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Enhancing Infrastructure Resilience Through Emergency Bridge Reconstruction: Lessons from the 2023 Tsarevo Floods

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Extreme rainfall events on 4–5 September 2023 caused severe flooding in the municipality of Tsarevo (Bulgaria), resulting in significant damage to local infrastructure, including the destruction of multiple bridge structures over the Cherna River. The event led to substantial material losses and human casualties, prompting the declaration of a partial state of emergency. The rapid increase in river and stream water levels caused extensive erosion of riverbanks, undermining reinforced-concrete abutments and piers, flooding urbanized areas, and depositing large quantities of debris, sediments, and vegetation within the riverbeds.

This paper presents the emergency reconstruction measures undertaken to restore the affected bridge structures and adjacent infrastructure. The main objectives include: (1) improving the long-term structural performance and load-bearing capacity of the new bridge designs; (2) ensuring safe and reliable traffic conditions and enhanced user comfort; (3) increasing hydraulic capacity to prevent future extreme overflow events; and (4) achieving an environmentally harmonious and aesthetically coherent river corridor.

The study discusses the engineering considerations, design criteria, and risk-mitigation strategies applied during the reconstruction process. The proposed solutions aim to enhance the resilience of critical infrastructure to future hydrological extremes, contributing to improved regional safety and sustainable development.

Keywords: Emergency bridge reconstruction, Infrastructure resilience, Structural reliability, Hydraulic capacity, Flood damage assessment.

1. Introduction

Floods remain one of the most significant threats to transport infrastructure, especially where bridge systems intersect small, steep, and rapidly responding catchments. In such settings, the combination of intense rainfall, high flow velocities, limited floodplain storage, and debris transport can quickly transform a local hydrological event into a multi-asset infrastructure failure. Bridges are particularly vulnerable because they concentrate structural, hydraulic, geotechnical, and operational risks in a single location. When a bridge fails, the consequences extend beyond direct material loss and often include traffic interruption, delayed emergency response, disruption of utility crossings, and reduced community resilience.

Fig. 1. Locations of the bridges (source: Google maps)

The flood event of 4–5 September 2023 in the municipality of Tsarevo, on the southern Bulgarian Black Sea coast, is a representative example of this type of compound failure.

The flood event of 4–5 September 2023 in the municipality of Tsarevo, on the southern Bulgarian Black Sea coast, is a representative example of this type of compound failure. According to the project documentation prepared after the event, intense rainfall caused a rapid rise in rivers and gullies, substantial erosion of riverbanks, undermining of abutments and supports, inundation of urbanised areas, and accumulation of trees, sediment, and waste within the riverbeds. The scale of damage led to a partial state of emergency and required immediate intervention on multiple bridge structures over the Cherna River – Fig. 1.

This paper is positioned as a resilience-oriented engineering case study of the emergency reconstruction of flood-damaged bridge infrastructure in Tsarevo after the 2023 event. The scientific contribution lies in demonstrating how post-flood damage assessment, hydrological and hydraulic re-evaluation, and reliability-oriented structural redesign can be combined under emergency conditions to improve the future robustness and recoverability of critical infrastructure. The hydraulic analyses are therefore used not as an end in themselves, but as the technical basis for identifying the main failure drivers—insufficient hydraulic capacity, debris accumulation, scour, and bank instability—and for selecting reconstruction measures that improve structural safety and functional continuity. In this sense, the paper should be understood primarily as a resilience case study with a hydraulic-analytical backbone, rather than as a purely hydraulic reconstruction study or a formal probabilistic reliability-resilience modelling exercise.

