Evidence from the www.MetaInfrastructure.org research group

Flood resilience in England – UK Parliament 2025

Submitted on behalf of the group by:

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Introduction

MetaInfrastructure is a leading research group specialising in sustainable and resilient infrastructure solutions, aligning with the United Nations Sustainable Development Goals and Net-Zero objectives. By integrating Artificial Intelligence, IoT, and data analytics, we develop predictive models and adaptive strategies that mitigate the impacts of floods and other climate hazards. Our work promotes the peoples-centric frameworks for sustainable development of resilient infrastructure policies and the implementation of sustainable flood management solutions, ensuring long-term protection and adaptability for communities and ecosystems (e.g. see BBC interviews on climate resilience[1] , on infrastructure response to climate[2] and on collapse of critical bridges[3]). Our team collaborates with leading global researchers, bringing diverse international experience and expertise to address critical challenges on infrastructure and climate adaptation. With over €6.6 million in research funding from funders like the UKRI, British Academy, Horizon 2020 and Horizon Europe and UK-charities, we have led pioneering projects focused on multihazard resilience and digitalisation in infrastructure. Through these efforts, we advance global knowledge (including Massive Open Online Courses[4]) and provide innovative solutions for sustainable and resilient infrastructure systems (see Podcast in ICE Knowledge[5]). In the following evidence, we address specific questions from the call for evidence for flood resilience in England, focusing on those where our group has the most significant technical insights. We use results from recent publications, related to flood and climate infrastructure resilience, combining advanced methodologies and cutting-edge technologies.

Question 1. To what extent are current flood resilience assets and interventions fit-for-purpose and what are the strengths and weaknesses? Are there alternative approaches from across the UK and elsewhere which could help inform improvements and innovation?

Current flood resilience assets and interventions in the UK have strengths, such as robust flood defences, advanced early warning systems, and well-established policy frameworks like the Flood and Coastal Erosion Risk Management programme. However, they face significant challenges, including ageing infrastructure, fragmented single-hazard approaches, limited integration of digital technologies like AI and IoT, insufficient focus on socio-economic resilience, and the escalating

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[1] https://www.linkedin.com/posts/dr-stergios-aristoteles-mitoulis-19165630_bbc-climate-resilience-activity-6962079854309593089-nTvN
[2] https://www.linkedin.com/posts/dr-stergios-aristoteles-mitoulis-19165630_bbc-climate-resilience-activity-6955199810840748032-FexT
[3] https://www.linkedin.com/posts/dr-stergios-aristoteles-mitoulis-19165630_bbc-interview-collapse-activity-7178417597816717312-L0Ub/
[4] https://metainfrastructure.org/massive-open-online-course/ (MOOC: Resilience, sustainability and digitalisation of critical infrastructure)
[5] https://iceknowledge.podbean.com/e/structural-resilience-and-the-role-of-the-civil-engineer/

impacts of climate change, which increase the frequency and intensity of extreme flood events. These challenges are further intensified by urbanisation, which compounds the vulnerabilities of modern cities by introducing cascading hazards and systemic failures that traditional risk assessment approaches fail to address.

Adopting a complex systems perspective is crucial for addressing coupled risks, as demonstrated by recent frameworks that emphasise four core components: a standardised taxonomy of hazards, integrated people-centric risk-assessment frameworks that span multiple dimensions (infrastructural, social, economic, environmental, and governmental), data-driven innovations for calibrating models in dynamic urban environments, and people-centric strategies aligning risk management with human needs and equity[6]. These perspectives, combined with emerging digital technologies like digital twins, AI, and machine learning, enable dynamic modelling of urban complexities, improve decision-making processes, and ensure equitable, inclusive solutions[7].

