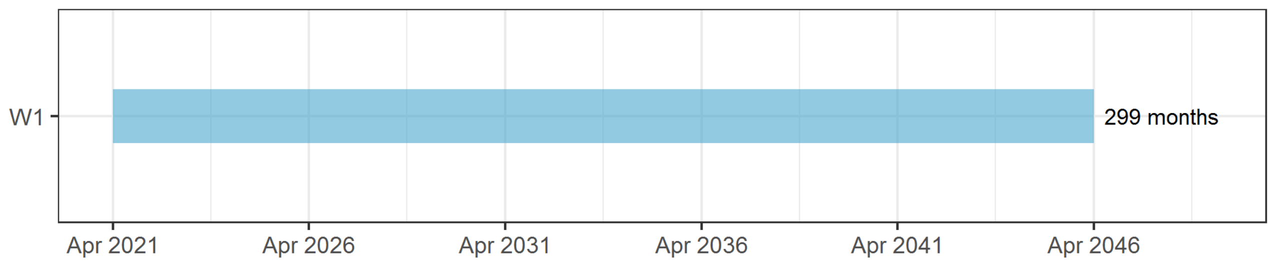
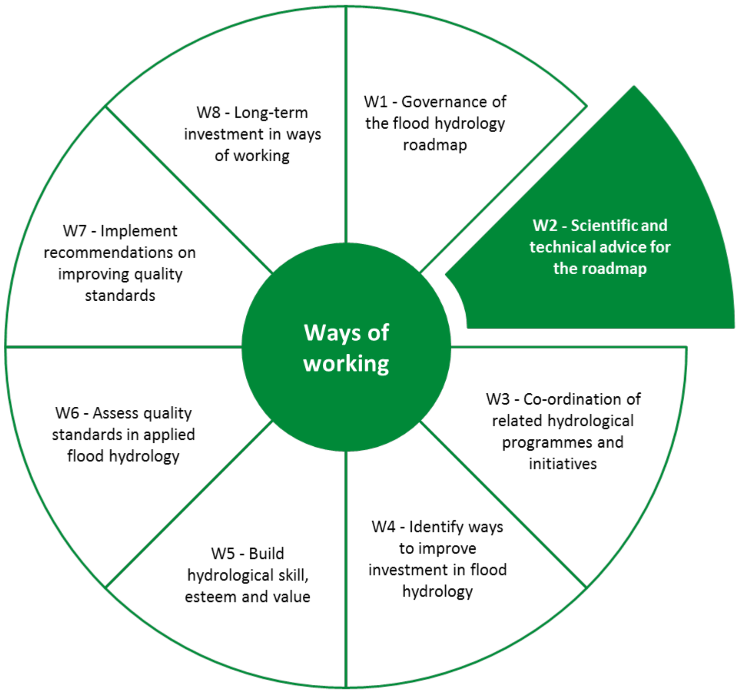


Figure G-4 – Estimated duration of action W1



Action W2: Scientific and technical advice for the roadmap



Objective

Establish a scientific and technical advisory group (STAG) to provide technical advice and steer to the governance board to help guide delivery of the roadmap.

Outline scope

This action will establish a scientific and technical advisory group (STAG) for the flood hydrology roadmap.

The flood hydrology roadmap governance board (established in action W1) will lead on this action and will be supported by organisations and individuals from across the UK flood hydrology community.

The roles and responsibilities of the STAG could include:

1. helping to shape and scope projects and initiatives to implement the roadmap
2. providing scientific and technical advice and steer to in-flight roadmap projects
3. providing peer review of project outputs prior to publication

This action should consider:

4. developing terms of reference of the STAG
5. governance of the STAG (for example, chair and secretariat arrangements)
6. the size of the STAG
7. a process for selecting members of the STAG to ensure the right blend of topic expertise and representation across main stakeholder groups[11] and to ensure diversity of thought and background so that discussions and decisions are informed by a diverse range of perspectives, including perspectives from underrepresented groups
8. duration of appointment to the STAG
9. the frequency of meetings and anticipated time commitment of members

The principles of equality, diversity and inclusion (EDI) must be considered when establishing membership of the STAG.

Intended outputs

1. Terms of reference for the STAG, to include its roles and responsibilities, governance arrangements, commitment expectations and member selection procedures.

Intended outcomes

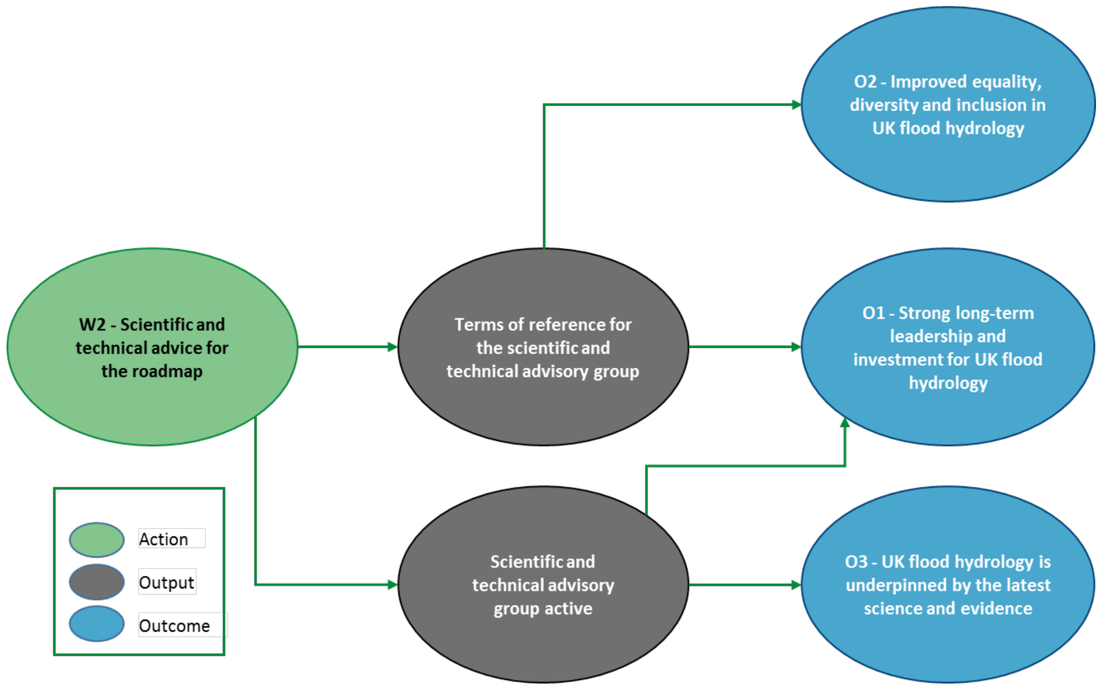
This action contributes to 3 outcomes:

- outcome 1 - strong long-term leadership and investment for UK flood hydrology
- outcome 2 - improved equality, diversity and inclusion in UK flood hydrology
- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence

The outcome map for this action is shown in Figure G-5.

[11] Stakeholder groups could be informed by the stakeholder analysis carried out as part of the flood hydrology roadmap project.

Figure G-5 – Outcome map for action W2



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-6. The profile assumes a £20,000 to £30,000 annual budget to cover meeting and travel costs (if required) and general expenses associated with running the STAG. This sum increases annually by 2% to account for inflation.

The duration of this action is for the lifetime of the roadmap and is shown in Figure G-7

Figure G-6 – Estimated spend profile for action W2

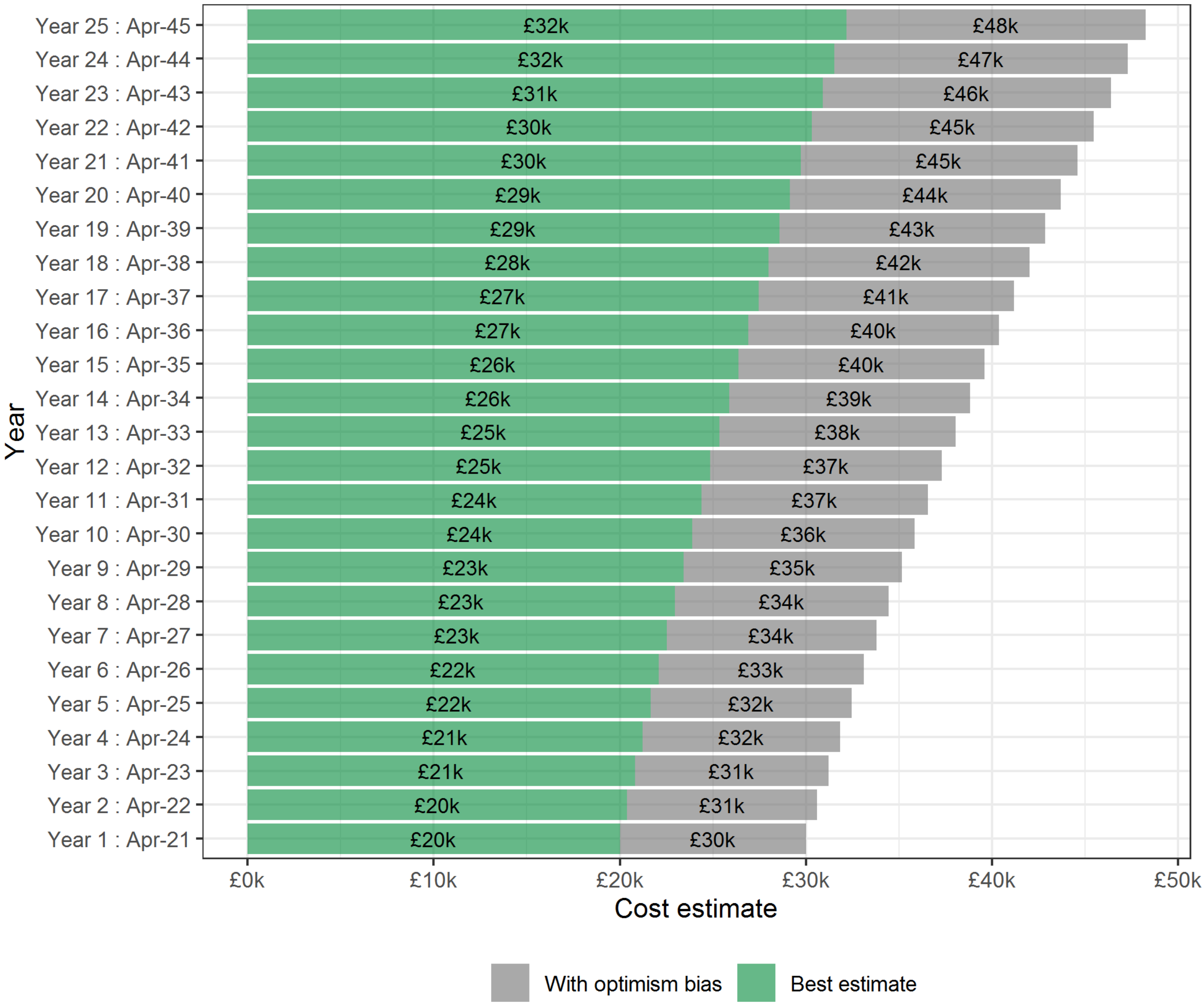
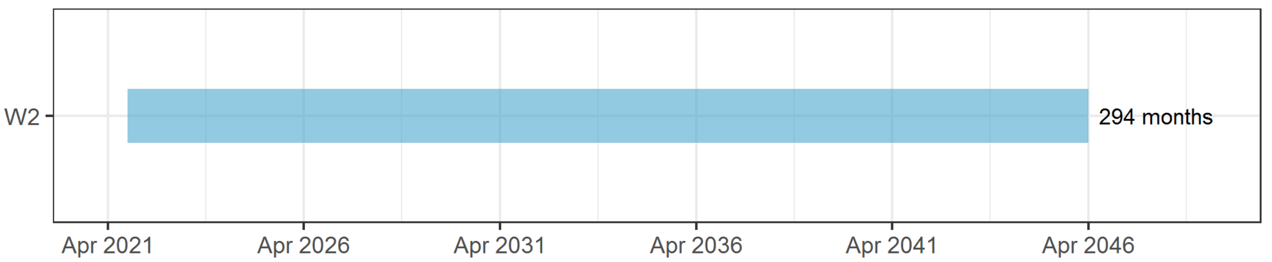
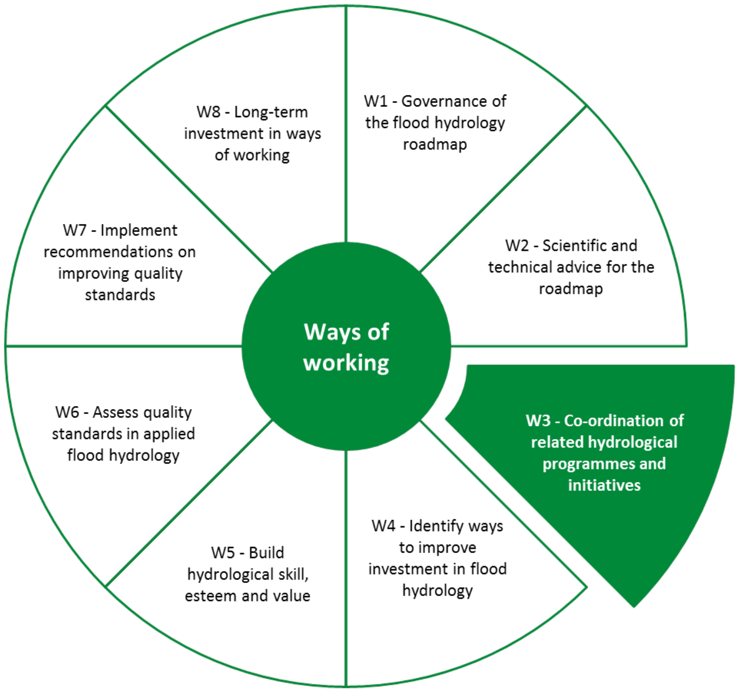


Figure G-7 – Estimated duration of action W2



Action W3: Co-ordination of related hydrological programmes and initiatives



Objective

Ensure visibility, coordination and collaboration between programmes and initiatives related to flood hydrology across the UK.

Outline scope

This action seeks to ensure that there is coordination between related hydrological programmes and initiatives across the UK, including, but not limited to:

- the flood hydrology roadmap
- NERC Flood Drought Research Infrastructure (FDRI) scoping study
- British Hydrological Society (BHS) Working Group on the Future of UK Hydrological Research
- Natural Environment Research Council (NERC) Hydro-JULES programme
- Platform for dynamic, hyper-resolution, near-real time flood risk assessment integrating repurposed and novel data sources (PYRAMID)
- Other related NERC and Engineering and Physical Sciences Research Council (EPSRC) programmes
- Scotland’s Centre of Expertise for Water (CREW)

- Scottish Government's Rural and Environment Science and Analytical Services Division (RESAS)
- Met Office Numerical Weather Environmental Predictor (NWEP) modelling programme
- Met Office Research and Innovation Strategy 2020
- Climate Change Risk Assessment (CCRA)
- Environment Agency/Defra flood and coastal erosion risk management research and development programme
- Hydrological software developers (to include commercial hydraulic models used in flood risk management applications)

This action could include:

1. both operational and scientific initiatives and programmes
2. a review of current communities of practice in and around UK flood hydrology
3. identification of relevant initiatives and work areas in flood hydrology across the UK
4. an open and accessible online catalogue of activities and linkages visible to the wider flood hydrology community, with an easy and sustainable mechanism for updating
5. a mechanism to ensure ongoing co-ordination with new and emerging activities
6. organisation and facilitation of meetings, workshops and other knowledge exchange activities (linking to actions S1 and S2)
7. a review of related international activities, groups and programmes to investigate the possible need for wider collaboration. For example:
    a. guidelines for determining flood flow frequency, United States
    b. flood studies update web portal, Ireland
    c. Australian Rainfall and Runoff (ARR)
    d. European Centre for Medium Range Weather Forecasts (ECMWF) initiatives and programmes
    e. European Flood Awareness System (EFAS)
    f. Global Flood Awareness System (GloFAS)
    g. International Association of Hydrological Sciences (IAHS) initiatives and programmes
    h. World Meteorological Organisation (WMO) initiatives and programmes
8. helping coordinate the outcomes of related programmes and initiatives to ensure that synergies can be maximised and duplication avoided
9. a report on the activities above

On completion of this action the STAG (or a sub-group of the STAG) would take ownership of longer-term co-ordination of related hydrological programmes and initiatives.

Intended outputs

1. Online catalogue of programmes and initiatives related to flood hydrology.
2. Plan for knowledge exchange between flood hydrology programmes and initiatives.

3. Published report/paper on the co-ordination of related hydrological programmes and initiatives.

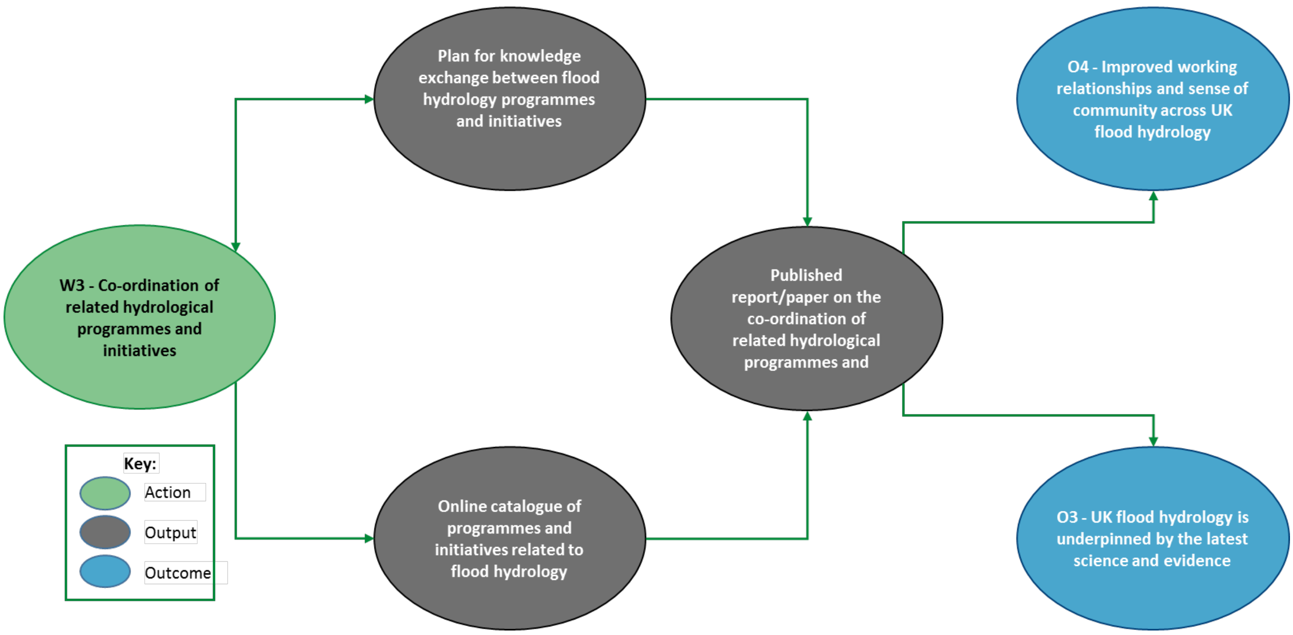
Intended outcomes

This action contributes to 2 outcomes:

- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence
- outcome 4 - improved working relationships and sense of community across UK flood hydrology

The outcome map for this action is shown in Figure G-8.

Figure G-8 – Outcome map for action W3



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-9. It is envisaged that this work will cost between £100,000 and £150,000 over one year (Figure G-10).

Figure G-9 – Estimated spend profile for action W3

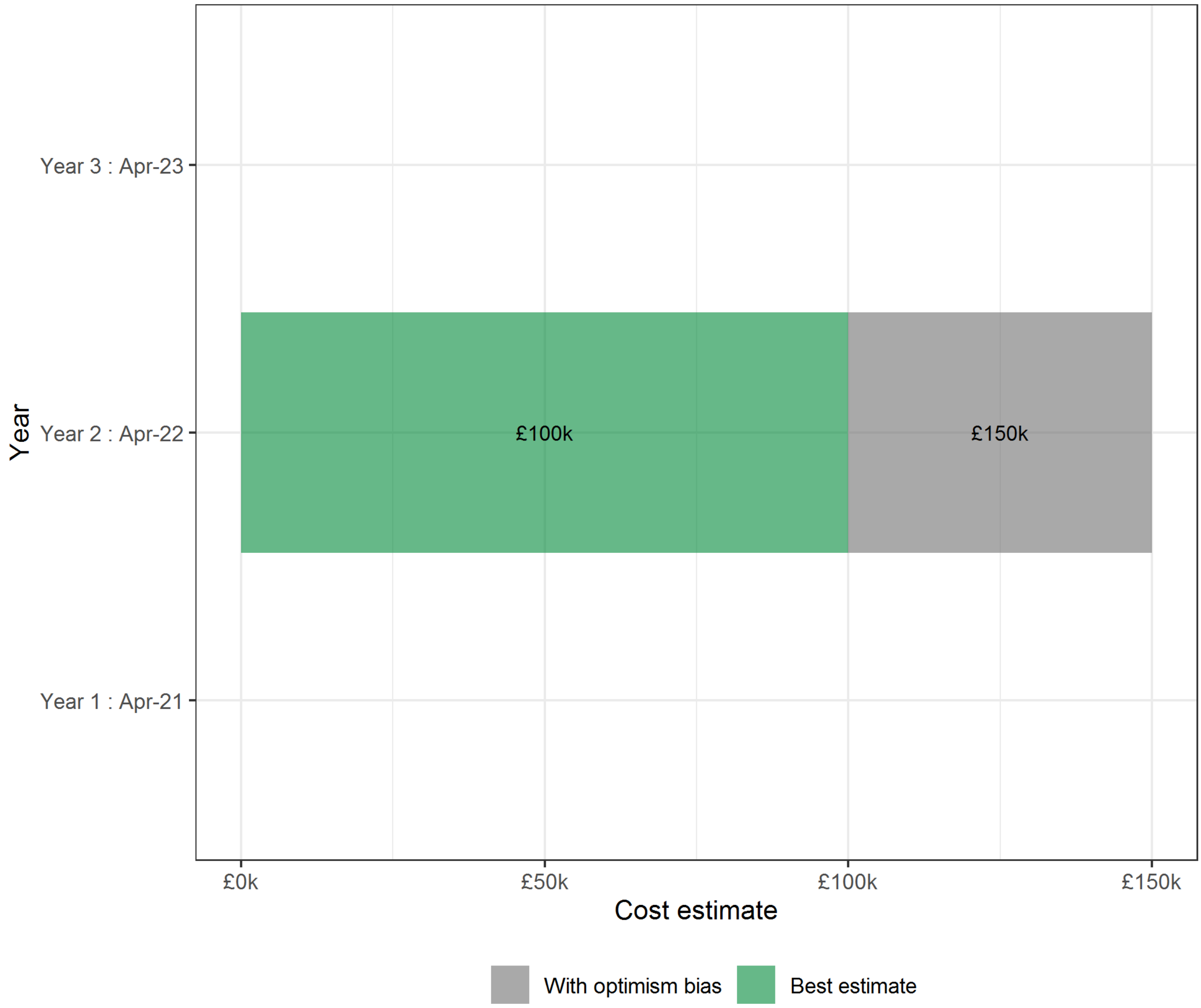
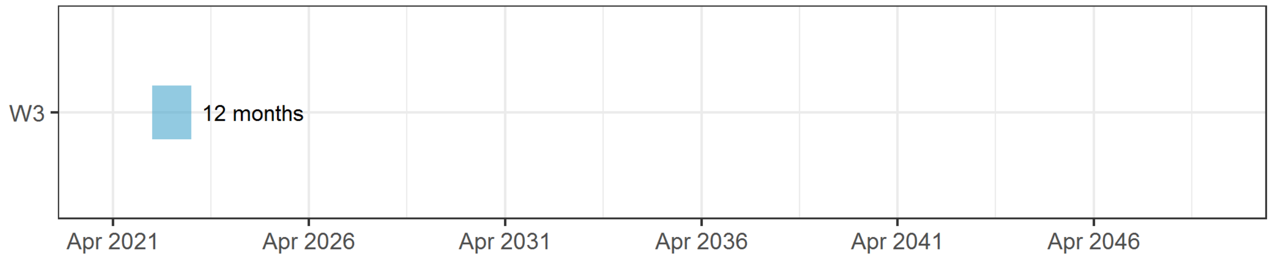
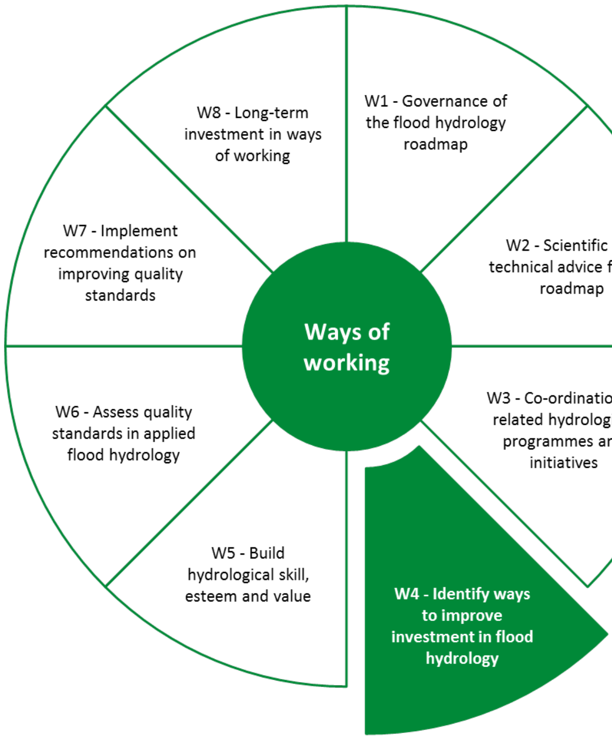


Figure G-10 – Estimated duration of action W3



Action W4: Identify ways to improve investment in flood hydrology



Objective

Understand the best way to improve investment in flood hydrology across the UK, ensuring greatest value to the economy, society and the environment.

Outline scope

This action could include:

1. demonstrating the value of hydrology by determining and if possible, quantifying the contributions made by flood hydrology and hydrometric data to achieving flood risk management outcomes for various end users, for example by undertaking value chain mapping (or dependency modelling)
2. identification of potential investment sources in flood hydrology, to include public and commercial sources of funding - this information should be fed into the flood hydrology roadmap governance board to help focus engagement activities

This work will require collaboration with economists to identify the best approaches to value UK flood hydrology.

Intended outputs

1. Report on the value chain modelling of flood hydrology with recommendations to improve investment in flood hydrology.

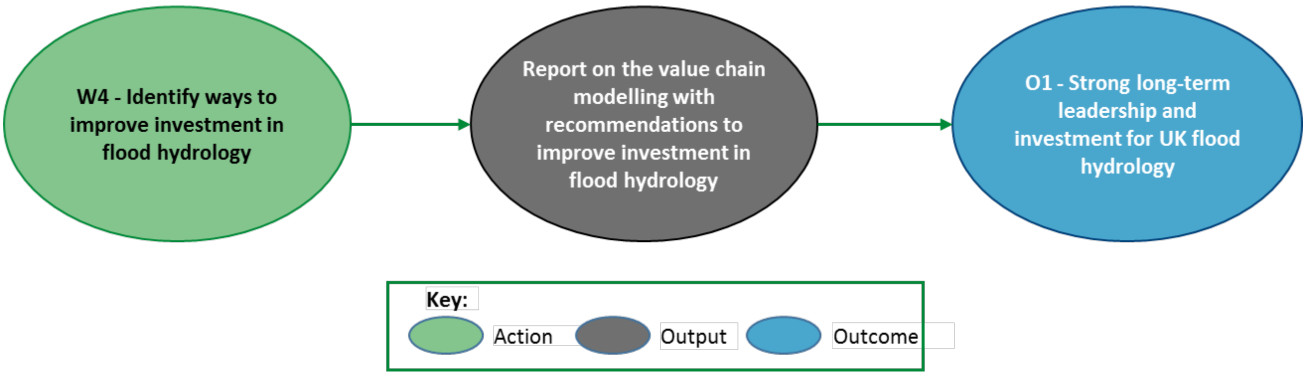
Intended outcomes

This action contributes to one outcome:

- outcome 1 - strong long-term leadership and investment for UK flood hydrology

The outcome map for this action is shown in Figure G-11.

Figure G-11 – Outcome map for action W4



Estimated spend profile and duration

It is estimated that this action will require funding of between £300,000 and £450,000 (Figure G-12) over 4 years (Figure G-13), equating to between £75,000 and £113,000 per year.

Figure G-12 – Estimated spend profile for action W4

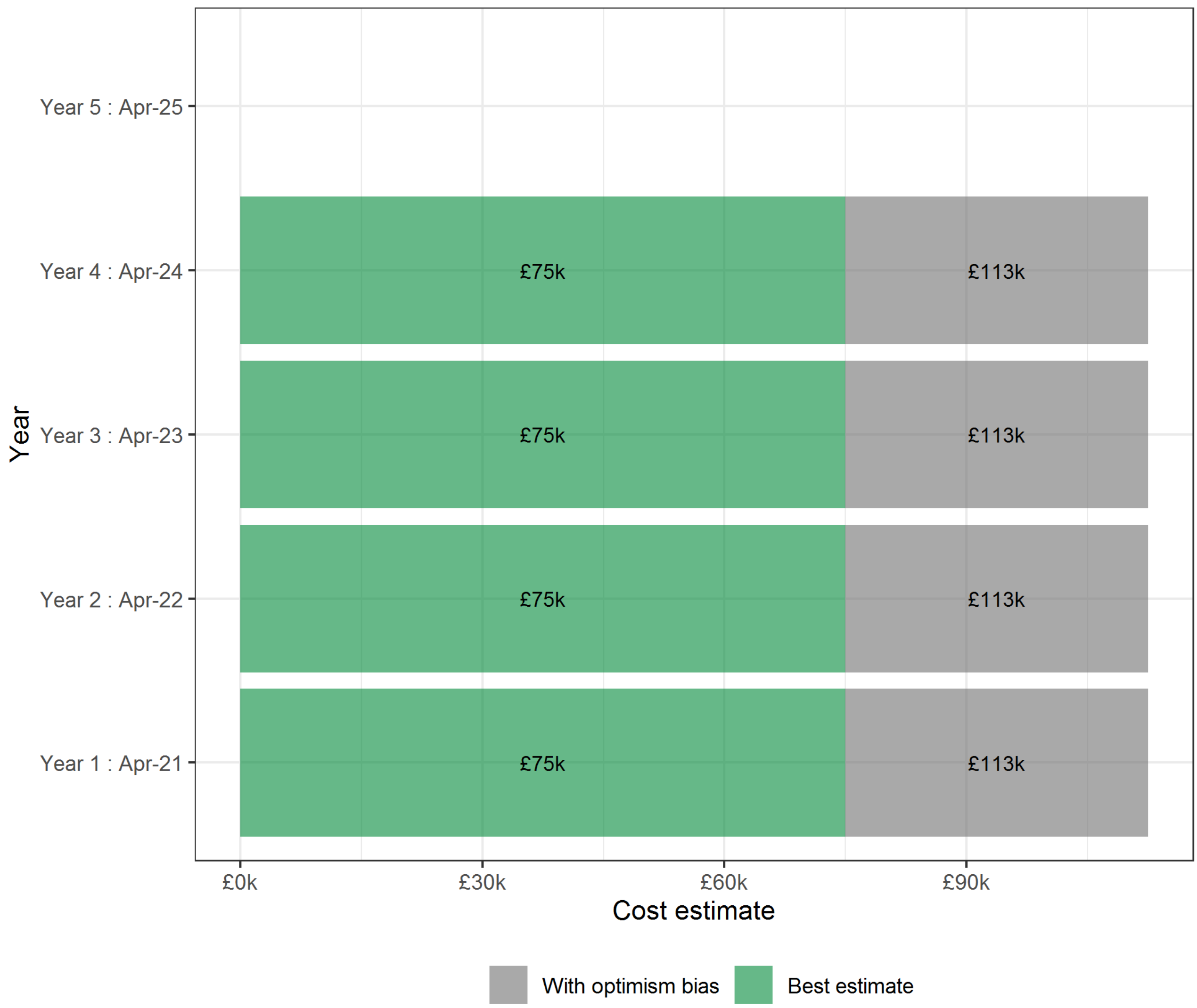
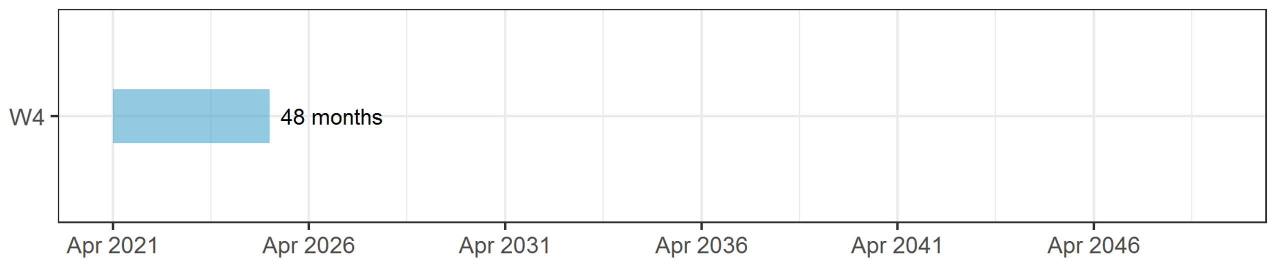


Figure G-13 – Estimated duration of action W4



Action W5: Build hydrological skill, esteem and value

Objective

Strengthen the flood hydrology profession by quantifying the size and diversity of the skill base and developing the skills needed for the next 25 years.

Outline scope

This action will assess current and future needs for flood hydrology skills, experience and staff numbers in the UK. It will develop a framework for nurturing and growing the number of flood hydrology professionals, their skills and knowledge.

Specific sub-actions could include:

- assessing the current landscape - quantify the flood hydrology 'workforce' in the UK working across all sectors (academia, regulators, science bodies and consultants)

  This could include a survey to establish:

  a. the number of UK hydrologists
  b. salary bands and organisational position of flood hydrologists
  c. the level of education and training of practising hydrologists
  d. the diversity of the flood hydrology workforce in the UK
  e. an understanding of non-graduate opportunities in flood hydrology careers

f. roles and responsibilities across the flood hydrology sector
g. knowledge and skills (and skills gaps) in flood hydrology
h. knowledge and skills (and skills gaps) in disciplines supporting flood hydrology (for example, hydrometry and hydrometeorology)
i. undergraduate and postgraduate courses available to flood hydrologists
j. future projections of hydrological skills and capacity (from academic course numbers)
k. mentoring and training opportunities in large organisation (for example, regulators, local authorities, water companies and large consultancies)
l. opportunities for further academic and vocational training for practitioners
m. what competency frameworks already exist in organisations
n. perceived future needs for hydrological skills

The findings of the survey should be published and used to help inform a new skills and development framework for UK flood hydrology.

- establishing a skills and development framework for UK flood hydrology to encourage the development and continual improvement of flood hydrology skills

  This could include:

  a. an assessment of future flood hydrology skills and resources required in the UK, and the investment and training needed to fulfil these needs
  b. an assessment of actual resource and skills against current and future projections to identify skill and resource gaps over time
  c. developing a strategy to improve diversity and promote equality of opportunity within the flood hydrology profession – this could include identifying ways to target underrepresented groups, proactively promoting socio-economic diversity, ethnic diversity and gender diversity, and ensuring that career opportunities in flood hydrology are accessible to people with disabilities
  d. assessing the need to develop and deliver formal training courses in flood hydrology
  e. publishing (online) a catalogue of flood hydrology learning and development offerings across the UK
  f. the development of competency frameworks that can be used across sectors and organisations
  g. clearly defining professional development pathways to chartership for flood hydrologists
  h. promotion and profile raising of flood hydrology to increase funding and a wider and more diverse talent pool
  i. developing methods to boost understanding of flood hydrology among linked disciplines to enhance the ability of hydrologists to work with others
  j. investigating ways to encourage more content on rivers and flooding in the national curriculum and providing more general content to schools/children’s groups

k. investigating ways to increase the exposure of degree level students to operational flood hydrology practice and skills
l. setting out clear roles and responsibilities for UK flood hydrology
m. funding arrangements for the new framework

Intended outputs

1. Report that quantifies the UK flood hydrology workforce.
2. A strategy to improve diversity and promote equality of opportunity within the flood hydrology profession.
3. A skills and development framework for UK flood hydrology.

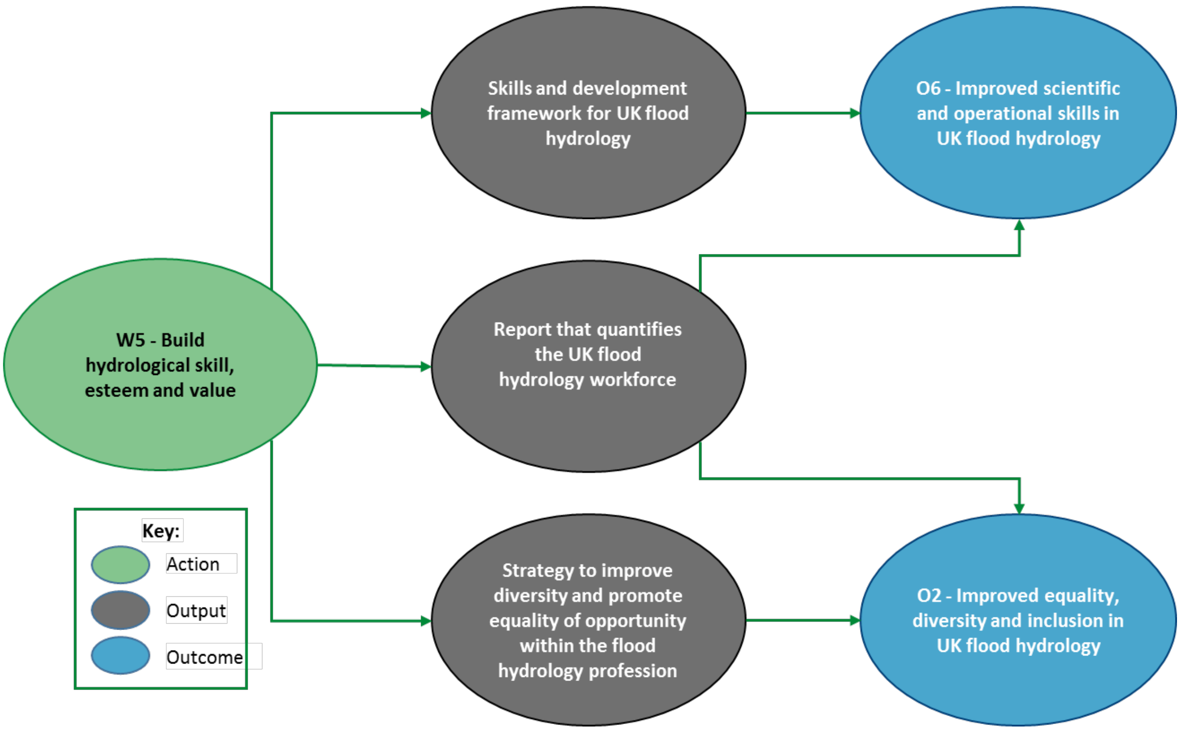
Intended outcomes

This action contributes to 2 outcomes:

- outcome 2 - improved equality, diversity and inclusion in UK flood hydrology
- outcome 6 - improved scientific and operational skills in UK flood hydrology

The outcome map for this action is shown in Figure G-14.

Figure G-14 – Outcome map for action W5



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-15. It is likely that the total cost estimate between £550,000 to £830,000 would be spread over 3 years (Figure G-16).

Figure G-15 – Estimated spend profile for action W5

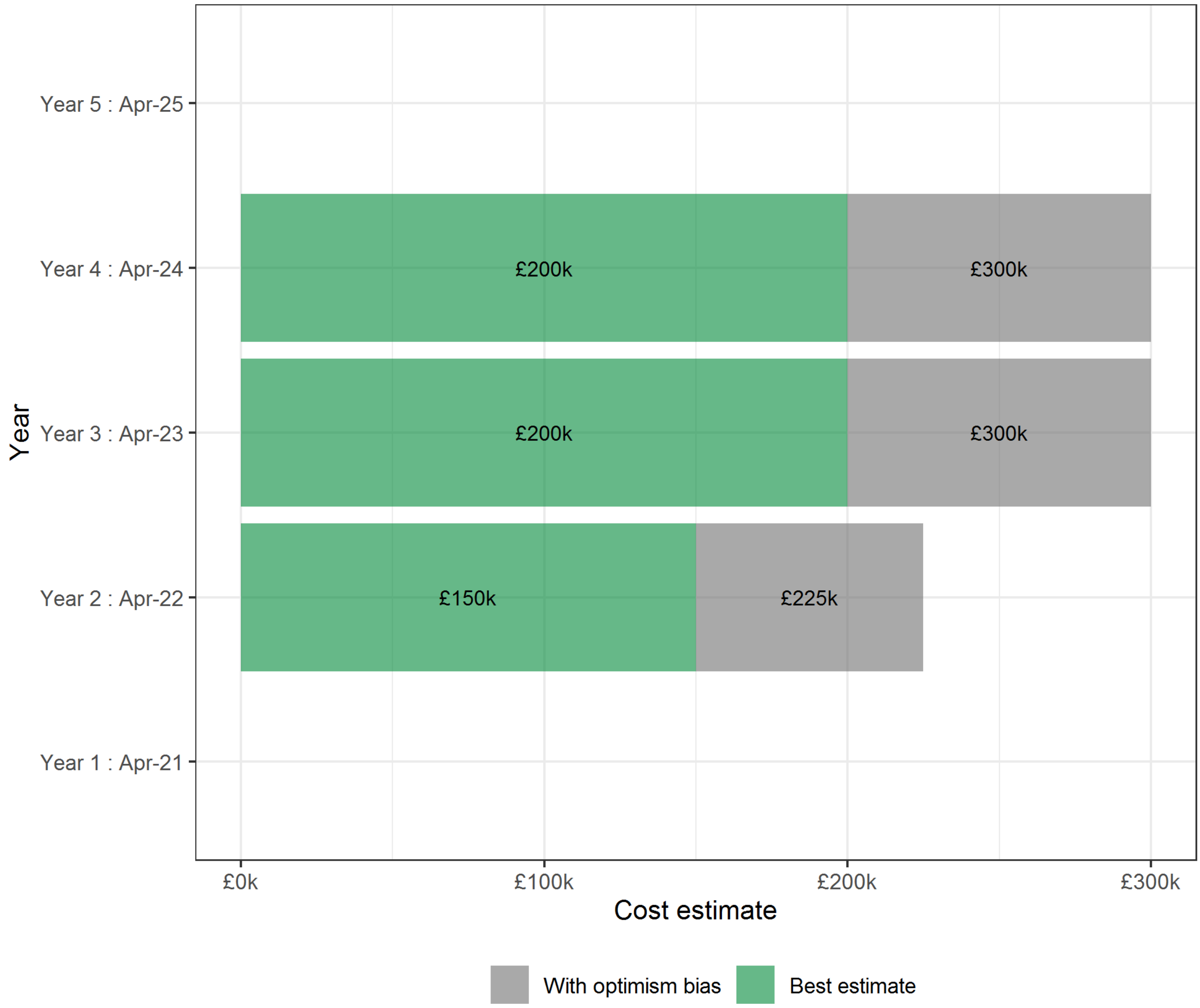
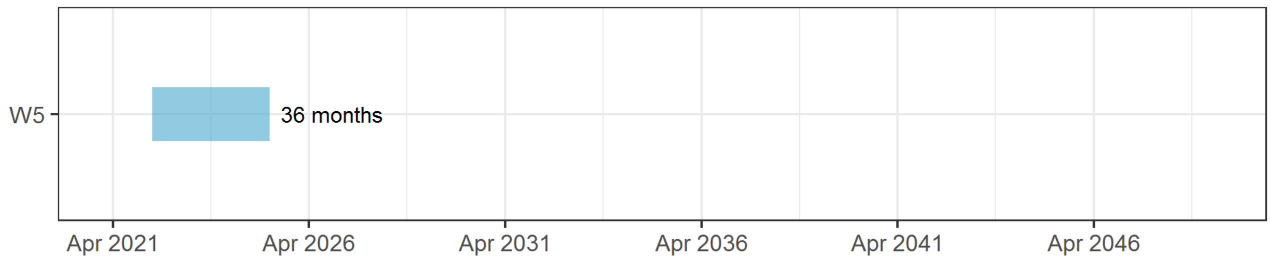
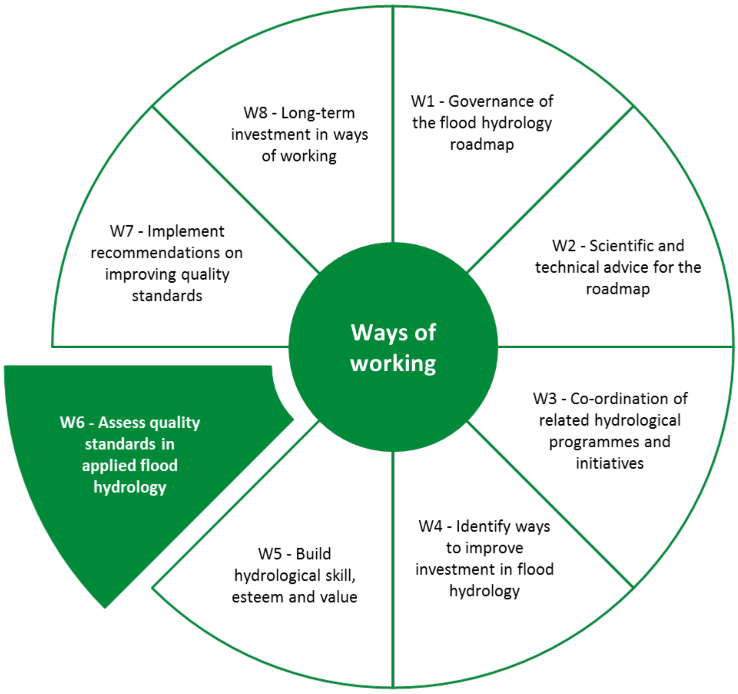


Figure G-16 – Estimated duration of action W5



Action W6: Assess quality standards in applied flood hydrology



Objective

Assess where quality improvement and consistency is needed in flood hydrology, and to drive quality improvements.

Outline scope

This action aims to examine where quality standards may be lacking or inconsistent in UK flood hydrology activities and understand the reasons for this.

Specific sub-actions are to identify where there are:

1. recognised shortfalls in quality standards being applied
2. examples of ‘good practice’ in flood hydrology quality standards being used
3. reasons for quality standards/procedures not being adhered to

The assessment will consider quality standards in flood hydrology models and associated uncertainty (for flood estimation and forecasting) and hydrometric data collection, processing and archiving. The assessment will also investigate what quality standards are required across the UK by commissioning agencies, how appropriate they are, and how rigorously they are being applied.

It will also:

4. examine the way in which quality standards are embedded in project scopes/terms of reference from commissioning bodies
5. make recommendations for quality standards in flood hydrology activities that seek to provide consistency across the UK for all bodies commissioning flood hydrology work
6. explore the possibility of using innovative technology such as machine learning to develop tools to identify quality issues
7. publish a report on the above, and ideally a peer-reviewed journal paper

Intended outputs

1. Report on the review of quality standards in applied UK flood hydrology with recommendations for improvements.
2. Peer-reviewed journal paper on quality standards.

