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Research paper

ANALYSIS OF FLOOD ZONES IN SECTION OF THE WEST MORAVA RIVER BASIN ALONG THE E-761 HIGHWAY (KM 26 – KM 42)

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Abstract

Analysis of floods in the part of the West Morava river basin, particularly in the area of the E-761 highway under construction, aims to assess the impact of floods on infrastructure and the environment, as well as to evaluate the influence of the highway structure on the flood waters flow, with the goal of identifying risk reduction etc. mitigation measures. Using hydrological (HEC-HM v.4.11) and hydraulic models (HEC-RAS v.6.0), meteorological parameters (precipitation), hydrological (discharge), and hydraulic (water levels and flood wave propagation) data were analyzed. By incorporating geographic data (GIS) and terrain topography information, a detailed assessment of flood risks in the areas influenced by the highway was conducted. The results of the analysis highlight critical sections of the basin where there is an increased risk of flooding, which could threaten the construction and functionality of the E-761 highway. This analysis provides important information for infrastructure planning and design, ensuring that the E-761 highway is resilient to floods and that negative environmental impacts are minimized. The case study focuses on the Riljačka River, a tributary within the West Morava basin, which intersects the E-761 highway corridor.

Key words: *Flood, the West Morava river, E-761 highway, hydrological analysis, hydraulic analysis, flood risk, infrastructure*

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1. INTRODUCTION

During April, and particularly in June 2023, Central and Eastern Europe were affected by a series of severe weather events. The magnitude of precipitation, the total volume of rainfall, and the duration of these events meet the criteria for classification as hydrometeorological natural disasters.

Serbia was also affected by this wave of natural disasters. Short-duration but extremely intense rainfall events triggered flash floods in torrential watercourses, leading to their swelling, splashing and flooding of agricultural as well as urban areas. These events caused substantial damage to infrastructure, buildings, and land.

Nearly all torrential watercourses within the entire basin area experienced significantly higher discharges than the hydraulic conductivity of their channels, resulting in overbank flow and the occurrence of flooding.

2. STUDY AREA AND INPUT DATA

In this study, hydrodynamic analysis of flood conditions was conducted for the Riljačka River at highway chainage km 37+000 during the high-water period. The Riljačka River is torrential stream that collects runoff from the Gledić Mountains and flows toward the villages of Drenova and Selište. As with all torrential watercourses, the discharge exhibits significant variability throughout the year, with the channel often carrying low flows or remaining dry for extended periods.

During rainy seasons, the discharge increases rapidly, and there are frequent instances of coinciding flood peaks on both the Riljačka River and the West Morava River (Figure 1).

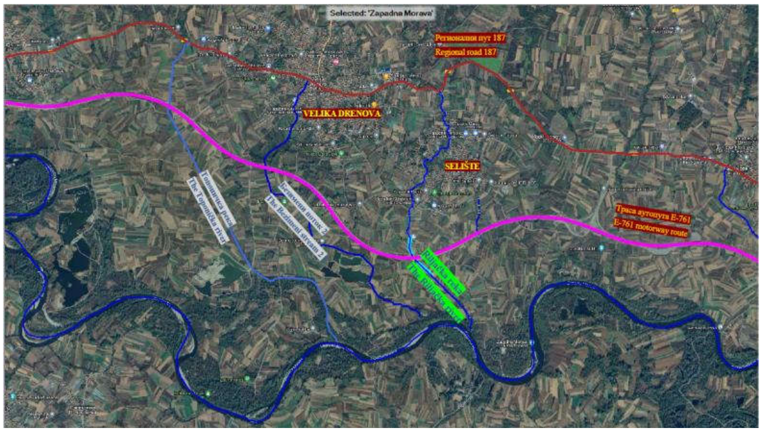

Figure 1. Overview of the E-761 highway section in the West Morava Valley with the axes of the Riljačka River, Bezimeni Stream 2, and Toponička River on the satellite image

2.1. Geodetic data (DEM)

Visualization of the terrain relief is commonly used nowadays for scientific, professional, and commercial applications. The Digital Elevation Model (DEM) is numerical and mathematical representation of the ground surface, most often in the form of a regular grid, in which a unique spatial elevation value is assigned to each pixel. DEM approximates the Earth's surface shape with a limited precision. The accuracy of terrain surface approximation depends on the distribution and density of the collected data by different types of geodetic survey [1].

