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Resilience to Fluvial Flooding: Knowns and Unknowns to Recommendations for Management

Policy Brief

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Recommendations

Through a critique of the academic literature and a workshop with key stakeholders, the following recommendations were identified which emerged from things we know about fluvial flood risk which need to be translated into policy, and also things that we don't know, or know with a low level of confidence, that need further research to address these priorities for flood resilience policy-making.

- **Mainstream and upscale Natural Flood Management (NFM) and/or Nature-based Solutions (NbS) implementation, supported by monitoring and maintenance. Ensure NFM is assessed holistically for use alongside hard engineered solutions.**
- **Contextualize flood management decisions to take into account hydrological complexity, non-linearity, and the unique geography of each catchment.**
- **Shift to adaptive planning, to account for future uncertainty associated with climate change, including in terms of mindset of planners, economic appraisal, and funding mechanisms.**
- **Encourage community co-creation of flood management for place-based, socially accepted policies, relating to standard of protection, risk perception, and balance of options.**
- **Address the many gaps in our knowledge, highlighted by scientific confidence assessments and Unknown Unknowns, which need future research.**

Background

Fluvial flooding is an increasing problem in Scotland, with high magnitude events occurring in 2000 (Edinburgh), 2007 (Aberdeen), 2012 (Tayside, Fife), 2015 (Dee, Storm Frank), 2020 (Dumfries and Galloway, Borders), 2023 (Brechin). Climate change, catchment-wide land use changes and urbanisation are all potential causes of increased runoff and flood risk, along with the impacts on vulnerability and resilience. Flood risk management is the responsibility of many actors in Scotland, including SEPA and Local Authorities.

The Flood Risk Management Act (2009) provides the policy framework for fluvial flood management, with an emphasis on public consultation and natural flood management. It is important to assess the current state of knowledge and critique what we know and what we do not know about fluvial flood risk, resilience and management. This assessment and policy brief aims to inform the Flood Resilience Strategy currently being developed by the Scottish Government.

Research undertaken

We have used the epistemological construct of "Known Knowns, Known Unknowns and Unknown Unknowns"[1] (Figure 1) to assess scientific knowledge on fluvial flooding through a literature review and stakeholder workshop. We used a wide range of search terms and combinations thereof relating to fluvial flood risk generation, management, and resilience using the Scopus and Web of Science platforms (Appendix A). The search was not constrained by time period or by geographical scope but did focus particularly on scientific journal publications. We utilised the power of AI to synthesise a large volume of information in an efficient manner to highlight emerging themes.

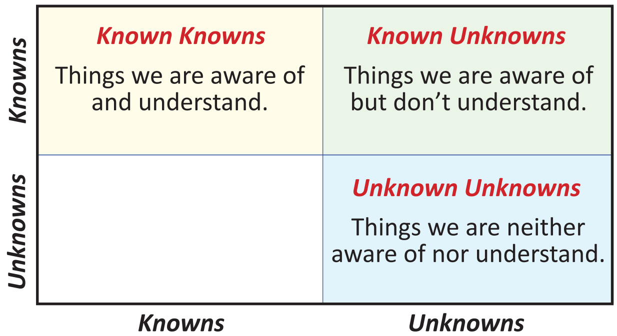

Figure 1: Knowns and Unknowns Construct.[1]

The themes which emerged from the bibliographic analysis were used to delve deeper into the literature by considering review papers associated with each theme and then discussed at a stakeholder workshop to get academic, policy and industry perspectives. We then listed Knowns and Unknowns under each theme and co-produced recommendations for the Flood Resilience Strategy for Scotland. These were not exhaustive but a summary of the key findings.

Critique of the AI Approach

To synthesise a large volume of information efficiently and highlight emerging themes, AI was used. This was done using VOSviewer, which analyses and visualises bibliographic networks. A co-occurrence analysis of the top 1000 keywords was conducted. This identified which keywords occur most frequently across the literature database; the strength of the relationship between items (in this case, the keywords) is based on how often they occur together in the database of literature records. In the network visualisation diagrams (Figure 2) the network lines indicate which keywords are connected. The scale of the keyword bubbles (i.e. the size of the circle) represents the 'total link strength' of that keyword. Each time a keyword is linked to another, that link is assigned a value of 'strength' based on the number of times they are linked; therefore, the keywords with the highest total link strength indicate those that are identified most frequently and repeatedly occur in relation to others. This approach allowed us to draw out the key themes that were repeatedly highlighted in the literature and intricately linked with other themes that arose.

AI has huge potential for synthesising large volumes of information quickly and conducting Natural Language Processing. However, there are some factors that need to be conisdered when using AI. First, the analysis is limited by the information that we provide it with (i.e. limited by the search terms). Second, the representativeness of the publication by the keywords listed in it was not assessed as part of this analysis. Finally, concepts or processes can be defined by a number of different keywords, particularly where terms are regionally different (e.g. catchment vs. watershed) and other concepts can encompass a number of more detailed items (e.g. nature-based solutions as an umbrella term encompassing natural flood management, green infrastructure).

Definitions

Return Period: A statistical metric of the probability that a flood exceeding a given magnitude will occur based on historical datasets. Peak flood discharge with a 100-year return period is likely to be exceeded once in every 100 years on average; it can also be defined as having a 1% chance of occurring within any given year. Events with a longer return period (e.g. 1000-year) have a lower probability of occurrence than low return period events (e.g. 2-year floods).

