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ORIGINAL PAPER

Bridge and infrastructure damages following the September 2024 floods in the Czech Republic: post-disaster field survey

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Abstract
Bridges play a critical role in society, yet their structural integrity is increasingly threatened by floods, often resulting in severe damage or collapse. This study investigates the catastrophic September 2024 flood in the Czech Republic, focusing on its impact on bridge infrastructure. Through a comprehensive methodology integrating field surveys, geospatial analysis, hydraulic data, photographic evidence, and damage analysis, the study assesses the extent of damage and the challenges posed by the flooding. To empirically quantify the observed damage, damage state (DS) thresholds—derived from various sources—are introduced to standardize the assessment process. These thresholds are then integrated with documented bridge performance along with photographic evidence. The findings reveal that of the 122 investigated bridges, 41 were not functional, 20 of which experienced total collapse. Scour, debris impact and accumulation, inadequate hydraulic openings with complete washout, and embankment failures are identified as primary failure mechanisms. In addition, DSs assigned from post-event unmanned aerial vehicle (UAV) orthophoto maps are compared against ground-truth field classifications, showing 73.3% agreement on the assigned DS and 93.3% agreement on the serviceability classification. By providing empirical damage data, photographic documentation, and analysis of critical factors affecting bridge resilience, this research offers a valuable resource for engineers, policymakers, and urban planners aiming to design more resilient infrastructure and prevent transportation network disruptions.

Keywords Reconnaissance · Bridge vulnerability · Flood · Damage states · Infrastructure resilience

1 Introduction

Flooding is a major global threat to bridges, causing severe structural damage that disrupts transportation networks and endangers public safety (Fournier Gabela and Sarmiento 2020; Pregnolato et al. 2020). Intense rainfall, storm surges, and river overflow can compromise the stability of bridges, increasing the risk of partial or total collapse (Porio 2011; Adhikari and Bhandari 2023). Aging infrastructure, combined with more frequent and severe floods

Extended author information available on the last page of the article

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due to climate change, exacerbates the problem, particularly in regions with inadequate maintenance and flood protection planning (Bridges et al. 2022; Habeeb and Bastidas-Arteaga 2023). The associated economic impact is significant, with costly repairs, loss of connectivity, and disruptions to supply chains affecting communities and industries (Thomson et al. 2012; Sati and Dubey 2021).

The European technical standard (CEN 2002) establishes the design working life for bridges at 100 years. However, the actual performance of bridges may deviate from 100-year lifetime expectation due to severe damage events such as floods (Shayan and Xu 2016; Karimpour et al. 2020). To guarantee the continuous functionality of infrastructure systems, including bridges, culverts, roads, and retaining walls, ensuring their resilience against extreme weather events is essential (Collings 2024). However, field investigations following major floods have consistently revealed the inadequate performance of infrastructure systems, particularly bridges (Argyroudis et al. 2019; Koks et al. 2021; Kelesoglu et al. 2023; Wolf et al. 2024; Burghardt et al. 2025). The primary causes of bridge failure are extreme hydraulic forces, vulnerabilities in the bridge structure, and poor maintenance (Caner et al. 2008; Deng et al. 2016; Avşar et al. 2017; Satish and Nirmal 2020; Zhang et al. 2022). Damages at the component level can significantly weaken the overall integrity of the bridge, potentially leading to a global failure mechanism (Derseh and Mohammed 2023; Liu et al. 2024). Moreover, a partial or total failure, or even moderate damage, can still represent a critical disruption in the transportation network, causing widespread systemic consequences (DesRoches and Rix 2006; Zhu et al. 2010; Kilanitis and Sextos 2019). Therefore, improved flood risk management strategies (Pregnolato et al. 2016; Gilissen et al. 2016), more resilient bridge designs (Leeson et al. 2014), risk identification (D'Angelo et al. 2025), and optimized maintenance strategies against natural hazards (Katikala et al. 2022) are of significant interest.

In mid-September 2024, a severe flood event struck several Central and Eastern European nations, including the Czech Republic, Austria, and Poland. Triggered by a low-pressure system originating from northern Italy, the event resulted in prolonged rainfall and a significant rise in water levels across the region. The northeastern regions of the Czech Republic were particularly affected, with rivers such as the Morava, Bělá, Opava, and Vidnávka experiencing unprecedented water level increases, with a 5-day cumulative rainfall total of 704.2 mm, and a recurrence period of more than 200 years (ČHMÚ 2024). This flood event is ranked as the most catastrophic in terms of human and infrastructural impact since the 1997 floods in that region, resulting in 13 fatalities, displacing 180 families, and severely disrupting transportation networks in major cities and towns such as Opava (population 55,600), Jeseník (population 10,619), and Krnov (population 22,716) (ČSÚ 2024). Flood responses and recovery actions were taken immediately (Gabzdyl 2024; U.S. National Guard 2025). Later, the European Parliament approved €114 million in aid to help cover the damages caused by the severe flood (Radio Prague International 2025).

The aim of this study is to evaluate the performance and failure mechanisms of bridge structures affected by the September 2024 flood event in the northeastern Czech Republic through post-disaster field reconnaissance, photographic documentation, and GIS-based mapping, with particular focus on damage to the structural and non-structural bridge components, as well as disruptions to bridge functionality. In addition, three important scientific gaps are addressed in the paper. First, no standardised framework for quantifying flood-induced bridge damage currently exists in the Czech Republic, despite the availability of

such classification systems internationally. Accordingly, a DS framework is proposed that is resolved by bridge element category and linked to bridge functionality. Second, although unmanned aerial vehicle (UAV) imagery is increasingly available immediately after flood events, its diagnostic reliability relative to conventional field inspections has rarely been evaluated using the same bridge inventory. This work addresses diagnostic reliability through a direct comparison of UAV-based and ground-based damage classifications for the same surveyed bridges. Third, empirical post-flood datasets linking documented bridge damage with geospatial and structural characteristics remain limited, constraining the identification of vulnerability indicators and the assessment of their transferability across different catchments. The systematically collected and publicly released dataset presented herein contributes to addressing this limitation, while the implications for future flood events are discussed in the concluding sections. To achieve this, the study (i) analyses flood hazard for the investigated region; (ii) identifies bridge vulnerability to flood damage based on structural characteristics; (iii) introduces a damage states (DS) framework to accurately represent physical bridge damage; (iv) assesses bridge damage in the study area by applying the DS framework; (v) compares UAV-based screening and in-person inspection in terms of assigned DSs and agreement on the serviceability classification; and (vi) analyses the bridge damages and underlying causes. The findings further contribute to validating future risk assessment methods and damage models while informing the development of more resilient infrastructure capable of withstanding the increasing frequency and intensity of extreme weather events.

2 Flood characteristics of studied area

2.1 Analysis of flood-affected area

The analysis focuses on the regions of the Czech Republic most severely affected by the flood event of September 2024, namely the northeastern regions (Fig. 1a). As a first step, the geospatial data (i.e., altitude data, regional geological and surface soil classification, topography, land-use) were collected for the flood-affected regions (Fig. 1b-d). Geospatial data, publicly available through web portals (ČGS 2024; ČÚZK 2024; VÚV TGM 2024), were integrated and analysed using GIS operations to support the study. The maps in Fig. 1b-d provide the geospatial characteristics of the study area.

As seen in Fig. 1b-d, the study area is characterised by significant topographic and land-use heterogeneity. The northern part is dominated by mountainous terrain with steep river gradients and forested upper catchments. The southern and valley areas feature agricultural lowlands and wider floodplains, with several mid-size urban centres including Krnov, Opava, and Jeseník. The region is underlain by bedrock to the north and sedimentary deposits in the river valleys, resulting in heterogeneous geological and soil conditions.

The same region experienced major flood events in 1997 (ČHMÚ 1998) and 2009 (ČHMÚ 2009), with the 1997 event causing significantly more severe damage than the 2009 event. The September 2024 flood represents the third major flood event to affect this region within approximately 30 years, underscoring the recurrent flood hazard to which the infrastructure of this region is exposed.