For the purpose of conducting the hydraulic analysis, a publicly available DEM over Europe (EU-DEM) was used in combination with traditional surveying data (Figure 2) [2].

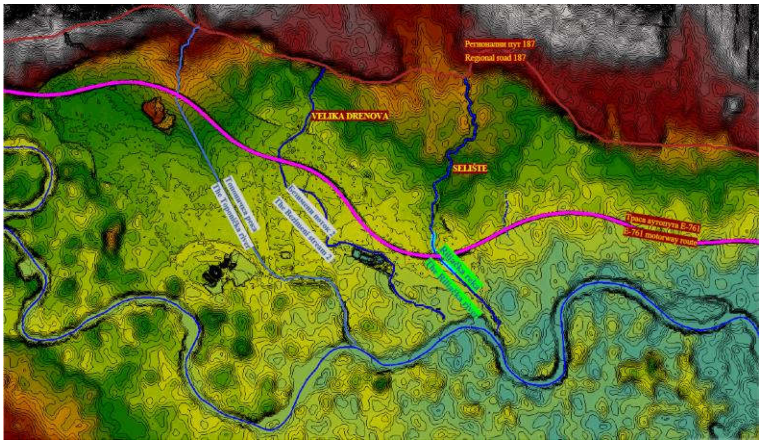

Figure 2. Overview of the E-761 highway section in the West Morava Valley with the axes of the Riljačka River, Bezimeni Stream 2, and Toponička River on the DEM

2.2. Hydrological data processing

The mathematical simulation of rainfall-runoff processes is contingent upon the specific hydrological problem under consideration. For computational flood estimation in small river basins, the model structure necessitates three fundamental components [3]: basin model, meteorological model and control specifications. The selection of process representations, spatial discretization, and temporal resolution is inherently problem-dependent, requiring careful consideration of basin scale, data availability, and desired accuracy in flood peak prediction. In this study, the Riljačka River basin was modeled using the software HEC-HMS v.4.11.

Terrain pre-processing is the first step in HEC-HMS modelling, converts raw DEM data (here, the EU-DEM DSM) into gridded and vector datasets for drainage network extraction and sub-basin delineation. The EU-DEM represents the first reflective surface (e.g., terrain, vegetation) across Europe at 25m resolution. The following steps were applied [4]:

- *Sink filling* modifies the DEM to remove depressions.
- *Drainage preprocessing* generates both flow direction and flow accumulation rasters from the elevation data.
- During *flow direction processing* (Figure 3), the model analyses the DEM to determine the steepest descent pathway for each grid cell.
- The *Flow Accumulation algorithm* (Figure 4) calculates the contributing drainage area for each cell by summing all upstream cells that drain to it.
- Using the derived flow direction data, the model extracts stream segments as connected flow paths between network nodes (Figure 5).
- The drainage area discretization establishes a hierarchical sub-basin structure where each stream reach receives runoff from its delineated contributing area (Figure 5).

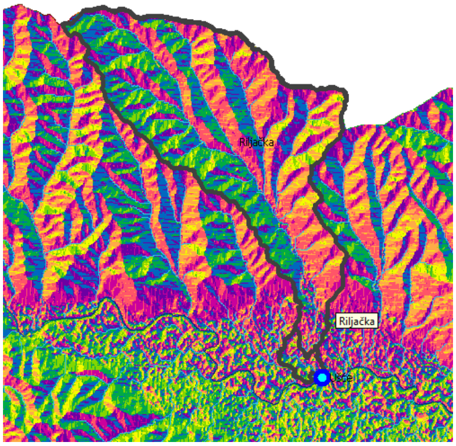

Figure 3. Flow direction

Figure 4. Flow Accumulation

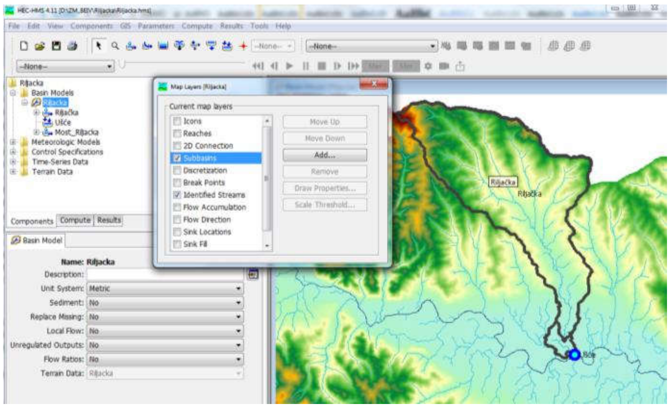

Figure 5. Stream identification and Elements delineation in HEC-HMS model

The second step involves **flood flow estimation**, which is highly dependent on data availability, basin size, and data quality. In contemporary hydrological practice, a combined approach is frequently employed, integrating:

- The Synthetic Unit Hydrograph (SUH) method for runoff hydrograph estimation;
- The SCS-CN (Soil Conservation Service Curve Number) method for effective rainfall separation.

Key emphasis is placed on establishing relationships between basin geomorphological characteristics (e.g., slope, drainage density, shape) and SUH parameters, including: effective rainfall duration (t_k), lag time (t_p), time of concentration (T_c), time to peak of hydrograph (T_p), recession time (T_r), time base (T_b) and peak discharge of unit hydrograph (q_{max}) [5]. Lag time (t_p) is usually defined as the time from the centroid of rainfall to the hydrograph peak. According to research results in Kolubara River basin in Serbia, the following formula is defined by Janković [6]:

$$t_p = 0.75\left(\frac{LL_c}{\sqrt{s}}\right)^{0.37} \tag{1}$$

Where the parameters refer to: the main stream distance from the divide to outlet (L), the main stream distance from the outlet to the basin centroid (Lc) and weighted channel slope (s).

In HEC-HMS, the synthetic unit hydrograph is derived from rainfall data. For ungauged basins, the dimensionless triangular unit hydrograph remains the most widely adopted approach due to its simplicity and reliance on empirical relationships.

The third step involves **model calibration**, which, due to the absence of local streamflow data, was conducted using regionalized hydrological parameters. Specifically, calibration was performed based on:

- The spatial distribution of specific runoff across the basin;
- Unit hydrograph characteristics (e.g., peak discharge, time parameters);
- Extreme flood probabilities (1% and 2% annual exceedance events).

These parameters were derived from regional studies of the Western Morava River basin [7], ensuring physically consistent estimates despite the lack of local gauging data.

Table 1 shows the characteristics of the Riljačka River basin, hydrologic soil group (*HsG*), ratio of time to peak to recession time (*k*), lag time (t_p) and the theoretical discharge values $Q_{1\%}$, $Q_{2\%}$, $Q_{5\%}$, and $Q_{10\%}$ and its specific runoff ($q_{1\%}$, $q_{2\%}$, $q_{5\%}$, and $q_{10\%}$).

Table 1. Characteristics of hydrological ungauged basin of the Riljačka River and theoretical discharge values and specific runoff at two profiles

Parameter	A	L	Lc	s	HsG	CN	k	tp
	km^2	km	km	%				h
Riljačka - Confluence	77.26	26.07	14.24	0.75	B	86.5	1.52	7.06
	$Q_{1\%}$	$q_{1\%}$	$Q_{2\%}$	$q_{2\%}$	$Q_{5\%}$	$q_{5\%}$	$Q_{10\%}$	$q_{10\%}$
	m^3/s	$m^3/s/km^2$	m^3/s	$m^3/s/km^2$	m^3/s	$m^3/s/km^2$	m^3/s	$m^3/s/km^2$
Theoretical values	101.36	1.31	87.54	1.13	69.79	0.90	56.52	0.73
Parameter	A	L	Lc	s	HC	CN	k	tp
	km^2	km	km	%				h
Riljačka – Bridge Profile	75.48	24.10	12.54	0.82	B	86.38	1.51	6.44
	$Q_{1\%}$	$q_{1\%}$	$Q_{2\%}$	$q_{2\%}$	$Q_{5\%}$	$q_{5\%}$	$Q_{10\%}$	$q_{10\%}$
	m^3/s	$m^3/s/km^2$	m^3/s	$m^3/s/km^2$	m^3/s	$m^3/s/km^2$	m^3/s	$m^3/s/km^2$
Theoretical values	107.57	1.42	92.90	1.23	73.89	0.98	60.10	0.80

Based on the calibrated model and the available rainfall data for the period April–June 2023, the daily peak values of flood waves were calculated. On April 4th, the peak was Q_a=17.8 m^3/s, while on June 12th, the value was Q_j=19.9 m^3/s.