Risk: The intersection of hazard and vulnerability[25]. Risk does not simply represent the probability that a hazard may or may not occur; a key element of risk is the "potential for adverse consequences for human or ecological society"[26] (p128) as a result of the hazard.

Natural Flood Management: Natural flood management involves techniques that aim to work with natural hydrological and morphological processes, features and characteristics to manage the sources and pathways of flood waters[2].

Lag Time: The time difference between peak rainfall of a storm event and the resulting peak flood discharge (or stage) at a chosen point of interest.

Non-Linearity: A description of the relationship between two variables. A change in one variable does not result in a proportional change to the other. The relationship between rainfall and runoff generation in a river catchment is a key example – i.e. a 10% increase in total rainfall will not result in a 10% increase in total runoff.

Uncertainty: The lack of definitive understanding of characteristics and behaviours of complex natural systems and processes (e.g. fluvial flood generation) and the lack of certainty in predicting future behaviours based on current knowledge and methodology (e.g. climate modelling and projections). The term can also define the reported range of error surrounding an observed or predicted variable.

Although the AI is an invaluable tool to manage large datasets of bibliographic information it is still important to check manually to capture any duplicate or near-duplicate terms (e.g. climate-change vs. climate change; flood event vs flooding event) and keywords with alternative terms (e.g. catchment vs. watershed).

Research Findings

Applying our search terms, inclusion and exclusion criteria resulted in thousands of papers. The keyword network analysis results are presented in Figure 2 for the Top 200 keywords, as it balances breadth of keywords and visualisation. The size of the bubbles represents how common each keyword was and the lines represent co-occurrence of the two keywords on each end of the line. This has allowed us to classify four significant themes that have emerged from Figure 2. More detailed VOSviewer networks can be found in Appendix B for each of the themes. First, climate change (Blue) was associated with keywords including variability and uncertainty relating to the hydrological processes of precipitation and streamflow (flooding and drought). Second, flood generation (Red) was associated with catchment scale hydrology, particularly runoff and the potential of numerical models to provide flood forecasting. Third, Natural Flood Management[2] (NFM) and associated terms Nature-based Solutions (NbS) (Yellow/Green) demonstrate linkages to land use changes, urbanisation and the wider ecosystem service benefits provided by this type of management. The final and fourth theme relates to wider flood management including the participation of stakeholders and linkages to policy (Yellow). The following sections report the key Knowns and Unknowns under each of these themes.

