Network- and bridge- level management under uncertainties associated with climate change

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ABSTRACT: Bridges are strategic connection points within the transport network, underpinning economic vitality, social-wellbeing, and logistics of communities. Currently, most of the transport authorities are not able to identify bridges at higher risk of disruptions, due to limited data or lack of a risk-informed assessment, and this is particularly true for bridge scour. The situation is exacerbated with the distributed knowledge about the condition of bridges, constrained resources, and concerns about the risks of climate change. To be effective, the strategies designed to improve the reliability and resilience of bridge assets needs to account for the uncertainties associated with predicting the performance of the bridge, progression of scour depth, and the impact of climate change hazards. To this end, this paper sets the scene for establishing a rational and systematic approach to evaluate the factors that affect bridge scour risk and condition, identify, and prioritise appropriate measures, thereby improving the allocation of scarce management resources. The bridge-level decisions are optimised to provide a wide range of monitoring and maintenance options that the network-level subsequently uses to prioritise based on budget availability, scheduling, probability of disruptions and the associated wider impacts. The functional framework presented within this paper would provide a basis for the development of a scour-focused module within the bridge management systems.

1 INTRODUCTION

1.1 *Background*

Bridges are critical infrastructure components of road and rail transport networks. A large number of these critical assets are exposed to river flooding effects such as scour which is the foremost cause of bridge collapse globally (Faulkner *et al.*, 2020). Scour is defined as the removal of sediment and gravel from the bed and banks of a river by the action of water. In the UK, 10 total and 30 partial scour-related bridge collapses were recorded in 2020 (RAC Foundation, 2021). Despite these failures, the level of risk of many bridges exposed to flood effects remains largely unknown, with scour risk ratings still missing for many bridges. The problem is exacerbated by the lack of comprehensive asset data due to infrequent inspections and lack of standardised inspection practices, especially in the case of older bridges, where foundation conditions are unknown.

Existing bridge asset management plans do not consider the impacts and risks associated with changing weather patterns attributed to climate change. Infrastructure authorities have recently pledged to develop and publish climate change adaptation plans for their infrastructures and to encourage the adoption of such practices by the asset managers (Climate Change Committee, 2021). To this end, technical changes have also been introduced to bridge design and management manuals to provide climate change allowances and guidelines to scour risk assessment and protection (Takano and Pooley, 2021). Such efforts also need to jointly consider the revamping of strategic and operational practices within the network. While the strategic practices might involve decisions to prioritise bridges for monitoring, maintenance and installation of flood defences and scour protection measures, the operational practices could inform bridge closures and traffic rerouting.

1.2 *Aim and contributions*

This study overviews current practices and challenges involved in bridge scour management, framing it within the infrastructure authorities' preparedness to deal with risks of climate change. To investigate this, a series of interviews were conducted with six local authorities (LAs) with one in Scotland (LA1) and five in England (LA2-6). It also discusses the development of a scour management module within a bridge management system (BMS) and conceptualises how it can be employed to make strategic and operational decisions at the network- and bridge level.

2 BRIDGE SCOUR MANAGEMENT IN THE UK

2.1 *Current practices*

The current scour management practices follow a reactive approach where repair or maintenance interventions are carried out after the scour has formed or has reached an unacceptable threshold where bridge closures or weight restrictions are necessitated. Unlike other transport infrastructure assets such as railway tracks or roads where predictive deterioration models are employed to inform budget requirements, the progressive nature of scour is not considered within the existing scour management practices (RSSB, 2005). They are often based on risk assessments mandated by the BD97/12 manual for the road bridges (DMRB, 2012) and EX2502 standard for the railway bridges (HR Wallingford, 1992). A review of these standards and procedures involved are detailed in Sasidharan, Parlikad and Schooling (2021a).

The bridges/locations at risk are usually identified based on criticality ratings considering route type, traffic, etc. For instance, Network Rail prioritises its bridges for scour vulnerability by considering the river type, depth and material of the foundation, and the predicted scour depth. On the other hand, LA2 does maintenance prioritisation by considering the BD97/12 scour risk assessment results alongside maintenance needs assessment (ranked from 1 to 12), route types (4 categories) and historical flood alert levels. The resilience of the bridge is also taken into consideration by the LA in Scotland when prioritising their bridge stock.