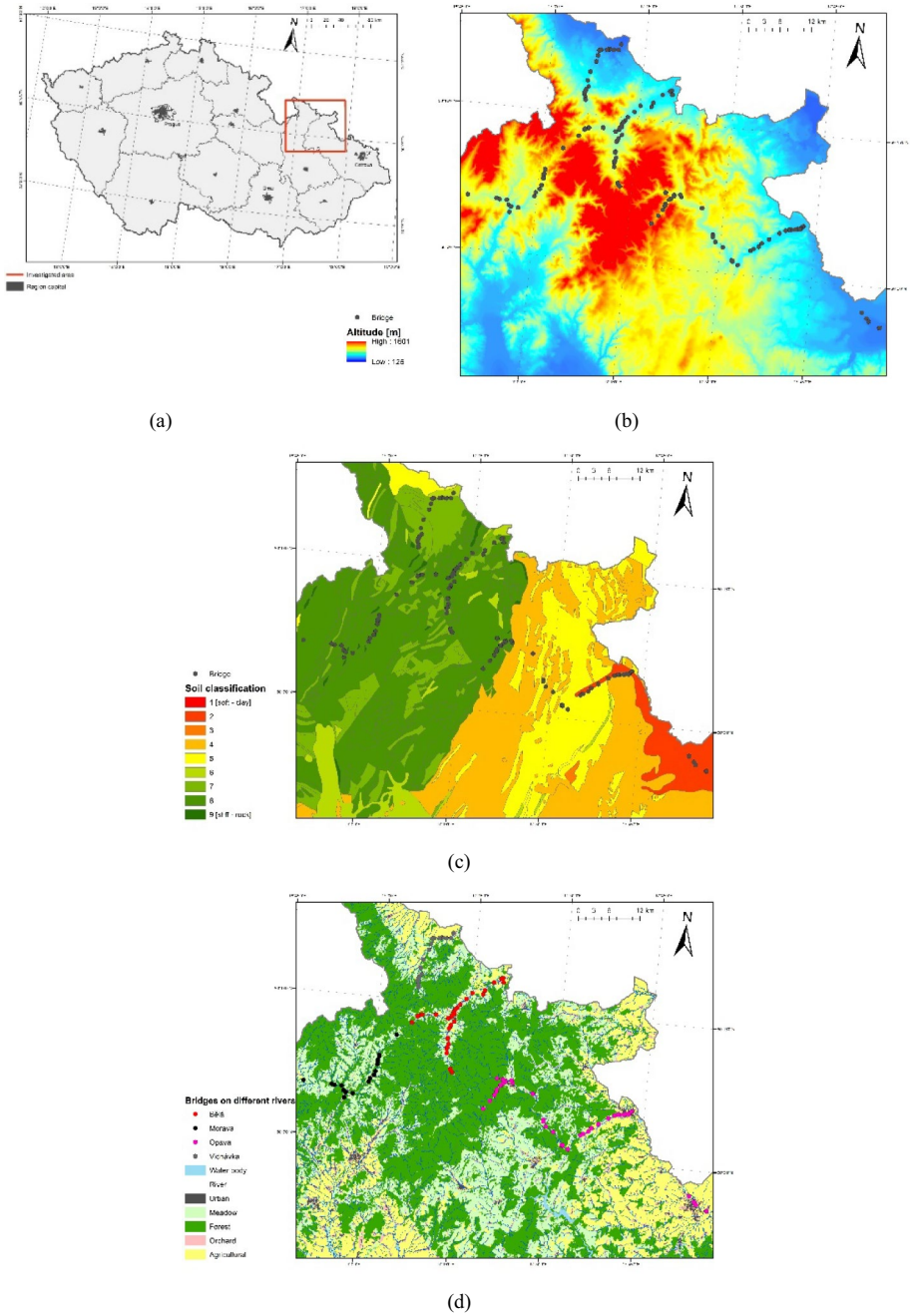


Fig. 1 Geospatial data generated from available datasets: **a** flood-affected regions in the Czech Republic (ČÚZK 2024), **b** altitude (ČÚZK 2024), **c** regional geological and surface soil classification (ČGS 2024; ČÚZK 2024), **d** topography, land use, and land cover (ČÚZK 2024)

Flood hazard regions and bridges potentially affected by flood hazard are depicted in Fig. 2. The data for the Q5 and Q100 flood extents were obtained from the available flood hazard datasets provided by VÚV TGM (2024). Figure 2 was regenerated in a GIS environment through spatial overlay of bridge locations with flood hazard zone polygons, coordinate reprojection, attribute joining, and thematic mapping**.** The events are characterized according to the probability of flood recurrence; for instance, the flood hazard *Q5* represents a flood extent with a recurrence interval of 5 years, while Q100 indicates an event that may occur once every 100 years. As seen in Fig. 2, many bridges in the studied area are located within mapped flood inundation extents even for at least Q5 flood extent. Bridges located within these inundation zones are referred to as "hazard-prone," whereas bridges outside Q5 extents are classified as "hazard-free." Namely, a "hazard-free" bridge lies outside the mapped Q5 inundation extent and is therefore not immune to flooding at longer return periods.

2.2 Summary of hydrometeorological analysis of the September 2024 flood

Between September 11 and 16, 2024, extreme precipitation totals were recorded, particularly in the Jeseníky Mountains. At Loučná nad Desnou, where the Švýcárna measuring station is located (see Fig. 2), 704.2 mm of cumulative rainfall was measured in 5 days, marking the highest recorded September rainfall (ČHMÚ 2024). Specifically, the September 2024 event was characterised by extreme precipitation across multiple temporal scales. Precipitation over 24h exceeded 100 mm at more than 70 stations, with maximum values surpassing 180 mm at several locations, such as 201.4 mm at Loučná nad Desnou, 186.1 mm at Rejvíz, 184 mm at Labská Bouda, and 183.7 mm at Zlaté Hory (ČHMÚ 2025).

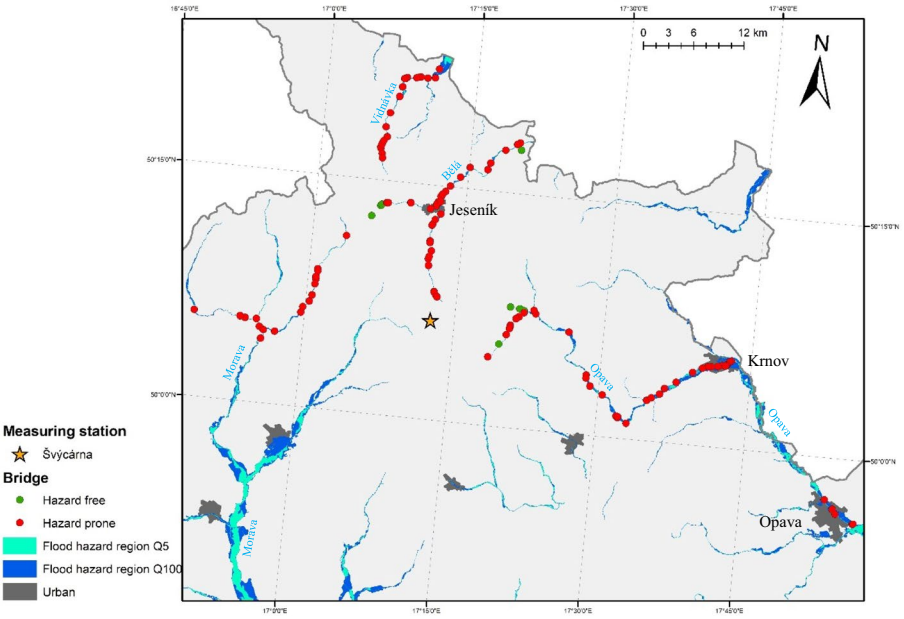


Fig. 2 Flood hazard zones with Q5 and Q100 inundation extents (VÚV TGM 2024) and potentially impacted bridge locations

Over 2–3 day accumulations, mountainous zones recorded 250–350 mm rainfall. At the 5-day event scale, totals exceeded 600 mm across the Jeseníky Mountains, with a maximum of 704.2 mm recorded at Loučná nad Desnou (ČHMÚ 2025). At least 37 monitoring stations exceeded precipitation levels associated with recurrence periods greater than 200 years over a 5-day period (ČHMÚ 2025). The average precipitation across monitoring stations in September 2024 was 179 mm, corresponding to 298% of the 1991–2020 climatological average. This made September 2024 the second wettest month recorded in the Czech Republic since 1961, surpassed only by July 1997, during which an average precipitation of 204 mm was recorded (ČHMÚ 2025).

Before the flood, stream levels were near hydrological drought conditions at approximately 50% of gauging stations as of 8 September 2024, based on measured records from ČHMÚ (2025). This trend was subsequently interrupted 7 days later by an extreme precipitation event. Initially, low soil saturation—especially in the eastern flood-affected area with permeable soils—delayed runoff, reducing the flood impact, particularly in the less affected zones. A significant rise in stream levels only occurred after 60–100 mm of rainfall. In areas downstream of reservoirs, controlled water releases helped manage flows, thanks to early forecasting and warnings. However, intensified rainfall toward the end of the event fell on already saturated soil, leading to rapid runoff in the Jeseník district (ČHMÚ 2024).

Among the 366 monitoring stations used by the Czech Hydrometeorological Institute-Flood Forecast and Reporting Service (ČHMÚ 2024), 180 stations recorded third-level flood activity, with over 42 stations reaching or exceeding extreme flood thresholds. The flood activity level is a standardised classification in the Czech Republic comprising three hierarchical levels: Level 1 (Alert Status), Level 2 (Standby Status), and Level 3 (Emergency Status). Level 3 corresponds to situations of imminent hazard, substantial damage, or direct threats to life and property, triggering comprehensive flood protection measures including emergency operations and evacuations.

The most severely affected areas included the Opava basin and the tributaries of the Kladská Nisa (Vidnávka, Bělá, and smaller streams—see Fig. 2 and Fig. 9a-d for close up views), where recorded water levels significantly exceeded Level 3 thresholds, reaching historic highs at several gauging stations. The southern slopes of the Jeseníky Mountains, including the Upper Morava and Desná rivers, also experienced extreme flooding. The Opava basin experienced exceptional flood waves, causing catastrophic flooding in towns such as Krnov and Opava. However, the convergence of flood waves from the Opava (Děhylov), Oder (Svinov), and Ostravice (Ostrava) rivers did not align. The Ostravice and Porubka rivers primarily drained due to sustained rainfall in their lower catchments, following a 24h period of stream drainage from the Jeseník district (ČHMÚ 2024).

3 Bridge profile

3.1 Bridge design criteria for flood

The design criteria for bridges in flood-prone areas are crucial for ensuring their safety, stability, and long-term resilience during flood events (Young and Davies 1989). Hydrological and hydraulic analysis is fundamental (Aureli et al. 2021), where flood water and discharge level assessments are conducted based on historical data and flood models. In the Czech

Republic, national bridge design standards, such as ČSN 73 6201 (2008), require that the bridge deck must be at least 1000 mm above the design flood level and 500 mm above the control design water level. The design flood water level corresponds to a return period of Q100, while the control design water level is defined as the water level associated with a discharge of 1.4 × Q100, determined by hydraulic modelling for the given cross-section. According to these requirements, the design water level should not reach the bridge deck.

3.2 Visual inspection grading principle in the Czech Republic

To maintain the required level of serviceability, bridge inspections based on visual assessment of the structural condition are scheduled every 2–6 years in the Czech Republic (ČSN 73 6221 2018). The standard outlines the types of inspections for road bridges, including their extent, processing rules, and detailed assessment characteristics (Meoni et al. 2025). It also defines assessments in two categories: (i) reliability of a bridge (structural condition of a bridge and its parts); and (ii) safety of operation (serviceability of a bridge and its parts). Grading assessment of the structural condition of a bridge is presented in Table 1. However, the grading, which is based on visual inspection, is inherently subjective, representing a significant drawback.