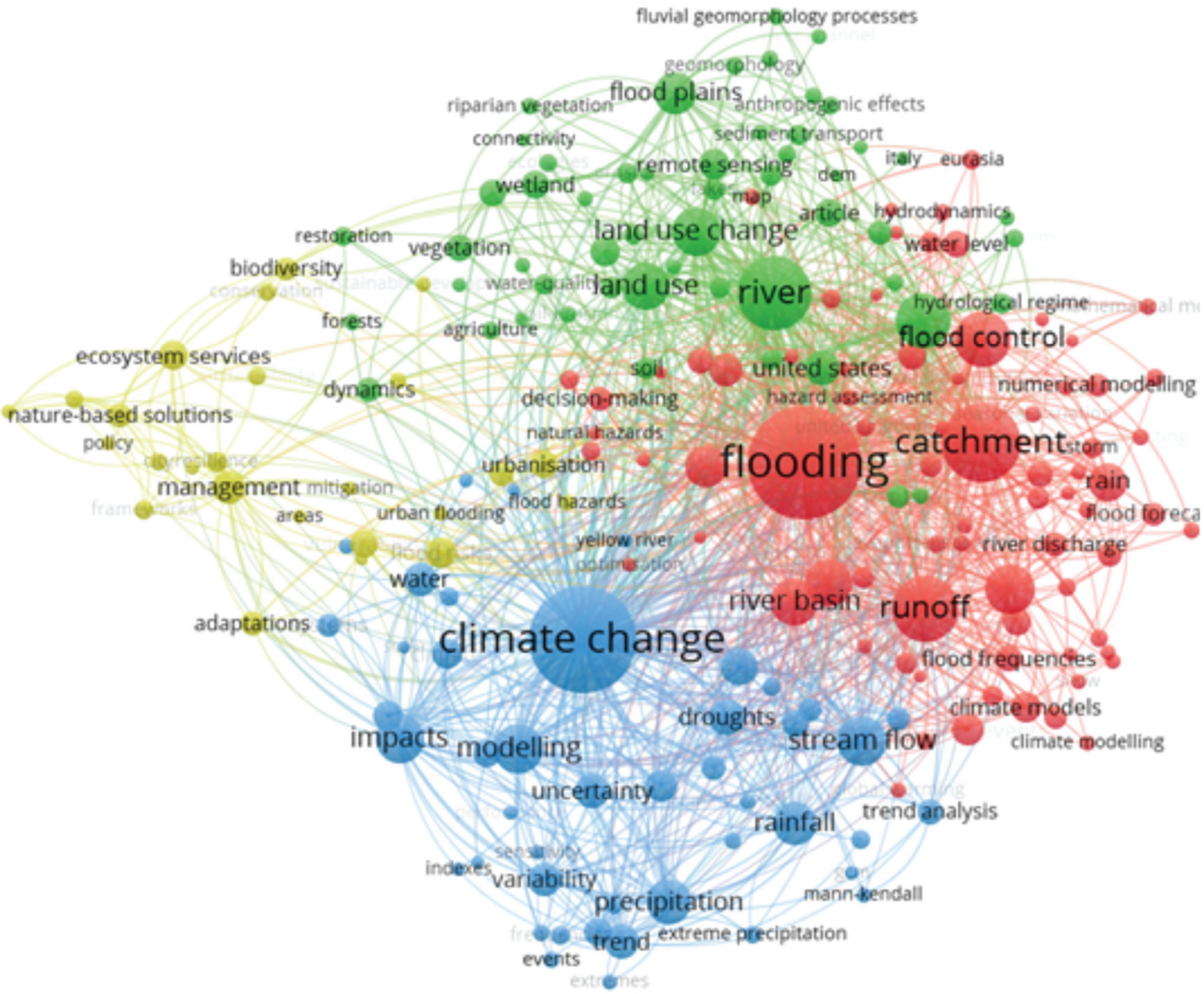

Figure 2: AI generated keyword network

Knowns

Climate Change: The UK is likely to experience increased precipitation in winter months which is expected to increase the frequency of occurrence and the severity of fluvial flooding.[3] The changes will not be spatially uniform; it is estimated that catchments in the north and west of Scotland will experience higher percentage increases in winter precipitation and flood peaks.[4, 5]

Flood Generation Hydrology: Fundamental principles of lag time between rainfall peaks and flood peaks, and lag times between peak flows from different tributaries[6, 7] control the generation of floods and the magnitude and shape of the downstream hydrograph. Desynchronising flood peaks from different tributaries reduces the magnitude of the flow downstream[8]. This potentially can be achieved through strategically implementing NFM which slows the flow in upstream areas. Conversion of rainfall to runoff is a non-linear process and is dependent upon the catchment characteristics, including initial soil saturation, and the storm event characteristics (rainfall volume, intensity and storm track).

Natural Flood Management: NFM has been proven effective for high-frequency, low return period, small storms.[9] For example, one study found that leaky barriers reduced flood peaks for low return period (1-in-1-year) storms.[10] In the Eddleston catchment (area 69 km^2), NFM was shown to increase the "lag time" between rainfall and peak river levels.[11] NFM can be combined with hard engineering approaches to increase its effectiveness.[12] Often, NFM brings additional benefits e.g. biodiversity, carbon storage.[13]

Stakeholder Engagement: Funding is only one of many issues that can affect NFM implementation. Other factors that affect stakeholder decision-making include traditional land use practices,[14] policies, and public perceptions.[15] Meanwhile, there are calls for increased and more meaningful public participation in flood risk management in general and NFM in particular.[16] Memory is an important factor in community perceptions of flood risk.[17]

Unknowns

Climate Change: Absolute estimates of the impacts of climate change on precipitation and flooding are unknown. Complex global and regional climate models and projections which inform current policy are probabilistic and are accompanied by estimates of uncertainties.[3] This is further compounded by uncertainty of other forcing factors such as land use change.[18]

Flood Generation Hydrology: Can NFM achieve the time lag delays needed to fully desynchronise tributary peaks and reduce downstream floods in larger catchments? Flood generating processes in terms of hydrograph convolution from upstream parts of the catchment are different in space and time and are therefore context-specific. Studies[19] are allowing some degree of understanding of flood generation beyond the specific catchment and event, but more research is needed to develop more comprehensive generalisations of this complex non-linear and scale dependent process.[20]

Natural Flood Management: NFM has not been proven effective for preventing flooding from large storms or in large catchments, defined as those greater than 100 km^2.[9] Challenges to proving NFM's effectiveness for high-return-period flood events include a lack of data and relatively small-scale implementation at a catchment scale to date. More data are needed[21] to build additional understanding of NFM's effectiveness in the face of diverse weather events, locations, and contexts.

Stakeholder Engagement: There is significant uncertainty associated with flood management, including in the realm of politics and decision-making processes.[22] Flood risk management, because it occurs at the community rather than household scale, opens the door to moral hazards such as the "safe development paradox".[23] Furthermore, flood risk management should be equitable, providing benefits across society.[24] Finding the right balance of NFM, grey infrastructure, do-nothing, and retreat is a difficult task that requires input and negotiation from affected people.

Stakeholder Workshop

A wide range of professional stakeholders from policy, academia and industry attended a workshop. The aim was to understand what practitioners thought in terms of what are Knowns and Unknowns with regard to the four themes identified in the literature review. Table 1 shows some of the common ideas brainstormed throughout the workshop. Some of the raw outputs of the workshop are in Appendix C.

Table 1

	Knowns	Unknowns
Climate Change	• "Climate change is happening" – it is increasing the likelihood of flooding and will lead to worsening impacts. • Climate change will lead to "wetter autumns/ winters" and "more intense rainfall events in summer and winter".	• Which representative concentration pathway (RCP) are we on?
Flood Generation	• "When rivers are out of bank this results in flooding." • Every water catchment/system is unique".	• How different distributions of rainfall will change volume of water might enter a river". • "Difficulties in modelling uncertainties"
NFM	• "NFM can influence flows" but "not many NbS/ NFM schemes have been designed". • NFM "requires partnership working" and is "location-specific" but brings "co-benefits enabling multiple funding streams".	• "Effectiveness of different NFM measures over larger spatial scales and larger timescales...to capture 'big' flood events". • "Impacts of new developments/housing on flood risk mitigation".
Stakeholders	• "Stakeholder decision making is a complicated system" in which "co-production with/involving/ led by stakeholders is essential". • "Public are becoming more receptive to Nature-Based Solutions for Flood Mitigation".	• "Who owns the risk?" • "What is the right level for action on resilience measures?"

