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CASE STUDY

REVISED Two pilot case studies for indirect bridge scour monitoring using low-cost remote sensing for river flow characterisations

[version 2; peer review: 2 approved, 1 approved with reservations]

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Abstract

Bridge scour is a leading cause of bridge failures worldwide, exacerbated by climate change and increasing flood risks. Real-time data collection plays a critical role in effective flood risk management and decision-making, ultimately enhancing infrastructure resilience. The EU-funded RAMOBRIS (Risk Assessment and Monitoring for Bridges under Scour Hazard) project investigated cost-effective monitoring approaches to develop a novel, multidisciplinary strategy for assessing the risk of critical bridges exposed to scour. This manuscript outlines the monitoring strategy developed during the project, with a focus on the application of cost-effective sensors for hydraulic monitoring. The adopted methodology employs an indirect approach using low-cost remote sensing sensors to assess hydraulic properties and estimate scour depth through advanced formulas. Two pilot case studies were conducted on high-risk masonry bridges over the River Nith in Scotland. Various sensors were installed to evaluate their effectiveness in capturing hydraulic data and monitoring scour dynamics. Data from low-cost sensors were evaluated against data collected from higher-cost sensors or other available datasets. The results showed that low-cost sensors for measuring water levels provided accuracy comparable to high-cost radar systems, while being more cost-effective and easier to install. Video data from solar cameras enabled extensive measurements of surface velocity and discharge, improving the understanding of flow dynamics. The study confirmed the feasibility of using image velocimetry techniques for long-term estimation of river velocity and discharge, although further validation is required. These findings highlight the potential of low-cost and innovative sensor technologies. The open-access dataset

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generated in this study, which will be periodically updated with new data, provides a valuable resource of real-world information for ongoing research in hydraulic monitoring and bridge safety assessment.

Plain language summary

Bridge scour, the erosion of riverbed material around bridge foundations, is currently a major cause of bridge failures worldwide. This problem is expected to worsen due to the increased intensity and frequency of precipitation driven by climate change, leading to higher flood risks. To improve flood risk management and enable data-informed decision-making to protect infrastructure, it is crucial to develop cost-efficient monitoring strategies. This study outlines the monitoring strategy tested during the EU-funded RAMOBRIS (Risk Assessment and Monitoring for Bridges under Scour Hazard) project, which relies on the use of low-cost technologies to measure hydraulic properties and then uses them to estimate scour depth through advanced formulas. The manuscript also describes the two pilot studies conducted to evaluate the proposed approach, where various sensors were installed, with a specific focus on analysing the data collected from the low-cost sensors used for hydraulic monitoring. The comparison between the water levels obtained from low-cost sensors and those obtained from more expensive radar systems showed that the former can provide accuracy comparable to that of the more expensive systems, but with the advantage of being more affordable and easier to install. The study also explored the use of image velocimetry techniques, which involve measuring the surface velocity of river water by analysing videos, confirming that these methods could be used for long-term assessments of river velocity and flow, encouraging further research in this field. In summary, this research highlights the feasibility of using low-cost sensors for hydraulic monitoring and bridge safety, promoting their use for indirect scour monitoring. The study also establishes an open-access dataset, which will be regularly updated, providing valuable real-world data for investigating flood risk.

Keywords

Bridge-scour; Filed Monitoring; Remote Sensing; Low-cost sensors

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REVISED **Amendments from Version 1**

This revised version incorporates all comments and suggestions received during the peer-review process. The main updates are as follows:

- The title has been updated to "*Two pilot case studies for indirect bridge scour monitoring using low-cost remote sensing for river flow characterisation*" to include additional information on the specific scour monitoring method employed.

- The literature review has been expanded to provide a broader overview of the current state of research and to better position the present work within the existing scientific context.

- Figure 3 has been revised to offer a clearer visual representation of the monitoring setup and the positioning of the instruments at the study sites.

- The mathematical formulations related to the α-method and the computation of discharge have been included to improve the completeness of the methodological section.

- Several sentences throughout the manuscript have been rewritten or refined to enhance clarity, precision, and readability, ensuring that the concepts and results are more effectively communicated.

- Typographical errors identified in the previous version have been corrected.

Overall, this version provides a clearer and more comprehensive presentation of the study, improving both its scientific quality and readability.

Any further responses from the reviewers can be found at the end of the article

1 Introduction

Bridges are crucial components of transportation networks, facilitating the efficient movement of goods and people. Their functionality and stability are influenced by various natural hazards, such as earthquakes, landslides, wildfires, and floods, and human-induced hazards, including collisions, overloading, and explosions (Mei & Guo, 2024). Among these, hydraulic hazards represent the leading cause of bridge failures globally. This is underscored by Zhang *et al.* (2022), who conducted a statistical analysis of ten prior studies encompassing over 4,500 bridge failure events. Bridges crossing rivers are subjected to various actions, such as hydraulic load, flood-induced scour and debris accumulation (Burghardt *et al.*, 2025; Carnacina *et al.*, 2019; Kabir *et al.*, 2023). Particularly, scour, the erosion of river sediments due to the action of the river water, can lead to the formation of deep holes around the bridge foundation, which can compromise the load-bearing capacity of a bridge, potentially resulting in structural failure or collapse.

Scour is generally classified into three primary categories: general scour, contraction scour, and local scour. General scour affects the entire area surrounding a bridge and is primarily a consequence of natural riverbed erosion during high flow conditions, independent of any structures present. In contrast, contraction scour occurs when the river channel narrows due to the presence of a structure, leading to an increase in water velocity and subsequent sediment removal. This type of scour is associated with the presence of bridge piers or abutments, which reduce the cross-sectional area and significantly influence flow dynamics, intensifying sediment erosion. Local scour, the third category, is induced by the interaction of water flow with the bridge structure, resulting in turbulence and vorticity that increase shear stress on the sediment. This type of scour is often the most critical, as it can lead to the creation of a scour hole around the bridge foundation, which may deepen over time and pose a serious risk to the structure's stability.

Bridge scour is currently one of the leading causes of bridge failure worldwide, resulting in significant economic losses and loss of life (Pizarro *et al.*, 2020), and its impact is expected to increase due to climate change (Sasidharan *et al.*, 2023). Dottori *et al.* (2023) estimate that river flooding currently causes approximately €7.6 billion in annual damages and exposes around 160,000 people per year to inundation across the European Union and the UK. In a 3°C global warming scenario, and without climate adaptation measures, annual flood damage in Europe is projected to rise to €44 billion, with nearly half a million Europeans exposed to flooding each year by the end of the century.

