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The aftermath of a flood: assessing its impact on roads and bridges with insights from the Road and Bridge Research Institute

Abstract: The article presents a case study of the activities of the Road and Bridge Research Institute related to the assessment of the technical condition of road and bridge infrastructure in areas affected by a natural disaster in 2024. Particular emphasis is placed on the characteristics of the assessment process and the analysis of inspection results based on 761 preliminary control reports. Floods, as one of the greatest threats to road infrastructure, cause both direct damage and indirect consequences, affecting transportation and interdependent sectors. The article discusses the scale of destruction, the spatial distribution of damage, and the categories of technical condition assessments for bridges and roads. The research findings emphasize the need to implement effective infrastructure protection measures to enhance resilience against future natural disasters. Additionally, they emphasize that assessing the technical condition of bridges and roads should be an integral part of a long-term road infrastructure management strategy during crisis situations. The findings are expected to provide valuable insights for policymakers, engineers, and urban planners, supporting the development of best practices to enhance the resilience of road and bridge infrastructure against future extreme weather events.

Keywords: flood, public roads, roads engineering structures, assessment of technical condition.

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1. INTRODUCTION

Bridges and roads are among the infrastructure elements most exposed to atmospheric conditions. Extreme weather events, such as floods, pose a particularly severe threat to their durability [1, 2], defined as the ability of a structure to maintain its properties and efficiency over the long term [3]. The increasing frequency and intensity of such extreme events, largely driven by climate change, exacerbate the risks to road and bridge infrastructure. A comprehensive review by Björnsdóttir et al. [4] highlights the potential impacts of climate change on bridges, emphasizing the need for adaptive strategies to enhance resilience.

During extreme weather events, road infrastructure can sustain both direct and indirect damage. These events not only pose risks to human safety but also severely disrupt transport mobility and supply chains, leading to substantial economic and social consequences [5-7]. For example, a study by Nemry and Demirel [8] estimates that climate change presents significant risks to European road transport infrastructure, potentially increasing maintenance costs and causing operational disruptions. Similarly, Pyatkova et al. [9] reference estimates from the UK Department for Transport, indicating that a single day of flooding on the motorway network accounts for 2% of the country's annual delays. The substantial impact of weather conditions on road infrastructure is further highlighted by the research of Michielsen et al. [10], which shows that maintenance costs resulting from weather-related stresses account for 30%–50% of total road transport infrastructure expenses, with 10% specifically attributed to extreme weather events.

Researchers Bil et al. [11] identify three levels of road infrastructure damage caused by floods: (i) complete destruction of the road, requiring the reconstruction of its load-bearing structure and the full restoration of road functionality; (ii) partial damage, necessitating the replacement of the surface layer or minor stabilization of the road embankment to restore usability; and (iii) temporary road closure due to flooding, which requires no repairs once the water recedes. Additionally, researchers Lu et al. [12] emphasize that approximately 39% of annual damage to transport infrastructure worldwide is caused by urban floods. It should be emphasized that climate risk of road infrastructure depends on various factors, including its nature, location, design features, and construction practices [13].

Floods can cause significant bridge failures, primarily due to the undermining and collapse of intermediate supports, displacement of spans, and embankment erosion [4, 14]. During floods, bridges are exposed to extreme loads resulting from a rapid rise in water levels and dynamic water flow. The forces exerted on the structure, the accumulation of debris, and global and local overloading can cause significant damage or total destruction [15]. Zhang et al. [16] emphasize the crucial importance of ensuring adequate structural redundancy and implementing load-bearing protection measures to reduce the risk of bridge failures under extreme hydrological conditions.

Despite technological advancements, flood risk remains a significant challenge, as floods are the most frequent natural disaster worldwide and cause extensive damage [17, 18]. Climate change is expected to further increase both the frequency and intensity of extreme rainfall events [19, 20]. The increasing risk of major floods in a changing climate is also highlighted by researchers Milly et al. [21], who advocate for a reevaluation of flood management strategies to account for these evolving risks.

Moreover, urban development and environmental protection often conflict with the need to protect urbanized areas from flood impacts [22]. Merz et al. [23] emphasize that transdisciplinary research is essential to better understand the potential for surprises in flood risk systems and to operationalize risk management concepts that account for limited knowledge and unexpected developments. A similar conclusion was formulated by Bruijn et al. [24], who stress that social vulnerability must be integrated into flood risk management. In addition, it is worth mentioning the opinion of Papilloud et al. [25], who argue that analyzing road infrastructure exposure to flooding is a crucial first step in risk assessment.

This article presents a case study of the activities of the Road and Bridge Research Institute related to the assessment of the technical condition of roads and bridges in areas affected by a state of natural disaster in 2024. The primary research focus is on characterizing the assessment process of the analysed structures and evaluating the results based on 761 preliminary inspection reports. A key aspect of this analysis was determining the necessary follow-up actions for the assessed structures based on observed damage. By examining the extent and nature of flood-induced damage, this study aims to provide insights into infrastructure vulnerabilities and contribute to the development of more effective disaster response and mitigation strategies. The findings are expected to provide valuable insights for policymakers, engineers, and urban planners, supporting the development of best practices to enhance the resilience of road and bridge infrastructure against future extreme weather events.

2. METHODS

The study employed secondary research methods and a case study approach. The document analysis included preliminary assessment reports of road sections and bridges affected by the flood, which contained information on the extent and nature of the damage, initial repair recommendations, and assessments of the impact of destruction on the functionality of the transport infrastructure. The data from these reports were entered into a database and subsequently analyzed statistically using SPSS software. Descriptive statistics and frequency distributions were applied, enabling the identification of dominant types of damage, their frequency of occurrence, and the assessment of the necessity for repair actions.

Additionally, the study utilized a case study approach, focusing on a detailed analysis of four cases of transport infrastructure severely affected by the flood – two road sections and two bridges that suffered significant damage during the September flood. To visualize and conduct a spatial analysis of the flood-affected areas, spatial maps were developed using QGIS software. The analysis of geographical data allowed for the determination of the scale of damage in different areas and facilitated the identification of regions requiring urgent intervention.

3. THE NATURAL DISASTER STATE IN SOUTHWESTERN POLAND IN 2024

The Central European flood that occurred in September 2024 also left its mark on Poland. The massive flood affected four voivodeships: Silesian, Opole, Lower Silesian, and Lubusz. Due to the dramatic nature of the disaster, which caused widespread destruction, on September 16, 2024, the Council of Ministers, based on the Regulation of the Council of Ministers of September 16, 2024, declared a state of natural disaster in the flood-affected areas [26]. The number of affected areas increased daily until October 9, 2024, when the final regulation added one more municipality to the disaster zone [27]. These regulations were repealed a week later – on October 16, 2024 – under the Regulation of the Council of Ministers of October 15, 2024 [28].

In total, the state of natural disaster covered 310 municipalities. Fig. 1 presents the areas affected in the southwestern part of Poland.