The LAs employ in-house approaches of varying sophistication to identify locations/bridges at risk during flooding to target operational practices. Some are subjective methods where reconnaissance teams were employed to identify locations/bridges at risk during a heavy precipitation or flooding event that informed where the bridge inspectors can carry out post-flood scour inspections (e.g. LA4). The LA in Scotland installed cameras that captures a photo every 20 seconds to monitor flood levels near bridges. Some LAs (LA5 and LA6) monitored the rainfall and river flow through near-real-time data provided by environmental agencies, river gauge stations and third-party providers to enforce operational procedures such as lane/bridge closures or traffic diversions. LA2 carried out visual surveys of debris accumulation near the bridge during heavy rainfall events. LA3, on the other hand, does not consider any real-time weather information within their decision making.

Every LA interviewed had different risk acceptance levels. For instance, the LA in Scotland enforced bridge closures for safety reasons if the river flow level or rainfall was above a certain threshold. Contrastingly, other LAs in England that were interviewed never resorted to bridge closures unless for maintenance interventions or if found to be structurally vulnerable. The consequences or severity of bridge scour-related disruption may vary for different bridges based on the route criticality, traffic and location-specific demographics. These are not often taken into consideration within the existing scour risk assessments. On the other hand, some authorities do not carry out any scour risk assessments. It is also pertinent to note that some LAs (e.g. LA3) do not follow the BD97/12 standard and lack any formal operational frameworks for scour management. They often resort to information from past incidents (if any) to identify scour vulnerable bridges.

The infrastructure authorities have recently adopted some approaches to progress from reactive to preventive asset management. For instance, LA2 is trialling aerial imagery to detect debris and subsequently capture them before they reach the structures (Panici *et al.*, 2020). River training works have also been implemented by the LA to control the riverbank erosion. LA4 has developed a risk-based approach, following widespread flood damage to its bridge stock, to minimise public risk and disruption (Mathews and Hardman, 2018). While the relative efficiency of the current and emerging bridge scour management practices (see Table 1) could not be judged, their very existence demonstrates the desire for a rational approach to prioritising bridges for scour management.

Table 1. Bridge scour management practices

	Local Authority					
	1	2	3	4	5	6
BD97 Stage 1 assessment		●		●		
BD97 Stage 2 assessment		●		●		
Flood risk assessment	●					●
Flood management		●		●	●	●
Scour monitoring						
Weather monitoring	●	●		●	●	●
Maintenance prioritisation	●	●	○			
Scour management framework						
Strategic planning		●		●		●
Operational management				○		
Climate change adaptation in:						
design & construction		○				
maintenance & operation	○			○		
Scour module within BMS		○		○		●

● Applicable to all bridges / matured practice
○ Applicable to some bridges / not a formal practice

2.2 *Challenges to scour management*

An accurate evaluation of the bridge scour risk requires information regarding hydraulic, soil, structural and traffic engineering. The depth and rate of scour development are linked to structural, hydraulic, geological, environmental, and human-induced factors (Sasidharan, Parlikad and Schooling, 2021b). There is a lack of standardisation in the data collection and inspection practices, particularly for hydraulic and geologic factors across different LAs (see

Table 2). Infrequent inspections, lack of data on the foundation and scour depths result in uncertainties. For instance, Only 37 LAs have carried out BD97 Stage 1 scour assessments on 17% of the UK's total local road bridge stock (RAC Foundation, 2021).

Table 2. Scour related data collected or employed by the local infrastructure authorities in the UK