Despite advancements in engineering methodologies and technologies for assessing the safety of waterway bridges, many of these methods depend on expensive sensors or involve costly and complex installations (Link *et al.*, 2020; Lu *et al.*, 2008; Wang *et al.*, 2017). As a result, current flood risk assessment and emergency management practices often rely on visual inspections and simplistic empirical formulas to estimate scour. However, these approaches are frequently inadequate, especially under rapidly changing conditions during flood events, highlighting the need for more robust and effective monitoring strategies (Tubaldi *et al.*, 2022). Scour holes can develop gradually over time and then rapidly deepen during severe weather events, potentially leading to sudden structural failure or collapse. Consequently, the risk of bridge scour failure is highest during intense flood events, which are also the most challenging to monitor. Moreover, inspections by divers cannot be conducted until the flood has receded, making them inadequate for assessing bridge safety.

To address these challenges, the EU-funded RAMOBRIS (Risk Assessment and Monitoring for Bridges under Scour Hazard) project investigated novel, low-cost approaches and strategies for monitoring and evaluating the scour risk of critical bridges (www.ramobris.eu). The outcomes of the study support the implementation of scour monitoring systems, contributing to improved flood risk management, more informed decision-making, and enhanced early warning capabilities, while strengthening the resilience and security of critical infrastructure. As part of the project, two case studies were developed at critical bridges in Scotland, where various sensors were installed to assess the effectiveness of low-cost monitoring strategies.

This paper describes the two pilot case studies, including the installation of instruments and the adopted strategy, with a focus on hydraulic monitoring. The deployed sensors range from expensive to low-cost options and include both underwater installations and remote sensing technologies. The establishment of the two monitoring sites enables the comparison of different monitoring strategies and techniques, while also providing insights into the practical aspects of on-site installation. Furthermore, the data collected from these sites constitute a rich dataset that forms the foundation for further analysis and contributes to the understanding of scour dynamics and bridge performance under varying flow conditions. The data obtained from these case studies are also being used in other research within the same project, aimed at developing new tools for scour risk assessment and decision support systems (DSS) based on observed data (Perugini *et al.*, 2024). Ultimately, this research seeks to enhance the resilience of bridge infrastructure in the face of climate change and increasing flood risks by suggesting tools and strategies to improve flood early warning systems as well.

The document is organised as follows: Section 2 presents the principles guiding the design of the two pilot case studies and the definition of the adopted monitoring approach. Section 3 outlines the methodology employed, including site selection and the specific sensors deployed. Section 4 provides a detailed description of the two pilot case studies, while Section 5 analyses the hydraulic data obtained from the sensors. Finally, the paper concludes with a summary of the findings and recommendations for future research and practice in the field of bridge scour monitoring and management.

2 Bridge-scour monitoring strategies

Establishing effective monitoring strategies for bridge scour is essential for several reasons. First, field monitoring provides real-world data crucial for understanding the complex processes of scour, the mechanisms leading to bridge instability, and the impacts of climate change. Additionally, it enables the detection of maximum scour conditions, which are critical for assessing infrastructure safety and providing early warnings. Secondly, the availability of high-quality monitoring data is fundamental for calibrating and validating numerical models, as well as for training and testing AI-based methods (Azma *et al.*, 2024; Kumar *et al.*, 2023; Tubaldi *et al.*, 2023). Furthermore, monitoring data are necessary for designing new structures, planning effective mitigation measures, and ensuring that risk assessment and asset management strategies are based on reliable data. Despite its importance, many streams and rivers worldwide remain inadequately gauged, partly due to the costs associated with the installation and maintenance of monitoring systems. As a result, the hydraulic properties of many rivers are often unknown, and the characteristics of extreme flood events remain poorly understood. For instance, during the 2022 flood in the Marche region of Italy, monitoring sensors were washed away, leaving no recorded measurements of peak flow rates or water levels. This highlights the urgent need for resilient and comprehensive monitoring solutions capable of capturing critical data even during extreme events.

An effective monitoring strategy should incorporate several key characteristics to ensure detailed and reliable data collection while overcoming practical challenges. First, the monitoring system must be adequately accurate to provide reliable measurements and capture the key physical characteristics of the phenomenon being observed. The required accuracy depends on the specific application, but it is crucial to provide uncertainty estimates alongside the measurements. This allows for a comprehensive understanding of the data and enhances its interpretation. Another important aspect is the use of non-contact sensors, which simplify installation and eliminate the need for time-consuming permissions typically required for sensors installed in riverbeds. These systems also reduce maintenance complexity and are less likely to be damaged during floods. Additionally, remote sensing strategies are of paramount importance for supporting data acquisition, especially in areas that are difficult to access. They offer the advantage of gathering data without the need for physical presence at the monitoring location, making the process more efficient. Furthermore, cost-effective solutions are essential to enable the widespread deployment of sensors, thereby improving the coverage and availability of data across larger regions. These solutions also support long-term monitoring applications. Continuous monitoring is crucial as it allows for a more comprehensive description of events, from low-flow conditions to extreme flooding, and facilitates historical analysis and climate change monitoring. This approach also helps overcome the limitations of sporadic measurements, which are often taken only under low-flow conditions or after an event when access to the river is safer. Finally, the ability to transmit data in real-time is vital for facilitating quick decision-making during extreme events. This enables timely actions, such as closing bridges or evacuating areas, in response to critical thresholds, ensuring the safety of infrastructure and communities.

Various approaches can be employed for monitoring bridge scour. A direct method involves measuring changes in the scour hole or bed level using sensors such as scour probes (Maroni *et al.*, 2020) or sonars (Rogers *et al.*, 2020), although these sensors tend to be expensive and require underwater installation. A second approach is the indirect evaluation of scour by monitoring structural changes, such as using inclinometers or accelerometers to track bridge stability, or employing radars to detect changes in bridge frequency (Kazemian *et al.*, 2023; Tola *et al.*, 2023; Tubaldi *et al.*, 2023). While these variations may indicate the evolution of scour, they often detect issues too late, after the bridge has already been affected. Another method is to directly measure flow properties, such as water level and velocity, and use these data as input to estimate scour depth through advanced scour formulas or artificial intelligence techniques, thereby indirectly determining the scour depth. Perugini *et al.* (2024) presented a proof of concept for near real-time estimation of scour at a bridge pier by combining low-cost sensors, large-scale image velocimetry techniques, and advanced scour models. Specifically, the flow properties collected by the sensors were used as input for a temporal scour model based on the dimensionless effective flow work (Link *et al.*, 2020; Pizarro *et al.*, 2017; Pizarro *et al.*, 2022). Kumar *et al.* (2023) evaluated

the performance of two ensemble methods and one standalone machine learning method for predicting time-dependent scour using laboratory data. Similarly, Azma *et al.* (2024) employed experimental data and deep learning algorithms to predict the evolution of scour depth downstream of a submerged weir.

