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A Systematic Review on Risk-Based Frameworks for Scour-Prone Bridges

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Abstract

Floods are a major cause of bridge failures worldwide, exerting direct forces (hydrodynamic and hydrostatic) and indirect effects such as scour. Scour can critically undermines a bridge's load-bearing capacity and increase failure risk. Accurately assessing the vulnerability of each bridge in a network is essential to prioritize interventions and reduce risk. This study presents a systematic review of existing research on risk-based approaches for evaluating flood-induced scour. Using Rayyan software, the retrieved studies were selected, screened and analyzed in terms of authorship, citations, publication year, bridge and hazard types, and geographical scope. The papers were then categorized by their methodology, with a detailed review of each approach. Special attention is given to recent advances integrating climate change considerations and sensor data into scour risk assessments. Finally, the review highlights emerging research directions and promising studies that could further advance the field. Overall, this paper synthesizes the current state of knowledge and identifies opportunities to strengthen future risk assessment frameworks for flood-prone bridges.

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Keywords: floods; bridges; risk; scour; sensors

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1. Introduction

Bridges are critical elements of transportation networks, enabling connectivity, economic activity, and daily mobility. However, they are exposed to multiple hazards, including earthquakes, landslides, and particularly flooding. Flood-related hazards pose a significant threat to bridges crossing rivers, streams, and coastal areas, as floods can induce hydrodynamic and hydrostatic forces, debris impacts, and scour (Garg et al., 2022; Wardhana & Hadipriono, 2003). Among these mechanisms, scour is the erosion of soil around bridge foundations during high-velocity flow events and is one of the leading causes of bridge damage and failure. Scour can occur as local scour around piers, general scour due to long-term riverbed degradation, or contraction scour when floodwaters are forced through narrowed flow sections (Arora & Banerjee, 2023).

Bridge risk is commonly conceptualized as the interaction of hazard, exposure, vulnerability, and consequences (Roca & Whitehouse, 2012). For scour-prone bridges, hazard relates to the probability and intensity of flooding, exposure reflects the characteristics of the bridge assets, and vulnerability depends on factors such as structural design, materials, age, and condition. The consequences of bridge damage include direct costs, such as repair or replacement, as well as indirect socio-economic impacts, including traffic disruptions and reduced network functionality (Pregnolato et al., 2024).

Bridges operate as interconnected components within wider transportation systems, meaning that the failure of a single bridge can disrupt entire corridors. This risk is further amplified by climate change, which is projected to increase the frequency and intensity of extreme flood events (Dikanski et al., 2017).

1.1. Background, gaps and aim

The literature identifies three main approaches for assessing risk to bridges. Quantitative approaches rely on extensive datasets, including real-time flood records, historical bridge performance, and detailed structural information (Inoue et al., 2020). While offering numerical precision, these methods are often impractical in data-scarce regions. Qualitative approaches, by contrast, are based on expert judgment, stakeholder engagement, and structured assessment frameworks (Alipour & Miner, 2025). Although less precise, they are easier to implement and more accessible to infrastructure managers, providing valuable decision-support insights. Hybrid approaches combine quantitative and qualitative methods to estimate risk, helping bridge the gap between theoretical models and real-world applications, particularly for large bridge networks exposed to flood-induced scour (Loli et al., 2022).

Despite their widespread use, traditional risk assessment methods face important limitations. They often rely on simplifying assumptions, inadequately address uncertainty, and extrapolate future extreme events from limited historical data. Also, they frequently identify scour only after structural damage has occurred; indeed, current risk management practices remain largely reactive rather than proactive. As a result, existing approaches are not yet sufficient to effectively minimize the risk of bridge failure due to flooding.

Recent advances in monitoring technologies offer new opportunities to improve risk assessment. Sensor-based systems enable continuous measurement of key structural and hydraulic parameters such as scour depth and flow velocity. These devices can be classified as direct sensors, which measure soil erosion near foundations, and indirect sensors, which infer scour through changes in structural response (Prendergast & Gavin, 2014). In parallel, there is a growing shift from physics-based modeling toward data-driven approaches that leverage real-world data to identify patterns and support decision-making (Chew et al., 2025). However, the lack of integrated risk-based frameworks incorporating these data-driven methods limits their current impact.