3. METHODOLOGY

3.1. HEC-RAS Model

HEC-RAS enables the modeling of unsteady flow regimes across an entire network of open channels. Unsteady flow is characterized by variability of hydraulic parameters (flow, water level, speed) in space and time [8, 9, 10, 11]. Basic equations for linear, unsteady flow in open channels are Saint Venant equations:

- Mass conservation equation (equation of continuity):

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{2}$$

- Equation of conservation of momentum - dynamic equation:

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right)+g\cdot A\frac{\partial Z}{\partial x}+g\cdot A\cdot I_e=0 \tag{3}$$

Where: Q – flow, A- surface area of the flow profile, I_e – friction slope.

The Saint Venant equations are partial differential equations of the hyperbolic type, which cannot be solved in the general case. By introduction of approximations these equations could be used for the calculation of water levels in open channels under unsteady conditions.

To solve them, it is necessary to set initial and boundary conditions. The initial conditions are the values of the variables along the channel at the initial moment of time (t_0). They are obtained by hydraulic calculation of steady flow for the initial flow value $Q(t_0)$.

Boundary conditions are posed:

- External – defined at the profiles at the upstream and downstream end of the calculation reach. At the upstream end, a hydrograph or graph of water levels can be specified, and at the downstream end a hydrograph, level graph or flow curve.
- Internal ones are given at profiles where there is an estuary, a dam, side overflow etc.

3.1.1. 1D Hydraulic model

Hydraulic flow calculations for the Riljačka River, based on computed discharge values during the flood events of April and June 2024, were performed using the HEC-RAS 6.0 software.

Hydraulic analysis of the Riljačka River flow were carried out along the section extending from nest in the West Morava River upstream to Regional Road 187, over a length of approximately 3.5 km.

The following characteristic discharge values were adopted: for the flood peak on April 4, Qa=17.8 m³/s; for June 12, Qj=19.9 m³/s; as well as the 50-year return period discharge ($Q_{2\%}$= 87.7 m³/s) and the 100-year return period discharge ($Q_{1\%}$=101 m³/s).

Due to vegetation growth within the stream channel, a Manning's roughness coefficient of n=0.08 $m^{-1/3}s$ was adopted. For overbank flow across agricultural areas, a value of n=0.12 $m^{-1/3}s$ was used.

Boundary conditions were posed at both ends of the modeled river reach as follows: at the downstream end "normal depth" boundary condition was applied with an energy slope of 0.01%, since the Riljačka River was effectively discharging into the West Morava without backwater effects. At the upstream end, "critical depth" condition was assigned, along with "mixed flow regime" specification to allow for a possible transition between flow regimes within the computational reach.

Two geometric scenarios were analyzed and compared.

- Flow of large floodwaters within the Riljačka River riverbed without a temporary crossing

- Flow of large floodwaters within the Riljačka River channel with installed temporary crossing with culvert designed of four pipes of inner diameter of 800 mm, immediately upstream of the highway route.

3.1.2. 2D Hydraulic model

2D model was developed, and unsteady flow analysis were performed to verify the flow regime during the large flood waves event appearance with return periods of 50 and 100 years. The 2D model was generated based on the Digital Elevation Model (DEM) for the area extending from km 27+500 to km 42+000.

To simulate the runoff, simulated 30-hour hydrographs were generated for the Riljačka River basin. All hydrographs have peaks equal to the maximum discharges calculated in HEC-HMS.

These simulated hydrographs (Figure 6) are very useful for obtaining the response of the basin, as well as for determining the flow paths and locations of runoff accumulation, and for assessing the impact of the E-761 highway on the water regime.