In this work, the latter approach was selected, as recent developments have led to the creation of various low-cost sensors and techniques for hydraulic monitoring. Therefore, in designing the case studies for this work, this indirect approach was employed, aiming to evaluate the feasibility of using these methods to collect data that can subsequently be used to determine scour through advanced temporal formulas.

3 Method

The methodological approach adopted in this study began with the identification of suitable bridge sites and the selection of appropriate monitoring technologies. After a thorough search for potential locations and a review of available sensors, two bridges were selected as pilot sites based on their structural characteristics and susceptibility to scour (Section 3.1). The most suitable instruments were then chosen according to the specific monitoring objectives and site constraints. Following this preliminary assessment, the sensors described in Section 3.2 were installed to establish two pilot case studies (Section 4), enabling continuous monitoring of the hydraulic and morphological conditions at the selected bridges. The implemented systems were designed to measure parameters such as water level, flow velocity, and bed elevation, providing real-time information on scour processes under varying hydraulic conditions, and to test both low-cost and more expensive sensor technologies. Subsequently, the data collected from the monitoring systems were processed and compared in order to evaluate the performance of the installed technologies.

3.1 Case studies

The selected case studies were the A76 31 old bridge at Auldgirth (55.1597°N, 3.7100°W) and the A76 200 bridge at New Cumnock (55.4013°N, 4.1829°W). These bridges were chosen based on their classification as high-risk structures for scour by Transport Scotland. Moreover, they are masonry bridges, which are more susceptible to scour due to their shallow foundations. Both sites are located along the River Nith (Figure 1.a), which originates in East Ayrshire, in the southwest of Scotland, and flows for approximately 110 km before entering the Solway Firth. The river's width ranges from 10 to 30 meters, and its bed consists of fine sand, gravel, and coarse sand sediments. Several SEPA river gauges are situated along the river, measuring water levels and, in some cases, providing discharge estimates using calibrated rating curves (https://waterlevels.sepa.org.uk/).

The first case study (Figure 1.b) was selected due to the visible presence of scour hole at the left pier, indicative of ongoing active scour. The structure is a three-span masonry arch bridge, with a span length of 20.10 meters and a width of 4.80 meters. The bridge is now pedestrian-only, as the Auldgirth New Bridge, located just a few dozen meters downstream, handles road traffic. The left pier is situated at the river's edge and is subjected to flow during medium to high water levels, with bed materials consisting of sand and gravel deposits around it. The right pier is located at the centre of the river, where it is supported by a rocky foundation. The SEPA gauge upstream of the bridge is positioned at Drumlanrig, while the downstream gauge is located at Friars Carse.

The second case study (Figure 1.c) was chosen due to the presence of two scour probes, one on the left pier to monitor



Figure 1. Overview of the case studies. a) Case study locations (red dots) and SEPA river gauges locations (green dots). **b**) Auldgirth Old case study. **c**) New Cumnock case study (adapted from Maroni *et al.*, 2020).

local scour and another in the centre of the river to assess general scour (Maroni *et al.*, 2020). Additionally, the site is easily accessible, with low water levels facilitating river entry. The bridge is a three-span stone masonry arch supporting a two-lane, single-carriageway. Its abutments and piers are founded on spread footings on the natural riverbed. The left pier is situated at the centre of the river, while the right pier is positioned at the river's edge. Immediately upstream of the masonry bridge, there is a pedestrian bridge. This bridge is a single-span, simply supported composite structure, with a clear span of 34 m. In this location, a scaffolding is already in place, which was used for the installation of the scour probes. SEPA river gauges consist of one station upstream of the bridge at Dalgig and another downstream at Hall Bridge.

3.2 Equipment

The sensors chosen for installation at the two case studies include: i) Scour probes to monitor changes in the riverbed and track the evolution of the scour hole, which have already been deployed at one of the sites; ii) RiverTrack sensors and Solar Cameras as low-cost sensors for monitoring the hydraulic properties of the river, and iii) a traditional radar system, used to validate the data collected from the low-cost sensors. A detailed description of these sensors is provided below.

Scour Probes. Scour probes (Figure 2.*a*) are devices equipped with electromagnetic sensors, commonly used for determining soil moisture. Prototypes of these probes have been employed in previous studies to monitor changes in scour near bridge piers (Maroni *et al.*, 2020). Each sensor measures the resonant frequency of the surrounding medium, which is then converted into permittivity values, allowing the identification of the material around the sensor. Once calibrated, the probes can differentiate between air, water, soil, and potentially detect sediment deposition. By knowing the elevation of the sensors, both the water level and riverbed elevation can be determined. The measurements are limited by the number and positioning of the sensors, offering a resolution of approximately 10 cm. The data are localised, meaning they are measured at the location where the sensor is installed. For the results to be meaningful, the probes must be placed at locations corresponding to the maximum depth of the scour holes. Despite their ability to directly monitor the scour process, these probes are costly and challenging to install. Installation requires embedding the probes into the riverbed, which presents both technical challenges and permitting issues for access. The data collected from the Scour *p*robes will be used in subsequent studies to evaluate the indirect monitoring approach.



Figure 2. Collection of installed and tested sensors. a) EnviroSCAN Scour Probe. **b**) OTT radars. **c**) Solar camera. **d**) RiverTrack sensor.

OTT Radar. Radars (Figure 2.b) are commonly used in riverine hydraulic monitoring, although they are expensive devices. In the project, two sensors were considered: the Radar Level Sensor (RLS) for water depth and the Surface Velocity Radar (SVR) for velocity, both from OTT (https://www.ott.com/products/water-level-1/ott-rls-radar-level-sensor-861/). This type of radar provides only an average velocity value over the sensor's footprint. While highly accurate, the measurements are localised. The installation, data transfer, and storage are managed by the supplier, and the system requires minimal maintenance.

