SHAPING THE FUTURE OF TUNNELLING
Innovation, Sustainability and Safety

PROCEEDINGS OF THE SOUTHEASTERN EUROPE TUNNELLING CONFERENCE (SETC-2025)

Papers on Technical Subjects Related to Tunnelling and Underground Space Planning and Engineering

EDITED BY
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ITA SERBIA
Serbian Association for
Tunnels and Underground Structures

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1–3 October 2025, Belgrade, Serbia

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SHAPING THE FUTURE OF TUNNELLING

Innovation, Sustainability and Safety

Shaping the Future of Tunnelling – Innovation, Sustainability and Safety contains the contributions presented at the ITA Awards & SETC-2025, held in Belgrade, Serbia, from 1 to 3 October 2025.

The papers cover a wide range of topics in the fields of tunnelling and underground engineering, including:

1. Advanced construction techniques
2. Use of new materials and machinery
3. Geological investigation and prediction
4. Numerical modelling
5. Instrumentation and monitoring/testing and inspection
6. Digital and information technology in design and construction
7. Strategic planning
8. Operational safety
9. Impact of climate change on tunnel infrastructure

Shaping the Future of Tunnelling – Innovation, Sustainability and Safety aims to provide a useful resource for everyone engaged in tunnelling and underground engineering, from students and young researchers to experienced professionals and engineers.

PREFACE

The ITA Tunnelling Awards and the Southeastern Europe Tunnelling Conference (SETC-2025) were held from the 1st to the 3rd of October 2025 in Belgrade, Serbia.

The Serbian Association for Tunnels and Underground Structures (ITA Serbia) was honoured and proud to host this outstanding event of the international tunnelling community. Bringing together hundreds of distinguished experts, researchers, and industry leaders from across the globe, the event served as a dynamic platform for sharing knowledge, presenting innovations, and advancing scientific and technical excellence in the field of tunnelling and underground construction.

Serbia, with Belgrade as its dynamic capital, is experiencing a period of intensive infrastructure development, particularly in the domain of underground construction and sustainable urban mobility. Landmark projects such as the Belgrade Metro, tunnel connections, and urban underground infrastructure systems are transforming the city's transport network and enhancing its connectivity and sustainability. These projects demonstrate Serbia's growing expertise in modern tunnelling technologies, geotechnical engineering, and integrated urban planning, positioning Belgrade as a regional hub for innovation and progress in underground construction.

The conference proceedings encompass a diverse range of nine thematic areas, reflecting the multidisciplinary nature and technological depth of modern tunnelling. Topics include advanced construction techniques, the use of new materials and machinery, geological investigation and prediction, numerical modelling, instrumentation, monitoring, testing and inspection, the application of digital and information technologies in design and construction, strategic planning, operational safety, and the impact of climate change on tunnel infrastructure. Together, these themes highlight the conference's focus on innovation, sustainability, and resilience in underground construction.

It is our sincere expectation that these proceedings will contribute meaningfully to the professional and scientific community, providing valuable insights for engineers, researchers, and decision-makers engaged in the development of underground infrastructure. The knowledge and experiences shared during SETC-2025 aim to foster innovation, collaboration, and sustainable practices, encouraging the continued advancement of tunnelling and underground construction in the years ahead.

Belgrade, October 2025

Prof. Dr Dejan Divac

Chair of the ITA Awards & SETC-2025 Organising and Scientific Committee
President of the ITA Serbia

ACKNOWLEDGEMENT

The Editors would like to thank and express their sincere gratitude to all members of the Scientific Committee for their effort and the valuable time devoted to reviewing the abstracts and manuscripts.

The SETC-2025 Organizing Committee, Scientific Committee, and Editors wish to express their sincere gratitude to the conference sponsors and exhibitors for their generous support and valuable contribution to the success of this Event.

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Enhancing Flood Resilience of Underground Traffic Tunnel through Direct Rainfall 2D Modeling - Case Study of the City of Belgrade

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Abstract: This paper examines the impact of climate change on underground traffic tunnel infrastructure, specifically focusing on the increased pluvial flooding risk associated with changing precipitation patterns and extreme weather events. We are presenting a 2D hydrodynamic model designed to assess and enhance the flood resilience of these tunnels during torrential events. The case study conducted in Belgrade, Serbia, evaluates the effectiveness of proposed flood risk management techniques aimed at safeguarding the city's underground transportation infrastructure from potential flooding.

Using the Direct Rainfall Method (DRM), our model simulates rainfall events with various return periods (e.g., 10, 100, and 500 years) to provide a comprehensive assessment of flood impacts on tunnel infrastructure. Detailed topographical data is utilized to accurately capture the complex geometry of the tunnel system and its urban context, allowing for a thorough investigation of factors such as tunnel portal design, raising entrance to the tunnel, drainage system capacity, surface runoff management, and the implications for traffic flow and emergency response.