Recent innovations, such as multi-scale tiered methodologies using satellite images, crowdsourced data, and deep learning for damage detection, demonstrate the potential of digital technologies to accelerate and automate risk assessment and restoration in urban and transport infrastructures[8]. Similarly, fragility models for critical infrastructure, such as bridges vulnerable to floods and scour, provide data-driven approaches to assessing and mitigating risks[9]. Such models can quantify losses and measure resilience for large portfolios of assets, considering multiple flood scenarios, climate exacerbations or ageing effects (Figure 1)[10]. As an example, evidence-based flood resilience models for bridges after the 2015 Cumbrian floods[11] can inform infrastructure improvements in other parts of the country, by addressing vulnerabilities more effectively and enhancing the overall resilience of flood-prone infrastructure. Moreover, convolutional neural networks (CNNs) optimised for real-time damage recognition in road networks highlight the potential of AI-driven innovations to enhance maintenance and resilience planning[12]. By integrating these advancements into urban and transport resilience strategies, we can better withstand coupled hazards and recover more efficiently. Establishing fit-for-purpose roadmaps focused on proactive rather reactive measures, and co-created with government stakeholders, is essential to align these methodologies with policy frameworks. Supported by extensive empirical case studies, this approach fosters an interdisciplinary collaboration, driving sustainable, inclusive, and resilient future cities and infrastructure. Therefore, co-creation process ensures that resilience strategies are not only technically robust but also practically implementable within existing governance structures.

Question 2 How appropriate is the current balance between 'green' nature-based solutions and 'grey' hard infrastructure resilience assets, and what adjustments, if any, are needed to improve it?

The balance between 'green' nature-based solutions (NbS) and 'grey' hard infrastructure in enhancing flood resilience remains skewed toward grey infrastructure due to its historical dominance in managing immediate risks. However, this balance requires a recalibration to achieve infrastructure that is not only efficient and resilient to climate change but also sustainable and less harmful to the environment[14]. Green infrastructure, such as wetland restoration, tree planting, and natural flood management techniques, offers significant potential to attenuate peak flows, reduce surface runoff, and contribute to broader biodiversity and climate objectives, including carbon sequestration and habitat restoration. Conversely, grey infrastructure, while robust, is often carbon-

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[6] Ouyang, M., Cheng, Z., Ma, J., Wang, H., Mitoulis, S.A. (2024). Coupled urban risks: a complex systems perspective with a people-centric focus. *Engineering*. https://doi.org/10.1016/j.eng.2024.12.023

[7] Argyroudis, S.A., Mitoulis, S.A., Chatzi, E., Baker, J.W., Brilakis, I., Gkoumas, K., ... & Linkov, I. (2022). Digital technologies can enhance climate resilience of critical infrastructure. *Climate Risk Management*, *35*, 100387 https://doi.org/10.1016/j.crm.2021.100387

[8] Kopiika, N., Karavias, A., Krassakis, P., Ye, Z., Ninic, J., Shakhovska, N., Argyroudis, S.A, Mitoulis, S.A. (2025). Rapid post-disaster infrastructure damage characterisation using remote sensing and deep learning technologies: A tiered approach. *Automation in Construction*, 170, 105955. https://doi.org/10.1016/j.autcon.2024.105955

[9] Argyroudis, S.A., Mitoulis, S.A. (2021). Vulnerability of bridges to individual and multiple hazards-floods and earthquakes. *Reliability Engineering & System Safety*, 210, 107564. https://doi.org/10.1016/j.ress.2021.107564

[10] Forcellini D, Mitoulis SA (2024). Effect of deterioration on critical infrastructure resilience–framework and application on bridges. *Results in Engineering*, 103834. https://doi.org/10.1016/j.rineng.2024.103834

[11] Beaver E., Mitoulis S.A. (2024). Evidence-based flood resilience models for bridges. Proc of the ICE-Bridge Engineering (pp. 1-15).

[12] Shakhovska, N., Yakovyna, V., Mysak, M., Mitoulis, S.A., Argyroudis, S., Syerov, Y. (2024). Real-time monitoring of road networks for pavement damage detection based on preprocessing and neural networks. *Big Data Cogn. Comput*, 8(10), 136. https://doi.org/10.3390/bdcc8100136

intensive and limited in adaptability to long-term climate projections. Integrating NbS into infrastructure design and adaptation strategies provides a hybrid approach that leverages the strengths of both systems, creating resilient and sustainable solutions to the escalating impacts of climate change and urbanisation.