The assessment of structural condition and grading is performed for the superstructure, and the substructure individually (ČSN 73 6221 2018). Conservatively, the overall assessment of the structural condition of a bridge is set as the lowest score of these separately assessed parts. Seven condition levels for any element are included in the current grading system. *Grade I* refers to excellent conditions of the bridge, while *Grade VII* is associated with seriously deteriorated conditions. The serviceability of the bridge components is limited to *Grade V*. The defects and failures threaten the reliability of the structures in this grade, which is considered as the repairability threshold value. When a bridge reaches *Grade V*, a major repair intervention is required to restore its structural reliability.

Table 1 Assessment of grade of structural condition in the Czech standard (ČSN 73 6221 2018)

Grade	Structural condition	Description
I	Excellent	Without evident defects, or failures
II	Very good	Local visual defects and damages that do not pose a significant risk to the long-term reliability of the bridge (over 10 years)
III	Good	Defects and damages of a larger scope that do not immediately affect the structure's reliability but may contribute to a higher risk in maintaining the long-term reliability of the bridge over a 10-year period
IV	Fair	Defects and damages that do not significantly impact the structure's reliability but may contribute to a higher risk in maintaining the long-term reliability of the bridge over a 5-year period
V	Poor	Defects and damages that significantly impact the structure's reliability, but can be repaired without major intervention into the bridge's main structural elements
VI	Very poor	Defects and damages that have a significant impact on the structure's reliability and can only be repaired through major intervention in the bridge's main structural elements
VII	Serious disrepair	Defects and failures that significantly impact the structure's reliability require immediate measures to prevent a breakdown (e.g., bridge closure or additional support)

3.3 Bridge conditions prior to the flood

In the Czech Republic, roads are classified into the following categories: (a) highways, (b) 1st class roads, (c) 2nd class roads, (d) 3rd class roads, (e) local roads/streets, and (f) purpose-built roads. 1st class roads and highways are managed by a national organization-Czech Roads and Highways Directorate. 2nd and 3rd class roads are managed by regional administrators while local roads are managed by the municipalities in which they are located, and purpose-built roads are managed by the owners who established them (Act No. 13/1997 Coll. 2020).

Lower-class roads, including bridges and retaining walls, are often in worse structural and technical condition due to the prioritization of repairs on roads with higher traffic volumes. Figure 3 presents the summary of the visual inspection grading prior to the flood [see Table 1*I=excellent, VII=serious disrepair*] for the affected bridges up to 3rd class roads. Pre-flood condition inspection data were not available for 66 bridges and are therefore excluded from the pre-flood condition analysis. Scored using Table 1, the majority of the bridges are classified as *Grade IV* or better (Fig. 3), indicating that they were generally in good condition prior to the flood.

4 Damage state thresholds

4.1 Review on bridge damage states

The assessment of a bridge's condition requires evaluating the severity and extent of its structural damage (Akula et al. 2014; Yurdakul et al. 2021, 2023, 2024; Hussain 2024). To

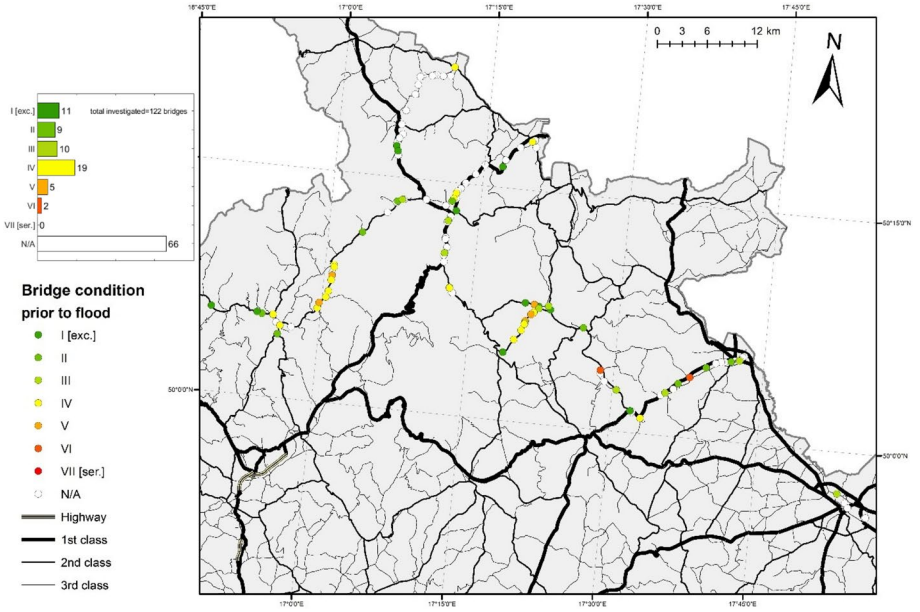


Fig. 3 Conditions of the bridges prior to the flood (ČÚZK 2024)

better understand the relative impact of the damage on the overall structural response and functionality, bridge components are classified into three categories in this study: serviceability elements, secondary elements, and primary structural elements. The classification of bridge components into serviceability, secondary, and primary structural elements partially aligns with general principles in AASHTO LRFD (2020), and PIARC (2025) guidelines, which categorize bridge components based on their criticality to structural integrity and functionality.

- *Serviceability elements* ensure the proper functioning and safety of the bridge without bearing loads. These include drainage systems, guardrails or barriers, lighting, pedestrian and bicycle facilities, parapets and crash barriers, maintenance access, noise and vibration control systems, utilities, etc.
- *Secondary elements* contribute to the overall functionality of the bridge, such as approach slopes, embankment fill, expansion joints, pavement, backwall, etc. The secondary elements do not directly bear primary loads.
- *Primary structural elements (i.e., load-bearing components)* are those that carry or transfer the loads directly such as suspension or tie-back cables, bridge deck, beam/girders, piers/columns, abutment, shallow/deep foundation, bearings, etc.

These categories are used to assess the DS in various components of the bridges. According to various sources (Basoz and Mander 1999; Hose et al. 2000; Stojadinovic and Mackie 2004; Liao and Loh 2004; Lehman et al. 2004; HAZUS 2020; Burghardt et al. 2025; Liu and Xiang 2024), DSs are classified into five classes. The thresholds for determining the classes can vary significantly based on the literature source. This variability introduces a considerable degree of subjectivity in determining the DS and corresponding repair action. Table 2 reports the various definitions/descriptions of DSs according to the different reviewed sources.

4.2 Definition of damage states

A standardized and consistent methodology to evaluate bridge damage after sudden events is currently missing in the Czech Republic, although such frameworks are available internationally. Therefore, using Table 2 and the scour evaluations assessed by several literature sources (USGS 2000; FHA 2012; Texas Department of Transportation 2023; Florida Department of Transportation 2024), this paper adopts the qualitative definitions of DSs as defined in Table 3, incorporating structural effect, damage level, repair possibilities along with socioeconomic considerations. These definitions provide a structured framework for assessing flood- or man-made-induced sudden bridge damage, ensuring consistency in damage evaluation. The qualitative descriptions of the categorized DSs obtained from Table 2 for each bridge component are detailed below. The proposed DSs offer a comprehensive understanding of the varying levels of structural and functional damage caused by flooding or other hazards affecting bridges in a qualitative way. When assigning the proper damage level, at least one DS must be met for each bridge component. The introduced DSs are as follows:

- *Damage State 1 (DS1)* indicates no or negligible damage in the overall assessment. Serviceability elements may experience minor to moderate damage, while cosmetic issues in other bridge components—such as primary structural elements or secondary elements—may be observed. For moderate damage to serviceability elements, more than cosmetic repairs may be needed.
- *Damage State 2 (DS2)* refers to minor or slight damage to the primary structural elements or moderate to major damage to non-load-bearing components, such as serviceability and secondary elements, respectively. The overall severity of the damage is slight, and the bridge's functionality is not significantly affected, keeping it in service even after reaching DS2. However, additional reparative measures may be required.
- *Damage State 3 (DS3)* involves macroscopic damage to some bridge components, categorizing them as moderately damaged. At this level, total failure or significant movement in secondary elements (such as approach slopes, embankment fill, expansion joints, pavement, backwalls, etc.) may occur. In primary structural elements, the initiation of local mechanisms is typically observed. The overall functionality of the bridge is temporarily interrupted. However, with appropriate remedial actions, the bridge's capacity can be restored.
- *Damage State 4 (DS4)* indicates severe damage in the overall assessment where load-bearing elements (such as connections, piers/columns, abutments, bridge deck, foundation, etc.) may suffer considerable deterioration. Extensive intrusive repairs or even full reconstruction may be required, leading to significant delays in bridge operation.
- *Damage State 5 (DS5)* indicates extensive damage to structural components, presenting an imminent risk of structural failure (i.e., near collapse) or total collapse. At this stage, bridge structural members experience significant damage, leading to a notable decrease in their resistance. This damage state encompasses failures such as tilting of the substructure, foundation failure, deck unseating of the bridge pier, and irreversible large movements at the connections. Repairing the bridge at this stage is difficult, time-consuming, and often impractical, with high costs involved.

Applying the framework in Table 3 to post-flood bridge assessments provided a structured approach to damage evaluation, enabling consistent classification and prioritization of repairs.