	Data	Local Authority					
		1	2	3	4	5	6
Hydraulic & Geological	Type of river flow	●	●	○	●	●	○
	Rainfall	■	■		■		■
	Flood return period		●		●		
	Wetted perimeter		●		●		
	Terrain type	●	●		●		●
	Manning's coefficient		●		●		
	Peak water level	■	■		●		
	River flow rate	■	●		●	●	
	River flow depth	■	●		●	●	
	Groundwater level						
	Slope of the stream		●		●		●
	Strahler order of reach						○
	Flood accommodation		●		●	●	
	Riverbed elevation		●		●	○	●
	Riverbed material		●		●	○	●
	Riverbank erosion	●	●		●		●
Structural	Bridge location	●	●	●	●	●	●
	Age of the bridge	○	●		●	●	○
	Span type	●	●		●	●	●
	Span width	●	●		●	●	●
	Bridge material	●	●		●	●	●
	Superstructure type	●	●		●	●	●
	Number of piers	●	●		●		●
	Type of piers	●	●		●		●
	Size of the piers	●	●		●		●
	Orientation of piers	●	●		●		○
	Shape of pier nose	●	●		●		○
	Size of the abutments	●	●		●		○
	Orientation of abutments	●	●		●		
	The shape of the abutment	●	●		●		○
	Type of foundation	○	○	○	○		●
	Depth of foundation	○	○		○		
Operational	Scour risk level	●	●		●	○	○
	Scour monitoring						
	History of scour		●			○	●
	Scour protection	○			●		●
	Measured scour depth					○	●
	Debris accumulation	●	●	○	●	○	●
	History of flooding		●	○		○	
	Earthquake-prone region						
	Riverbed mining		●				
	Hydraulic structures		●			○	○
	Route type	●	●	●	●	●	●
	Traffic on the route		○	○	○	○	

● Collected in-house and available for all the bridges
○ Data is available only for a few bridges
■ Collected from external agencies for all bridges

Scour monitoring techniques ranging from visual monitoring of water level (Roca *et al.*, 2021) to bridge deck settlement through satellite radar imagery (Selvakumaran *et al.*, 2018) offer promising results. However, scour monitoring is not prevalent in the industry due to budget constraints, challenges associated with power in rural areas and monitoring techniques not providing information in an understandable format to the bridge managers. One of the LAs feared a political and legal backlash in the event of a monitored bridge collapsing due to scour.

The lack of a systematic bridge management framework means that often LAs do not work in tandem with other stakeholders such as environmental agencies. This often results in operational challenges when the latter's approval is needed for installing flood defences and scour protection measures.

2.3 *Managing the risks of climate change*

The risks of climate change are not formally taken into consideration by any of the interviewed infrastructure authorities within their scour management processes (see Table 1). However, there is a consensus that changing weather patterns, if not understood and prepared for, are likely to result in an increased risk of scour. There is also a varied level of climate preparedness amongst the bridge managers. For instance, one LA in England is considering an increase of the flood return periods within its design to provide an allowance for rising river flow. The LA in Scotland is planning to gather near-real-time information of heavy-localised and prolonged-light rainfall events to better inform operational procedures. LA4 has developed an in-house flood risk management plan that not only sets the path for managing flood risks but also necessitates a post-flood assessment of the bridge stock, including scour inspections. They also recognise the need for hydraulic and geological factors to be considered within scour risk assessments and are gathering information on the wetted perimeter of the river near each bridge to understand the impact of extreme weather events on fluvial flooding.

Climate adaptation needs to be considered within design, construction, operation and maintenance processes to make bridges resilient. A recent update to the BD917/12 standard on designing new structures (CD356) and asset management of existing structures (CS469) sets practical requirements for bridge design and management to determine the impact of hydraulic actions on structures. It also includes provisions for climate change (Takano and Pooley, 2021). In comparison to the EX2502 railway standard, the BD97/12 is more suitable for the adaptation to capture climate change effects on bridge scour as the former estimates the river flow depth as a function of channel width and does not consider any future changes in river flow.

3 SCOUR MANAGEMENT FRAMEWORK

Bridge infrastructure owners and managers need to manage a variety of risks such as floods, structural deterioration and budget cuts. Effective risk mitigation plans need to consider the scour susceptibility of the bridge and the associated impacts. All the interviewed infrastructure authorities highlighted the lack of a standardised framework that aids the asset management at the network and bridge level to inform strategic and operational decisions. There is also a need for integrating different stakeholders and their interests when making such decisions.

Figure 1 conceptually summarises decision-making at the network- and bridge-level, through the four management functions: strategic planning, programming, preparations and operations management (Robinson, 2008). This relates to short-, medium-, and long-term decisions ranging from managing a bridge to the whole network.