Solar Camera. Solar cameras are affordable, low-power sensor systems, typically used for surveillance, that can also be employed for monitoring river flows. The solar camera system consists of a photovoltaic panel, a battery, and an optical camera (https://www.hikvision.com/en/products/IP-Products/Network-Cameras/solar-powered-security-camera-setup/ds-2xs6a25g0-i-ch20s40-no-battery/). For this project, the Hikvision DS-2XS6A25G0 camera was selected (Figure 2.c). This optical sensor features a 2.8 mm focal length, records video at 2 MP resolution and 30 fps, and is equipped with infrared (IR) light for video capture in low-light conditions. The system utilises a 5G wireless network for data transmission and is capable of automatically recording short video clips. The use of these cameras requires post-processing of the recorded video. The camera is primarily used for image velocimetry, providing surface velocity and discharge measurements when the cross-section is available. While image velocimetry is widely used, long-term applications remain limited.

River track. The RiverTrack sensors (Figure 2.d) are affordable, low-power devices designed for local community flood alert systems (https://www.rivertrack.org/). They can be connected to either the LoRaWAN or 5G network, providing real-time data. The water level measurement model, which features a 40kHz ultrasonic transducer, is used by several communities in the UK. The sensor provides precise measurements, is very cost-effective, and is easy to install. A version of the sensor, enhanced with an optical sensor to detect velocity, is currently under validation.

4 Pilot case studies

Two pilot case studies were established at the critical bridges identified in Section 3.1, where the selected sensors (described in Section 3.2) were installed to implement an indirect monitoring strategy. These case studies have already successfully collected valuable data and continue to operate effectively.

At Auldgirth (Figure 3.a), the focus is on the left pier due to its higher exposure to scour, while the presence of a rocky formation at the base of the right pier reduces its susceptibility. A scaffolding structure was erected to support the installation of the sensors in front of the left pier. The monitoring system deployed at this site includes a solar camera, a RiverTrack sensor, an OTT radar system with a velocity sensor and a water level sensor, as well as a scour probe. The camera captures the stretch of river upstream of the bridge, and a topographical survey of Ground Control Points was conducted on the day of installation to calibrate the camera and perform image orthorectification. Soil samples

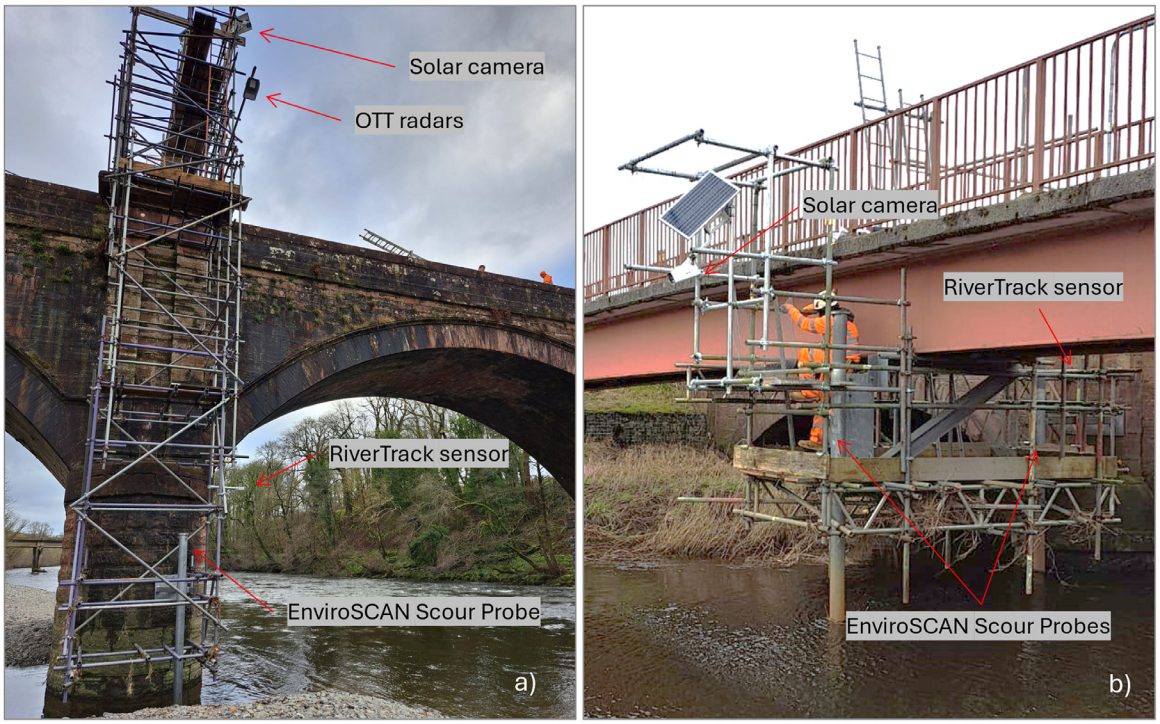

Figure 3. Overview of the two pilot cases with installed sensors. a) Auldgirth Old Bridge. **b**) New Cumnock Bridge.

from the vicinity of the riverbed were also collected for sieve analysis to establish the grain size distribution curve for use in future analyses. The OTT radar, which measures water level, and the RiverTrack sensor are positioned perpendicular to the river surface near the left pier, while the velocity sensor of the OTT radar is directed at the area in front of the pier. However, the left pier is only partially within the riverbed, becoming fully submerged only during medium to high flow conditions. Moreover, the sensor is installed immediately downstream of a bend, which causes the footprint of the OTT velocity sensor to cover areas that are not consistently submerged. Consequently, velocity measurements are available only when the area is actually wet. The scour probe was placed at the centre of the scour hole to detect the maximum scour depth. Unfortunately, shortly after installation, during a significant flood, water entered the device, damaging it. This highlighted a practical issue with the proper sealing of the top cup. The sensor will be replaced with a new one, and to address the issue, the probe's end will be raised to prevent submersion. Additionally, a new end cover design will be implemented to facilitate easier access to the probe and ensure proper sealing.

At New Cumnock (Figure 3.b), in addition to the two previously installed scour probes, a RiverTrack sensor and a solar camera were mounted on the existing scaffolding. The RiverTrack sensor is positioned perpendicular to the river surface near the left pier, where one of the scour probes is also located. The camera is placed at the centre of the river's cross-section, facing the stretch of river immediately upstream of the bridge. At this site, the camera was frequently vandalised, and additional protective measures were implemented to safeguard it. Furthermore, on the day of the camera installation, a survey of Ground Control Points was carried out to calibrate the camera. Additionally, a soil sample was collected near the riverbed for sieve analysis to determine the grain size distribution curve, which will be used in subsequent analyses.