This review aims to synthesize existing risk-based frameworks for bridges exposed to flooding, with particular emphasis on scour-related challenges and the emerging role of sensor-based monitoring systems and data-driven approaches.

2. Methodology

This systematic review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (Page et al., 2021) to ensure transparency, reproducibility and methodological rigor. The review process is structured around three main steps: *(i)* defining a comprehensive search strategy, *(ii)* screening and

selecting relevant studies based on predefined inclusion and exclusion criteria, and *(iii)* analyzing the selected literature using multiple analytical lenses.

A set of primary and secondary keywords was developed to capture the core themes of the review. The primary keywords include *bridge*, *flood*, *scour*, and *risk-based framework*, while secondary keywords cover related aspects such as *climate change*, *uncertainty*, *optimization*, *health monitoring*, *maintenance*, and *data-driven frameworks*. Variations in terminology (e.g., *flooding*, *scouring*, *risk management approach*) were also considered to ensure broad coverage (see Appendix A). The search was conducted across two major online databases (Scopus, Web of Science) and initially yielded 913 records.

The article screening process applied several exclusion criteria (Figure 1). Duplicate records were first removed, followed by the exclusion of studies that were not fully accessible, not written in English, or limited to abstracts only. Non-journal publications, including review papers and conference proceedings, were also excluded. Finally, content-based criteria were applied to remove studies not focused on risk-based approaches, those addressing other types of infrastructure (e.g., embankments), other hazards (e.g., earthquakes), or flood-related mechanisms not directly associated with scour. This multi-stage filtering process resulted in a final dataset of 40 journal articles. The overall screening and selection procedure is illustrated in Figure 1.

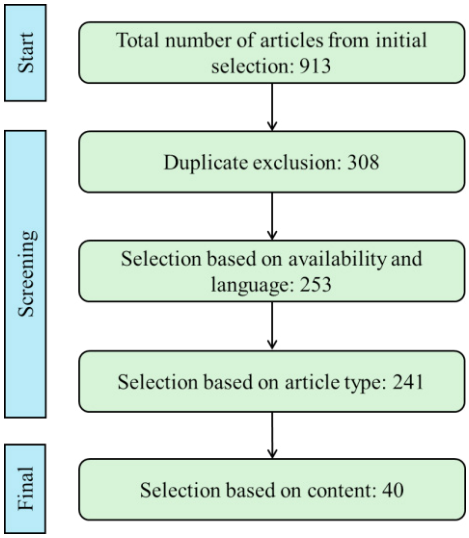


Fig. 1. Screening and selection procedure of the 40 selected papers.

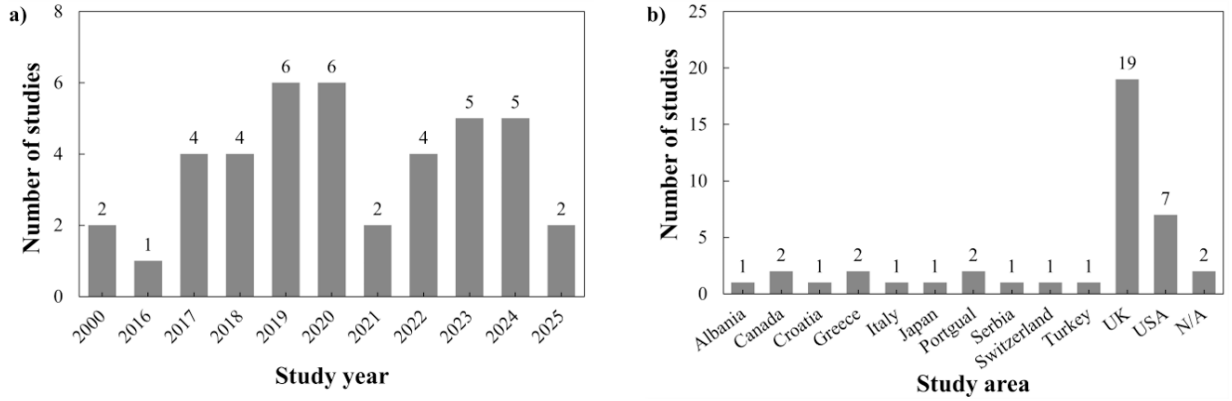
The selected studies were then examined using several analytical lenses. First, descriptive statistics were compiled, including publication year, geographical location of case studies, bridge types, and hazard characteristics. Second, the studies were categorized according to their methodological approach (quantitative, qualitative, or hybrid) providing insight into prevailing risk assessment practices. Third, the review assessed whether and how climate change considerations were incorporated into risk-based frameworks. Finally, the integration of sensor data and structural health monitoring technologies into risk computation was analyzed. Together, these analytical lenses enable a structured synthesis of existing approaches to flood-induced scour risk assessment and highlight current gaps and emerging trends in the literature.