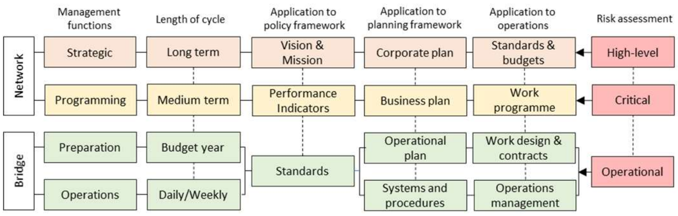

Figure 1. Risk informed network- and bridge-level bridge management framework (adapted from Sasidharan, Parlikad and Schooling 2021b).

At the network level, the infrastructure authority sets the asset management framework and service levels to deliver the strategic objectives and performance targets. These targets provide a measure of how bridge inspection and maintenance impact the performance of the transport networks (e.g. connectivity, costs, safety, delays etc.). Risk assessment is often carried out at the network level to identify critical structures where interventions need to be prioritised and risks associated with any operational activities. This in turn informs the budget and risk mitigation plans.

At the bridge level, each structure is inspected for its structural integrity. The frequency of these inspections is usually governed by standards (e.g. general inspection every two years and detailed inspection every six years). Such inspections and structural examinations would inform the maintenance and repair requirements for each bridge on the network. Such bridge-level decisions are optimised to provide a wide range of monitoring and maintenance options that the network level subsequently uses to prioritise based on budget availability, scheduling, probability of disruptions and the associated wider impacts.

3.1 *Strategic*

Strategic planning involves the estimation of long-term budget requirements for monitoring and maintenance of all bridges in the network (see Figure 2). This would involve predicting bridge conditions, identifying maintenance strategies and forecasting life cycle costs (LCC). Such exercises would contribute to a high-level scour risk assessment for the whole network to identify mitigation plans for reducing the risks as reasonably possible. The bridges are likely to be clustered based on route criticality, traffic flow, bridge type and span, geological factors, flood threshold levels and future rainfall and river flow levels etc.

A key part of dealing with climate change-related uncertainties is to monitor the intensity of rainfall and river flow. Infrastructure authorities need to establish agreements with meteorological agencies to obtain severe weather forecast warnings in advance of high-intensity rainfall and subsequent flooding occurring. This will allow time to prepare operational procedures like bridge closures and/or weight restrictions and rerouting the traffic. In locations where existing meteorological sites or gauging stations are not in place, the authorities can employ hydrological modelling to estimate the range of river flow levels near individual bridges (Kay *et al.*, 2021).

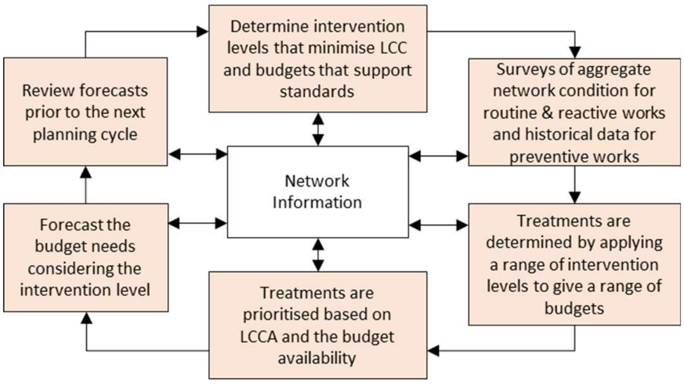

Figure 2. Strategic planning.

3.2 *Programming*

Programming involves the development of multi-year work programmes involving the identification of bridges that are likely to require flood and scour protection measures and repairs (see Figure 3). Critical bridges are considered on a route-by-route basis, characterised by route/traffic types and scour susceptibility. To this end, the structural, hydrological, hydraulic and geological factors that contribute to scour formation needs to be analysed in detail. Ideally, a life cycle cost analysis (LCCA) should also be undertaken for different treatment types on an annual or rolling basis for each route to determine the economic feasibility of the work programmes. A key aspect of the programming level is to prioritise works that give the best value for money under constrained budgets. Approvals from the environmental agencies also need to be considered for installing flood defences. The enforcement of restrictions based on the threshold levels and diversion routes needs to be agreed upon with stakeholders such as the police and the transport authorities. Restrictions might vary depending on the route criticality and bridge condition.