Two digital terrain models were used, and thus two scenarios were created:

- Before the construction of the highway E-761
- During the construction of the highway E-761

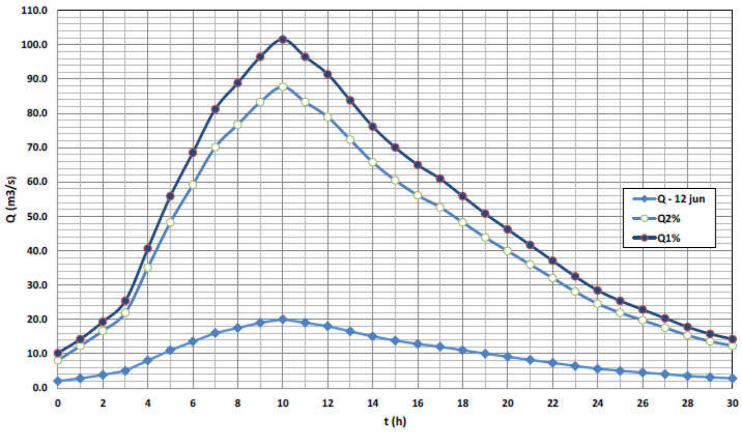

Figure 6. Hydrographs of the flood waves on the Riljačka River

4. RESULTS AND DISCUSSION

4.1 Results of 1D calculations

For the flood peak Qj= 19.9 m³/s in Scenario 1 (without a temporary crossing), water would overflow the riverbed downstream of the crossing location, as well as over a shorter section immediately upstream of the temporary crossing location.

In the case of Scenario 2, water also overflows the natural riverbed, but the impact of the temporary crossing is minimal and not significant, as the crossing would be completely submerged. Under real field conditions, the soil embankment would quickly wash away and disintegrate.

Flood peak discharges $Q_{2\%}$ = 87.7 m³/s and $Q_{1\%}$ = 101 m³/s, for both scenarios would result in extensive water overflow across both riverbanks along the entire section downstream of Regional Road 187.

The computed longitudinal profiles are shown in Figures 7 and 8.

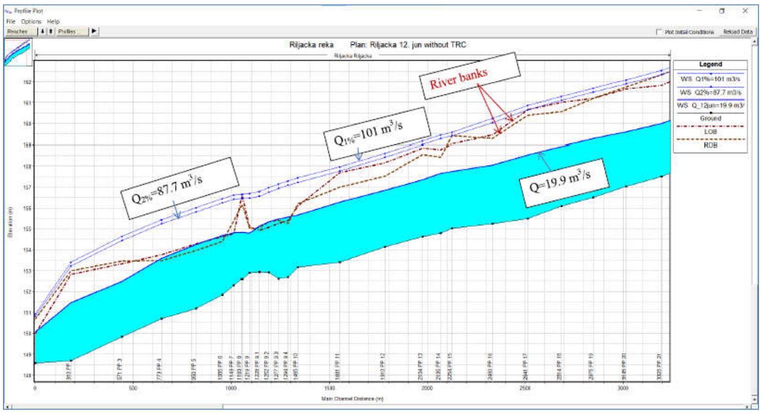

Figure 7. Longitudinal profile of the Riljačka River without the temporary crossing (Scenario 1) – Qj=19.9 m³/s, $Q_{2\%}$=87.7 m³/s, $Q_{1\%}$=101 m³/s

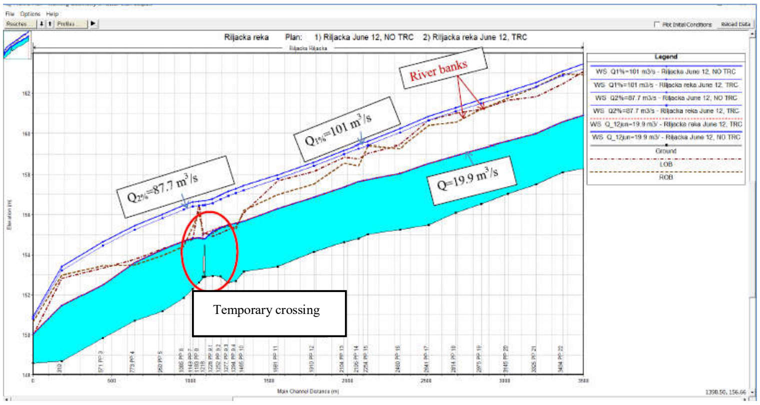

Figure 8. Longitudinal profile of the Riljačka River with the temporary crossing (Scenario 2) – Qj=19.9 m³/s, $Q_{2\%}$=87.7 m³/s, $Q_{1\%}$=101 m³/s