The simulations reveal critical insights into water levels, discharge, and inundation zones under differing rainfall scenarios. The findings underscore the necessity for resilient design strategies, including road design adaptations (elevation adjustments), construction of flood barriers, implementation of effective water management systems, and sustainable drainage solutions. Furthermore, future considerations regarding these issues are focused on the integration of green construction practices and energy-efficient designs as strategies to enhance the resilience of tunnel infrastructure in response to climate-related challenges.

By delineating flood-prone areas and proposing targeted drainage improvements, this research contributes to developing effective flood risk management plans. Ultimately, this study emphasizes the importance of integrated and systemic approach that merges planning strategies and structural improvements to bolster the safety and resilience of the Belgrade underground transportation system, solving similar issues on tunnelling projects worldwide.

Keywords: flood resilience; underground traffic tunnels; flood risk management; climate change; 2D hydrodynamic modelling

1. Introduction

Urban underground transportation systems, including metro tunnels, are increasingly exposed to flooding as a consequence of extreme weather events resulting from climate change and rapid urbanization (IPCC, 2021). Intensifying rainfall events and more frequent extreme weather conditions, coupled with growing impervious surface areas, have led to higher volumes of surface runoff, overwhelming existing drainage networks (Nodine et al., 2024). These phenomena pose significant safety hazards, financial losses, and interruptions to urban mobility.

In contemporary engineering practice, the planning and design of underground transportation infrastructure present complex challenges (von der Tann et al., 2020). Stormwater management plays

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a pivotal role in ensuring the operational integrity and safety of these facilities. The risks posed by pluvial and fluvial flooding, as well as by sewer surcharges, require integrated approaches to hazard assessment and mitigation.

Flooding is among the most frequent natural hazards affecting urban environments. It impairs the resilience of city systems, prolongs recovery efforts, and often results in substantial technical and economic consequences (Batica and Gourbesville, 2020). Urban underground networks are particularly vulnerable due to their low-lying locations, limited natural drainage, and often aging infrastructure. Pluvial flooding, which occurs when intense rainfall overwhelms drainage capacity, is especially problematic in urbanized areas where infiltration is minimal and overland flow rapidly accumulates (Yosua et al., 2023).

Globally, over 70% of the population is projected to reside in urban areas by 2050 ("Overview," n.d.), significantly increasing disaster risk due to high population density and asset concentration. It is worth considering that interventions outside the tunnel portals can influence the vulnerability of the urban environment to hydrometeorological hazards (Lyu et al., 2018).

This study focuses on assessing the flood resilience of a planned twin-bore traffic tunnel in Belgrade, Serbia, using advanced two-dimensional (2D) hydrodynamic modeling techniques. The objective is to simulate flood scenarios based on various return periods and to evaluate terrain modifications and infrastructure enhancements that can mitigate flood risks. The research contributes to a growing body of work emphasizing proactive and adaptive strategies for urban flood risk management in the context of climate variability.

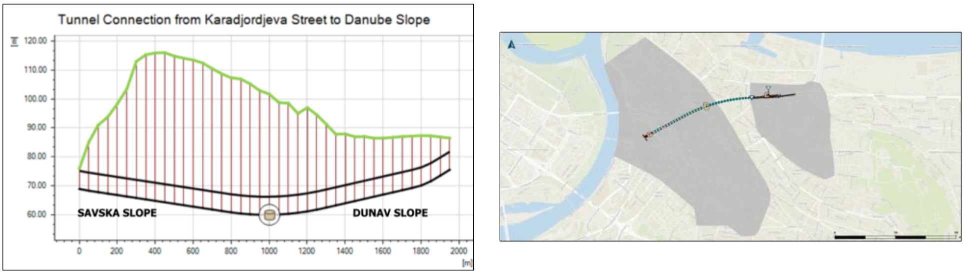
2. Case Study

Belgrade, the capital of Serbia, is situated at the confluence of the Sava and Danube rivers, a strategic location that has shaped its history and urban development. As part of a broader traffic and urban transformation strategy, a twin-bore urban traffic tunnel has been designed to connect the Sava and Danube slopes in central Belgrade. The tunnel alignment establishes a direct underground connection between Karađorđeva Street (on the Sava side) and Bulevar Despota Stefana (on the Danube side), aiming to reduce traffic congestion in the city center and improve environmental conditions.