2. Study area and flood context

The analysed structures are in the urban territory of Tsarevo, Burgas region, along the lower reach of the Cherna River before its outflow into the Black Sea. The hydrological studies used in the reconstruction projects define the catchment upstream of the bridge sites as approximately 9.63 km2, with a main flow length of about 7.5 km. The basin is situated in the Strandzha area, with hilly terrain, elevations up to roughly 380 m in the contributing area, around 70% forest cover, and the remainder split between agricultural and urbanised land. The combination of short concentration time, steep slopes, and urban exposure makes the area sensitive to flash-flood processes. An important constraint for the analysis is the lack of a hydrometric station within the basin. The project documentation explicitly states that the Cherna River is hydrologically under-studied at the project locations and that the flood characteristics had to be determined using analogy, empirical and transfer formulae, and regional graphical dependencies. The maximum flows were ultimately estimated using the established method of Prof. Gerasimov, based on rainfall information and basin characteristics. For the examined bridge sites, the resulting characteristic discharges were identical: $Q_{5\%}$ = 37.11 m3/s, $Q_{1\%}$ = 81.08 m3/s, and $Q_{0.1\%}$ = 211.01 m3/s. These values formed the basis for the hydraulic design of the bridges.

Fig. 2. Catchment area of the extent to the project site

The regulatory basis used in the designs is also important from a resilience perspective. For bridges and river training works in urbanized areas, the documents require design for the 1% annual probability of exceedance (AEP) flood and check for the 0.1% AEP flood. The Tsarevo area is additionally classified in flood-risk planning documents as an area with significant potential flood risk (APSFR), where flash flooding from the Cherna River is specifically recognised. This means the reconstruction works were not developed in an ordinary design setting, but in a location already identified as highly exposed to hydrological extremes – Fig. 2.

3. Post-flood damage assessment

The post-event technical assessments at all three bridge sites led to the same essential conclusion: the existing structures were no longer suitable for operation and had to be replaced rather than repaired. The documents describe the bridges as being in critical condition, with defects and destruction affecting their overall serviceability, Load-bearing capacity, and traffic function. In several cases the technical conclusion is stated as "complete destruction," which justified emergency reconstruction in urgent order.

At "White shore", the damaged bridge had been a single-span reinforced-concrete structure with a clear opening of only about 5.0–6.0 m, carrying a roadway and two pedestrian sidewalks. The project assessment concluded that the structure had inadequate hydraulic capacity and could no longer serve as a safe support for the existing utility crossings. The hydraulic study further notes that the design flood passed with flooding of adjacent terrain and significant backwater, aggravated by the insufficient opening and by communication crossings located below the superstructure, which increased the risk of blockage by floating debris.

Fig. 3. Bridge – "White shore" – damages

At Mandrata, the pre-flood bridge was a single-span structure with a simple beam scheme and a composite concrete superstructure, with total superstructure length of 15.40 m and clear opening of about 14.0 m. It had no sidewalks and included suspended utilities. Despite its larger opening compared with "White Shore", the structure was still judged to be fully destroyed and hydraulically insufficient under the required flood scenarios. The studies also identified a need for riverbed cleaning, removal of sediment islands, and construction of retaining and wing-wall elements.

At the Coastal Alley site, the situation was even more complex because the bridge is located at the river mouth, where river flooding interacts with marine conditions. The damaged bridge was a two-span reinforced-concrete structure with openings not exceeding about 5.0 m.

Fig. 4. Bridge – "Mandrata" – damages

The hydrology report states that the Q1% flood overtopped adjacent terrain and the bridge approaches because of the inadequate opening and the low southern terrain. Owing to the river-mouth location, the hydraulic assessment also considered sea levels and wave-related effects, which adds an additional hazard component, not present at the upstream sites.

Fig. 5. Bridge – "Coastal Alley" – damages

Across the three sites, the damage mechanisms were therefore consistent: under-capacity bridge insufficient bridge clearance strong backwater, debris blockage potential, bank and bed erosion, undermining of structural supports, and loss of safe operational functionality. This common failure pattern is a central lesson of the Tsarevo event.