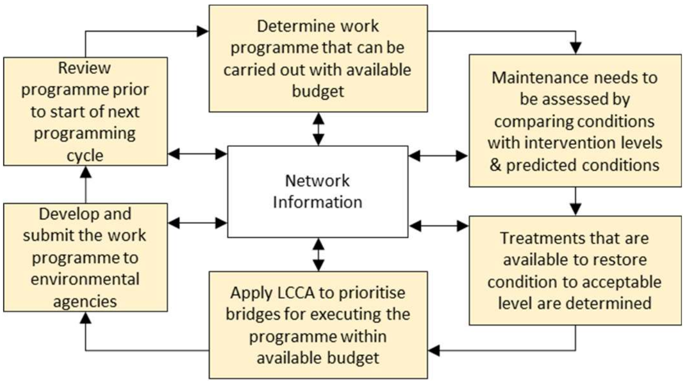

Figure 3. Programming.

3.3 *Preparation*

The bridges are prioritised for work programmes and preparations are done for its implementation (see Figure 4). Works on adjacent bridges may be combined so that it is cost-effective for execution and reduced disruption to users. Detailed specifications and costing are done for the economically feasible work programme identified at the programming level. Any LCCA may be re-visited to confirm the value for money before tenders are called for and contracts are drawn. Budgets would normally have been approved every year.

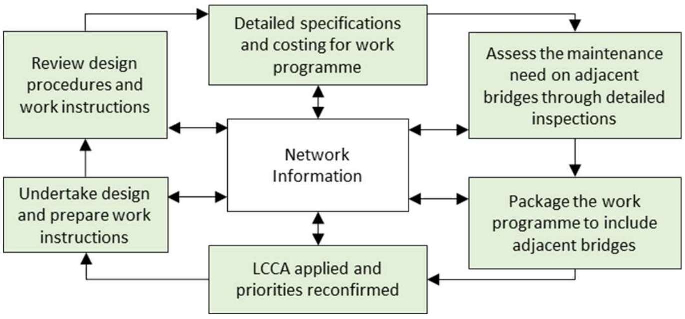

Figure 4. Preparation.

An information dissemination strategy should also be identified between, where appropriate, the transport and environmental authorities, the police and any public information dissemination organisations involved to alert the users of potential closures and traffic diversions. The role and responsibilities of each stakeholder before, during and after an incident need to be agreed upon.

3.4 *Operations*

Operational management is associated with standards and intervention levels for repair and river flow and/or rainfall levels for traffic detour (see Figure 5). This is associated with decision making related to work scheduling and resource allocation on a daily/weekly basis. Inspections are often made at a relatively detailed level for each bridge. This is followed by the design and implementation of necessary work programmes such as maintenance, flood defences and scour protection measures.

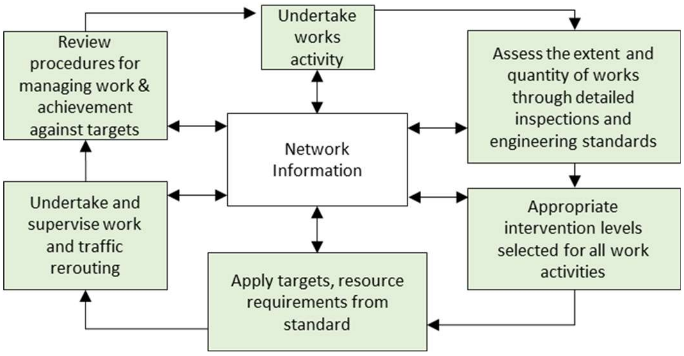

Figure 5. Operations management.

To ascertain the level of restriction applied to each bridge, pre-determined threshold values of river flow and rainfall are monitored in real-time. This should also include threshold values at which restrictions can be removed. Considering that the rate of scouring is aggravated during extreme flooding events, the definition of these threshold levels may require specialist consultants to model their impact on scour depth formation for each bridge.