Future Perspectives

This review has highlighted what we know we know, albeit with a level of confidence (Knowns), and what we know we don't know (Unknowns) about fluvial flood risk generation, management and resilience. It is important to consider the fundamental hydrological processes which cause floods and work with natural processes to develop sustainable flood management strategies. However, there are great uncertainties and complexities associated with what causes every unique flood event. We need to start to account for this complexity as we develop catchment-wide management, including in our hydrological modelling to assess impacts and develop optimal solutions (combinations of hard and soft engineering). However, it is not as simple as what we know and understand, as first some knowledge is contested by different stakeholders, and second it needs to be applied within a specific place and time. It is this specific context which means that different types of knowledge need to be weighted and considered within the decision-making process by all those who have a stake in that particular problem. Academic, scientific knowledge should not be considered superior to community knowledge and lived experiences, but combined together to co-produce place-based solutions, where place accounts for the catchment location, characteristics and hydrology, as well as the societal factors.

Furthermore, there may be unexpected Unknown Unknowns which we need to be adaptive enough to respond to in the long term as those events and knowledge emerge. Climate change[27] is one of the biggest uncertainties, and the extent to which flooding has moved into a non-stationary[28] world is an Unknown Unknown and depends on many decisions we make in the near future. The specific sequencing and magnitude of future flood events, and how they interact uniquely in time (event) and space (catchment) results in uncertainties associated with catchment-wide flood management. Balancing flood risk management decisions with a wide range of other competing policies e.g. urbanisation, food security, is an ongoing challenge that could be affected by changing stakeholder priorities, sudden events, and/or new technologies.

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Visual minutes from project workshop.
Graphic Artist: Jenny Capon.

Appendix A

Literature Review search terms

Search terms used in a range of combinations to identify relevant papers in Web of Science and Scopus.

Appendix B

VOSViewer AI Outputs

Theme 1 – Climate change (blue):

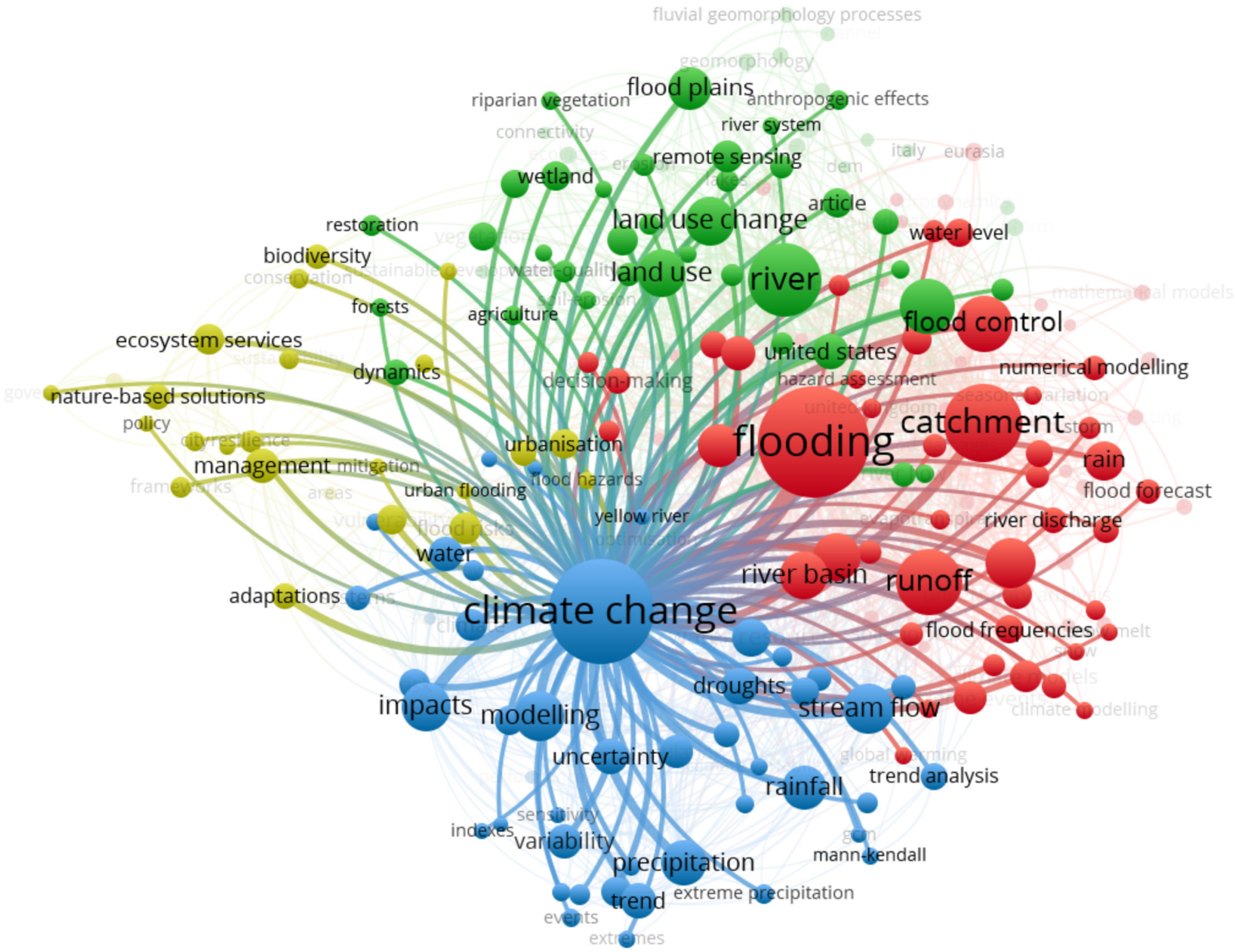


Figure A-1 VOS Viewer output highlighting climate change and its co-occurrence with other key words used within literature.