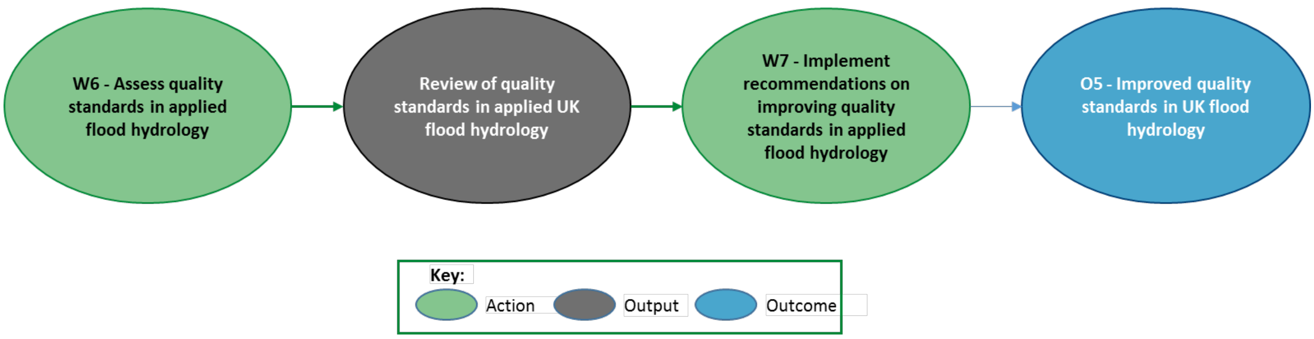
Intended outcomes

This action contributes to one outcome:

- outcome 5 - improved quality standards in UK flood hydrology

The outcome map for this action is shown in Figure G-17.

Figure G-17 – Outcome map for action W6



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-18. It suggests funding of between £360,000 and £540,000 is required over a 3-year period (Figure G-19).

Figure G-18 – Estimated spend profile for action W6

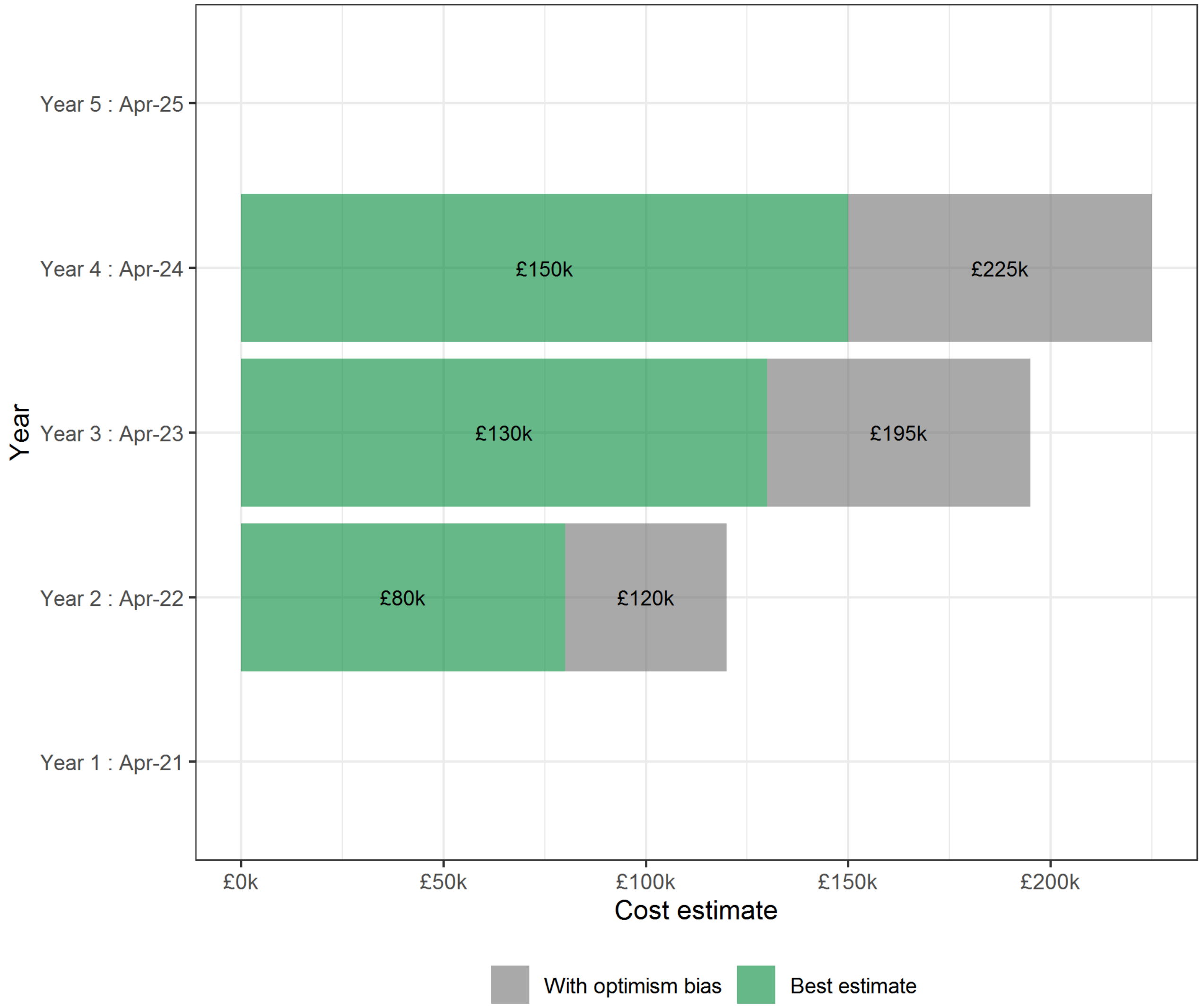
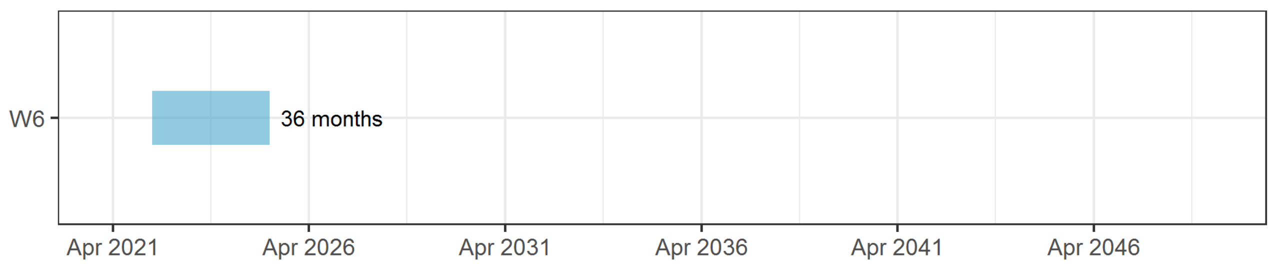
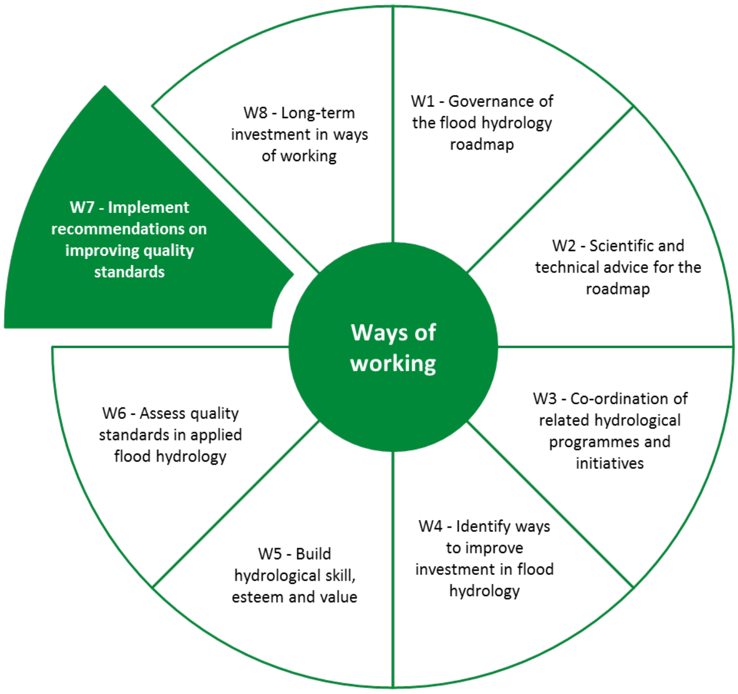


Figure G-19 – Estimated duration of action W6



Action W7: Implement recommendations on improving quality standards in applied flood hydrology



Objective

To implement the recommendations of action W6.

Outline scope

This action will implement recommendations from action W6. Scope and detailed timescales will be determined towards the end of action W6 and agreed by the flood hydrology roadmap governance board (established in action W1).

As a minimum, this work will include:

1. developing quality standards based on the recommendations from action W6
2. establishing an owner for the new quality standards who is responsible for:
    a. hosting the standards in an online environment
    b. communicating the standards and gaining accreditation for these from relevant institutions (for example, Institution of Civil Engineers (ICE), CIWEM, BHS, British Society for Geomorphology (BSG), British Dams Society (BDS), Royal Geographical Society (RGS), The Geological Society (GeolSoc)
    c. updating the standards periodically or when improvements are identified

Intended outputs

1. Implementation of quality standards for UK flood hydrology.
2. Implementation of other recommendations from action W6.

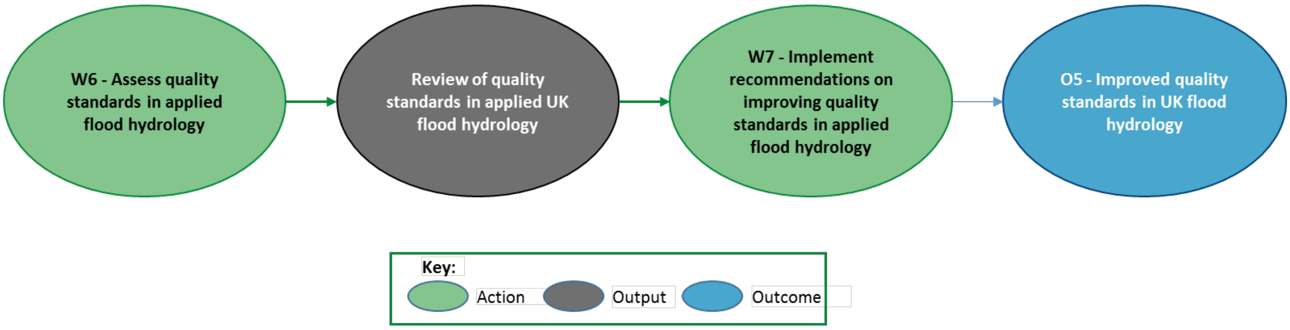
Intended outcomes

This action contributes to one outcome:

- outcome 5 - improved quality standards in UK flood hydrology

The outcome map for this action is shown in Figure G-20.

Figure G-20 – Outcome map for action W7



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-21. It suggests funding of between £450,000 and £680,000 over 3 years (Figure G-22) would be required for this action.

Figure G-21 – Estimated spend profile for action W7

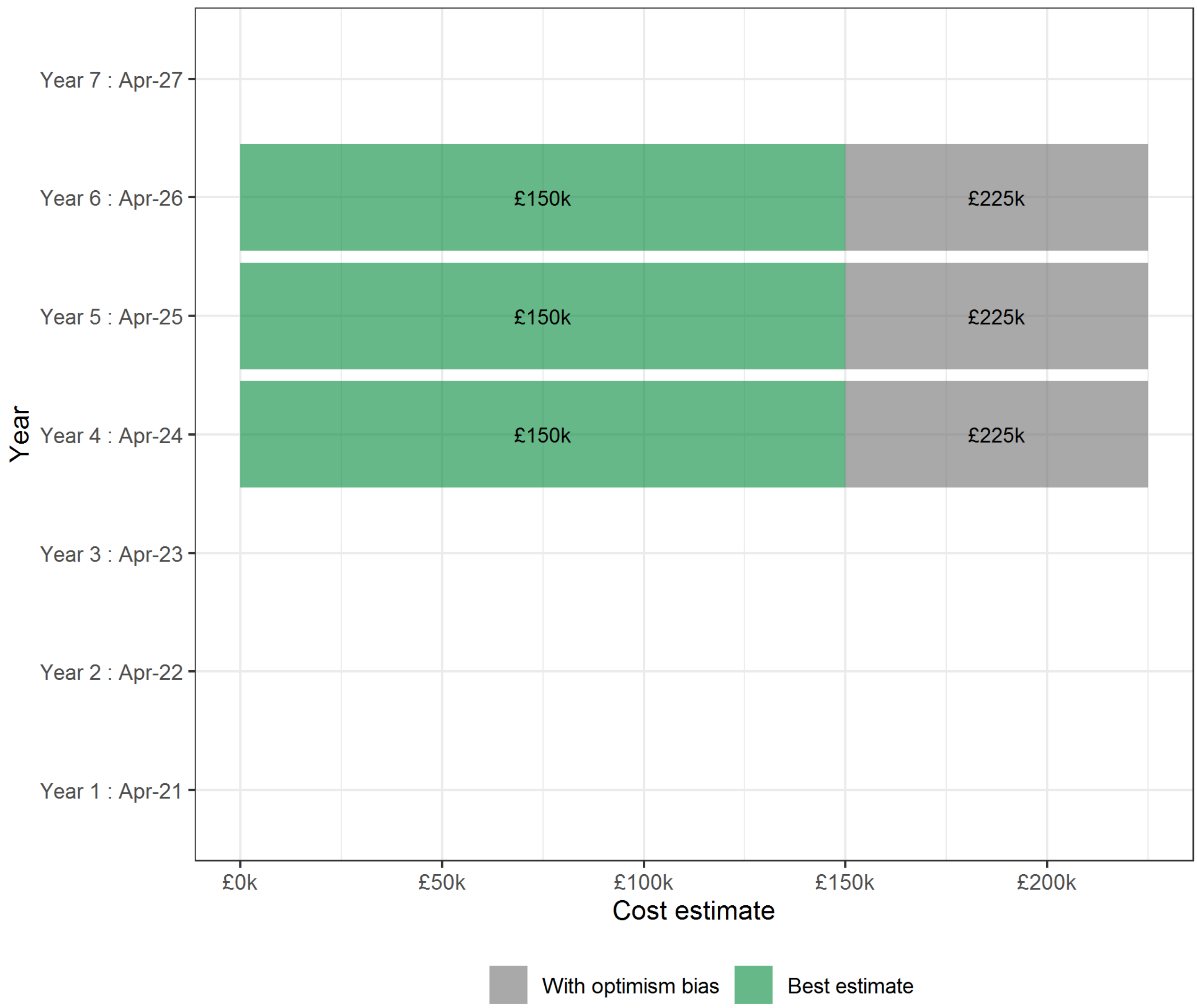
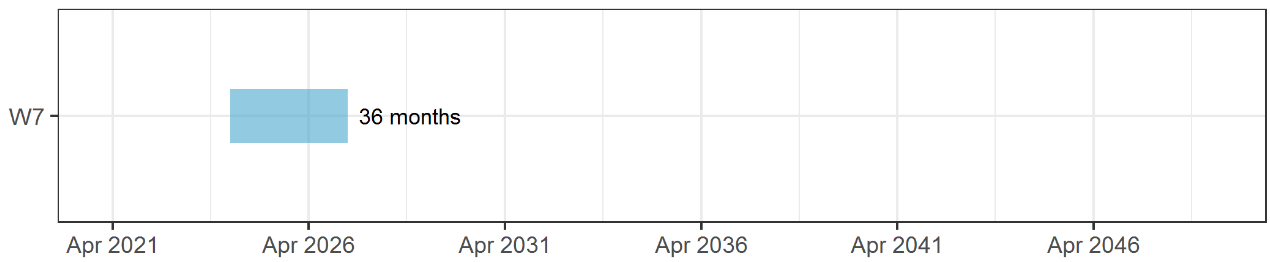


Figure G-22 – Estimated duration of action W7



Action W8: Long-term investment in ways of working

Objective

To carry out long-term actions to turn the ways of working vision of the flood hydrology roadmap into outcomes.

Outline scope

The detailed scope of long-term actions to improve ways of working in the roadmap will become clearer as implementation of the roadmap progresses and will be informed by the findings and outputs of actions W1 to W7.

The following areas may be part of this long-term programme of work, but will be subject to change and review as part of the periodic refresh of the roadmap and its action plan (likely to be every 3 years), which will be led by the governance board as part of action W1:

1. periodic reviews of the purpose, membership and effectiveness of the scientific and technical advisory group (STAG) established in action W2
2. a review of the work done to improve the visibility, coordination and collaboration between programmes and initiatives related to flood hydrology across the UK as part of action W3 – there may be further actions required to ensure continued coordination and collaboration
3. further work to demonstrate the value of UK flood hydrology and encourage longer-term investment (building on action W4)

4. a refresh of the survey of the flood hydrology community to help continue building on action W5 – this could help understand how the roadmap is having an impact in the flood hydrology community and could be done as part of the 3-yearly refresh of the roadmap described in item 10 of the scope of action W1
5. reviewing and updating the strategy to improve diversity and promote equality of opportunity within the flood hydrology profession developed in action W5
6. reviewing and updating the skills and development framework for UK flood hydrology developed in action W5
7. a review of quality standards after a period of embedding and use (building on actions W6 and W7)
8. communication and engagement activities to build on the sense of community and encourage uptake of roadmap outputs and outcomes

Intended outputs

To be defined – dependent on the findings, recommendations, outputs and outcomes of actions W1 to W7.

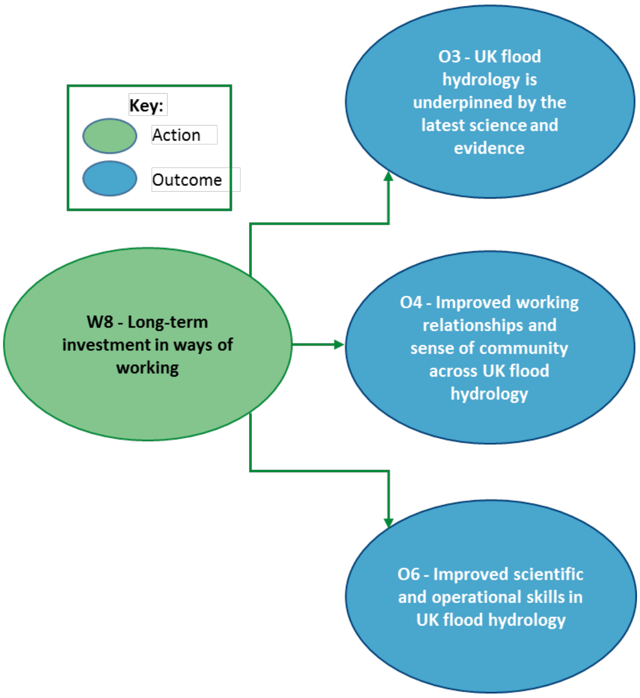
Intended outcomes

It is likely that this action contributes to 3 outcomes (although this will be dependent on the scope of the work):

- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence
- outcome 4 - improved working relationships and sense of community across UK flood hydrology
- outcome 6 - improved scientific and operational skills in UK flood hydrology

The outcome map for this action is shown in Figure G-23.

Figure G-23 – Outcome map for action W8



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-24. Due to the uncertain nature of the longer-term actions in the roadmap, which will be subject to cycles of review and refresh, the funding outlined in Figure G-24 is indicative only. It comprises between £300,000 and £450,000 from year 7 (April 2027), rising by 2% annually for the lifetime of the roadmap (Figure G-25). This cost estimate should be refined as the roadmap actions on ways of working progress.

Figure G-24 – Estimated spend profile for action W8

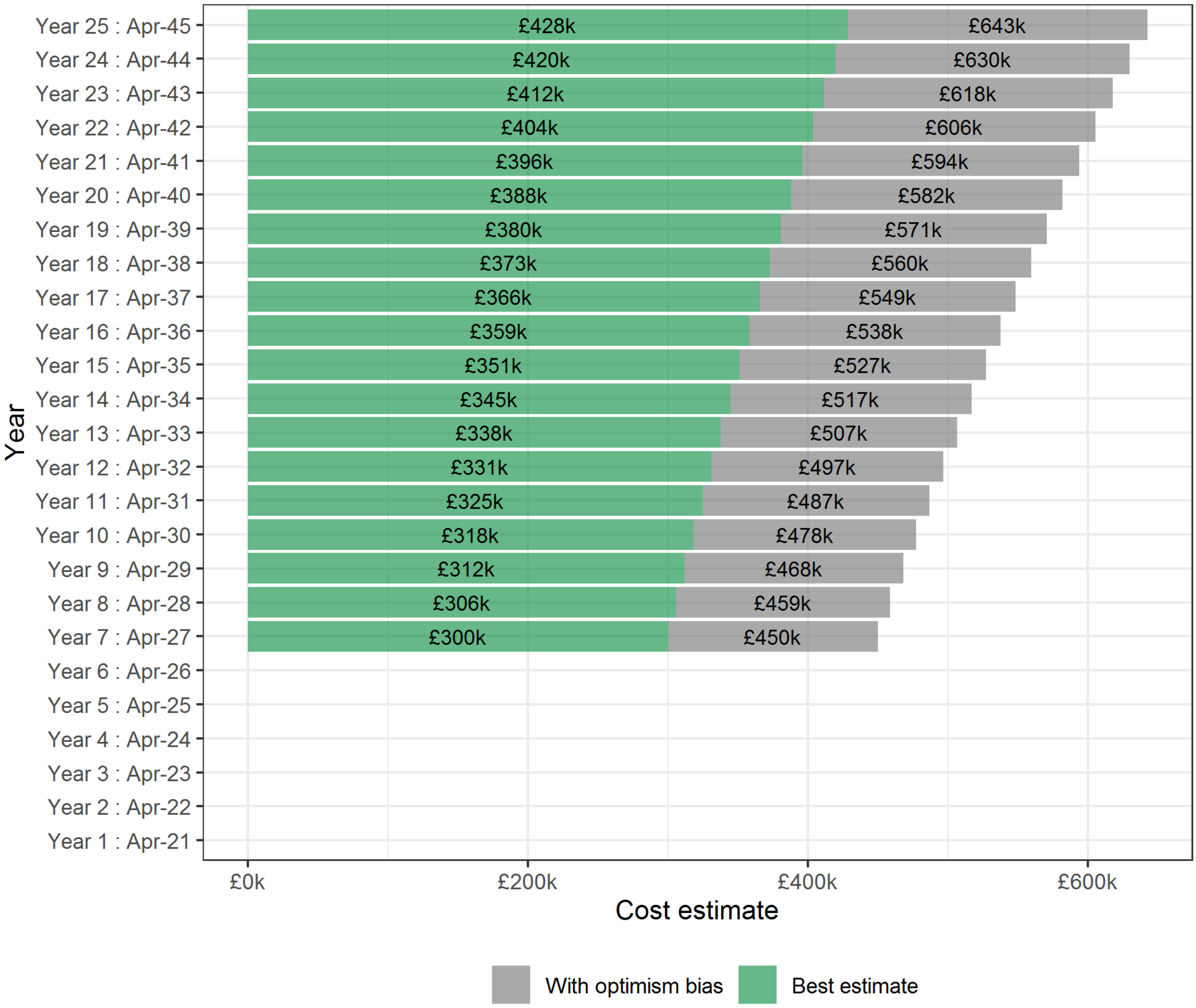
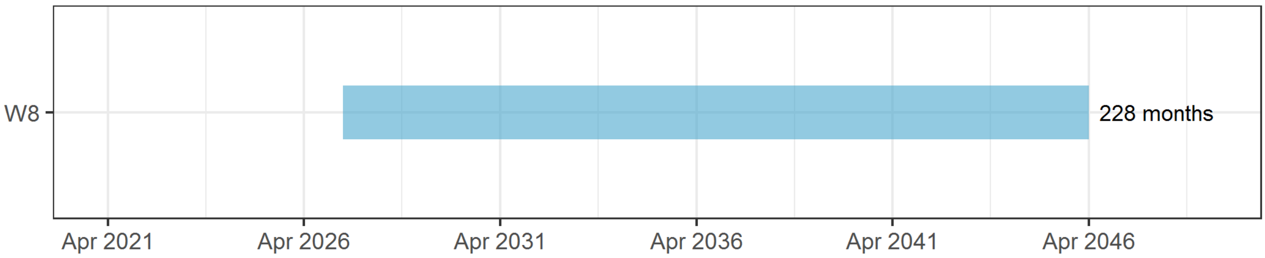
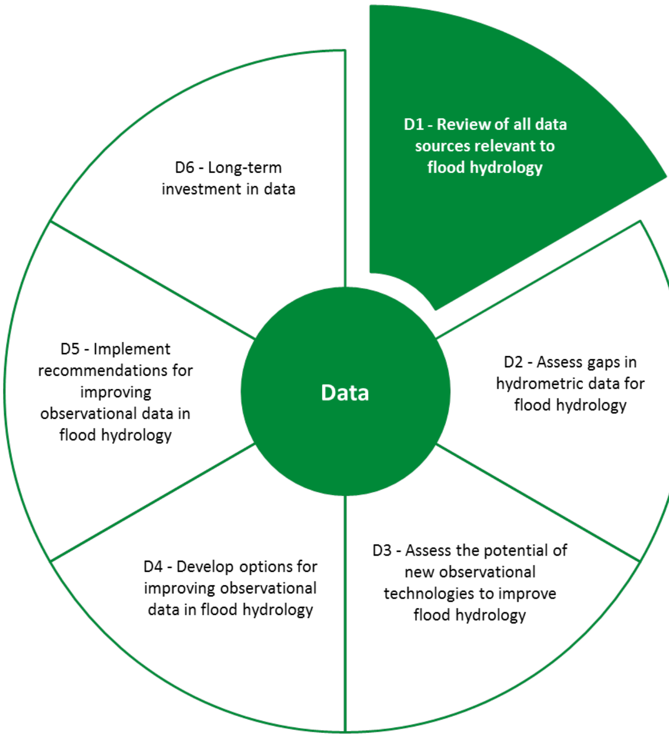


Figure G-25 – Estimated duration of action W8



Action D1: Review of all data sources relevant to flood hydrology



Objective

Understand the status of flood hydrology data accessibility in the UK and setting out options for improvement.

Outline scope

This action will:

1. identify all sources of data relevant to flood hydrology in the UK and create an online register of flood hydrology data, including hydrometric data such as river flows and levels, groundwater levels and rainfall, and also other data sources that are of hydrological relevance[12]

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[12] There are many observations and data types that could be relevant to flood hydrology and the wider water cycle. A non-exhaustive list of data that may potentially be of interest includes: soil moisture, evaporation fluxes, snow, soils, geology, geomorphology and sediments, land cover, historic floods, paleo flood data,

2. review data produced from operational and academic work
3. establish a mechanism for maintaining and updating the register of flood hydrology data
4. consider real-time and non-real-time data
5. consider data relating to all sources of inland flooding
6. review the accessibility of data identified in the flood hydrology data register by answering the following questions:
    a. who manages and who owns the data?
    b. who uses the data, and for what purpose(s)?
    c. what licensing arrangements exist for use of the data?
    d. which data are freely available to all, which are freely available to some, and which are not freely available?
    e. what are the arrangements for updating the data?
    f. how are new data sets made available to the flood hydrology community?
7. review the quantity, quality (in parallel with action W6) and known uncertainty of data in the flood hydrology data register to help understand data applicability to particular technical areas, and scope improvements
8. work with all bodies with responsibility for flood hydrology data (for example, the UK surface and groundwater archives (SAGA) committee)
9. work with bodies that could advise on improvements to flood hydrology data (for example, the Geospatial Commission, the James Hutton Institute and the Centre for Environmental Data Analysis (CEDA))
10. produce a report on the findings of this investigation, setting out options for improvement to inform subsequent action D4

Intended outputs

1. An online register of flood hydrology data.
2. Report that reviews the accessibility of flood hydrology data and sets out options for improvement.

Intended outcomes

This action contributes to 3 outcomes:

- outcome 7 - flood hydrology models and data are easily accessible and freely available
- outcome 8 - uncertainty in UK flood hydrology data and models is better quantified and communicated

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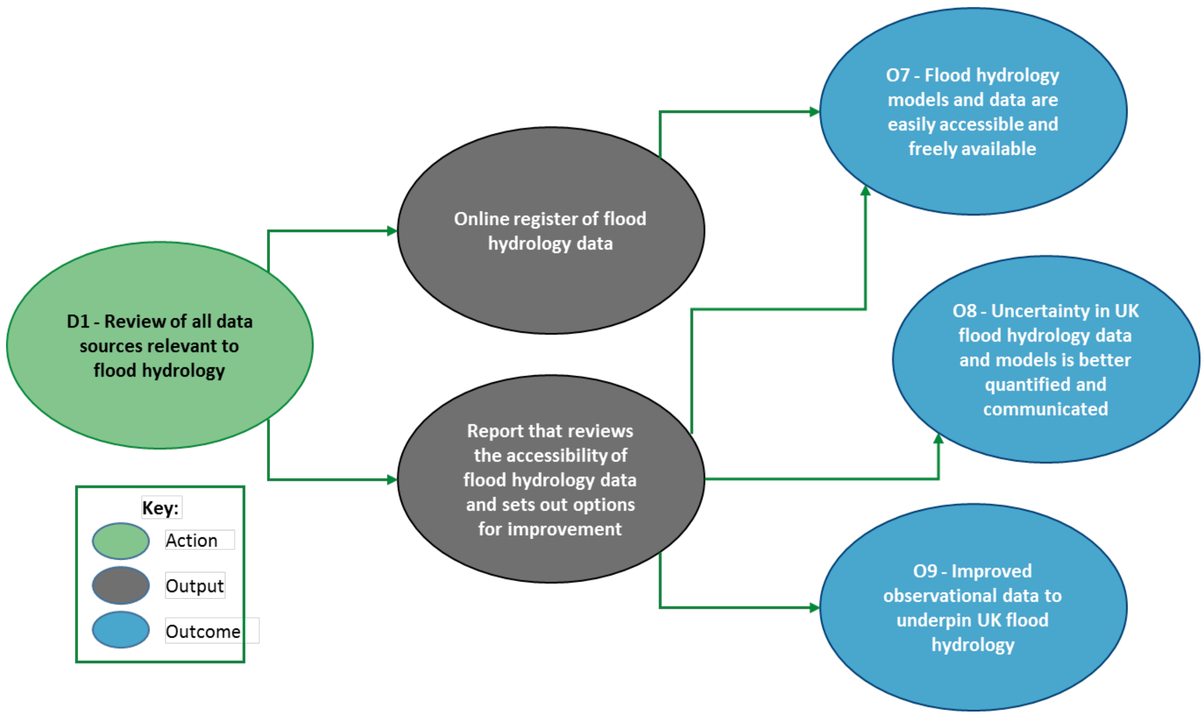
citizen science observations, documentary data sources, tracers, earth observations from space, topography, reanalysis and model outputs.

- outcome 9 - improved observational data to underpin UK flood hydrology

The outcome map for this action is shown in Figure G-26.

Figure G-26 – Outcome map for action D1



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-27. It comprises between £300,000 and £450,000 over 4 years (Figure G-28).

Figure G-27 – Estimated spend profile for action D1

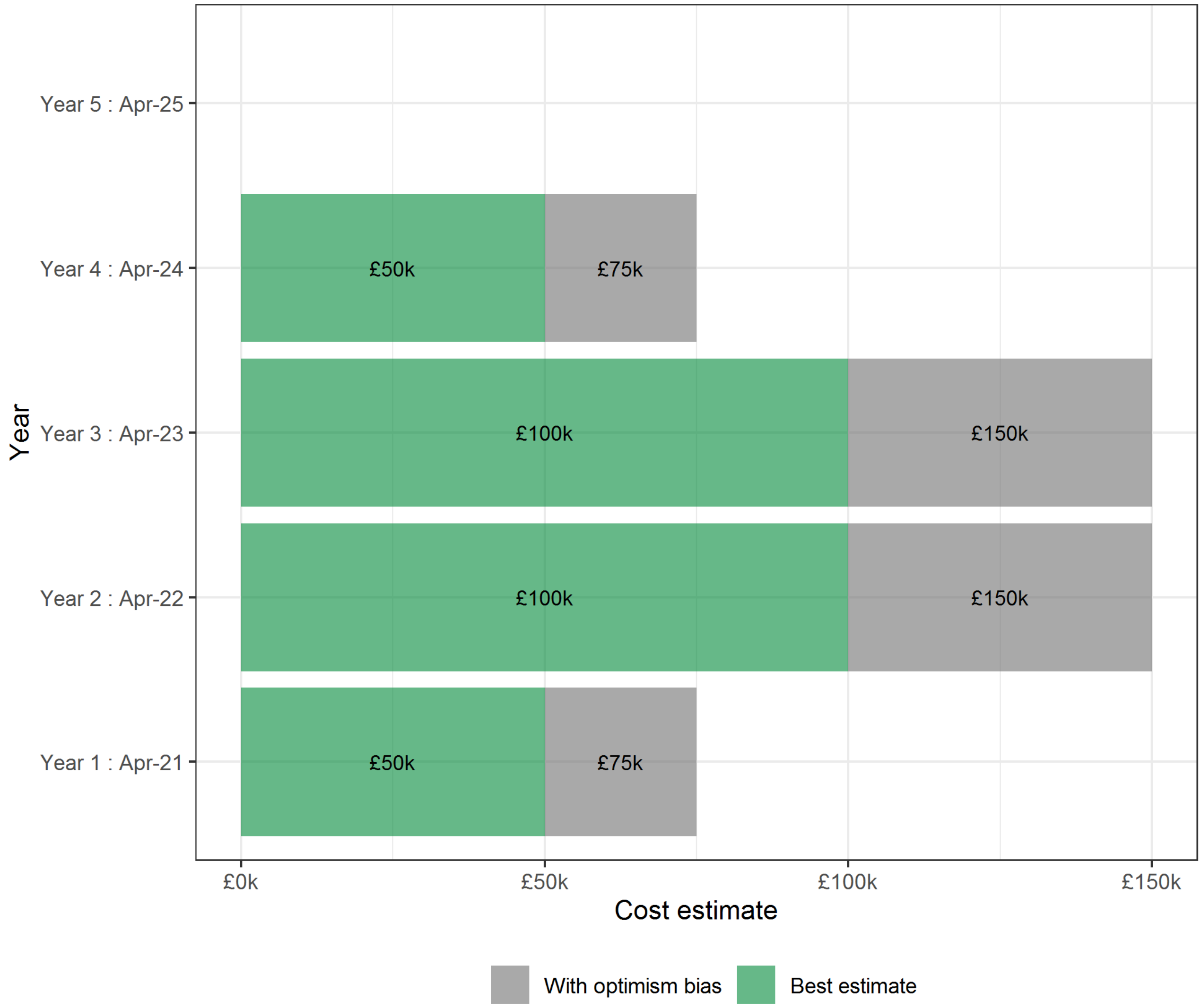
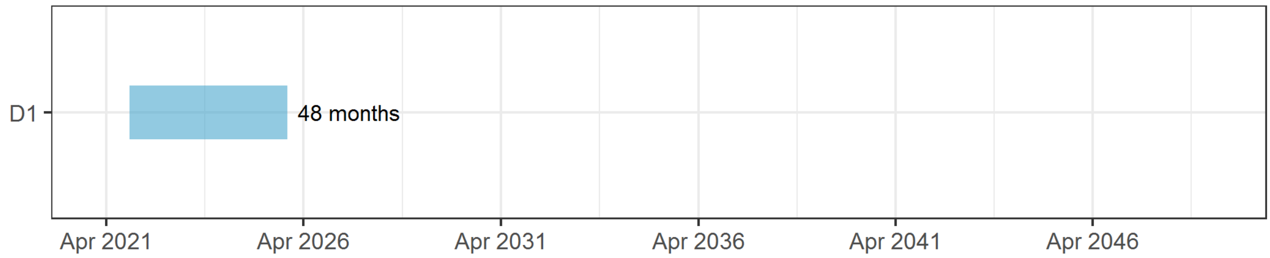


Figure G-28 – Estimated duration of action D1



Action D2: Assess gaps in hydrometric data for flood hydrology

Objective

Make recommendations to improve UK hydrometric data to better support scientific research and operational activities.

Outline scope

This action could:

1. assess where there are gaps in the UK hydrometric data set[13] and network via a strategic review of national monitoring networks (could be carried out in parallel with action D1)
2. consider both scientific and operational needs
3. give special consideration to gaps in areas of future development outlined in local development plans

[13] This refers to all holdings of hydrometric data in the UK, not just the centralised national river flow archive (NRFA) holdings.

4. consider hydrometric data used in real-time and non-real-time
5. consider hydrometric data for all sources of inland flooding
6. work with the UK SAGA Committee
7. assess and evaluate the need for improved high flow gauging (this could build on the Environment Agency R&D proposal for 'Improving flood flow measurements in flood and coastal risk management' [FRS18198])
8. assess the availability and need for hydrometric data for reservoir inflow calculations
9. consider what hydrometric data and infrastructure should be maintained long-term (for example, the benchmark catchment network)
10. consider how data rescue (data that exists but is not easily available) could contribute to this action
11. ensure links are made to related programmes (for example, FDRI)
12. consider future funding for a sustainable hydrometric network (linked to action W4)
13. produce a report with options and recommendations to address gaps in hydrometric data and infrastructure, which will inform implementation via actions D4 and D5

Intended outputs

1. Report with options and recommendations to address gaps in hydrometric data and infrastructure in the UK.

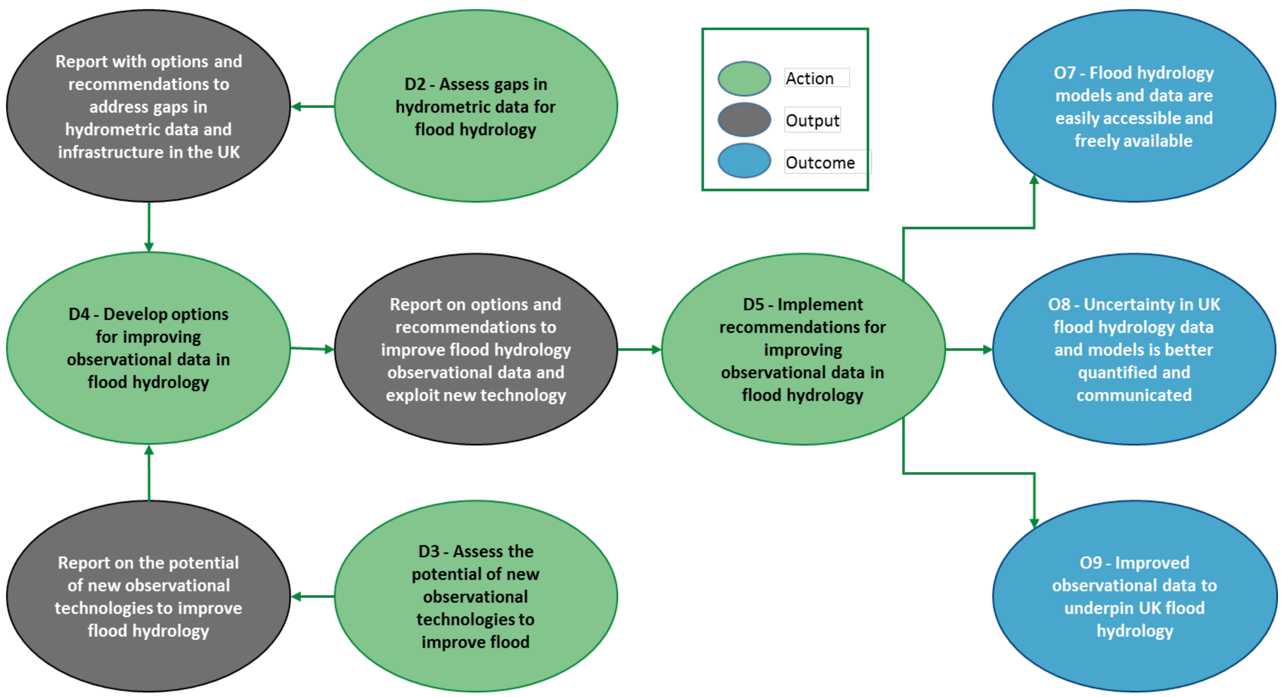
Intended outcomes

This action contributes to 3 outcomes:

- outcome 7 - flood hydrology models and data are easily accessible and freely available
- outcome 8 - uncertainty in UK flood hydrology data and models is better quantified and communicated
- outcome 9 - improved observational data to underpin UK flood hydrology

The outcome map for this action is shown in Figure G-29.

Figure G-29 – Outcome map for action D2



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-30. It comprises between £300,000 and £450,000 over 4 years (Figure G-31).

Figure G-30 – Estimated spend profile for action D2

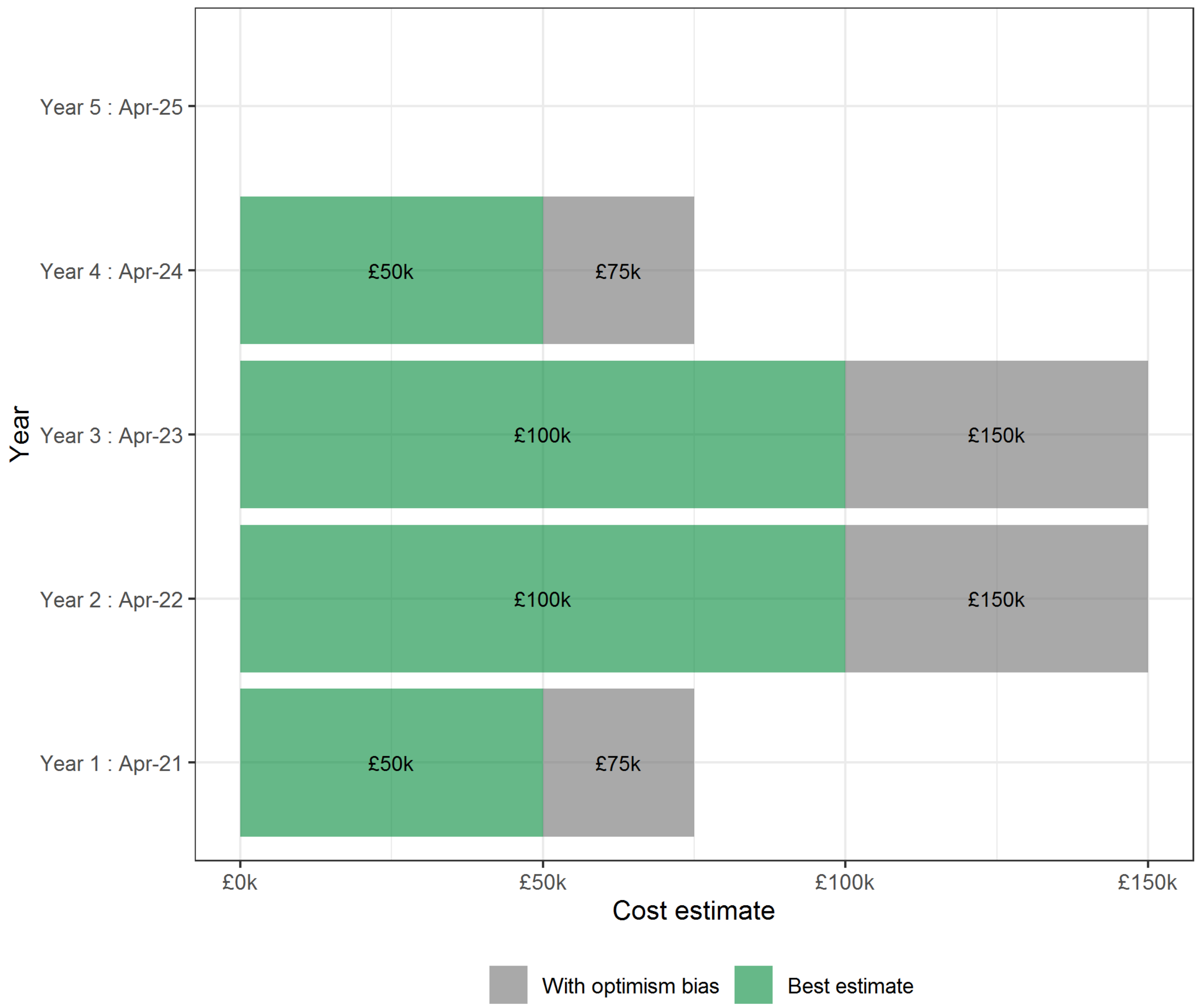
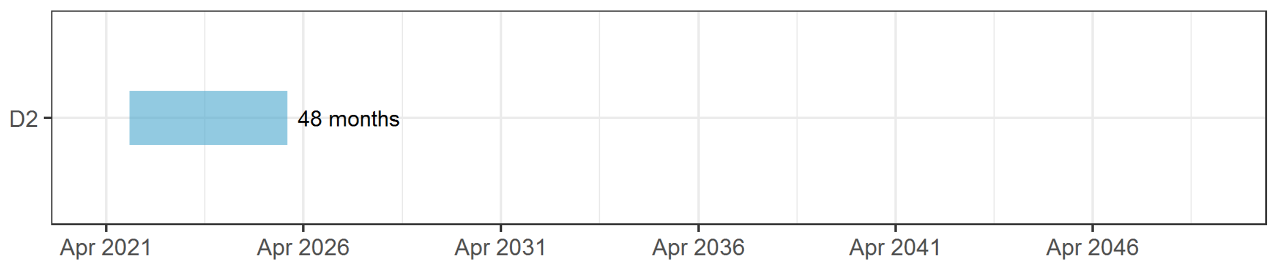


Figure G-31 – Estimated duration of action D2



Action D3: Assess the potential of new observational technologies to improve flood hydrology

Objective

Identify options for using new observational technology to capture flood hydrology data.

