Response to Independent Reviewer Comments RC1

Comment: Challenges and directions of future research in bridge flood resilience are discussed in this perspective article, based on the results of a workshop and a survey organised by the University of Strathclyde with experts from different fields. The article is timely, well written and deserves publication. I have a few comments and suggestions for improvement:

Reply: We thank the Independent Reviewer for their appreciation of the merits of the work and for the suggestions for improvement.

Comment: Please highlight the innovation of the paper against the state-of the art. If this is an agenda-setting paper, please comment on the timescales and mechanisms needed for solving these issues/problems. Why do the authors believe these challenges still exist? Perhaps a table explaining the causes and suggested solutions would be useful. This could include technical (engineering) but also other factors (accessibility, lack in methods, financial (resources), organisational, governance etc) to improve the significance of this paper.

Reply:

The use of a workshop to elicit the opinions of interested practitioners is not in itself innovative, having been demonstrated in Lamb et al (2017). However, in this case the intention was to focus primarily on the aspects of the response of bridges to scour and flood loadings that are often overlooked. Thus, the selection of attendees was weighted more towards engineers with experience in the management, assessment and modelling of bridges subjected to flood induced damage. In particular, several of the attendees had direct experience of preparing for and responding to the major floods in North West England in December 2015. This perspective, which included comparison of actual damage with the level of risk identified by UK standards (Hardman and Mathews 2017), was seen as important in identifying the issues requiring the most urgent investigation.
We have added the following sentence (highlighted in yellow) to explain what in our opinion are the causes of the identified issues and challenges:

"The fact that bridges continue to fail at a very high rate and the severe disruptions caused by bridge closures due to floods demonstrates the issues and uncertainties associated with current procedures and practices for assessing and mitigating the flood risk. These issues are due to a combination of

factors, among which the lack of knowledge of the problem, the gaps existing between the advanced techniques and methodologies developed by researchers and the more practical approaches adopted in risk management procedures, the lack of adequate human and technical resources, significant budget constraints, the tendency to acknowledge and address issues only when they manifest themselves in a catastrophic manner and to suppress rather than resolve problems. An analysis carried out by the RAC Foundation (2021) on bridges managed by local highways authorities in Great Britain has shown that there has been an apparent large decline in the number of bridges being assessed for risk of damage caused by river flow, despite 10 bridges fully collapsed and 30 partially collapsed in 2010. Thus, it is not surprising that the level of risk of many bridges exposed to flood effects remains largely unknown, with risk ratings still missing for many structures on secondary routes (more than 1000 structures in Cumbria County alone).
While efforts have been made to increase the robustness of bridges to withstand flood actions, transportation infrastructure managers face a unique challenge to prevent additional economic damage, often using maintenance budgets that are already stretched. For example, Transport Scotland spends £3-5m per annum on flood repairs and resilience works. The estimated cost to retrofit the 3,105 bridges managed by local councils classified as "substandard" is approximately £1 Billion (£985 million). However, budget restrictions mean that only 392 of these substandard bridges"

This is an agenda setting paper, intended to identify topics of research likely to yield the most significant benefits for bridge managers. The suggestion of detailing methodologies and timescales for resolving issues impacting bridge vulnerability is thus very helpful, although timescale can be very uncertain and strongly affected by governmental choices and allocation of resources for research and risk mitigation. Moreover, the research needs and challenges identified in Table 1 refer to various areas, where different experts and stakeholders should be involved (e.g. from hydrologists to structural engineers and bridge managers and inspectors). Thus, the various actions identified in Table 1 should and could be carried out in parallel. For these reasons, rather than adding an estimate of timeframes in the table, we have added a list of actions aimed at filling research gaps and addressing the identified needs and challenges. The revised Table 1is attached at the end of this document.

Comment: It is suggested to discuss the challenges and knowledge gaps in the definition of sufficient risk and resilience metrics for flood critical bridges. Also, discuss the challenges in the communication of risk and resilience assessments to the stakeholders and decision makers.