3. Results

Research on risk-based assessment of flood-induced scour has grown steadily since 2000, with a marked increase after 2016. This rise reflects the increasing frequency and severity of extreme flood events worldwide and their substantial impacts on bridge infrastructure. Several recent flood disasters highlight this trend, including the 2015-16 winter floods in the UK, which damaged or destroyed more than 100 bridges, the 2018 Kerala floods in India that

caused extensive infrastructure losses and human casualties, and the 2019 Mississippi River floods in the United States, which disrupted access to major bridges and transportation corridors.

The geographical distribution of the reviewed studies indicates a strong concentration in regions with both high research activity and/or significant vulnerability to scour-related bridge failure. Nearly half of the studies focus on the UK (c.a. 48%), followed by the USA (c.a. 18%), with further contribution from a few European countries (such as



Greece and Portugal). A small number of studies (N/A in Fig. 2b) adopt a non-region-specific approach, proposing generalized frameworks applicable across different contexts. Figure 2 illustrates the statistics.

Fig. 2. (a) Yearly categorization. (b) Study areas.

Across the reviewed literature, a range of hazard categories is addressed, including general flooding, multiple hazards, debris-induced scour, climate-driven flood-induced scour, and flood-induced hydraulic actions. However, nearly half of the studies focus specifically on flood-induced scour. With respect to infrastructure type, road bridges dominate the literature, accounting for approximately 53% of the studies, whereas comparatively fewer contributions focus on railway bridges, culverts, or mixed transport assets.

Methodologically, quantitative approaches prevail, representing roughly 73% of the studies, while qualitative methods account for about 12%, and the remaining studies adopt hybrid approaches. Within these categories, a variety of techniques are employed to evaluate scour-related risk, reflecting the methodological diversity of the field.

3.1. Climate change and sensors adoption

The explicit integration of climate change into bridge scour risk assessment has gained attention over the past decade, with approximately 23% of the reviewed studies addressing climate-related effects. Early work by Dikanski et al. (2017) employed causal chain models and probabilistic frameworks to evaluate how climate-driven changes in river flow may increase scour risk, highlighting limitations in traditional assessment methods. Khandel and Soliman (2019) further demonstrated that conventional approaches are inadequate for predicting future scour hazards under evolving flood regimes, advocating for probabilistic models incorporating climate projections. More recent studies have focused on developing practical and implementable frameworks. For example, Sasidharan et al. (2023) proposed a time-dependent probabilistic approach combining climate projections, hydraulic modeling, and Monte Carlo simulations to quantify uncertainty in scour risk, while Habeeb et al. (2024) developed a stochastic framework showing that substantial scour risk persists even under low-emission scenarios.

Several studies partially incorporate climate change through improved flood frequency analysis or adaptation strategies. Bento et al. (2020) used statistical flood modeling to better represent future extreme events, while Liu et al. (2020) and Takano and Pooley (2021) emphasized retrofitting strategies and the integration of climate considerations into design codes. Abdel-Mooty et al. (2024) proposed a risk-based prioritization framework for UK bridges that incorporates climate change effects alongside structural and hydro-geological factors.