The tunnel consists of two separate tubes, each carrying two traffic lanes, with cross-passages. The total length of the traffic route, including access ramps and transitional structures, is approximately 2.6 km. According to the planned project concept, the traffic lanes descend from Karađorđeva Street through the Luka Ćelović Park toward the Savska Slope portal. The approach road passes underneath Gavrila Principa Street and continues to descend into the tunnel, reaching its lowest point approximately at the tunnel midpoint, after which it ascends toward the Danube Slope portal. The portal is connected to Despot Stefan Boulevard via a dedicated ascending ramp, bringing the alignment back to street level. This longitudinal profile was determined by the presence of existing underground sewer collectors and the planned metro corridor, both of which imposed stringent spatial and engineering constraints. As a result, the adopted tunnel gradient could not be avoided and represents the only feasible engineering solution within the urban context.

The tunnel portals are located in low-lying urban areas along the Sava and Danube rivers. These regions, including the Savska padina (Sava slope) and Dunavska padina (Danube slope), have a history of flooding because of their closeness to the rivers and limited natural drainage. Moreover, the central Belgrade sewer system functions as a combined network, carrying both stormwater and sewage through the same pipelines. During heavy rainfall events exceeding the 2-year return period, the system becomes overwhelmed, causing water to overflow and spill onto the streets. This excess water naturally moves toward lower areas, significantly raising the flood risk at the tunnel portal zones.

The planned tunnel connection from Karađorđeva Street to the Danube slope is susceptible to flooding during intense rainfall events or other extreme hydrological conditions. This vulnerability is further amplified by the effects of extreme weather conditions, which are contributing to more frequent and intense precipitation over shorter durations. As a critical component, the tunnel must be comprehensively protected against external floodwaters that could interrupt traffic, compromise structural integrity, and cause significant economic, operational, and safety-related consequences.



(a) **(b)**

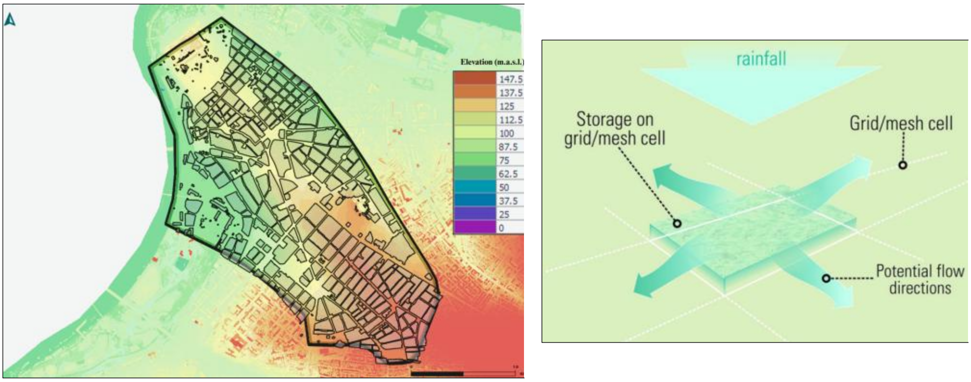
Fig. 1. (a) Longitudinal profile of the traffic Tunnel Connection from Karađorđeva Street to Danube Slope; (b) Location of the planned tunnel alignment between the Sava and Danube slopes with delineated catchment areas contributing to each tunnel portal.

3. Methodology

Accurate topographic data are essential for reliable urban flood modelling, enabling precise simulation of flow distribution, directions, and surface velocities. In this study, a LiDAR-derived point cloud was processed to produce a bare-earth Digital Elevation Model (DEM) at 1×1 meter resolution, eliminating vegetation, buildings, and anomalies. This high-resolution DEM accurately depicted local depressions, infrastructure features (e.g., curbs, ramps), and micro-catchment flow paths near tunnel portals. The DEM was iteratively updated as the tunnel design and terrain evolved, ensuring consistency throughout simulations. Results indicated that minor elevation changes (30 – 50 cm) significantly influence runoff behavior, emphasizing the importance of terrain modifications for flood mitigation.

The study employed the Direct Rainfall Methodology (DRM), which applies precipitation directly to the 2D model grid to simulate overland flow using shallow water equations. This approach treats each cell as a micro-catchment, dynamically generating runoff based on parameters such as cell area, rainfall intensity and duration, Manning's roughness, slope, and infiltration losses. Using synthetic hyetographs based on the Chicago Design Storm (CDS) and Intensity-Duration-Frequency (IDF) curves tailored to Belgrade, simulations for return periods of T = 10, 100, and 500 years were performed using the approach Keifer and Chu (1957). Net rainfall, accounting for drainage system losses, was applied to capture realistic runoff from the terrain, enabling detailed analysis of flood risks and terrain-based interventions.

