Data Collection, hydraulic and morphological modelling of the Danube River and the Sava River in the Republic of Serbia
Lot 1: Hydraulic and morphological modelling of the SRB-HRV common stretch of the Danube River

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INTEGRATED STUDY ON ALTERNATIVE SOLUTIONS

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EXECUTIVE SUMMARY

Project purpose and context

The sustainable development and maintenance of inland waterways stand at the intersection of environmental protection, transport infrastructure policy, and regional cooperation. Nowhere is this more evident than along the shared Serbian–Croatian stretch of the Danube River, where environmental sensitivity, transboundary coordination, and navigational needs converge. As a core component of the Trans-European Transport Network (TEN-T), this section of the Danube holds strategic importance for the economic and logistical integration of the region, while also constituting a valuable aquatic and ecological corridor protected under multiple layers of international, EU, and national legislation.

In this context, the project titled **Data Collection, hydraulic and morphological modelling of the Danube River and the Sava River in the Republic of Serbia, Lot 1: Hydraulic and morphological modelling of the SRB-CRO common stretch of the Danube River** was launched with the primary objective of identifying the most appropriate and sustainable alternatives for improving navigation conditions, while simultaneously ensuring full compliance with environmental protection standards.

The Contract is financed by the European Union through the Connecting Europe Facility (CEF) and the European Investment Bank (EIB), under the Finance Contract Serbian Inland Waterway Infrastructure between the European Investment Bank and the Republic of Serbia.

The project serves the following core purposes:

- **Support EU Integration and TEN-T Objectives**: By improving conditions along a key segment of the Danube Corridor, the project contributing to cross-border connectivity, trade, and mobility and advances Serbia's integration into the Trans-European Transport Network (TEN-T), strengthening alignment with EU transport policy objectives;
- **Achieve Good Navigation Status (GNS)**: in accordance with the **EU NAIADES Action Plan** and national commitments. The project addresses navigational challenges (bottlenecks) - primarily caused by dynamic water level variations - on the shared Croatian–Serbian stretch of the Danube River which may hinder navigability if unmitigated;
- **Address Navigation Bottlenecks**: Frequent and significant water level fluctuations, sedimentation, and morphological changes create physical bottlenecks that hinder safe and efficient transport. The project aims to identify and mitigate these issues through hydrological and morphological modelling
- **Promote Environmentally Sustainable Transport**: Inland waterways are a low-emission alternative to road transport. The project supports modal shift goals by making river navigation more attractive, safe, and reliable - thereby reducing carbon emissions and contributing to climate goals;
- **Enable Evidence-Based Planning**: By generating high-quality data and modelling results, the project provides a technical foundation for future investment, and maintenance planning across the common Danube sector.

Key issues addressed include the development of **hydrological and morphological models**, reassessment of **Low and High Navigation Water Levels (LNWL/HNWL)**, analysis of **critical bottlenecks**, and formulation of sustainable mitigation measures - variants for future infrastructure related measures on the common Danube sector. These efforts are supported by stakeholder collaboration through the Stakeholders' Forum platform and contribute to the integration of the Danube Corridor into the Trans-European Transport Network (TEN-T).

Scope and limitations

Key Technical Components of the Project:

- Development of a 1D hydraulic model, as stipulated in the Terms of Reference (ToR), to simulate flow conditions, support the calculation of updated Estimated Navigation References (ENRs), and provide an initial understanding of the river's hydraulic behavior. However, the Consultant opted to develop a 2D hydraulic model covering the entire river stretch, as this approach proved more suitable—the outcomes of the 2D model offered significantly greater analytical value;
- **Prioritization of critical river sections** based on hydraulic performance, navigational constraints, and environmental sensitivity;
- Implementation of a **2D hydrodynamic and morphological model** for detailed analysis of sediment transport and riverbed evolution;
- Application of **multi-criteria analysis** to evaluate and define optimal intervention variants considering technical, environmental, and economic criteria;
- **Definition of next steps** to guide planning for potential future investments in the identified priority sections.

Key limitations of the Project:

1. Data and Modelling Constraints

- Data availability and quality: Incomplete hydrological, topographical, and sediment data confined the model’s applicability to medium- and low-discharge conditions;
- As a result, the model's resolution and calibration involved a trade-off between spatial and temporal detail and computational feasibility. This compromise has implications for predictive reliability.
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2. Environmental and Regulatory Challenges

- Cross-border coordination: The Danube stretch is shared between Serbia and Croatia; differing national priorities or regulatory interpretations can affect planning and implementation;
- Environmental sensitivity: Interventions may conflict with Natura 2000 or other ecological protection requirements, limiting the range of viable engineering solutions.