5 Evaluation of hydraulic monitoring strategies

The data recorded by the sensors at the two pilot case studies constitute an open-access dataset that provides valuable field data for further research. This dataset will be continuously updated, as the case studies are expected to remain active and contribute to a long-term data repository. A preliminary analysis of the hydraulic data collected so far has already revealed several important insights.

The comparison between the OTT radar sensor (a high-cost solution) and the RiverTrack sensors (a low-cost alternative) highlighted the potential of economic monitoring tools. As shown in Figure 4, the RiverTrack sensor measured water level variations, expressed in mAOD (metres Above Ordnance Datum), with the same accuracy as the OTT radar sensor, while offering significant advantages in terms of cost. Additionally, the RiverTrack sensor is powered by simple lithium batteries, in contrast to the photovoltaic panels required by the OTT radar, and its compact design (12 × 12.3 × 5.1 cm) makes installation considerably easier. The absence of data observed in November for the RiverTrack sensor installed at Auldgirth (Figure 4) is likely due to foliage or other flood debris becoming tangled in the scaffolding or bridge structure. This suggests that the sensor should be positioned at a sufficient distance from the structure to avoid interference with water level readings. Despite this minor issue, the results highlight the reliability and practicality of low-cost sensors like the RiverTrack for water level monitoring applications.

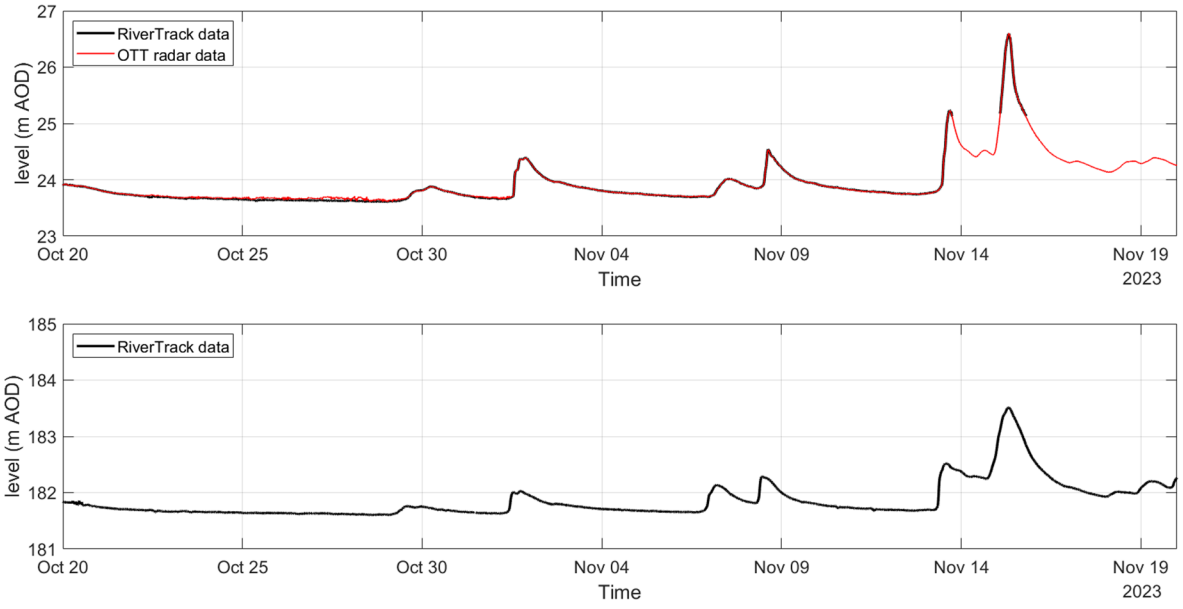

Figure 4. Water level monitoring using RiverTrack and OTT radar at Auldgirth Old Bridge (top panel) and New Cumnock Bridge (bottom panel).

The video data captured by the cameras were analysed to monitor velocity and discharge in the upstream sections of the bridges. This approach enables distributed measurements across the entire river cross-section, offering a significant advantage over localised velocity measurements obtained from the SVR radar. By capturing spatially extensive data, this method reduces the uncertainty associated with assumptions regarding the horizontal velocity profile. The camera system continuously recorded short oblique videos of the river surface at a specified sampling frequency. To extract quantitative information from the optical data, it was essential to resolve the camera geometry by defining the camera matrix, a process that enabled the conversion of image coordinates into real-world coordinates and eliminated perspective distortion (Bruder & Brodie, 2020). The camera matrix consists of two main components. The intrinsic parameters, such as focal length, zoom, and pixel scale, depend on the camera's specific features and were calibrated in the office using the open-source software Camera Calibration Toolbox for Matlab (Bouguet, 2022). The extrinsic parameters, which describe the camera's position and orientation, required a field survey to identify ground control points directly at the site. This calibration process ensured accurate data extraction for subsequent analyses.

For the estimation of surface velocity, several image velocimetry technologies were tested, including Particle Tracking Velocimetry (PTV), Particle Image Velocimetry (PIV), and Space-Time Image Velocimetry (STIV). A test video was recorded at New Cumnock, accompanied by a simultaneous manual measurement of river velocity at a specific cross-section immediately upstream of the analysed bridge using a mechanical flowmeter. The results from different image velocimetry methods were compared with the measured data, leading to the selection of the Particle Image Velocimetry (PIV) approach. The comparison was conducted under low-flow conditions to allow safe access to the river for manual measurements. This also provided an opportunity to evaluate the technique under scenarios that are typically more challenging for such methodologies, particularly due to the difficulty in identifying flow patterns. PIV is an Eulerian technique commonly used to determine velocity at fixed spatial positions. Initially developed for laboratory analyses, PIV has been adapted over the years for field applications, evolving into Large-Scale Particle Image Velocimetry (LSPIV). It computes the displacements of surface flow features travelling along the river by evaluating the cross-correlation of small sub-images (Hauet *et al.*, 2008), therefore, it requires the presence of visible patterns or floating objects on the water surface.

The displacement vectors, expressed in pixels per frame, were estimated using the PIVLab_2.59 code. To convert the field velocities into meters per second, the Rectification of Image Velocity Results (RIVeR_2.6) toolbox was employed, a standalone MATLAB application designed for large-scale water surface characterisation (Patalano *et al.*, 2017). This approach allowed for the identification of the horizontal profile of surface velocity at a specific cross-section. Any data gaps in the horizontal profile were subsequently filled by the software, which applied an appropriate horizontal distribution to complete the velocity profile. The surface velocities (V_s) were then converted into mean stream velocity (V_m) using the alpha method, which defines the relationship between surface and mean velocity through a dimensionless coefficient ($\propto$):

$$V_m = \propto V_s \quad (1)$$

From the velocity survey conducted at New Cumnock, an alpha value of 0.9 was estimated. Discharge (Q) was then calculated by multiplying the mean velocity by the wet area (A):

$$Q = V_m A \quad (2)$$

The water level data recorded by the RiverTrack sensor was used to calculate the wet area and wet perimeter.