4. Hydrological and hydraulic assessment

To support reconstruction, the design team built a hydraulic model of the most downstream approximately 800 m long reach of Cherna River, encompassing the three affected crossings. The analyses were carried out by using one-dimensional HEC-RAS model under two main scenarios: existing/compromised conditions and design solution. The application of a one-dimensional hydraulic model was governed by the presence of two main factors - (1) temporal limitations, determined by the urgent need for site survey, design and construction works, (2) local site limitations, expressed by the dense seasonal vegetation and urban landshaft, preventing the application of affordable aerial survey techniques. The above factors obstruct the generation of a more extensive and detailed digital terrain model, that covers the wider valley floodplain and hence do not allow the application of a more complex hydraulic model.

The calculations were prepared for the characteristic flood discharges Q5%, Q1%, and Q0.1%, with the main design check focused on the 1% exceedance event and verification under the 0.1% event.

Coastal surge effects are accounted by using data for the maximum sea water levels (including wave set-up and run-up) at the coastal area of Tsarevo. This data originates from a national study, incorporated into the *National methodology for flood hazard and flood risk mapping* in Bulgaria. A downstream boundary condition, corresponding to a constant water level elevation was considered for all scenarios to assess the potential backwater effect of the sea water. The modelling results consistently showed that the existing configurations did not satisfy statutory requirements. At "White Shore", the Q1% flood produced significant backwater and flooding of surrounding terrain due mainly to the inadequate bridge opening and downstream constriction. The existing utility crossing at the bridge inlet further increased the blockage risk. At Mandra, the existing arrangement was also hydraulically deficient, while at the Coastal Alley site the Q1% event overtopped neighbouring terrain and approach areas – Fig. 6.

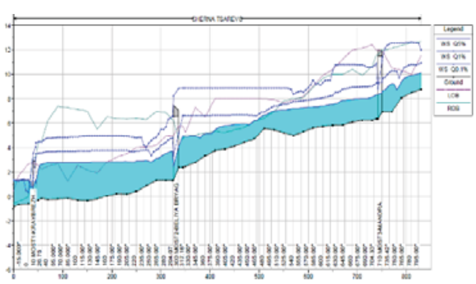

Fig. 6. Longitudinal profile with calculated lines of the free water surface in the research section of the Cherna River for a scenario of the existing situation and maximum water quantities

From an engineering viewpoint, three hydraulic findings are particularly important.

First, the problem was not limited to the bridge openings themselves. The studies repeatedly note that local performance depended on the condition of the river corridor before and after the structures, including vegetation, sediment deposits, approach geometry, and downstream constrictions. In other words, bridge resilience could not be restored by superstructure replacement alone.

Second, the modelling highlighted the role of erosive processes. In the reconstructed cases, even when Q0.1% did not produce overtopping, the flow at the bridge sections often entered a weakly pressurised or near-critical regime, implying the need for dedicated bed and bank protection. This is especially explicit at Mandra and the Coastal Alley, where the documentation discusses hydraulic jump formation, local erosion risk, and the necessity of scour protection.

Third, the Tsarevo case confirms that utility crossings can be a critical hidden vulnerability. At "White Shore", the reports state that the aerial sewer collector did not satisfy hydraulic-conveyance requirements and should be reconstructed as an underground siphon, because the insufficient clearance increased the likelihood of floating-body retention and partial blockage.

5. Emergency reconstruction solutions

The adopted design strategy was to replace the compromised bridges with new single-span structures offering substantially improved hydraulic and structural performance. A single span bridge solution was set as a requirement for the structural design due to the following reasons: (1) the water course is susceptible to excessive sediment and debris transport, which could reduce or block the bridge opening if piers are present; (2) spatial limitations such as urban planning boundaries, buildings, street and underground infrastructure limit the options for variations in the clear opening of the bridge and the transition to the existing river bed geometry; (3) relatively high design and control discharges and insufficient hydraulic capacity of the river channel set the need to seek for a design solution, that provides the highest possible hydraulic capacity of the bridges, given the available spatial limitations. As a leading design criteria the concept for channel-controlled flow conditions, even in case of potential future river training, was considered. This concept is driven also by the high degree of uncertainty of the hydrological inputs, given the lack of direct hydrometric observations.