In parallel, a growing body of research highlights the value of integrating sensor data into risk-based frameworks for bridge management. Structural health monitoring systems, particularly scour monitoring devices, enable real-time risk updates and uncertainty reduction. Bayesian network-based approaches have been widely adopted to assimilate sensor data into scour risk assessment, as demonstrated by Maroni et al. (2022, 2023). Other studies explored complementary monitoring technologies, including weather and hydrological sensor platforms (Bekić et al., 2018), drone-based photogrammetry for hydrodynamic modeling (Hackl et al., 2018), satellite imagery for debris tracking (Panici et al., 2020), and monitoring-informed decision support systems (Tubaldi et al., 2022). Together, these studies demonstrate the growing potential of sensor-based and probabilistic approaches to enhance flood-induced scour risk assessment, while also highlighting the continued reliance on simplified assumptions and the need for more integrated frameworks.

4. Discussion and conclusion

Historically, the use of sensors in bridge risk assessment has been limited by high installation and maintenance costs, operational challenges during extreme events, and the lack of reliable long-term monitoring devices. Recent technological advances have substantially reduced these barriers, making scour-detection sensors more affordable and capable of accurately monitoring both scouring and refilling processes. In parallel, improvements in weather stations and river gauges have increased the availability and quality of hydrological and environmental data, supporting more informed assessments. These developments also enable data-driven modeling approaches, which leverage observed data to reduce reliance on simplifying assumptions and purely physics-based models.

Despite the growing attention to climate change in scour risk studies, several limitations remain. Many assessments depend on uncertain climate projections and hydrological models, assume extreme events as independent, or consider only single flood scenarios. Advanced monitoring sensors (such as Doppler velocity sensors, water-level loggers, and flow meters) offer opportunities to directly measure hydraulic conditions, improve model calibration, and reduce uncertainty. Continuous monitoring can also lessen dependence on single-event analyses by capturing the temporal evolution of flood and scour processes.

Recent studies have begun integrating sensor data into risk-based frameworks, primarily using probabilistic methods such as Bayesian networks. However, these approaches remain limited in number and scope, often being region- or bridge-specific and reliant on individual sensor types. Moreover, continuous exposure of sensors to harsh environments and the absence of generalized frameworks constrain broader application. There is therefore strong potential to integrate data from multiple sensors into existing risk-based frameworks, enabling dynamic updates and more realistic representation of bridge behavior under flooding.

This systematic review synthesizes 40 selected studies on risk-based frameworks for bridges affected by flood-induced scour. The findings show a strong focus on flood-induced scour hazards and road bridges, limited use of qualitative approaches, and climate change considerations in limited number of studies. The review highlights significant opportunities for future research to develop generalized, multi-sensor, and potentially qualitative or hybrid frameworks that are more accessible to decision-makers and better suited to updating design guidelines and bridge management practices.

Data availability

The data supporting the findings of this review are publicly available in a data repository at https://doi.org/10.4121/ee593bf2-818e-4adc-8e95-6d8e08c35e82

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Appendix A. Search syntax

Table 1. Adopted search syntax

Database	Syntax
Scopus	(TITLE-ABS-KEY(bridge OR "bridge network") AND TITLE-ABS-KEY(scour OR scouring) AND TITLE-ABS-KEY(flood OR flooding) AND TITLE-ABS-KEY(risk OR "risk based approach" OR "risk management approach")) AND TITLE-ABS-KEY("climate change" OR "future effect" OR "extreme effect") AND TITLE-ABS-KEY(uncertainty OR sensitivity OR fragility) AND TITLE-ABS-KEY(optimization OR optimum) AND TITLE-ABS-KEY("structure health monitoring" OR "bridge health monitoring") AND TITLE-ABS-KEY(maintenance OR prioritization OR retrofit) AND TITLE-ABS-KEY("data driven" OR "real time data" OR "sensor data")
Web of Science	(TS=(bridge OR "bridge network") AND TS=(scour OR scouring) AND TS=(flood OR flooding) AND TS=(risk OR "risk based approach" OR "risk management approach")) AND TS=("climate change" OR "future effect" OR "extreme effect") AND TS=(uncertainty OR sensitivity OR fragility) AND TS=(optimization OR optimum) AND TS=("structure health monitoring" OR "bridge health monitoring") AND TS=(maintenance OR prioritization OR retrofit) AND TS=("data driven" OR "real time data" OR "sensor data")

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