4 SCOUR MANAGEMENT MODULE

Most of the BMSs can perform essential functions such as data storage, asset condition prediction, cost modelling, optimisation. However, they often lack mechanisms for achieving trade-offs between investments and risks of bridge disruption/failure (Jeong *et al.*, 2018). Moreover, the majority of BMSs focus on structural issues without adequate emphasis on bridge scour (Pregnolato, 2019). Figure 6 conceptualises a scour management module that includes the type of information and the outputs from different scour management functions described earlier. The different approaches and techniques for processing the information are discussed below.

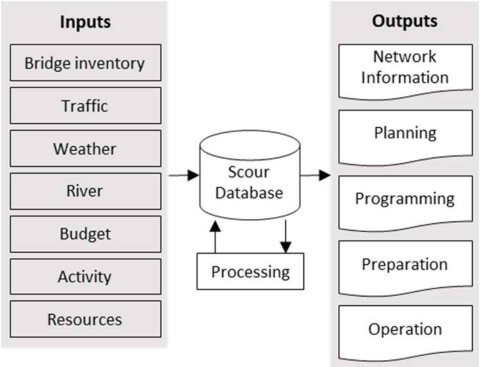

Figure 6. Bridge scour management module adapted from Robinson (2008)

4.1.1 *Scour database*

Across all the four management functions, the understanding of the bridge deterioration through better condition information is important. It is key to quantifying the costs of bridge management strategies and the associated impact on users, safety, environment and society (Sasidharan, Parlikad and Schooling, 2021b). Fit for purpose information is essential for developing the appropriate asset strategies and for producing and implementing work and operational plans. To this end, an up to date bridge database is a key foundation for any BMS module.

Standardised data collection and inspection practices need to be set in place. It is evident from Table 2 that the existing bridge database needs to be augmented. This is particularly the case for hydraulic and geological data that is key for designing climate adaptation measures. Approaches such as Line of Sight (Parlikad, Schooling and Heaton, 2017) can be used to systematically identify the data and information requirements.

4.1.2 *Bridge scour rating*

When conditions of individual bridges are compared with each other, or when one bridge is tracked over time, it is common to use condition ratings or health indexes. Condition ratings are often used by infrastructure authorities to trigger inspections or interventions for their bridge stock. However, the existing bridge condition indexes do not accurately reflect the impact of scour on the structural integrity of the bridge (Yianni *et al.*, 2017). For the task in hand, a bridge scour condition rating is presented in Table 3. It is based on bridge scour rating (R_S) that is the ratio of measured/predicted scour depth to the foundation depth. It represents the condition or state of scour in bridges across the network to reflect the intervention required to maintain the network in a desirable state.

Table 3. Bridge scour rating

Scour rating		Description & intervention
Low	R_S< 0.49	No or insignificant damage: continue the existing inspection strategy
Moderate	R_S = 0.5-0.74	Some damage: suitable for increasing the frequency of inspection
High	R_S = 0.75-0.99*	Significant damage: maybe suitable for increased inspection and monitoring
Extreme	$R_S > 1$*	Complete damage: suitable for increased inspection and monitoring

* or if the foundation depth is unknown

4.1.3 *Predicting scour progression*

Scour depth prediction models are usually classified as time-dependent and equilibrium based (see Sasidharan, Parlikad and Schooling (2021b) for a review). The design practices followed by infrastructure authorities are typically based on the equilibrium scour depth associated with a discharge of a given return period (e.g. 1 in 200-year flood). Such models are usually based on laboratory experiments and often result in overestimations in real-world scenarios (Choi and Choi, 2016). Considering the impact of changing environmental conditions, it would be prudent to consider the increase in temperature and precipitation and subsequent change in river flow while predicting the scour progression (Nasr *et al.*, 2019).

Academic efforts have been undertaken to consider the impact of climate change-induced floods on scour progression (Kallias and Imam, 2016; Dikanski *et al.*, 2017; Yang and Frangopol, 2020). Climate change effects are usually considered based on the results from downscaled global climate model data and hydrological modelling to predict the impact on river flows.