An integrated modeling framework was developed to evaluate the flood resilience of the tunnel system by combining multiple hydraulic components: two-dimensional (2D), one-dimensional/two-dimensional (1D/2D), and one-dimensional (1D) simulations. The 2D models represented the Sava and Danube slope catchments, which naturally drain toward the tunnel's descending ramps. These models simulated overland flow across a bare-earth DEM, enabling detailed analysis of terrain-runoff interactions in the presence of planned infrastructure. The Sava slope model covered approximately 411 hectares with 4.4 million grid cells, requiring 38 hours per simulation, while the Danube slope model spanned 120 hectares with 1.6 million cells and typically took 6 hours to run. Cross-sections placed at the bottom and top of the tunnel ramps were used to extract hydrographs (flow rates and volumes), which were then applied as inflow boundary conditions for the 1D/2D simulations. The 1D/2D model combined the tunnel drainage pipe network with overland surface flow, allowing assessment of water levels, velocities, flood extents, and pump discharge needs during extreme rainfall events. The 1D model mainly generated longitudinal water surface profiles along the tunnel axis for various return periods. In this configuration, the tunnel was modeled as a closed conduit with cross-sectional geometry and dimensions matching the actual tunnel design.



(a) **(b)**

Fig. 2. (a) Digital elevation model (DEM) of the Sava slope catchment area with defined 2D computational domain (b) Conceptualisation of Direct Rainfall (ARR, Project 15, Figure 11-1).

Iterative simulations were used to test and optimize grading strategies near tunnel portals. These adjustments included localized elevation increases and protective grading patterns aimed at diverting overland flow. The simulations confirmed that small topographical interventions could substantially influence flood exposure and dewatering times, supporting evidence-based infrastructure design.

3.1. Key Parameters Evaluated

The hydraulic model facilitated a comprehensive assessment of critical parameters influencing flood risk within and around the tunnel area, with particular focus on the sensitivity of runoff dynamics to small elevation changes near the portals. Emphasis was placed on the sensitivity of overland flow to small-scale intervention changes near the tunnel portal. The results demonstrated that even minor topographic modifications, such as elevation increases of 30 to 50 cm, had a measurable impact on flow pathways and flood extents.

The broader context of urban flood risk was considered within the tripartite framework of hazard, exposure, and vulnerability (Zhang et al., 2024). Hazard refers to the frequency and intensity of rainfall events; exposure denotes the spatial distribution of assets at risk, including tunnel portals and electrical systems; vulnerability reflects the capacity of systems to resist and recover from flood impacts.

Effective flood mitigation in dense urban environments requires both horizontal and vertical planning. Horizontally, interventions such as terrain regrading, drainage enhancement, and protective barriers reduce flood hazards across the spatial extent. Vertically, coordination across governance levels is crucial for integrating institutional responsibilities for climate adaptation, land use management, and infrastructure resilience (Yu et al., 2015; Qiu, 2017).

Within the study, it is revealed that a complex interplay of physical infrastructure, spatial configuration, and hydrometeorological variability influences localized flood risk. Thus, integrated strategies are essential for improving the robustness and adaptability of underground traffic systems facing growing climatic uncertainties.

3.2. Flood Risk in the Context of Underground Structures

Underground systems are inherently vulnerable to flooding due to their subterranean location and limited capacity for passive drainage (He et al., 2024). During high-intensity rainfall or elevated water table events, such systems face substantial risks, including operational disruption, structural damage, and compromised passenger safety. Vulnerability extends beyond the physical integrity of tunnels to encompass drainage system performance, passenger safety, emergency access, and response capabilities.

A comprehensive flood risk assessment requires an evaluation of hydrological patterns, historical flood data, and existing drainage network capacity. Sensitivity factors influence system resilience, such as construction material conditions, the effectiveness of existing drainage solutions, and the ability to deploy rapid response measures.

Conducting comprehensive flood risk analyses enables targeted design modifications, infrastructural improvements, and community engagement to strengthen system robustness. Such proactive measures are critical for safeguarding urban mobility and supporting sustainable urban development amid increasing climate variability. Ultimately, enhancing flood resilience involves quantifying risks and implementing mitigation strategies, understanding that resilience is defined as the capacity of an urban system to adapt and maintain functionality when exposed to hazards (UN/ISDR, 2004).

Resilience in this context refers to the capacity of the tunnel system and its associated infrastructure to maintain or rapidly restore function following a disruptive flood event. This necessitates quantifying potential hazards and systematically reducing risk through both structural interventions and institutional adaptation strategies. Ultimately, an effective flood risk management approach for underground transportation systems combines engineered defenses with adaptive operational planning, ensuring long-term safety and service continuity among evolving climate threats.