Climate change was one of the most common keywords found in the literature database. Within the climate change cluster (blue) other important keywords and themes that fed into the policy recommendations include uncertainty, variability, impacts, modelling, trends and precipitation.

Theme 2 – Flood generation and hydrology (red):

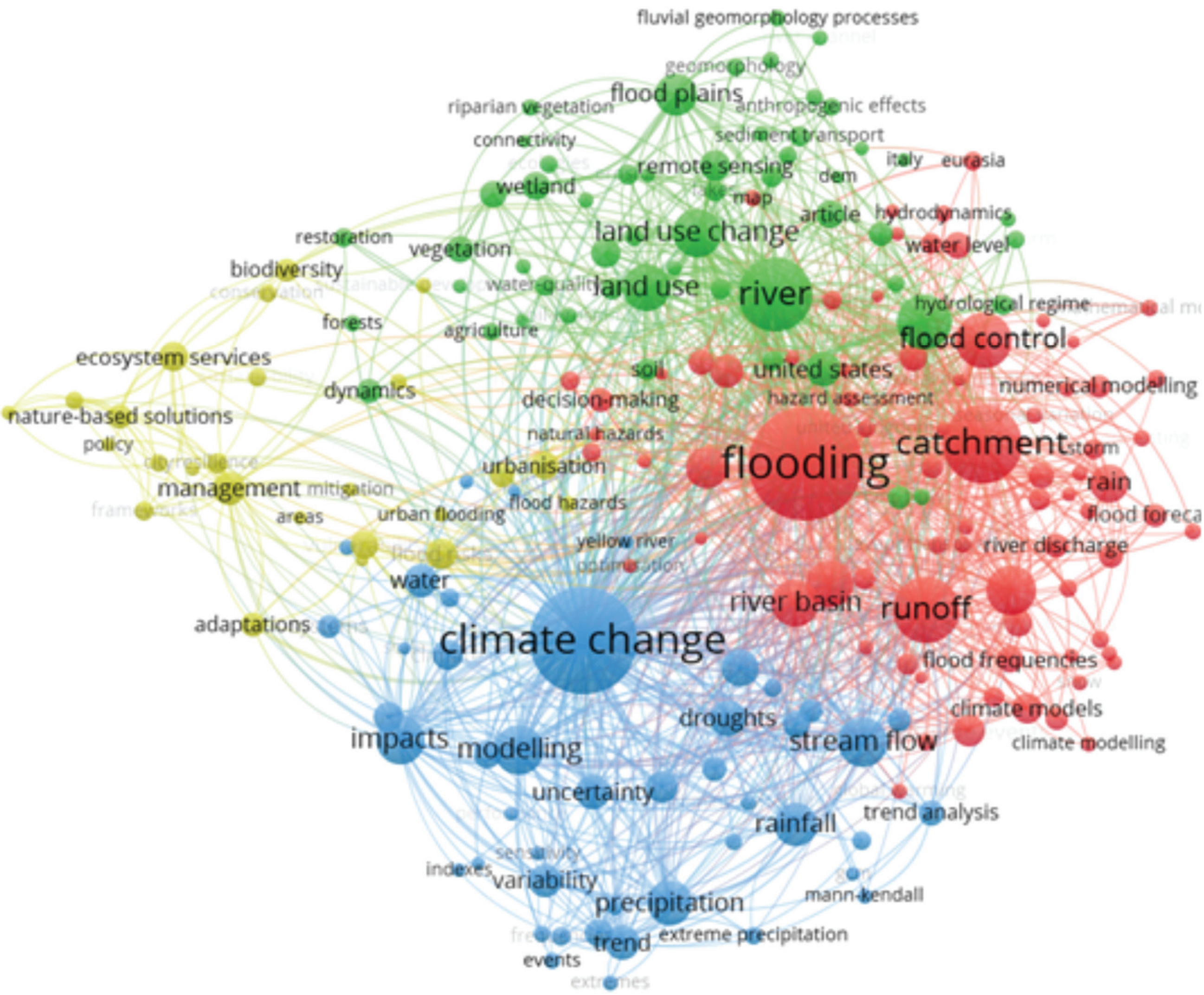


Figure A-2 VOS Viewer output highlighting the keyword flooding. This red cluster informed our second theme of flood generation and hydrology.

The theme of flood generation is strongly interconnected within all of the themes identified in this project. Important key words highlighted within this cluster include runoff, catchment, hydrological modelling, rain and river discharge. It also strongly links to hydrology (green), bridging the gap between the themes of flood generation and Natural Flood Management.