5 Assessed bridge damages

5.1 Reconnaissance mission

The damage survey was conducted over two days: September 20, 2024, five days after the event, and October 12, 2024, nearly one month later. These dates were strategically chosen to enable a comprehensive assessment—one immediately following the event and another after debris removal. A team from the University of Pardubice carried out site visits to document the condition of the structures and evaluate the extent of damage or failure. Given the significant number of bridges affected by the major flood, conducting post-flood damage assessments posed a considerable challenge for the team as well as for engineers and authorities alike. The 122 investigated bridges were inspected systematically during two

Table 2 Literature overview of bridge functionality and damage state frameworks

Damage state	Notes	FEMA-HAZUS (2020)	Hose et al. (2000)	Liao and Loh (2004)	Basoz and Mander (1999)	Liu and Xiang (2024)	Lehman et al. (2004)	Stojadinovic and Mackie (2004)	Burghardt et al. (2025)
DS1	Definition	Null	No	N/A	N/A	Null	N/A	Null	Null
	State of Damage	N/A	Barely visible cracking						
	Residual deformation in members								
	Bridge functionality		Fully operational			0 days closure		Immediate access	
	Performance level		Cracking					Vertical load capacity loss < 5%	
	Remarks		No repair					Traffic remaining < 100%	
DS2	Definition	Minor	Minor	Slight	Slight	Slight	Minor	Slight	Minor
	State of Damage	Minor cracking and spalling at the abutment, cracks in the shear keys at abutments, minor spalling and cracking at hinges, minor spalling at the column, or minor cracking in the deck	Onset of hairline cracks	Minor cracks and spalling in the column, abutment, girder, or deck, expansion joint, or approach slab	Cracking and spalling		Hairline cracks		Loss of handrail, guardrail, and decorations, small-scale (< 1 m^2) detachment of pavement, clogging of road drainage
	Residual deformation in members		Cracking < 1 mm						

Table 2 (continued)

Damage state	Notes	FEMA-HAZUS (2020)	Hose et al. (2000)	Liao and Loh (2004)	Basoz and Mander (1999)	Liu and Xiang (2024)	Lehman et al. (2004)	Stojadinovic and Mackie (2004)	Burghardt et al. (2025)
	Bridge functionality		Operational			7 days closure	Full service/ Fully operational	Weight restriction	
	Performance level		Yielding					Vertical load capacity loss < 20%	
	Remarks	No more than cosmetic repair	Possible repair					Traffic remaining < 75%	
DS3	Definition	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate	Moderate
	State of Damage		Open cracks, onset of spalling		Abutment and backwall collapse		Open cracks, spalling		Minor to moderate cracks in concrete (< 50 cm), light exposure of reinforcement, demolition of access ramps
	Residual deformation in members	< 5.0 mm (abutment)	Cracking > 1 mm and < 2 mm Spalling 1/10 of cross-section						
	Bridge functionality		Life safety			30 days closure	Delayed operation/Limited service	One lane-open only	

Table 2 (continued)

Damage state	Notes	FEMA-HAZUS (2020)	Hose et al. (2000)	Liao and Loh (2004)	Basoz and Mander (1999)	Liu and Xiang (2024)	Lehman et al. (2004)	Stojadinovic and Mackie (2004)	Burghardt et al. (2025)
	Performance level		Initiation of local mechanism					Vertical load capacity loss < 35%	
	Remarks	Economic threshold for repair	Minimum repair				Epoxy injection and concrete patching	Traffic remaining < 50%	
DS4	Definition	Extensive	Major	Extensive	Extensive	Extensive	Severe	Major	Major
	State of Damage	Column exhibiting moderate shear cracks, general cracking, and spalling (while remaining structurally sound), moderate movement of the abutment, significant cracking and spalling of shear keys, any connection with cracked shear keys or bent bolts, keeper bar failure without unseating, rocker bearing failure, or moderate settlement of the approach	Very wide cracks, extended concrete spalling/spalling over full local mechanism region	A degraded column without collapse or shear failure, substantial movement at the connections, and significant misalignment of the abutment.	Pier concrete failure		Buckling, bar fracture concrete crushing		Large cracks in concrete (> 50 cm), pervasive cracks in concrete (> 1 m), settlement, displacement, tilting, and demolition of piers, demolition of the superstructure and individual abutments, scouring of the piers, large scale removal of building fabric (> 1 m3)

Table 2 (continued)

Damage state	Notes	FEMA-HAZUS (2020)	Hose et al. (2000)	Liao and Loh (2004)	Basoz and Mander (1999)	Liu and Xiang (2024)	Lehman et al. (2004)	Stojadinovic and Mackie (2004)	Burghardt et al. (2025)
	Residual deformation in members		Cracking > 2 mm and concrete spalling in the range of ½ cross-section depth						
	Bridge functionality		Near collapse			120 days closure	Stability issue/Closed	Emergency access only	
	Performance level		Full development of local mechanism					Vertical load capacity loss < 50%	
	Remarks	Extensive reconstruction with intrusive repair	Repair				Replacement of damaged section	Traffic remaining < 25%	
DS5	Definition	Extreme	Local Failure/ Collapse	Complete	Complete	Complete	N/A	Extreme	Collapse
	State of Damage	Any column collapsing and connections losing all bearing support, potentially leading to imminent deck collapse, or tilting of the substructure due to foundation failure	Visible permanent deformation buckling/rupture of reinforcement,	Partial collapse or significant movement of connections, deck unseating, and substructure tilting due to ground failure	Deck unseating, pier collapse				Complete collapse, demolition (afterwards)
	Residual deformation in members		> 2 mm crack in concrete core and measurable dilation > 5%						
	Bridge functionality		Collapse			365 days closure		Closed	

Table 2 (continued)

Damage state	Notes	FEMA-HAZUS (2020)	Hose et al. (2000)	Liao and Loh (2004)	Basoz and Mander (1999)	Liu and Xiang (2024)	Lehman et al. (2004)	Stojadinovic and Mackie (2004)	Burghardt et al. (2025)
	Performance level	Collapse or almost collapse state	Strength degradation					Vertical load capacity loss > 50%	
	Remarks		Replacement	Replacement				Traffic remaining = 0%	

Table 3 Proposed DSs along with socio-economic considerations

Damage states	Overall classification	Description*		Structural Effect / Safety	Repair needed	Operational status
DS1	Null	Serviceability elements	Minor to moderate damage and/or detachment requiring more than cosmetic repairs	No loss of capacity	No or cosmetic repair	Fully operational
		Secondary elements	From cosmetic damage to onset of movement of components			
		Primary structural elements	Null			
DS2	Minor	Serviceability elements	Major damage and/or total loss of some or all elements	Localized and reduced margin of safety	Minor repair	Operation with caution/ Limited service (full recovery in days)
		Secondary elements	Moderate movement of components while remaining structurally stable			
		Primary structural elements	Clogging of the bridge opening with partial impact on components, minor cracking and spalling, and slight scouring in bridges with shallow foundations, or partial exposure of the pile/shaft toe or first pile segment in deep foundations (bearing capacity intact)			
DS3	Moderate	Serviceability elements	N/A	Noticeable loss of capacity with reduced load rating / Potential for progressive damage	Moderate repair	Interim suspension/ Service paused temporarily (full recovery in weeks)
		Secondary elements	Total failure and/or major movement of approach slopes, embankment fill, expansion joints, pavement, backwall, etc			

Table 3 (continued)

Damage states	Overall classification	Description*		Structural Effect / Safety	Repair needed	Operational status
		Primary structural elements	Clogging with a major effect on components, cracking with moderate residual deformations or spalling, initiation of local failure mechanisms, minor to moderate misalignment in super- or substructure components, minor to moderate movement at the connections, and visible moderate settlement of shallow foundation due to scouring, visible scouring around the pier and/or exposed piles not causing significant risk with bearing capacity partially intact			
DS4	Heavy (Extensive or severe)	Serviceability elements	N/A	Bridge structurally compromised/ Imminent partial collapse possible	Major structural overhaul	Long-term service suspension (full recovery in months)
		Secondary elements	N/A			
		Primary structural elements	Major degradation in piers/columns without collapse, significant degradation in the superstructure, significant misalignment of the abutment, substantial movement at the connections, significant deck movement, risky major undermining of shallow foundations accompanied by differential settlement, and significant scour with noticeable undermining in pier base posing risk for structural integrity, significant settlement, visible rotation and/or large tilt			

Table 3 (continued)

Damage states	Overall classification	Description*		Structural Effect / Safety	Repair needed	Operational status
DS5	Extreme	Serviceability elements	N/A	Near collapse or total collapse—catastrophic	Rebuilt, repair may not be feasible	Closed until reconstruction or replacement
		Secondary elements	N/A			
		Primary structural elements	Total collapse or partial collapse of super- or substructure components, foundation or abutment failure, significant movement and/or even loss of connections, deck unseating, extreme tilting, shallow/deep foundation failure, and/**or** extreme scour			

Serviceability elements (i.e., components for functionality and safety of the bridge without bearing loads): Drainage system, guardrails or barriers, lighting, pedestrian and bicycle facilities, parapets and crash barriers, maintenance access, noise and vibration control systems, utilities, etc

Secondary elements (i.e., components for the overall functionality of the bridge without bearing significant load): Approach slopes, embankment fill, expansion joints, pavement, railway superstructure, backwall, etc

Primary structural elements (i.e., load-bearing components): Suspension or tie-back cables, bridge deck, beam/girder, pier/column, abutment, shallow/deep foundation, bearing, etc

*when classifying, it is assumed that at least one DS is reached in each bridge component

field campaigns along pre-planned routes traversing the main flood-affected river corridors, namely the Opava, Vidnávka, Bělá, and Morava rivers. The dataset therefore constitutes a route-based systematic sample of the most affected river corridors rather than a complete regional inventory. Data collection involved photographic documentation and detailed visual inspections to assess the extent of the damage.

5.2 Bridge damages: photographic documentation

The primary causes of the damage were examined by analysing the photographic evidence to identify the underlying factors contributing to the observed damage. Since the extent of damage varied significantly between serviceability, secondary, and primary structural elements of the bridge, the severity levels were investigated individually for each element but evaluated as a whole. The DSs were estimated using the method described in Sect. 4.2 and Table 3 of this paper, which provides a systematic framework for evaluating structural damage. This method enabled precise categorization of damage into predefined levels (i.e., null, minor, moderate, heavy, and extreme) based on specific structural indicators, ensuring consistency and accuracy in the assessment.

Serviceability elements ensure the proper functioning and safety of the bridge without bearing any loads. Extreme damage to these elements often results in reduced usability, user inconvenience, or compromised safety. However, their impact on the overall functionality of the bridge is limited, allowing damage classification to reach up to DS2 in the overall damage evaluation (Table 3). Figure 4a and b illustrate selected examples of DSs and assigned classifications for serviceability elements on bridges over the Opava and Bělá rivers. In Fig. 4a, DS1 is assigned due to damage to the drainage pipe, while in Fig. 4b DS2 is reached due to the loss of guardrails.