Reply: Following the Reviewer's recommendation, we have added the following sentence:

The definition of the resilience of bridges to natural hazards such as floods and earthquakes is a matter of continuous debate, and there is no consensus on which tools and metrics to use or how and when to apply them. As pointed out in Alipour (2017), one of the key concerns regarding the definitions of resilience currently available is the over-emphasis on the pre-disaster side of the problem and the measures that aim to reduce potential capacity losses (i.e., rip-rap) (Badroddin and Chen 2021), and the less attention given to the emergency response and recovery phases and measures following the disaster. However, in the authors' opinion, both aspects are significant, as both proactive and reactive measures need to be implemented to mimimise the impact of floods. The ability to quickly restore bridges whose stability or functionality has been or might be impaired by floods is essential to improve the resilience of transport infrastructure. It is perhaps the most pressing challenge for road and railway operators who manage bridges. The challenge is related to the prioritisation of mitigation measures, due to limited resources prior and/or after extreme floods, and the uncertainties associated to future events, the bridge performance, and the emergency and post-emergency management.

Apart from the technical challenges, the communication of resilience to stakeholders, which can include for example resilience metrics based on the cost of traffic detour and CO_2 emissions (see *e.g.,* Smith et al. 2021) is the crux of bridge flood resilience. After solutions are delivered on paper, resilience communication should then enable stakeholders' understanding and therefore facilitate them to implement resilience practices in their everyday tasks and justify spending in an objective manner. There is an urgent need to communicate resilience among engineers, governmental bodies, local authorities and the general public. As noted in Minsker et al. (2015), resiliency requires public awareness and a clear communication about disasters and the operation of critical infrastructure during flood events.

The following references have been added:

Minsker, B., Baldwin, L., Crittenden, J., Kabbes, K., Karamouz, M., Lansey, K., ... & Williams, J. (2015). Progress and recommendations for advancing performance-based sustainable and resilient infrastructure design. *Journal of Water Resources Planning and Management*, *141*(12), A4015006.

Smith, A. W., Argyroudis, S. A., Winter, M. G., & Mitoulis, S. A. (2021). Economic impact of bridge functionality loss from a resilience perspective: Queensferry Crossing, UK. In *Proceedings of the Institution of Civil Engineers-Bridge Engineering* (pp. 1-11). Thomas Telford Ltd.

Comment: It is suggested to illustrate the impact of uncertainties on the hazard, vulnerability and restoration models, in the resilience assessment of flood critical assets. For example, show qualitatively how these uncertainties can change the resilience curve.

Reply: Following the Reviewer's suggestion, we have added the text below and Figure 6

The workshop and subsequent meetings have highlighted significant gaps and uncertainties in bridge hazard assessment, vulnerability assessment and risk management. The gaps have a direct effect on the lifetime flood resilience of bridges, as illustrated in Figure 6. The uncertainty in the hazard leads to inaccurate models for the temporal occurrence of the flood events, and their intensity, with a direct effect on the expected levels of functionality drops. The uncertainty in the vulnerability results in the inability to predict the levels of functionality drop under different hazard scenarios. Inaccurate procedures for identifying the bridges at risk due to flooding results in non-optimal allocation of resources for increasing robustness. Moreover, ineffective management procedures and lack of resources impede the speedy recovery and bounce back to bridge full functionality.