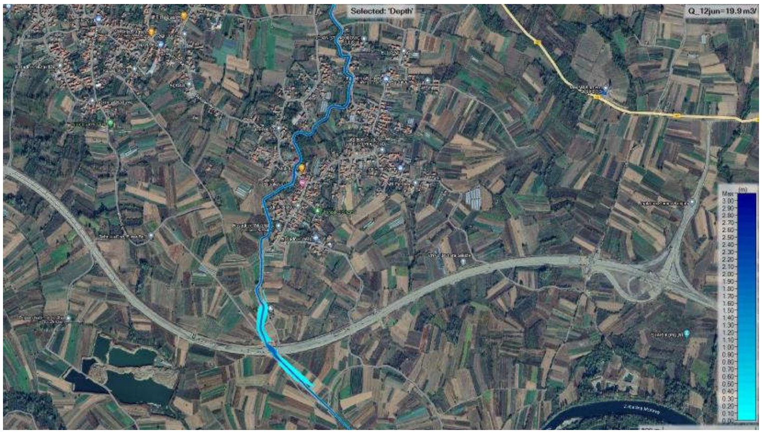

Figure 9. Comparative Analysis of Scenario 1 – Existing Riverbed Conditions and Scenario 2 – Temporary Crossing Installed for the peak flood wave on the Riljačka River (Qj=19.9 m³/s).

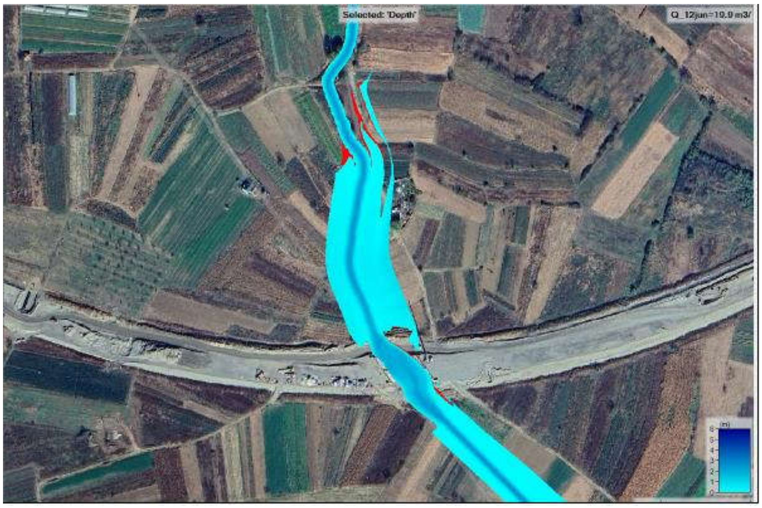

Figure 10.Extent of flooded area without and with the temporary crossing installed, Qj=19.9 m³/s.

Figures 9 and 10 show the extent of the flooded area for April 4, 2023, and June 12, 2023, corresponding to the flood peak discharge of Qj = 19.9 m³/s. The flooded area in Scenario 1-flow within the river channel without a temporary crossing-is shown in blue, while the flooded area in Scenario 2-with temporary crossing placed within the channel-is shown in red in the lower layer.

4.2 Results of 2D calculations

Figure 11 shows the flooded area resulting from the arrival of a 50-year flood wave of the Riljačka River ($Q_{2\%}$=87.7 m³/s) for Scenario 1, representing the terrain conditions prior to highway construction. Due to the flat terrain in the West Morava valley, there is a clear possibility of water overflow from the Riljačka River into the basin areas of the Bezimeni Stream 2 and the Toponička River. The highway alignment intersects the Riljačka River floodplain, making it very difficult to fully preserve the pre-construction hydraulic regime.

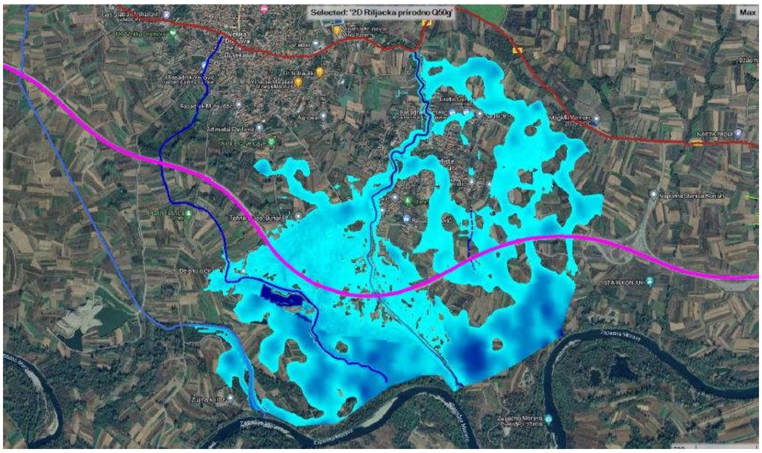

Figure 11. Flooded area resulting from the 50-year flood wave of the Riljačka River ($Q_{2\%}$=87.7 m³/s) under pre-construction conditions of the E-761 highway