This analysis was repeated for all images where surface patterns were visible (Figure 5). Not all available video footage could be used, as the methodology is sensitive to visibility conditions. Factors such as rain and wind can also affect the accuracy of the analysis. The discharges estimated from the suitable videos are shown in Figure 5 as asterisks. These data were then linearly interpolated to obtain the continuous time series of discharge estimated from the videos. This video-derived discharge time series was validated against the discharge data provided by SEPA for the nearby upstream and downstream gauges (refer to Figure 1 for the location of the river gauges). The results showed that the temporal variation in discharge and the identification of flood events were well estimated. A correlation analysis was also performed to evaluate the reliability of the estimated data (see also Perugini *et al.*, 2024), confirming that image velocimetry results can be used to characterise the river properties at the Nith Bridge, even if further validation and comparison with measured data at the bridge are required. Additionally, further analysis is necessary to better understand the influence of uncertainty in the alpha parameter.

To enable the adoption of long-term applications, it is essential to advance the automation of the analysis process, minimising manual inputs during post-processing and improving the handling of unreliable results. This refinement is particularly important as the methodology is highly sensitive to environmental conditions such as lighting, rain, and wind. Nonetheless, the results obtained so far are highly encouraging and warrant deeper investigation into this research area.

6 Conclusion

The findings of this study underscore the critical importance of effective bridge scour monitoring strategies in enhancing the resilience of transportation infrastructure against hydraulic hazards and highlight the need for innovative, cost-effective monitoring solutions. The comparative analysis between the OTT radar system and the RiverTrack sensors demonstrates that low-cost monitoring solutions can achieve comparable accuracy in measuring water levels, offering a viable alternative to more expensive technologies. These solutions

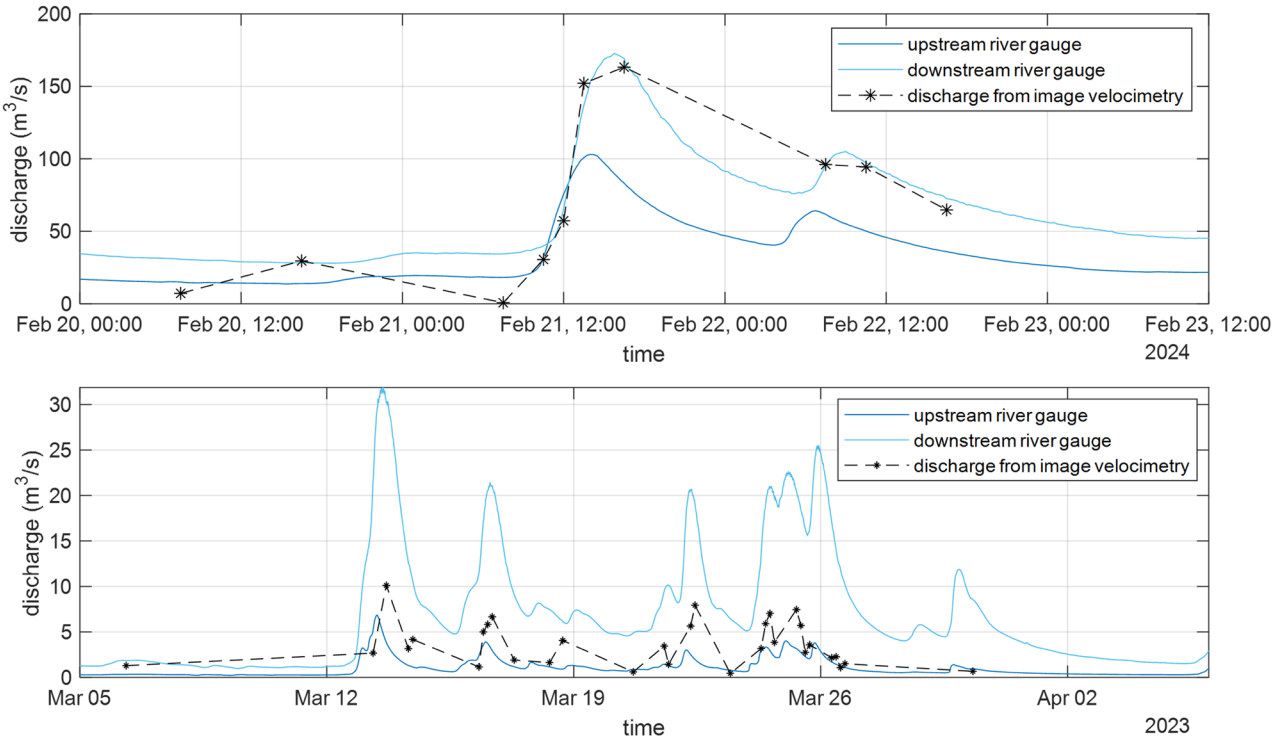

Figure 5. Discharge estimated from the cameras at Auldgirth Old Bridge (top panel) and New Cumnock Bridge (bottom panel, adapted from the paper included in the proceedings of the River Flow conference (Perugini *et al.*, 2024)).

also have the advantage of being easier to install and having low energy consumption, making them sustainable tools. Furthermore, they can transmit data remotely, which is essential for enabling real-time monitoring.

Moreover, the use of cameras for image velocimetry should be further promoted, as they represent an effective low-cost tool capable of capturing spatially extensive velocity measurements across the river's cross-section, significantly reducing the uncertainties associated with localised measurements. However, the installation of cameras is often vulnerable to vandalism; therefore, involving the local community in preventing such incidents and installing protective measures is crucial. Additionally, further research is needed to make this technology more user-friendly for long-term use.

Lastly, it is important to emphasise that for a successful monitoring system, proper data management must be defined in advance, as sensors will collect large volumes of data that need to be georeferenced and synchronised.

In conclusion, this work contributes to addressing the pressing need for robust monitoring strategies to assess bridge scour risks. The findings emphasise the importance of effective monitoring in capturing the complexity of real-world conditions.

Ethics and consent

Ethics and consent were not required.