A sensitivity analysis with respect to the hydrological inputs, i.e. maximum design and control discharges, were performed as part of the design procedure. The latter indicates sufficient safety margins for the design flood discharges, especially if the bridge construction is followed by river training works to increase the channel capacity. It was concluded that a sufficient hydraulic performance is to be expected even with a 100% increase of the design discharge for the bridges at "Mandra" and "White shore" and even higher at "Coastal alley".For "White Shore", the final solution was a new single-span bridge with hydraulic clear width B = 17 m; because of the adopted skew of 57 g, this corresponds to a clear opening of 21.78 m measured along the bridge axis. The structural solution uses six prestressed wide-flange girders type GT-95 with length 24.0 m, supporting a cast-in-place reinforced-concrete deck slab of minimum thickness 20 cm. The bridge carries a 6.0 m roadway and two 2.0 m sidewalks. The design also includes reinforced-concrete wing walls and bed lining for scour protection.

Fig. 7. Bridge – "White shore" – new structure

For Mandra, the selected solution is also a fully new single-span bridge, but with a clear opening of 17.10 m and six prestressed GT-95 girders of length 19.0 m. The cross-section includes a 6.0 m carriageway and two 2.0 m sidewalks. The structural scheme eliminates the previous vulnerable arrangement and introduces reinforced-concrete abutments, independent wing walls, and an overall geometry better aligned with the flow.

Fig. 8. Bridge – "Mandrata" – new structure

For the Coastal Alley bridge, the new configuration again adopts a single-span solution with a 17.10 m clear opening and six GT-95 girders of length 19.0 m. Because of local spatial constraints, the sidewalks are asymmetric, but the main resilience logic is the same: larger opening, simpler hydraulic behaviour, reinforced approaches, and dedicated protection against both fluvial and coastal effects. At this site, the project specifically prescribes rock-armour protection with characteristic parameters such as d50 = 750 mm, dmax = 1200 mm, minimum layer thickness 1.2 m, and slope 1:2, which is appropriate given the river-mouth and wave-exposed environment.

Fig. 9. Bridge – "Coastal Alley" – new structure

The hydraulic checks of the reconstructed solutions show substantial improvement. At "White Shore", the project solution satisfies the required conveyance and freeboard criteria; under Q1% the backwater is minor, the minimum freeboard is about 1.4 m, the bearing seats retain about 1.1–1.2 m reserve, and the Q0.1% flood still passes without overtopping the structure.

At Mandra, the Q1% water level at the inlet is 9.32 m, corresponding to about 1.35 m minimum freeboard and about 1.1 m reserve at the bearing seats. Under Q0.1%, the flow passes in weakly pressurised mode, but without overtopping the bridge. Average velocities in the opening at Q1% are about 1.63–1.73 m/s, increasing to 3.5–3.6 m/s outside the bridge and wing-wall zone, which confirms the need for riverbed and bank protection.

At the Coastal Alley, the Q1% backwater is minor, the minimum freeboard is about 0.76 m, and the bearing-seat reserve is about 0.46 m, both above the required minimums. The Q0.1% flood again passes without overtopping. Importantly, the comparison with the old configuration shows a significant reduction in upstream water levels under design flood conditions.

A comparison between the design scenario and the existing (base) scenario is presented in the following table for the maximum design discharge (Q1%). The table presents the computed water surface elevations (WS Elev) and the corresponding energy grade elevation (EG Elev) in the immediate vicinity of all 3 bridges (approximately 50 to 60 meters up- and downstream from each structure).