As mentioned before, the state of natural disaster ultimately covered 310 municipalities, home to a total of 3,104,571 residents. The most populous cities within the disaster-affected area were: Bielsko-Biała (Silesian Voivodeship) – 165,127 inhabitants, Wałbrzych (Lower Silesian Voivodeship) – 99,463 inhabitants and Legnica (Lower Silesian Voivodeship) – 91,335 inhabitants [29].

The southwestern region of Poland is characterized by its upland and mountainous terrain, which results in a dense network of watercourses and other surface water forms. The largest rivers in the analysed area are the Oder (Odra), Vistula (Wisła), Nysa Kłodzka, and Lusatian Neisse (Nysa Łużycka). With the exception of the Vistula, which has its own basin, these rivers belong to the Oder basin and are part of the Baltic Sea drainage system.

According to the conducted analyses, the disaster-affected area includes 134 rivers with a total length of 4,110 km and streams extending over 36,296 km. Fig. 2 presents the hydrographic network of the study area, as well as the elevated surface water levels resulting from last year's flood [30]. Additionally, a buffer zone has been delineated on the map to identify areas most affected by the flood's consequences.

The area covered by the state of natural disaster has a well-developed road network, including national roads (motorways and expressways), regional (voivodeship) roads, county roads, and municipal roads. The most important road sections passing through this area include the motorways A1, A2, A4, and A18, as well as the expressways S1, S3, and S8.

The total length of the road network in the disaster-affected area is 29,748 km, with the largest share belonging to municipal roads (14,654 km), which play a crucial role in ensuring local accessibility. The second-longest category is county roads (10,095 km), connecting towns within counties. Voivodeship roads total 3,175 km and serve a regional function, while national roads, the shortest in the network (1,824 km), act as the primary interregional routes. The dominance of local roads, such as municipal and county roads, highlights their essential role in servicing the flood-affected areas. At the same time, motorways and expressways play a key role in maintaining transit and interregional traffic flow. Fig. 3 presents the map of the road network in the area affected by the state of natural disaster.

Due to the high density of rivers, streams, and watercourses, the flooded area contains a significant number of bridge structures. Based on the BDOT10k database [31], bridges located on national, voivodeship, county, and municipal roads, as well as footbridges, were identified.

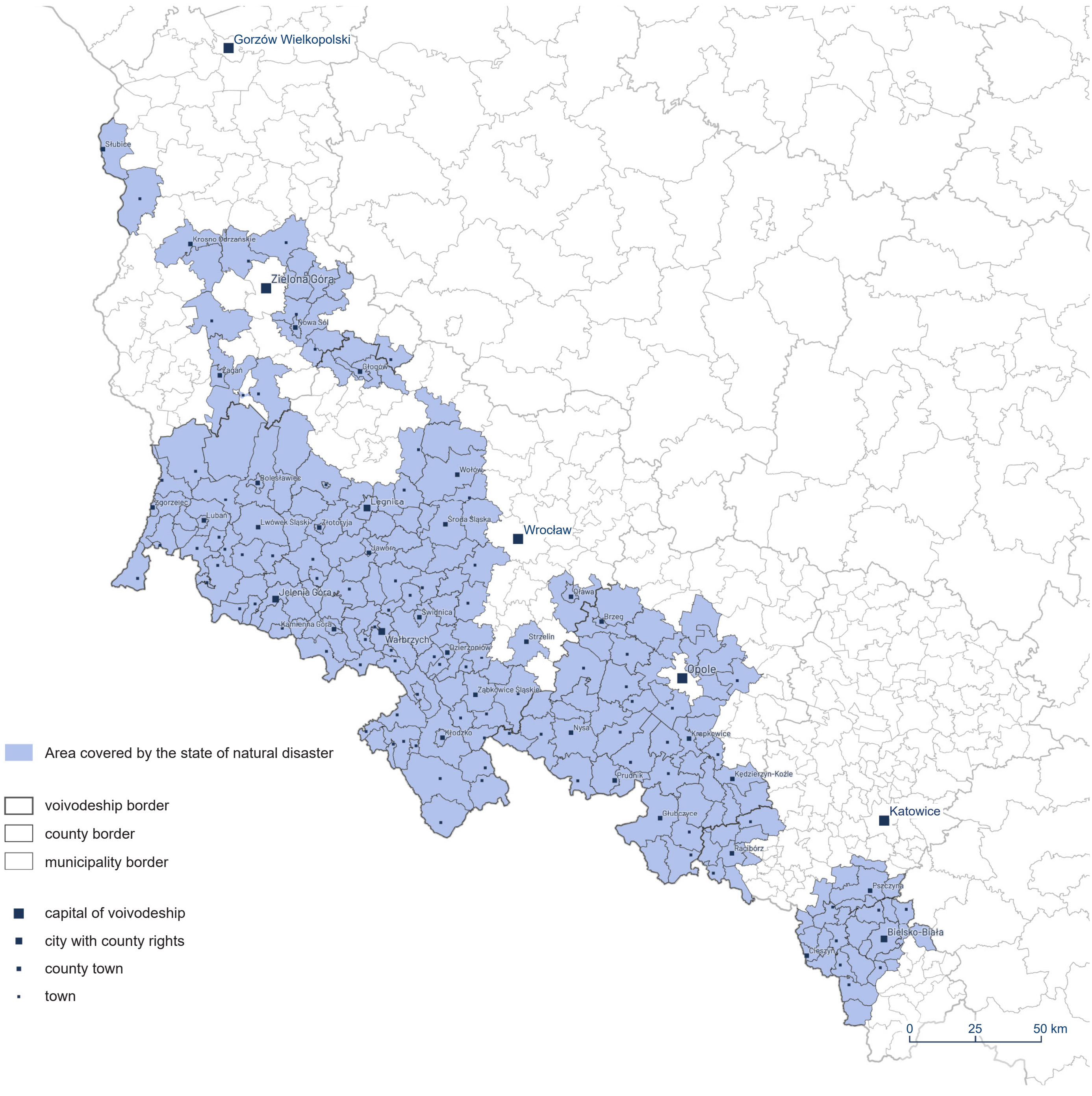

Fig. 1. Administrative map of south-western Poland with marked areas affected by the state of natural disaster