4.1.4 *Life cycle cost analysis*

Bridge asset managers need to identify strategies that maintain the bridge's structural integrity and performance within acceptable levels throughout their life-cycle. The inspection, monitoring and maintenance interventions based on the scour progression predictions have associated expenditures and impacts that can be estimated using an LCCA model. Different LCCA models consider a variety of costs and benefits. For example, LCCA may account only for agency costs (Mondoro and Frangopol, 2018); or alongside user costs (Yang and Frangopol, 2020), such as costs incurred by users when delayed or detoured due to disruptions or bridge closures. Very rarely, they may include environmental impacts (Sasidharan, Parlikad and Schooling, 2021b) and traffic flows (Pant, Hall and Blainey, 2016).

4.1.5 *Risk model*

The basis of effective scour management depends upon the identification of the exposed locations or bridges on the network that is susceptible to scour. Existing scoured bridges are obvious locations where flooding could impact the operational effectiveness of the network. It is also necessary to consider other exposed locations where user safety can be compromised due to the increasing frequency and severity of flood-induced heavy precipitation events. These can be obtained from the scour progression prediction models described earlier.

Infrastructure authorities should also be responsible for estimating the consequence of scour-related disruptions to their network. This could, alongside the outputs from LCCA, include a stakeholder consultation and a review of flooding related accident statistics as well as using specialist services to undertake flood profiling, climate trend analysis etc. to identify all the potential risk areas. Table 4 demonstrates how the scour condition ratings (from Table 3) can be compared with the consequences of scour-related disruptions to facilitate a risk-based monitoring and maintenance strategy for bridges across the network.

Table 4. The decision matrix for scour management

		Consequence			
		L	M	H	E
Bridge scour condition ratings	Low (L)	S1	S1	S2	S3
	Moderate (M)	S1	S2	S3	S4
	High (H)	S2	S3	S4	S4
	Extreme (E)	S3	S4	S4	S4

S1 Continue the existing inspection strategy
S2 Suitable for increased inspection
S3 Maybe suitable for increased inspection and monitoring
S4 Suitable for increased inspection and monitoring

4.1.6 *Decision-making model*

There has been considerable research to inform bridge asset management using reliability-based models (Bertola and Brühwiler, 2021), multi-utility theory (Allah Bukhsh *et al.*, 2019) and decision trees (Orcesi and Frangopol, 2011; Sasidharan, Parlikad and Schooling, 2021a) by prioritising bridge interventions under budget constraints and future climate uncertainties (Liu, Yang and Frangopol, 2020; Yang and Frangopol, 2020).

5 CONCLUSION

The sophistication of the systems and approaches for managing bridge scour varies across the infrastructure authorities in the UK. While the owners of strategic infrastructure assets such as National Rail or National Highways have comparatively mature systems, LAs are not in a position to invest resources in developing their systems to the same level. Therefore, it is unrealistic to roll out a nationwide BMS. For any BMS to be viable, it must be modular and capable of being introduced in stages (Flaig and Lark, 2000). It also needs to adopt a standardised approach to prioritise bridges for monitoring and maintenance based on safety, traffic delays, economic feasibility and vulnerability to extreme events.

The interactions with different infrastructure authorities in the UK highlighted the need for a common framework that integrates strategic and operational practices. To this end, a structured approach for managing bridges at the network- and bridge-level is presented. Such an approach will provide a systematic path for managing bridge scour. The proposed scour management module will improve the infrastructure authorities' understanding of the scour vulnerability of its bridge network, prioritise bridges for repair and appraise scour risk mitigation strategies.

The type and quality of data collected is key to the successful prediction and management of scour. This means that the existing bridge databases need to be augmented with comprehensive information on the structural, hydraulic and geologic factors that contribute to scour formation.

Climate change needs to be a routine consideration, factored into the authorities' operational management. To this end, scour prediction models and risk assessments techniques need to consider the impacts of change in precipitation and temperature on the river flow and subsequent floods. Consideration must also be given to the adaptation of design, construction, operation and maintenance processes to ensure the resilience of the transport network.

6 ACKNOWLEDGEMENTS

This work was supported by the Engineering and Physical Science Research Council (EPSRC) through the grant EP/N021614/1 (CSIC Innovation and Knowledge Centre Phase 2), Innovate UK through the grant 920035 (Centre for Smart Infrastructure and Construction).

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