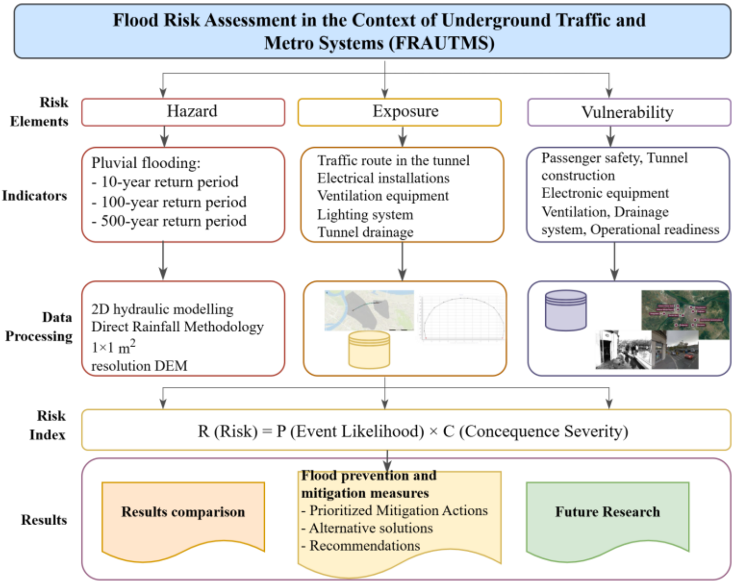


Fig. 3. Flood Risk Assessment of Underground Traffic and Metro Systems Scheme.

The flowchart presents a structured framework for flood risk assessment in underground traffic and metro systems. It begins with the evaluation of hazards, exposure, and vulnerability. These inputs feed into the development of a flood risk model, leveraging tools such as hydraulic simulations and historical data analysis. The model's findings inform flood prevention and mitigation strategies, including both prioritized actions and alternative solutions. The results are compared to baseline scenarios to assess the effectiveness of proposed measures. This process informs future research directions, ensuring continuous improvement and adaptation of strategies. The integrated approach aims to enhance resilience and safeguard urban infrastructure against flood risks.

3.3. Quantitative Risk Assessment

Quantifying flood risk to underground traffic and subway systems involves a structured evaluation of hazard, exposure, and vulnerability components (Forero-Ortiz, et al., 2020). Hazard assessment comprehends estimating the probability and severity of flood events such as pluvial or river flooding using historical data, hydrological models, and climate projections. Exposure assessment then characterizes the spatial extent and value of assets at risk, including tunnel entrances, electrical and signaling infrastructure, and surrounding landforms that influence flood dynamics. Vulnerability quantifies the system's susceptibility, considering factors like structural integrity, drainage capacity, and redundancy. To facilitate the prioritization of mitigation efforts, a probabilistic risk metric is applied. This approach multiplies the annual probability of occurrence (P) by a severity score (C), producing a composite risk index (R = P × C). Severity scores are assigned based on predefined impact criteria, ranging from negligible service delays to catastrophic infrastructure failure.

$$R = P(Event\ likelihood) x C(consequence\ severity) \tag{1}$$

The range is provided as:

Table 1. Standardized severity scale used in this study.

Severity Score	Description	Example Impacts
1	Negligible	Minor traffic delays, slight wear of equipment, and minimal operational impact
2	Very Low	Slight inconvenience, minor repair needs, limited-service disruption
3	Low	Localized flooding, minor infrastructure impact, manageable repairs
4	Moderate	Noticeable flooding affecting operation, minor structural damage, manageable recovery
5	Significant	Disruption to operations in affected areas, moderate infrastructure damage
6	High	Major service interruptions, structural damage requiring extensive repairs
7	Very High	Large-scale flooding, significant safety hazards, and substantial economic impact
8	Severe	Widespread infrastructure failure, serious safety risks, and long-term disruption
9	Critical	Catastrophic damage, loss of service, and significant safety hazards
10	Catastrophic	Extreme impact, including loss of life, total infrastructure failure, extensive economic and social consequences

This framework empowers an evidence-based understanding of the risk landscape associated with underground tunnel systems. By ranking scenarios from high to low risk based on modelled probabilities and potential impacts, decision-makers can allocate resources more effectively, prioritizing interventions that yield the greatest resilience gains. The use of quantitative risk indices supports transparent communication of risks and enhances coordination across engineering, planning, and emergency response domains.

4. Flood Risk Profile for the Traffic Tunnel

The entrance portals of the Tunnel Connection from Karađorđeva Street to the Danube Slope are located at the lowest points along the alignment. Moreover, the natural slopes of surrounding urban areas, such as Kalemegdan, Kosančićev Venac, Terazije, and Nemanjina Street on the Sava Slope, and Bogoslovija and Cvijićeva Street on the Danube Slope, concentrate surface runoff toward the tunnel entrances, significantly increasing flood exposure.