Data availability

The dataset recorded from the two case studies is progressively updated due to the continuous nature of the monitoring strategy and the most recent version can be found in the following repository.

zenodo: "Two pilot case studies for bridge-scour monitoring"

RAMOBRIS_field_dataset

https://doi.org/10.5281/zenodo.14237317. (Perugini, 2024)

The dataset contains the following underlying data:

- README.pdf. (This document describes the structure of the dataset and all the files included.)
- Hydraulic monitoring (Folder containing the dataset, including the raw and elaborated data for both pilot case studies.)

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0)

Acknowledgements

The authors would like to thank Transport Scotland for providing access to the case studies and for their invaluable collaboration and support during the field activities. Special thanks are due to Gary Martin, the developer of the RiverTrack sensor, for his expertise, as well as for his training and assistance with the installation and maintenance of the sensors.

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Open Peer Review

Current Peer Review Status: ✔ ✔ ?

Version 2

Reviewer Report 05 January 2026

https://doi.org/10.21956/openreseurope.23578.r65443

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?

Francesco Ballio
Politecnico di Milano, Milano, Italy

The manuscript discuss some strategies for bridge hydraulic monitoring, with particular focus on water depth and velocity. The final aim of the project would be to use flow variablesn as control parameters of scour models, thus inferring local scour (at piers) without direct measurement. Conclusions from present studies are only partial, in that the feasibility of deriving reliable estimates of scour depths from flow variables is not proven. However, due to the strong interest of the bridge managers in hydraulic monitoring approaches, results from the two field cases discussed in the manuscript are surely interesting and valuable.

As a general comment I would recommend authors to better clarify their strategy of “indirect bridge scour monitoring”: in facts, no such result is here shown, nor it is made explicit how scour values should be derived from measured quantities; on the other hand, field installations comprehend scour sensors (for direct monitoring), but the role of such sensors is not specified, nor measured data are shown.

Some more specific comments follow (all related to the “introduction” section).

1. Contraction scour is not only due to the “presence of bridge piers or abutments”. It can also be due to (i) embankments and (ii) natural narrowing of the river channel or overbank areas.

2. Local scour is not only due to ”turbulence and vorticity that increase shear stress”. The very first effect of the presence of a pier (or abutment in the flow) is to locally increase the time-averaged velocity and, consequently, the shear stress.

3. When describing the process of scour holes more or less gradually deepening in time, authors should also mention that such holes tend to be refilled in the aftermath of hydraulics events.

Is the background of the case’s history and progression described in sufficient detail?
Yes

Is the work clearly and accurately presented and does it cite the current literature?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Is the case presented with sufficient detail to be useful for teaching or other practitioners?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: River hydraulics, scour at bridges

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 27 December 2025

https://doi.org/10.21956/openreseurope.23578.r65018

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José C Matos
University of Minho, Guimarães, Portugal
Sinem Tola
ISISE-Civil Engineering, Universidade do Minho Departamento de Engenharia Civil (Ringgold ID: 549494), Guimaraes, Braga, Portugal

Dear Dr Perugini and co-authors,

We have checked the changes against my previous minor comments. I am pleased to confirm that all points have been properly addressed: the revised title and expanded context in the early sections improve the framing and relevance, the figure references and caption formatting have been corrected, the monitoring setup is now clearly illustrated, and the methodological section is more complete with the added formulations and clearer discussion of the results.

Thank you.

Kind regards,
Sinem Tola & Jose C. Matos

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Bridge scour detection using drive-by monitoring signals

We confirm that we have read this submission and believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 11 December 2025

https://doi.org/10.21956/openreseurope.23578.r65017

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Manu Sasidharan
Civil, Environmental and Geomatics Engineering, University College London (Ringgold ID: 4919), London, UK

The authors have revised and updated the manuscript and can be indexed.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Infrastructure asset management, bridge scour management, risk modelling, climate resilience

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 25 January 2025

https://doi.org/10.21956/openreseurope.20649.r49272

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José C Matos

University of Minho, Guimarães, Portugal
Sinem Tola
ISISE-Civil Engineering, Universidade do Minho Departamento de Engenharia Civil (Ringgold ID: 549494), Guimaraes, Braga, Portugal

Manuscript: Two pilot case studies for bridge-scour monitoring.
Summary: The research proposes an affordable scour monitoring based on the acquisition of flow characteristics using video data acquired by solar cameras and the use of acquired hydraulic data to estimate scour depth with formulas. The superiority of the proposed monitoring equipment is its lower cost and ease of installation compared to OTT radars. The researchers achieved accuracy comparable to OTT radars.
Recommendation: Accept with minor revisions

1. The title is concise but should include further information regarding the specific scour monitoring method employed, i.e., image velocimetry techniques.
2. The introduction provides a comprehensive overview; however, it would be beneficial to incorporate a concise discussion of the study's practical implications at the outset.
3. In Section 2, the second secondary argument of the first paragraph, i.e., the expression "Secondly, the availability of high-quality monitoring data is fundamental for calibrating and validating numerical models, as well as for training and testing AI-based methods," can be enriched by the addition of references to previous research.
4. The last paragraph of Section 2 discusses the bridge monitoring approaches. A couple of references to former research could be added for the mentioned methods. Specifically, the presentation of the limitations of a former radar-based scour monitoring research study could provide a very supportive argument for the proposed methodology using lower-cost monitoring.
5. It appears that some of the details of the case studies provided in Section 3.1 are more suitably placed in Section 4. Therefore, a minor reorganization of the information may enhance the research narrative. It is recommended that Section 3 be initiated with an introductory paragraph that provides a concise overview of the methodological steps (including data processing) before the subsections.
6. In Section 3.2, the reference figure for River Track sensors is Figure 2.d instead of Figure 1.d; the reference figure for OTT Radars is Figure 2.b instead of Figure 1.b; the reference figure for the solar camera is Figure 2.c instead of Figure 1.c.
7. Section 3.2 references the first case study in Figure 1.b instead of Figure 2.b.
8. In Section 3.2, additional clarification regarding the concept of "localized data" could facilitate a more lucid reading of the text.
9. The captions of Figures are not consistently rendered in bold; this practice should be uniform.
10. The slight blurring observed in Figures 5 and 6 may be attributed to the printing of the document as a Portable Document Format (PDF); however, higher resolutions are recommended for optimal visual clarity.
11. In Section 4, at the following expression: “Additionally, due to the bridge’s position immediately downstream of a bend, the radar often pointed to regions that were not consistently submerged, leading to occasional inaccuracies in velocity measurements. “ The presence of such inaccuracies is acknowledged, and it is recommended that their extent be specified.
12. It is recommended that a sketch be included in Section 4 to illustrate the positioning of the

monitoring equipment.
13. The unit for the level of Figure 4 should be clarified since the notation mAOD isn't explicitly defined in the text.
14. The numerical results that Figure 5 reveals should be discussed more in the text.
15. Section 5 could be made more explicit in presenting formulations such as the alpha method.