Outline scope

This action could:

1. consider new technologies for real-time and non-real-time data
2. consider new technologies for all sources of inland flooding
3. examine opportunities for improving understanding of characterisation of rainfall from weather radar, and the spatial measurement of rainfall, focusing on flood-producing rainfall events
4. examine opportunities for other data types to support flood hydrology: for example, for estimating soil moisture, evaporation, snow, geo-spatial data, soils, geology, catchment descriptor type data and data for process understanding (for example, subsurface flows, chemical tracers), or other types of observations indicated in action D1
5. investigate how geomorphological processes resulting in river channel change impact data quality over the flood event and inter-event time scale

6. examine new technologies for high flow gauging that could enable safe collection of reliable flow estimates at main sites during periods of high flow, to both improve data quality at existing monitoring stations and to extend the spatial coverage of high flow data (this aligns with the Environment Agency R&D proposal for improving flood flow measurements in FCERM [FRS18198])
7. examine technological advances in observational techniques, data processing and modelling, machine learning and artificial intelligence (internationally) - this should include remote sensing from drone to satellite scale
8. consider the uncertainties associated with new technologies
9. examine new technologies for citizen science data collection, storage and management (this should review and build on previous research), including phone apps
10. consider the accuracy of citizen science and its quality control
11. consider how new technologies could improve the efficiency of data collection
12. consider the role of using existing technologies in different ways (for example, blended data sets)
13. carry out a benefit-cost options assessment of these technologies
14. develop a mechanism for continued appraisal of new and emerging technologies
15. be informed by the FDRI initiative and the BHS working group on the future of UK hydrological research
16. engage with leading stakeholder groups (for example, hydrometry practitioners and researchers)
17. consider the potential of new technologies to help with multi-disciplinary issues (for example water resources)
18. produce a report to inform action D4 with options and recommendations on future observational technology

Intended outputs

1. Report on the potential of new observational technologies to improve flood hydrology.

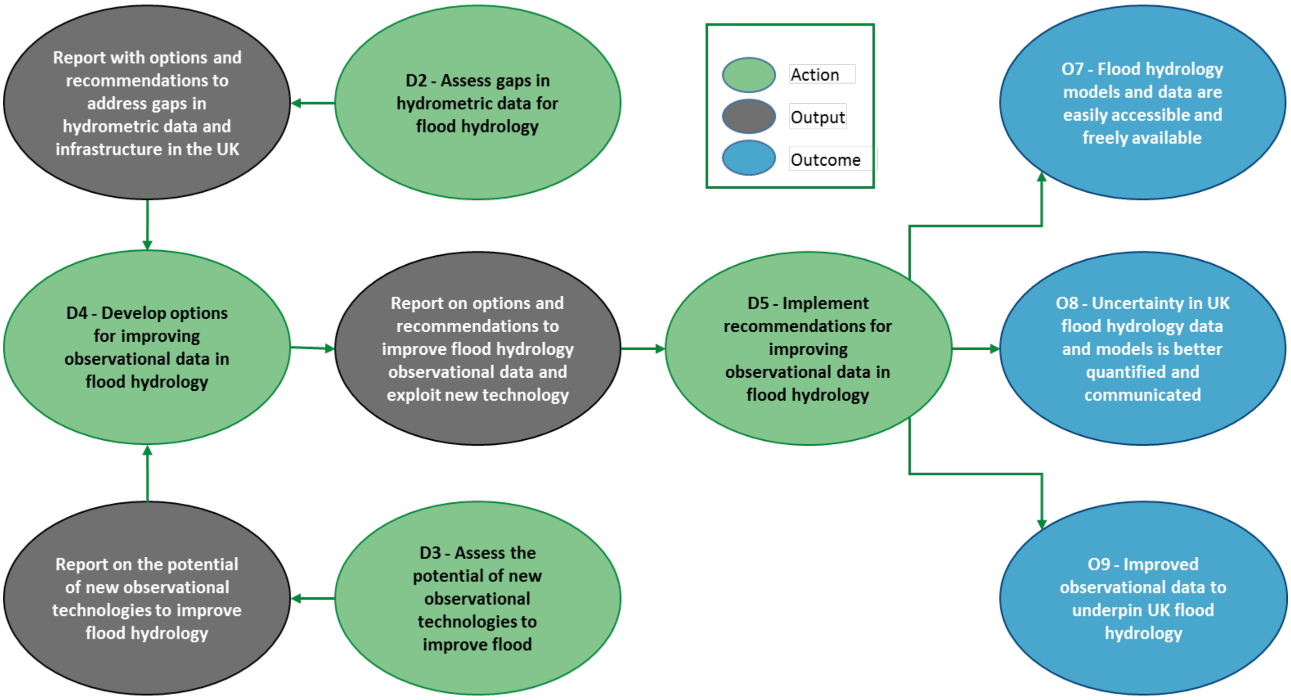
Intended outcomes

This action contributes to 3 outcomes:

- outcome 7 - flood hydrology models and data are easily accessible and freely available
- outcome 8 - uncertainty in UK flood hydrology data and models is better quantified and communicated
- outcome 9 - improved observational data to underpin UK flood hydrology

The outcome map for this action is shown in Figure G-32.

Figure G-32 – Outcome map for action D3



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-33. It is likely that funding of between £300,000 to £450,000 is required over a 1.5 year period.

The duration of this action is for the lifetime of the roadmap and is shown in Figure G-34.

Figure G-33 – Estimated spend profile for action D3

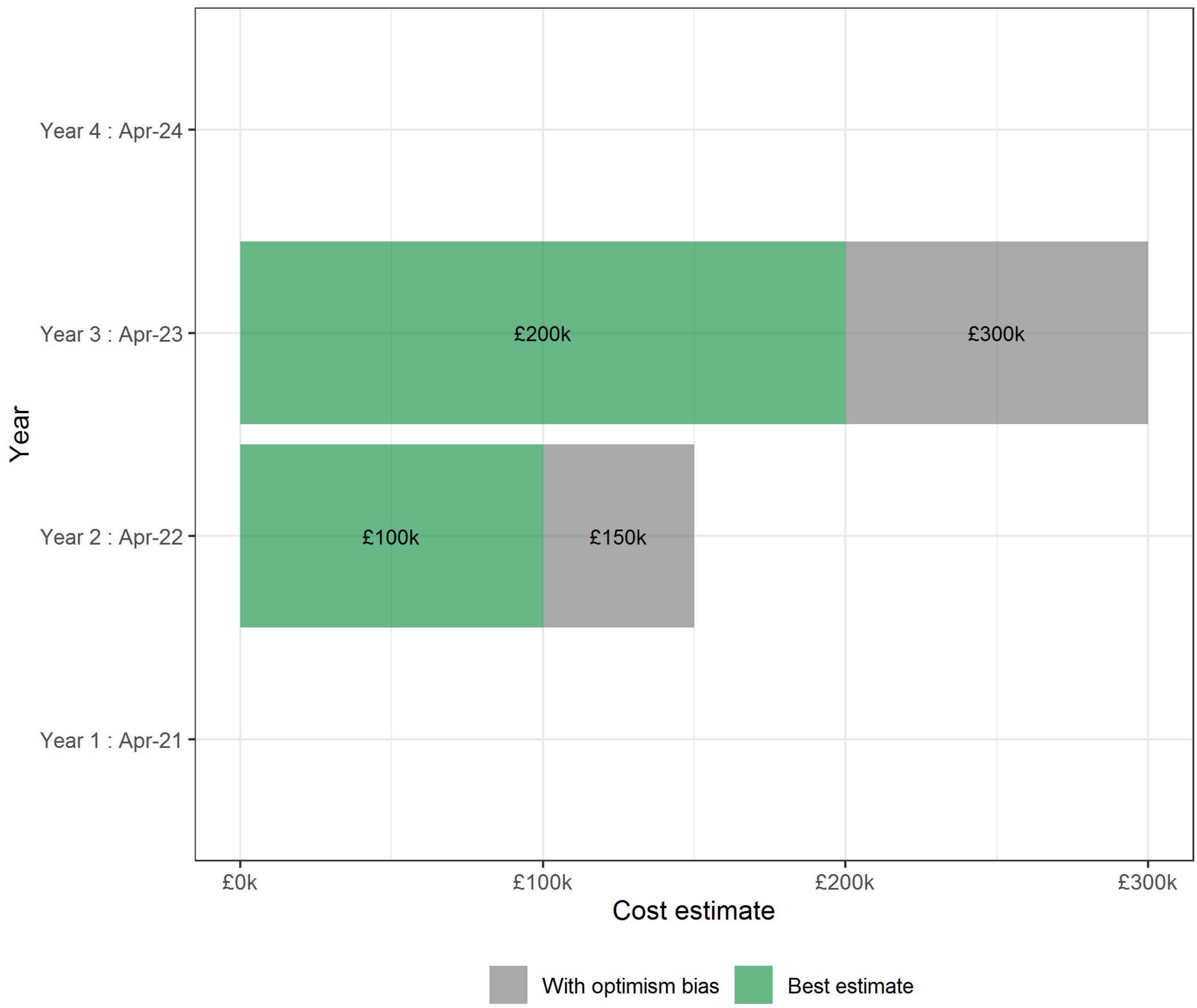
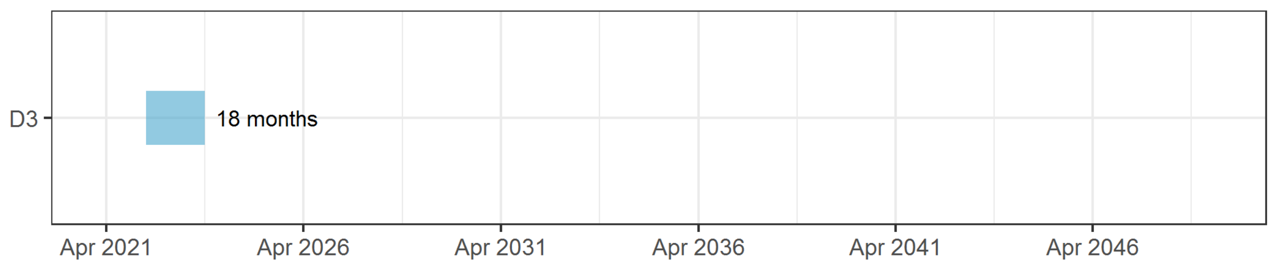
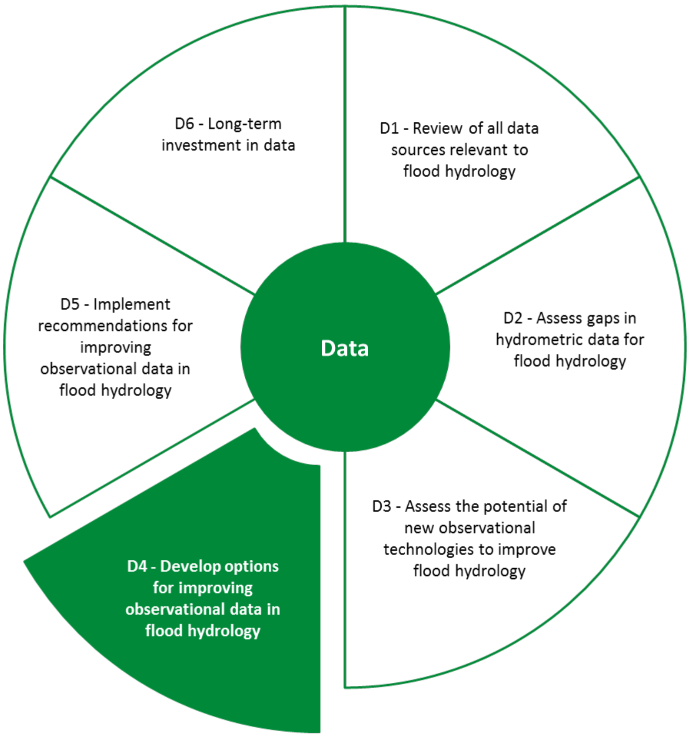


Figure G-34 – Estimated duration of action D3



Action D4: Develop options for improving observational data in flood hydrology



Objective

Develop a series of options to improve future accessibility, quantity and quality of flood hydrology data in the UK.

Outline scope

This work will follow on from actions D1, D2 and D3 and could:

1. develop a series of integrated options for the future of UK flood hydrology data, which should:
    a. consider a discoverable portal or portals for all UK flood hydrology data (this could hold links to data sets rather than try to bring data together in one place)
    b. outline options for hosting, funding and licensing of data with the aspiration that quality controlled data are ‘freely available to all’ (to include national hydrometric data sets)
    c. examine international data availability approaches such as those of the USA and other European countries to identify learning points for the UK, to help answer the question, ‘how do freely available flood hydrology data benefit society, the economy and the environment?’

    d. examine opportunities for salvaging historical, non-digitised data
    e. examine opportunities to improve efficiency in data collection
    f. examine opportunities and need for a comprehensive ‘local data’ archive (to include local historical data, near-real time local data, palaeoflood and citizen science data), building on examples such as the BHS Chronology of Flooding data base and more local initiatives like the Environment Agency’s Wessex Area community flood archive project
    g. develop options for improving UK flood hydrology data quantity and quality
    h. identify possible funding routes for the preferred options
2. ensure that the options and recommendations from actions D1, D2 and D3 are integrated to improve observational data
3. ensure all options and recommendations consider real-time and non-real-time data
4. ensure all options and recommendations consider all sources of inland flooding
5. produce a report with integrated options and recommendations for the future of flood hydrology observational data and new technology

Intended outputs

1. Proposals for an online register of flood hydrology data.
2. Report with integrated options and recommendations to improve flood hydrology observational data and exploit new technology.

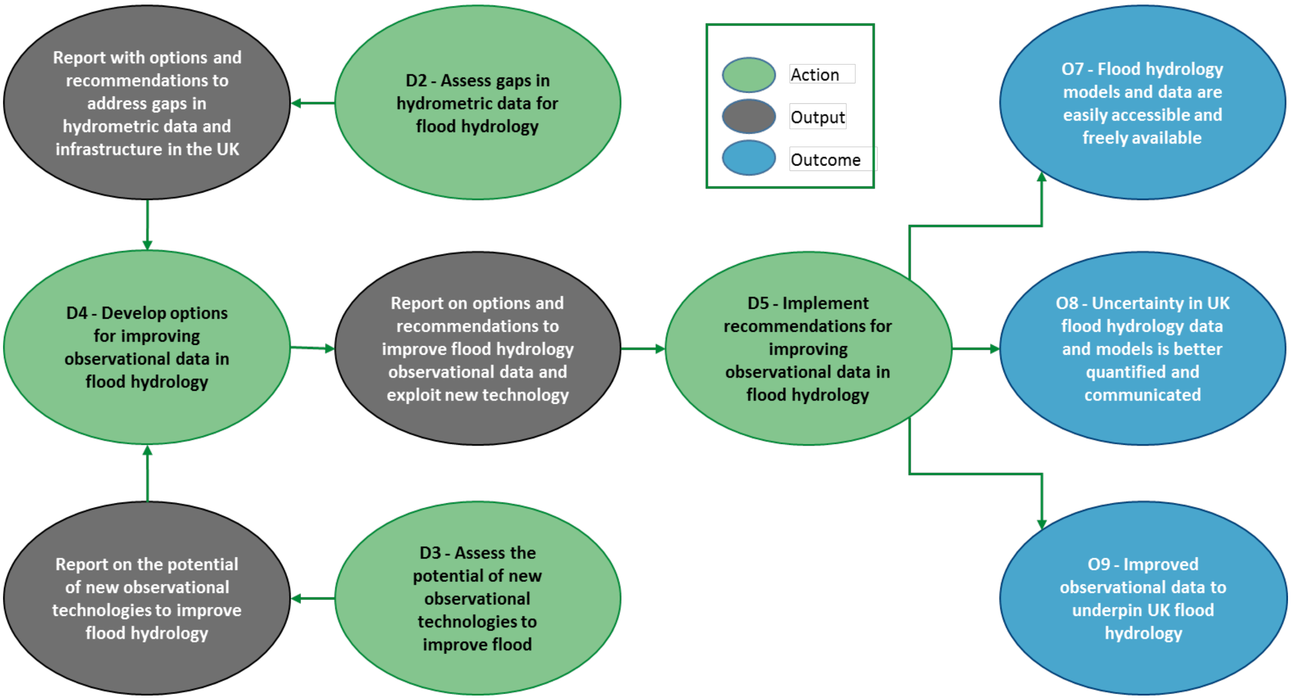
Intended outcomes

This action contributes to 3 outcomes:

- outcome 7 - flood hydrology models and data are easily accessible and freely available
- outcome 8 - uncertainty in UK flood hydrology data and models is better quantified and communicated
- outcome 9 - improved observational data to underpin UK flood hydrology

The outcome map for this action is shown in Figure G-35.

Figure G-35 – Outcome map for action D4



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-36. It is anticipated that this action will require between £435,000 and £653,000 of funding over a 4-year period (Figure G-37).

Figure G-36 – Estimated spend profile for action D4

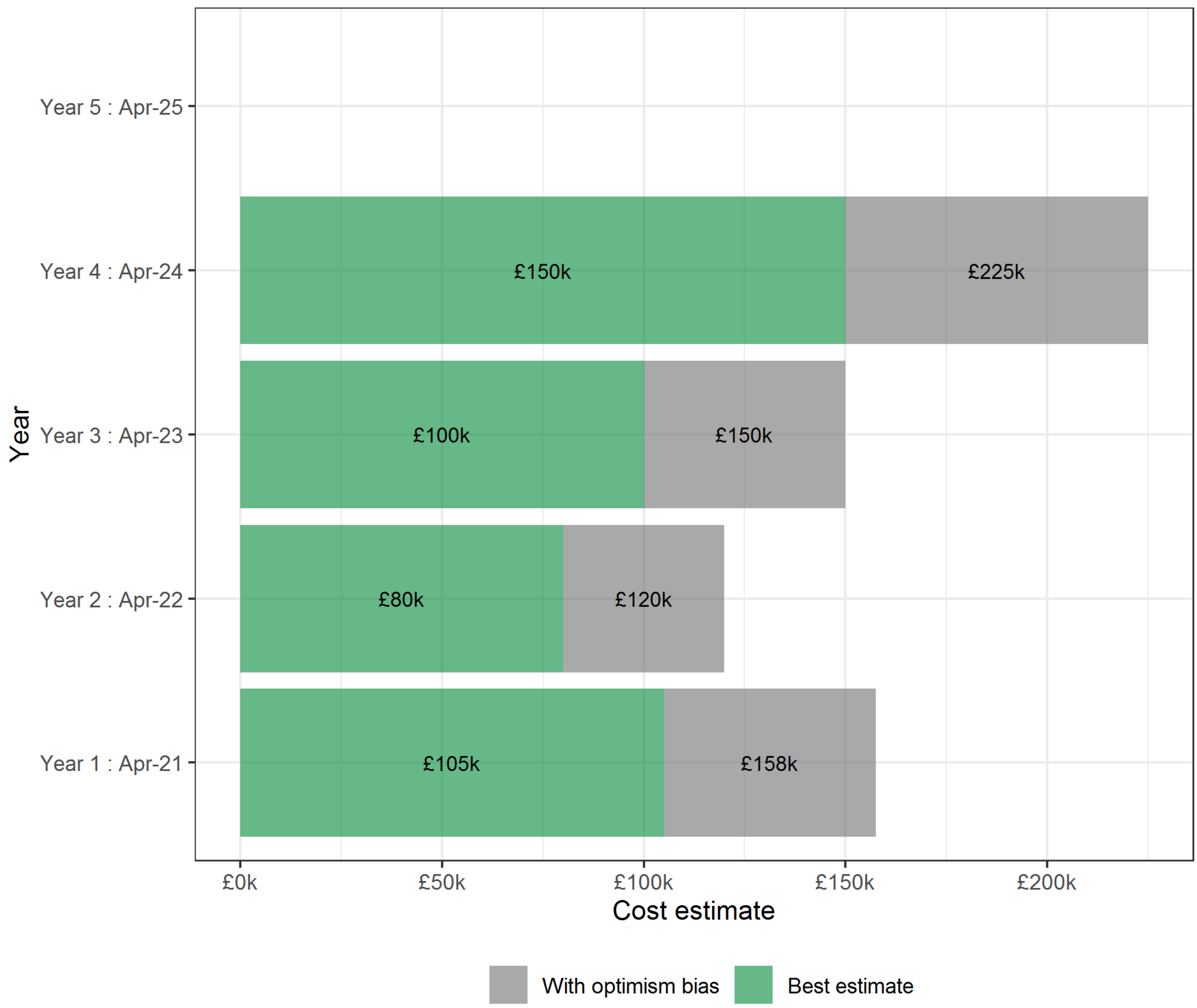
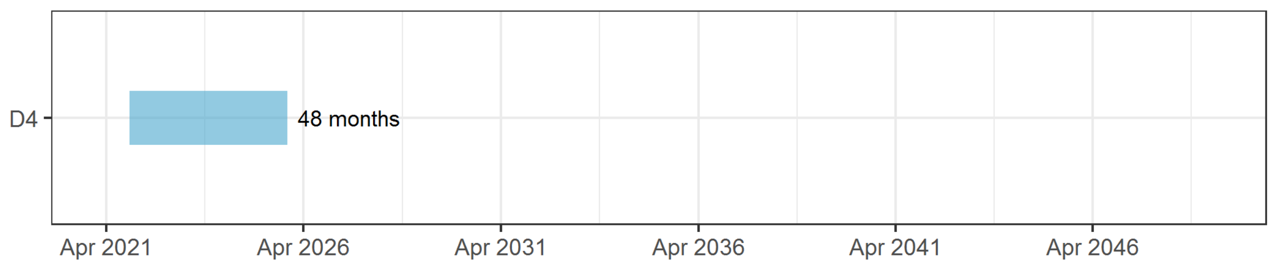


Figure G-37 – Estimated duration of action D4



Action D5: Implement recommendations for improving observational data in flood hydrology

Objective

To implement the preferred options for improving future accessibility, quantity and quality of flood hydrology data in the UK.

Outline scope

This action will implement recommendations from action D4 on observational data and new technologies for observational data.

Intended outputs

1. Implementation of recommendations from action D4.

Intended outcomes

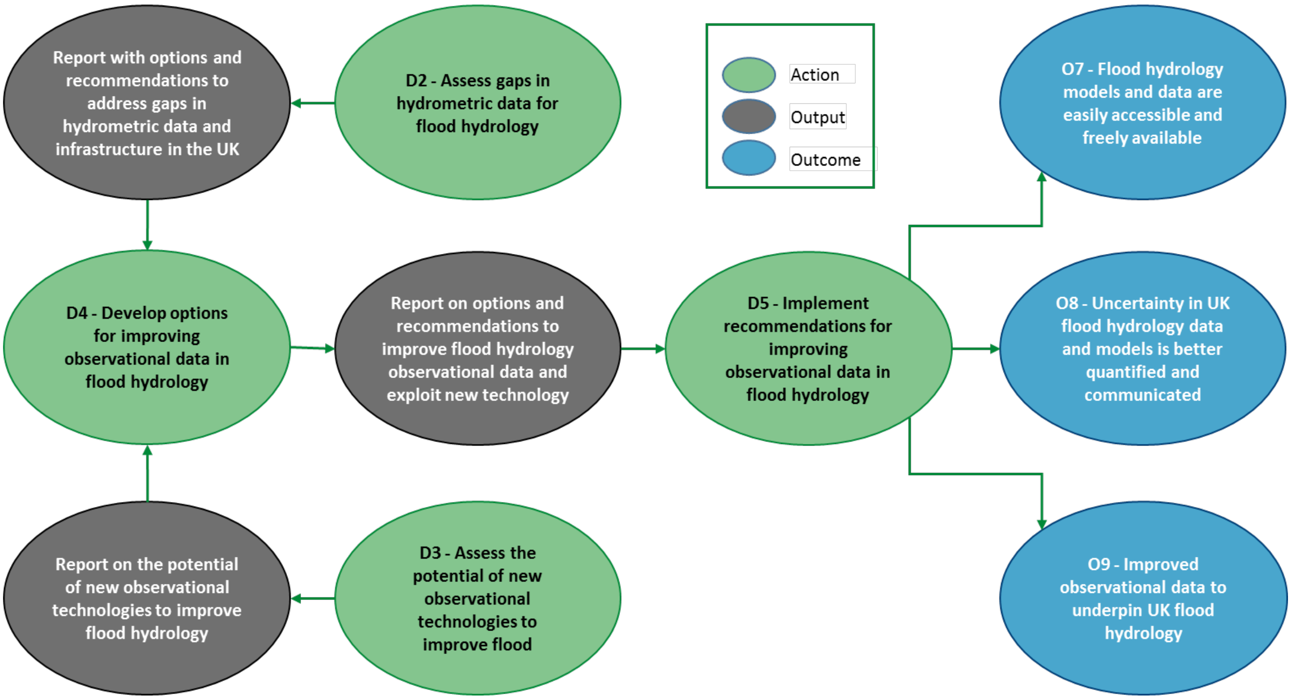
This action contributes to 3 outcomes:

- outcome 7 - flood hydrology models and data are easily accessible and freely available

- outcome 8 - uncertainty in UK flood hydrology data and models is better quantified and communicated
- outcome 9 - improved observational data to underpin UK flood hydrology

The outcome map for this action is shown in Figure G-35.

Figure G-35 – Outcome map for action D5



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-36. The costs of implementing this action are dependent on the findings and recommendations of other roadmap actions on data, so are uncertain. Best estimates suggest that between £6.2 million to £9.3 million may be required to implement recommendations for improving observational data in flood hydrology over a 5-year period (Figure G-37). This cost estimate should be refined as the roadmap actions on data progress.

Figure G-36 – Estimated spend profile for action D5

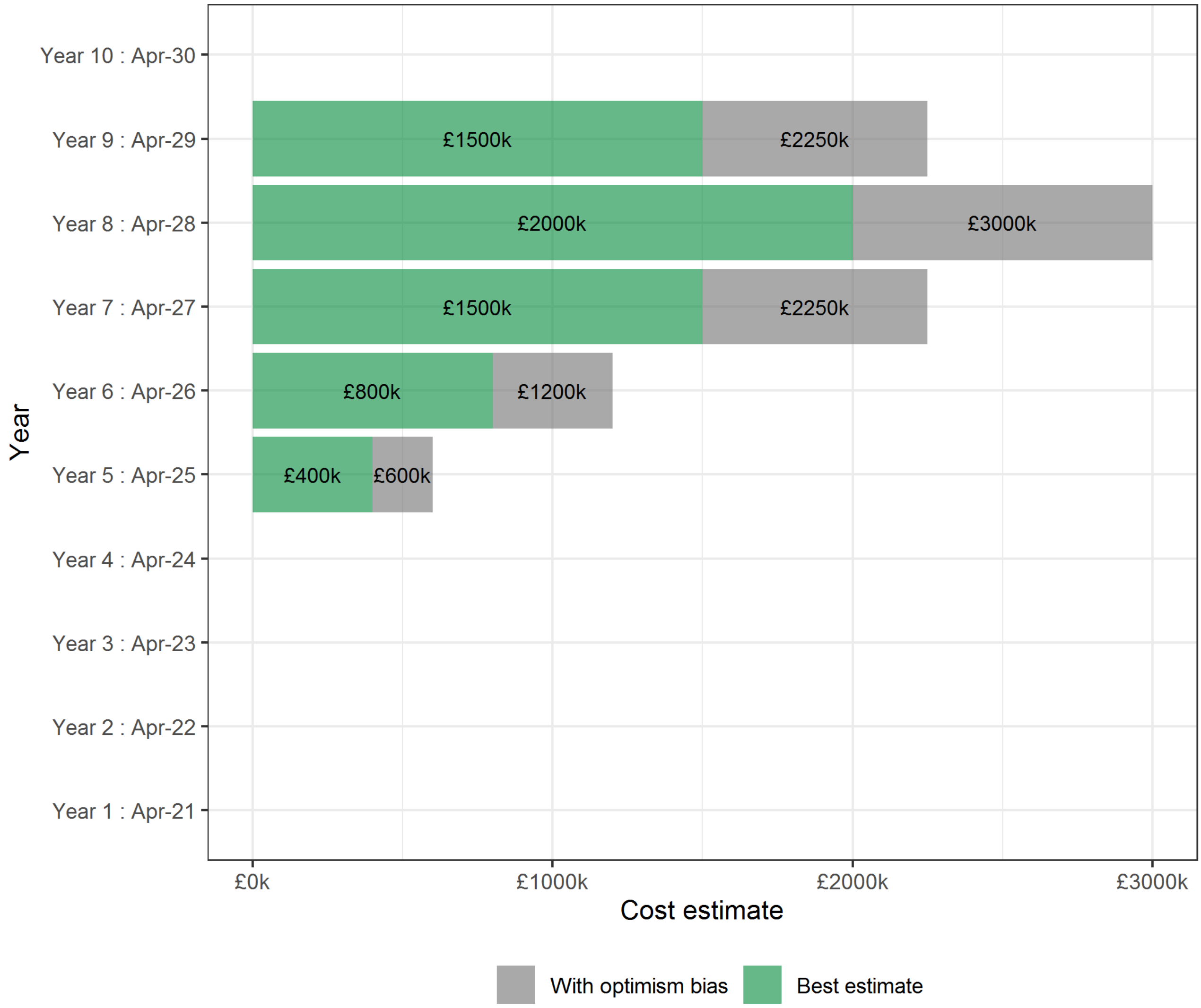
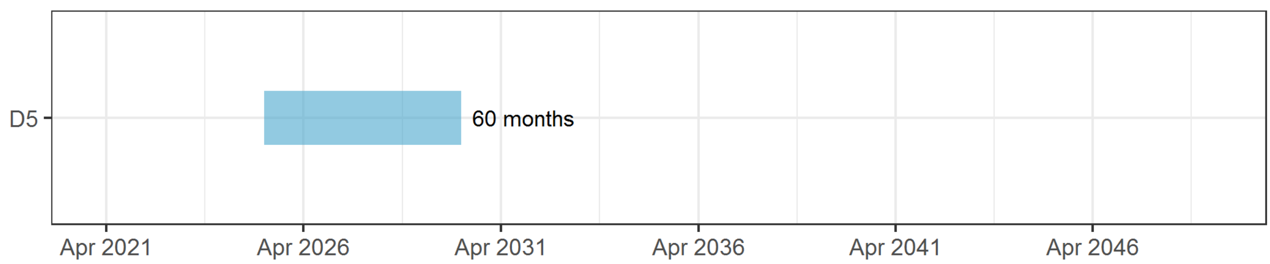
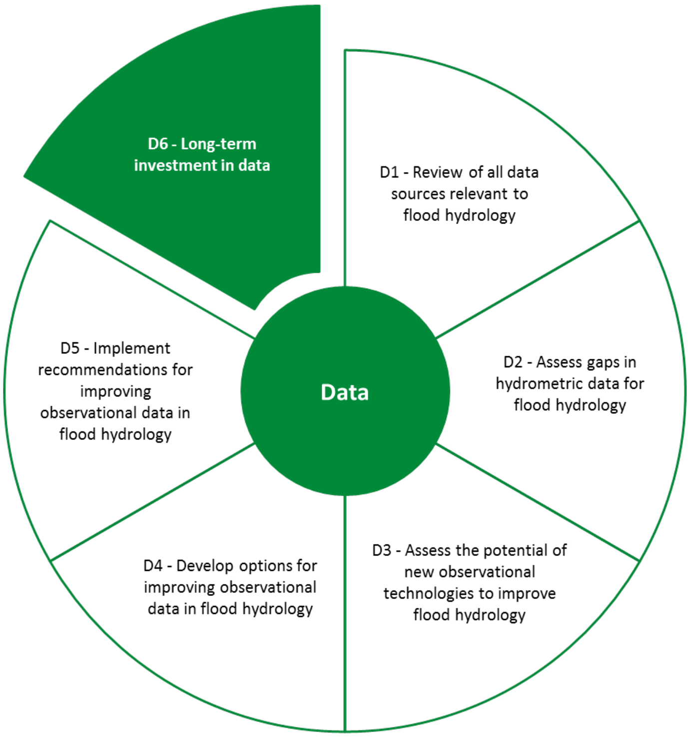


Figure G-37 – Estimated duration of action D5



Action D6: Long-term investment in data



Objective

To carry out long-term actions to turn the data vision of the flood hydrology roadmap into outcomes.

Outline scope

The detailed scope of long-term actions for flood hydrology data in the roadmap will become clearer as implementation of the roadmap progresses and will be informed by the findings and outputs of actions D1 to D5.

The following areas may be part of this long-term programme of work, but will be subject to change and review as part of the periodic refresh of the roadmap and its action plan (likely to be every 3 years), which will be led by the governance board as part of action W1:

1. the implementation of a national system that hosts the UK's flood hydrology data
2. further work on improving the quality of high flow data using emerging technology
3. ensuring that long-term hydrometric resources are sustainably funded
4. improving the capture of data on extreme events in small and urban catchments
5. periodic reviews of national data to ensure that the online register of flood hydrology data (from action D1) is up to date

Intended outputs

To be defined – dependent on the findings, recommendations, outputs and outcomes of actions D1 to D5.

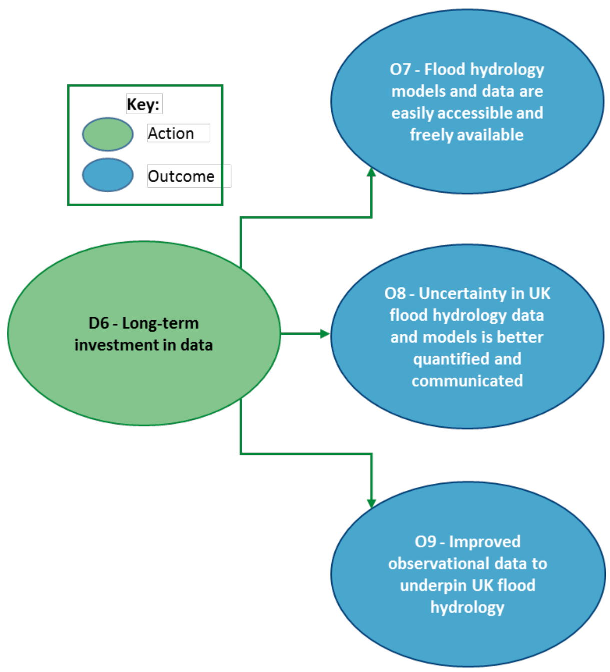
Intended outcomes

It is likely that this action contributes to 3 outcomes (although this will be dependent on the scope of the work):

- outcome 7 - flood hydrology models and data are easily accessible and freely available
- outcome 8 - uncertainty in UK flood hydrology data and models is better quantified and communicated
- outcome 9 - improved observational data to underpin UK flood hydrology

The outcome map for this action is shown in Figure G-38.

Figure G-38 – Outcome map for action D6



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-39. Due to the uncertain nature of longer-term actions in the roadmap, which will be subject to cycles of review and refresh, the funding outlined in Figure G-39 is indicative only. It suggests a total of £12.2 million to £18.3 million of funding will be required over 16 years (Figure G-40), starting in year 10 of the roadmap (April 2030). It is envisaged that longer-term investment on data will peak around years 12 (April 2032) and 13 (April 2033) between £2 million and £3 million per year. This will coincide with the implementation of a national system to host the UK's flood hydrology data outlined in the scope of this action. This cost estimate should be refined as the roadmap actions on data progress.

Figure G-39 – Estimated spend profile for action D6

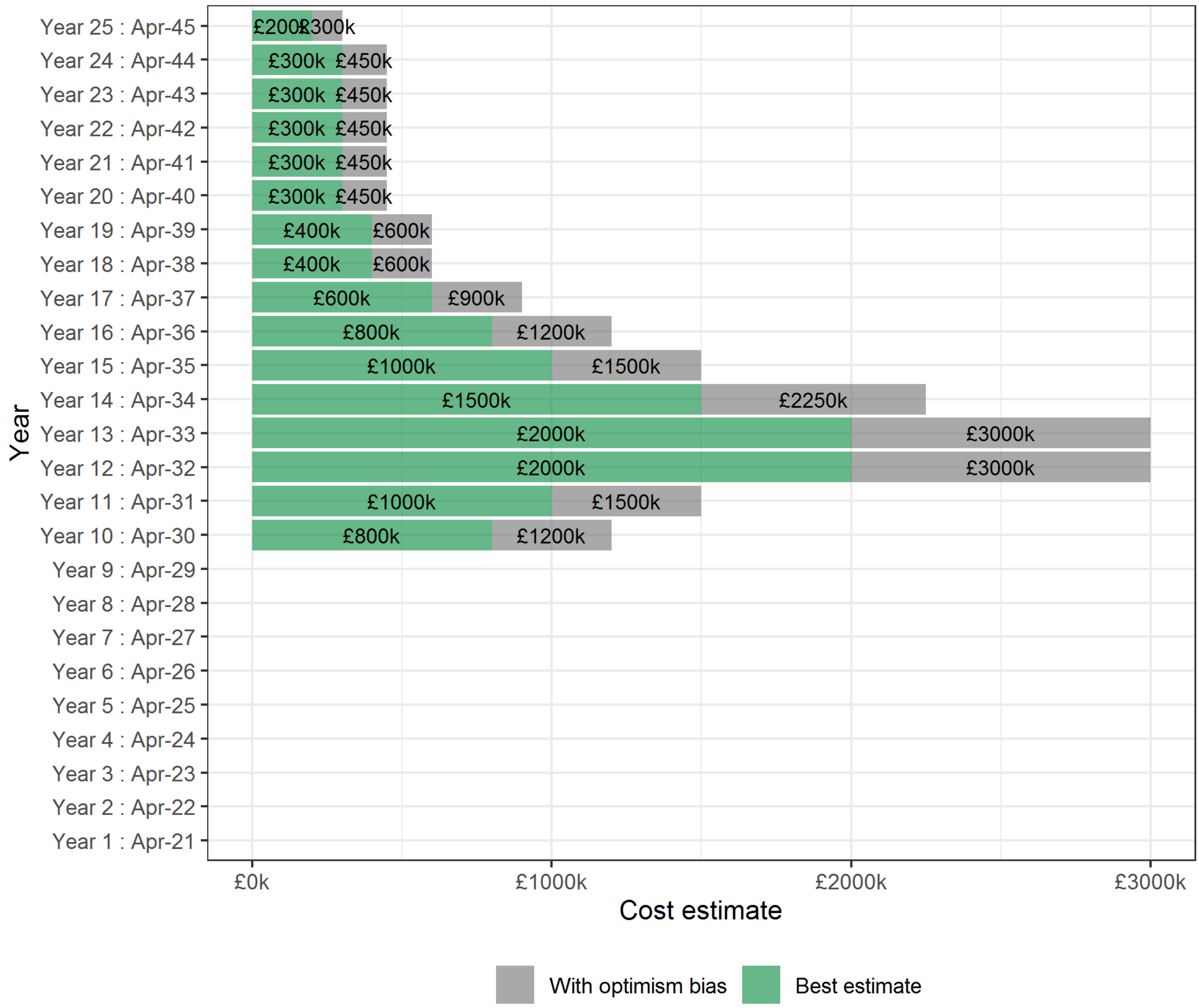
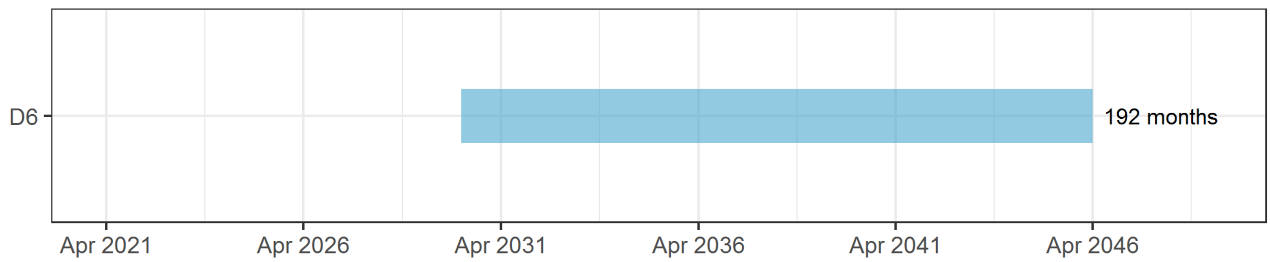
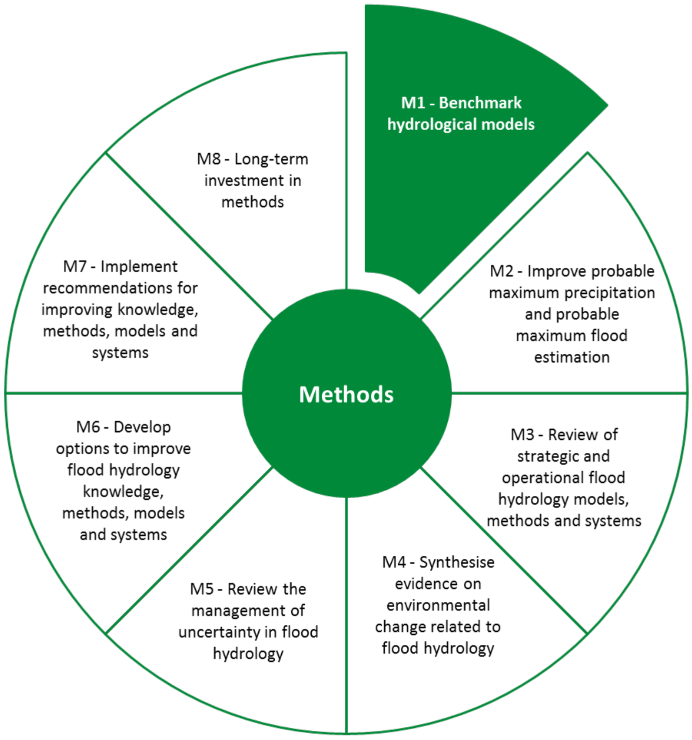


Figure G-40 – Estimated duration of action D6



Action M1: Benchmark hydrological models



Objective

Develop benchmarking tests and data sets to test and compare the performance of hydrological models for operational use.

Outline scope

This action aims to develop benchmarking tests and data sets (in a few densely monitored laboratory catchments) to test and compare the performance of hydrological models for operational use.

This action is likely to include:

1. defining metrics that will be used for benchmarking
2. identifying hydrological models and methods to be benchmarked (to include models used for real-time and non-real-time applications)
3. identifying a selection of hydrologically diverse catchments to be used as ‘labs’
4. developing and trailing tests and data sets (to cover all sources of flooding)
5. establishing a transparent and repeatable method for benchmarking
6. ensuring appropriate benchmarks for different/integrated sources of flooding
7. establishing a clear process for benchmarking new models (after the initial project), which states how the comparison to existing models that have already been benchmarked should be carried out

8. producing a report and/or peer-reviewed paper on the methods developed

Intended outputs

1. Data, tests and a process to benchmark the performance of existing and future hydrological models.
2. Report on the development and findings of the benchmarking tests.
3. Peer-reviewed journal paper on the development and findings of the benchmarking tests.

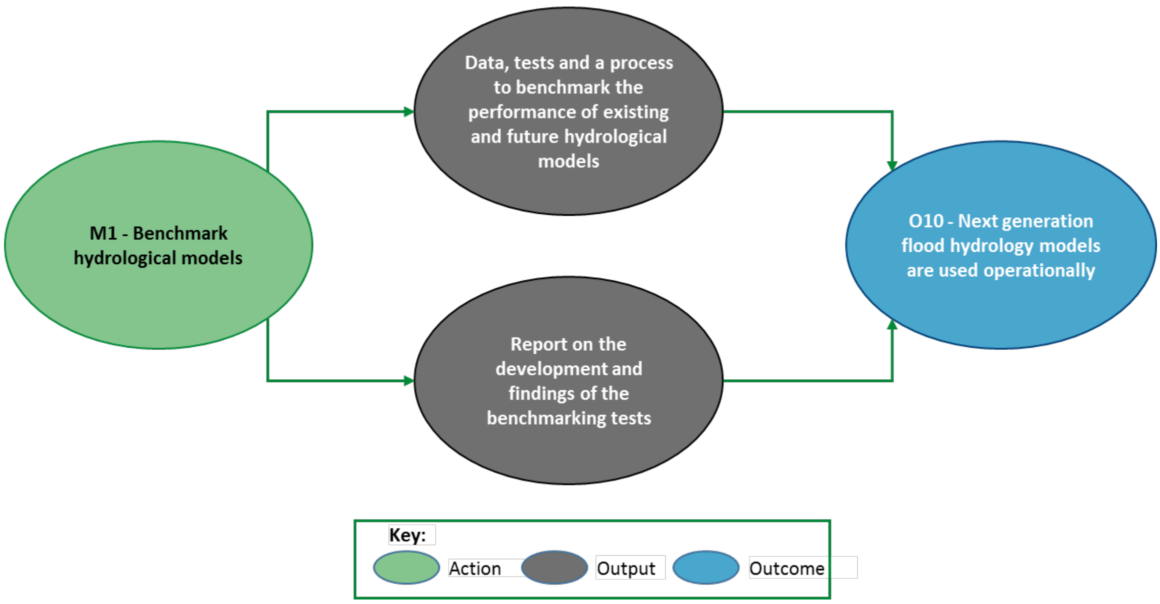
Intended outcomes

This action contributes to one outcome:

- outcome 10 - next generation flood hydrology models are used operationally

The outcome map for this action is shown in Figure G-41.

Figure G-41 – Outcome map for action M1



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-42. It is anticipated that this action will require between £400,000 and £600,000 of funding over a 5-year period (Figure G-43).

Figure G-42 – Estimated spend profile for action M1

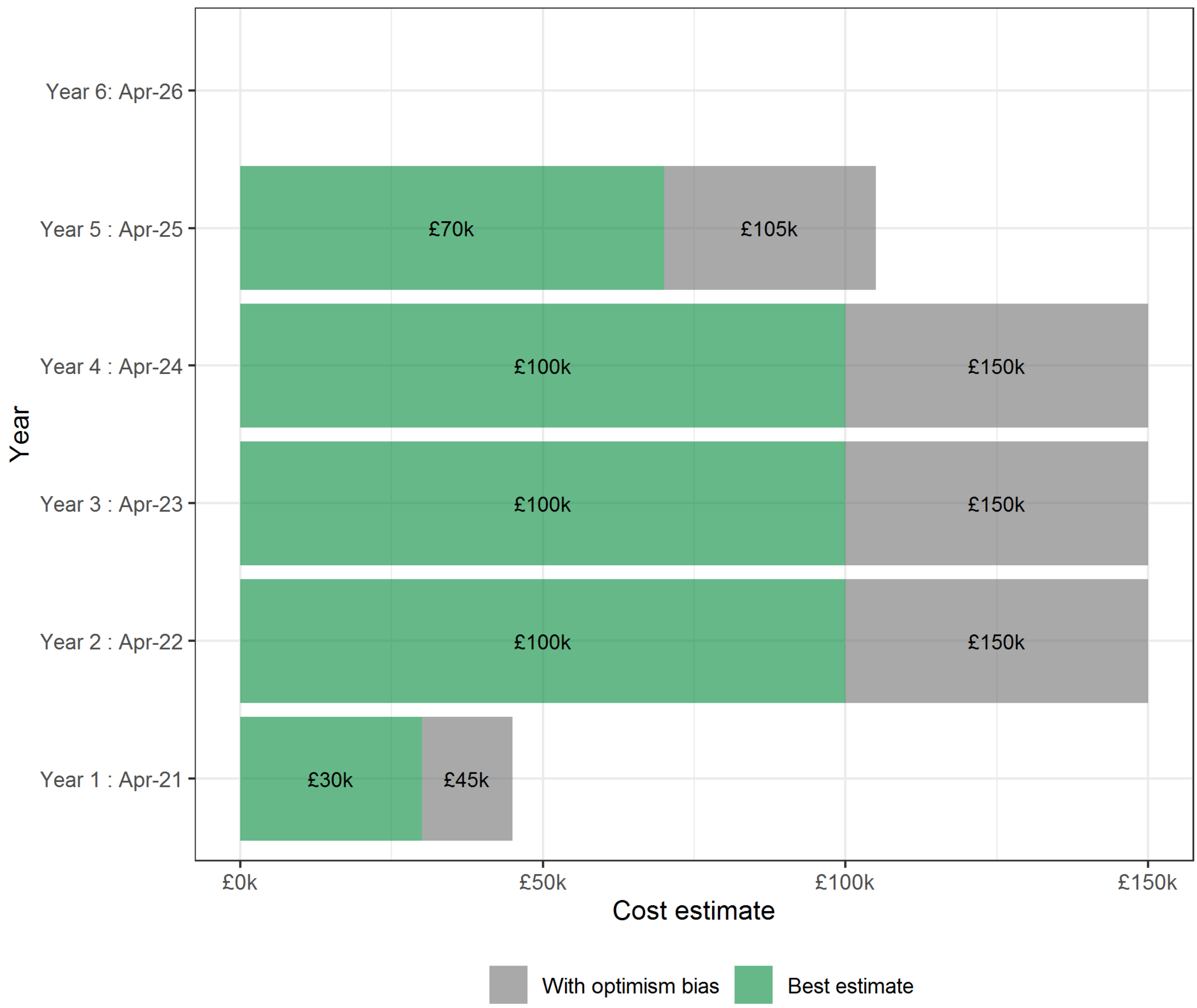
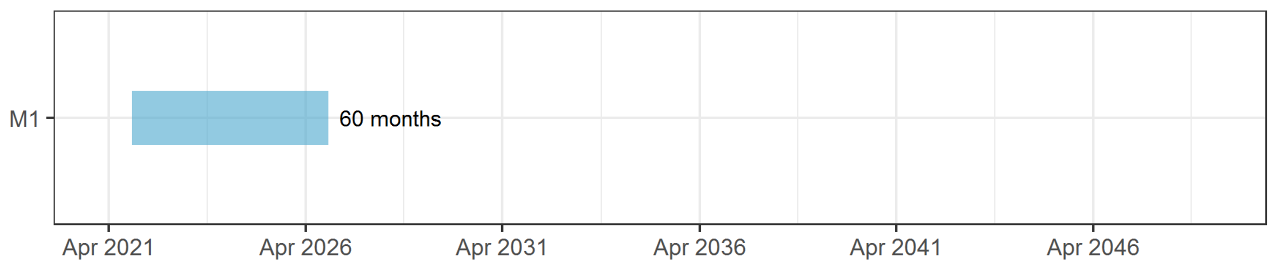
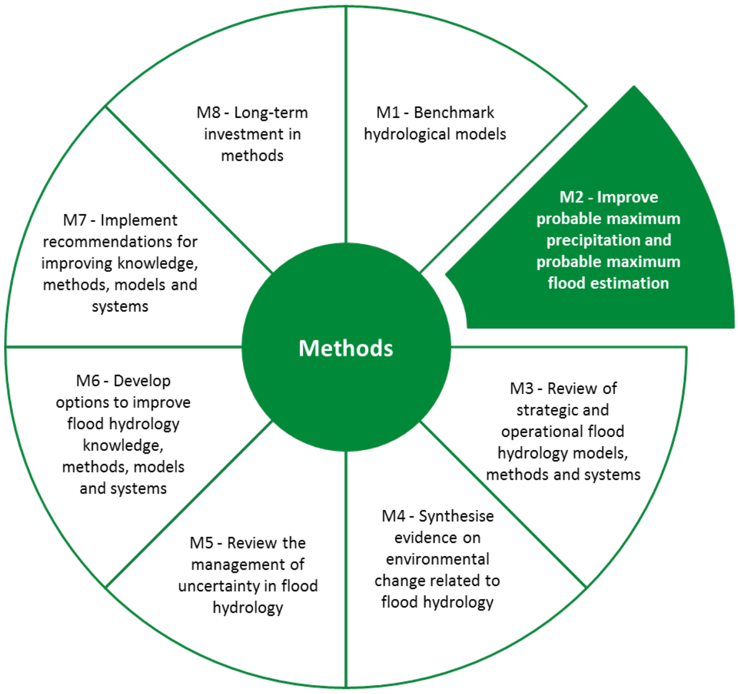


Figure G-43 – Estimated duration of action M1



Action M2: Improve probable maximum precipitation and probable maximum flood estimation



Objective

Develop new methods and guidance for the derivation of reservoir flood inflow for extreme events up to and including the probable maximum flood (PMF).