Figure 12 shows the flooded area resulting from the arrival of a 50-year flood wave of the Riljačka River ($Q_{2\%}$=87.7 m³/s) for Scenario 2, representing the terrain conditions after highway construction. In Scenario 2 as well, water overflows into the basin areas of the Bezimeni Stream 2 and the Toponička River. A noticeable change in the shape of the floodplain is observed compared to the pre-construction state, as part of the area on the southern side of the highway is effectively protected, while on the northern side the floodplain extends westward.

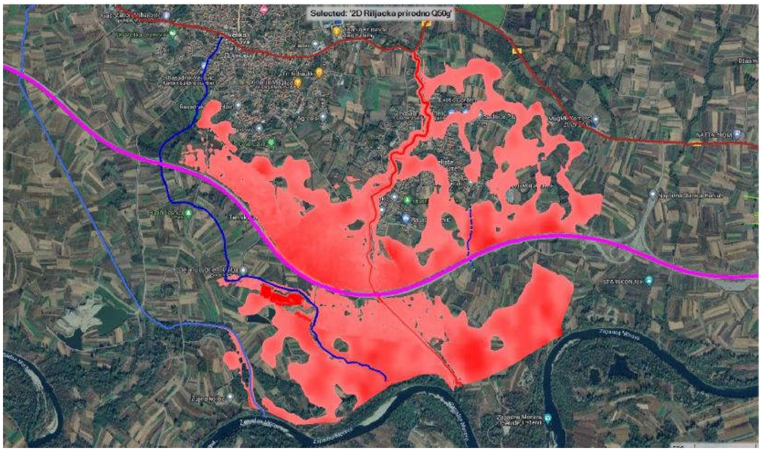

Figure 12. Flooded area resulting from the 50-year flood wave of the Riljačka River ($Q_{2\%}$=87.7 m³/s) under post-construction conditions of the E-761 highway.

Figure 13 shows the flooded area resulting from the arrival of a 100-year flood wave of the Riljačka River ($Q_{1\%}$=101 m³/s) for Scenario 1, representing the terrain conditions prior to highway construction. Due to the flat terrain in the West Morava Valley, there is a clear possibility of water overflow from the Riljačka River into the basin areas of the Bezimeni Stream 2 and the Toponička River. The highway alignment intersects the Riljačka River floodplain, making it very difficult to fully preserve the pre-construction hydraulic regime. The shape and extent of the floodplain are very similar to those for the 50-year flood.

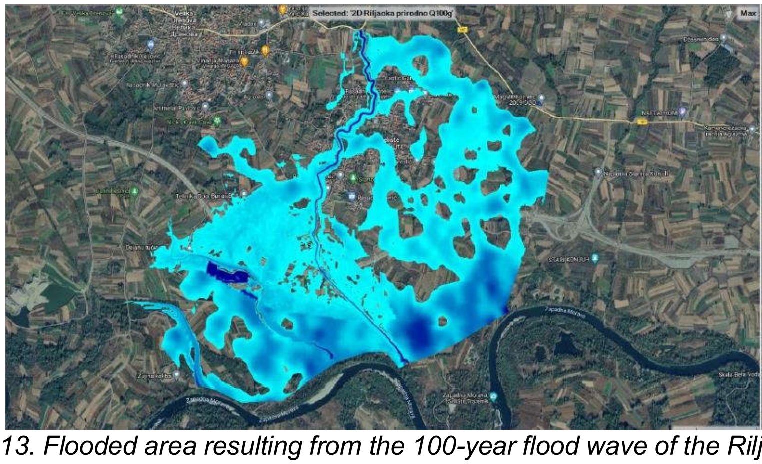

Figure 13. Flooded area resulting from the 100-year flood wave of the Riljačka River ($Q_{1\%}$ = 101 m³/s) under pre-construction conditions of the E-761 highway.