Table 1. Comparison between computed water surface and energy grade elevations for existing/ base and design scenario

River Station	Scenario	W.S. Elev	E.G. Elev
m	(-)	(m)	(m)
760	Design	10.16	10.94
760	Existing	10.16	10.94
	(Elev.$_{Exist}$-Elev.$_{Design}$)	0	0
740	Design	8.84	10.21
740	Existing	10.28	10.55
	(Elev.$_{Exist}$-Elev.$_{Design}$)	1.44	0.34
721.66	Design	9.51	9.61
721.66	Existing	9.63	10.33
		0.12	0.72
710	**Bridge "Mandra"**		
708.65	Design	9.49	9.58
708.65	Existing	9.27	9.59
	(Elev.$_{Exist}$-Elev.$_{Design}$)	-0.22	0.01
700	Design	9.02	9.5
700	Existing	9.03	9.51
	(Elev.$_{Exist}$-Elev.$_{Design}$)	0.01	0.01
680	Design	8.96	9.3
680	Existing	8.97	9.3
	(Elev.$_{Exist}$-Elev.$_{Design}$)	0.01	0
660	Design	8.91	9.18
660	Existing	8.92	9.18
	(Elev.$_{Exist}$-Elev.$_{Design}$)	0.01	0
360	Design	5.76	6.04
360	Existing	6.63	6.65
	(Elev.$_{Exist}$-Elev.$_{Design}$)	0.87	0.61
340	Design	4.46	5.63
340	Existing	6.63	6.64
	(Elev.$_{Exist}$-Elev.$_{Design}$)	2.17	1.01
320	Design	4.54	5.18
320	Existing	6.62	6.63
	(Elev.$_{Exist}$-Elev.$_{Design}$)	2.08	1.45
314.32	Design	4.54	4.75
314.32	Existing	6.62	6.63
	(Elev.$_{Exist}$-Elev.$_{Design}$)	2.08	1.88
313.07	Design	4.39	4.73
312.82	Design	4.52	4.67
304.57	Design	4.52	4.65
	Bridge "White shore"		
294.07	Design	4.52	4.62
294.07	Existing	4.77	4.9
	(Elev.$_{Exist}$-Elev.$_{Design}$)	0.25	0.28
284.07	Design	4.48	4.61
		4.23	4.33
280	Design	3.96	4.55
280	Existing	4.42	4.82
	(Elev.$_{Exist}$-Elev.$_{Design}$)	0.46	0.27
260	Design	3.49	4.26
260	Existing	3.78	4.54
	(Elev.$_{Exist}$-Elev.$_{Design}$)	0.29	0.28
60	Design	1.98	2.18
60	Existing	3.42	3.46
	(Elev.$_{Exist}$-Elev.$_{Design}$)	1.44	1.28
40	Design	1.49	1.99
40	Existing	3.38	3.44
	(Elev.$_{Exist}$-Elev.$_{Design}$)	1.89	1.45
26.75	Design	1.38	1.81
26.75	Existing	3.16	3.39
	(Elev.$_{Exist}$-Elev.$_{Design}$)	1.78	1.58
20	Design	1.36	1.73
20	Existing	2.85	3.31
	(Elev.$_{Exist}$-Elev.$_{Design}$)	1.49	1.58
15.5	Design	1.4	1.68
15.5	Existing	2	3.13

River Station	Scenario	W.S. Elev	E.G. Elev
m	(-)	(m)	(m)
	$(Elev._{Exist}-Elev._{Design})$	0.6	1.45
10	Bridge "Coastal alley"		
9.12	Design	1.28	1.61
9.12	Existing	1.46	2.82
	$(Elev._{Exist}-Elev._{Design})$	0.18	1.21
0	Design	1.05	1.16
0	Existing	0.01	1.89
	$(Elev._{Exist}-Elev._{Design})$	-1.04	0.73
-20	Design	1	1.1
-20	Existing	1	1.1
	$(Elev._{Exist}-Elev._{Design})$	0	0

6. Discussion: resilience lessons from Tsarevo

Several lessons can be drawn from the Tsarevo case.

First, emergency reconstruction should be corridor-based, not object-based. The bridge opening alone is not the sole determinant of performance; debris pathways, utility crossings, downstream controls, riverbed morphology, and approach embankments are equally important. The Tsarevo projects correctly addressed these issues through larger openings, wing walls, bed lining, approach shaping, vegetation cleaning, and local river training.