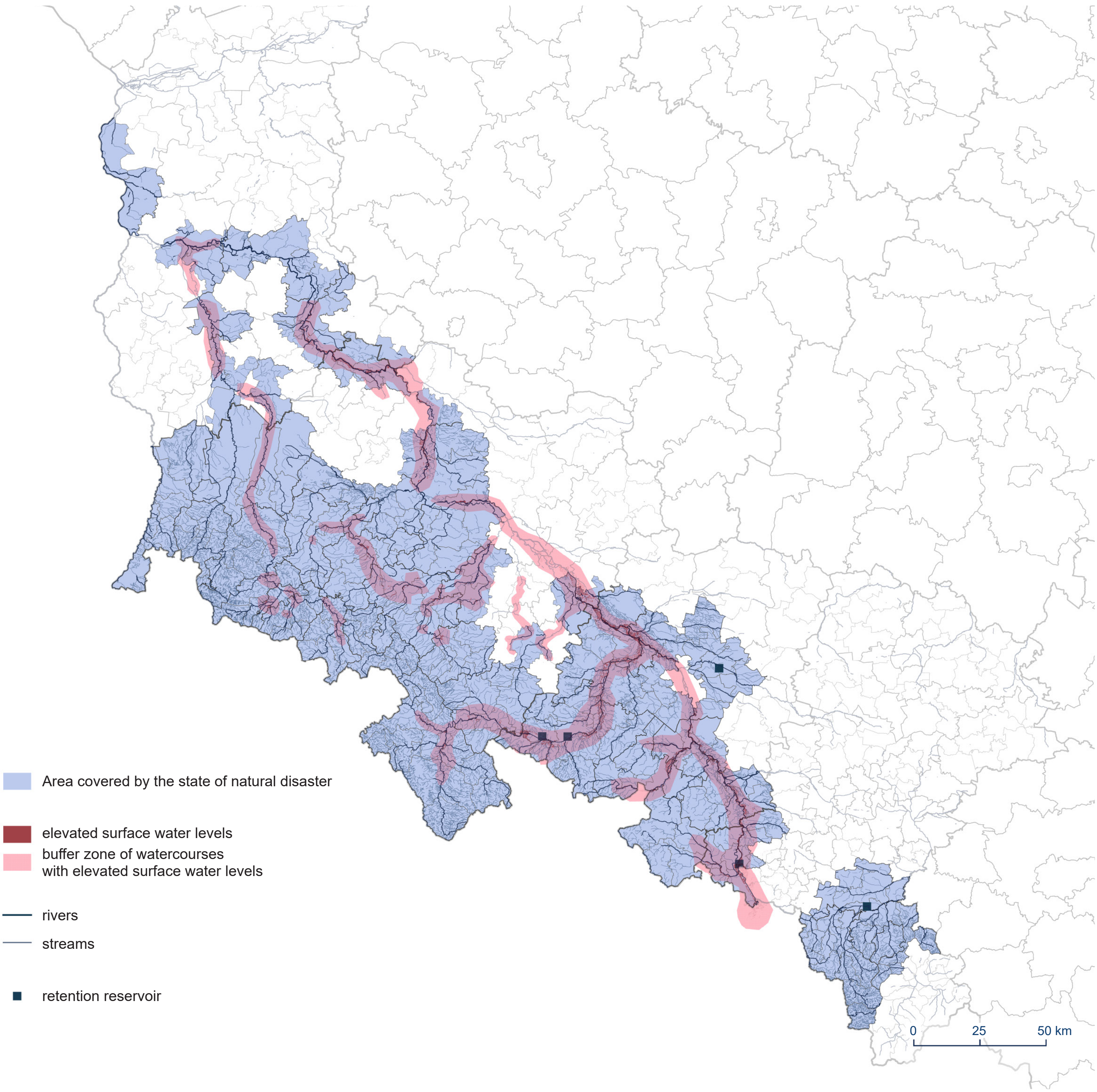

Fig. 2. Map of hydrological conditions

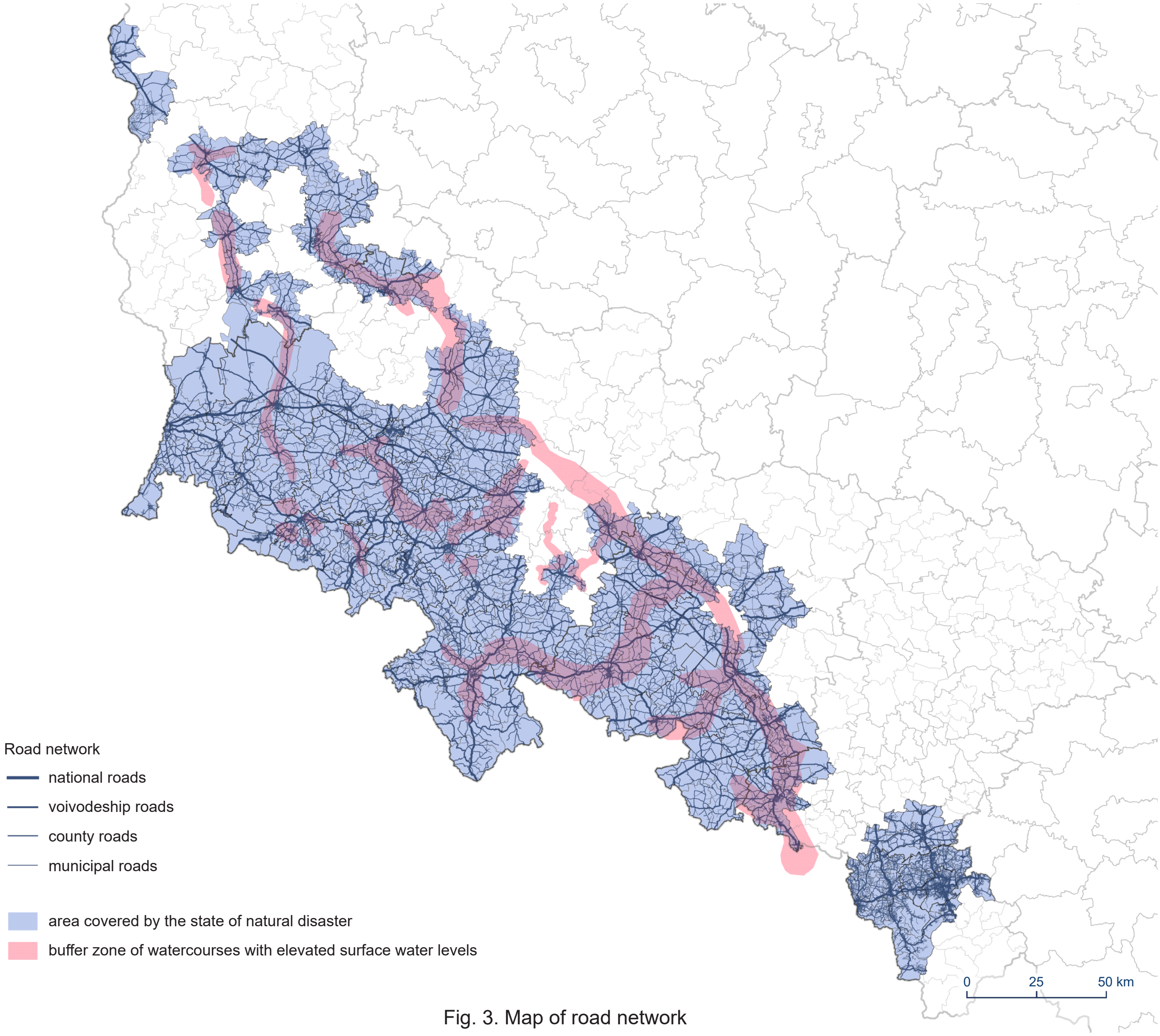

Fig. 3. Map of road network

Research findings indicate the following:

- National roads contain 327 bridges with a total length of 14.6 km, playing a crucial role in maintaining continuity on major transport routes.
- Voivodeship roads have 546 bridges spanning 11.3 km, highlighting their importance in regional connectivity.
- County roads have the highest number of bridges, with 1,934 structures covering a total length of 22.6 km, reflecting an extensive infrastructure network connecting towns within counties.
- Municipal roads include 1,780 bridges with a combined length of 18 km, demonstrating a well-developed local infrastructure.