Outline scope

This action is being taken forward by an Environment Agency R&D project called, ‘Improving probable maximum precipitation (PMP) and probable maximum flood (PMF) estimation for reservoir safety’ (FRS19222). Its primary purpose is to improve reservoir spillway flood hydrology in the UK.

The first phase of this project is underway (Nov 2020 to Nov 2021) and will:

1. create and populate a catalogue of extreme historical rainfall and flood events
2. review methods for estimating PMP and PMF to identify current state-of-the-art methods and help develop options for improving PMP and PMF estimation in the UK
3. develop and present options for improving estimation of PMP and PMF in UK catchments
4. provide a science report with recommendations for phase 2 of the project

The second phase is likely to:

5. develop new/updated methods for estimating PMP and PMF in the UK
6. provide tools and methods that are freely available to all potential users
7. take account of past and future non-stationarity
8. take account of climate change projections for extreme rainfall
9. embed the results in new practitioner guidance
10. produce a science report of the development of the new methods
11. produce a peer-reviewed journal paper on development of the new methods

Intended outputs

1. New freely available methods and guidance for the estimation of PMP and PMF.
2. Science report on the development of the new methods for PMP and PMF estimation.
3. Peer-reviewed journal paper on the development of the new methods for PMP and PMF estimation.

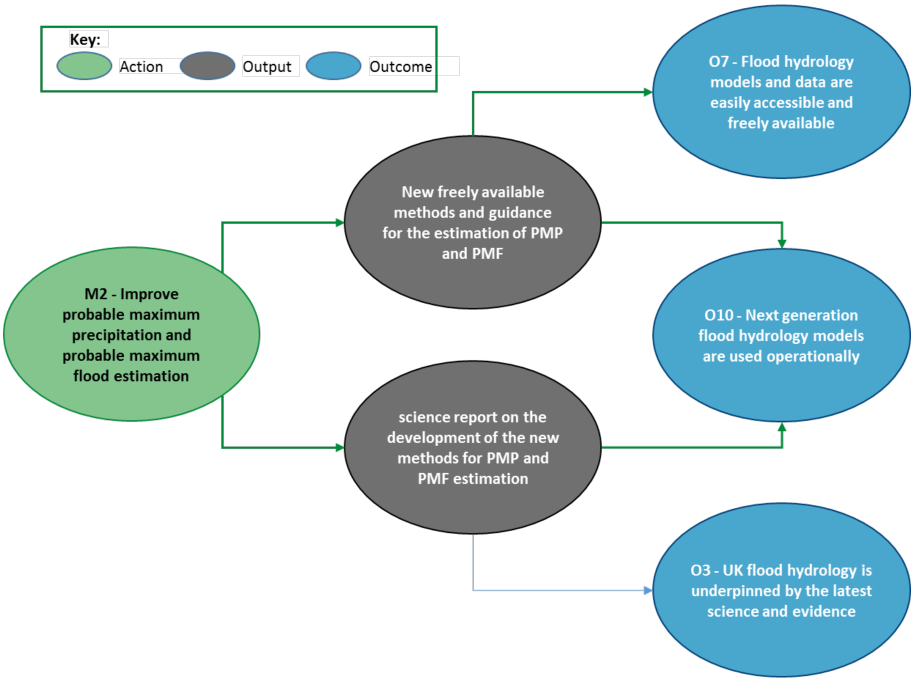
Intended outcomes

This action contributes to 3 outcomes:

- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence
- outcome 7 - flood hydrology models and data are easily accessible and freely available
- outcome 10 - next generation flood hydrology models are used operationally

The outcome map for this action is shown in Figure G-44.

Figure G-44 – Outcome map for action M2



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-45. It's likely that this action will require between £450,000 and £680,000 of funding over 4 years (Figure G-46). At the time of writing, the Environment Agency already has approval to spend £150,000 in 2021/22 (with a £7,000 contribution from the Department for Infrastructure, Northern Ireland) to carry out the first phase of a 2-phase project (FRS19222). Funding for subsequent years still requires approval.

Figure G-45 – Estimated spend profile for action M2

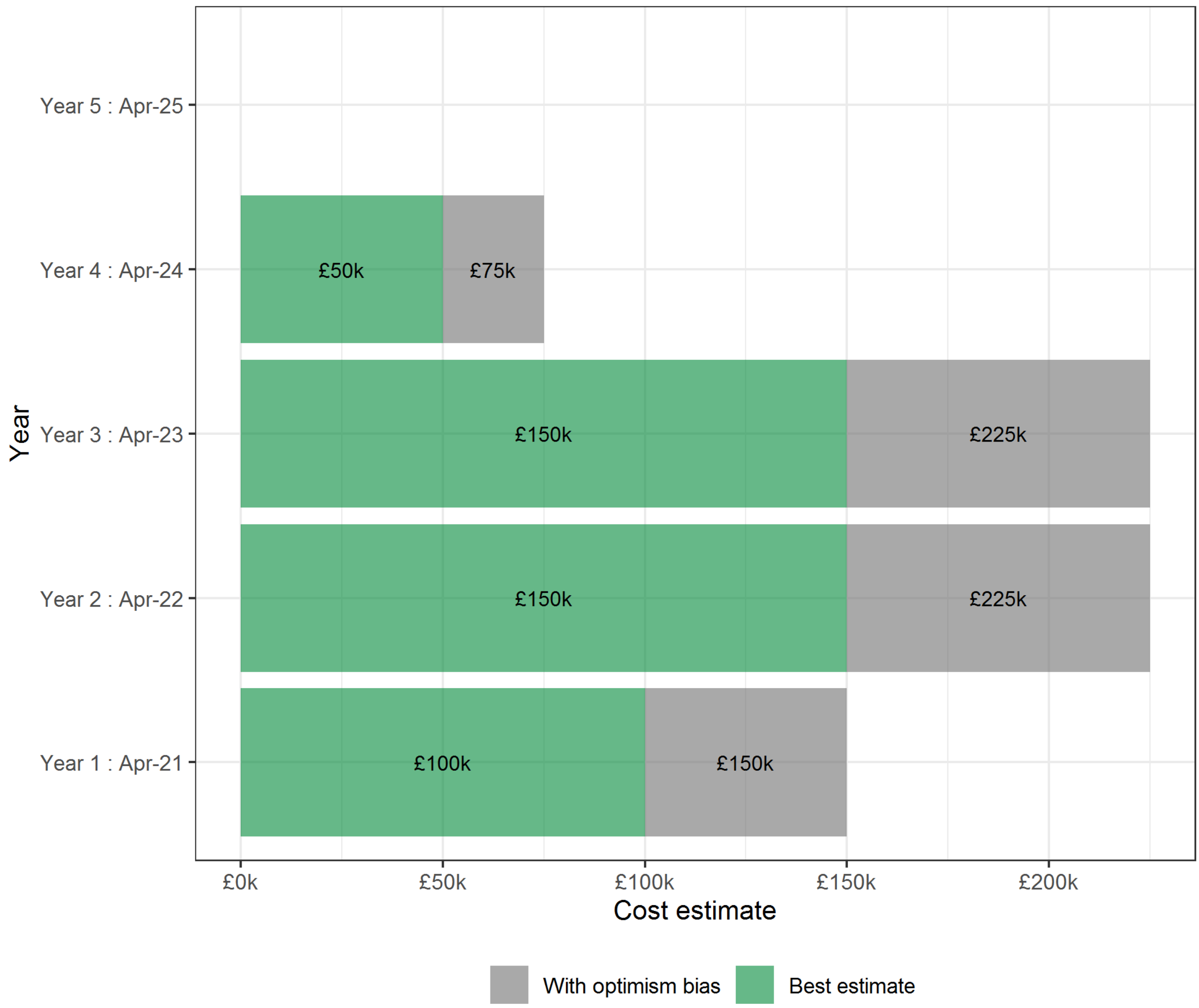
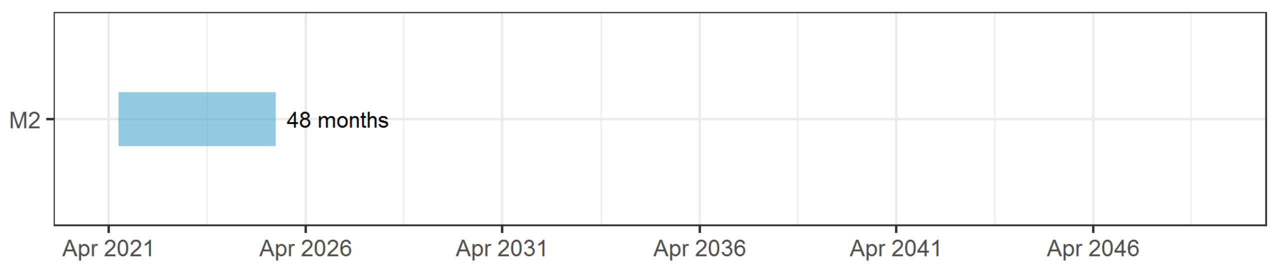
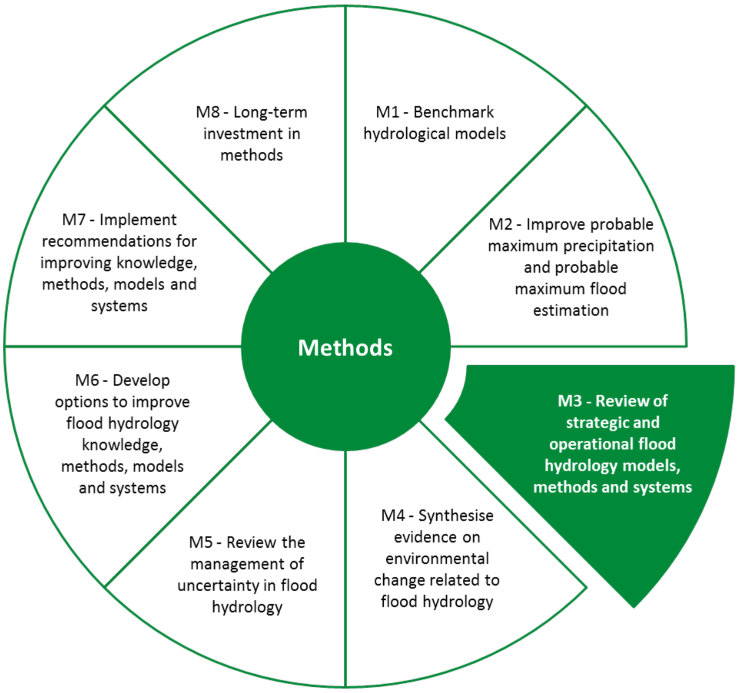


Figure G-46 – Estimated duration of action M2



Action M3: Review of strategic and operational flood hydrology models, methods and systems



Objective

Review strategic and operational flood hydrology models, methods (process based, statistical and machine learning) and systems and make recommendations for improvement.

Outline scope

This review will consider all models, methods (process based, statistical and machine learning) and systems used in strategic and operational applications of flood hydrology covering both flood estimation and flood forecasting. It will consider the current state-of-the-art and define what is possible during the early part of the roadmap (around 6 years) and what may be possible over the 25 year life of the roadmap.

The review would aim to:

1. identify models, methods, data and systems relevant to flood hydrology
2. understand who benefits from and values flood hydrology models and data, including the research community
3. understand the needs of end users
4. investigate technology and software solutions to meet end user needs
5. rapidly iterate outline plans for software and IT infrastructure solutions

6. consider how community accessibility to software could be improved (with the aspiration for open and free access)
7. identify where improvements to models, methods and systems would enable better uptake of (existing) scientific advances
8. identify where new fundamental science is required to develop future models, methods and systems (feeding into action S6)
9. identify opportunities to reduce uncertainty is small catchments, urban catchments and permeable catchments
10. produce a report with options and recommendations for improving flood hydrology models, method and systems

Elements to be included in the review are:

11. new approaches to provide modular, open access methods, models and systems for flood estimation
12. new approaches for the detection and attribution of hydrological variability in flow peak magnitude, frequency, seasonality, duration/persistence, volume and spatial extent, rainfall, sub-surface flows and other environmental variables related to flooding over a range of timescales (from millennia to interannual) and spatial scales, including historical and palaeoflood data
13. support for seamless approaches for modelling past and future climate change impacts, taking account of both statistical hydrology approaches and physically-based climate or land use change modelling
14. translating model results into guidance and data that can be used for estimating future river flow and rainfall scenarios to improve FRM decisions, and to assess the robustness of existing analyses that have been based on stationarity assumptions
15. support for more flexible approaches to joint probabilities from all sources of flooding at multiple scales (as spatially and temporally coherent events) and other complex cases such as joint analysis of volumes and peak flows, long durations and sequences of events (to include estuaries and coasts where appropriate)
16. improved support for methods and models that look beyond the use of annual maximum data in statistical flood hydrology
17. improving understanding of the role of flood volumes in assessment of risk
18. improving understanding of long duration rainfall methods
19. assessing the role of data-driven methods based on machine learning and artificial intelligence to augment or improve on hydrological methods and models
20. assessing the scope for improvements to data assimilation methods applied in flood forecasting
21. updating uncertainty analysis in long-term risk models
22. assessing the potential of more integrated hydro-meteorological modelling
23. methods and systems that would enable flood hydrology and geomorphological methods and models to be linked
24. proposals to ensure that all guidance on operational models, methods and systems is open, accessible, readily discoverable and up to date with the latest developments in science (for example, to reduce the fragmented nature of current UK flood estimation guidance for practitioners)

Intended outputs

1. Detailed report reviewing the current state of flood hydrology models, methods and systems, with recommendations on how to improve based on user needs and the best scientific evidence.
2. Open-source software/systems demonstrators and prototype designs.

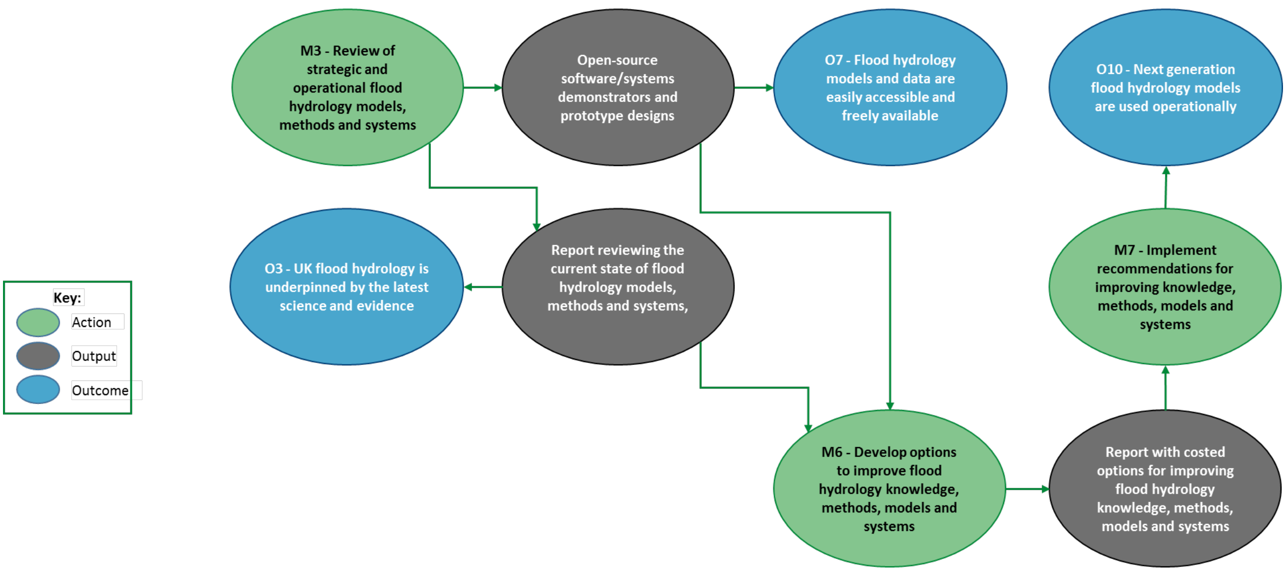
Intended outcomes

This action contributes to 3 outcomes:

- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence
- outcome 7 - flood hydrology models and data are easily accessible and freely available
- outcome 10 - next generation flood hydrology models are used operationally

The outcome map for this action is shown in Figure G-47.

Figure G-47 – Outcome map for action M3



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-48. It is anticipated that this action will require between £550,000 to £825,000 of funding over a 3-year period (Figure G-49).

Figure G-48 – Estimated spend profile for action M3

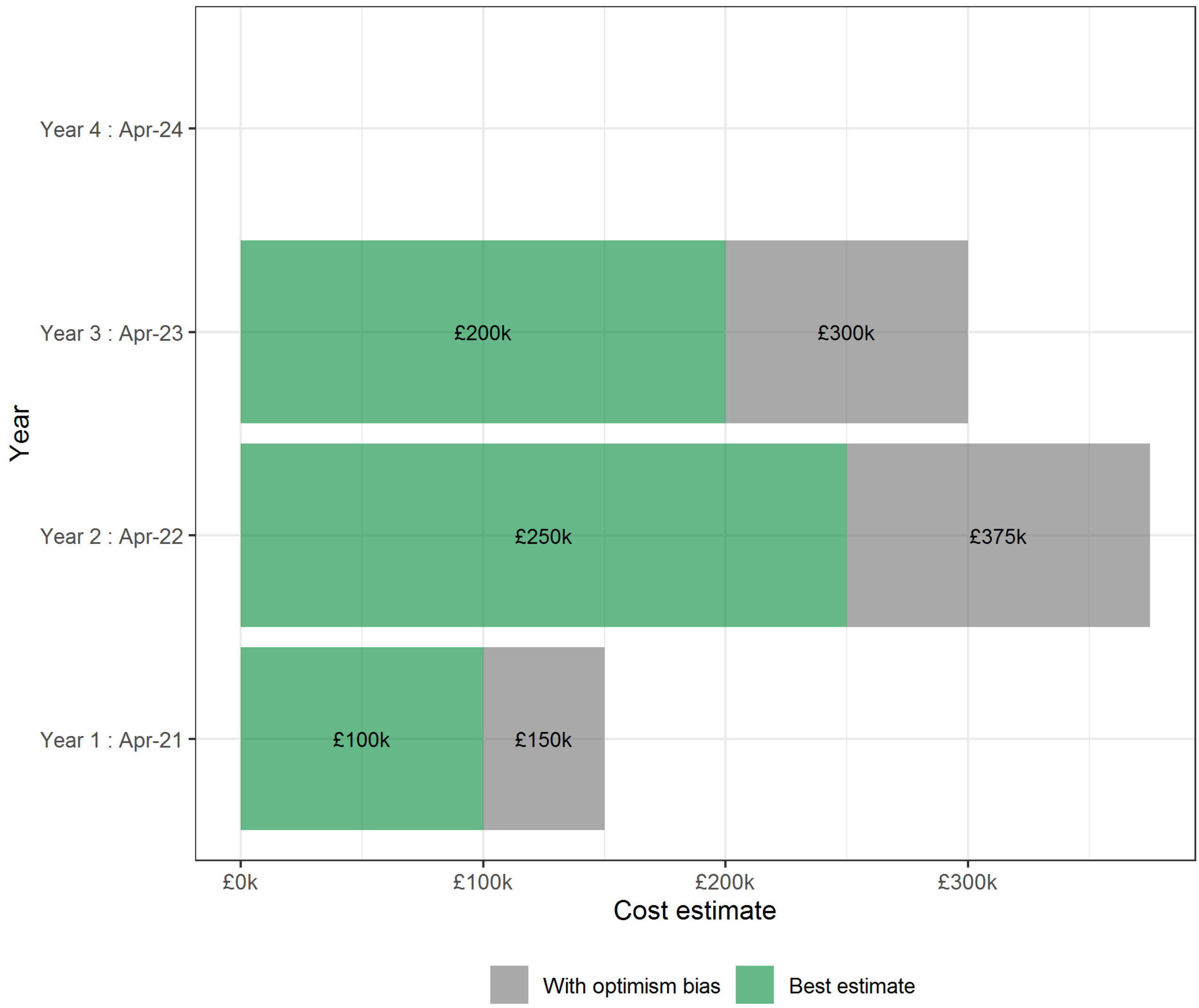
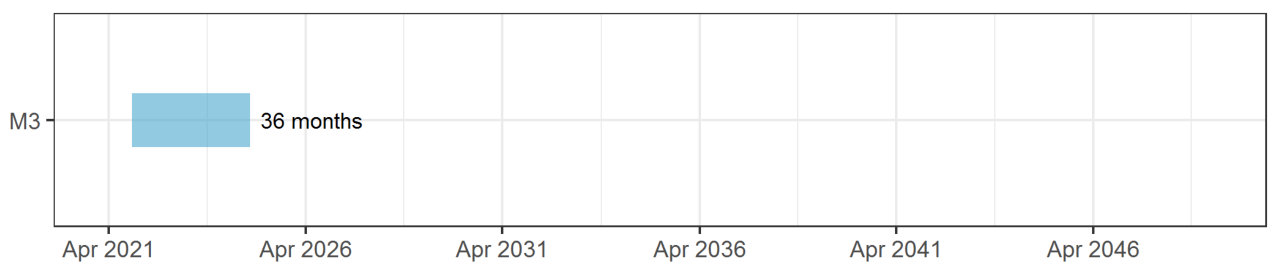
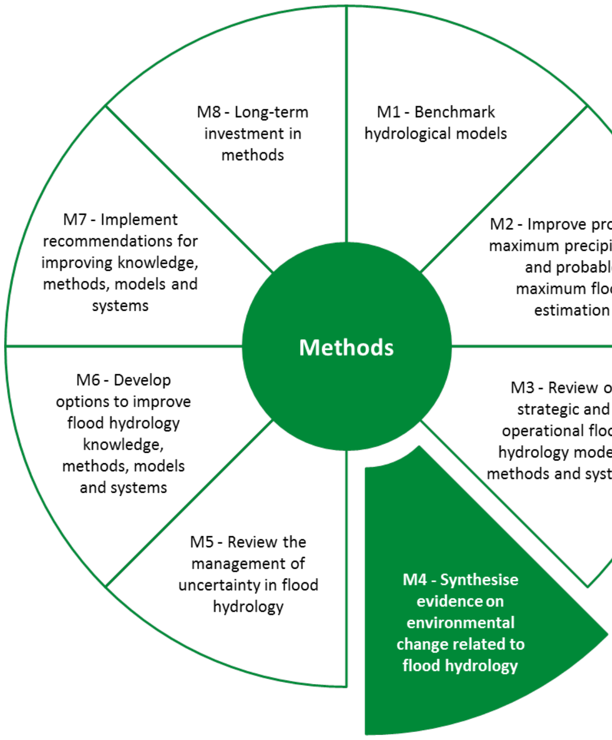


Figure G-49 – Estimated duration of action M3



Action M4: Synthesise evidence on environmental change related to flood hydrology



Objective

Synthesise existing evidence and knowledge on environmental change related to flood hydrology, and identify knowledge gaps in operational practice and scientific knowledge.

Outline scope

This action will provide a synthesis of existing evidence and knowledge on environmental change[14] related to flood hydrology, and aims to identify knowledge gaps in operational practice and scientific knowledge.

The synthesis could take the form of a systematic review or rapid evidence assessment[15].

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[14] Environmental change from climatic variability, catchment land use, management and river engineering over decadal to multi-centennial timescales.

[15] [Guide to the production of quick scoping reviews and rapid evidence assessments]

The primary question of the review could be:

1. what knowledge and methods relating to environmental change are required to achieve the strategic ambitions of the flood hydrology roadmap?

Secondary questions for the review could be:

2. what environmental changes can have an impact on flood hydrology?
3. how has environmental change impacted flood hydrology over the last millennia?
4. what can past environmental change tell us about future flood hydrology?
5. how might future environment change impact on flood hydrology?
6. how might environmental change influence how we do flood hydrology?

The review should consider past, present and future environmental change and the implications of each for flood hydrology practice and fundamental research. It should be complemented with additional work to identify a series of options and recommendations to:

7. address knowledge gaps and answer important questions raised in the systematic review
8. improve operational practice relating to past, present and future environmental change
9. identify opportunities to translate existing science into practice
10. identify future research needs, ranging from fundamental research to near-operational research

Intended outputs

1. Review of evidence on environmental change related to flood hydrology.
2. Peer-reviewed journal paper on the main findings of the systematic review.

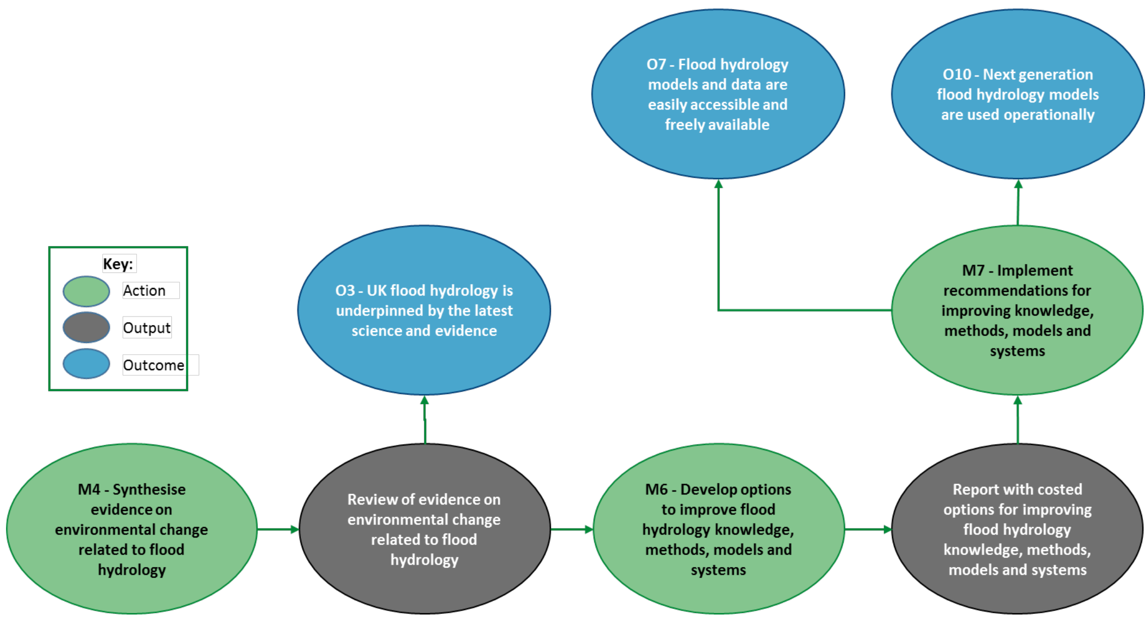
Intended outcomes

This action contributes to 3 outcomes:

- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence
- outcome 7 - flood hydrology models and data are easily accessible and freely available
- outcome 10 - next generation flood hydrology models are used operationally

The outcome map for this action is shown in Figure G-50.

Figure G-50 – Outcome map for action M4



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-51. It is likely that this action will require between £400,000 and £600,000 of funding over a 3-year period (Figure G-52.)

Figure G-51 – Estimated spend profile for action M4

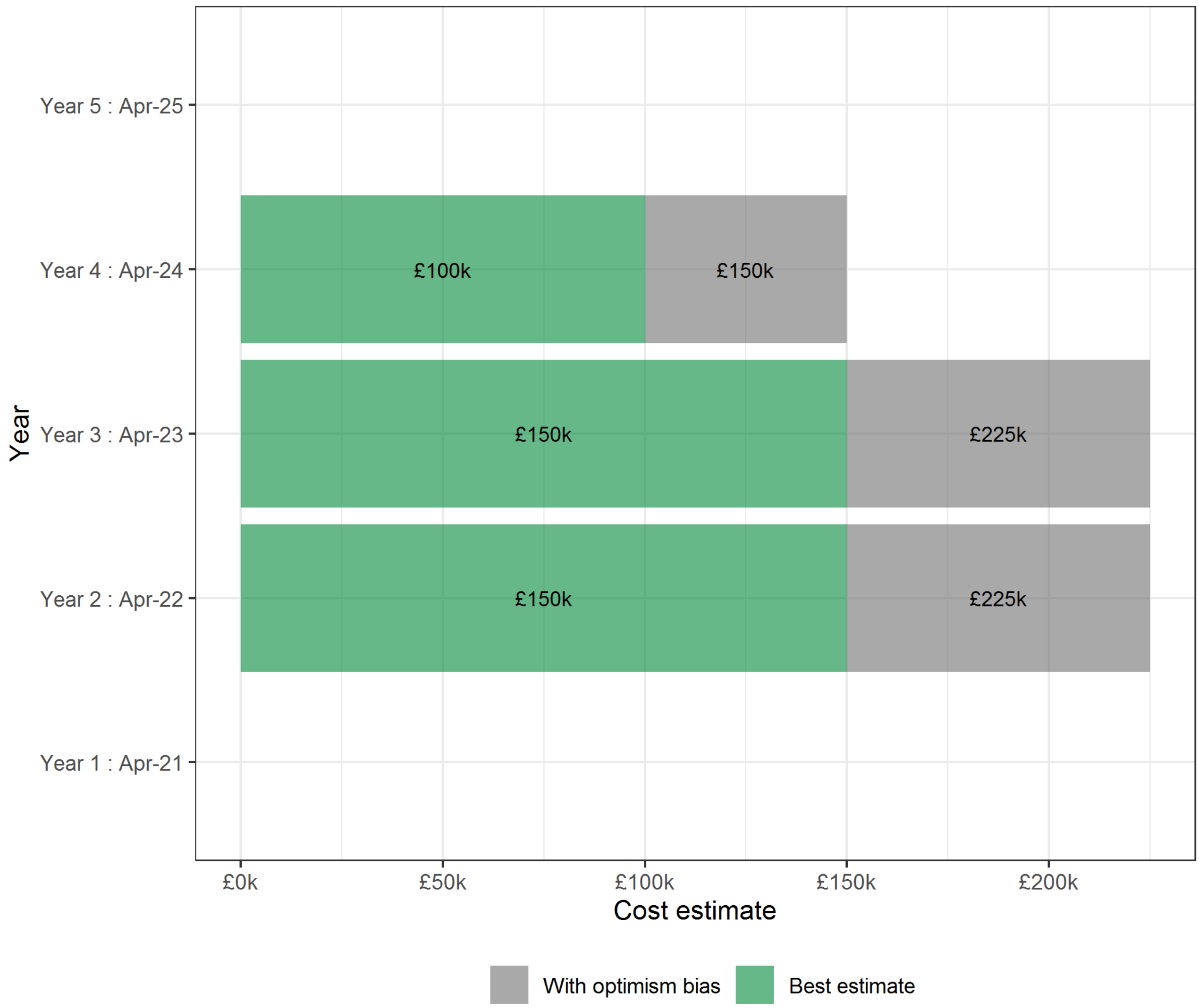
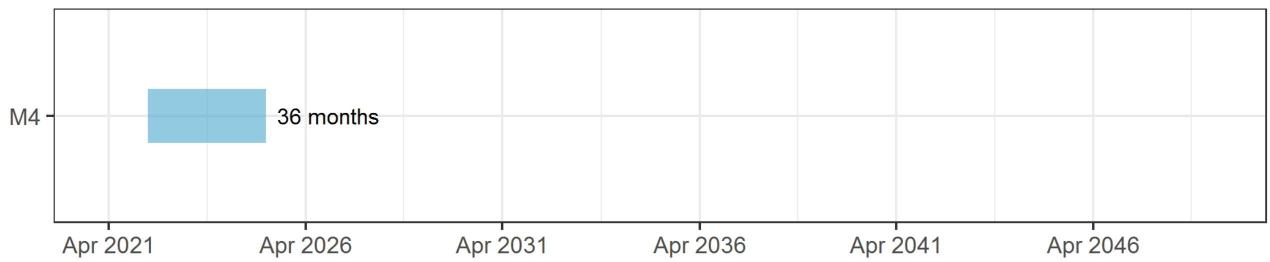
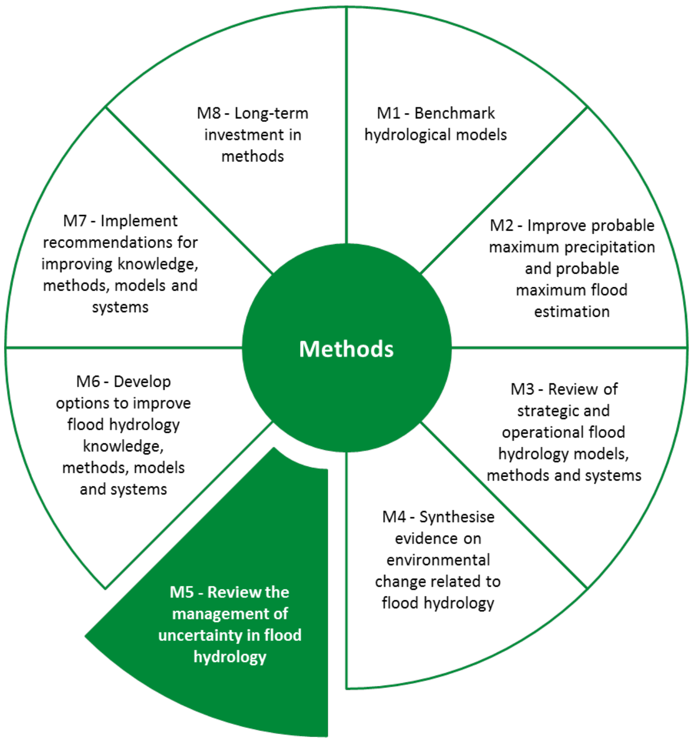


Figure G-52 – Estimated duration of action M4



Action M5: Review the management of uncertainty in flood hydrology



Objective

Review the management of uncertainty in flood hydrology and make recommendations for improvement.

Outline scope

This action would carry out a review of the rationale and motivation for the management of uncertainty in flood hydrology, clarifying the associated value (economic or otherwise) within FCERM. It would cover both real-time and non-real-time application and would aim to establish clear answers to the questions:

1. Why is uncertainty management important?
2. Who is uncertainty management important for?
3. How do organisations use information about uncertainty?
4. What are the sources of uncertainty in flood hydrology?
5. Which types of uncertainty are important?
6. How can the uncertainty in future projections be included?
7. Can we use probabilistic approaches to help us quantify uncertainty?
8. What are the costs and benefits of more explicit consideration of uncertainty in decision-making?

9. Under what circumstances would it be beneficial to spend more effort to move beyond a baseline approach of using judgement and tolerating the resulting residual risk?
10. How would updated guidance on uncertainty management improve decision-making/practice across different areas of hydrology?
11. How should we communicate uncertainty in flood hydrology?
12. When should we use automated analysis of uncertainty versus human interpretation?

This review could consider the value of analysing uncertainty in the flood modelling chain. This could help answer questions like:

13. What are the greatest sources of uncertainty in modelling for flood risk management?
14. What is the relative importance of different assumptions/data sets that contribute to uncertainty?
15. How much is the assumption of data stationarity important compared to other assumptions involved in the estimation of design floods?

This action could also aim to define the scope of new guidance for the management of uncertainty in flood hydrology:

1. What kind of guidance is needed for operational decision-making?
2. What is scientifically valid?
3. What is practical for different applications in flood hydrology?
4. How would new observations help to constrain uncertainties in hydrological knowledge and predictions?

This action would review state-of-the-art in scientific research and in practice and aim to learn from the implementation of previous guidance such as the Environment Agency project SC120014 ‘Accounting for residual uncertainty: an update to the fluvial freeboard guide’ (2017).

A report would be produced which included options and recommendations on managing uncertainty for further development and implementation via actions M6 and M7.

Intended outputs

1. Report reviewing the management of uncertainty in flood hydrology, with options and recommendations for improvement, to include case studies and examples.

Intended outcomes

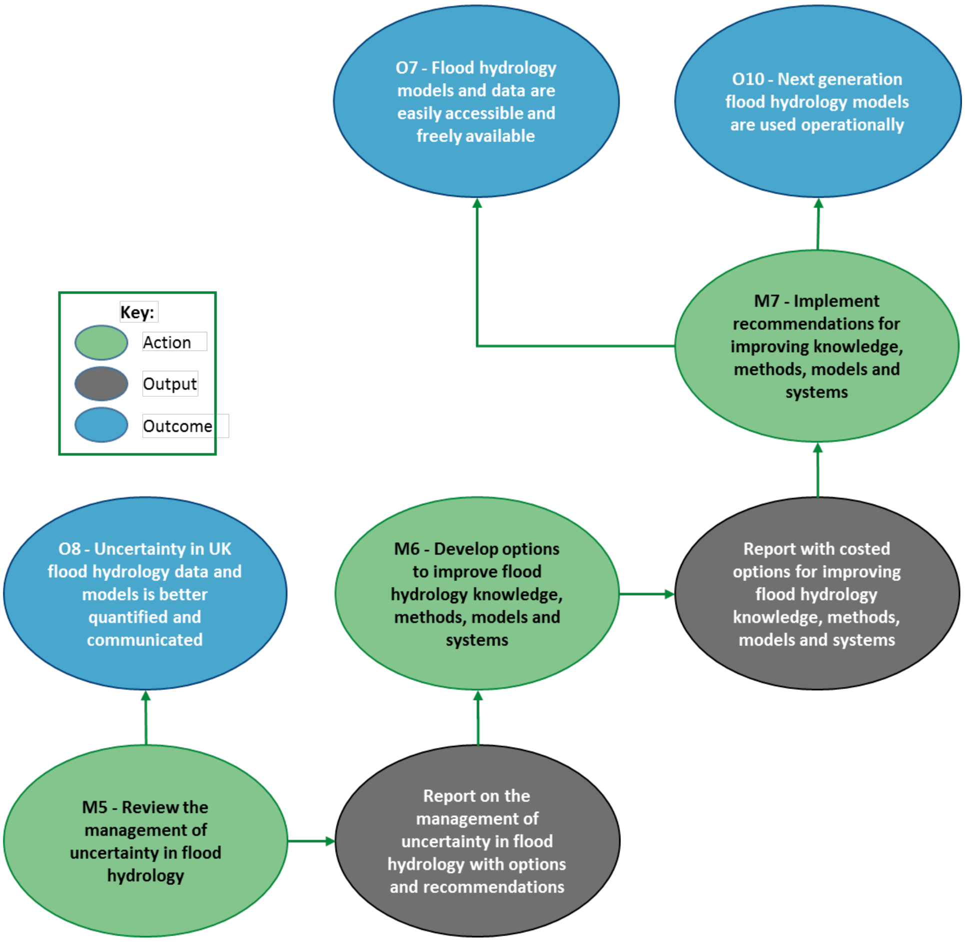
This action contributes to 3 outcomes:

- outcome 7 - flood hydrology models and data are easily accessible and freely available

- outcome 8 - uncertainty in UK flood hydrology data and models is better quantified and communicated
- outcome 10 - next generation flood hydrology models are used operationally

The outcome map for this action is shown in Figure G-53.

Figure G-53 – Outcome map for action M5



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-54. It is anticipated that this action will require between £600,000 and £900,000 of funding over a 4-year period (Figure G-55).

Figure G-54 – Estimated spend profile for action M5

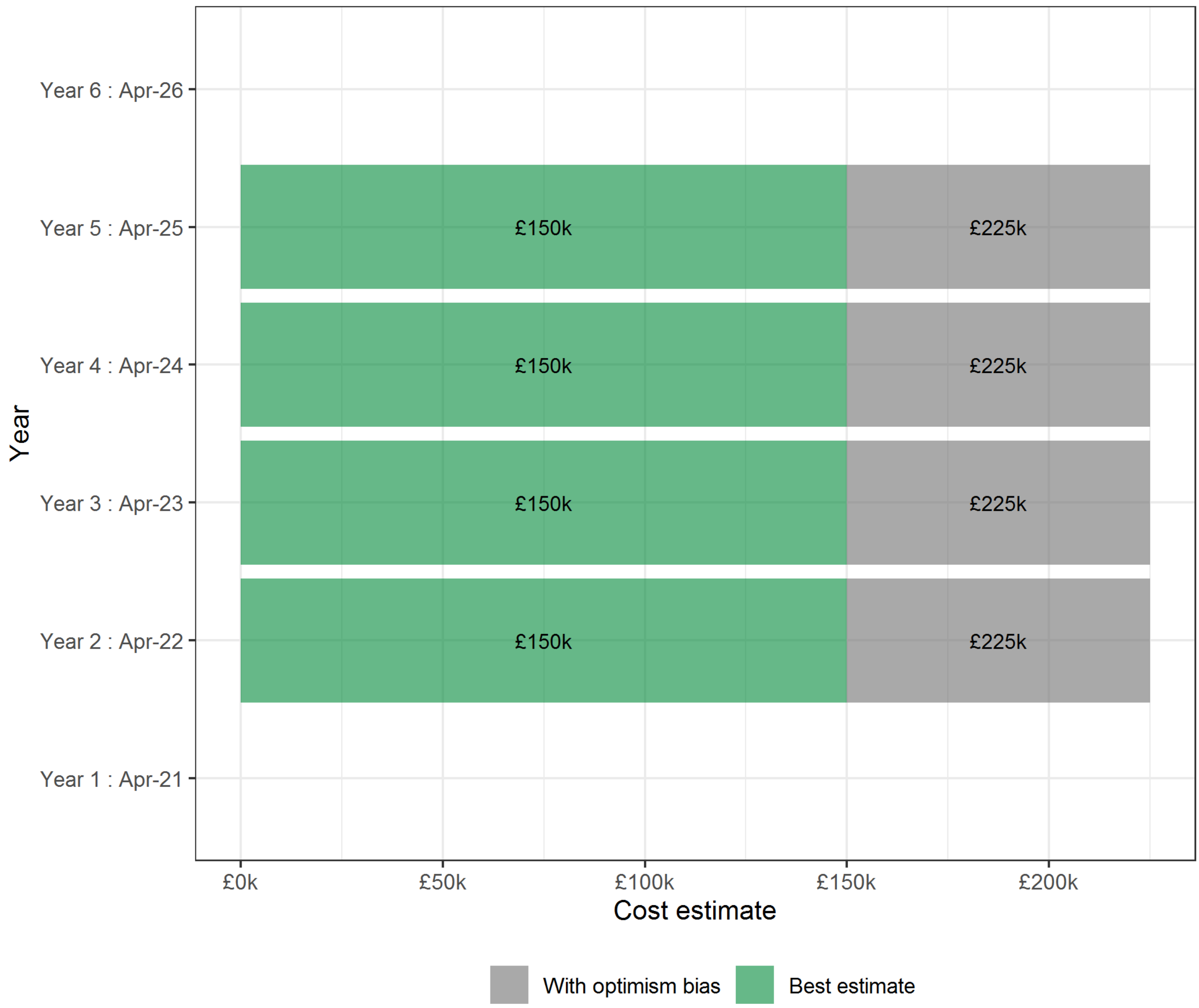
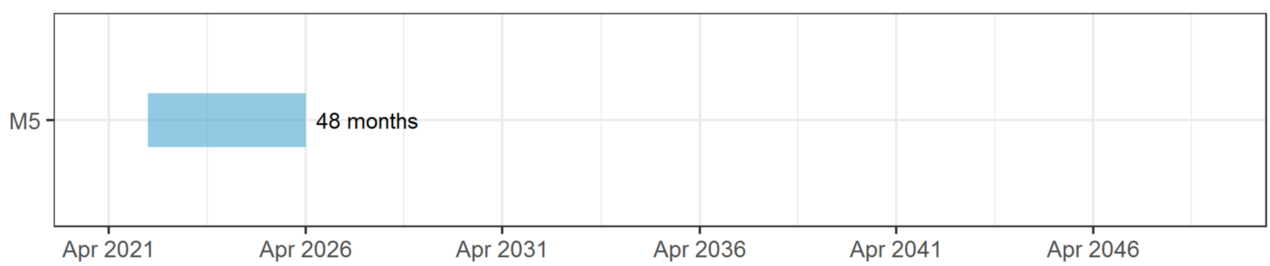
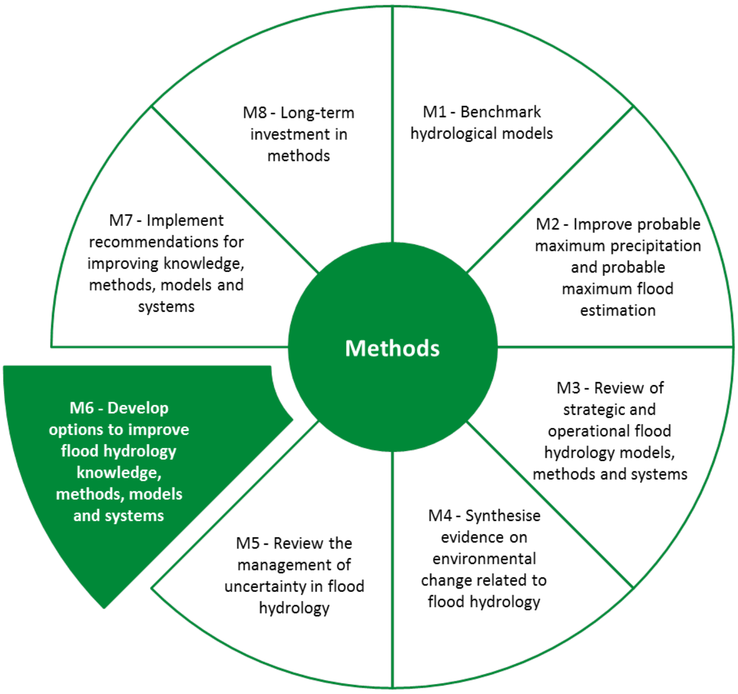


Figure G-55 – Estimated duration of action M5



Action M6: Develop options to improve flood hydrology knowledge, methods, models and systems



Objective

Develop integrated options to improve knowledge, methods, models and systems in UK flood hydrology.