Savska Slope portal of Tunnel Connection from Karađorđeva Street to Danube Slope is strategically located adjacent to the right bank of the Sava River, with an elevation of approximately 75-78 meters a.s.l. This positioning makes it only 2 to 4 m above average river flow, increasing its vulnerability to flood. The flood risk in the Sava zone near Belgrade is projected to increase, according to analysis by the World Bank (WB, 2015, 2025). This increase is driven by the impacts of extreme weather events, which is expected to lead to more severe and frequent storm events, as well as increasing property values in the Belgrade Waterfront area, which heightens the potential vulnerability.

To address these vulnerabilities, targeted mitigation measures are essential. These include improving drainage systems around the portal to effectively intercept and divert surface runoff, building barriers or flood gates at the tunnel entrance to block water ingress during floods, and installing early warning systems for river flooding or severe storm. Enhancing the tunnel's waterproofing and sealing infrastructure, properly sizing and conducting routine maintenance of drainage and pumping systems, and integrating flood resilience features into the new tunnel are essential strategies to mitigate flood hazards and ensure the continued operational safety and integrity of the infrastructure.

Additionally, ongoing urban development in Belgrade has led to a significant increase in surface runoff. The runoff coefficient, which was historically below 0.4, has now risen to over 0.8 in some areas due to extensive paving and construction. This doubling of the runoff coefficient results in a substantial increase in peak flow during storm events, further exacerbating flood risks and stressing drainage systems in the area.

Hazard identification in this context includes both natural and infrastructural risks. Pluvial flooding, driven by high-intensity short-duration rainfall, represents the most probable hazard. Riverine flooding, while less frequent, poses significant risks due to backwater flooding. Infrastructure-related hazards include sewer surcharge during peak flows, pump station failure due to power outages or mechanical failures, drainage blockages from debris or ice, and elevated river water levels. The hazards include pluvial flooding caused by localized, high-intensity downpours with rates of at least 50 mm/h, occurring with return periods from 10 to 100 years. River flooding is a significant threat due to elevated water levels in the Sava River, which has a flow rate of 6,500 m^3/s as documented in Q100. There is also a risk of combined sewer surcharge, where stormwater mixed with fecal waste backflows during heavy rains, and drainage system failures caused by pump breakdowns or clogged drains that hinder flood management.

The tunnel portals are located at the lowest points of the old city center, in areas highly exposed to concentrated surface runoff from surrounding slopes. Their close proximity to both the Sava and Danube rivers further increases their vulnerability to flooding. The infrastructure is highly valuable, supporting critical transportation functions such as electrical and signaling equipment located in the roadway zone. Vulnerability stems from the tunnel entrance's design, which lacks a natural overflow or protective barrier, making it prone to flooding.

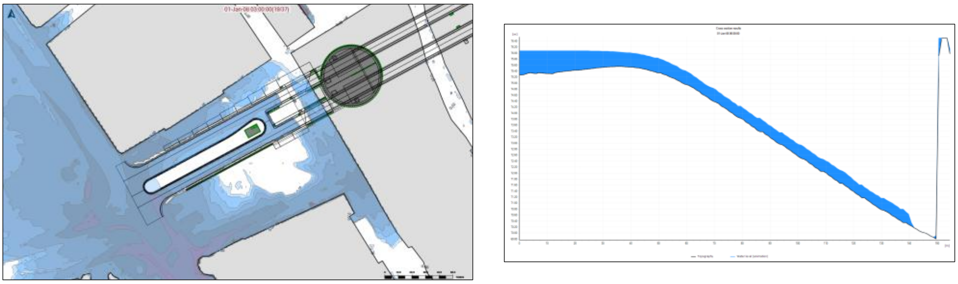
The system depends heavily on the continuous operation of pumps and functioning backflow valves, creating reliance on mechanical components that may fail. Additionally, the sewer infrastructure is relatively old, dating back to the early 20th century, with limited capacity to manage increased loads. The surrounding area also demonstrates low capacity for sustainable drainage solutions, leading to insufficient rainfall retention and management, which heightens overall flood risk.

5. Results on Modelling Outcomes and Risk Assessment

Comprehensive 2D hydrodynamic simulations were conducted to evaluate the flood vulnerability of the planned tunnel between Karađorđeva Street and the Danube slope. These simulations tested chosen return periods and informed the development of integrated flood mitigation strategies.