Although bridges on national roads are fewer in number, they have the largest average length, reflecting their significance for transit traffic. Bridge infrastructure plays a key role in ensuring transport accessibility, particularly in the disaster-affected area, where its functionality is essential for mobility and the transport of aid. Fig. 4 presents the road and pedestrian bridges location in the area affected by the state of natural disaster.

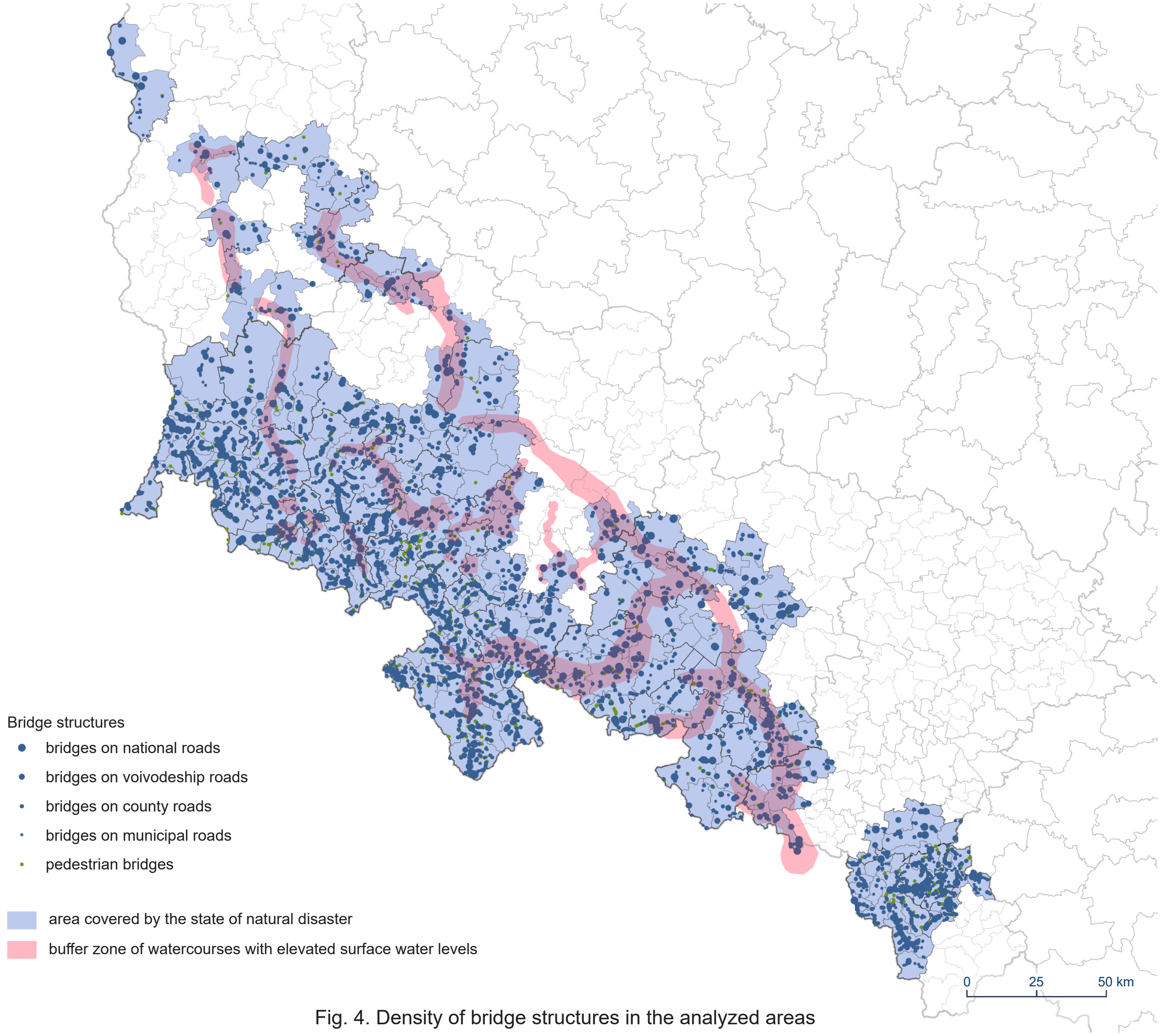

Fig. 4. Density of bridge structures in the analyzed areas

4. THE PROCESS OF ASSESSING THE TECHNICAL CONDITION OF BRIDGES AND ROADS

As part of the Institute's organizational structure, a five-member coordination team was established specifically to manage the process of assessing the technical condition of bridges and roads. The main task of this team was to ensure effective communication, integration of actions across different organizational units, and monitoring of work progress, which was crucial for the smooth execution of the entire process. To support ongoing operations, the team was assisted by additional personnel, including: 1) work time and cost monitoring specialists, responsible for tracking and recording expenses related to the task, including travel, materials, and equipment costs, 2) logistics support specialists, who provided technical assistance for field inspection teams, organizing transport and necessary equipment (they were also responsible for booking accommodations), 3) personnel handling inspection reports, including report authorization, as well as office, communication, and information management staff.

An important factor that significantly improved the efficiency and speed of flood damage assessment was the collaboration between the Institute, the Polish Chamber of Civil Engineers (PIIP) and the Polish Bridge Engineers Association (ZMRP). This unprecedented initiative enabled the effective use of the expertise and practical experience of professional engineers during a crisis situation. Owing to exemplary work organization and precise management of the ongoing flood response, the Institute was able to assign specific tasks to a group of volunteer engineers who actively contributed to the assessment of flood effects.

Fig. 5 illustrates the main workflow of activities related to the assessment of structures, whose technical condition was evaluated during inspections. Operationally, the diagram represents the sequence of physical and informational actions performed at various stages, enabling progression through subsequent phases of the process. The task began with the launch of two separate information campaigns: one for bridge inspections and the other for road inspections. These campaigns targeted local government units located in areas affected by the state of natural disaster.

Fig. 5. Diagram of the process for assessing the technical condition of bridge structures and roads

In response to these campaigns, the Institute received requests for technical assessments of 620 bridge structures and 425 road sections, submitted by local government units from 45 municipalities. Data analysis showed that 81% of reported bridges and 68% of reported roads were from the Lower Silesian Voivodeship. The number of submissions from other voivodeships was relatively low and remained at a similar level, except for a higher number of road section reports from the Lubusz Voivodeship and bridge reports from the Opole Voivodeship.

The next stage involved registering submissions in the system and conducting verification procedures to ensure that the reported data was complete, accurate, and concerned public roads and engineering structures within disaster-affected areas. Following this, transport was organized for field inspections, prioritizing the urgency of submissions and the availability of field teams.