Outline scope

This action will aim to build on and integrate options and recommendations identified in actions M3, M4 and M5. It will:

1. set out clear (costed) plans to improve flood hydrology knowledge, methods, models and systems for flood estimation and flood forecasting over the next decade
2. include costed options for maintaining any new methods, models and systems beyond initial development to enable continuous improvement through implementing new scientific advances
3. produce a report with detailed project scopes and business cases for the preferred options to improve flood hydrology knowledge, methods models and systems

Methodological, modelling and system options for improvement could include:

4. new open source, freely accessible modular approaches to flood estimation
5. seamless modelling of the past and future

6. quantification and communication of hydrological variability over multiple space and time scales
7. further development of methods and models to detect and attribute non-stationarity in hydrological variables
8. complementary application of physics-based and statistical approaches
9. methods to assess the real-world hydrological effectiveness of natural flood management

Options to improve knowledge in flood hydrology could include:

10. improving the accessibility of practitioner guidance
11. new guidance for the management of uncertainty in flood hydrology
12. attribution studies to examine the causative role of potential drivers of change on flood risk
13. improved assessment of changing risk of prolonged rainfall extremes
14. further development of future river flow and rainfall scenarios to improve flood risk management planning and strategy decisions

Intended outputs

1. Report with costed options for improving flood hydrology knowledge, methods, models and systems for flood estimation and flood forecasting over the next decade.

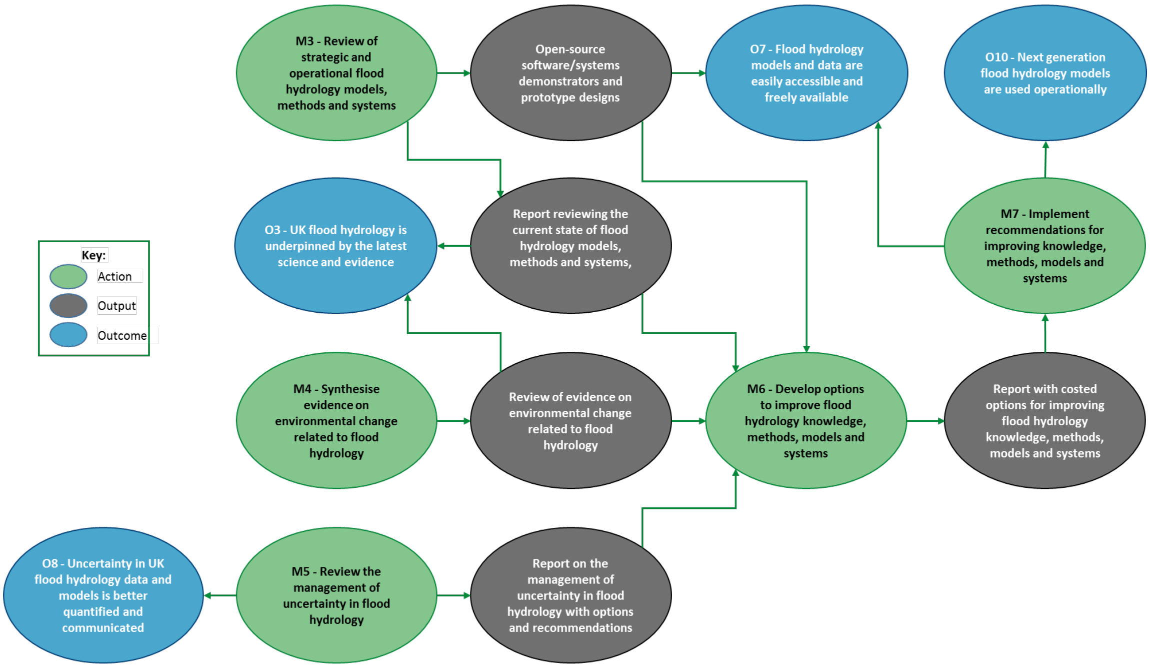
Intended outcomes

This action contributes to 4 outcomes:

- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence
- outcome 7 - flood hydrology models and data are easily accessible and freely available
- outcome 8 - uncertainty in UK flood hydrology data and models is better quantified and communicated
- outcome 10 - next generation flood hydrology models are used operationally

The outcome map for this action is shown in Figure G-56.

Figure G-56 – Outcome map for action M6



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-57. The profile shows that between £950,000 and £1.43 million of funding will be required for this action over a 4-year period (Figure G-58).

Figure G-57 – Estimated spend profile for action M6

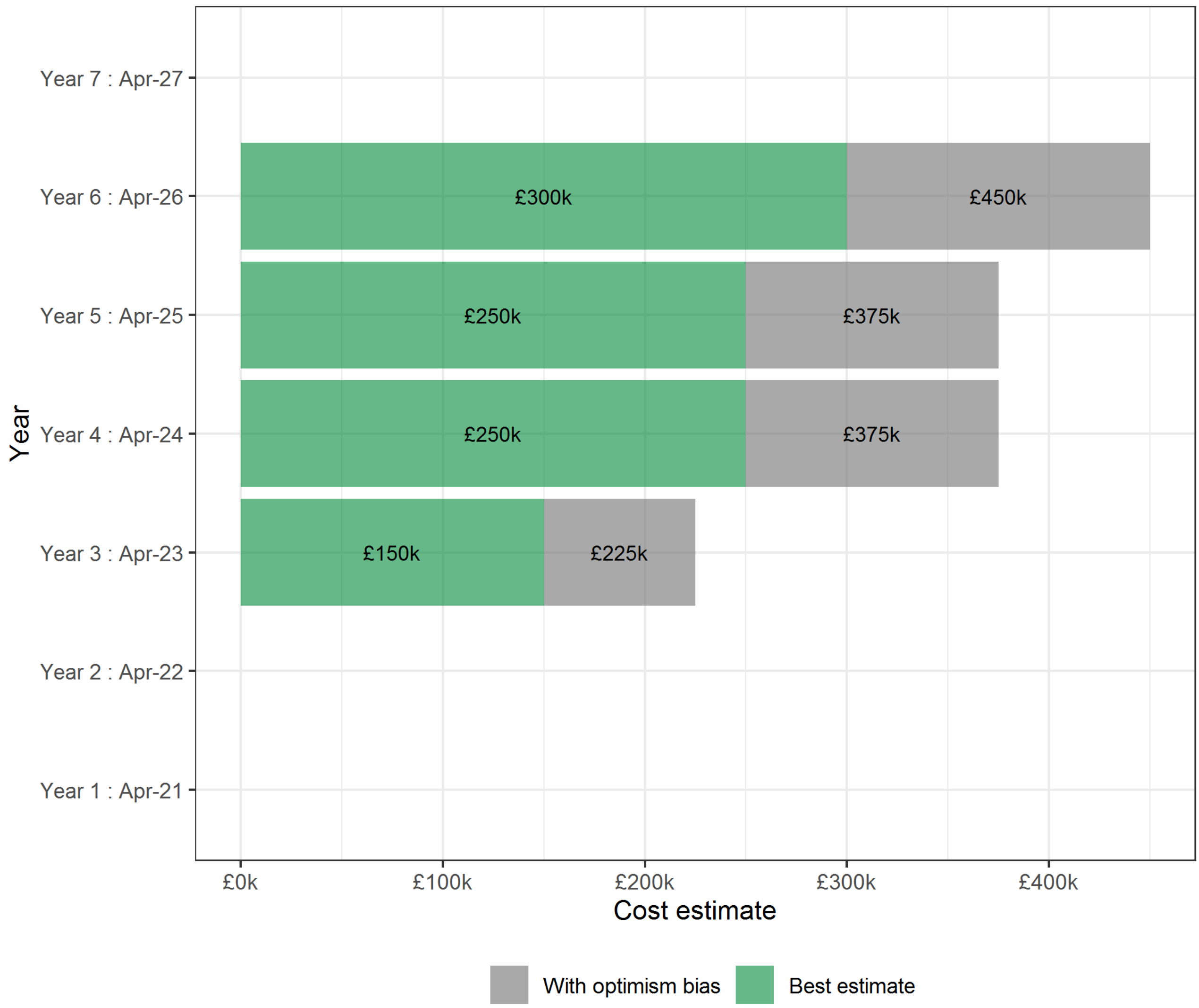
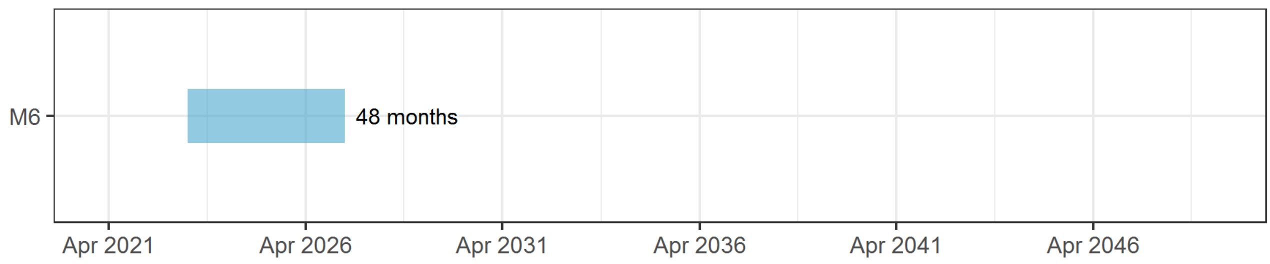
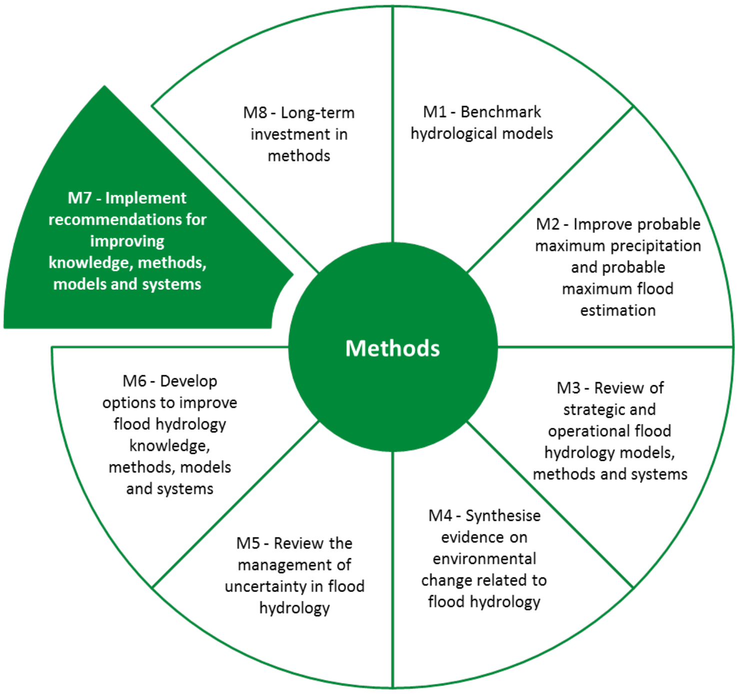


Figure G-58 – Estimated duration of action M6



Action M7: Implement recommendations for improving knowledge, methods, models and systems



Objective

Implement the preferred options and recommendations to improve flood hydrology knowledge, methods, models and systems.

Outline scope

This action will implement recommendations from action M6. It is likely that this action will include the implementation of new (next generation) methods, models and systems to underpin flood hydrology and flood risk management) for decades to come.

Intended outputs

1. Implementation of recommendations from action M6.

Intended outcomes

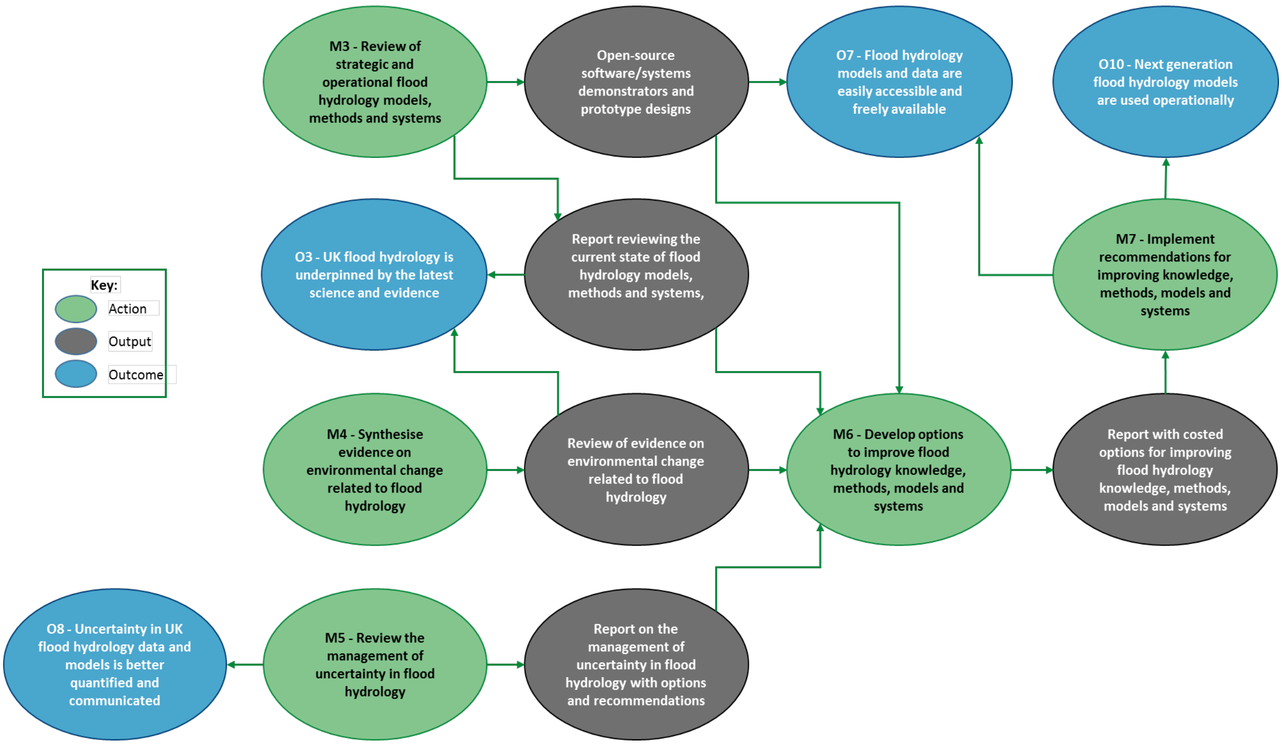
This action contributes to 4 outcomes:

- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence

- outcome 7 - flood hydrology models and data are easily accessible and freely available
- outcome 8 - uncertainty in UK flood hydrology data and models is better quantified and communicated
- outcome 10 - next generation flood hydrology models are used operationally

The outcome map for this action is shown in Figure G-59.

Figure G-59 – Outcome map for action M7



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-60. The costs of implementing this action are dependent on the findings and recommendations of several other roadmap actions on methods, so are uncertain. Best estimates suggest that between £25 million and £37.5 million may be required for the implementation of new (next generation) methods, models and systems to underpin UK flood hydrology. It is anticipated that funding would be required to start around year 7 of the roadmap (April 2027) and continue for 6 years (Figure G-61), peaking in year 10 (April 2030) between £7 million and £10.5 million. This cost estimate should be refined as the roadmap actions on methods progress and the scale of implementation become clearer.

Figure G-60 – Estimated spend profile for action M7

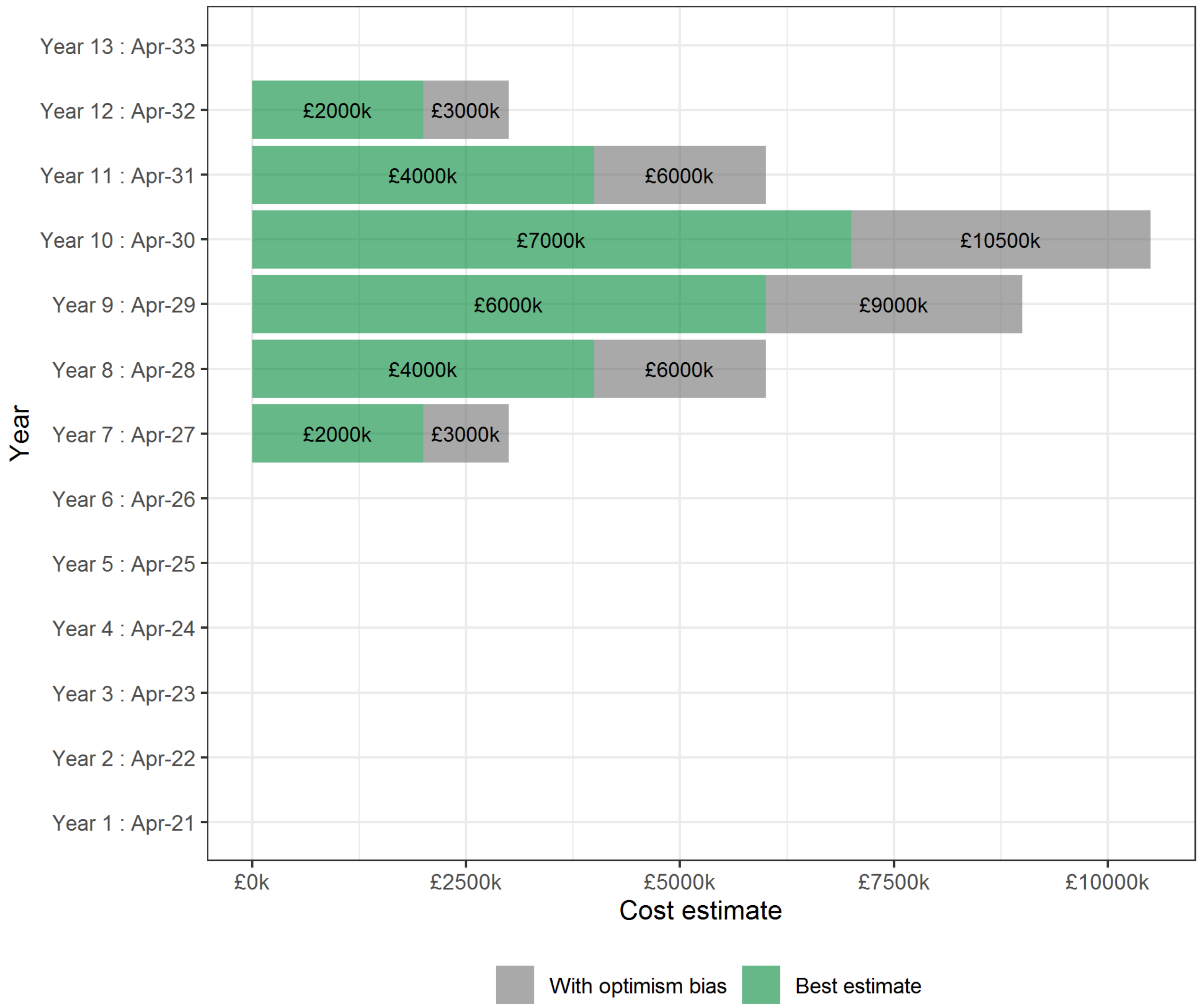
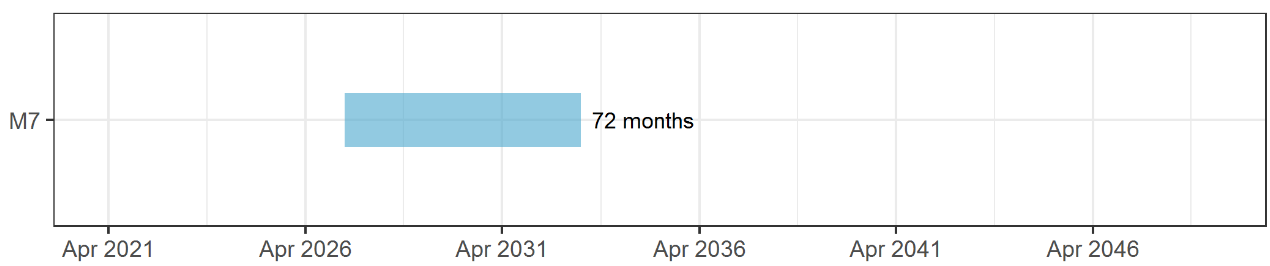
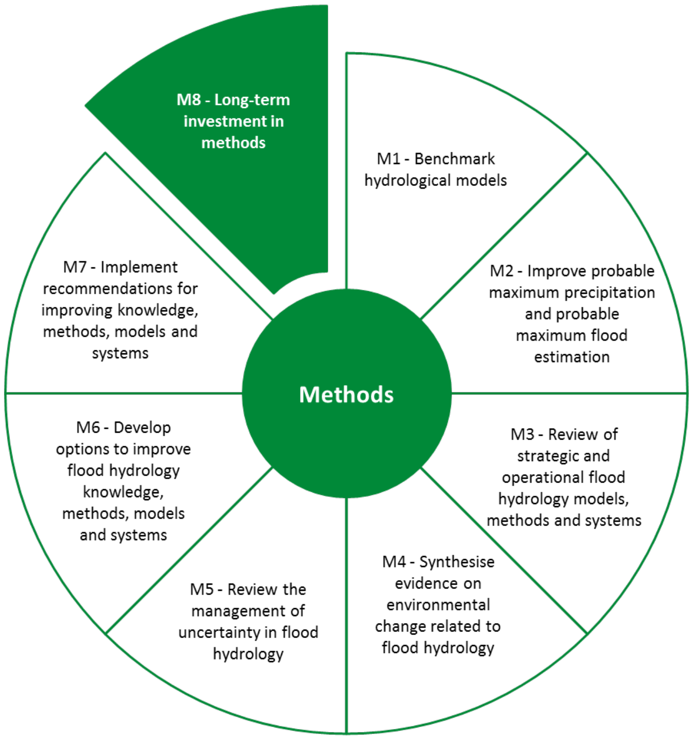


Figure G-61 – Estimated duration of action M7



Action M8: Long-term investment in methods



Objective

To carry out long-term actions to turn the methods vision of the flood hydrology roadmap into outcomes.

Outline scope

The detailed scope of long-term actions to improve ways of working in the roadmap will become clearer as implementation of the roadmap progresses and will be informed by the findings and outputs of actions M1 to M7.

The following areas may be part of this long-term programme of work, but will be subject to change and review as part of the periodic refresh of the roadmap and its action plan (likely to be every 3 years), which will be led by the governance board as part of action W1:

1. further development of the next generation modelling tools and systems from actions M6 and M8
2. long-term investment in the digital infrastructure to support next generation modelling
3. development and implementation of more integrated flood hydrology modelling

Intended outputs

To be defined – dependent on the findings, recommendations, outputs and outcomes of actions M1 to M7.

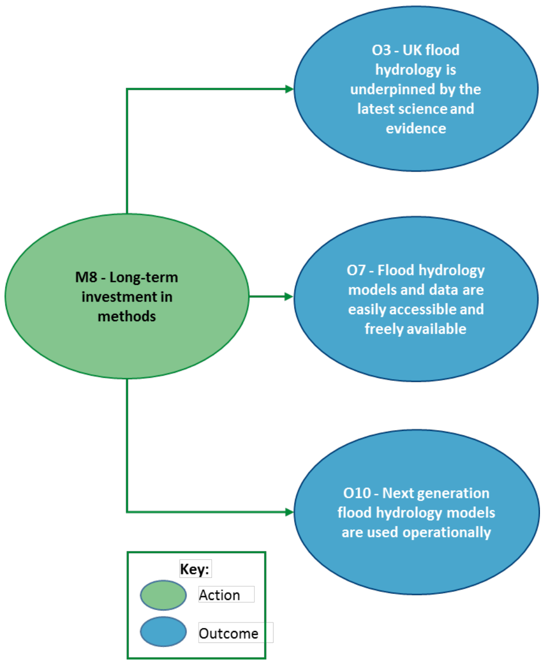
Intended outcomes

It is likely that this action contributes to 3 outcomes (although this will be dependent on the scope of the work):

- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence
- outcome 7 - flood hydrology models and data are easily accessible and freely available
- outcome 10 - next generation flood hydrology models are used operationally

The outcome map for this action is shown in Figure G-62.

Figure G-62 – Outcome map for action M8



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-63. Due to the uncertain nature of longer-term actions in the roadmap, which will be subject to cycles of review and refresh, the funding outlined in Figure G-63 is indicative only. It suggests a total of between £11.5 million and £17.25 million of funding will be required over 16 years (Figure G-64), starting in year 13 of the roadmap (April 2033). It is envisaged that longer-term investment on data will peak around years 17 (April 2037) and 18 (April 2038) at between £2 million and £3 million per year. This will coincide with the development and implementation of improvement outlined in the scope for this action. This cost estimate should be refined as the roadmap actions on methods progress and the scale of longer-term investment and need become clearer.

Figure G-63 – Estimated spend profile for action M8

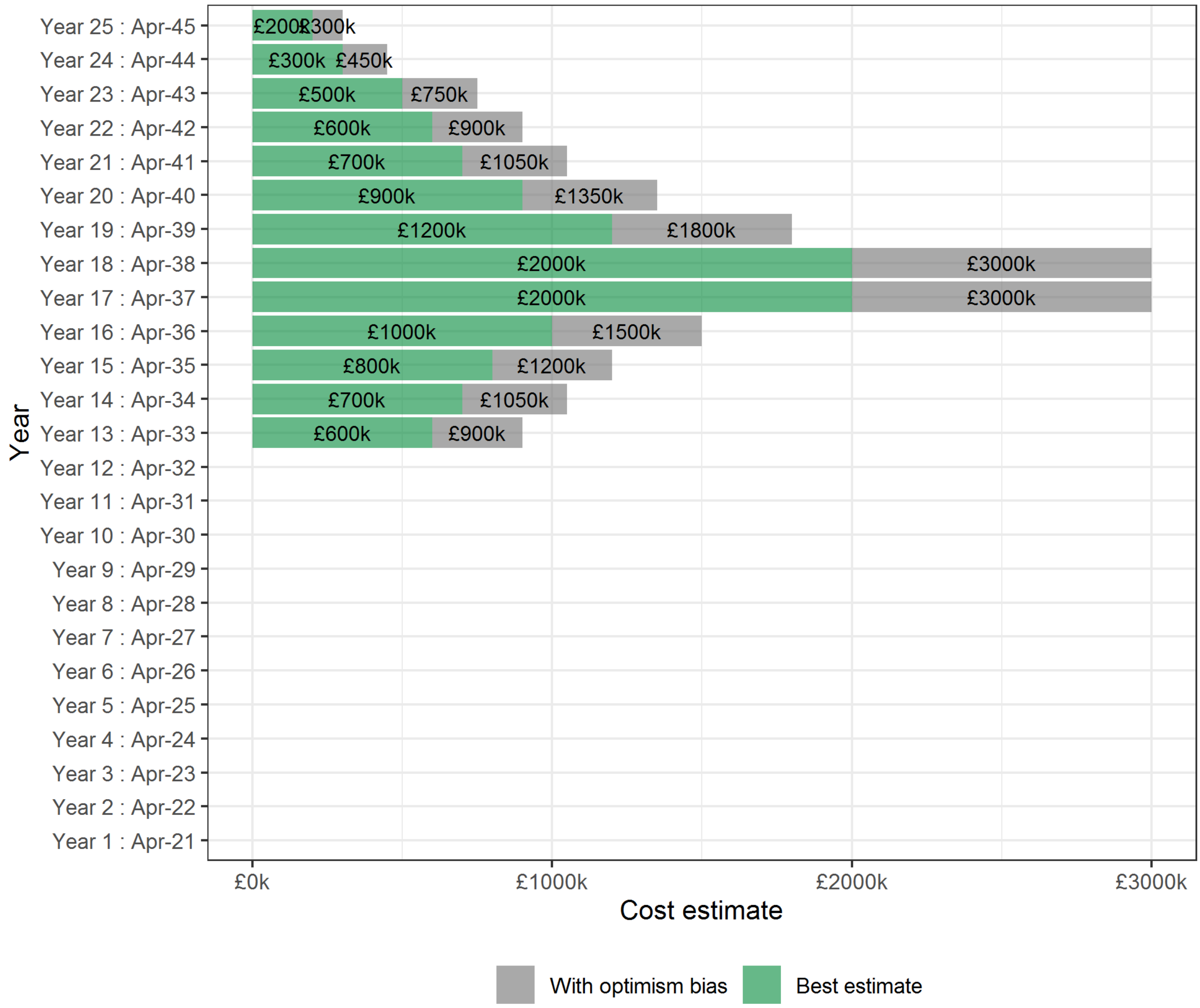
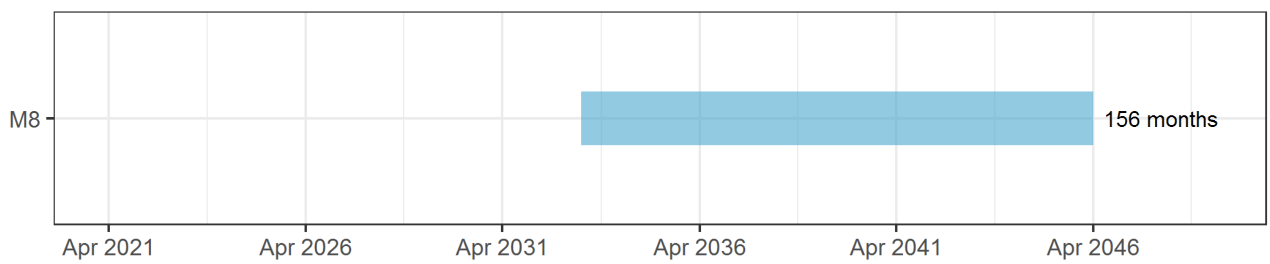
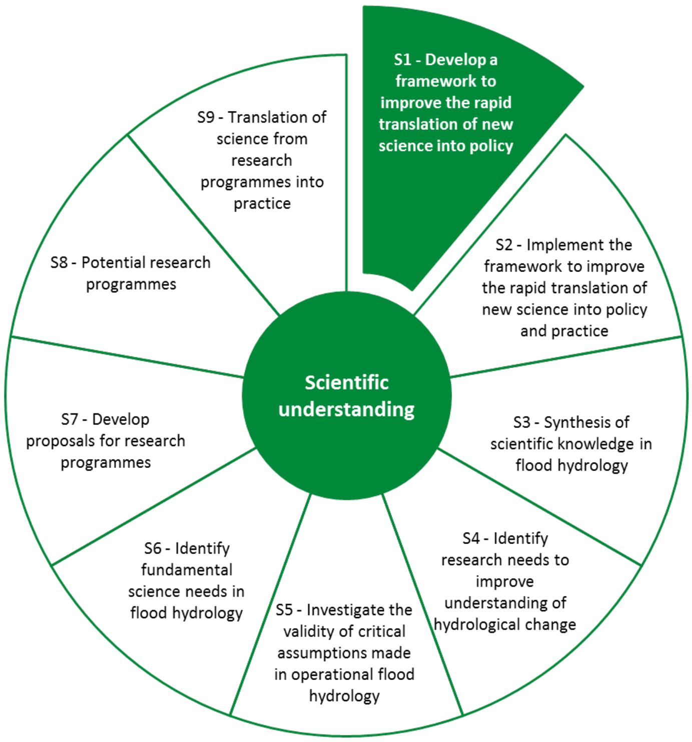


Figure G-64 – Estimated duration of action M8



Action S1: Develop a framework to improve the rapid translation of new science into policy and practice



Objective

Develop a framework to enable:

1. the rapid translation of new science into policy and practice
2. the scientific needs of practitioners to be visible to the science community

Outline scope

This action seeks to promote the rapid uptake of science into practice and also ensure that the science community have sight of the scientific and technical needs of practitioners.

The framework could:

1. be led by a group drawn from the science and practitioner community
2. identify gaps in knowledge exchange across the community
3. identify novel and innovative ways to exchange knowledge between scientists and practitioners
4. have a 3-year reporting cycle which outlines how new science could be translated into practice based on:
    a. a literature review of recent scientific developments in flood hydrology

    b. expert opinion and judgment
5. produce a regular report via action S3

This framework could be complemented by more traditional knowledge exchange activities, which could include:

6. knowledge exchange fellowships[16]
7. work placements/secondments for early career researchers, with an emphasis on improving diversity within the profession
8. placements at academic institutions for practitioners
9. promoting and organising workshops/meetings/conferences and other novel knowledge exchange methods/actions
10. presentation series/webinars via organisation such as ICE/BHS, CIWEM, BSG, BDS, RGS and GeolSoc
11. encouraging non-academic PhD supervision from the wider professional community
12. developing Collaborative Awards in Science and Engineering (CASE) studentships with NERC ad EPSRC
13. identifying better ways to engage with PhD and postdoctoral researchers
14. increasing the visibility of ongoing academic research to the professional community
15. producing a clear long-term published plan with recommendations for implementation

Intended outputs

1. A proposal for a framework to improve the rapid translation of new science into policy and practice.

Intended outcomes

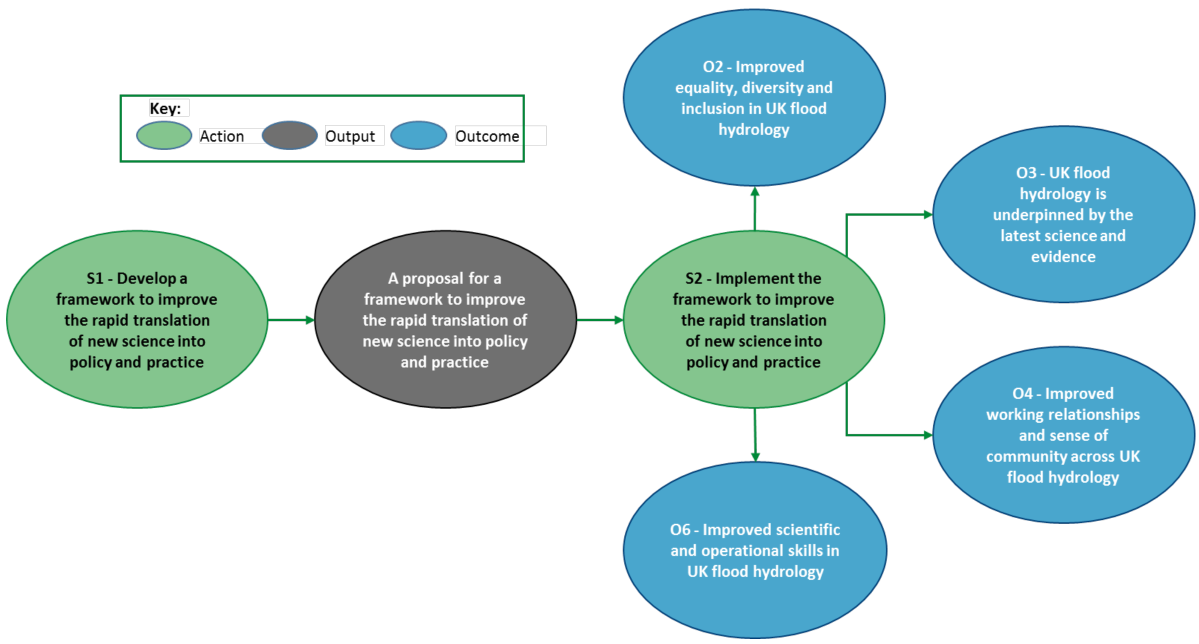
This action contributes to 4 outcomes:

- outcome 2 - improved equality, diversity and inclusion in UK flood hydrology
- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence
- outcome 4 - improved working relationships and sense of community across UK flood hydrology
- outcome 6 - improved scientific and operational skills in UK flood hydrology

The outcome map for this action is shown in Figure G-65.

[16] UKRI knowledge exchange fellowships [last accessed 18 November 2021]

Figure G-65 – Outcome map for action S1



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-66. It is anticipated that this action would require between £150,000 and £225,000 of funding over 18 months (Figure G-67).

Figure G-66 – Estimated spend profile for action S1

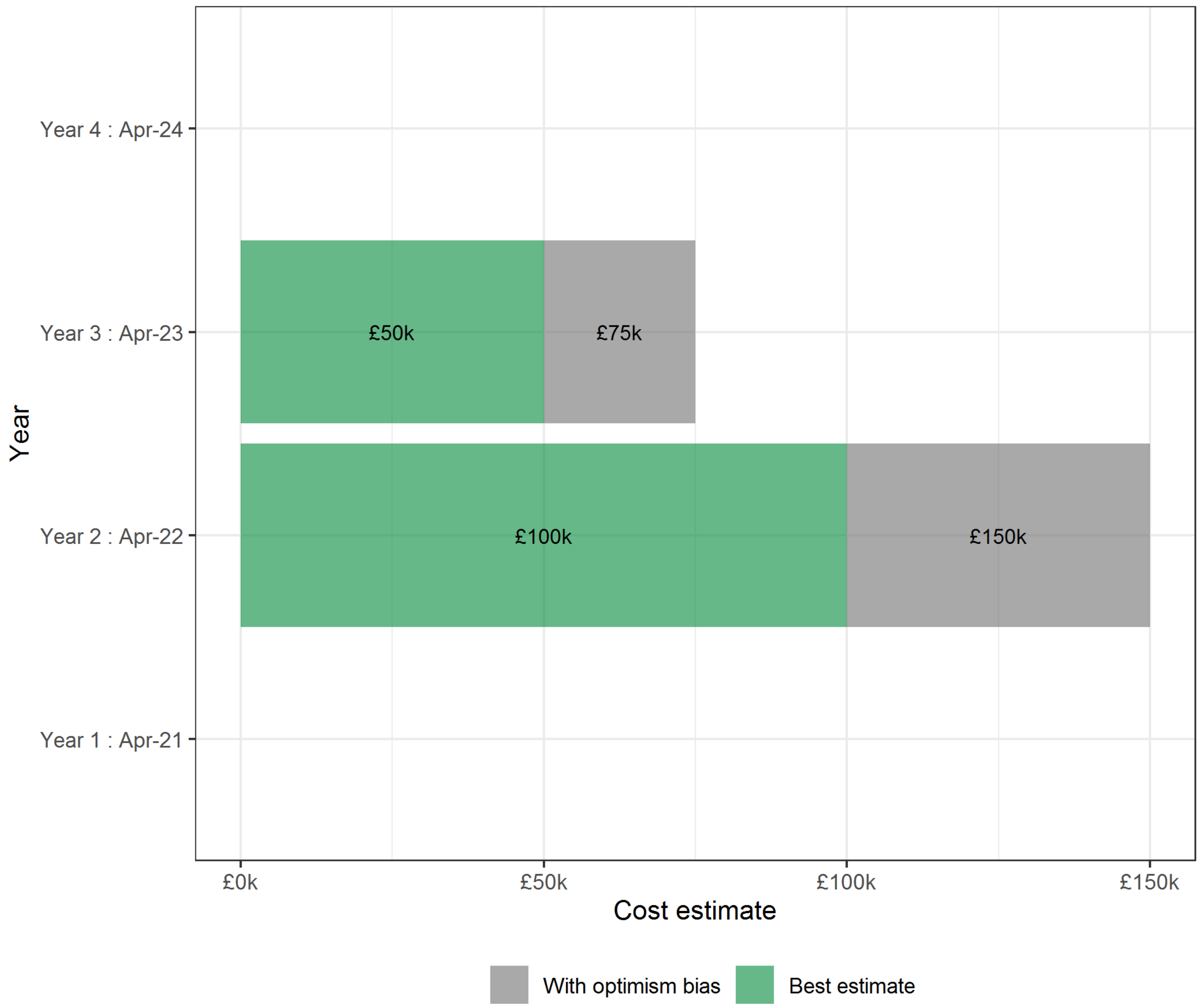
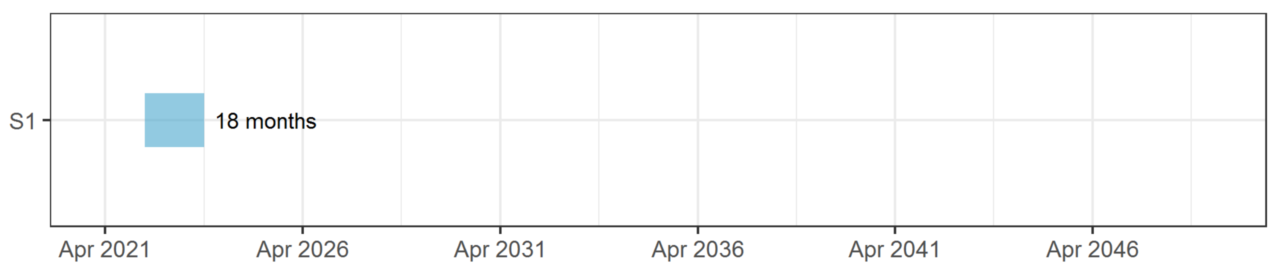
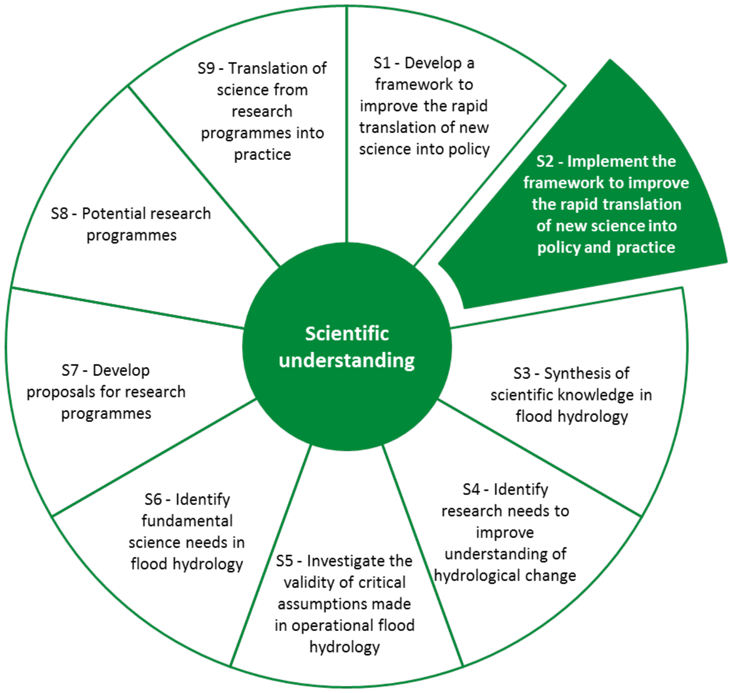


Figure G-67 – Estimated duration of action S1



Action S2: Implement the framework to improve the rapid translation of new science into policy and practice



Objective

Implement the proposals for a framework to improve the rapid translation of new science into policy and practice.

Outline scope

This action will implement recommendations from action S1.

Intended outputs

1. Implementation of recommendations from action S1.

Intended outcomes

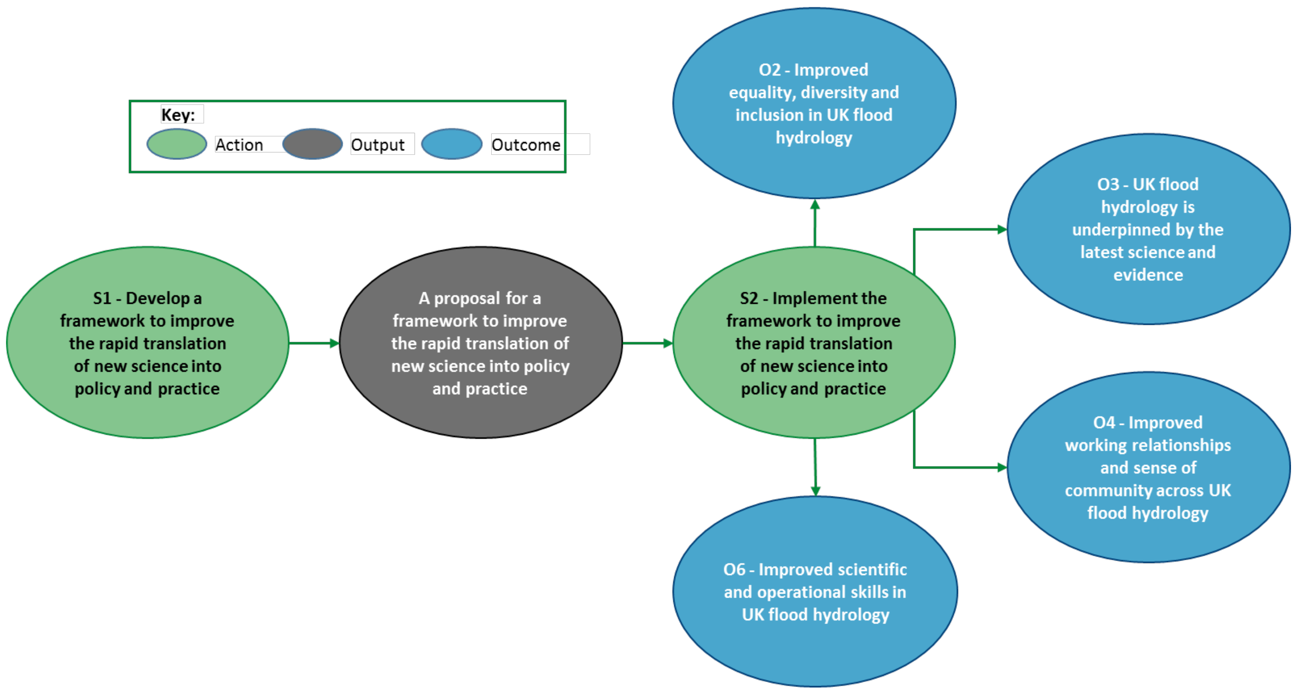
This action contributes to 4 outcomes:

- outcome 2 - improved equality, diversity and inclusion in UK flood hydrology
- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence
- outcome 4 - improved working relationships and sense of community across UK flood hydrology

- outcome 6 - improved scientific and operational skills in UK flood hydrology

The outcome map for this action is shown in Figure G-68.

Figure G-68 – Outcome map for action S2



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-69. It is anticipated that funding of between £100,000 and £150,000 would be required from year 3 of the roadmap (April 2023), increasing by 2% annual (to account for inflation) for the lifetime of the roadmap (Figure G-69). This would ensure that action S1 could be implemented and make funding available for ongoing activity to aid the rapid translation of new science into policy and practice.