Theme 3 – Natural Flood Management (yellow/green):

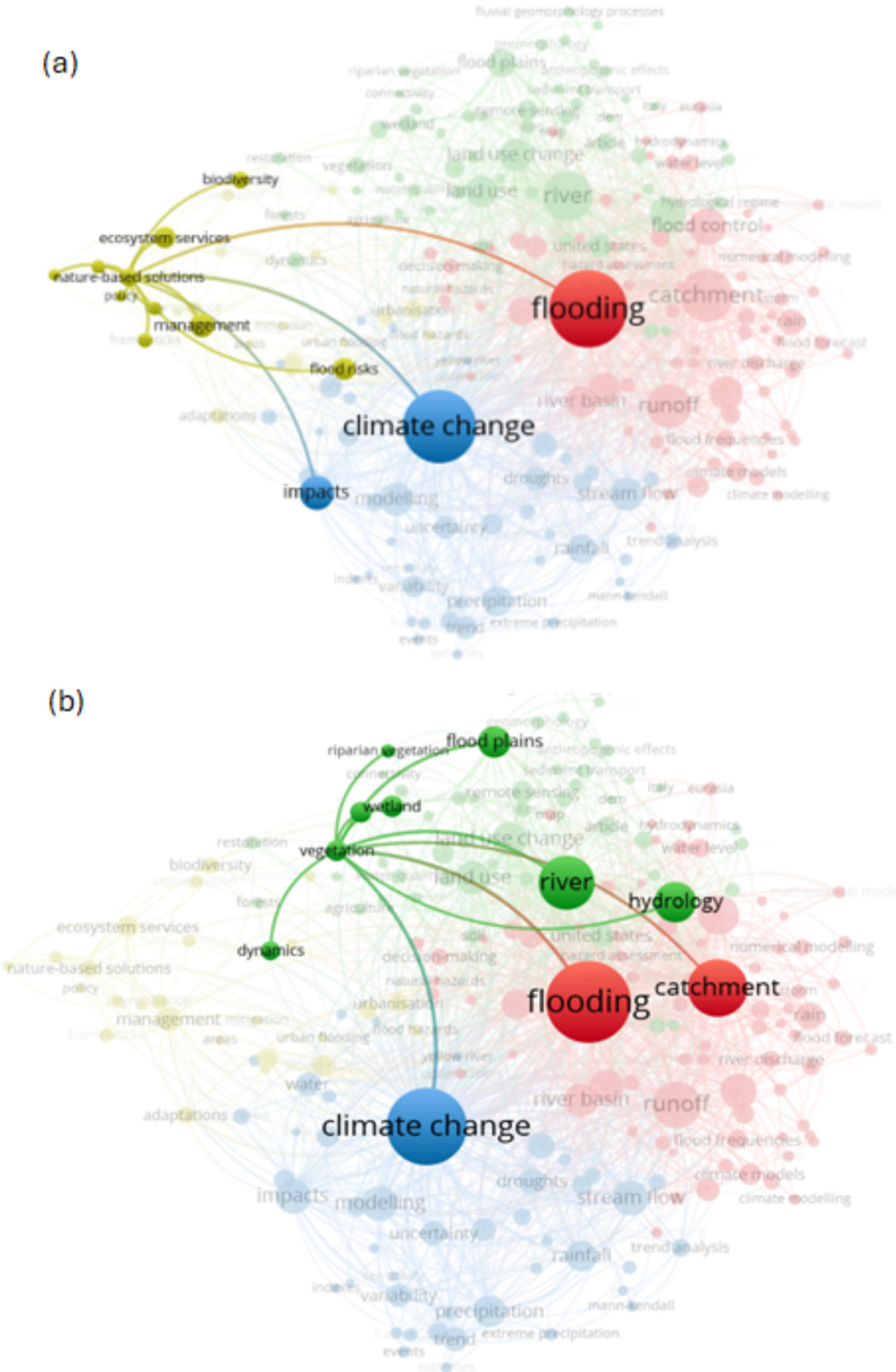


Figure A-3 VOS Viewer outputs highlighting keywords within Theme 3 – Natural Flood Management.

Natural Flood Management (NFM) falls under the wider umbrella of Nature-Based Solutions (NBS). Vegetation is an important element of NFM and NBS strategies and can be incorporated into measures such as afforestation, wetland creation, sustainable agricultural practices or riparian planting.

Theme 3 – Natural Flood Management (yellow/green):