The field inspections were carried out by 2-, 3-, or 4-person field teams consisting of engineers and technicians. Their main tasks included: 1) technical condition assessment – verifying the structural integrity of objects in terms of damage, deformations, and other signs of deterioration, 2) technical documentation – preparing detailed descriptions and photographic documentation, 3) identification of intervention priorities – pinpointing locations requiring immediate repair actions or further in-depth diagnostic studies. These activities formed the basis for decision-making in the next phases of the process, including data collection, analysis, and reporting of results to various stakeholders. At this stage, all collected data was systematized and analysed. The process involved data consolidation and entry into the road and bridge infrastructure database. The information was processed and analysed using geographic information systems (GIS) and applications such as Google Earth, enabling precise object localization and identification of key issues.

5. ASSESSMENT OF THE TECHNICAL CONDITION OF BRIDGE STRUCTURES

The task of assessing the technical condition of road engineering structures damaged by floods or landslides in September 2024 was carried out between September 23 and December 15, 2024. As part of this task, inspections of 483 bridge structures were conducted.

The technical condition assessment was based on a preliminary inspection report, whose key element was determining the necessary follow-up actions based on the observed damage. The detailed analysis included assessments of abutments and piers, load-bearing elements of spans, roadway surfaces, access roads, surroundings, and other identified damage.

The bridge assessment categories, in accordance with the adopted protocols, were divided into four main groups. The largest portion, 67.49%, consisted of structures approved for continued use under current conditions, classified as category A, meaning no immediate intervention was required. The next group, making up 7.45% of structures classified as category B, included those approved for limited use, indicating that certain operational restrictions needed to be implemented. Another 10.76% of structures were classified as category C, meaning they were not approved for use and required repairs or reconstruction before they could be safely utilized again. The last category, comprising 7.66% of cases classified as category D, consisted of structures in such poor condition that they requires demolition or the construction of a temporary crossing. Among these assessments, 11.80% of structures were classified as category E, indicating the need for a detailed expert assessment.

The spatial distribution of the assessed bridge structures along with their assigned categories is presented in Fig. 6. Data analysis indicates that the largest number of category C and D structures is located in Lower Silesian Voivodeship, the area most affected by the September flood.

In category B, over 67% of the structures were located in Lower Silesian Voivodeship, more than 16% in Opole Voivodeship, and over 14% in Silesian Voivodeship, while only 2% were in Lubusz Voivodeship. The majority of structures in this category were bridges (75.50%), followed by pedestrian footbridges (10.20%), access footbridges (10.20%), and culverts (4.10%). The study results indicate that over 77% of the structures classified in this category exhibited multiple damages, while in the remaining cases, only minor technical defects were found. Regarding structural damage, over 65% of assessed structures showed an unsatisfactory condition of abutments and piers, with more than 4% classified as very poor, indicating the need for urgent repairs or modernization to ensure safety and continued use. An unsatisfactory condition of the load-bearing spans was found in 53% of structures, with 6% rated as very poor.

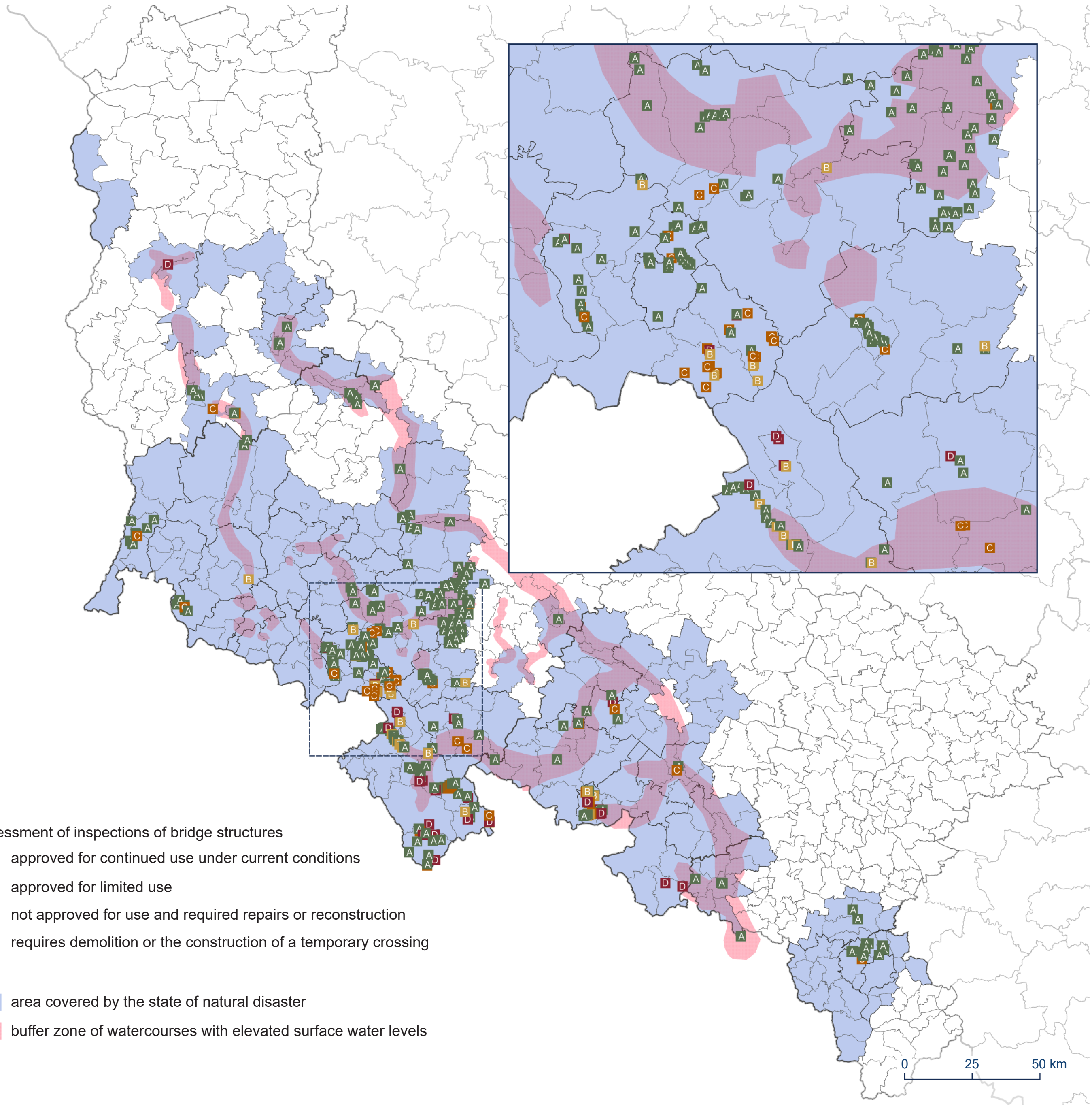

Fig. 6. Spatial distribution of bridge structures with assigned rating categories

This suggests that the main structural components responsible for transferring loads from the roadway to the supports showed significant damage, deformations, or weakening.