Secondary elements indirectly affect the bridge's structural performance by contributing to overall functionality, stability, and durability. These components do not carry primary loads but ensure seamless operation in a supportive role in maintaining the overall functionality. Depending on the severity of the damage, secondary elements can contribute to an overall bridge damage classification ranging from DS1 to DS3 (Table 3). Figure 5a-f depicts the various damage levels in the embankment fills and corresponding DS for secondary elements. In Fig. 5a, the bridge over the Morava River is classified as DS1 due to a small detachment in the abutment. Figure 5b shows a bridge at DS2 level, resulting from moderate movement of the embankment fill, while the overall functionality is unaffected. Figure 5c

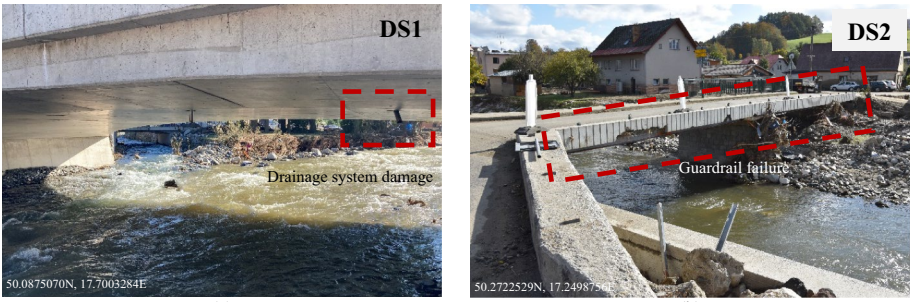


Fig. 4 Damage assessment in serviceability elements: **a** DS1, **b** DS2

and d depict bridges at DS3, characterized by the total failure of the embankment fill, while the primary load-bearing superstructure remained intact; however, the complete loss of the approach embankment renders the bridge entirely inaccessible and constitutes an immediate safety hazard. The overall functionality of these bridges is temporarily interrupted, and the bridges were closed to traffic, requiring appropriate remedial actions to restore their functionality.

Primary structural elements are critical load-bearing components essential for the stability and safety of bridges. Damage to load-bearing components poses severe risks to the structural integrity of the bridge (Sano et al. 2023), potentially leading to catastrophic failures. The extent of the damage can vary from DS1 to DS5.

Various damage levels in the *substructure elements* are presented in Fig. 6a-f. The onset of minor spalling in the abutment, which retains a large reserve of deformation capacity, classifies the bridge as DS2 (Fig. 6a). When clogging of the bridge opening partially affects the overall load-bearing components, it is also graded as DS2 (Fig. 6b). Scour, where the piles are exposed, can deteriorate the load-bearing capacity, potentially contributing to higher DSs such as DS3 (Fig. 6c). Misalignment of the abutment, despite the absence of shear damage in the micropiles, corresponds to a damage severity of DS4 (Fig. 6d). Notably, this bridge was rebuilt after the 2009 flood event, yet it has once again experienced failure. DS5 is assigned when the superstructure tilts due to scour and subsequent abutment failure (Fig. 6e). Abutment failure can also lead to total or partial collapse (e.g., DS5), as shown in Fig. 6f.

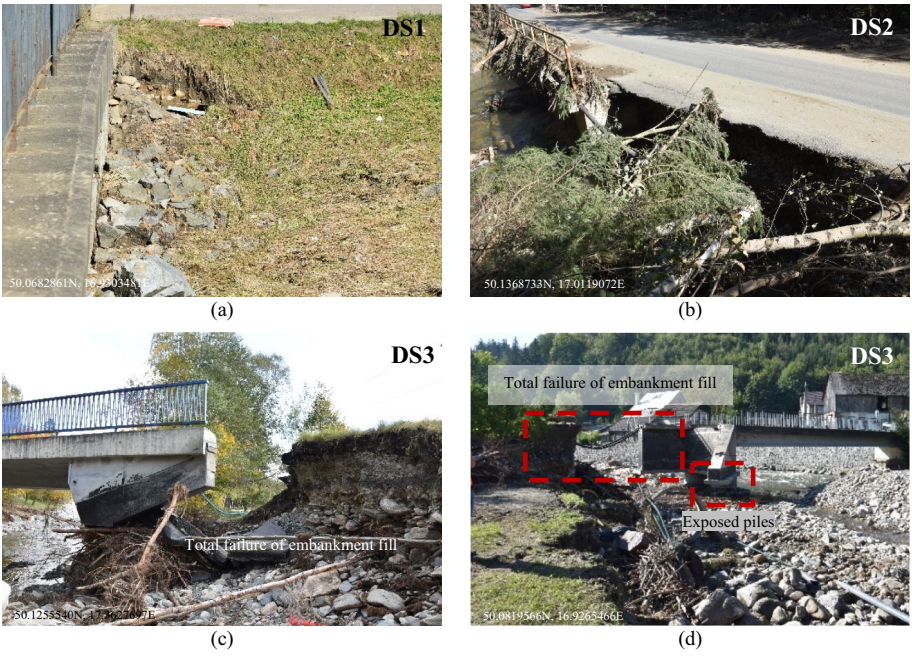


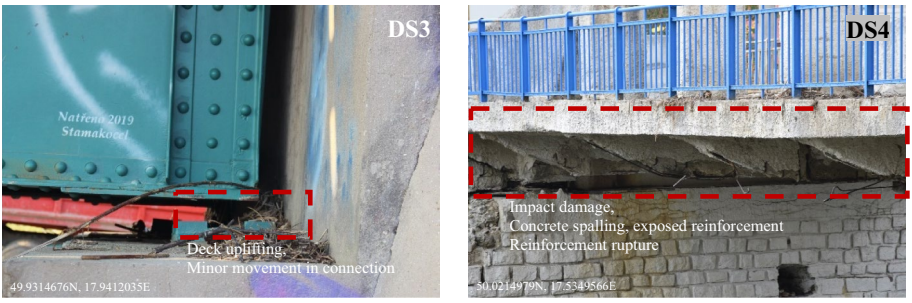
Fig. 5 Damage assessment in secondary elements: **a** detachment in the abutment, **b** moderate movement of the embankment fill, and (**c**) and (**d**) total failure of the embankment fill



Fig. 6 Damage assessment in the substructure: **a** detachment in the abutment, **b** bridge clogging, **c** significant scour, **d** abutment misalignment, **e** tilted superstructure due to abutment damage, and **f** further tilting of the superstructure caused by abutment failure

Regarding the *bridge superstructure*, the most commonly observed damages include deck uplifting (i.e., loss of contact between the bearings and the deck). Figure 7a illustrates deck uplift accompanied by minor movement in the connection, contributing to DS3, requiring repair work to restore the functionality. Figure 7b highlights a more severe scenario where impact damage results in significant deterioration, characterized by concrete spalling, exposed reinforcement, and reinforcement rupture, ultimately reaching DS4, rendering the bridge inoperable.

Figure 8a-f illustrates the structural failures of several DS5 bridges, following significant flooding events. This state usually coincides with the total collapse of the structure. Piers and columns often suffer complete damage, further exacerbating the collapse. Additionally,



(a) (b)

Fig. 7 Damage assessment in the super-structure: **a** DS3 due to deck uplift, **b** impact damage contributing to DS4

sections (or whole) of the superstructure frequently detach and fall into the riverbed. As seen in Fig. 8a, the deck has been moved approximately 30 m from its original position. Figure 8b shows a collapsed bridge with extensive damage to its support structures. The bridge deck was removed from the riverbed due to superstructure failure (Fig. 8c). Figure 8d and e demonstrate the superstructure collapse, showing only the abutment of the bridge. Similarly, Fig. 8f depicts a complete superstructure collapse, with the remains scattered and debris visible throughout the affected area. Such failures result in DS5 level, underscoring the extensive damage caused by the floods. It also highlights the vulnerability of bridge infrastructure to such natural disasters.

5.3 Extent of bridge damages

DSs in Table 3 offer a method to assess structural damages in bridges, but also the operational status, ranging from fully operational (corresponding to DS1) to closed (corresponding to DS5). Following this methodology, the severity of damage to the investigated bridges is visually presented in the road network map of the flood-affected zone (Fig. 9a). Through color-coding and detailed annotations (from green to red, corresponding to DS1 to DS5), the maps emphasize the extent of damage. For example, the 20 bridges classified as DS5 (red dots in Fig. 9a) due to total or partial collapse severely disrupt transportation networks, posing significant challenges to local communities and emergency response operations. Heavy damage (DS4) to 5 bridges and moderate damage (DS3) to 16 bridges are likely to cause network interruptions in the short to medium term. Close-up maps highlight the most affected cities or towns and their road networks with a 100-year flood hazard return period, marking the DSs of bridges and potential road closures (Fig. 9b-e). The severe disruptions in transportation and connectivity impacted the movement of goods, services, and individuals. Critical access routes to key infrastructure, including hospitals, emergency facilities, and essential supply chains, have been cut off, leaving some communities isolated and vulnerable (Abebe et al. 2025). The damage has also affected the disaster response efforts and delayed the restoration of vital utilities, further exacerbating the situation. Consequently, the GIS-driven data plays a critical role in understanding the far-reaching impacts of the flood and estimating the extensive efforts required to restore connectivity across the region.



Fig. 8 **a-f** Collapsed bridges

5.4 Multi-source reconnaissance approach: UAVs vs. Ground-truth damage assessment

The UAV campaign produced high-resolution true orthophoto maps of individual municipalities impacted by the event. The orthophoto layers were imported into a GIS environment, where visible damage features were systematically analysed and DSs were assigned to individual bridges. The UAV survey was conducted by a third party. The acquired imagery reflects post-event conditions after floodwaters had receded but before substantive reconstruction. The spatial resolution cannot be reported, as no acquisition metadata accompanied the processed orthophotos. Nevertheless, the image quality was sufficient to identify damage to the components, enabling reliable assignment of bridge damage states.