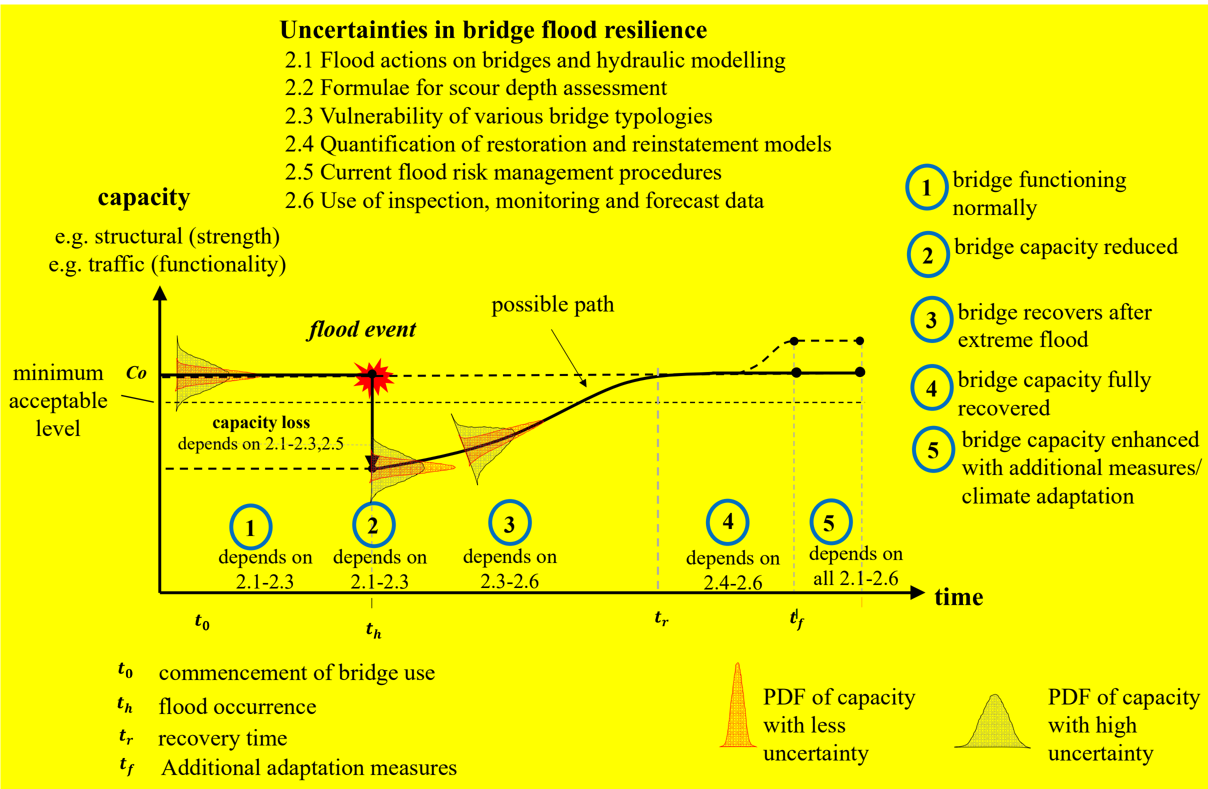


Figure 6. Contribution of uncertainties in hazard, vulnerability and emergency and post-emergency management to resilience.

We have also modified the original sentence in Section 3 of the manuscript:

“The workshop and subsequent meetings have highlighted many areas where further efforts and research is needed in order to improve bridge resilience to floods. Table 1 provides a list of the most important actions that should be taken for achieving this challenging goal. This list has been prepared taking into account the limited resources available to bridge owners and managers. These actions will help to refine and improve further the already advanced tools for modelling and monitoring of floods and bridges, and for identifying the optimal decisions to take in both emergency and long-term flood risk management of bridges. This can help shift the flood risk assessment paradigm from manual and inaccurate diagnoses that rely heavily on costly and potentially inaccurate visual inspections, towards impact-based forecasting and near real-time evaluations of the risk supported by digital twinning technologies (Ye et al. 2019). It can also help to better define strategies to tackle the uncertain effects of climate change and socio-economic growth.”

and extended it as follows:

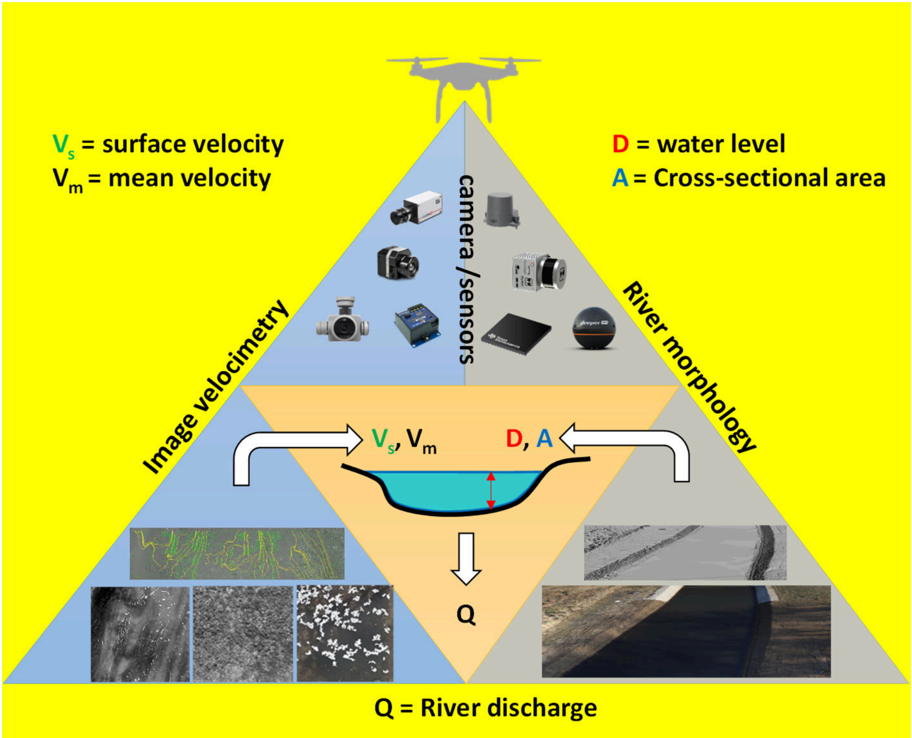
“Table 1 provides a list of the most important research challenges, needs, and relevant actions that could contribute to the challenging goal of improving bridge resilience to floods. This list has been prepared taking into account the limited resources available to bridge owners and managers.
The actions outlined in Table 1 are expected to provide a manifold contribution to the various dimensions of life-cycle bridge resilience, namely robustness, resourcefulness, rapidity and redundancy (Mitoulis et al. (2021)). More accurate models of the flood hazards and of the associated actions would help to understand and predict the causes of the drop in the performance of bridges in a context that could be significantly affected by climate change. Improved methodologies for evaluating the vulnerability of the components of different bridge typologies would allow identifying critical elements and techniques for increasing their robustness. Better-informed rating systems and emergency and long-term risk-management strategies, accounting explicitly for the consequences of bridge failure and supported by forecasted and real-time monitoring data, can contribute to reduce the probability of bridge failure due to floods, the impact of the potential failure on transport networks and society, and the time to recovery. The results of the actions described in Table 1 can help shift the flood risk assessment paradigm from manual and inaccurate diagnoses that rely heavily on costly and potentially inaccurate visual inspections, towards impact-based forecasting and near real-time evaluations of the risk supported by sensor technologies. This would ultimately help to accelerate the development of SHM-based digital twin platforms (Ye et al. 2019) for the management of bridges at risk of flooding, which are currently missing. It can also

help to better define strategies to tackle the uncertain effects of climate change on the risk of bridge failure due to floods."

The revised Table 1 is attached at the end of this document.

Comment: Figure 5: please improve the figure, also explain the symbols Vs, Vm, D, A, Q

The figure has been improved, and an explanation of the symbols has been added.



Comment: Please check the citations, eg, line 244-245 should be Argyroudis and Mitoulis (2021) instead of Argyroudis et al (2021)

Reply: The citation has been corrected. Thanks for highlighting this.