Further data analysis revealed that in 38.80% of cases, both issues occurred simultaneously, meaning that both the abutments and piers, as well as the load-bearing spans, were in a state of significant operational wear. This situation could considerably increase the risk of further structural degradation, potentially leading to the need for comprehensive repairs or even complete reconstruction of some structures. In over 77% of the inspected structures, no negative impact of the September flood was recorded on the road surface condition. Similarly, for access roads, 88% of structures were rated positively, with 36.7% receiving a good rating and 4.1% rated as very good. Additionally, in 15 cases, other damages were noted, most commonly related to broken railings and damaged riverbeds.

Analysing the location structure of category C objects, which required a complete closure until comprehensive renovation, more than 67% were in Lower Silesian Voivodeship, nearly 19% in Opole Voivodeship, 8% in Lubusz Voivodeship, and over 5% in Silesian Voivodeship. In terms of structure type, 65% of assessments concerned bridges, 27% pedestrian footbridges, and 8% culverts. In 86.5% of these structures, multiple damages were identified, nearly 10% more than in category B structures. In almost one in four inspections, the necessity for a more detailed technical assessment was confirmed. Considering the type of damage, the study results indicate that over 78% of structures exhibited an unsatisfactory condition of abutments and piers, with 38% rated as very poor, nearly 34% more than in category B. Additionally, most structures (54%) had an unsatisfactory condition of the load-bearing spans, with almost 30% classified as very poor. For comparison, in category B, only 6% of inspections found a very poor condition of the load-bearing spans.

A total of 46% of structures exhibited both an unsatisfactory condition of abutments and piers and an unsatisfactory condition of the load-bearing spans, indicating serious structural issues. This combination of damages suggests a significant reduction in load-bearing capacity and structural stability, which, if used, could pose a serious risk to users. In more than 20% of cases, additional damages were identified, such as broken railings, damaged riverbeds, and deteriorated riverbank reinforcements.

Fig. 7 presents the characteristics of a sample bridge structure classified as category C. Inspection results show that the bridge in Kłodzko suffered significant damage due to the flood, requiring its immediate closure and a more detailed technical assessment. Key repair actions include stabilizing the foundation of the piers, repairing the displaced load-bearing structure, and replacing the railings to ensure pedestrian safety. Urgent intervention by the road authority is necessary to carry out the required construction and maintenance work.

Inspection Results:

Condition of abutments and piers: Scouring of the pier on the Wodna Street side – foundation expertise required, damage to reinforcements near abutments and piers.
Condition of the load-bearing structure of spans: Displacement of the load-bearing structure by 2-5 mm downstream – possible span rotation, requiring expertise and repairs. Local damage to the steel girder due to impact from debris carried by the water.
Condition of the roadway surface: No visible flood-related damage.
Condition of access roads: Damaged barriers on the access road from Wodna Street.
Condition of the surrounding area: Deformed and damaged railing – urgent replacement required. Lack of pedestrian safety measures necessitates the closure of the structure. Deformed and damaged embankments and riverbed reinforcements.

Decision: the bridge is not approved for use, a technical assessment of the pier foundation and load-bearing structure is required, repair work should be carried out, including pier stabilization, load-bearing structure repairs, and railing replacement.

Fig. 7. Description of a bridge structure case with category C

Structures classified as category D, indicating the need for demolition and the construction of a temporary crossing, were primarily located in Lower Silesian Voivodeship (78.6%), less frequently in Opole Voivodeship (17.9%), and least commonly in Silesian Voivodeship (3.6%). In most cases, this classification applied to bridges (67.9%), followed by pedestrian footbridges (28.6%) and access footbridges (3.6%). Almost all inspected structures exhibited multiple damages (96.4%), with the vast majority (71.42%) being destroyed and requiring reconstruction. The condition of abutments and piers was rated negatively in 96.4% of cases, with 75% classified as very poor. A similar situation was observed for the load-bearing spans – 89.3% of structures received a negative rating, with 75% classified as very poor. In 75% of the assessed structures, the road surface condition was also rated negatively, with 60.7% classified as very poor. Damage related to access roads was slightly less frequent – negative ratings were given in 64.3% of cases, of which 35.7% were classified as very poor. Additionally, five cases recorded other severe damages, including destroyed riverbeds, damaged bank reinforcements, and compromised railings.

Fig. 8 presents the characteristics of a bridge structure classified as category D. The technical assessment of the bridge in Ołdrzychowice Kłodzkie indicated severe flood damage, making further use of the structure impossible. The decision to demolish and build a temporary crossing is essential for ensuring safety and maintaining regional connectivity. Preventive measures should be considered in future projects to enhance the durability of the new structure in the face of extreme weather events.

Inspection Results:
Main piers: Damaged, deformed, and undermined.
Load-bearing structure: Completely destroyed, with the bridge structure displaced from its support points.
Road surface: Bridge entirely destroyed.
Bridge approaches: Locally washed out and deformed.
Surroundings: Cleanup work is required, including removing the damaged load-bearing structure.
Decision: Complete demolition of the bridge is necessary due to extensive damage. A temporary crossing should be arranged to maintain connectivity. A hydrotechnical analysis should be conducted to assess risk factors for future projects. It is recommended to modernize or rebuild the structure in a way that enhances its resilience to future flooding.

Fig. 8. Description of a bridge structure case with category D

6. ASSESSMENT OF THE TECHNICAL CONDITION OF ROAD SECTIONS

The assessment of public roads damaged by floods or landslides in September 2024 was conducted between October 1 and December 15, 2024. As part of this task, 278 road sections were inspected.

The technical condition assessment was based on a preliminary post-flood road inspection report, whose primary purpose was to determine the necessary follow-up actions based on observed damage. The analysis included an assessment of pavement condition, road shoulders, culverts, road equipment, traffic safety devices, and other damage within the roadway corridor.

The assessment categories for road sections, as defined in the protocols, are as follows. Category A includes 76.62% of road sections, indicating they are approved for continued use under existing conditions. Category B covers 18.34% of road sections, allowing for continued use with recommended monitoring of specific segments. Category C accounts for 1.80% of road sections and permits limited use. Category D, covering 1.40% of road sections, indicates that the road is not approved for use and requires repairs or reconstruction. Category E, also at 1.80%, means that the road requires demolition or the construction of a temporary road. Additionally, 48 road sections, representing 17.26%, were classified as Category F, requiring a detailed expert evaluation.

The spatial distribution of road sections and their assigned assessment categories is presented in Fig. 9. The analysis shows that the highest number of road sections in categories D and E are located in Lower Silesian Voivodeship, the area most affected by the September flood.