The transition toward a better balance is hampered by systemic challenges, including inadequate private-sector engagement, insufficient financing for resilience-building activities, and a disconnect between centrally designed resilience plans and localised hazard-specific needs. Traditional cost-benefit analyses often fall short in capturing the broader societal, environmental, and economic co-benefits of NbS, making it difficult to build a compelling business case for their adoption. Emerging frameworks, such as those optimising sustainability (e.g., greenhouse gas emissions), climate resilience, e.g., restoration time (Figure 2)[13], and cost, offer a way forward[14]. For instance, studies on transport infrastructure adaptation under climate projections show that low-carbon restoration strategies can significantly enhance resilience and sustainability, while justifying investments through quantifiable trade-offs between GHG reductions, resilience, and cost-effectiveness (Figure 3)[14]. Similarly, frameworks incorporating resilience and sustainability metrics in recovery planning for larger bridge portfolios demonstrate how strategic investments can address overlapping challenges of degradation and climate change[15]. To ensure meaningful progress, it is critical to develop integrated metrics, incentivise private-sector participation, and foster hybrid solutions while addressing localised needs and vulnerabilities. By doing so, infrastructure can be both adaptive to future hazards and a driver of sustainable economic and environmental outcomes.

Question 3. To what extent are current metrics for monitoring the effectiveness of flood resilience fit for purpose, and what improvements could make them more effective?

Current metrics for monitoring the effectiveness of flood resilience often focus on direct, quantifiable outcomes, such as reductions in flood damage, cost-benefit ratios, and the structural performance of hard infrastructure. While these metrics offer insights into resilience measures' effectiveness, they often fall short by not viewing resilience through system lenses, which capture broader, interconnected dimensions and complex interdependencies. For example, they may overlook social, environmental, and economic co-benefits, such as enhanced biodiversity, carbon sequestration, or improved community preparedness. Additionally, many metrics are designed to evaluate traditional 'grey' infrastructure solutions, which do not adequately capture the contributions of 'green' NbS or hybrid approaches. This creates a misalignment between the metrics used and the increasingly multifaceted goals of flood resilience, particularly under the pressures of climate change and urbanisation.

To improve the effectiveness of flood resilience metrics, several key adjustments are necessary. First, metrics should be expanded to integrate sustainability dimensions, such as greenhouse gas (GHG) emissions and long-term environmental impacts, alongside resilience performance indicators. For instance, recent frameworks that quantify trade-offs between GHG reductions, restoration times, and costs offer a more holistic view of infrastructure resilience[8]. Second, the inclusion of socio-economic metrics, such as community vulnerability, adaptive capacity, and equity in resource distribution, would ensure a more comprehensive assessment of resilience. Third, digital technologies, such as IoT, AI, and remote sensing, can enhance the granularity and timeliness of resilience monitoring by providing real-time data on infrastructure performance, ecosystem health, and flood dynamics[2,3]. Lastly, metrics should be designed to evaluate the effectiveness of integrated green-grey solutions and hybrid strategies, recognising their combined benefits in reducing direct costs due to floods and delivering broader sustainability objectives. By adopting these improvements, flood resilience metrics can better align with modern challenges, ensuring they are fit for purpose in guiding investments, policy decisions, and adaptive management strategies[16].

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[13] Mitoulis, S.A., Argyroudis, S.A., Loli, M., Imam, B. (2021). Restoration models for quantifying flood resilience of bridges. *Engineering Structures*, 238, 112180. https://doi.org/10.1016/j.engstruct.2021.112180

[14] Mitoulis, S.A., Bompa, D.V., Argyroudis, S. (2023). Sustainability and climate resilience metrics and trade-offs in transport infrastructure asset recovery. *Transportation Research Part D: Transport and Environment*, 121, 103800. https://doi.org/10.1016/j.trd.2023.103800

[15] Kopiika N, di Bari R, Argyroudis S, Ninic J, Mitoulis SA (2025). Sustainability and resilience-driven prioritisation for critical infrastructure reconstruction in conflict-affected regions. *Transportation Research Part D: Transport and Environment* (accepted).