Figure G-69 – Estimated spend profile for action S2

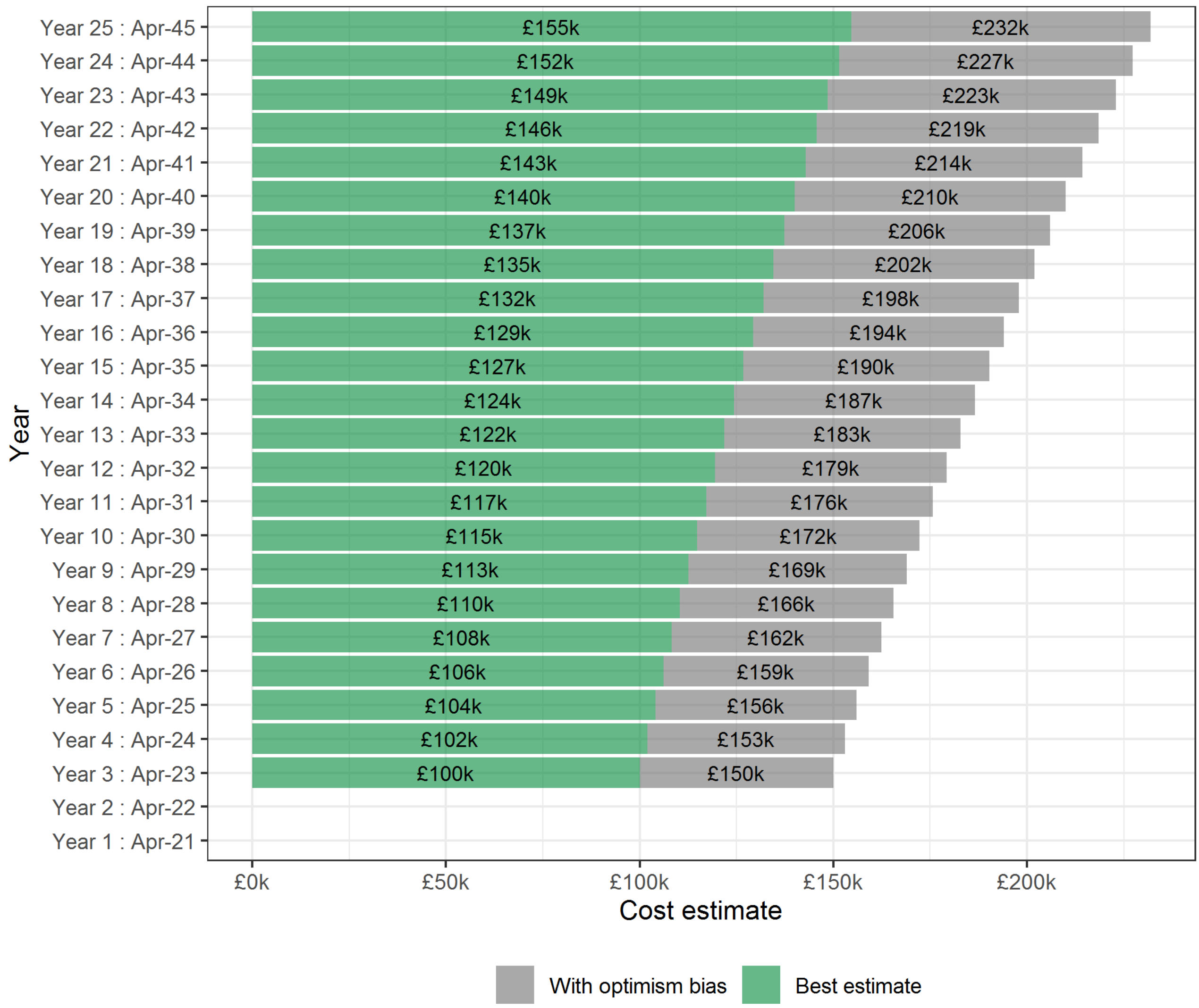
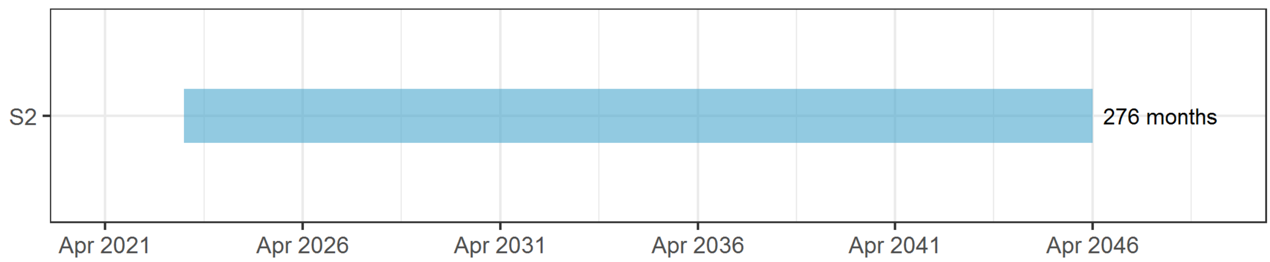
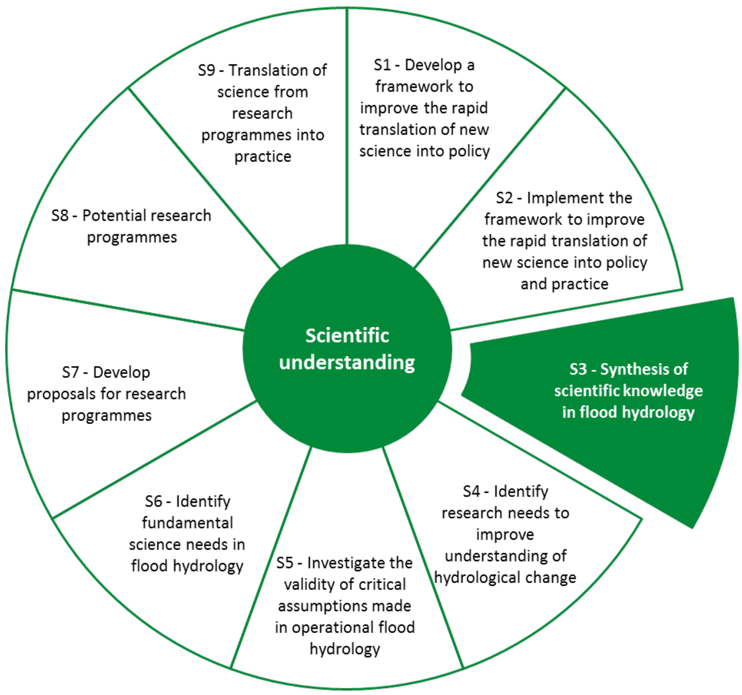


Figure G-70 – Estimated duration of action S2



Action S3: Synthesis of scientific knowledge in flood hydrology



Objective

Create and maintain an up-to-date comprehensive synthesis of the state of scientific knowledge in flood hydrology.

Outline scope

Carry out a comprehensive synthesis of the state of knowledge in the science of flood hydrology (including process-based modelling, statistical modelling, machine learning and field and laboratory-based experiments as a minimum). This could:

1. be in the form of an IPCC style report that can be periodically updated (for example, every 3 to 5 years)
2. aim to provide practitioners and academics with regular scientific assessments on the science behind flood hydrology, its implications and potential future risks
3. be linked to the outcomes and findings of actions W4, S1 and S2
4. contain the latest state of scientific knowledge in the following areas:
    a. observational methods
    b. conceptual models of UK hydrology
    c. perceptual models of UK hydrology

d. latest evidence on past environmental change and variability related to UK flood hydrology[17], including attribution to drivers of change
e. analytical and modelling methods applied in (a)
f. development of data-driven methods based on machine learning and artificial intelligence to augment or improve on hydrological methods and models (for both real-time and long-term applications)
g. transferability of knowledge from case studies across different catchments and environments
h. latest evidence on future projections for flood hydrology variables
i. latest developments in flood estimation
j. latest developments in flood forecasting
k. current understanding of hydrological processes
l. the gaps between scientific knowledge and operational activities with implications for
    i. planning for future flood risk
    ii. measuring authorities and practitioners
m. future research needs (to feed into action S6)

5. be accompanied by scientific journal publications and/or a special publication series

Intended outputs

1. IPCC style report of the state of knowledge in the science of flood hydrology.
2. Identification of future research needs.
3. Peer-reviewed journal publication on the synthesis.

Intended outcomes

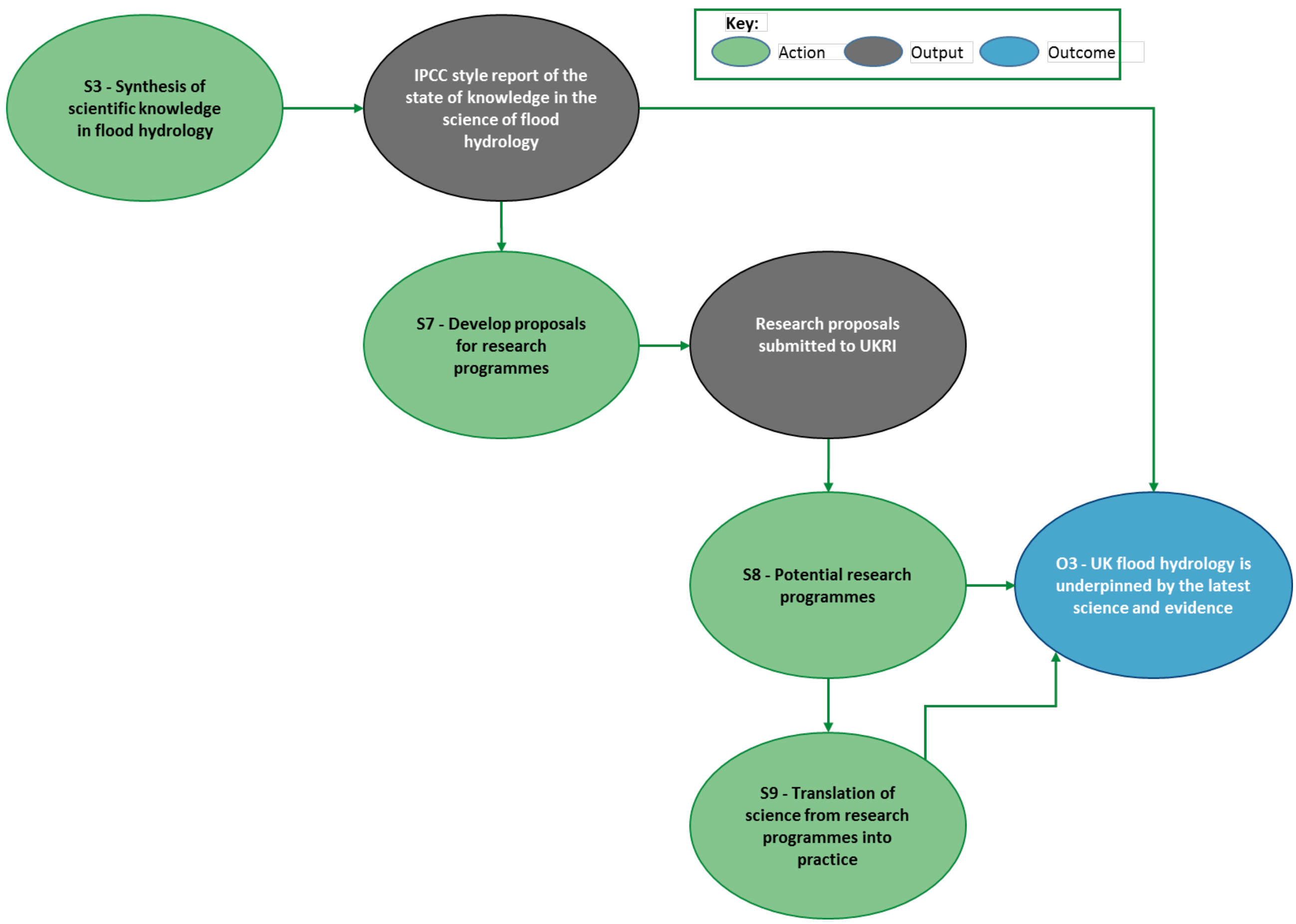
This action contributes to one outcome:

- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence

The outcome map for this action is shown in Figure G-71.

[17] Variables related to flood hydrology include those considered in M3/M4 (that is, peak flow magnitude, frequency, seasonality, duration/persistence, volume and spatial extent, extreme rainfall, soil moisture), but should also consider other related environmental variables.

Figure G-71 – Outcome map for action S3



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-72. It is envisaged that this action would require initial funding of between £300,000 and £450,000 to carry out the first synthesis of scientific knowledge in flood hydrology. This would be followed by updates every 3 years (each taking 12 months shown in Figure G-73) costing a further £150,000 to £225,000 (adjusted for inflation of 2% per year).

Figure G-72 – Estimated spend profile for action S3

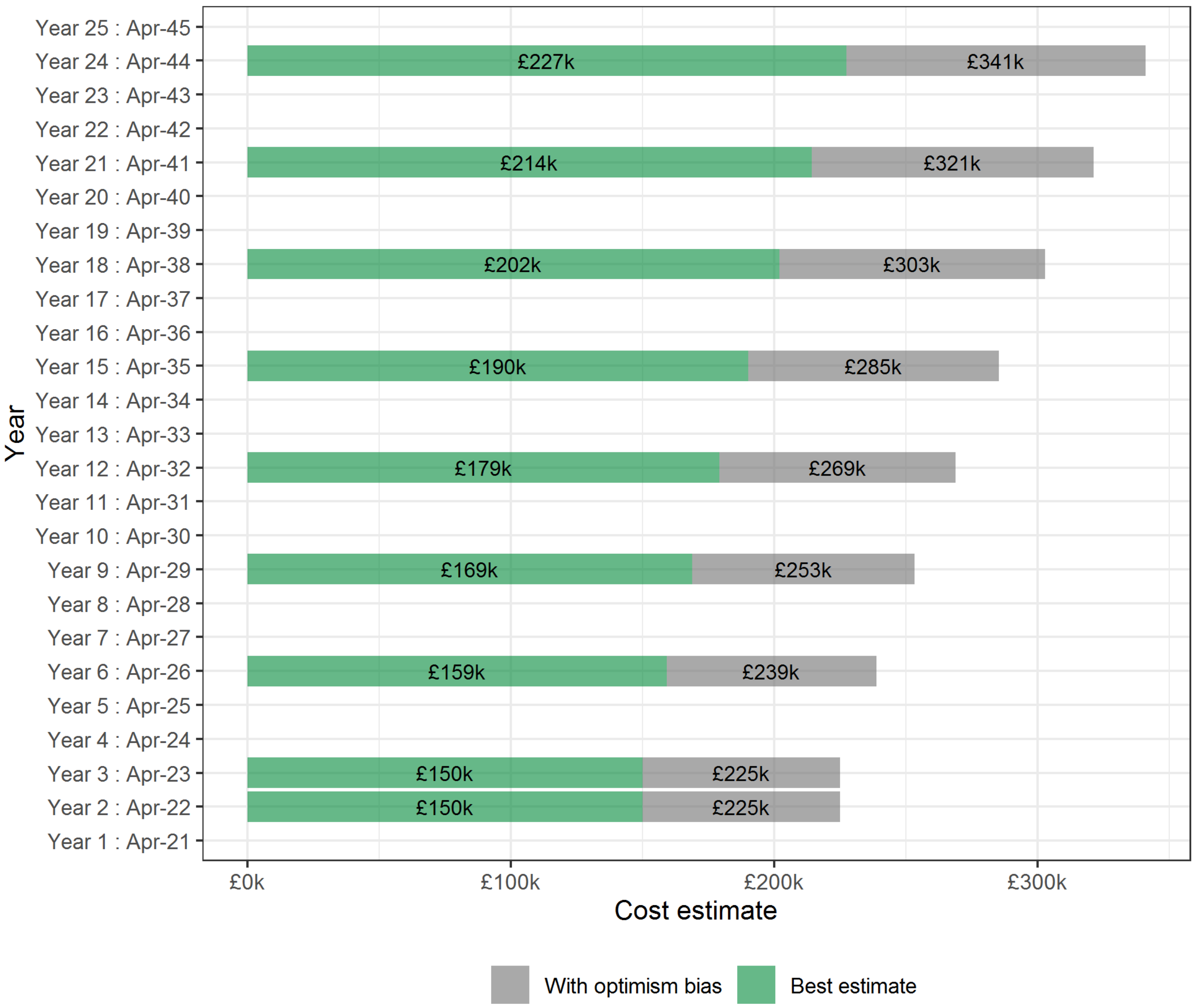
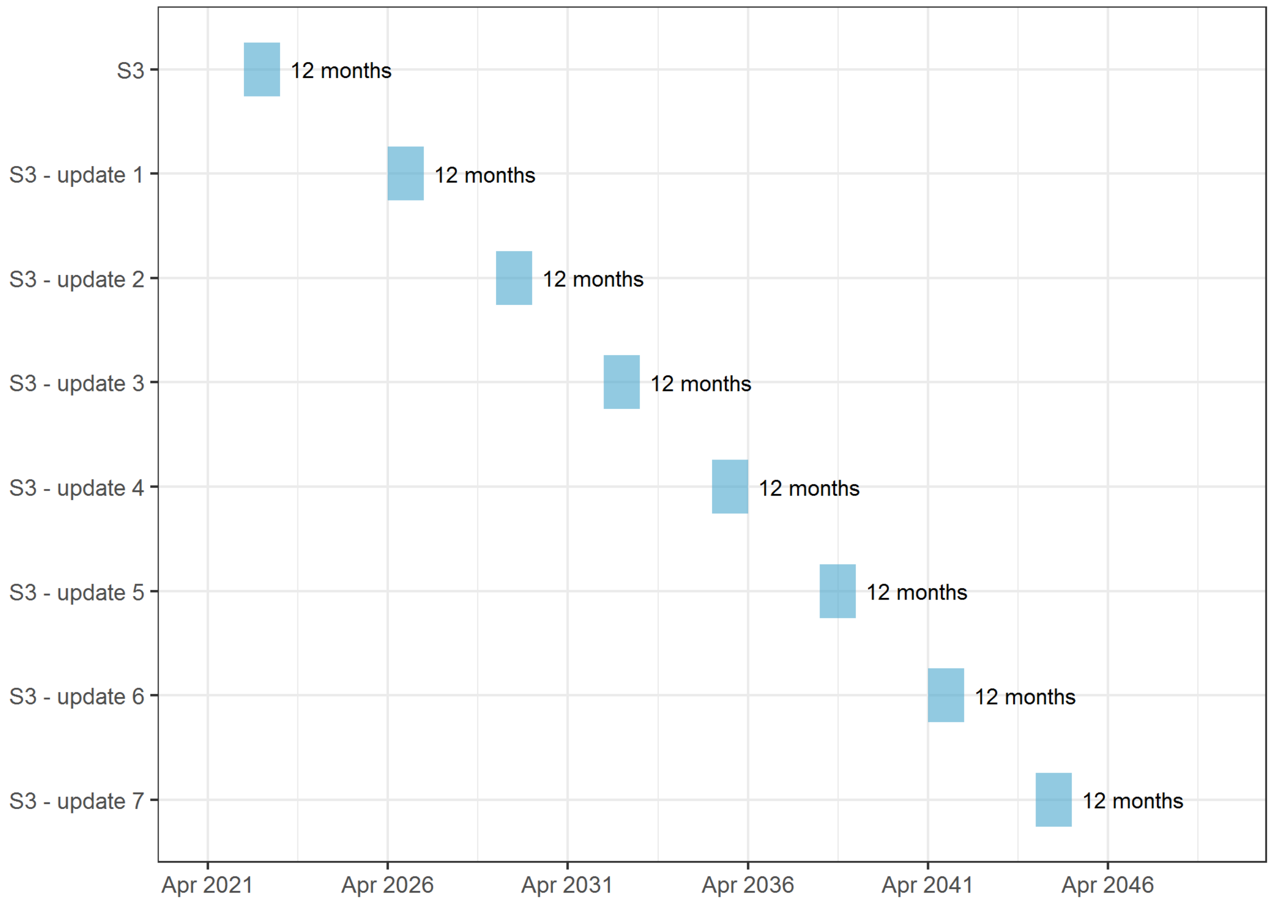
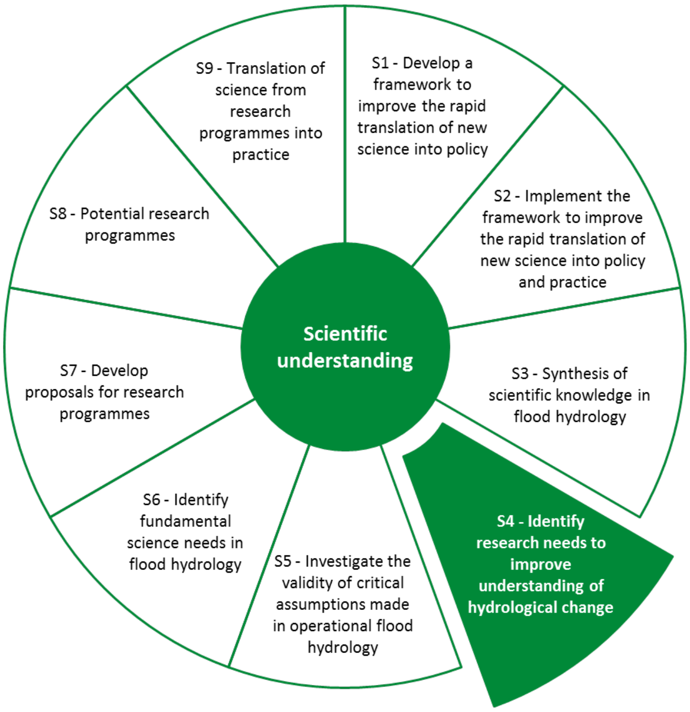


Figure G-73 – Estimated duration of action S3



Action S4: Identify research needs to improve understanding of flood generation processes and drivers of hydrological change



Objective

Provide a better understanding of the physical processes governing flood generation, in particular run-off generation, including in surface water flooding, interactions with groundwater and extreme events.

Outline scope

This action could:

1. issue a call for evidence (structured around the British Hydrological Society (BHS) Working Group on the Future of UK Hydrological Research[18] and a sub-set of the International Association of Hydrological Sciences (IAHS) 23 unsolved problems in

[18] BHS WG Hydrological Futures (hydrology.org.uk) [Last accessed 27 September 2021]

hydrology[19], aimed at encouraging submissions and research proposals to UKRI on the topic of understanding of the physical processes governing flood generation and driving hydrological change and variability
2. review physical process linkages framed within a rapid evidence assessment of perceptual models in flood hydrology, aligning with the BHS working group on the future of UK hydrological research
3. consider processes in flood hydrology holistically, including those in urban systems, groundwater systems, interactions with coastal systems, atmospheric exchanges, co-evolution of vegetation and landscapes, and influences of anthropogenic activity
4. include interactions between flood hydrology and ecological responses, water quality, hill-slope river coupling, woody debris, sediment transport, geomorphological change and sustainable drainage systems (SuDS)
5. include past, present and future perspectives
6. investigate how well models can represent flood generation processes
7. assess how flood generation processes might change in a changing climate
8. produce a report which will synthesise knowledge in these areas and make recommendations for consideration via action S6

Intended outputs

1. Report that identifies research needs to improve understanding of flood generation and drivers of hydrological change.

Intended outcomes

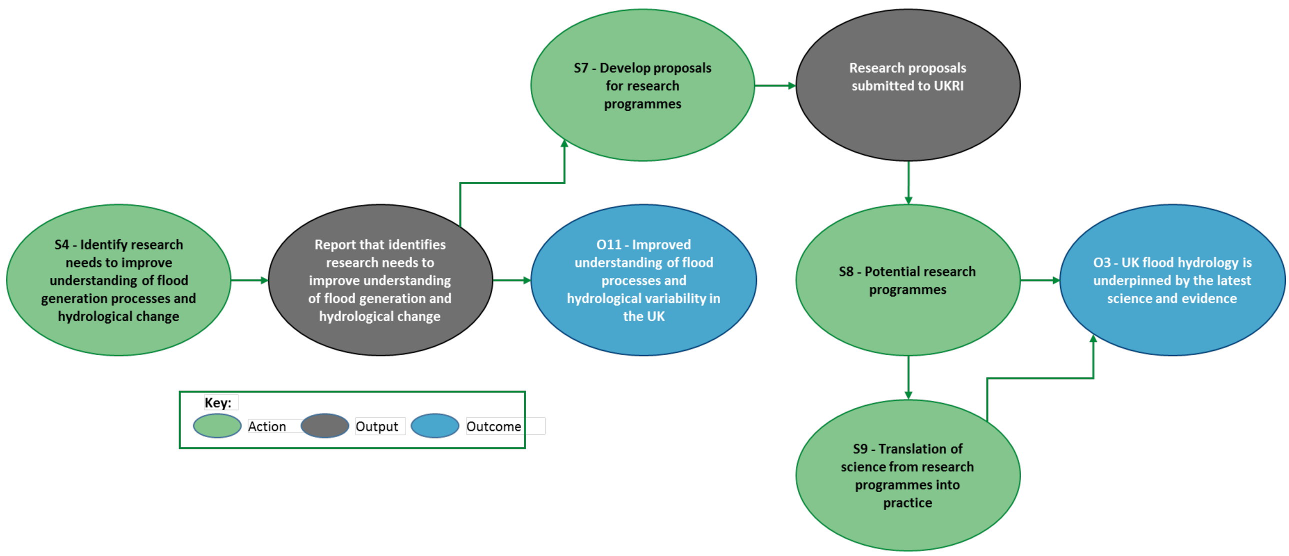
This action contributes to 2 outcomes:

- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence
- outcome 11 - improved understanding of flood processes and hydrological variability in the UK

The outcome map for this action is shown in Figure G-74.

[19] IAHS 23 unsolved problems in hydrology [Last accessed 18 November 2021]

Figure G-74 – Outcome map for action S4



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-75. It is envisaged that this action would require funding of between £300,000 and £450,000 over 2 years (Figure G-76) starting in year 3 of the roadmap (April 2023).

Figure G-75 – Estimated spend profile for action S4

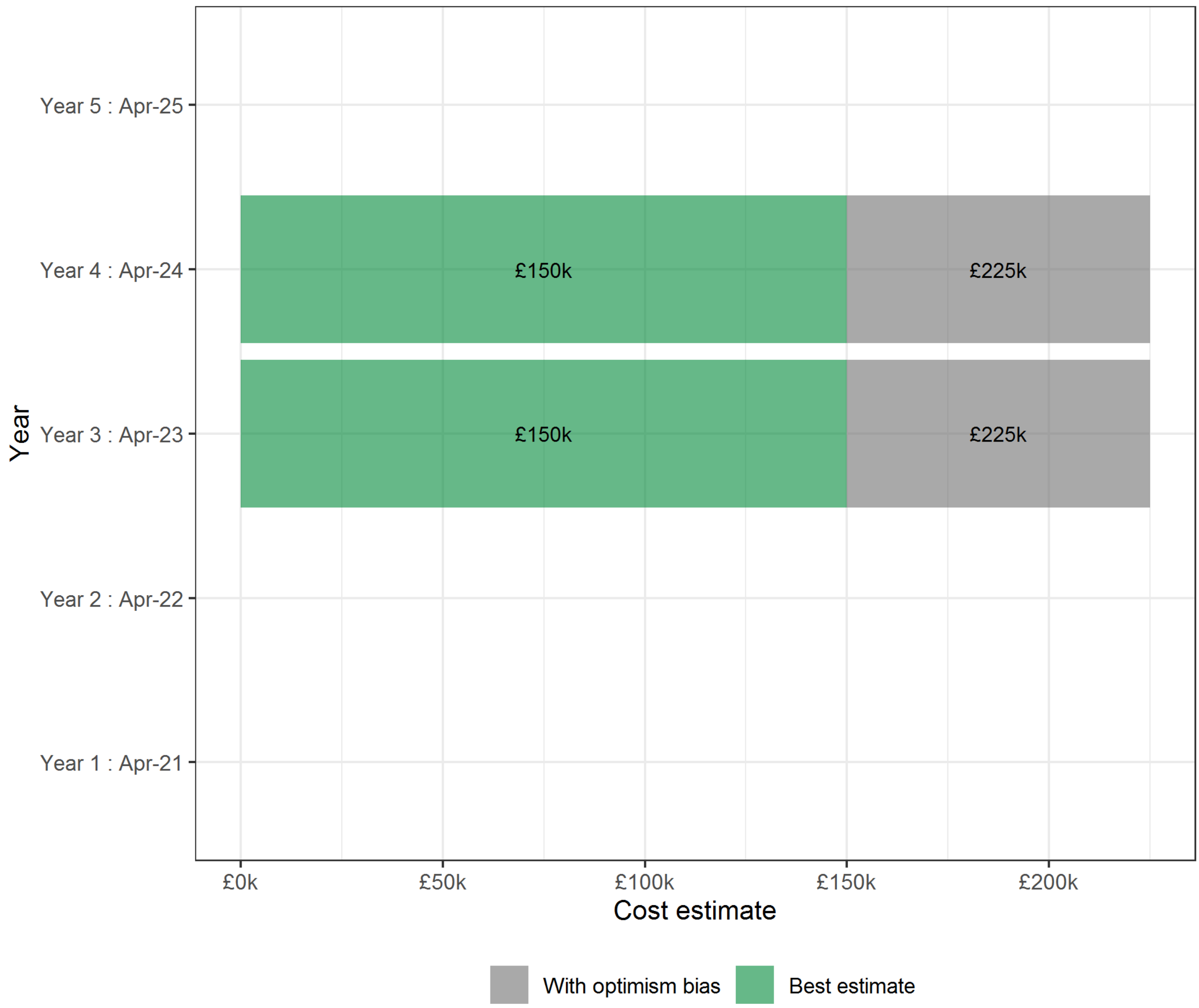
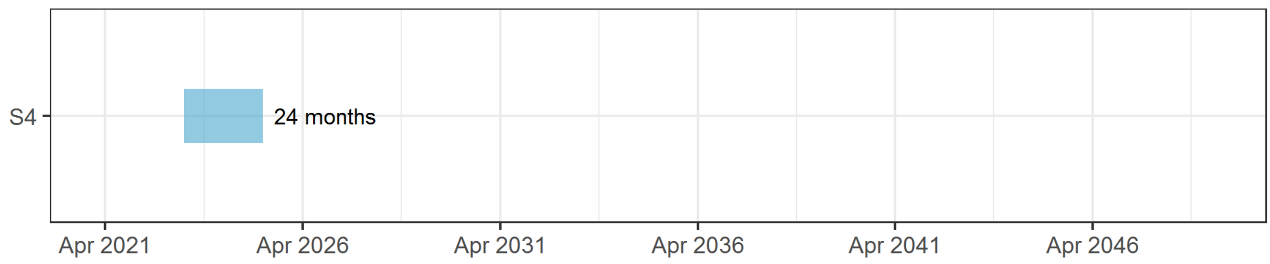
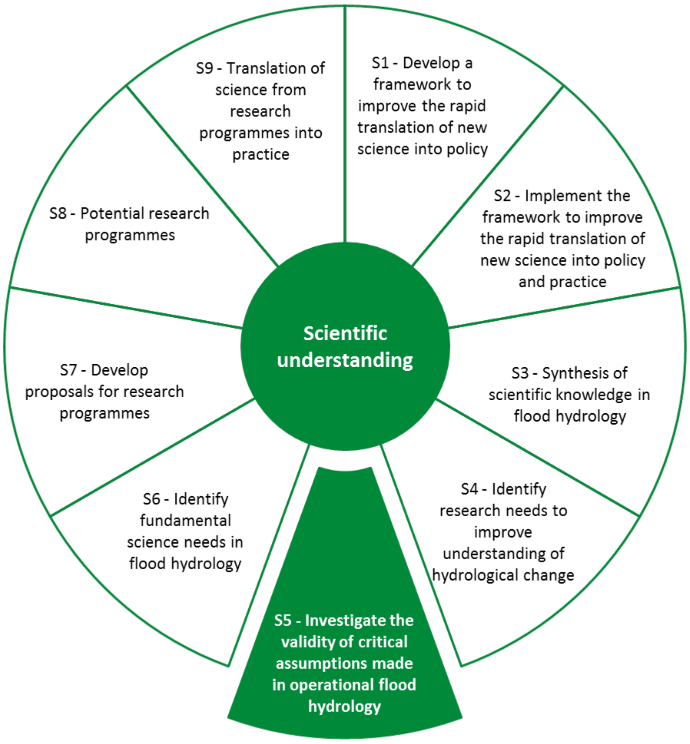


Figure G-76 – Estimated duration of action S4



Action S5: Investigate the validity of critical assumptions made in operational flood hydrology



Objective

Better understand the validity of critical assumptions that are made in operational flood hydrology.

Outline scope

This action could implement a project to:

1. capture critical assumptions made in current practice and design (conceptually) using a set of experiments that would test those assumptions - an example may be the structure of rainfall-runoff models, tested against evidence from observations, including both intensive field campaigns and remote sensing
2. develop case studies illustrating where critical assumptions in modelling/theory have and have not worked, with recommendations for improvement
3. produce a report and ideally peer-reviewed papers describing the motivations, design and expected outcomes of the proposed experiments
4. investigate funding sources and mechanisms for incorporating the experiments into other research proposals, to be published as a report designed to influence research funding organisations such as UKRI
5. make recommendations from this action that can be considered in action S6

Intended outputs

1. Report on a set of experiments to test the critical assumptions made in current flood hydrology practice and design.
2. Peer-reviewed journal paper(s) on the investigation and findings.

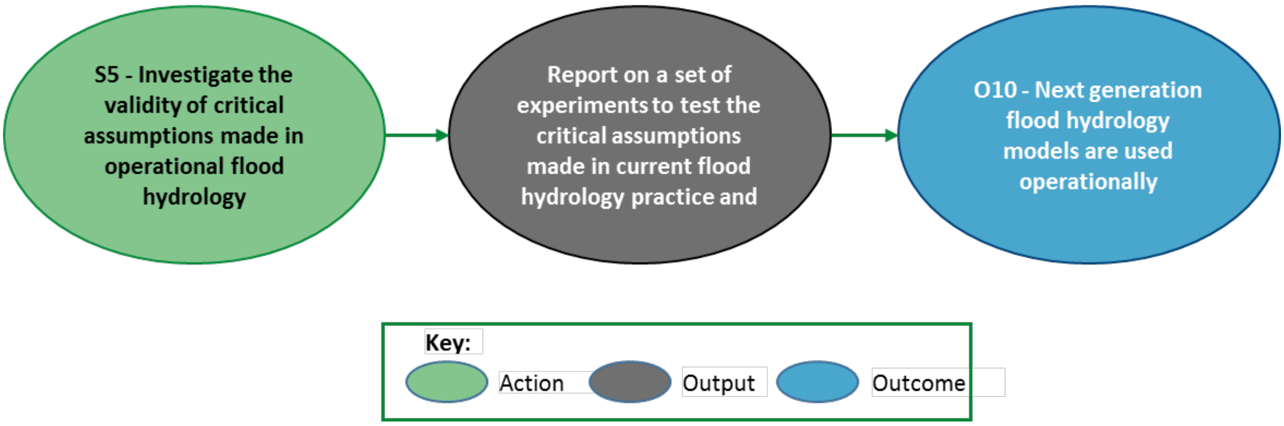
Intended outcomes

This action contributes to one outcome:

- outcome 10 - next generation flood hydrology models are used operationally

The outcome map for this action is shown in Figure G-77.

Figure G-77 – Outcome map for action S5



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-78. It is anticipated that this action will require funding of between £300,000 and £450,000 over 2 years (Figure G-79).

Figure G-78 – Estimated spend profile for action S5

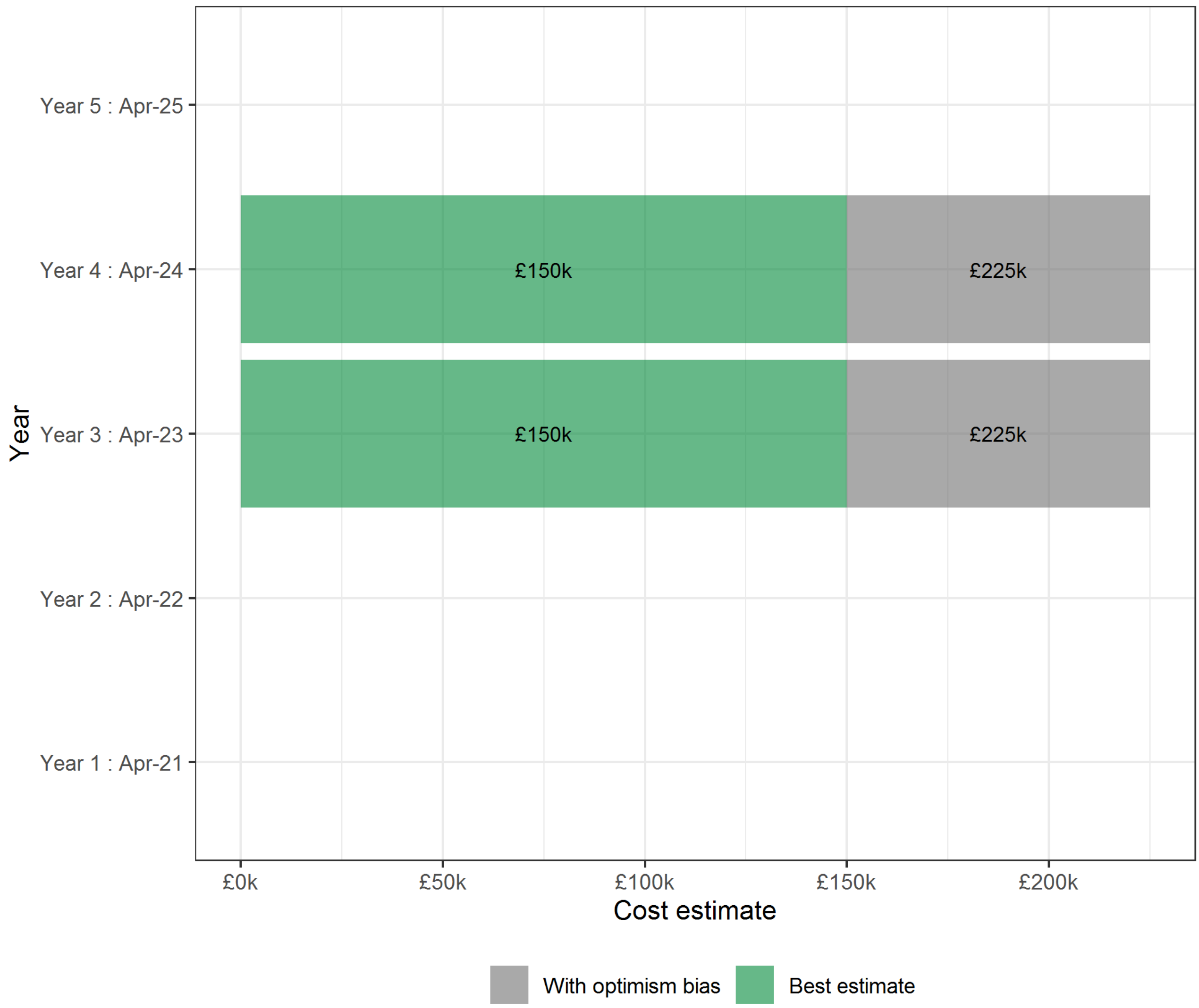
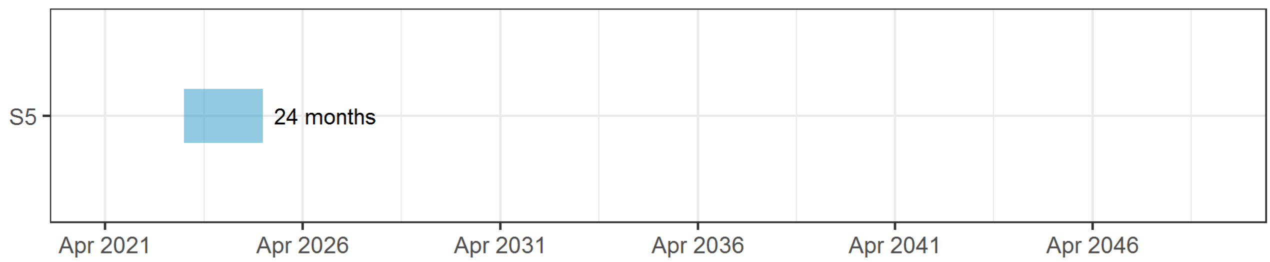
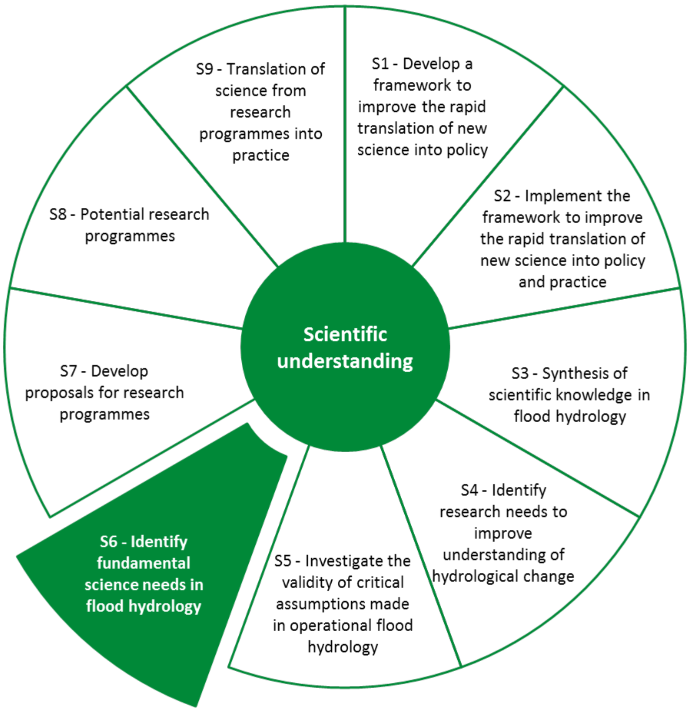


Figure G-79 – Estimated duration of action S5



Action S6: Identify fundamental science needs in flood hydrology



Objective

Identify new scientific knowledge required in flood hydrology to deal with future environmental change.

Outline scope

This action aims to build on and integrate fundamental research needs identified in actions S3, S4 and S5.

It will also take account of research needs identified by the BHS working group on the future of UK hydrological research[20], and the International Association of Hydrological Sciences (IAHS) 23 unsolved problems in hydrology[21].

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[20] BHS working group on the future of UK hydrological research [Last accessed 18 November 2021]

[21] IAHS 23 unsolved problems in hydrology [Last accessed 18 November 2021]

Main challenges include:

1. closure of water and energy balances over control volumes at multiple scales (for example, surface catchment, groundwater system)
2. characterisation of uncertainty in fluxes and closures
3. attribution and separation of changes in hydrological responses to local and large-scale drivers (for example, changes in river structures, land cover and climate)
4. extrapolation of small-scale observations to larger-scale land cover changes
5. integration of knowledge from empirical regionalisation and local dynamic model-based studies
6. information management and computational frameworks to allow competing perceptual and predictive models to be compared, debated and rejected

Ambitions for the programme may include:

1. development of an evolving, open-access perceptual model of UK flood hydrology
2. a system for linking and accessing heterogeneous data sources, with a particular focus on data collected routinely for operational (rather than research) purposes by regulators, water companies and others
3. national model ensemble linked to data assimilation and sensitivity analysis tools to enable uncertainty reduction and support hypothesis testing in the presence of uncertainties (an ‘observation-simulation system experiment’)
4. testing of hypotheses corresponding to place-specific perceptual models and data, including novel measurement techniques, merging statistical and process-based hydrology

These research needs will then be shaped into a proposal which can be presented to UKRI for funding opportunities.

Intended outputs

1. Report and other media (presentations, videos, events) outlining fundamental research needs in UK flood hydrology to shape proposals for research programmes.

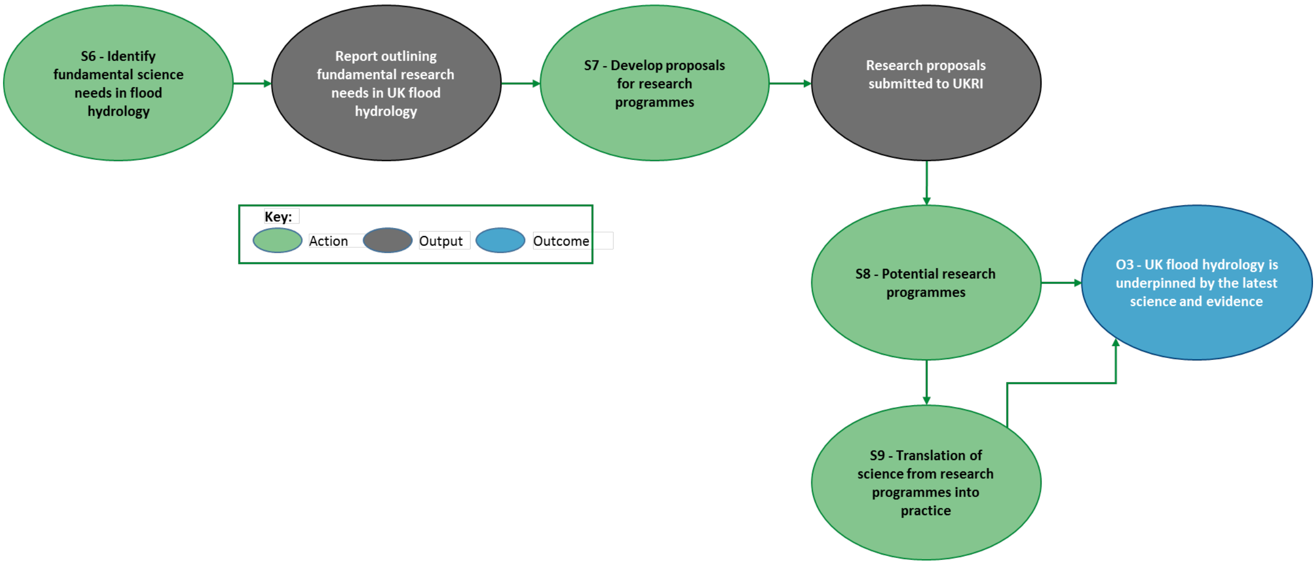
Intended outcomes

This action contributes to one outcome:

- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence

The outcome map for this action is shown in Figure G-80.

Figure G-80 – Outcome map for action S6



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-81. It is likely that this action will require between £300,000 and £450,000 of funding over 3 years (Figure G-82).