Figure 14 shows the flooded area resulting from the arrival of a 100-year flood wave of the Riljačka River ($Q_{1\%}$=101 m³/s) for Scenario 2, representing the terrain conditions with the built highway E-761. In Scenario 2 as well, water overflows into the basin areas of the Bezimeni Stream 2 and the Toponička River. A noticeable change in the shape of the floodplain is observed compared to the pre-construction period, as part of the area on the southern side of the highway remains effectively protected, while on the northern side the floodplain extends westward. The shape and extent of the floodplain are very similar to those for the 50-year flood.

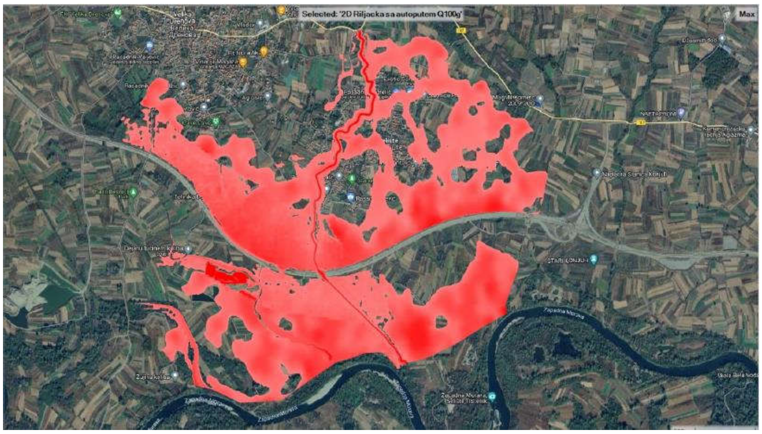

Figure 14. Flooded area resulting from the 100-year flood wave of the Riljačka River ($Q_{1\%}$=101 m³/s) under post-construction conditions of the E-761 highway.

5. CONCLUSION

The magnitudes of the extreme flow events of the Riljačka River were estimated based on created digital terrain model and data analysis from the nearest rainfall stations.

An analysis in the HEC-HMS software determined that on April 4th and June 12th, large flow waves occurred, resulting in water overflowing beyond the main riverbed of the Riljačka River.

From the calculated data, it can be concluded that the lowest part of the Riljačka River channel, downstream of the E-761 highway route, has a very small impact on runoff formation, meaning that the dominant influence comes from the wave collecting in parts of the basin area upstream of the E-761 highway. Additionally, and importantly, the maximum flow values at the bridge profile remain unchanged, indicating a very limited impact of the highway on the hydrological regime.

For the isolated events that occurred on April 4th and June 12th, for Scenario 1, under natural conditions before the highway construction, there is a minor overflow of the watercourse in the highway alignment zone. For Scenario 2, due to the installation of a temporary crossing with the culvert 4x800 mm, a slight backwaters is created over a length of approximately fifty meters upstream of the installed crossing.

During major 50-year and 100-year flood events, significant overflow occurs from the riverbed of the Riljačka River. Such events are not uncommon on the Riljačka River; on the contrary, they can be considered frequent. This is further exacerbated by the condition of the watercourse, which is overgrown with vegetation and contains large amounts of deposited waste material in certain sections, often leading to flooding of nearby settlements.

For the calculation of flood zones during major flow events, a 2D unsteady flow model was applied using generated 30-hour flood wave hydrographs.

It was observed that, due to the terrain configuration, flood flows of the Riljačka River-particularly in areas located within the floodplain of the West Morava River-result in overflow from the Riljačka River basin into the basins of the Bezimeni Stream 2 and the Toponička River.

Following the partial construction of the E-761 highway, changes in the hydrological regime have occurred. On the northern side of the E-761, the highway interrupts the natural north-south surface flow, causing water to accumulate on the western side of the bridge over the Riljačka River, while changes on the eastern side are significantly less pronounced. On the southern side of the highway, certain areas have become considerably less susceptible to flooding due to the construction of the highway.

Due to the terrain configuration along which the E-761 alignment runs-specifically, along the edge of the 100-year floodplain of the West Morava River-the natural hydrological regime has inevitably been altered, resulting in changes to the shape of the floodplains of both the Riljačka River and other torrential watercourses.

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