Is the background of the case's history and progression described in sufficient detail?
Yes

Is the work clearly and accurately presented and does it cite the current literature?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Is the case presented with sufficient detail to be useful for teaching or other practitioners?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Bridge scour detection using drive-by monitoring signals

We confirm that we have read this submission and believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however we have significant reservations, as outlined above.

Author Response 30 Oct 2025

Eleonora Perugini

We thank the reviewers for the constructive feedback and the opportunity to improve our manuscript. We have carefully addressed all points and revised the manuscript accordingly. Below, we provide a detailed point-by-point response. We appreciate the opportunity to enhance the clarity and robustness of our study and hope the revised version meets your expectations.

1. We have revised the title to include additional information on the specific scour monitoring method employed. The new title is: "Two pilot case studies for indirect bridge scour monitoring using low-cost remote sensing for river flow characterisation."
2. A brief discussion of the study's practical implications has been added to Section 1,

stating: “The outcomes of the study support the implementation of scour monitoring systems, contributing to improved flood risk management, more informed decision-making, and enhanced early warning capabilities, while strengthening the resilience and security of critical infrastructure.”

3. The reference to previous research has been added as requested.
4. In the revised version, we have included references to previous research that offer an overview of the current state of the art and limitations in scour monitoring techniques.
5. Section 3.1 presents the two selected case studies, outlining their main characteristics and the rationale for their selection. Section 4, instead, provides a detailed description of the monitoring systems implemented at the two sites, which were adapted to the site-specific features of each bridge. This distinction between the two sections has been made clearer in the revised introduction of Section 3. Moreover, the introduction of Section 3 has been rewritten to provide a concise overview of the methodological steps. The revised text now reads as follows: “The methodological approach adopted in this study began with the identification of suitable bridge sites and the selection of appropriate monitoring technologies. After a thorough search for potential locations and a review of available sensors, two bridges were selected as pilot sites based on their structural characteristics and susceptibility to scour (Section 3.1). The most suitable instruments were then chosen according to the specific monitoring objectives and site constraints. Following this preliminary assessment, the sensors described in Section 3.2 were installed to establish two pilot case studies (Section 4), enabling continuous monitoring of the hydraulic and morphological conditions at the selected bridges. The implemented systems were designed to measure parameters such as water level, flow velocity, and bed elevation, providing real-time information on scour processes under varying hydraulic conditions, and to test both low-cost and more expensive sensor technologies. Subsequently, the data collected from the monitoring systems were processed and compared in order to evaluate the performance of the installed technologies.”
6. Thank you for this observation. The references to the figures have been checked and corrected.
7. The reference has been checked and corrected.
8. By “localized data” we mean measurements obtained at a specific location, as in the case of scour probes, or averaged over the footprint of the sensor, as in the case of RiverTrack or OTT radar. This differs from data acquired by solar cameras, which cover the entire cross-section or a portion of the river. This distinction has been clarified in the text.
9. The formatting of the figure captions has been updated.
10. We attempted to enhance the quality of the images.
11. We have rewritten the sentence to clarify the issue. The new sentence is: “However, the left pier is only partially within the riverbed, becoming fully submerged only during medium to high flow conditions. Moreover, the sensor is installed immediately downstream of a bend, which causes the footprint of the OTT velocity sensor to cover areas that are not consistently submerged. Consequently, velocity measurements are available only when the area is actually wet.”
12. The positioning of the monitoring equipment has been illustrated and specified in

Figure 3.
13. The unit mAOD (metres Above Ordnance Datum) has now been explicitly defined in the text.
14. The results derived from image velocimetry and shown in Figure 5 have been better described, and the following sentence has been added to the text: "The discharges estimated from the suitable videos are shown in Figure 5 as asterisks. These data were then linearly interpolated to obtain the continuous time series of discharge estimated from the videos."
15. The formulas have been specified in the text.

Competing Interests: No competing interests were disclosed.

Reviewer Report 21 January 2025

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Manu Sasidharan
Civil, Environmental and Geomatics Engineering, University College London (Ringgold ID: 4919), London, UK

The paper reports on two pilot case studies for bridge scour monitoring and underscores the necessity of such measures for managing bridge scour. The discussions and findings from the paper is academically sound and serves as an enabler for developing business cases for scour monitoring.

Considering that the paper adopts the approach of measuring the river flow properties, the literature review of time-dependent scour prediction models that employ such datasets to predict the occurrence or progression of scouring is missing. Recent research such as [Ref 1], [Ref 2] and [Ref 3] etc. have proposed different models that employs hydraulic data for modelling scour progression. The literature review within this manuscript needs to capture this effectively.

References

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3. Sasidharan M, Kumar Parlikad A, Schooling J, Hadjidemetriou G, et al.: A bridge scour risk management approach to deal with uncertain climate future. *Transportation Research Part D:*

Transport and Environment. 2023; **114**. Publisher Full Text

Is the background of the case's history and progression described in sufficient detail?
Yes

Is the work clearly and accurately presented and does it cite the current literature?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
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Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Is the case presented with sufficient detail to be useful for teaching or other practitioners?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Infrastructure asset management, bridge scour management, risk modelling, climate resilience

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 30 Oct 2025

Eleonora Perugini

We thank the reviewer for their valuable comments and suggestions, which have helped us to improve the manuscript. Accordingly, the literature review has been expanded in the second version of the manuscript, and the following paragraph has been added to Section 2: "Another method is to directly measure flow properties, such as water level and velocity, and use these data as input to estimate scour depth through advanced scour formulas or artificial intelligence techniques, thereby indirectly determining the scour depth. Perugini et al. (2024) presented a proof of concept for near real-time estimation of scour at a bridge pier by combining low-cost sensors, large-scale image velocimetry techniques, and advanced scour models. Specifically, the flow properties collected by the sensors were used as input for a temporal scour model based on the dimensionless effective flow work (Link et al., 2020; Pizarro et al., 2017; Pizarro et al., 2022). Kumar et al. (2023) evaluated the performance of two ensemble methods and one standalone machine learning method for predicting time-dependent scour using laboratory data. Similarly, Azman et al. (2024) employed experimental data and deep learning algorithms to predict the evolution of scour depth downstream of a submerged weir."

Competing Interests: No competing interests were disclosed.