[16] Mitoulis SA, Argyroudis SA (2023). UNDP – CDRI – Financing for disaster and climate resilient infrastructure for a net-zero economic transition – The case of transport infrastructure. In the Global Infrastructure Resilience: Capturing the Resilience Dividend – A Biennial

Conclusion

The increasing frequency of natural and human-induced disasters, compounded by climate change, demands a threat-agnostic framework[17], which is beyond current scenario-based, or stress testing established methods. MetaInfrastructure specialises in developing innovative, hybrid solutions that combine nature-based solutions (NbS) with advanced digital technologies such as AI, IoT, and digital twins to address cascading hazards and systemic vulnerabilities. Our expertise spans the creation of fragility models for hydraulic stressors, recovery frameworks for prioritising restoration, and multi-scale damage assessment methodologies, offering practical and scalable tools for infrastructure adaptation. Our frameworks optimise resilience and sustainability by balancing greenhouse gas emissions, restoration time, and cost, enabling informed decision-making under severe uncertainty. By integrating green-grey strategies and leveraging metrics that align with global and national sustainability goals, our group provides actionable solutions for building adaptable, inclusive, and future-ready infrastructure. Through collaboration with academia, industry, and policymakers, MetaInfrastructure empowers communities and infrastructure operators with robust, data-driven strategies to withstand, recover from, and adapt to a wide range of threats, ensuring infrastructure systems remain resilient, sustainable, and equitable.

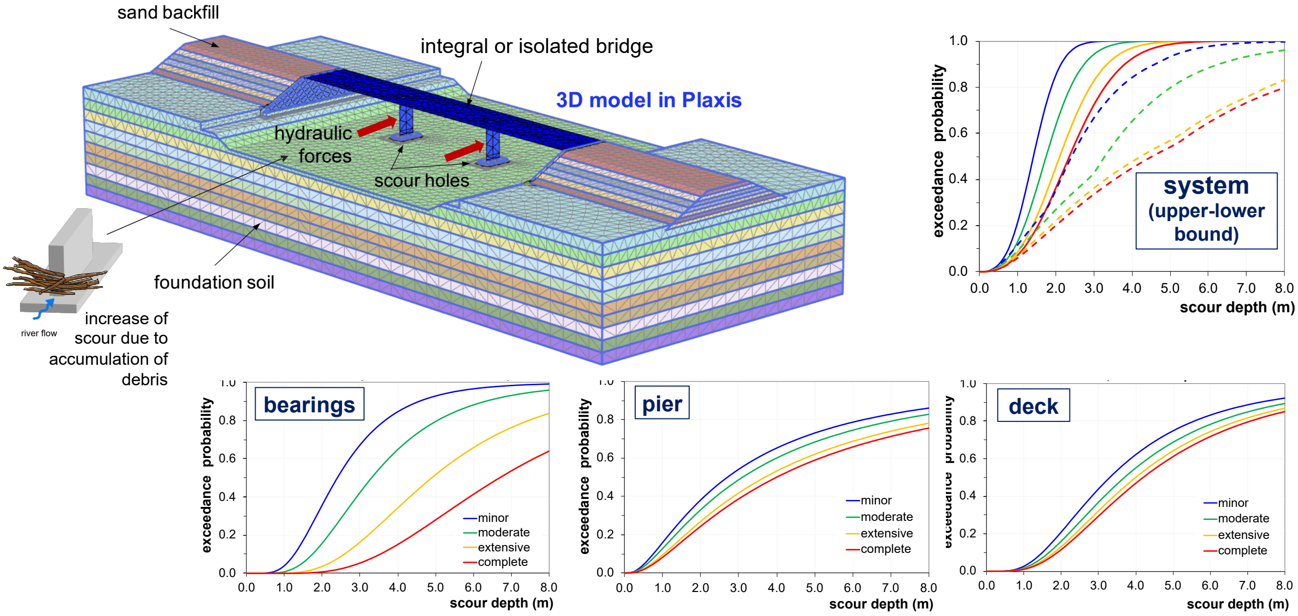
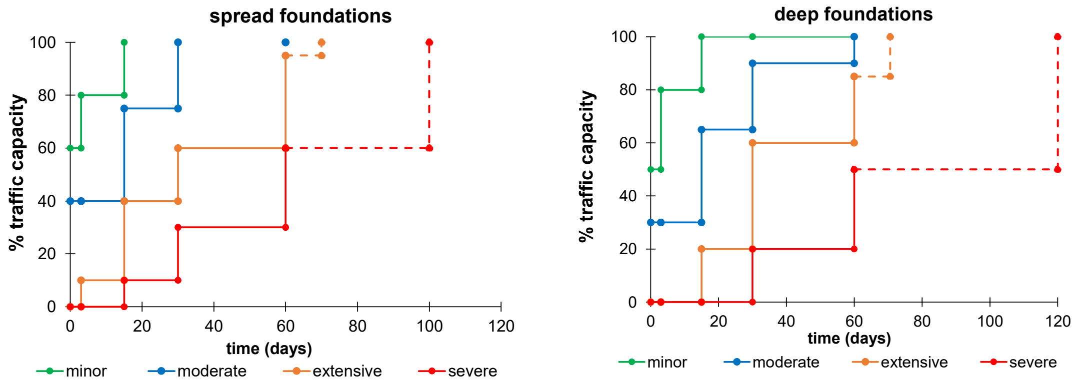