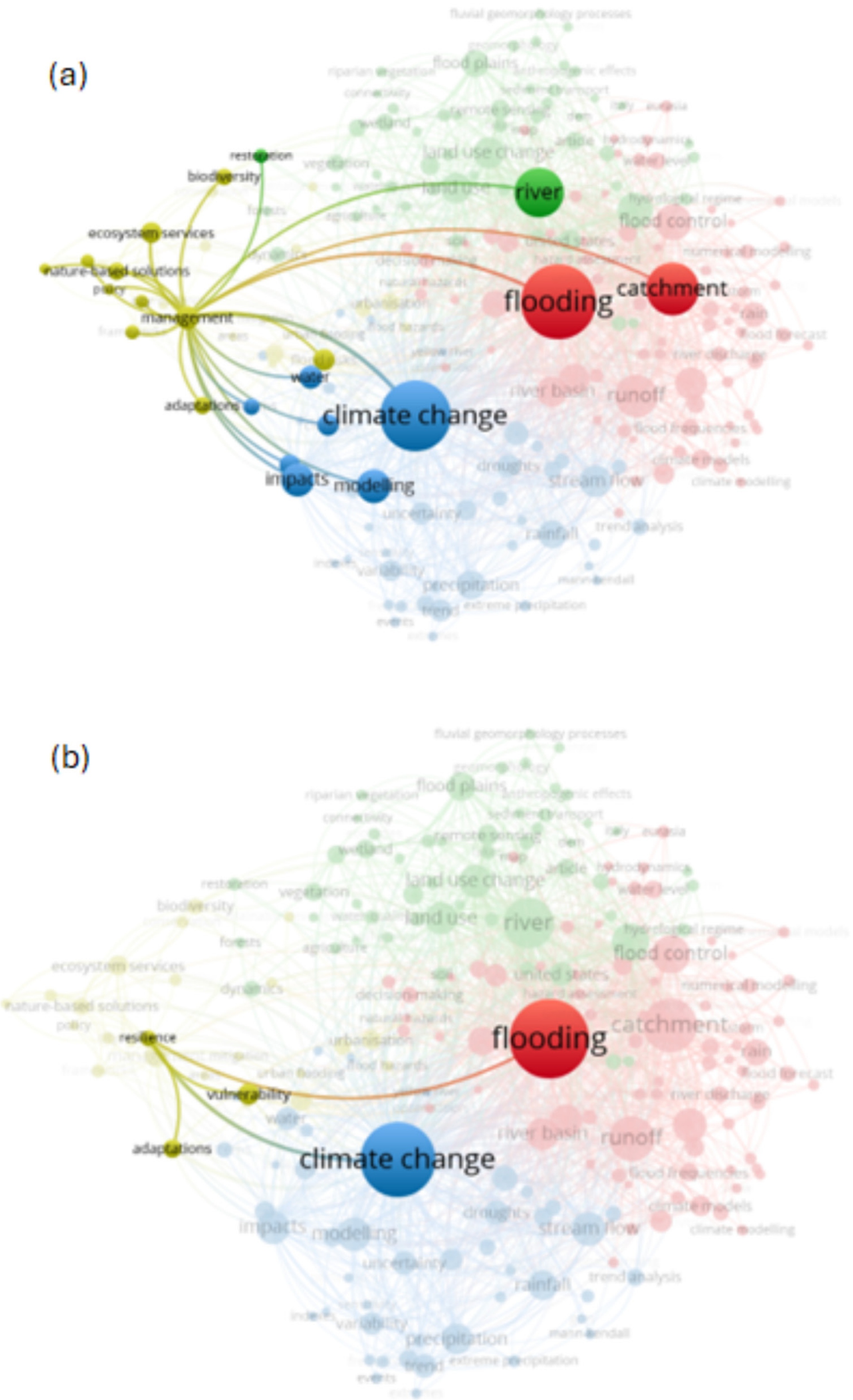


Figure A-4 VOS Viewer outputs highlighting keywords from the theme of stakeholder participation.

The theme of stakeholder engagement and participation was derived from keywords such as management, resilience and vulnerability. These words highlighted the research undertaken surrounding strategies for adaptation to climate change and flooding and how these needed to be linked with policy and management. This cannot be done without stakeholder and community engagement.