Second, resilience requires replacement, not cosmetic repair, when failure mechanisms are systemic. In all three cases the assessments concluded that the structures were either fully destroyed or no longer reliable. Choosing complete replacement made it possible to remove inherited hydraulic deficiencies rather than lock them into the next lifecycle.

Third, hydraulic capacity and structural reliability must be treated jointly. The Tsarevo reconstructions increased clear openings and freeboard, but they also improved load-bearing arrangements, simplified superstructure behaviour, and introduced scour protection. This is a good example of resilience-oriented engineering, where structural adequacy is inseparable from hydraulic and geotechnical robustness.

Fourth, data scarcity does not justify under-design. Even without direct hydrometric observations, the designers used conservative and normatively grounded methods to estimate design floods and verify performance under a 0.1% event. For municipalities exposed to flash floods, this is a pragmatic model for rapid but technically defensible decision-making.

Finally, post-disaster reconstruction can serve adaptation goals. The new bridges are not merely replacements of lost assets; they represent an upgrade in functional reliability, hydraulic performance, and future flood tolerance. In that sense, emergency reconstruction becomes a mechanism for climate adaptation and risk reduction.

7. Conclusions

The September 2023 floods in Tsarevo exposed critical vulnerabilities in bridge infrastructure along the Cherna River. The damage was driven by a combination of extreme runoff, insufficient bridge clearance, debris blockage potential, bank and bed erosion, and loss of structural and operational integrity. At "White Shore", Mandra, and the Coastal Alley, post-event investigations demonstrated that the existing or damaged structures no longer met the required performance criteria and should be replaced by new one-span bridges with greater hydraulic capacity and improved scour resistance.

The reconstruction strategy adopted in Tsarevo demonstrates that resilience enhancement after a disaster depends on more than rapid reinstatement. It requires integrated assessment of hydrology, hydraulics, structures, foundations, utilities, and river morphology. The new bridge solutions significantly improve freeboard and conveyance, reduce upstream water levels, and allow even the 0.1% check flood to pass without overtopping the reconstructed structures. At the same time, the design recognises residual erosion hazards and addresses them through wing walls, bed lining, bank protection, and river training measures.

The main scientific contribution of this study is to present a resilience-oriented post-disaster reconstruction case, showing that effective recovery of flood-damaged bridge infrastructure requires more than rapid replacement of the failed asset. The Tsarevo case demonstrates that the observed failures were caused by the interaction of hydraulic insufficiency and structural vulnerability, and that successful reconstruction therefore depended on the combined use of hydraulic reassessment, scour and channel-stability evaluation, and reliability-oriented structural redesign. The paper thus contributes a practical example of how emergency bridge reconstruction can be used as a resilience-enhancing intervention that improves future flood robustness, functional continuity, and infrastructure safety. It should therefore be read primarily as a resilience case study supported by hydraulic reconstruction analysis and reliability-informed design decisions.

References

Ministry of Environment and Water (MoEW) (2023). Flood risk management plan of Black Sea River Basin Directorate – 2022-2027

General Directorate for Hydrology and Meteorology at the Bulgarian Academy of Science (GDHM-BAS). Hydrological reference manual – *Series, Volume II and III*

Lissev, N., Tachev, S., Kukurin, Vl., Todorov, P. (2013) Considerations by selecting adequate hydraulic model for flood hazard maps preparation. 6th Bulgarian-Austrian Seminar, Practice and research in flood risk management

Lisev N., Tachev S., Kukurin V., (2012, June 25-29) Practical Aspects Of Application Of EU Flood Directive In Bulgaria, Numerical Simulation Tools for Protection of Coasts against Flooding – Project Consortium Meeting and 3rd Research Seminar – SimCoast, Varna

Kukurin, Vl., Lissev, N., Tachev, S. (2012) Hydrodynamic modelling of river section with variable flow regime. Annual of UACEG-Sofia, Volume XLVI 2012-2013, Scroll VIII, Scientific studies 2012

Gerasimov, Str. (1998). Methods for analysis and calculation of the maximum river runoff. *Monograph*