5.1. Terrain Elevation and Grading near Tunnel Portals

Iterative simulations optimized terrain grading and elevation around the tunnel portals to minimize surface runoff and stormwater inflow. Results revealed high sensitivity of overland flow to small elevation changes, enabling precise design adjustments. For the Savska slope, the terrain was raised to a maximum of 75.3 m a.s.l., constrained by the access roundabout. Despite this, some upstream runoff during a 10-year rainfall event still reached the tunnel, producing manageable inflows, while a 100-year storm caused significant inundation. Protective walls about 1 m high were constructed along adjacent streets to mitigate lateral inflow. Conversely, the Danube slope was elevated to 87.5 m a.s.l., effectively isolating the portal from the catchment and redirecting surface runoff to natural detention zones. An independent drainage system, including high-capacity inlets, was installed, complemented by lateral barriers along Despot Stefan Boulevard to prevent uncontrolled inflows during extreme events.



(a) **(b)**

Fig. 4. (a) The flood simulation result near the Sava tunnel portal presents the modelled flood extent and water depth in the area surrounding the tunnel entrance on the Sava slope during a 100-year rainfall event. Blue shading indicates areas with surface water accumulation, highlighting potential inflow zones toward the tunnel. (b) The profile of the approach road and descending ramp toward the tunnel portal on the Sava slope under a 100-year rainfall event. The blue water surface profile indicates that the runoff overtops the elevated terrain in front of the tunnel and enters the tunnel infrastructure. The maximum recorded water depth on the ramp reaches approximately 0.4 m.

5.2. Drainage System and Pumping Stations Design

Drainage and pump capacities were dimensioned based on runoff hydrographs for a 10-year rainfall event. The Savska portal pump station was designed for approximately 100 l/s, and the Danube portal for 150 l/s, each with standby pumps for redundancy. Shaft pumps at each tunnel end, capable of over 250 l/s, serve to evacuate internal runoff under normal and extreme conditions, ensuring full dewatering within a reasonable timeframe and enhancing resilience. The adopted drainage pump capacities are more than double compared to the sizing of fire event pumps in tunnels as required by NFPA 502.

5.3. Risk Matrix Evaluation

A quantitative risk matrix was used to evaluate flood scenarios by combining event probability (P) and consequence severity (C), yielding a risk index (R = P × C). Key modelled scenarios are summarized in Table 2.

This analysis reinforces the importance of a layered mitigation strategy: topographic barriers, independent drainage systems, robust pumping infrastructure, and operational redundancies. It also illustrates the utility of risk indexing for strategic investment and emergency planning. Proposed mitigation measures for the considered demonstration site are listed in the table below, focusing on both prioritized and alternative solutions.

Table 2. Results of risk levels based on the results of hydraulic 2D modelling for the tunnel infrastructure.

Risk	**Event Probability (P)**	**Consequences (C)**	**Risk Index (R = P × C)**	**Risk Level**
Pluvial Flood (T = 1/10 yr)	0.1	5 (traffic disruption and damages)	0.50	High Risk
Pluvial Flood (T = 1/100 yr)	0.01	9 (full evacuation, huge damage)	0.09	Medium Risk
River Flood (Q100 = 6500 m³/s)	0.01	8 (water entering the tunnel, long reparation period)	0.08	Medium Risk
Sewer Surcharge (in the tunnel)	0.05	4 (local flooding, pollution)	0.20	Medium Risk
Pump Station Failure During Rain	0.03	7 (fast charging tunnel with water)	0.21	Medium to High Risk
Drain Clogging	0.20	3 (local flood waves)	0.60	High Risk
Groundwater Leakage	0.01	5 (construction degradation)	0.05	Low to Medium Risk

Table 3. Proposed key mitigation measures for the flooding of the tunnel infrastructure

Key Mitigation Measures	**Description**
Prioritized Mitigation Actions	
Portal elevation and grading	Elevate terrain and install protective side walls to redirect surface runoff and minimize direct inflow
Redundant pumping systems (N+1 configuration)	Pump stations are equipped with backup pumps and a diesel/UPS power supply for uninterrupted operation.
High-capacity linear drainage channels	Deployment of clog-resistant drains across the portal width, connected to an independent collector system.
Elevation of electrical equipment	Positioning critical electrical and signaling infrastructure above the design flood level to prevent damage
Alternative solutions	
Flood gates and portable barriers	Implementation of manually deployable or remotely monitored gates for sealing tunnel portals during extreme events
Increased monitoring capacity	Use integrated hydrometeorological sensors and systems to automate responses
Integrated urban catchment management	Improve upstream stormwater control with Low Impact Development (LID) techniques such as detention zones and surface infiltration techniques
Rain forecasting	Coordination with the national hydrometeorological service (RHMZ) to manage runoff from steep urban slopes (e.g., Kosanciceva) ahead of major storms.