Damage classification was possible for 75 out of the 122 bridges surveyed in the field, limited to locations for which suitable orthophoto coverage was available. Comparison between

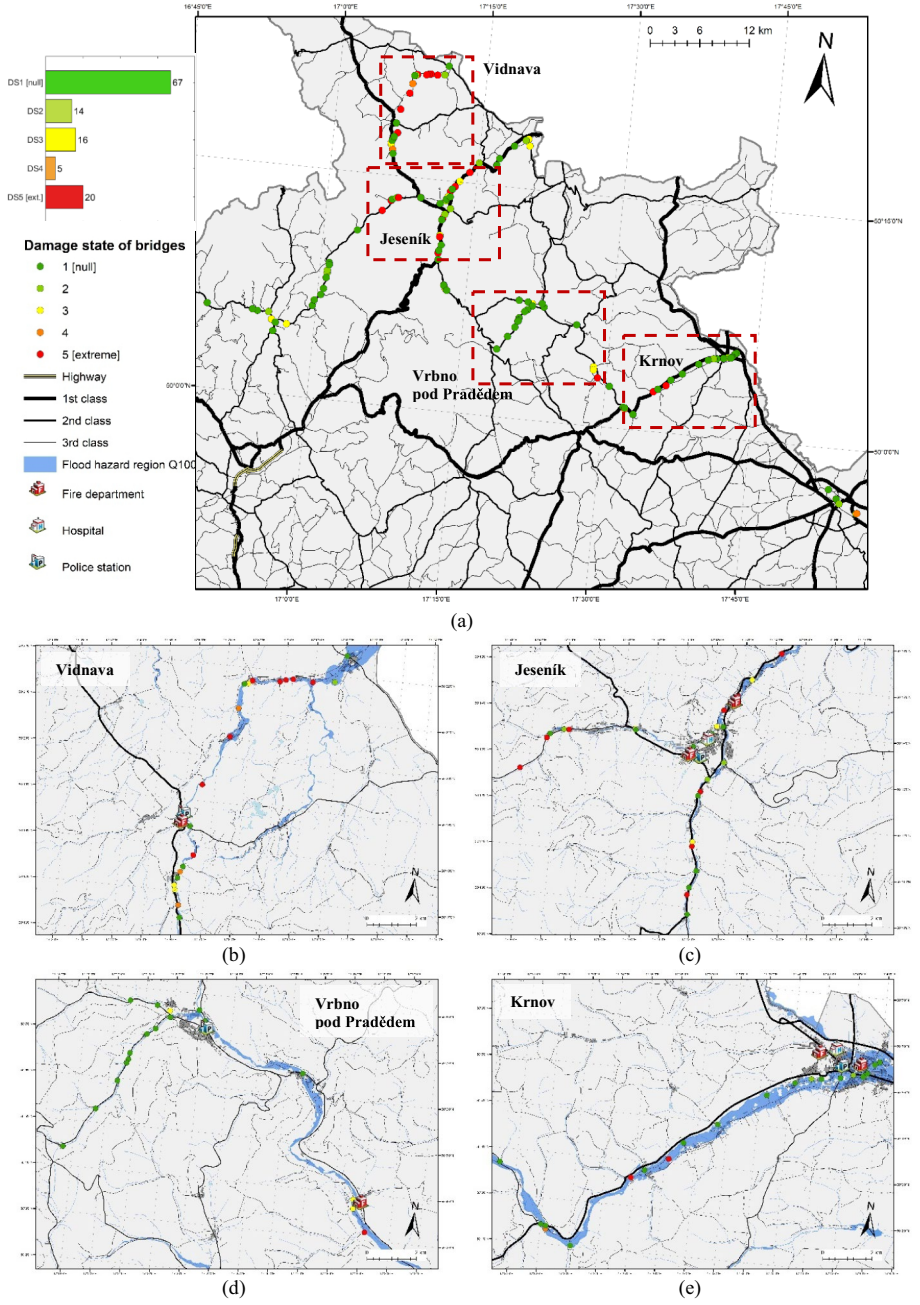


Fig. 9 **a** Post-flood DSs in investigated bridges; close-up views of cities/towns: **b** Vidnava, **c** Jeseník, **d** Vrbno pod Pradědem, **e** Krnov (ČÚZK 2024; VÚV TGM 2024)

UAV-based and field-based classifications (i.e., ground-truth) revealed strong agreement. Identical DSs were assigned in 73.3% of cases (Fig. 10a). Discrepancies mainly occurred between neighbouring damage states, reflecting the limitations of aerial imagery in capturing hidden or small-scale defects. These discrepancies were concentrated where the diagnostic evidence was sub-surface or occluded, such as pile exposure beneath the deck, undermining at the abutment face, and cracking on surfaces not visible from above. The two methods therefore differ less in their conclusions than in the type of damage they can detect: UAV imagery primarily resolves surface-visible damage, which most often governs whether a bridge remains serviceable. In contrast, the serviceability classification showed a higher level of consistency, with agreement achieved for 93.3% of the assessed bridges (Fig. 10b). This indicates that UAV-based assessments are particularly reliable for distinguishing between serviceable and non-serviceable structures at the network scale. UAV-based detection may support a rapid serviceability screening and the prioritisation of subsequent in-person field assessment.

Overall, the results confirm that UAV-derived orthophotos are highly effective for rapid regional screening, network-level damage mapping, and the preliminary identification of potentially non-serviceable bridges following flood events. This enables the efficient prioritisation of field investigations, which can then be focused on those structures flagged as critical. UAV-based and field-based approaches together form a robust, multi-tiered framework for post-flood bridge damage assessment. Nevertheless, field inspections remain indispensable for identifying hidden damage, verifying structural integrity, and defining appropriate repair or intervention strategies.

5.5 Disruptions to road and railway networks

Another possibility of network disruptions, regardless of the damage to the bridge is the damage to the road sections (Fig. 11a-d). Specifically, severe scour was frequently observed along the sides of the roads or near retaining walls (Fig. 11a). The lack of flood barriers, such as retaining walls, also resulted in road damage (Fig. 11b). Significant damage was observed across the road and railway networks, with several areas experiencing complete washouts (Fig. 11c and d). Such damage to the road network commonly occurred at locations where the riverbed curves.

The railway network, once an essential link within the transportation network, has suffered extensive damage, with several tracks washed out or rendered unusable (Fig. 12a and b). Even though precautions against floods existed, such as constructing a retaining wall (Fig. 12c), the damage to railway superstructure was not prevented. Failure of both substructure and superstructure just downstream of a bridge in a low-lying area disrupted the railway network (Fig. 12d). The bridge opening or clearance was insufficient to accommodate the flood discharge. These disruptions halted both freight and passenger services. According to the railway infrastructure portal (SŽ 2025), minor to major repairs are expected to restore operations in many sections in the short term. However, the restoration of three heavily damaged railway sections and some bridges is expected to take approximately 9 months for one section and 14 months for the other sections, following the flood event (SŽ 2025).

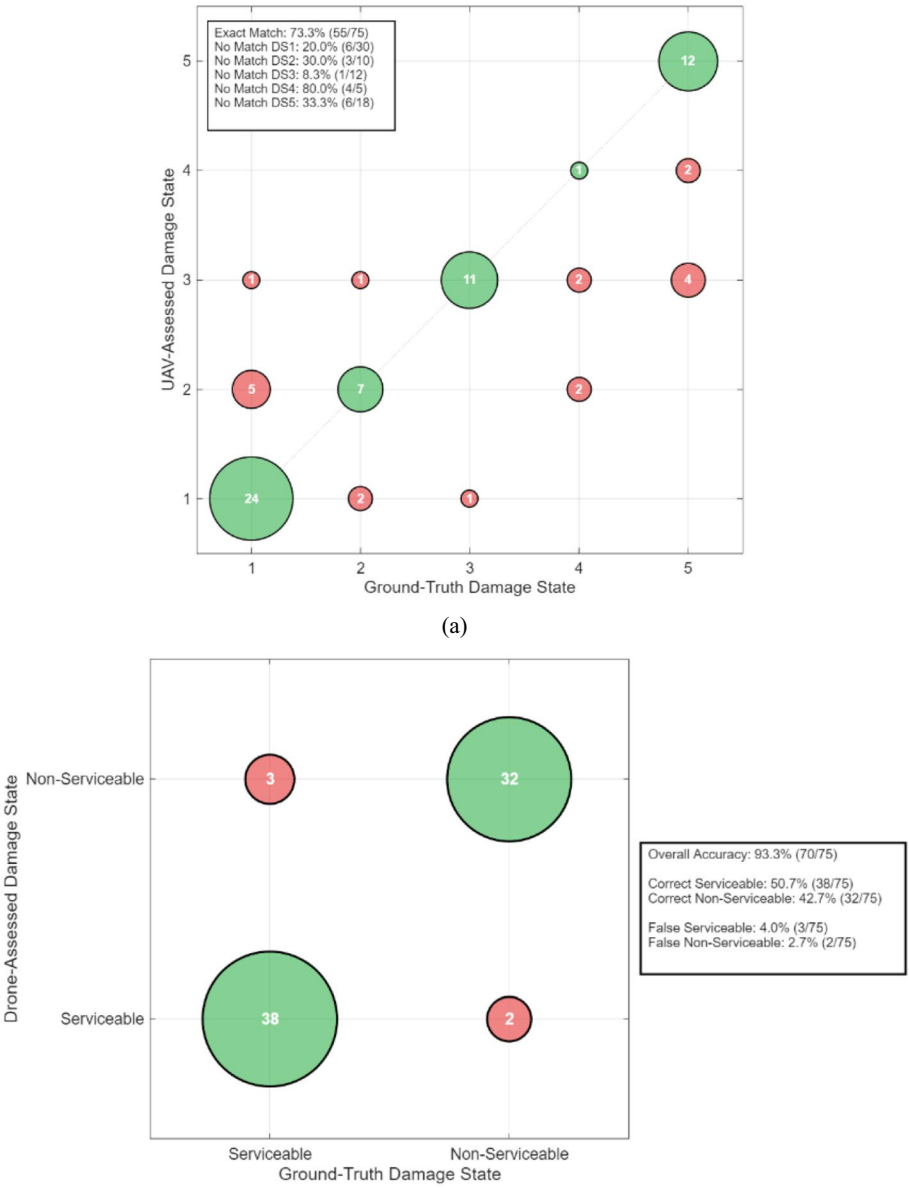


Fig. 10 Comparison of post-flood bridge damage assessed using ground-based inspections and UAV-based methods: **a** damage state (DS) classification; **b** serviceability classification