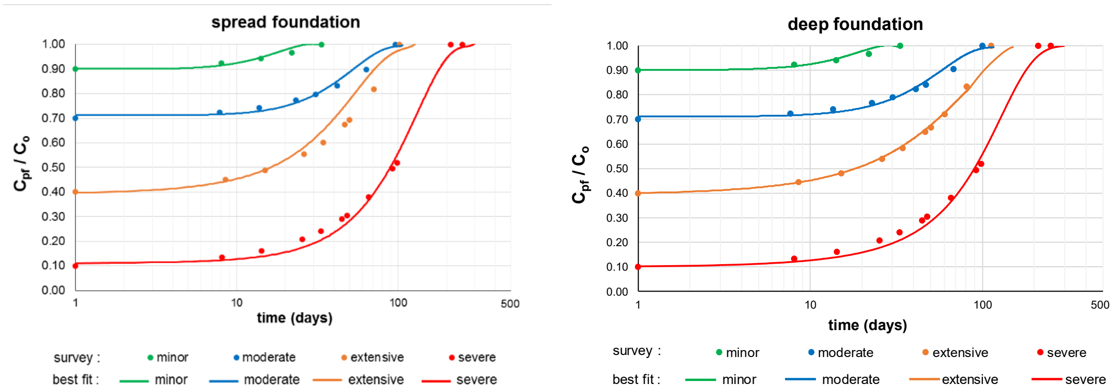
Figure 1. Fragility functions for flood critical bridges based on numerical modelling. Fragility functions can be used to quantify losses for a given hazard intensity (e.g. scour depth) [9].

Report from the Coalition for Disaster Resilient Infrastructure, New Delhi – (United Nations Development Programme Presented at G20). https://cdri.world/upload/biennial/CH4.6-IR.pdf

[17] Trump, B.D., Mitoulis, S., Argyroudis, S., Kiker, G., Palma-Oliveira, J., Horton, R.,...Linkov, I. (2025). Threat-agnostic resilience: framing and application for critical infrastructure. arXiv preprint https://arxiv.org/abs/2501.01318



(a) Reinstatement models illustrating the post-flood gain of the traffic capacity (%) of the bridge for spread and deep foundation



(b) Restoration models for post-flood bridge capacity (C_{pf}) over original capacity (C_o) for spread and deep foundations

Figure 2. Reinstatement (a) and restoration models (b) for bridges with varying foundation types and damage levels [13].