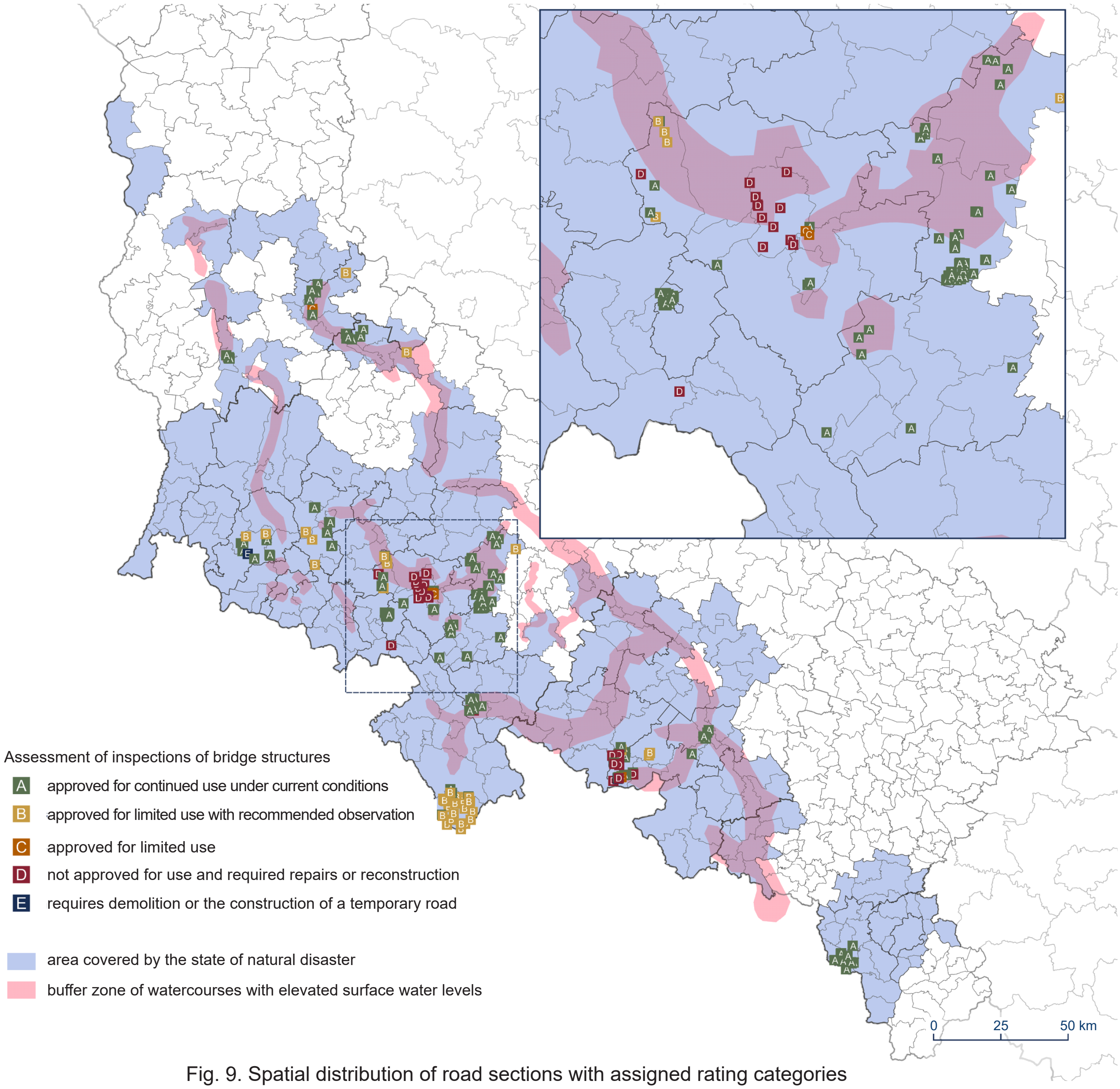

Fig. 9. Spatial distribution of road sections with assigned rating categories

In category B, over 82% of road sections were in Lower Silesian Voivodeship, more than 16% in Opole Voivodeship, and less than 6% in Lubusz Voivodeship. The majority of roads in category B were municipal roads (88.5%), followed by county roads (9.6%), and regional roads (1.9%). Regarding pavement type, 86.5% of road sections had hardened surfaces, including 59.6% with improved hard surfaces. In the remaining cases, unpaved roads were present. The most common pavement types were asphalt (44.2%), crushed stone (25.0%), bituminous (9.6%), and gravel (7.7%). The inspected road sections varied significantly in length. The average length was 716.98 m, with a standard deviation of 1041.69 m.

The study results indicate that over 48% of the roads in this category showed multiple damages, while in 50% of cases, only minor technical defects were found. One case of partial road destruction was recorded. Most road sections, 65.4%, require additional assessment due to uncertain damage severity and the need for further analysis. A total of 84.6% of the inspected roads had damage caused by the flood. In 11.5% of cases, the cause of damage could not be definitively determined, while in 3.8%, the damage was not related to the flood.

Regarding the identified damages, less than 27% of the inspected road sections exhibited an unsatisfactory pavement condition, including less than 2% classified as very poor. A similar distribution was observed for road shoulders. The study results indicate that one in four assessed sections had an unsatisfactory shoulder condition. Deterioration of culverts due to flooding was less common, observed in only 15.4% of the inspected road sections. In 7.7% of inspections, an unsatisfactory condition of road equipment was noted. Inspectors frequently reported additional damages within the roadway corridor, most commonly involving eroded roadbeds and clogged or blocked drainage systems.

Road sections classified as Category C, meaning they could be used with limited access, were 50% located in Lower Silesian Voivodeship and 25% in Opole and Lubusz Voivodeships. In 75% of cases, these were municipal roads, while the remaining sections were county roads. Regarding pavement type, improved hard surfaces dominated (75%), with 50% being asphalt and the remainder bituminous surfaces. These roads suffered greater damage due to the flood, as reflected in their rating. In 75% of cases, partial destruction of the road was recorded, while in 25%, extensive damage was observed. In all cases, the cause of damage was the flood, which had the most significant impact on the pavement condition. Data shows that 75% of the assessed road sections exhibited an unsatisfactory pavement condition, with 25% classified as very poor, potentially affecting structural integrity. However, no major damage was reported regarding shoulders, culverts, or road equipment. Most assessment reports included additional remarks indicating the need for pavement replacement, tree inspections along the road, and the presence of sinkholes.

The next category included road sections classified as Category D, indicating they were not approved for use and required repairs or reconstruction. All category D sections were located in Lower Silesian Voivodeship. Similar to previous cases, 75% were municipal roads, while the remaining sections were county roads. Regarding pavement type, improved hard surfaces dominated (75%), with 50% being asphalt and the rest asphalt concrete. The study confirmed that all road sections sustained damage due to the September flood. In 75% of cases, partial road destruction was recorded, while minor damages were observed in the remaining cases.

Compared to the previous categories, a broader range of flood-related damages to road conditions was observed. All assessed road sections had an unsatisfactory pavement condition, with 75% rated as very poor. Similarly, 75% of inspections reported an unsatisfactory condition of road shoulders, with 50% classified as very poor. Additionally, 25% of cases exhibited unsatisfactory culvert conditions. However, the flood did not significantly impact road equipment. Most inspected road sections also exhibited other damages, such as retaining wall failures, parking lot surface damage, and road crown erosion.