5.6 Recovery actions

The government responded immediately to the flood event, and recovery actions were promptly undertaken (Gabzdyl 2024; U.S. National Guard 2025). The army and firefighters

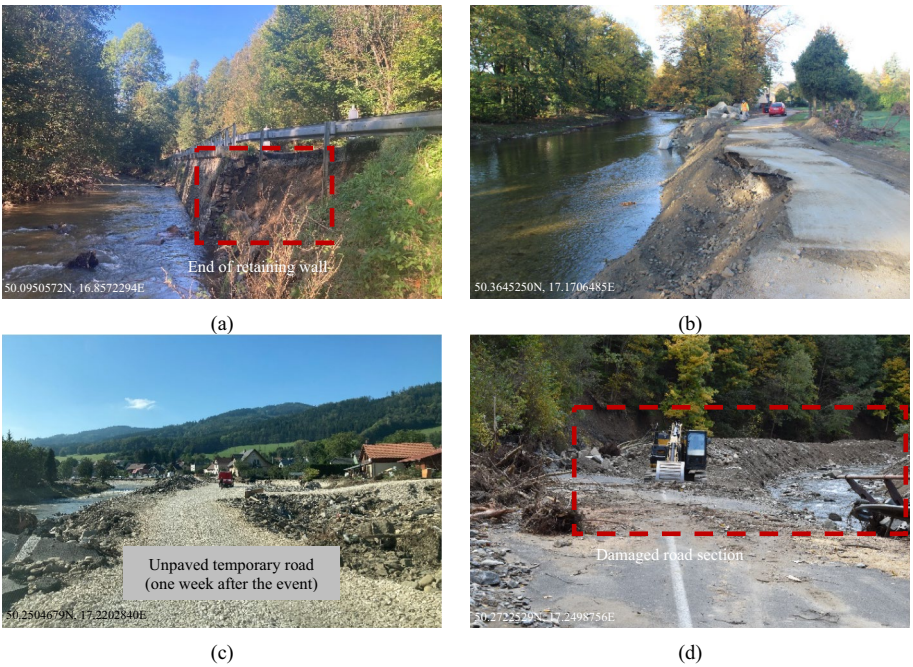


Fig. 11 Road network damage: **a** end of retaining wall causing road scour; **b** road edge failure; **c** unpaved temporary road one week after the event; **d** damaged road section

played a key role in these efforts. Subsequently, the European Parliament approved €114 million in aid to help cover the damages caused by the severe floods (Radio Prague International 2025). Additionally, initial road network recovery relied on unpaved roads immediately after the event (Fig. 11c and Fig. 13c). The temporary structures were deployed 3–8 weeks after the event to restore connectivity on critical road network while permanent repairs or replacements were underway (Fig. 13a and b). Priority for constructing temporary bridges was given to those serving critical transportation routes, as their failure had the most significant socio-economic impact.

The interdependency between bridges and other infrastructure systems is also revealed. Many bridges in the affected regions not only serve as transportation links for vehicles and pedestrians but also carry utilities such as water pipes, electric lines, and communication cables (Fig. 13d). The failure of these bridges during the flood event disrupted not only transportation networks but also essential services, including water supply and electricity. Cities like Opava suffered electricity and water shortages for more than 2 weeks.

6 Discussion

6.1 Reasons behind damage: general observation

A database was developed with 122 surveyed bridges. These bridges are not hydraulically equivalent. They vary in bridge types, which shows the distribution of superstructure and sub-



Fig. 12 Railway network damage: **a** embankment erosion and track displacement; **b** ballast and track washout; **c** retaining wall failure; **d** bridge opening insufficiency causing backwater and downstream failure

structure types. Beyond structural typology, the bridges also vary considerably in number of spans, waterway opening area, foundation details, abutments, and construction period, etc. This heterogeneity limits the direct comparability of damage observations across structures, as bridges with different hydraulic capacities may respond differently to the same flood event. Therefore, the findings should be interpreted as observational and exploratory, characterising a route-based survey sample rather than a controlled population of hydraulically comparable structures. However, the reconnaissance mission identified several factors that influenced the damage to the bridges, including: (i) scour is the main cause of damage to some of the primary elements such as foundations and abutments, resulting in misalignment and tilting; (ii) debris accumulation—including not only natural materials such as woody material and boulders, but also anthropogenic elements from infrastructure, houses, retaining walls, and collapsed bridges—clogged bridge openings, generating substantial backwater effects and additional hydrostatic forces that contributed to further structural deterioration; and (iii) direct debris impact caused failure of bridge piers and decks, with concrete spalling, reinforcement rupture, and deck displacement documented at multiple surveyed structures.

Two recurring categories of design deficiency were identified from the field reconnaissance observations. The first was insufficient hydraulic opening capacity relative to the flood discharge, which resulted in overtopping of bridge decks at multiple locations despite the design clearance requirements of 1000 mm for Q100 and 500 mm for 1.4×Q100 specified in ČSN 73 6201 (2008). Complete washout of embankment fills, disturbing the transportation network, was frequently observed as a result of the insufficient hydraulic opening. It should be noted, however, that the September 2024 event exceeded the 200-year recurrence interval at no

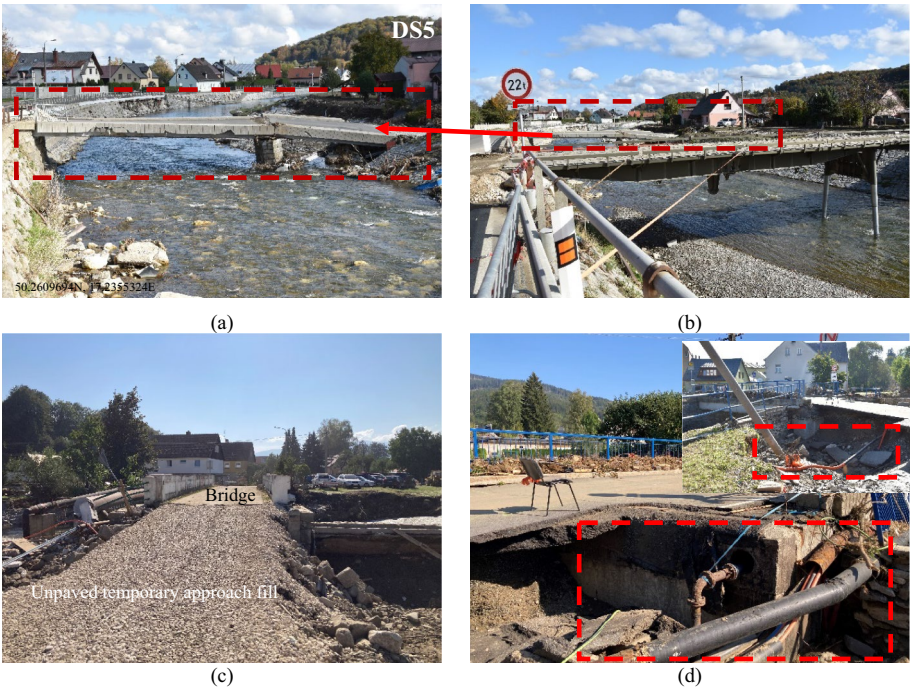


Fig. 13 **a** Partially collapsed bridge; **b** temporary bridge to restore traffic; **c** unpaved road to bridge; **d** utilities

fewer than 37 gauging stations over the 5-day accumulation period, so the observed overtopping occurred under hydraulic loading well beyond the design envelope and does not indicate non-compliance with the standard. The frequency with which overtopping was nonetheless observed raises the question of whether a clearance criterion anchored to Q100 remains appropriate under changing flood hazard conditions. The second deficiency was the oblique angle of some bridges relative to the river trajectory, which significantly exacerbated debris accumulation, as these skewed bridges presented a larger obstruction to the flow and promoted earlier and more extensive blockage of the hydraulic opening compared to bridges aligned with the river axis.