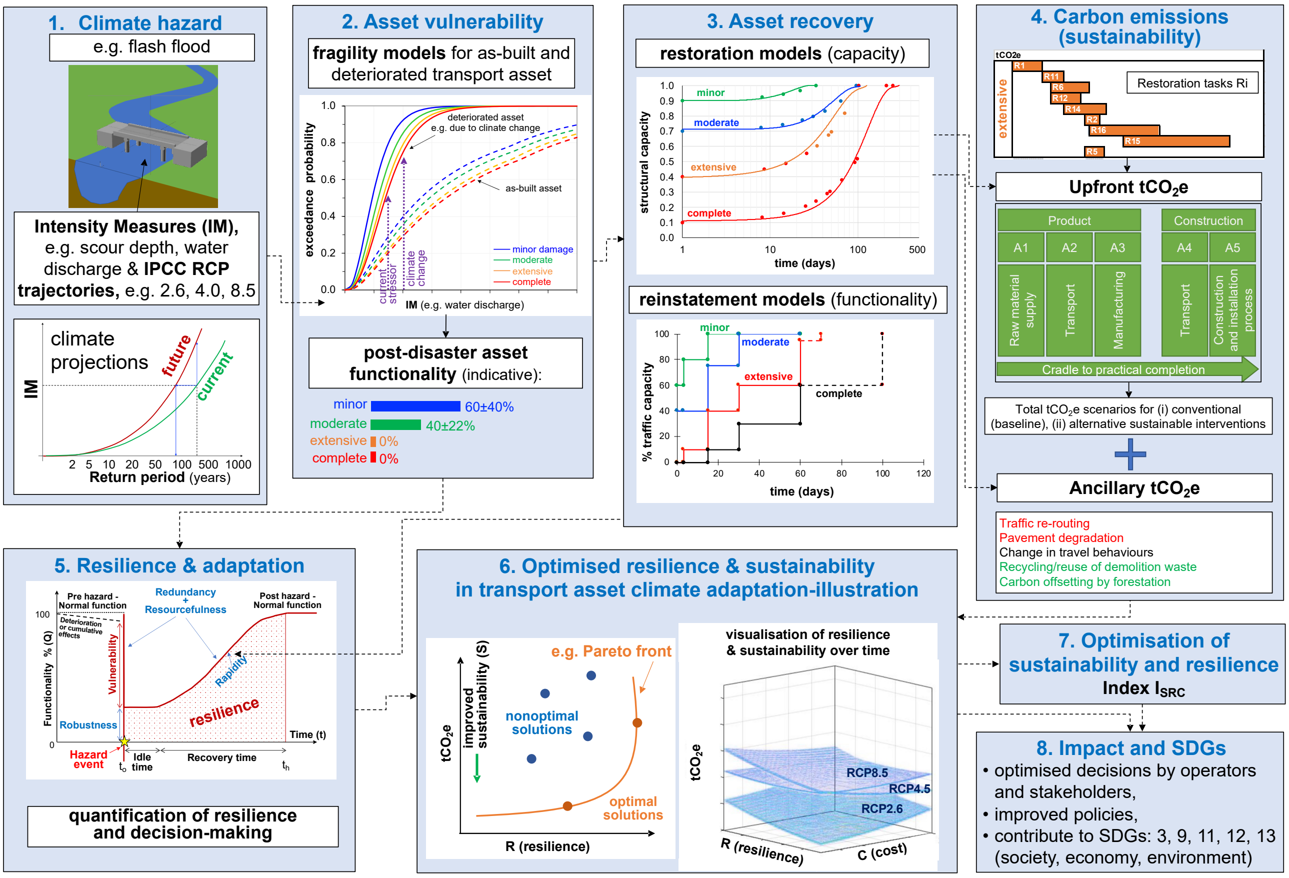


Figure 3. Framework for sustainability and resilience optimisation for infrastructure climate adaptation [14].