Figure G-81 – Estimated spend profile for action S6

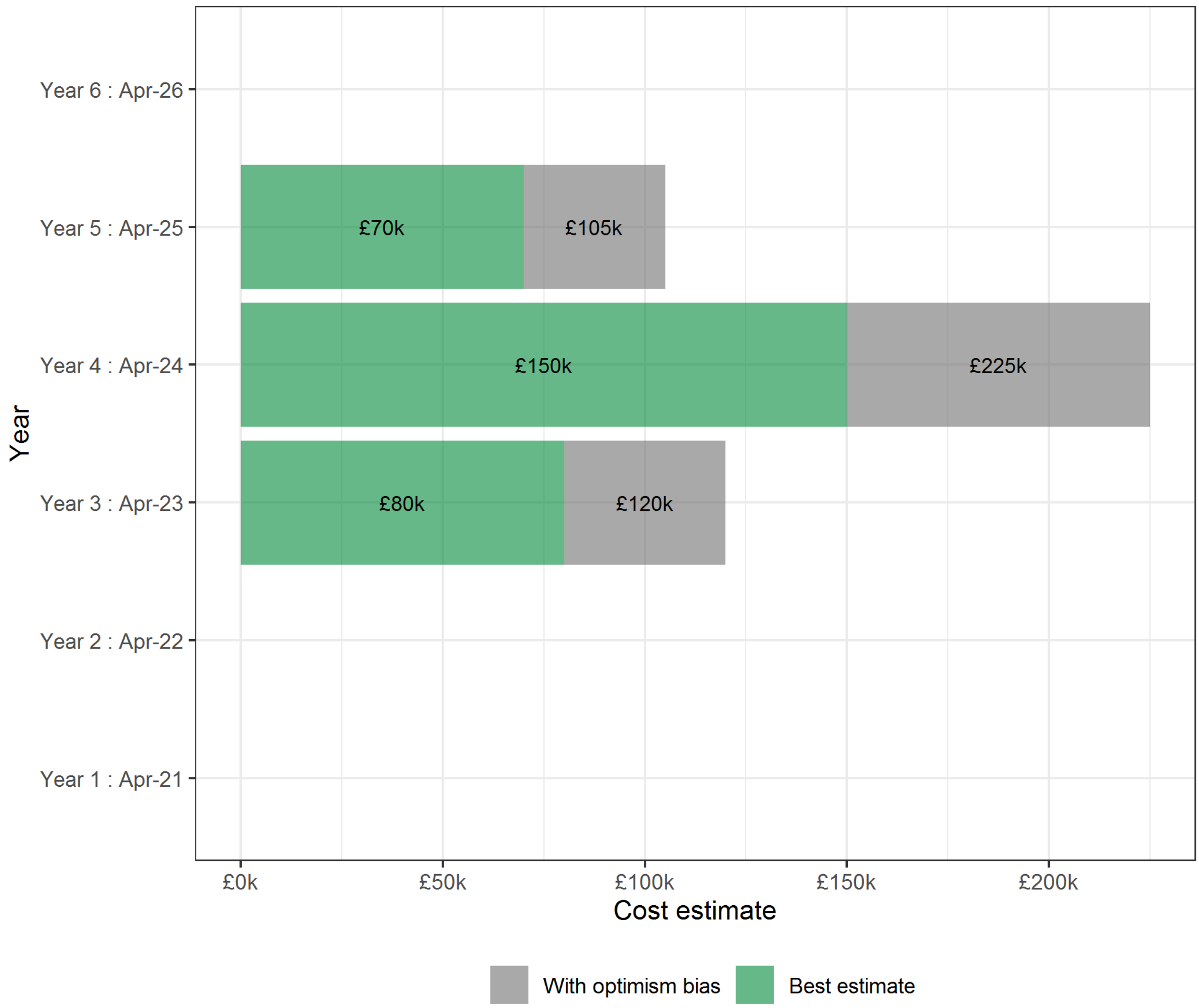
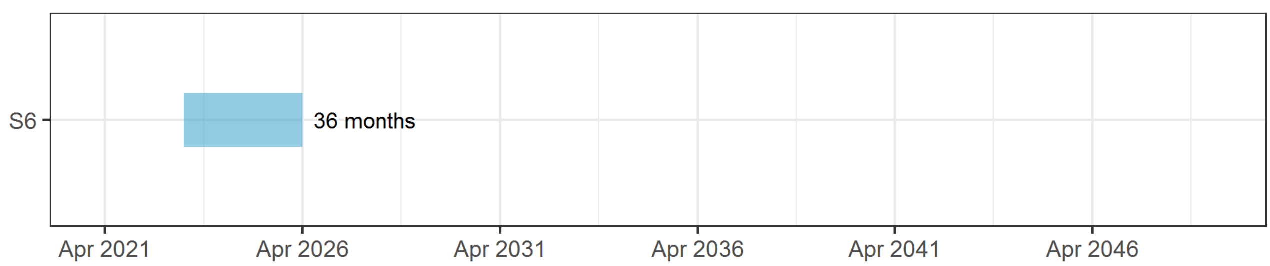
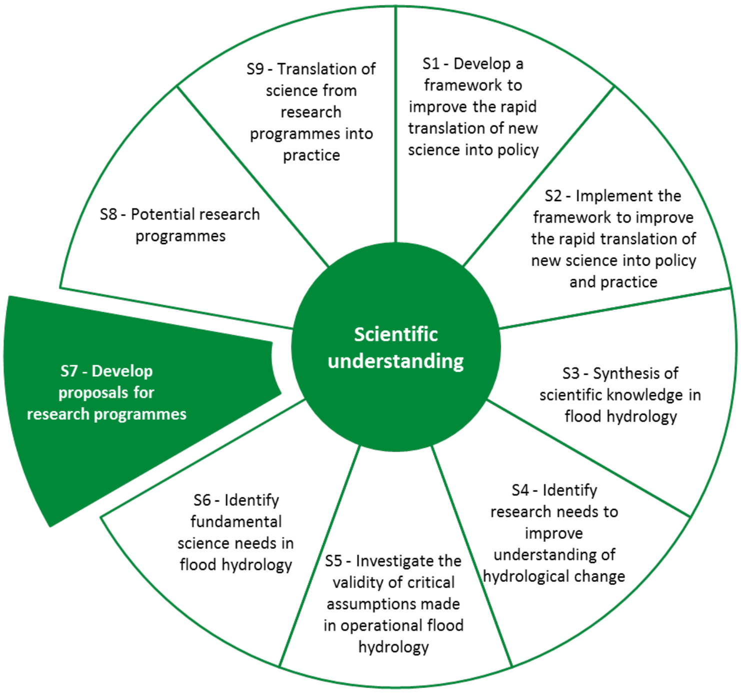


Figure G-82 – Estimated duration of action S6



Action S7: Develop proposals for research programmes



Objective

Develop proposals for a major fundamental research programme in the field of flood hydrology.

Outline scope

This action will build on the research needs identified in action S6 and work across the academic and practitioner community to develop proposals for a major research programme in the field of flood hydrology.

The proposal will ensure that it links and utilises other UK research programmes such as FDRI and its potential capital investment in research infrastructure.

The proposal will also seek opportunities for multi-disciplinary research programmes (for example, through joint proposals with low flow (drought) hydrology and wider water research programmes.

The proposal(s) will be put to UKRI to discuss potential funding opportunities.

Intended outputs

- Research proposals submitted to UKRI.

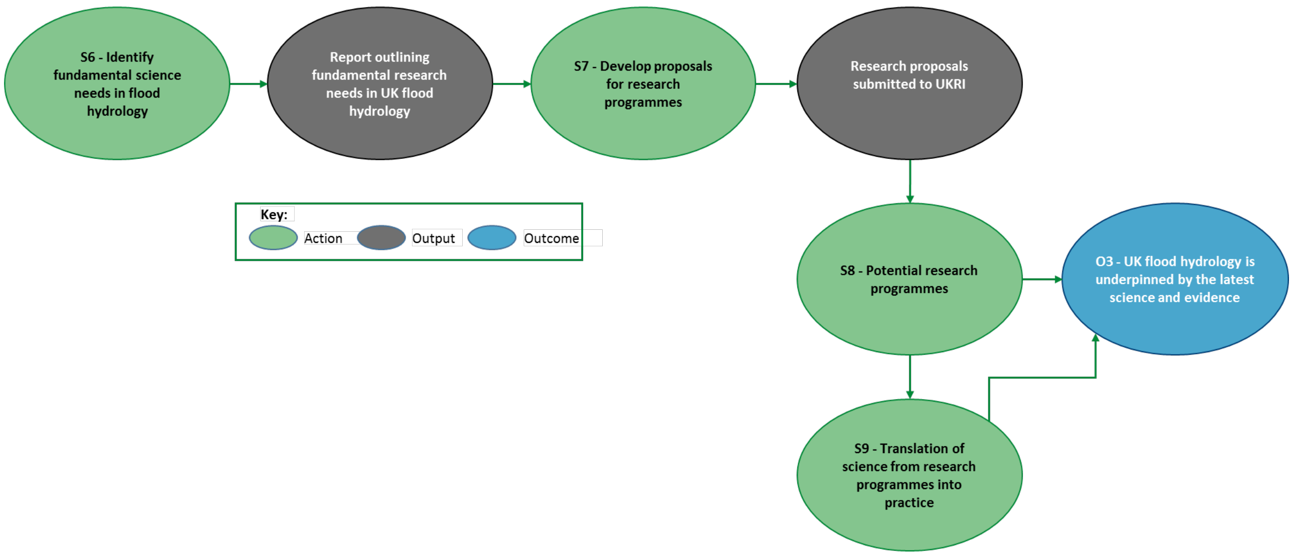
Intended outcomes

This action contributes to one outcome:

- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence

The outcome map for this action is shown in Figure G-83.

Figure G-83 – Outcome map for action S7



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-84. It is likely that this action will require between £200,000 and £300,000 of funding over 2 years (Figure G-85).

Figure G-84 – Estimated spend profile for action S7

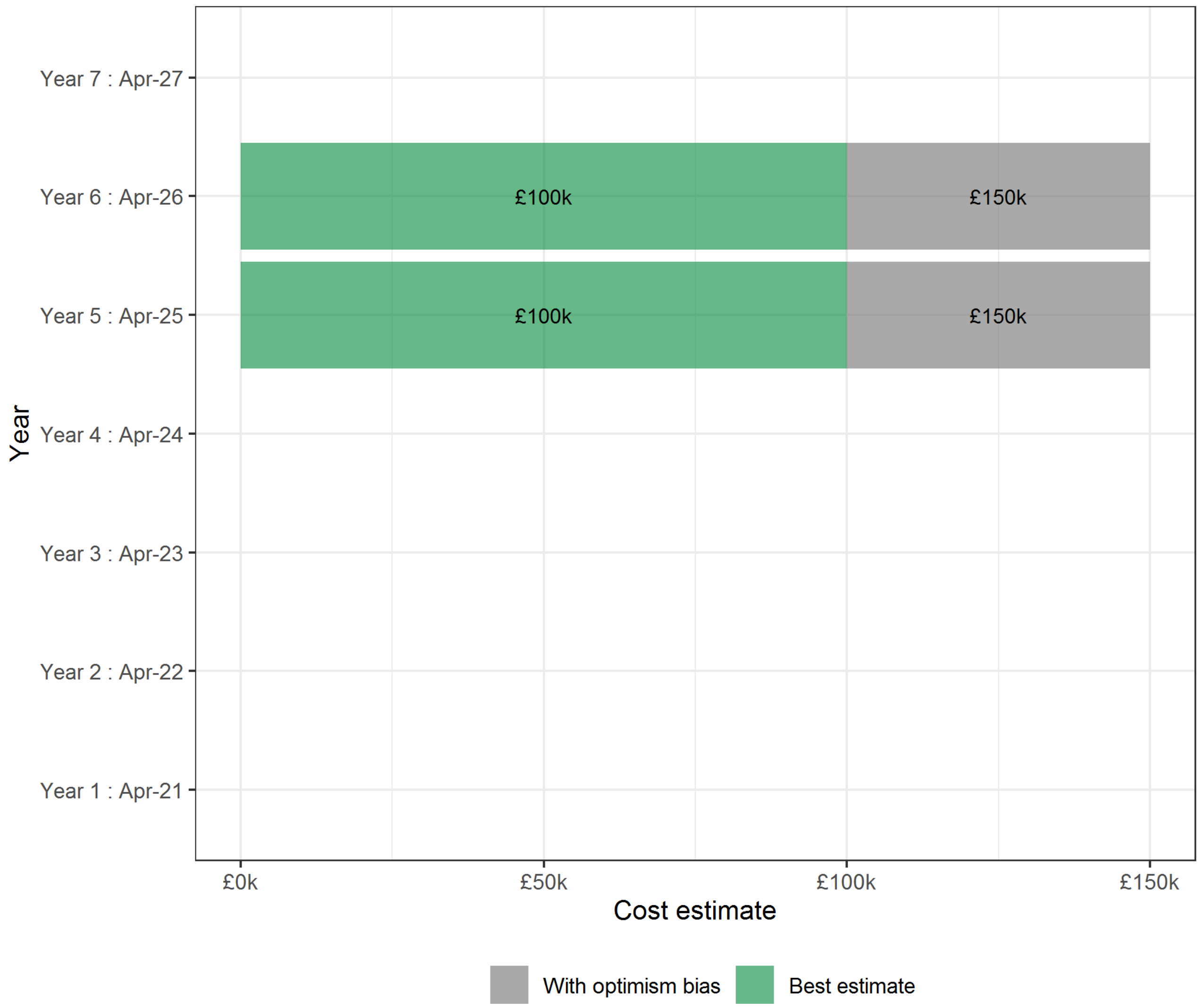
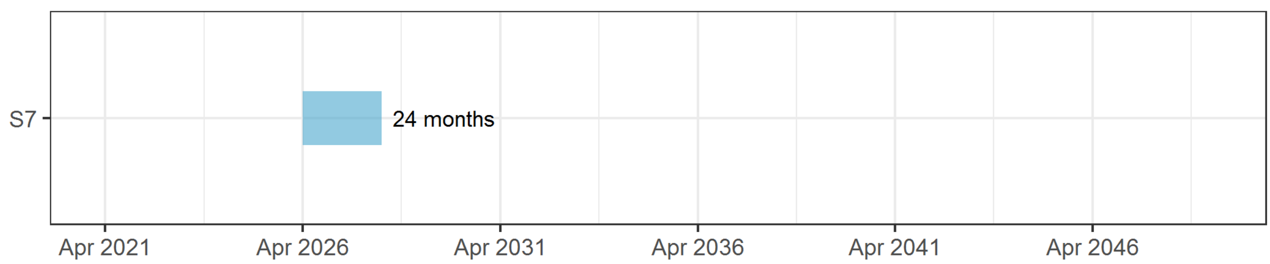
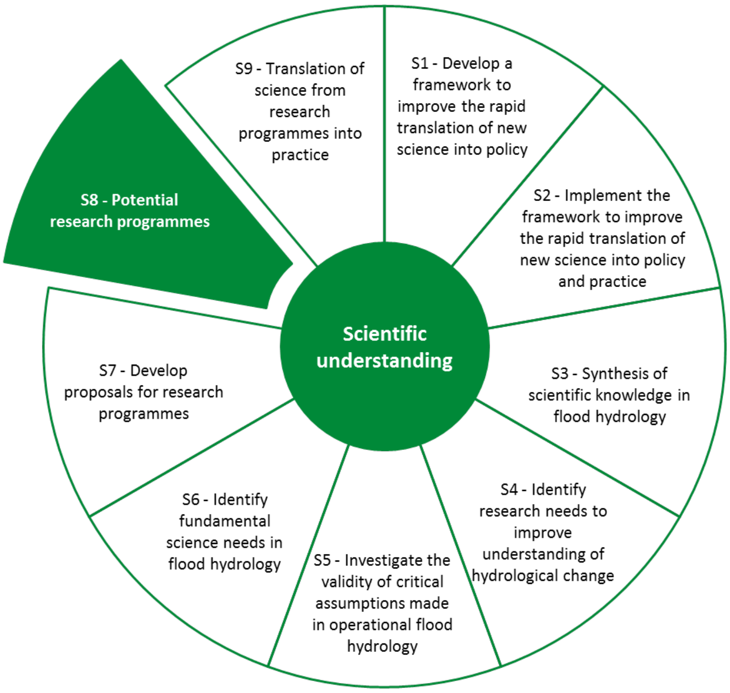


Figure G-85 – Estimated duration of action S7



Action S8: Potential research programmes



Objective

To attract funding for 3 research programmes related to flood hydrology over the next 25 years.

Outline scope

The detailed scope of research programmes related to flood hydrology will be defined by action S7. This action sets out the aspiration from the flood hydrology community to aim for 3 research council funded programmes over the 25 year lifetime of the flood hydrology roadmap. The approximate value assigned to the programmes (figure G-86) are indicative of the scale of the science challenges faced by flood hydrology.

It is anticipated that these programmes may be part of other, larger multi-disciplinary programmes and not focused solely on flood hydrology.

Intended outputs

1. Peer-reviewed publication of scientific advances.
2. New data, methods, models and knowledge of UK (and global) flood hydrology.

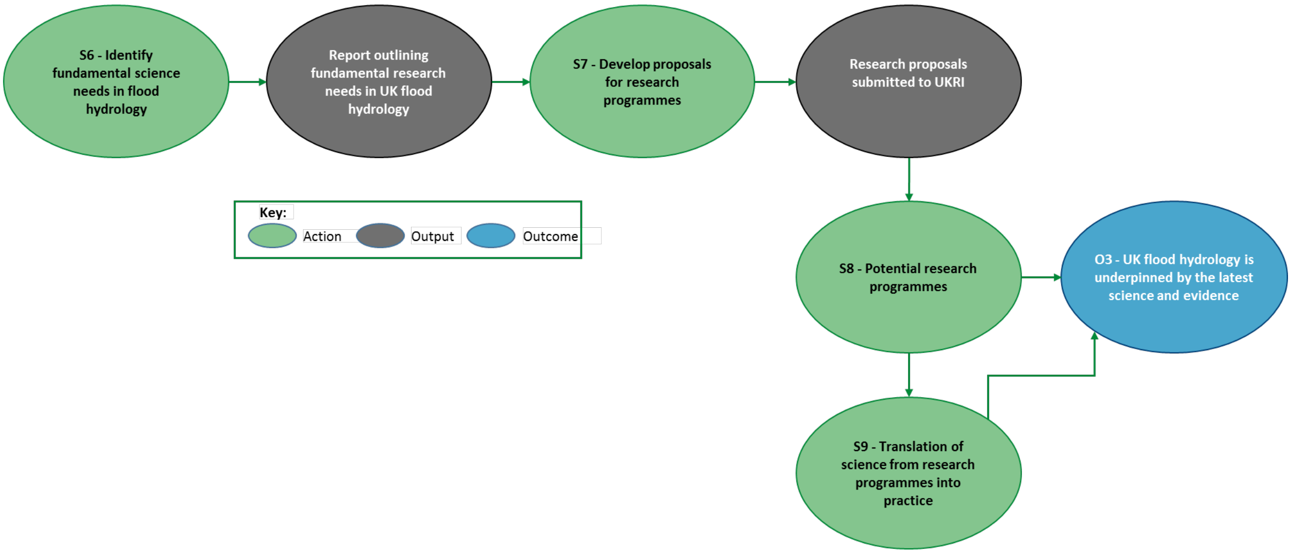
Intended outcomes

This action contributes to one outcome:

- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence

The outcome map for this action is shown in Figure G-86.

Figure G-86 – Outcome map for action S8



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-87. The profiles in Figure G-87 are indicative only, and aim to highlight the scale of investment required in the science underpinning UK flood hydrology. Three programmes are suggested with idealised value in the region of £6 million to 9 million, £6.6 million to £9.9 million and £7.5 million to £11.25 million over the 25 year lifetime of the roadmap.

The duration of this action is for the lifetime of the roadmap and is shown in Figure G-88. It is envisaged that there would be 3 research programmes over the next 25 years, each of a 3-year duration. The first programme would ideally start in 5 to 6 years' time.

Figure G-87 – Estimated spend profile for action S8

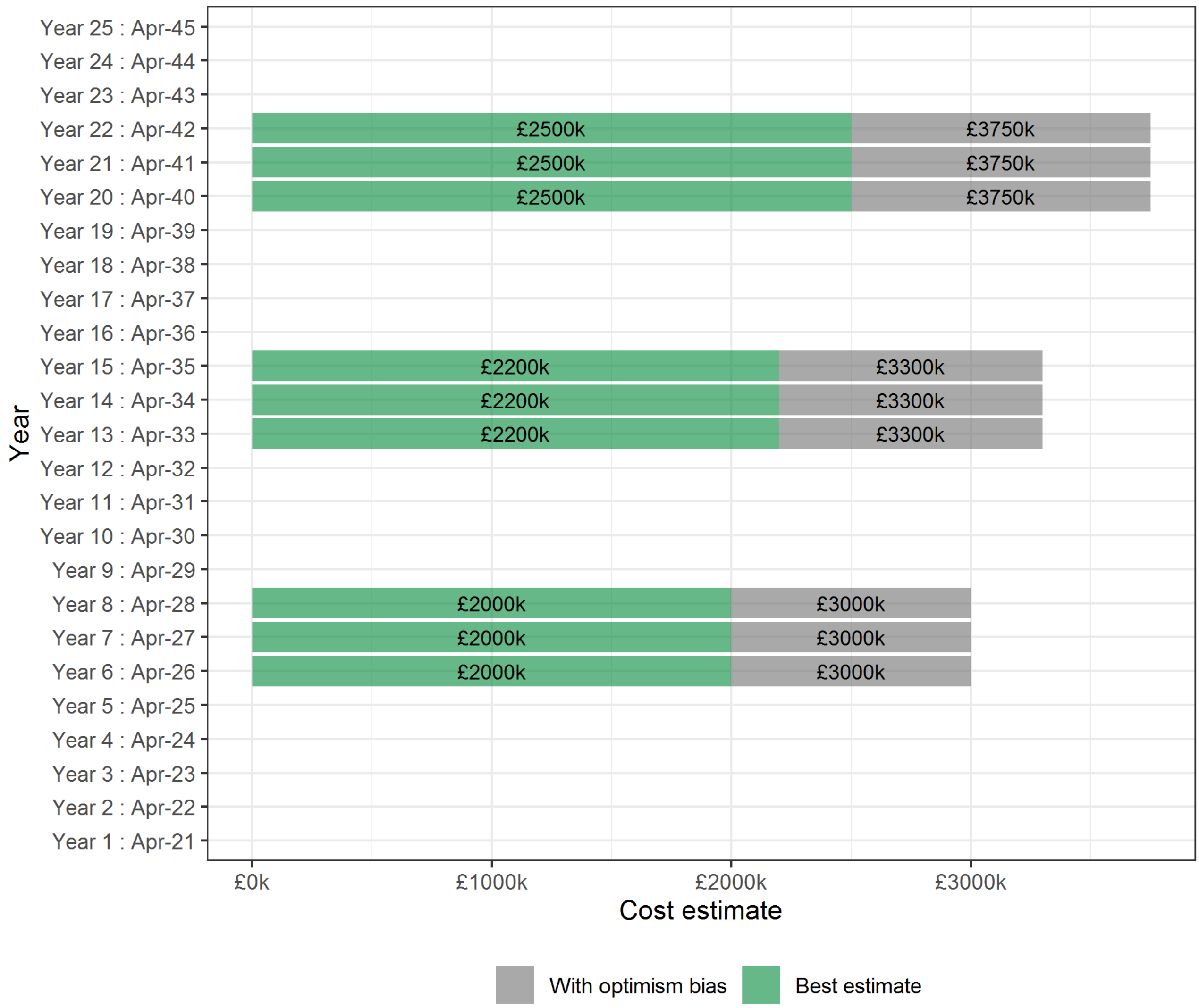
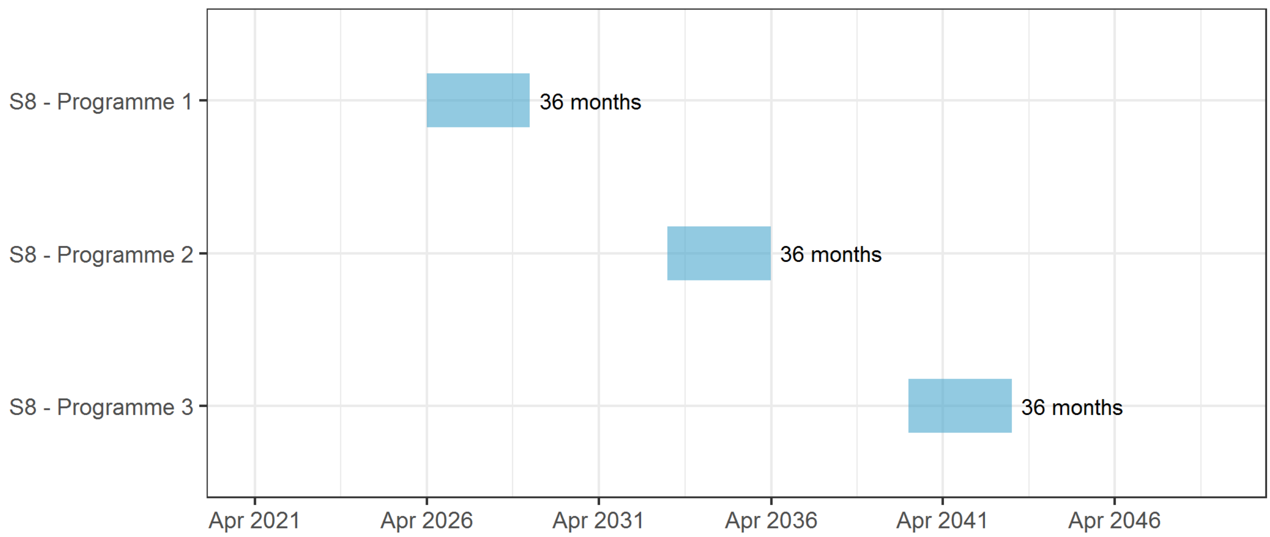
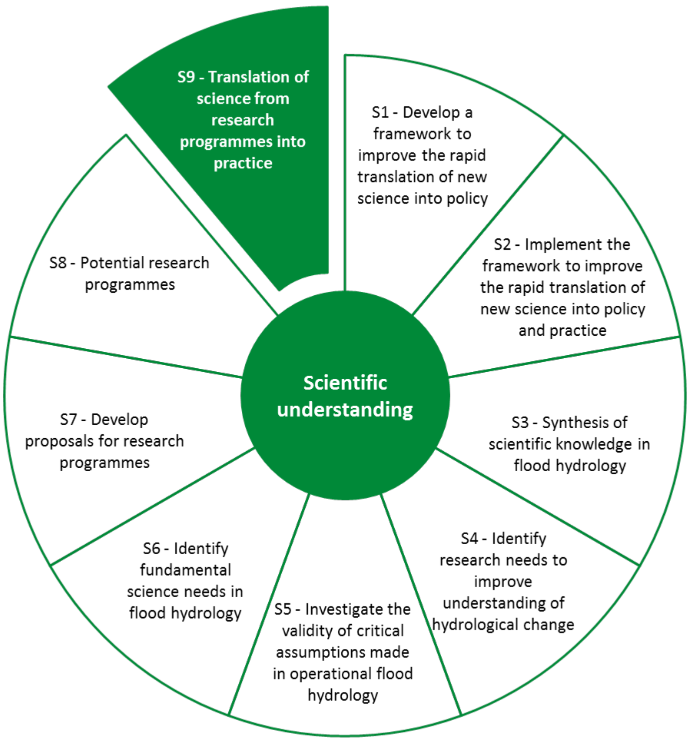


Figure G-88 – Estimated duration of action S8



Action S9: Translation of science from research programmes into practice



Objective

To rapidly translate new science from research programmes into operational practice.

Outline scope

Action S8 outlines the aspiration to bid for funding for 3 major research programmes related to flood hydrology over the lifetime of the flood hydrology roadmap. This action would focus on rapidly translating the new science from these research programmes into operational practice. It would use the framework developed by actions S1 and S2 and seek to improve that framework further.

Intended outputs

1. Rapid operational use of new scientific knowledge, methods and models.
2. Impact statements describing how new scientific knowledge, methods and models have been operationalised.

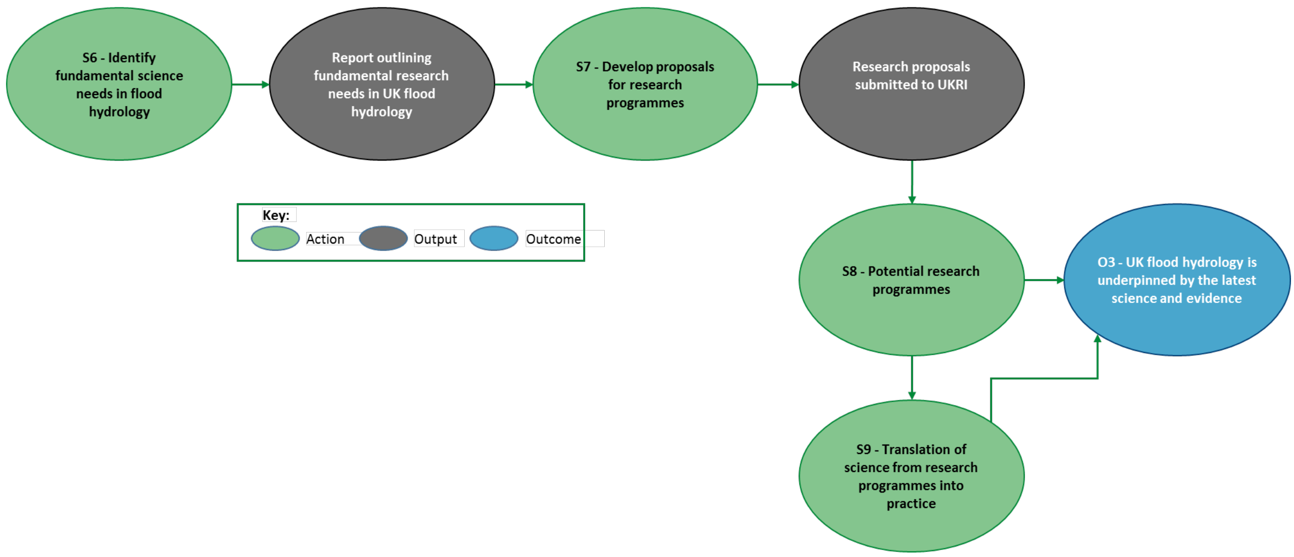
Intended outcomes

This action contributes to one outcome:

- outcome 3 - UK flood hydrology is underpinned by the latest science and evidence

The outcome map for this action is shown in Figure G-89.

Figure G-89 – Outcome map for action S9



Estimated spend profile and duration

The estimated spend profile for this action is summarised in Figure G-90. The cost of implementing new science is highly uncertain and depending on the findings of the new research, so the figures here are indicative only. It is envisaged that funding would be required from year 8 of the roadmap (April 2028) assuming that the first research programme bid outlined in action S8 is successful. Three peaks in funding are suggested to coincide with the aspirational research programmes in S8, with peak annual funding of between £1.5 million and £2.25 million suggested. The costs of this action should be reassessed when there is more certainty on future science programmes.

The duration of this action is likely to be from year 8 and then for the lifetime of the roadmap, and is shown in Figure G-91.

Figure G-90 – Estimated spend profile for action S9

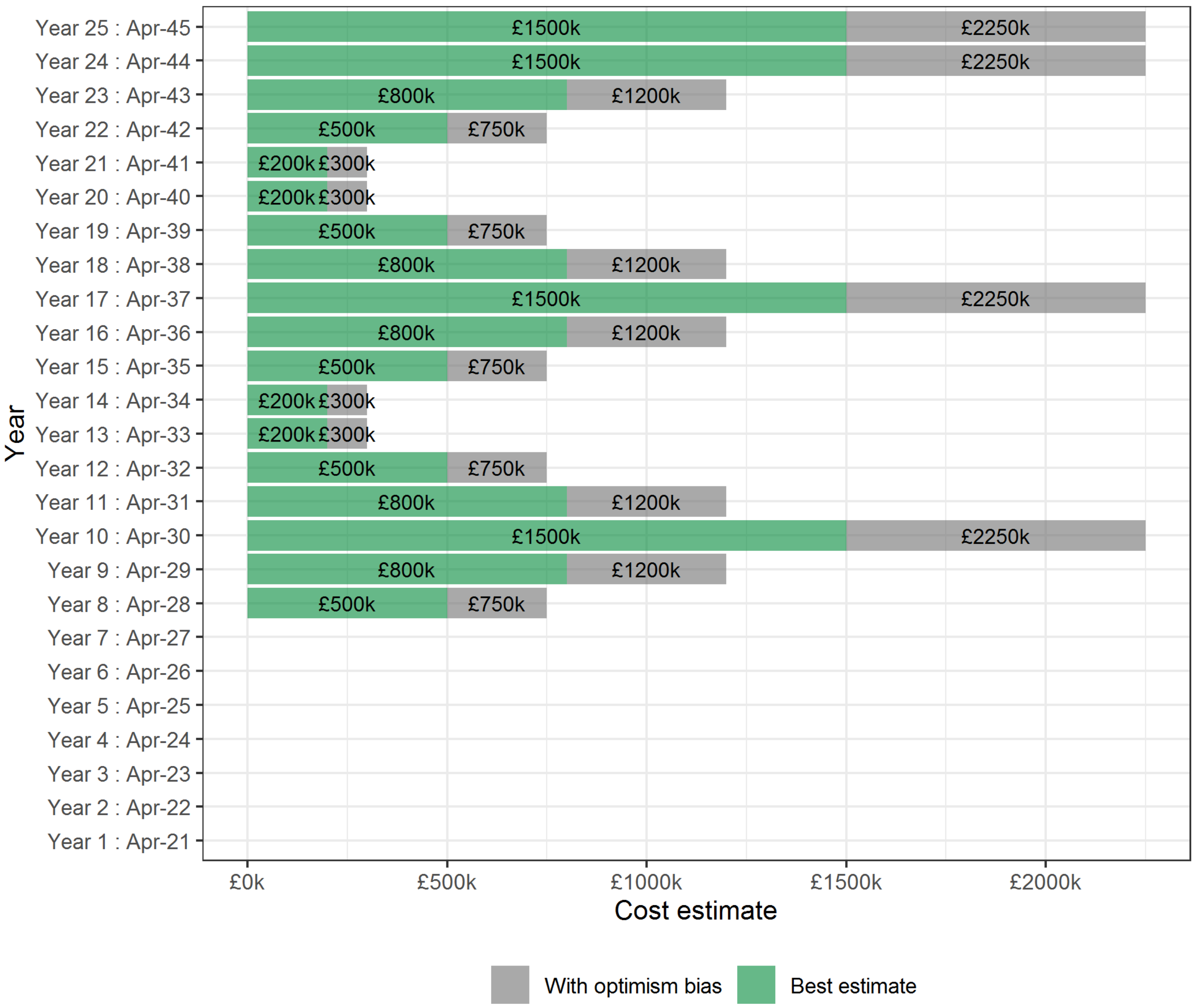
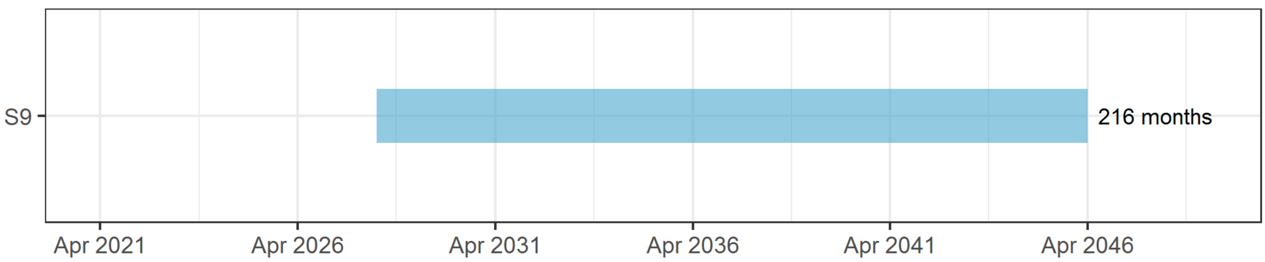


Figure G-91 – Estimated duration of action S9



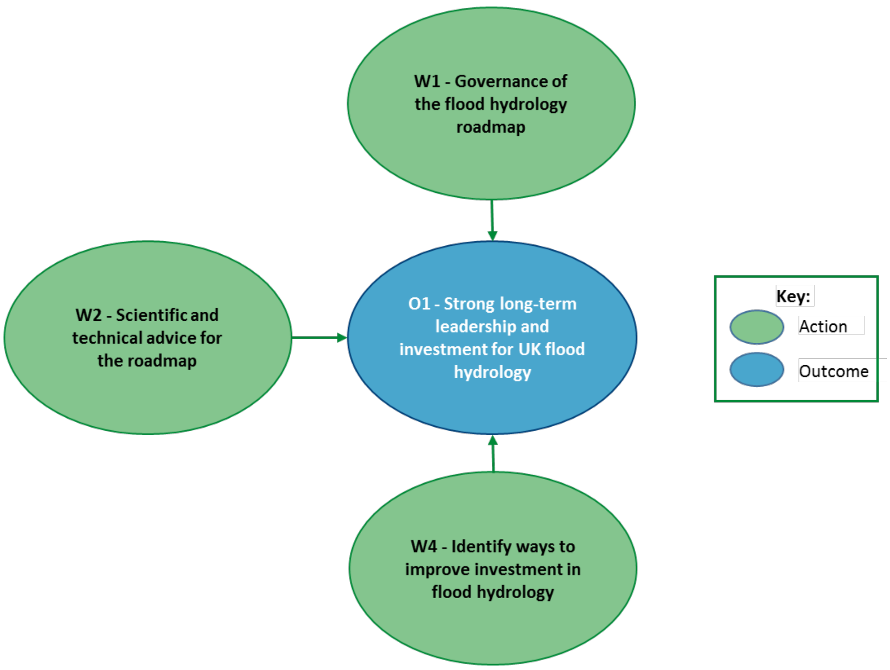
Appendix H – Outcome mapping

Outcome 1: Strong long-term leadership and investment for UK flood hydrology

Outcome 1 will be achieved if:

- there is visible and effective leadership for UK flood hydrology
- the profile of UK flood hydrology is raised
- long-term investment in UK flood hydrology is increased
- research initiatives relating to flood hydrology are better targeted at achieving impact
- the value of flood hydrology to the UK is clearly articulated
- there is improved scientific and technical steer for UK flood hydrology projects of national significance

Figure H-1: Outcome map for outcome 1

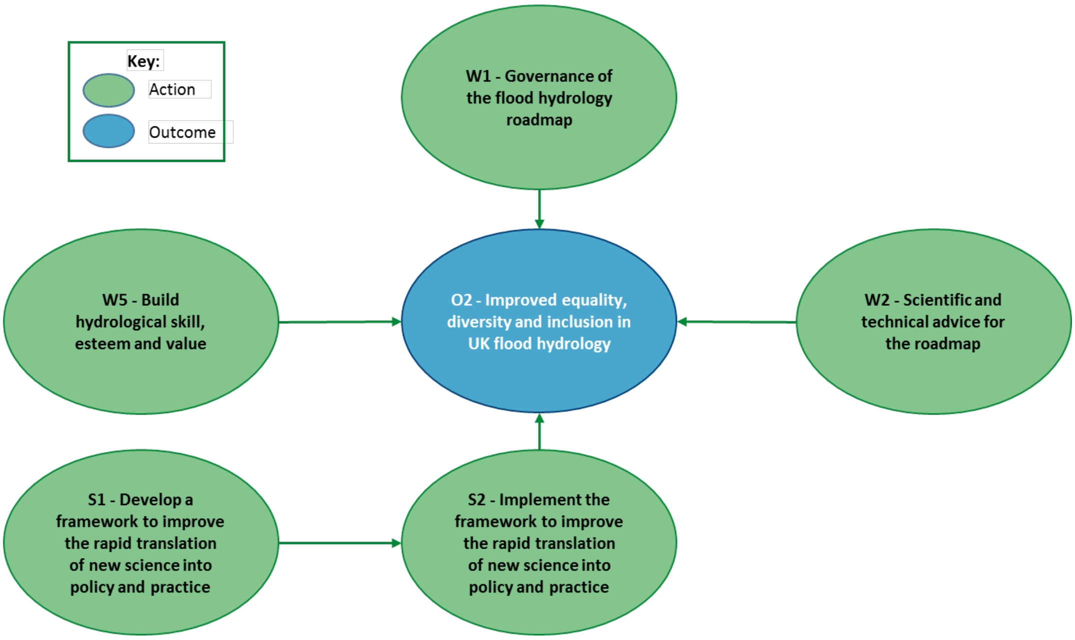


Outcome 2: Improved equality, diversity and inclusion in UK flood hydrology

Outcome 2 will be achieved if:

- the diversity of the UK flood hydrology community is better understood
- the flood hydrology workforce is more representative of the diverse communities it serves
- individuals and groups are treated fairly and have access to equality of opportunity
- there is improved diversity of thought and background in UK flood hydrology

Figure H-2: Outcome map for outcome 2

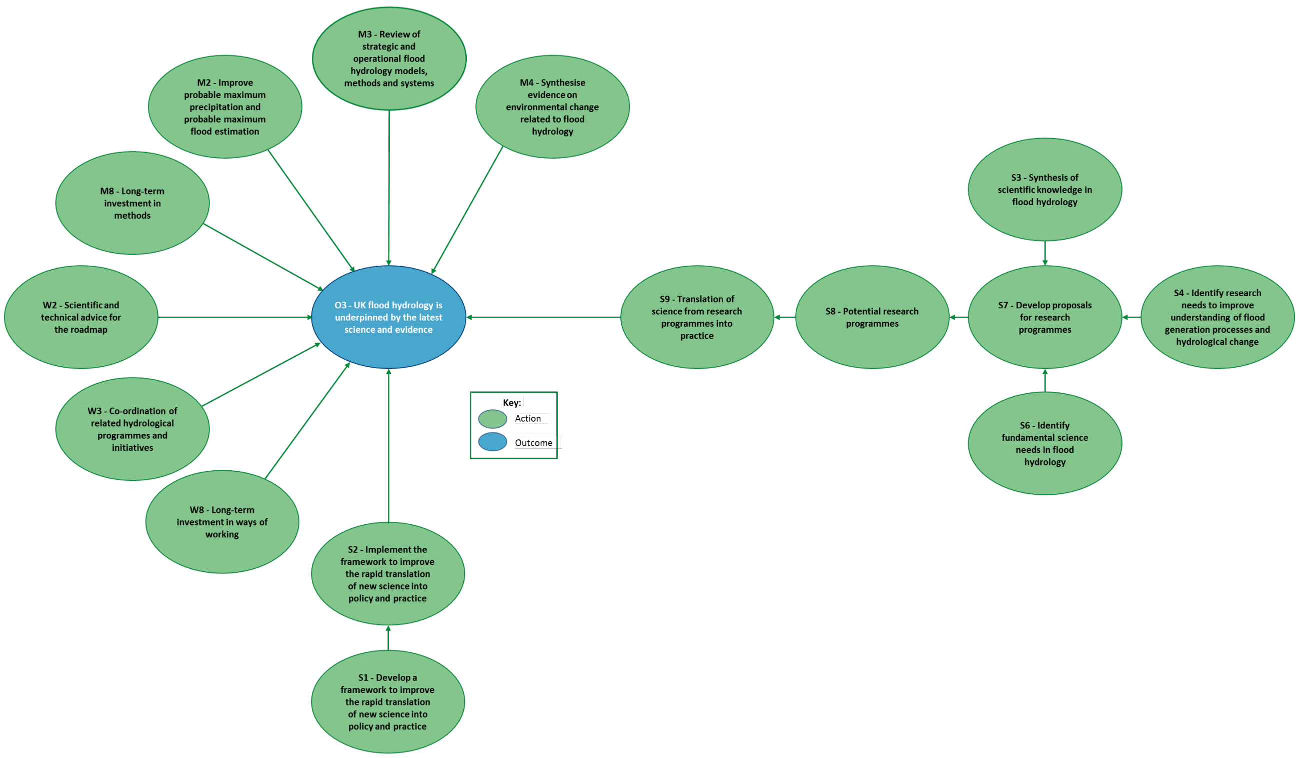


Outcome 3: UK flood hydrology is underpinned by the latest science and evidence

Outcome 3 will be achieved if:

- practitioners are more aware of, and better equipped to implement scientific advances in flood hydrology
- improved decision-making in flood risk management where decisions are informed by the latest science and evidence from flood hydrology
- the latest scientific advances in flood hydrology are synthesised regularly for scientists and practitioners
- the speed of uptake of new science into practice is improved

Figure H-3: Outcome map for outcome 3

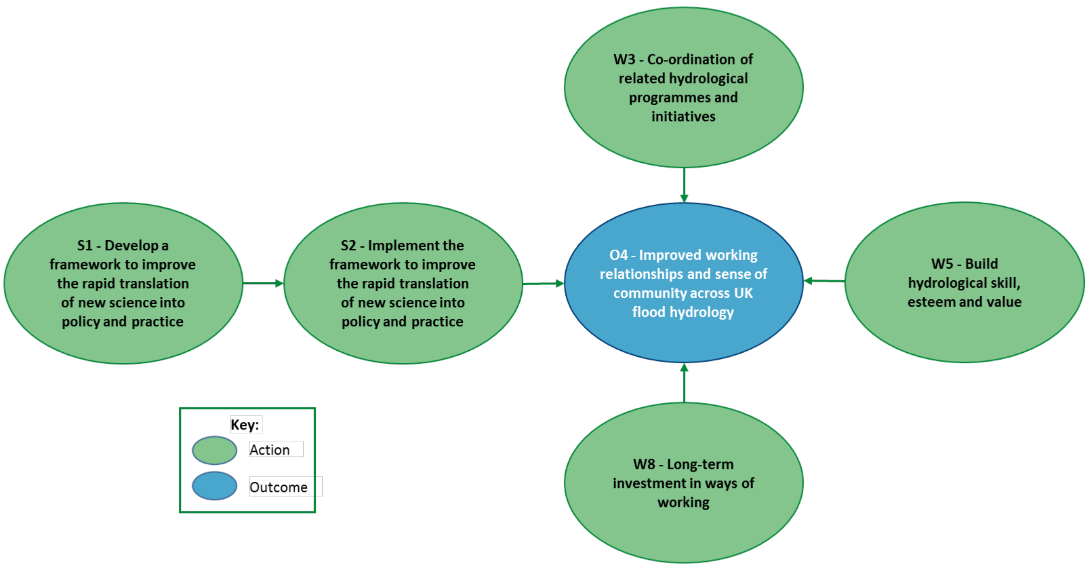


Outcome 4: Improved working relationships and sense of community across UK flood hydrology

Outcome 4 will be achieved if:

- there is improved collaboration between flood hydrology scientists and practitioners
- the scientific needs of practitioners are more visible to the science community
- the visibility of flood hydrology programmes and initiatives across the UK is improved
- the coordination and collaboration between programmes and initiatives related to flood hydrology in the UK is improved

Figure H-4: Outcome map for outcome 4

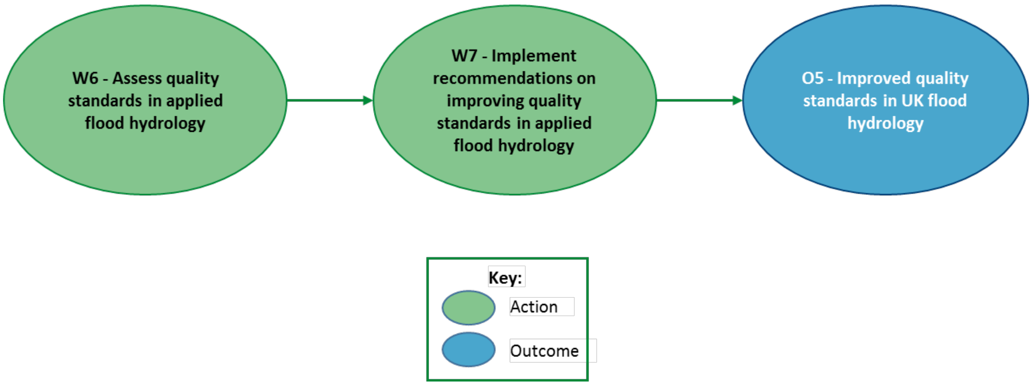


Outcome 5: Improved quality standards in UK flood hydrology

Outcome 5 will be achieved if:

- the accuracy and reliability of UK flood hydrology data is improved
- there is improved decision-making in flood risk management where decisions are based on high quality data
- the confidence in hydrological estimates is improved
- the consistency of data and modelling approach across the UK is improved

Figure H-5: Outcome map for outcome 5

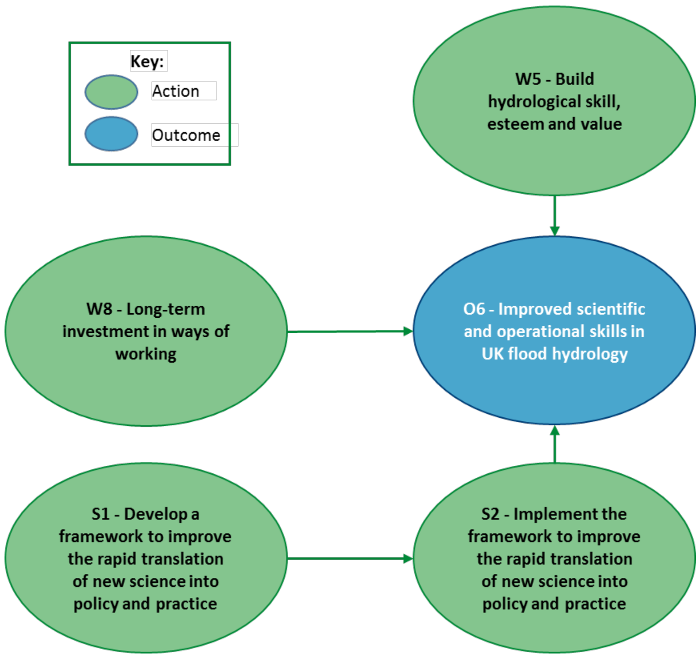


Outcome 6: Improved scientific and operational skills in UK flood hydrology

Outcome 6 will be achieved if:

- there is a better understanding of the skills of the UK flood hydrology workforce
- flood hydrology skills are more valued
- professional esteem and the profile of flood hydrologists is raised
- flood hydrology skills in the UK are continuously improved and developed
- knowledge exchange and communication between flood hydrology researchers and practitioners is improved
- flood hydrology professionals feel valued and supported

Figure H-6: Outcome map for outcome 6

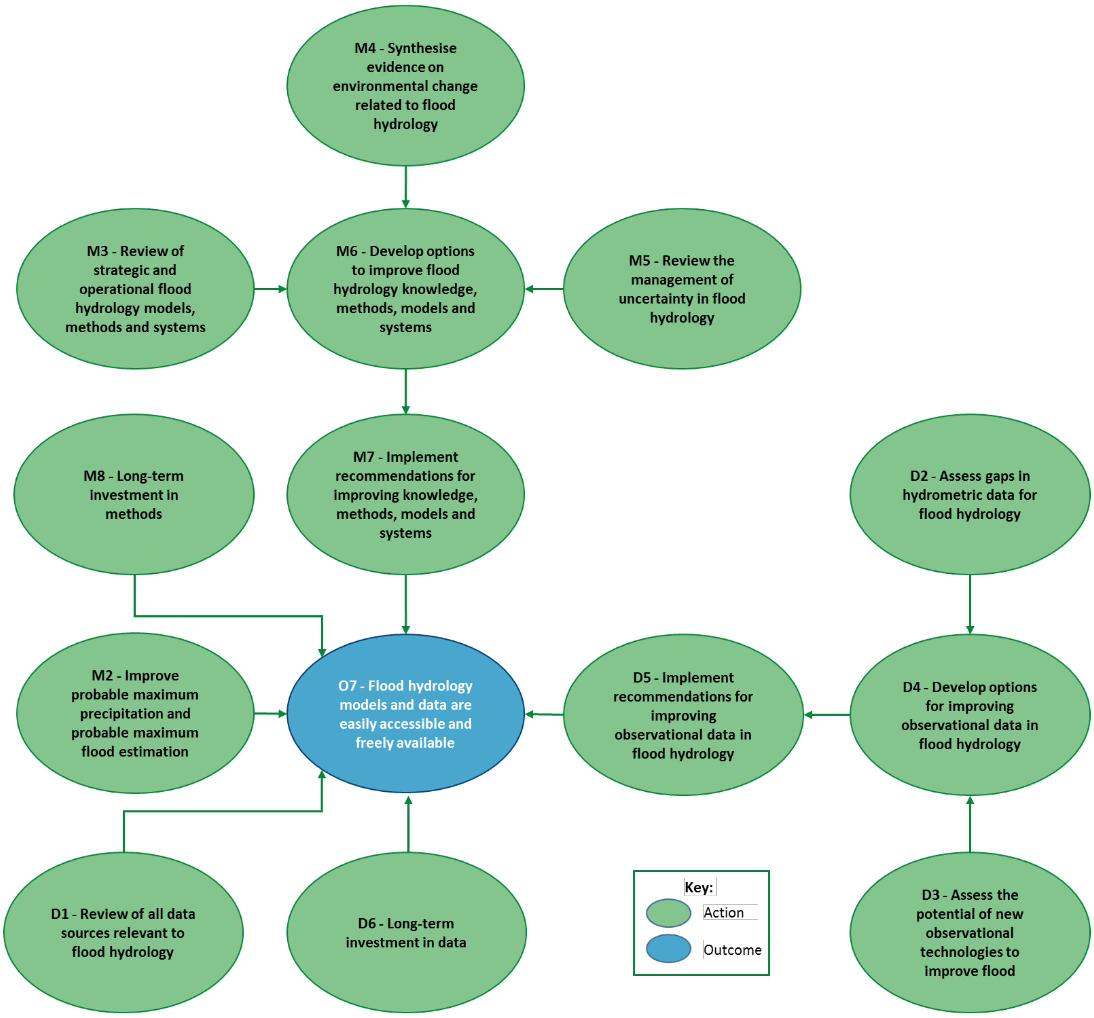


Outcome 7: Flood hydrology models and data are easily accessible and freely available

Outcome 7 will be achieved if:

- the accessibility to flood hydrology data, models, software and tools is improved
- flood hydrology data and models are open source and freely available to all
- there is improved decision-making in flood risk management where decisions are made using the best available data, methods and tools
- there is greater access to data for scientific research and development
- the UK hydrometric data better supports scientific research and operational activities

Figure H-7: Outcome map for outcome 7



Outcome 8: Uncertainty in UK flood hydrology data and models is better quantified and communicated

Outcome 8 will be achieved if:

- flood hydrologists can better quantify uncertainties in flood hydrology data and models
- the uncertainties associated with flood hydrology data and models can be clearly communicated to a range of audiences
- there is improved decision-making in flood risk management where decisions are informed by a clear understanding of the uncertainties in flood hydrology

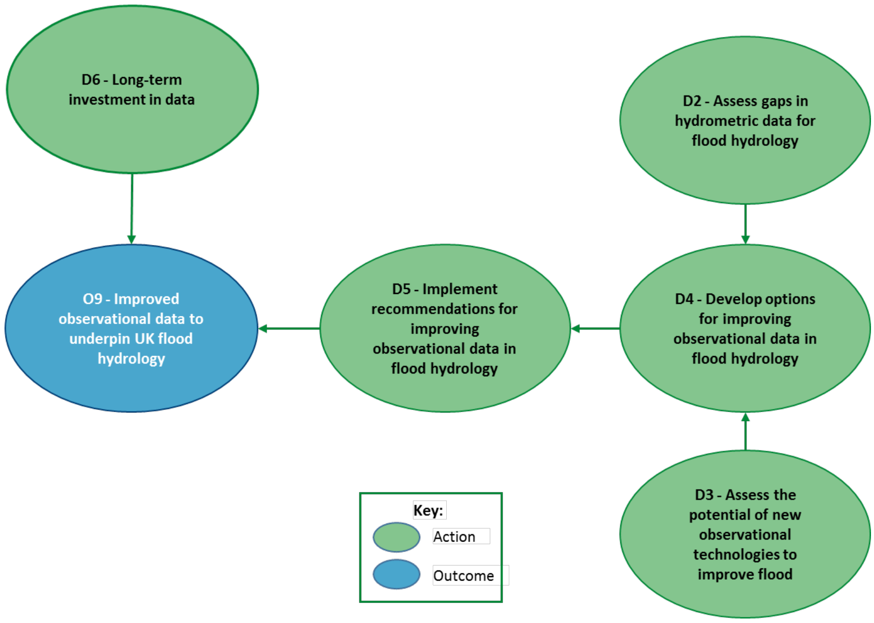
Figure H-8: Outcome map for outcome 8

Outcome 9: Improved observational data to underpin UK flood hydrology

Outcome 9 will be achieved if:

- there is a better understanding of how new observational technology can improve data quality and capture of high flows and floods
- there is a step change in the quantity and quality of high flow data collected, with a clear understanding of measurement uncertainty
- engagement with the public is increased through collecting and using citizen derived observational data on floods
- the use of radar and rain gauge data is increased in flood hydrology research and projects

Figure H-9: Outcome map for outcome 9

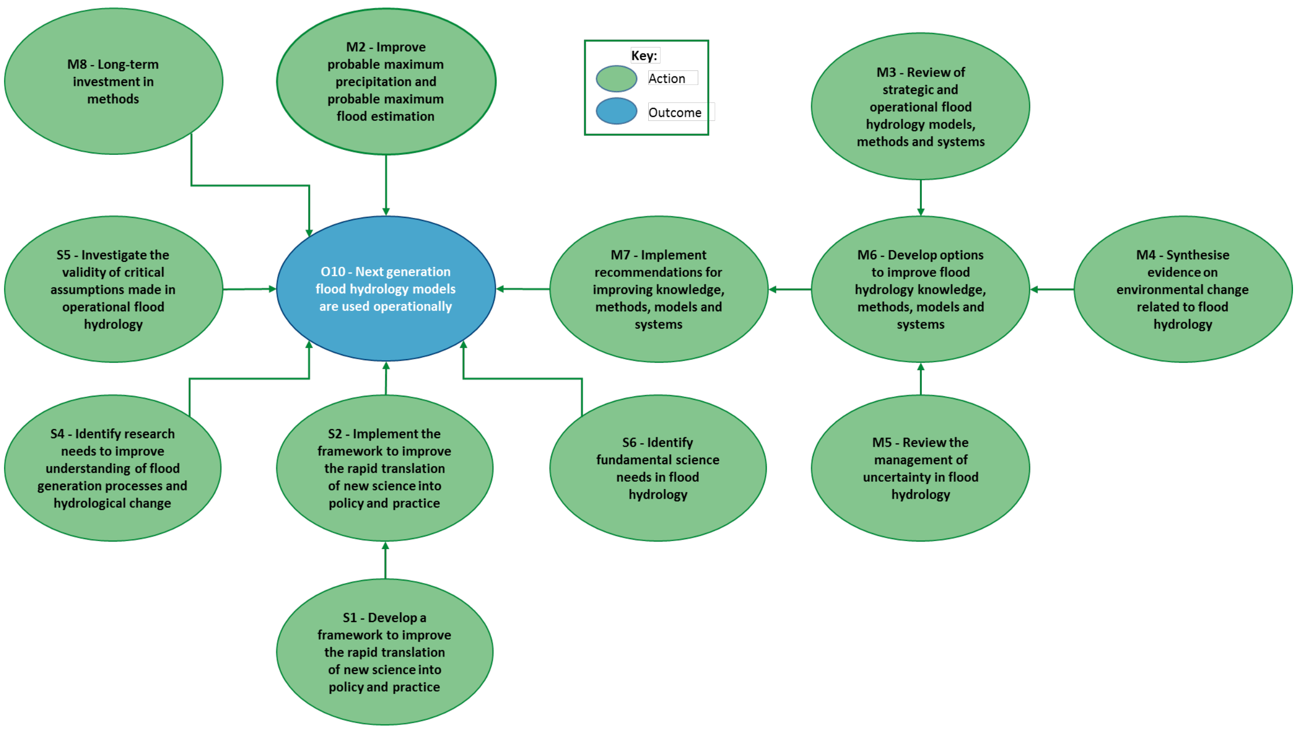


Outcome 10: Next generation flood hydrology models are used operationally

Outcome 10 will be achieved if:

- there is community-wide buy-in for the models and systems needed for flood hydrology in a changing climate
- improved understanding of the hazard faced at UK dams and reservoirs due to extreme precipitation and river flow
- next generation flood hydrology models contribute to reducing risks to life and the economy
- there is improved understanding of flood risk from fluvial, pluvial, groundwater and reservoir sources in the UK

Figure H-10: Outcome map for outcome 10

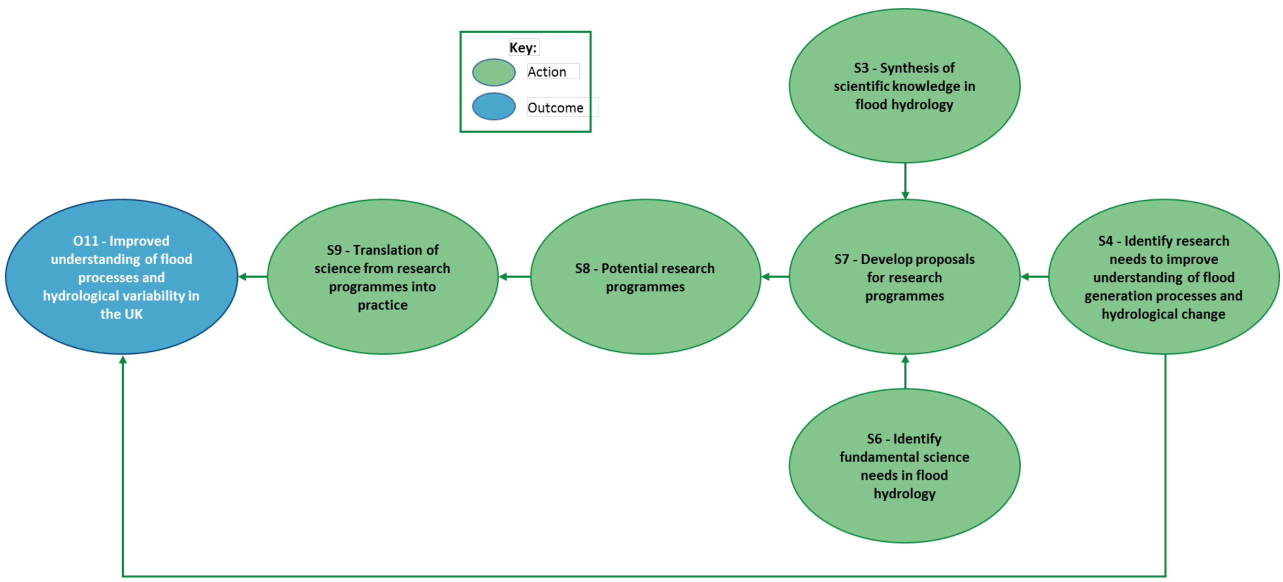


Outcome 11: Improved understanding of flood processes and hydrological variability in the UK

Outcome 11 will be achieved if:

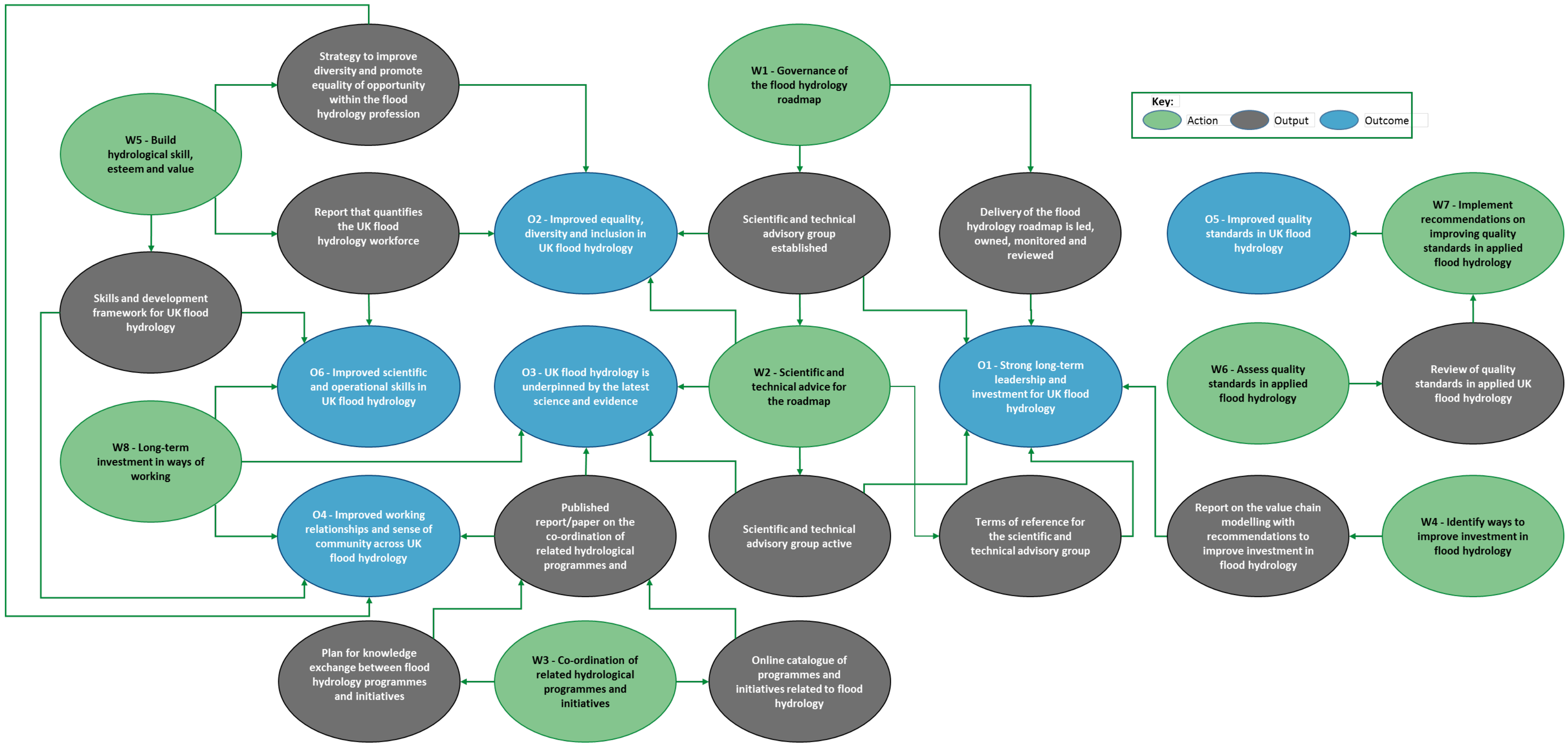
- there is improved understanding of the potential impacts of future climate variability on flood hydrology and flood risk management operations
- there is improved decision-making in flood risk management where decisions are informed by the latest knowledge and science on environmental change and process understanding
- the uncertainties around future environment change are understood and communicated

Figure H-11: Outcome map for outcome 11



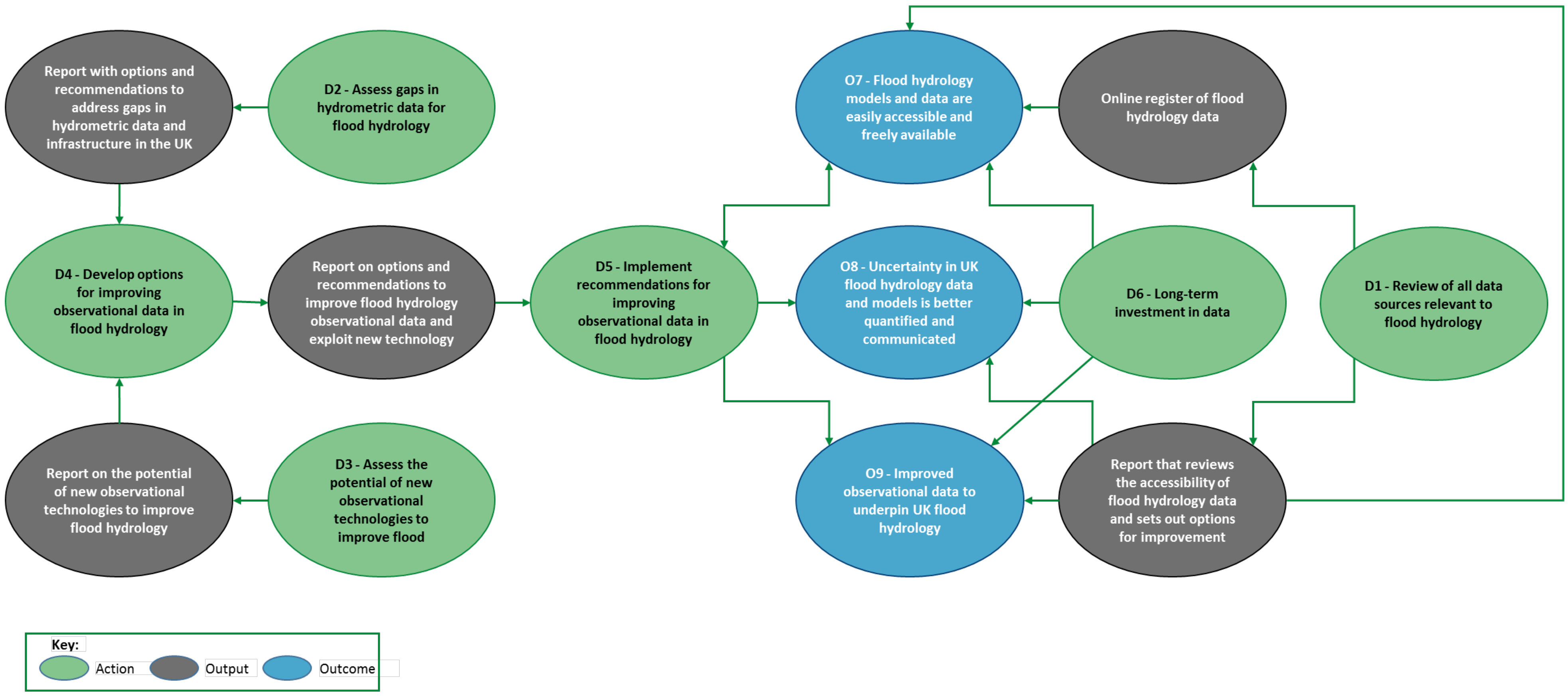
Outcome mapping for the ways of working theme

Figure H-12: Outcome map for ways of working



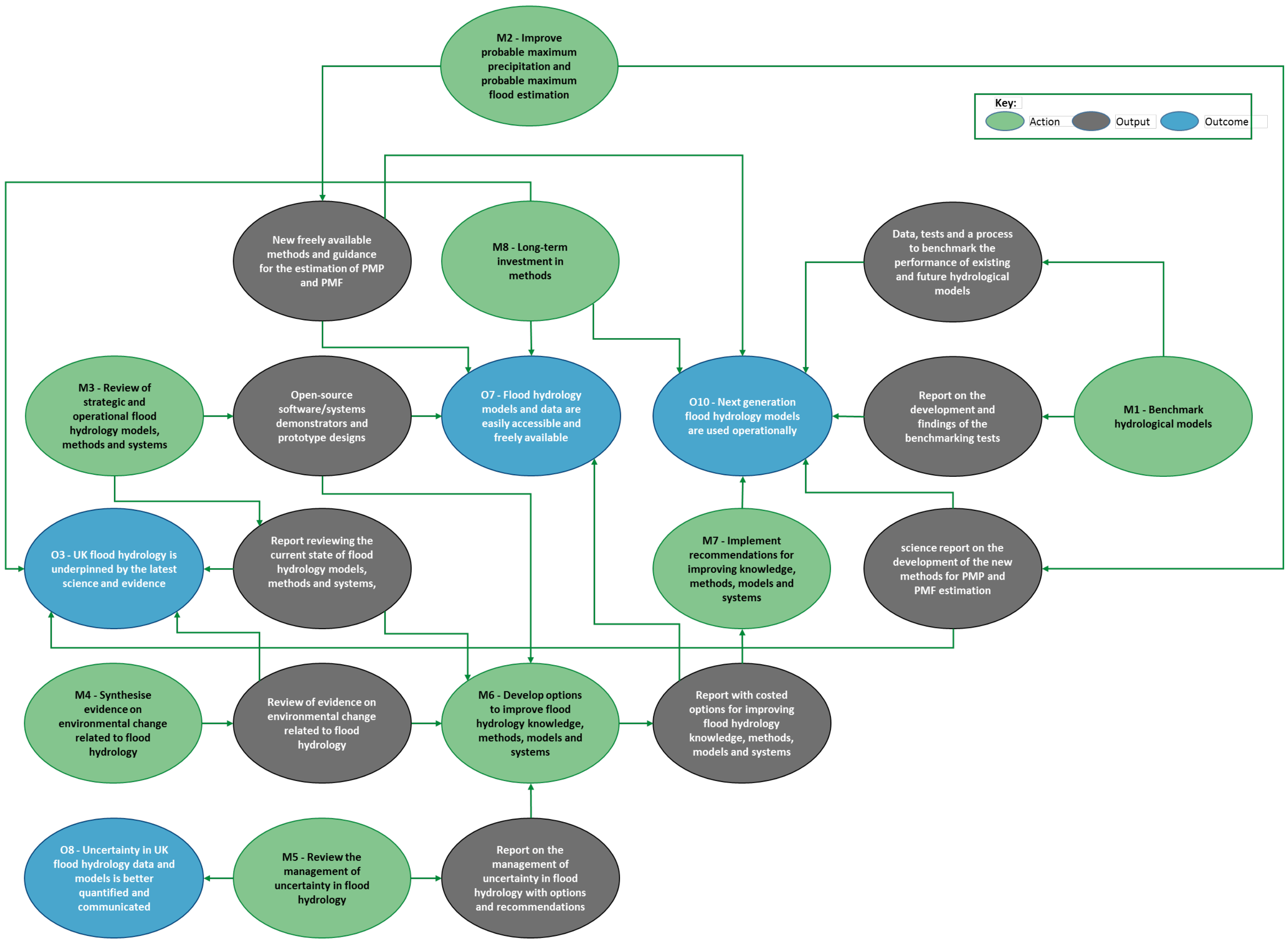
Outcome mapping for the data theme

Figure H-13: Outcome map for data



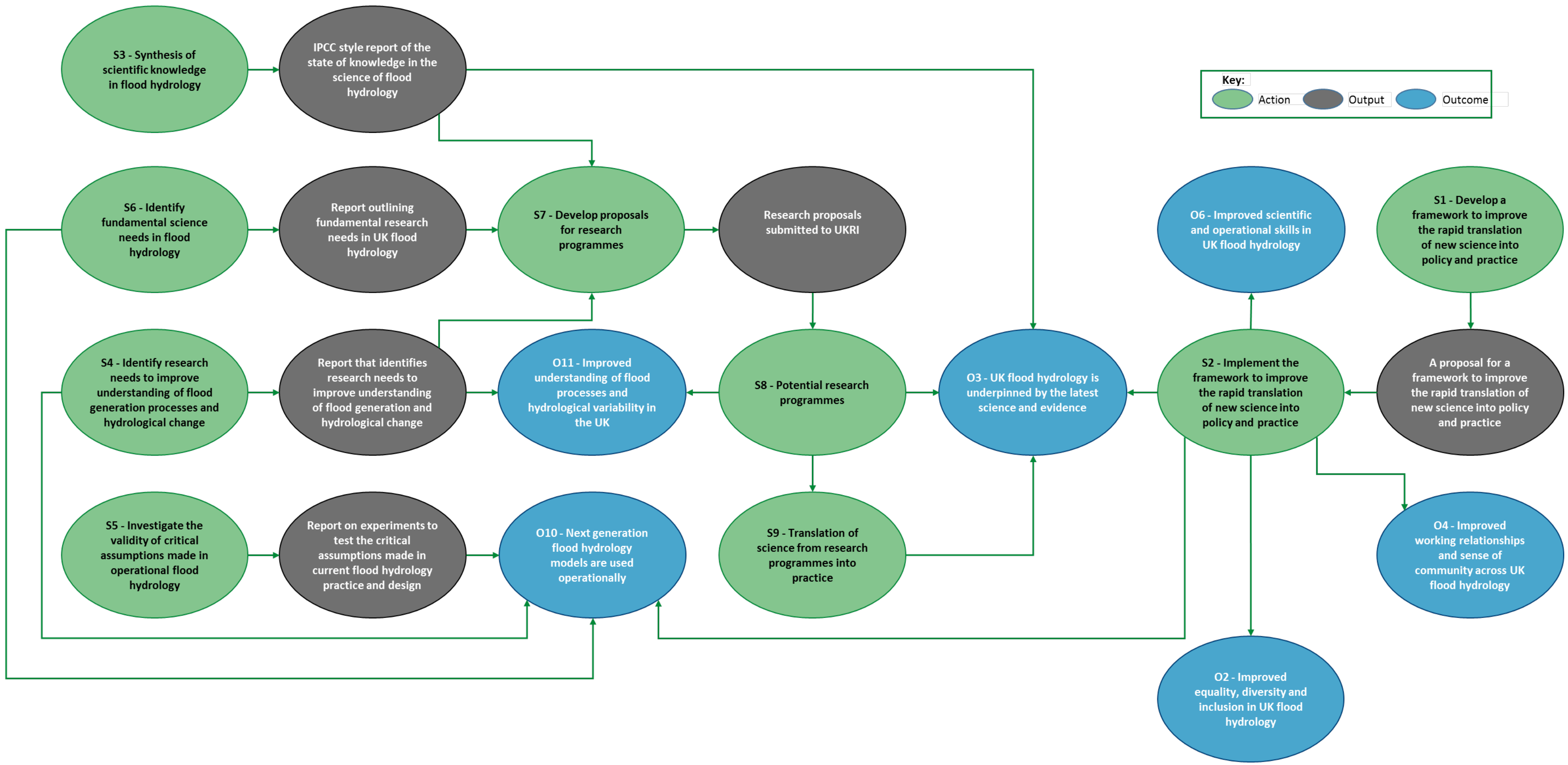
Outcome mapping for the methods theme

Figure H-14: Outcome map for methods



Outcome mapping for the scientific understanding theme

Figure H-15: Outcome map for scientific understanding



Appendix I – Machine learning interpretation of questionnaire responses

The description of this machine learning work was written by **Professor Rob Lamb** of the JBA Trust and Lancaster University. The work was carried out by **Henry Moss**, under the supervision of **Professor David Leslie**, both from Lancaster University.

Question 2 of the initial questionnaire (see appendix A) and the file FRS18196-A2-Flood hydrology roadmap - questionnaire.xlsx on GOV.UK) was:

‘We will develop a joint vision for flood hydrology 10 to 20 years from now. Please imagine you are in the future and that things are working well. Please describe what flood hydrology work looks like. We’re not asking for any suggestions of solutions but rather short descriptions of what the future could provide.

Please write as many future vision statements as you’d like.’

The text below describes an analysis of the responses to Question 2.

To augment the interpretation of the questionnaire survey responses, a parallel analysis was carried out by Lancaster University and the JBA Trust using machine learning methods. The machine learning approach was applied to all responses received to the question ‘What is your vision for flood hydrology in the UK?’

The overall aim of the analysis was to test whether a machine learning approach could augment human interpretation of the survey responses by discovering any relevant patterns in the data. Specifically, the objective was to see whether the 4 themes that had been determined by the steering group as anchors for the roadmap vision would also be discoverable from the survey by machine learning, which could be helpful in confirming the interpretations made by the steering group, or whether any alternative themes might be suggested.

The group’s 4 themes were:

- ways of working
- methods
- scientific understanding
- data

Lancaster postgraduate researcher Henry Moss, working under the guidance of Prof David Leslie, tested several relevant models for unsupervised clustering of text data. The models tested were latent Dirichlet allocation (LDA), grouped LDA, and both Frobenius and Kullback based non-negative matrix factorization (NMF).

The most interpretable model for this problem was the Frobenius-based NMF, which seeks out topics that have distinctive meanings as groups of key words, in this case the 10 most frequent words associated with each topic. To enable comparison with the steering group's interpretation, it was decided to search for 4 topics. The best-fitting model, which took 0.32 seconds to run, suggested the following 4 topics:

1. **flood hydrology risk management uses understanding models estimation natural catchment** – this is interpreted as scientific understanding and technical methods and shows a close match to steering group vision themes
2. **data access rainfall hydrometric quality flow high open available catchment** – this is interpreted as data and ways of working and shows a close match to steering group vision themes
3. **change climate future account non-stationarity land projections use changes** – this is interpreted as non-stationarity and environmental change and suggests a blend of scientific understanding and technical methods with a tilt towards strategic term applications and long-time scales
4. **non-real time modelling accessible forecasting communities little differentiation seasonal** – this is interpreted as real-time modelling, forecasting and impacts on communities and suggests a blend of scientific understanding and technical methods with a tilt towards operational applications and short time scales

The topics discovered by machine learning appear, with some overlaps, to translate readily to the vision themes that had been identified by the steering group. Perhaps the weakest interpretation is of the 'ways of working' theme, which can be linked to the significance of 'open', 'access' and 'available' in machine-discovered topic number 2, although these key words most obviously apply to data.

Machine-discovered topics number 3 and number 4 both appear to combine aspects of scientific understanding and technical methods. It is interesting to reflect that during the two-day flood hydrology community workshop in Birmingham, which followed after the questionnaire survey, the distinction between different scales of applications (for example, real-time forecasting versus long-term planning) emerged conspicuously in the development of specific areas of research and development, along with an aspiration to achieve greater integration of models used for real-time and long-term applications.

Broadly then, the machine learning interpretation of the survey responses was consistent with the choice of themes made by the steering group, and appeared to anticipate the attention on time scales that was apparent in the subsequent community workshop.

The description of this machine learning work was written by **Professor Rob Lamb** of the JBA Trust and Lancaster University.

Appendix J – Optimism Bias Calculation

Strategic 25-year Costs – Optimism Bias Calculation

Method: Annex 2 of Defra Guidance Document 'FCDPAG3 Economic Appraisal Supplementary Note to Operating Authorities' (March 2003).

Starting (upper bound) Optimism Bias factor for **Strategy** costs: **60%**

Risk components contributing to bias (%, summing to 100)		**Average % for FDC Projects**	**% for Flood Hydrology Roadmap**
Procurement	Late contractor involvement in design	1	1
	Dispute and claims occurred	11	5.5
	Other	1	1
Project-specific	Design complexity	4	6
	Degree of innovation	4	8
	Environmental impact	13	2.6
	Other	9	9
Client-specific	Inadequacy of the business case	23	23
	Funding availability	2	2
	Project management team	1	1
	Poor project intelligence	8	8
Environment	Public relations	5	1
	Site characteristics	4	0.8
External Influences	Economic	5	5
	Legislation/regulations	4	4
	Technology	4	4
	Other	1	1
	TOTAL	**100**	**82.9**

Optimism bias calculation = (100 – 17.1) / 100 x 60 = 49.7%

Therefore, optimism bias allowed at 50%

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INSTITUTE OF HYDROLOGY, 1999. Flood Estimation Handbook, 5 Volumes, Institute of Hydrology, Wallingford, UK. [Last accessed 22 November 2021].

NERC, 1975. Flood Studies Report. 5 Volumes, Natural Environment Research Council.

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The Environment Agency **project board** responsible for overall delivery of the roadmap project. The project board members were: Craig Woolhouse (Project Sponsor), Dr Sue Manson (Project Executive), Dr Sean Longfield (Project Manager), Anita Asadullah (Senior User) and Dr Mike Vaughan (Senior User).

The **project steering group** who provided invaluable advice, direction and peer review throughout the project. The steering group members were: Professor Hannah Cloke (University of Reading), Dr Charlie Pilling (Flood Forecasting Centre), Professor Rob Lamb (JBA Trust and Lancaster University), Nick Reynard (UKCEH) and Owain Sheppard (Natural Resources Wales).

Individuals who helped develop the project proposal. From the **Incident Management and Modelling Theme Advisory Group** (IMM TAG) of the Joint Environment Agency, Defra, Natural Resources Wales and Welsh Government Flood and Coastal Erosion Risk Management Research and Development Programme: Andy Wall (Natural Resources Wales), Andy Tagg (HR Wallingford), Dr Steve Cole (UKCEH), Nick Reynard (UKCEH), Professor Hannah Cloke (University of Reading), Dr Micha Werner (Deltares), Professor Rob Lamb (JBA), Max Tant (Kent County Council), Graeme Boyce (Flood Forecasting Centre). From the Environment Agency: Dr Sue Manson, Dr Sean Longfield, Dr Chrissy Mitchell, Anita Asadullah, Dr Mike Vaughan, Shirley Greenwood and Dr Harriet Orr.

51 respondents (representing 270 individuals) to a **questionnaire** sent out in May 2018 to gather initial thoughts and ideas on a vision for the flood hydrology roadmap and current challenges and opportunities.

Participants of a **workshop in Birmingham** on 24 and 25 September 2018 to start to develop the vision and needs of the flood hydrology roadmap: Craig Woolhouse (Environment Agency), Dr Sean Longfield (Environment Agency), Anita Asadullah (Environment Agency), Dr Sue Manson (Environment Agency), Alan Brown (Reservoir Safety Advisory Group), Amanda McKevitt (Environment Agency), Becky Wilson (Scottish Environment Protection Agency), Bridget Woods-Ballard (HR Wallingford), Dr Charlie Pilling (Flood Forecasting Centre), Dr David MacDonald (British Geological Survey), Dr David Mould (CIWEM Rivers and Coastal Group), Deborah Lee (Met Office), Debra Thomson (Environment Agency), Duncan Faulkner (JBA Consulting), Emma Bergin (Insurance industry- FloodRe), Professor Hannah Cloke (Reading University), Professor Hayley Fowler (Newcastle University), Helen Harfoot (Aecom), Ian Scholefield (United Utilities), Dr Ilaria Prosdocimi (University of Bath), J. Murphy (Northern Ireland Rivers Agency), John Waddingham (Environment Agency), Jude Jeans (Wallingford

HydroSolutions), Dr Mark Whiteman (Environment Agency), Peter Spencer (Environment Agency), Phil Raynor (Jacobs), Richard Davis (Environment Agency), Rob Lamb (JBA Trust), Ruth Kelman (Natural Environment Research Council), Sam Everitt (Environment Agency), Dr Shaun Harrigan (European Centre for Medium-Range Weather Forecasts), Shirley Greenwood (Environment Agency), Sophie Vanicat (Environment Agency), Richard Robinson (Environment Agency), Steve Cole (Centre for Ecology and Hydrology), Sun Yan Evans (Mott Macdonald), Professor Thorsten Wagener (Bristol University), Tim Harrison (Environment Agency), Tim Hunt (Environment Agency), Professor Tom Coulthard (Hull University).

Facilitators of the Birmingham workshop: Helen Bovey (Icarus), Matt Croney (Icarus), David Bliss (Environment Agency), Fiona Green (Environment Agency), Kate McNally (Environment Agency), Liz Etheridge (Environment Agency), Liz Fowler (Environment Agency), Rachel Walters (Environment Agency) and Sarah Blenkin (Environment Agency).

125 respondents to an **online survey** that sought wide input on draft vision statements and potential work areas in the flood hydrology roadmap.

4 voluntary **current practice task groups** were established to summarise current practice in flood hydrology for reservoirs, groundwater, surface water and fluvial flood risk for both forecasting and planning perspectives.

Fluvial task group members were: Phil Raynor (Jacobs), Dr David Mould (CIWEM and Canal and River Trust), Dr Mike Vaughan (Environment Agency), and Dr David Price (Flood Forecasting Centre).

Surface water task group members were: Bridget Woods-Ballard (HR Wallingford), Dr David Price (Flood Forecasting Centre), Richard Robinson (Environment Agency), Richard Kellagher (HR Wallingford), Richard Body (HR Wallingford), Adrian Lee (NWL), Mel Harrowsmith (Met Office), Duncan Faulkner (JBA Consulting), and Dave Smith (Environment Agency).

Groundwater task group members were: Dr Mark Whiteman (Environment Agency), Dr Geoff Parkin (Newcastle University), Dr David MacDonald (British Geological Survey), Dr David Price (Flood Forecasting Centre), and Nigel Hoad (Environment Agency).

Reservoir task group members were: Dr Thomas Kjeldsen (University of Bath), Dr David Mould (CIWEM and Canal and River Trust), Duncan Faulkner (JBA Consulting), Alan Brown (Jacobs), Alan Warren (Mott MacDonald), Peter Ede (British Hydrological Society), Tony Deakin (Environment Agency), and Luke Ballantyne (Arup).

Prioritisation task group members who helped prioritise potential work areas in the flood hydrology roadmap: Alan Brown (Reservoir Safety Advisory Group), Becky Wilson (Scottish Environment Protection Agency), Bob Moore (UK Centre for Ecology and Hydrology), Bridget Woods-Ballard (HR Wallingford), Dr Charlie Pilling (Flood Forecasting Centre), Claire Samuel (Jacobs), Dr David MacDonald (British Geological Survey), Glenda Tudor-Ward (Natural Resources Wales), Professor Hannah Cloke (Reading University),

Professor Hayley Fowler (Newcastle University), Dr James Miller (UK Centre for Ecology and Hydrology), Kim Hearn (AECOM), Dr Louise Slater (Oxford University), Dr Matt Horritt (Horritt consulting), Dr Megan Klaar (Yorkshire Integrated Catchment Solutions Programme (iCASP), University of Leeds), Dr Micha Werner (Deltares), Nick Reynard (UK Centre for Ecology and Hydrology), Owain Sheppard (Natural Resources Wales), Pascal Lardet (Scottish Environment Protection Agency), Peter Spencer (Environment Agency), Phil Raynor (Jacobs), Professor Simon Dadson (UK Centre for Ecology and Hydrology), Sun Yan Evans (Mott Macdonald), Dr Thomas Kjeldsen (University of Bath), Professor Thorsten Wagener (Bristol University), Tim Hunt (Environment Agency), and Tony Deakin (Environment Agency).

The **delivery partners group** who helped develop the flood hydrology roadmap action plan: Anita Asadullah (Environment Agency), Craig Woolhouse (Environment Agency), Andy Wall (Natural Resources Wales), Becky Wilson (Scottish Environment Protection Agency), Dr Charlie Pilling (Flood Forecasting Centre), Martin Best (Met Office), Professor Rob Lamb (JBA Trust and Lancaster University), Ruth Bond (Department for Infrastructure, Northern Ireland), Ruth Kelman (UK Research and Innovation), Dr Shaun Harrigan (European Centre for Medium-Range Weather Forecasts) and Eoghan Daly (Department for Infrastructure, Northern Ireland).

The **enablers group** who helped develop the flood hydrology roadmap action plan: Aidan Hannah (Department for Infrastructure, Northern Ireland), Steve Cole (UKCEH), Peter O'Flaherty (Waterman Infrastructure & Environment Ltd and CIWEM), Professor Hayley Fowler (Newcastle University and the British Hydrological Society), Nick Reynard (UKCEH), Bryony Smith (Capita and CIWEM), Dr Charlie Pilling (Flood Forecasting Centre), Owain Sheppard (Natural Resources Wales), Fiona Barbour (Mott MacDonald and CIWEM) and Ruth Bond (Department for Infrastructure, Northern Ireland).

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List of abbreviations

AEP	Annual exceedance probability
AMAX	Annual maximum peak flow
ARMA	Auto-regression moving average
ARR	Australian Rainfall and Runoff
BDS	British Dam Society
BGS	British Geological Survey
BHS	British Hydrological Society
BSG	British Society for Geomorphology
CASE	Collaborative Awards in Science and Engineering
Icasp	Yorkshire Integrated Catchment Solutions Programme
CCRA	Climate Change Risk Assessment
CEDA	James Hutton Institute and the Centre for Environmental Data Analysis
CIWEM	Chartered Institution of Water and Environmental Management
COSMOS	Cosmic-ray soil moisture monitoring network
CREW	Scotland’s Centre of Expertise for Water
DDF	Depth-duration-frequency model
DWF	Dry weather flow
ECMWF	European Centre for Medium-Range Weather Forecasts
EDI	Equality, diversity and inclusion
EFAS	European Flood Awareness System
EPSRC	Engineering and Physical Sciences Research Council
FCERM	Flood and coastal erosion risk management
FDRI	Flood Drought Research Infrastructure
FEH	Flood Estimation Handbook
FEH13 DDF	Flood Estimation Handbook 2013 rainfall depth duration frequency

FFC	Flood Forecasting Centre
FRM	Flood risk management
FRMRC	Flood Risk Management Research Consortium
FRS4	Floods and Reservoir Safety (ICE, 4th Edition)
FSR	Flood Studies Report (1975)
G2G	Grid-to-grid model
HOST	Hydrology of soil types
Hydro-JULES	Hydro-Joint UK Land Environment Simulator
IAHS	International Association of Hydrological Sciences
ICE	Institution of Civil Engineers
ICM	Integrated catchment modelling
IMM TAG	Incident Management and Modelling Theme Advisory Group
IPCC	Intergovernmental Panel on Climate Change
IPR	Intellectual property rights
ISIS	Hydraulic modelling software
ISO	International Organization for Standardization
IT	Information technology
JBA	Jeremy Benn Associates
LANDWISE	Project on land-based NFM measures to reduce the risk from flooding
LDA	Latent Dirichlet Allocation
MOGREPS	Met Office Global and Regional Ensemble Prediction System
NERC	Natural Environment Research Council
NFM	Natural flood management
NFRR	National Flood Resilience Review
NMF	Non-negative matrix factorization
NWEP	Numerical weather environmental predictor

NWP	Numerical weather prediction
ONR	Office for Nuclear Regulation
PDM	Probability Distributed Rainfall Runoff Models
PhD	Doctor of Philosophy
PMF	Probable maximum flood
PMP	Probable maximum precipitation
Protect-NFM	Project on upland restoration and reducing flood risk
PYRAMID	Platform for dynamic, hyper-resolution, near-real time flood risk assessment integrating repurposed and novel data sources
QA	Quality assurance
QMED	Median annual maximum flood
ReFH1	Revitalised Flood Hydrograph (ReFH) version 1
ReFH2	Revitalised Flood Hydrograph (ReFH) version 2
RESAS	Scottish Government's Rural and Environment Science and Analytical Services Division
RGS	Royal Geographical Society
SAGA	Surface and Groundwater Archives committee
SMS	Short Message Service
SPR	Standard Percentage Runoff
STAG	Scientific and Technical Advisory Group
STEM	Science, Technology, Engineering and Mathematics
STEPS	Short-Term Ensemble Prediction System
SuDS	Sustainable drainage systems
SWFDST	Surface Water Flooding Decision Support Tool
SWFHIM	Surface Water Flooding Hazard Impact Model
TOPMODEL	A semi-distributed topographic hydrologic model
TUFLOW	Hydraulic modelling software

UKCEH	UK Centre for Ecology and Hydrology
UKCP18	UK Climate Projections 2018
UKRI	UK Research and Innovation
UKWIR	UK Water Industry Research
WISKI	System used by the Environment Agency for the management of hydrometric and hydrological measured values
WMO	World Meteorological Society
WRAP	Winter Rainfall Acceptance Potential

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