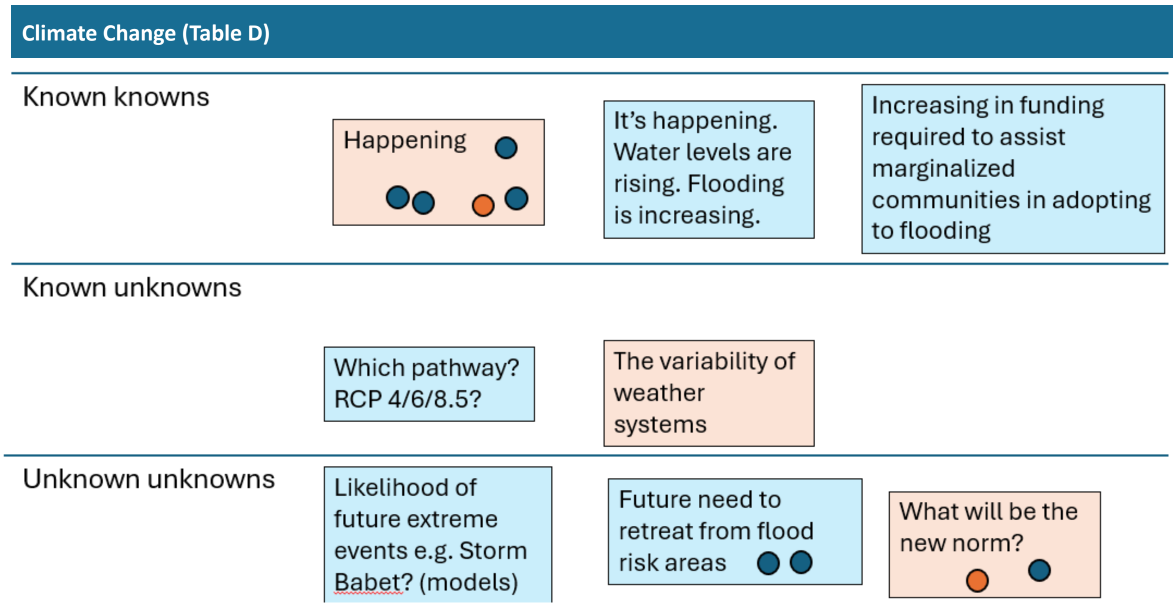
Appendix C

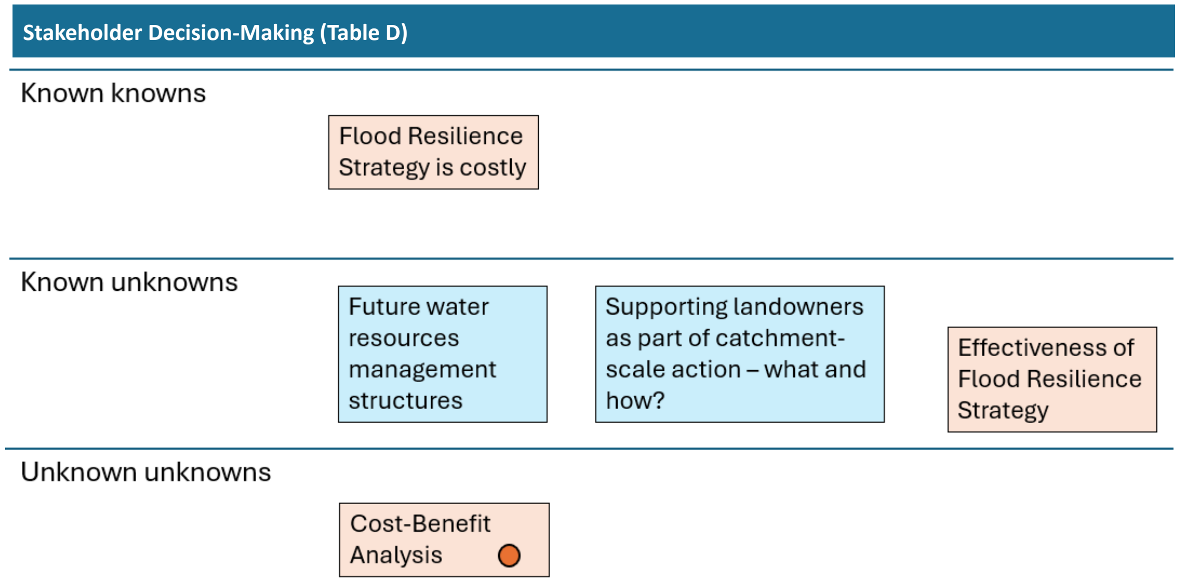
Stakeholder workshop outputs

Brainstorming Knowns and Unknowns

Natural Flood Management/Nature-Based Solutions (Table D)			
Known knowns	Requires partnership working	Linkage with water resources/ drought management	Location-specific. Part of package of measures
Known unknowns	Cumulative effect of NFM at catchment scale	Opportunity mapping for floodplain restoration on agricultural land	Does it work? Do communities understand?
Unknown unknowns			

Flood Generation Hydrology (Table B)					
Known knowns	Rain causes floods	Catchment management influences flows	Dredging is not effective		
Known unknowns	How much catchment management can influence flows	When we will place value on climate adaptation	The value of acting now versus later	How AI might be used to generate information in real time	How technology advances can help mitigate flood risk
Unknown unknowns	Other things that may influence our flood exposure				





A subset of the outputs from the workshop are included in Appendix C. Stakeholders attending were asked to brainstorm their ideas individually on each of the four themes. Different coloured post-its were used for different groups of stakeholders. Following this, each table discussed their ideas and used stickers to highlight their priorities in terms of gaps in knowledge.

Contributors

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Ian is an Associate Professor in Physical Geography at Heriot Watt University. His research interests include Natural Flood Management at local and catchment scales using field monitoring and hydrological modelling. Other aspects of his work include stakeholder engagement, flood forecasting and multiple benefits of Nature-based Solutions.

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Copper is a PhD student at Heriot Watt University. Her current research focuses on understanding the performance of Natural Flood Management features within and alongside modified catchment systems. She has previously worked in environmental consultancy, utilising hydraulic modelling and GIS analysis to inform flood risk understanding and local authority planning.

Andrew Tabas

Andrew is a second-year PhD student at Heriot-Watt University and Hydro Nation Scholar. His research focuses on Natural Flood Management, upstream-downstream cooperation, and serious games. Previous work focused on water policy and stormwater regulations.

Published by CREW – Scotland's Centre of Expertise for Water. CREW connects research and policy, delivering objective and robust research and expert opinion to support the development and implementation of water policy in Scotland. CREW is a partnership between the James Hutton Institute and all Scottish Higher Education Institutes. The Centre is funded by the Scottish Government.

This document was produced by:
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CREW Project Manager: Rebekah Burman

Please reference this policy brief as follows:
Pattison I, Lewis CME, Tabas AD (2024) *Resilience to Fluvial Flooding: Knowns and Unknowns to Recommendations for Management.* CSPF2023_02. Centre of Expertise for Waters (CREW).

Available online at: crew.ac.uk/publication/fluvial-flooding-knowns-and-unknowns

ISBN: 978-1-911706-21-2

Dissemination status: Unrestricted

Acknowledgements: We would like to thank CREW for funding this Science Policy Fellowship on Fluvial Flooding and Rebekah Burman and Nikki Dodd for organising the workshop. We also want to thank the participants who attended the project workshop at The Royal Botantic Garden Edinburgh.

Cover photographs courtesy of: Andrew Tabas.

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and all Scottish Higher Education Institutes and Research Institutes.
The Centre is funded by the Scottish Government.

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