6. Recommendation

Based on the findings of hydraulic modeling and technical evaluations, a set of recommendations is proposed to enhance flood resilience for the tunnel infrastructure:

- Elevation of terrain at tunnel portals to divert runoff and minimize inflow from surrounding catchments, considering both functional and spatial constraints.
- Implementation of protective side walls at vulnerable locations to prevent lateral inflows during extreme events.
- Dedicated point drainage systems are designed independently from the main urban network, enabling rapid collection and redirection of runoff.

- Redundantly configured pumping stations with sufficient capacity to handle both basic and emergency scenarios, including backup pumps to ensure reliability.

In the cases where the risk of tunnel flooding cannot be eliminated, advanced traffic signaling systems are essential for ensuring user safety. These systems should:

- Deliver clear and timely warnings to drivers through signage installed along access roads and directly in front of tunnel portals.
- Enable traffic rerouting or tunnel closure in response to real-time flood risks.
- Be integrated with automated water level detection systems and the extensive urban emergency response network.

To preserve the functionality of pumping stations during flooding, it is essential to ensure an uninterrupted power supply. This requires:

- Elevated positioning of transformer stations and backup diesel generators above the design flood level (e.g., above 64 m a.s.l. for the 100-year rainfall scenario).
- Physical protection of electrical components from water ingress through sealed enclosures and raised platforms.

This measure ensures the continuous operation of drainage systems even under catastrophic conditions, minimizing tunnel downtime and structural damage.

To ensure readiness for the most critical scenarios, the drainage system must be sized to accommodate the worst governing event, considering both flooding and fire-related water ingress. This requires designing capacity based on peak runoff from a 100-year rainfall event, with additional margins to account for extreme events. The system should also be capable of handling the volume of water used during fire suppression activities, such as firefighting water, which can significantly increase the water load within the tunnel.

7. Effectiveness of the proposed flood risk management approach

To assess the effectiveness of proposed flood risk management measures for Belgrade's underground traffic system, a comprehensive, multi-criteria approach is recommended. Initially, advanced 2D hydrodynamic modelling, such as the Direct Rainfall Method (DRM), should be employed to simulate diverse rainfall scenarios and evaluate the tunnel's response to mitigation strategies. This includes analysing flood levels, flow velocities, and inundation extents before and after measures like portal elevation and drainage improvements. Subsequently, a probabilistic risk assessment should be conducted, involving hazard characterization, exposure evaluation (including populations and infrastructure), and vulnerability analysis. The resulting risk index helps prioritize interventions by quantifying their potential to reduce flood likelihood and impact severity.

Sensitivity testing and gap analysis through iterative simulations are crucial for refining designs, identifying weaknesses, and determining the most effective measures, such as pump capacity and barrier height under various flood conditions. Real-time hydro-meteorological monitoring should be deployed during rainfall events to enable dynamic feedback and model validation, enhancing response reliability. Stakeholder engagement, including authorities, emergency services, and local communities, is vital to ensure measures are practically effective, acceptable, and capable of operational optimization. Finally, post-event reviews should be conducted after major storms to evaluate performance, adapt strategies, and incorporate emerging insights and technologies to sustain or improve flood resilience over time.

8. Conclusion

The Karađorđeva Street tunnel is situated in a flood-prone area featuring three primary vulnerabilities: proximity to the Sava River, concentrated surface runoff from the steep slopes of Stari Grad, and an aging or limited-capacity combined sewer system. While pluvial flooding presents the most statistically probable scenario, river flooding and hydraulic backpressure pose the highest potential failure costs. Therefore, a holistic mitigation strategy integrating structural measures such as portal elevation, enhanced pumping systems, and retention structures with operational strategies like early warning systems and routine maintenance is essential to reduce risk to an acceptable level corresponding to a 1% annual probability (T = 1/100).

The hydrodynamic modelling and risk analysis confirmed that mitigation must address a combination of hydrometeorological hazards and infrastructural vulnerabilities intensified by climate change and urbanization. The findings support a resilience-based approach, emphasizing the importance of redundancy, real-time response systems, and climate-adaptive planning.

Proactive flood management also relies on advanced early detection, real-time monitoring, and automated response systems to ensure continuous safety and operation during extreme events. Integrating these technical solutions with strong institutional coordination, contingency planning, and adaptive management practices strengthens system resilience against current and future hydrometeorological hazards. Lessons from the Karađorđeva Danube tunnel case study advocate for best practices such as extensive 2D hydrodynamic modelling with direct rainfall input to evaluate terrain sensitivity and runoff pathways; designing with redundancy to handle failure scenarios; and adopting cross-sectoral planning that aligns tunnel flood protection with broader urban drainage, transportation safety, and climate resilience strategies.

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