Fig. 10 presents the characteristics of a road section classified as Category D. The road section in Rybnica Leśna suffered severe damage due to extreme weather conditions, resulting in slope failure, pavement destruction, and shoulder collapse. Despite the road authority's attempt to secure the damaged area by filling it with aggregate, the appearance of cracks indicates continued instability of the roadbed. Further use of the road is impossible without repairs. The priority action should be restoring slope stability through the reconstruction of the retaining wall.

Inspection Results:
Pavement: Completely destroyed over a length of approximately 12 meters and a width of 1.3 meters.
Shoulders: Completely destroyed.
Culverts: No culvert present at the damaged site.
Retaining wall: The existing stone retaining wall was destroyed in sections before and after the damaged area.
Traffic safety devices: Energy-absorbing barriers remain in good condition.
Decision: the retaining wall must be reconstructed to ensure road stability, further expert evaluation is required to determine the detailed scope of repairs.

Fig. 10. Description of the road section with a rating of D

Inspection Results:
Pavement: The river eroded the slope along a 65-meter section, leading to the destruction of one traffic lane.
Shoulder: The shoulder on the river side, where a parking area was located, was completely destroyed.
Culverts, Traffic safety devices, other damages: Not applicable to this section.
Decision: Road reconstruction/repair is necessary to restore full traffic flow, if repairs are delayed, a temporary single-lane road must be built, an additional expert assessment should be conducted to determine methods for stabilizing the slope and preventing further degradation.

Fig. 11. Description of the road section with a rating of E

Road sections classified as category E, indicating the need for road demolition or the construction of a temporary road, applied exclusively to municipal roads. The majority of these roads (75%) were located in Opole Voivodeship, while the remaining 25% were in Lesser Poland Voivodeship. Similar to category D, 75% of these roads had an improved hard surface, while the rest were unpaved. The study results indicate that all road sections were affected by the September flood. In 50% of cases, the roads were completely destroyed, while in the remaining cases, partial destruction was recorded. The extent of the damage was significant: in every case, pavement damage was observed, with 75% classified as very poor. Additionally, 50% of road sections had poor shoulder conditions, and in 25% of cases, both culverts and road equipment were rated as unsatisfactory. Other damages were also identified in 50% of the assessed sections. In one case, a longitudinal crack in the road was observed, potentially indicating further slope movement. In another case, slope undercutting and the destruction of one traffic lane were recorded.

Fig. 11 presents the characteristics of a road section classified as Category E. The assessed road section in Prudnik has suffered severe damage due to flooding. It is necessary to carry out repairs, rebuild the damaged traffic lane, and conduct an additional expert assessment. The roadside on the river side has ceased to exist, and the road can only be used to a limited extent. Therefore, it is recommended to construct a temporary road and conduct further analyses to develop a repair plan.

7. CONCLUSIONS

The Road and Bridge Research Institute played a key role in assessing the technical condition of road and bridge infrastructure following the natural disaster. Through the coordinated efforts of a team of experts, detailed inspections of 483 bridge structures and 278 road sections were conducted, enabling the rapid identification of damage and the development of priority repair recommendations. The Institute's research findings provide valuable insights to support decision-making processes related to reconstruction and future preventive measures aimed at protecting road infrastructure from the effects of flooding.

Based on the analysis and results of the technical inspections of roads and bridges in the regions affected by the 2024 flood, the following key conclusions can be drawn:

1. Floods are among the most severe natural disasters impacting road infrastructure. Their effects include both direct damage to bridges and roads and indirect consequences such as disruptions in transport mobility. Infrastructure destruction leads to reduced accessibility, increased transportation costs, and difficulties in economic and social functioning in flood-affected areas.
2. The process of assessing the technical condition of bridges and roads should be an integral part of a long-term road infrastructure management strategy in crisis situations. Further improvements, such as automating data collection, using drones for inspections, and developing digital predictive models, can significantly enhance the efficiency and accuracy of future assessments.
3. The analysis of technical condition assessments revealed that road infrastructure sustains varying degrees of damage, ranging from minor cracks and weakened surfaces to complete bridge collapses and road embankment washouts. Structures located near rivers and areas with high water flow dynamics are particularly vulnerable to destruction.
4. Inspection results clearly indicate the need for systematic preventive measures and reinforcement of bridges and roads in flood-prone regions. The application of modern technologies, such as strengthening bridge foundations, using erosion-resistant materials, and constructing scour protection systems, can significantly reduce the risk of future damage.
5. Considering the scale of flood-related destruction, efficient resource management for infrastructure reconstruction is crucial. Cost optimization may include prioritizing repair efforts, using modern and durable construction technologies, and integrating monitoring systems to enable early threat detection and minimize future losses.
6. To improve the resilience of road infrastructure in crisis situations, it is essential for road administrations at all levels to implement a formal classification of roads based on their criticality during emergencies. The proposed categories include: (i) permanently passable roads, designed according to guidelines with a defined acceptable risk of exceedance; (ii) flooded but water-resistant roads, which can be used immediately after water recedes; (iii) remaining roads, which may become temporarily unusable during and after a flood event. Such a classification will support more effective emergency

response planning, resource allocation, and climate-resilient infrastructure design.

The study results provide critical insights for policymakers, engineers, and urban planners by highlighting the vulnerabilities of road and bridge infrastructure to extreme weather events. By identifying patterns of damage, assessing the effectiveness of current mitigation strategies, and proposing targeted improvements, this research supports the development of best practices aimed at enhancing infrastructure resilience, optimizing resource allocation, and reducing long-term maintenance costs in the face of future climate challenges.

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Skutki powodzi: ocena wpływu na drogi i mosty z uwzględnieniem doświadczeń Instytutu Badawczego Dróg i Mostów

Streszczenie: Artykuł przedstawia studium przypadku działań Instytutu Badawczego Dróg i Mostów związanych z oceną stanu technicznego infrastruktury drogowo-mostowej na obszarach dotkniętych klęską żywiołową w 2024 roku. Szczególny nacisk położono na charakterystykę procesu oceny oraz analizę wyników przeglądów na podstawie 761 wstępnych protokołów kontrolnych. Powodzie, jako jedno z największych zagrożeń dla infrastruktury drogowej, powodują zarówno bezpośrednie zniszczenia, jak i skutki pośrednie, wpływając na transport oraz powiązane sektory. W artykule omówiono skalę zniszczeń, rozkład przestrzenny uszkodzeń oraz kategorie ocen stanu technicznego dróg i mostów. Wyniki badań podkreślają konieczność wdrażania skutecznych środków ochrony infrastruktury w celu zwiększenia jej odporności na przyszłe klęski żywiołowe. Wskazują również, że ocena stanu technicznego obiektów mostowych i drogowych powinna stanowić integralną część długofalowej strategii zarządzania infrastrukturą drogową w sytuacjach kryzysowych. Wnioski mogą stanowić cenne źródło wiedzy dla decydentów, inżynierów oraz planistów miejskich, wspierając rozwój dobrych praktyk w zakresie zwiększania odporności infrastruktury drogowo-mostowej na przyszłe ekstremalne zjawiska pogodowe.

Słowa kluczowe: drogi publiczne, powódź, ocena stanu technicznego, obiekty inżynieryjne.