Table 1. List of research areas, challenges & needs, and actions for improving bridge resilience to flooding.

Area	Research challenges & needs	Actions
Hazard assessment and mitigation	- Characterization of likelihood of debris accumulation at bridge piers.	(1)-(5)

	- Critical evaluation of the effectiveness of technical solutions for mitigating hydrodynamic forces for bridges at risk of inundation. - Extension of current flood forecast and warning capabilities to longer lead times and uncertainty characterization. - More accurate modelling of the impact of climate change on frequency and intensity of flooding.	
Hydraulic actions modelling	- Additional field research, data collection and analyses also needed to characterize the interrelated flood actions and validate models. - Characterization of the temporal evolution of scour under the influence of time-varying intervening variables characteristic of flow and debris, with further experiments extending the range of applicability of developed approaches. - Characterization of the effect of bridge pier and foundation geometries on the development of scour and on the scour hole shape. -Development of models for establishing the relationships between measured river parameters (flow height, surface water velocity) and parameters controlling scour and hydraulic actions (e.g. depth averaged velocity).	(1)-(5)
Vulnerability assessment and reduction	- Identification of optimal intensity measures to be used in fragility analyses for describing the joint effect of various flood actions on bridges. - Definition of methodologies for evaluating the vulnerability of various bridge types to concurrent flood-induced actions, accounting for cumulative effects (e.g. scour accumulated in previous floods) and the effects of debris through advanced modelling of water-soil-bridge assets. - Statistics of the principal causes of failure and collapse mechanisms for various bridge typologies. - Cost-benefit analysis of alternative solutions for mitigating the risk of different bridge components (e.g. deck unseating and uplift).	(1)-(6)
Risk management	- Development of decision support tools to aid bridge managers to identify optimal actions for emergency/long-term flood risk management (including restoration and/or adaptation measures to climate change). These should take into account the bridge fragility and the consequences of bridge failure. - Identification of actions that could be taken in the short term to mitigate the impact of forecasted floods (e.g. removal of debris accumulated at piers). - More explicit considerations of structural vulnerability indicators and consequences in risk rating procedures.	(2),(4)-(8)

	- Improvement of response and recovery procedures that are kept up to date with the most recent technologies.	
Impact-based forecasting	- Tools enabling the paradigm shift from flood hydrograph to impact-based forecasting, so that mitigation measures can be better planned and justified using cost-benefit criteria. This could contribute to an increased awareness of the actual risk of bridges and a better acceptance of mitigation measures by affected communities.	(2)-(5)
Monitoring	- Evaluation of the metrological effectiveness of sensors for monitoring the effects of floods on structures. - Development of approaches for fusing information from numerical models and heterogeneous sensing systems, providing observations and measurements of different parameters involved in the risk assessment. - Incorporation of monitoring technologies into risk management procedures.	(2)-(8)
Value of information of data	- Quantification of the benefits, in terms of cost savings to bridge operators and ultimately to communities, of data and information from sensors. This requires the development of a methodology for comparing the value of information from systems characterized by different measured quantities, accuracy, and spatiotemporal resolution. This effort could help to increase the adoption of sensors for monitoring bridges and rivers by bridge managers and operators. - Cost-benefit analysis of risk mitigation measures (rip-rap) vis-a-vis bathymetric surveys and accurate foundation depth evaluations for identifying the most effective scour management strategies in case of unknown foundation depths.	(2)-(8)
Resilience quantification	- Restoration models for different types of bridges and different operators (masonry arch bridges vs. multi-span concrete bridges, road or railway bridges). - Life-cycle resilience metrics for multiple flood scenarios including climate projections	(4),(5),(6),(7)

Actions: (1) Laboratory and in-field experiments; (2) Development of models and techniques; (3) Numerical analyses; (4) Pilot case studies; (5) Data collection (through monitoring or desk studies); (6) Academic-industry workshops and engagement events; (7) Engagement with general public; (8) Training of experts, inspectors, recovery teams.