6.2 Geospatial characteristics and bridge damage

Fig. 14a correlates the pre-flood bridge conditions and damage to bridges. As in many other practices, the current code for bridge inspections to evaluate bridge condition (ČSN 73 6221 2018) focuses on slow degradation rather than sudden events. Therefore, the comparison between pre-flood bridge conditions (Fig. 3) and post-flood damage levels (Fig. 9) revealed no clear correlation (Fig. 14a), although the analysis was limited to the 56 bridges, out of the total 122 bridges investigated, for which pre-flood inspection data were available. This absence of correlation is physically consistent with the nature of the inspection standard: structural condition grades reflect long-term deterioration and do not capture flood hazard, hydraulic vulnerability indicators. Future bridge inspection and risk assessment frameworks should therefore

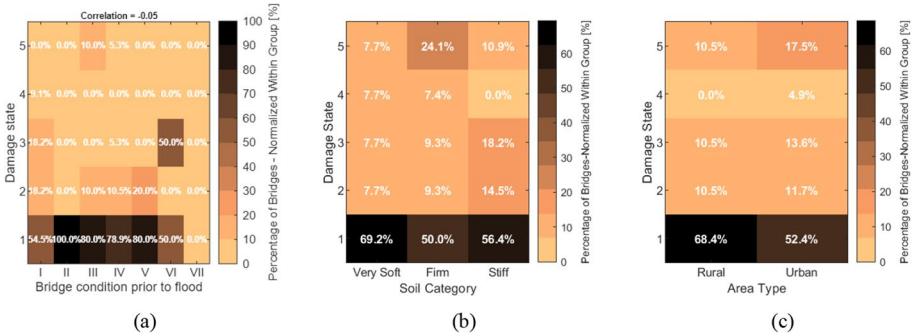
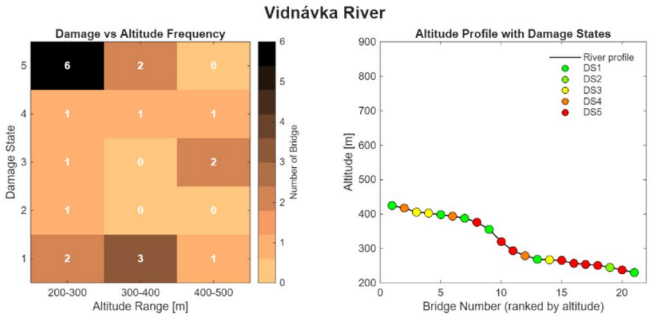


Fig. 14 **a** Correlation between damage states and condition of bridge prior to flood **b** damage frequency versus regional soil classification, **c** damage frequency versus urban settings

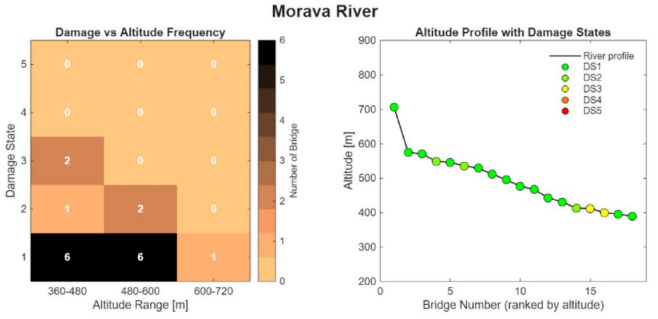
incorporate dedicated flood-related performance indicators alongside conventional structural condition grades.

The regional geological and surface soil classification, grouped into three stiffness classes (Fig. 1c), was used as a geospatial proxy representing generalized surface geological conditions at the regional scale. The highest proportion of non-functional bridges was observed on firm soil, with 40.8% classified as DS3 or higher, followed by stiff soil at 29.1% and very soft soil at 23.1%. Data on bridge foundation type (shallow vs. deep) were not available, although foundation characteristics can significantly affect damage independently of soil type; incorporating foundation type together with a more detailed soil classification could therefore clarify the factors influencing bridge damage. Foundation type could nonetheless be identified visually at bridges where scour had exposed the substructure. At these locations, bridges founded on piles generally exhibited less severe damage despite pile exposure, whereas bridges without visible pile support more frequently showed settlement, rotation, or tilting under comparable conditions. This observation is qualitative and based solely on field evidence, as foundation records were not available. Furthermore, detailed riverbed granulometry data and foundation depth records were not available for the surveyed bridges. A reclassification by erodibility would be more informative, as stiffness and erodibility are not equivalent, but this would require granulometric data that were not available. Therefore, the relationship between soil stiffness or erodibility and observed damage frequency cannot be confirmed as a causal mechanism.

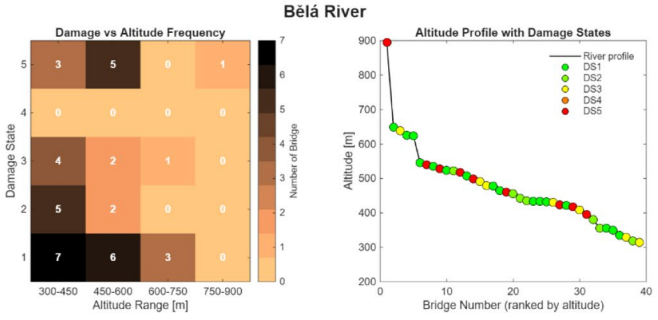
The integration of land-use data into the topographic maps (i.e., urban settings) highlights urbanized areas with bridge locations (Fig. 1d). Approximately 84% of the bridges are located in urban areas. Since the dataset is predominantly populated with urban bridges, there may be greater variability in the rural bridge data. Consequently, the probability of observing more damage in rural bridges could be skewed due to the smaller sample size. Individual analysis shows that 21% of rural bridges were non-functional (DS3 or higher), whereas 36% of urban bridges were non-functional, indicating a higher proportion of severe damage in urban areas (Fig. 14c). Urban reaches are commonly laterally constrained by embankments, retaining walls, and adjacent development, so that flood discharge that would otherwise spread across a rural floodplain is conveyed through a more confined cross-section, potentially increasing water levels and flow velocities at the bridge. In addition, bridge decks in urban areas, while keeping design criteria, are often constrained vertically by the elevation of the connecting roadway, limiting the available freeboard. The predominance of urban bridges in the surveyed inventory also has implications for vulnerability modelling. Reconnaissance datasets are often biased



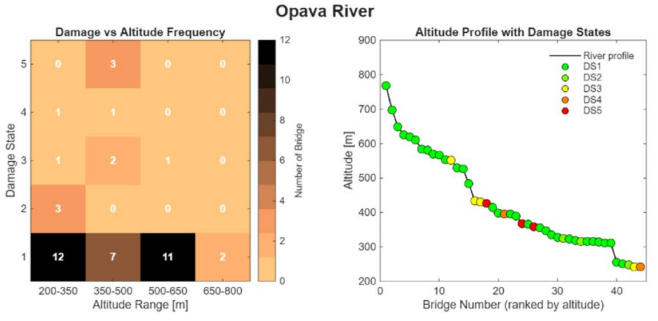
(a)



(b)



(c)



(d)

Fig. 15 Relationship between bridge damage states (DS1–DS5) and altitude **a** Vidnávka river; **b** Morava river **c** Belá river **d** Opava river

towards urban areas because of their greater infrastructure density and accessibility following extreme events. Consequently, vulnerability models calibrated using such datasets may primarily reflect urban conditions unless sufficient representation of rural crossings is included. Deliberate sampling of rural bridges would therefore improve the transferability of future vulnerability models.

Figure 15a-d presents an analysis of bridge damage along the different rivers, combining frequency distribution by altitude with detailed DS profiles across individual bridges. The slope-related interpretation in Fig. 15a-d was not based on direct field measurements or explicit river-gradient calculations, but rather on altitude values extracted from the GIS-based altitude dataset in the current study. Therefore, it represents a qualitative interpretation of the observed topographical influence on flood behavior and bridge exposure, rather than a quantitatively evaluated hydraulic parameter. Besides, steeper gradients not only increase flow velocity and depth, intensifying hydraulic forces on structures, but mountainous terrain also enhances sediment mobilization and debris transport capacity that can impact or block bridges. The distribution of bridge damage with respect to altitude indicates that the relationship between bridge altitude and flood-induced damage is not uniform across the investigated river systems, as altitude is interpreted in this analysis as a simplified geospatial proxy parameter rather than a direct causative factor.

7 Conclusions

This study examines the major flooding event that impacted the Czech Republic in September 2024, with a specific focus on bridges. On-site inspections were conducted to gather firsthand information on bridge conditions, including damage documentation, structural integrity assessments, and post-flood evaluations. The extent of damage observed in the bridges was evaluated using proposed DS thresholds. A comprehensive assessment, integrating field observations, photographic documentation, geospatial and hydraulic data collection, and DS categorization, was conducted to evaluate the extent of the damage and the challenges posed by the flooding.

Based on the study results, the following conclusions were drawn:

- There is no established method for DS estimation after flood (or other hazard) events in the Czech Republic. The proposed DSs provide a comprehensive qualitative understanding of the varying levels of structural and functional damage to bridges caused by such hazards.
- Scour led to structural failures. Misalignment and tilting were the primary causes of abutment and pier failures, further exacerbating structural damage in vulnerable bridges.
- The absence of systematic information regarding bridge foundation type and foundation depth represents an important limitation of the present study. Nevertheless, several field observations qualitatively indicated that bridges with visible pile foundations generally exhibited better scour resistance and maintained structural stability even under significant foundation exposure, whereas bridges without visible pile-supported systems appeared more vulnerable to severe scour-related damage.
- Inadequate hydraulic openings, combined with debris accumulation, increased hydrau-

lic pressure and caused significant structural deterioration. Additionally, embankments were washed out in many cases due to inadequate hydraulic openings or clogging.

- The comparison between pre-flood structural condition grades and post-flood damage states revealed no clear systematic correlation. This finding suggests that current bridge inspection practices mainly assess long-term physical deterioration rather than hydraulic vulnerability. Future bridge assessment procedures should therefore incorporate flood-related risk assessment procedures.
- Comparison between UAV-based and field-based damage classifications demonstrated strong agreement, confirming that drone imagery represents a powerful rapid-screening tool for post-disaster assessment. UAV data proved particularly valuable for identifying non-serviceable bridges and supporting prioritisation of field inspections, while on-site surveys remained essential for detailed diagnosis and repair planning.
- Some bridges that were replaced after the 2009 flood failed again 15 years later during the current flood. These bridges had also been significantly affected during the 1997 flood. This recurring failure highlights the need for more robust design principles in flood-prone zones and/or the implementation of effective flood protection measures to enhance long-term resilience.
- The authors acknowledge that due to data limitations, the assigned DSs could not be linked to key structural details such as foundation type, superstructure design, and overall bridge typology. Providing quantitative DS descriptions for specific bridge types and configurations is essential for improving flood risk management and bridge design standards. Additionally, integrating geospatial data, hydrological analysis, bridge characteristics, and DS assessments could support the validation of future risk assessment methodologies and damage models.

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Data availability The primary field-survey data and the corresponding analysis results will be made publicly available and, until then, are available from the corresponding author upon reasonable request. However, data and images that are subject to GDPR restrictions, owned by a third party, and covered by data-sharing agreements cannot be publicly released or redistributed by the authors.

Declarations

Conflict of interest The authors declare that they have no known conflict of interest or personal relationships that could have appeared to influence the work reported in this study.

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