3. Institutional and Operational Barriers

- Stakeholder alignment: Achieving consensus among agencies, ministries, and local communities may be time-consuming and politically sensitive.
- Follow-up investment uncertainties: The project defines next steps, but securing funding and political commitment (including unresolved border issue) for potential interventions can pose future risks.

4. Limitations in Scope

- Non-navigation-related impacts: Broader basin-scale issues such as climate change, land use changes, and upstream sediment management may lie outside the project’s remit yet significantly affect outcomes.
- Focus on priority sections: Improvements in selected critical areas may not resolve systemic issues without complementary interventions upstream or downstream.

- The divergence between some Stakeholder Forum members' expectations regarding the integrative approach and the Consultant’s Terms of Reference (ToR) suggests a misalignment in operational scope. While stakeholder engagement is essential for ensuring inclusive and sustainable outcomes, it is equally important that expectations are grounded in the agreed mandate and deliverables of the Consultant. This gap may reflect differing interpretations of what constitutes an "integrative approach"—whether it emphasizes ecological restoration, multimodal transport planning, or cross-sectoral coordination. If joint goals were not clearly defined or communicated at the outset, it could lead to perceived underperformance, even if the Consultant operated within the boundaries of the ToR.

Project Approach Overview

The project adopts an integrated, data-driven, and stakeholder-informed methodology aimed at supporting evidence-based planning for inland waterway infrastructure enhancement along the common Danube sector.

1. **Frameworks and Methodological Orientation** - the approach is grounded in EU best practices and the strategic orientation of the *NAIADES Action Plan* and the *TEN-T policy framework*. It aligns with requirements for achieving Good Navigation Status (GNS) under the EU Common Transport Policy, while also addressing environmental compatibility and cross-border coordination obligations.
2. **Data Acquisition and Analysis**
    - Quantitative data:
        - Historical and real-time hydrological datasets, topographical surveys (including bathymetric measurements), sediment transport data, and flow regime statistics;
        - Cross-sectional measurements and riverbed morphology assessments;
        - Water level and discharge series at various gauging stations.
    - Qualitative inputs:
        - Expert elicitation, institutional feedback, and river administrations experience;
        - Environmental and regulatory constraints collected from stakeholders.
3. **Modelling Tools and Techniques**
    - Development of a **1D hydraulic model** to simulate flow profiles along the river sector under varying discharge conditions;
    - Deployment of a **2D hydrodynamic and morphological model** to assess sediment dynamics and predict riverbed evolution over time;
    - **Scenario-based simulation** to evaluate impacts under different navigation, infrastructure, and water level conditions. Calibration and validation were based on observed datasets to ensure technical robustness and predictive reliability.
4. **Stakeholder Engagement** - A Stakeholders’ Forum was established to ensure transparency, gather multi-sectoral input, and foster coordination. Participants included representatives of different governmental and non-governmental bodies.

5. **Analytical and Decision-Support Tools**
    - Use of **multi-criteria analysis (MCA)** to compare potential intervention options based on economic, technical, environmental, and navigational performance indicators;
    - Development of prioritization metrics to rank critical sections of the river for future investment.

    These tools ensured objectivity and traceability in the selection of preferred variants.

6. **Planning for Future Investment** - the approach initial proposal of **recommended measures and next steps**, including preliminary technical concepts, risk factors, and data needs to support investment programming and permit procedures for subsequent infrastructure works.

Key findings

Based on the activities conducted and analyses presented throughout the project, several substantive insights have emerged. These findings reflect both technical achievements and critical observations, offering a foundation for future planning, decision-making, and potential investment. They highlight the strengths of the applied methodology, identify remaining data or coordination gaps, and underscore the practical implications of the modelling outcomes. Key findings are summarized below:

- The development of a comprehensive hybrid 2D hydraulic model covering the entire joint river stretch has resulted in a tool that supported the revision of **Low Navigation Water Levels** (LNWLs) and provides a solid foundation for more detailed 2D hydraulic analyses of the most critical sectors;
- Despite identified limitations in available topographic and hydrological datasets, the hybrid model demonstrated satisfactory agreement between simulated and observed water surface levels within the low-flow domain;
- The hydrological analysis highlighted the need to enhance the quality of hydrological data and improve data harmonization between Serbian and Croatian gauging stations to ensure consistency and reliability in future modelling efforts;
- Based on the available hydrological data at 8 hydrological stations, the hydrological study delivers information on hydrological regime of the Danube River along the common stretch of the Danube River from the Hungarian border to Bačka Palanka. All aspects of water regime are covered (mean, low and flood flows);
- All newly observed **LNWL and HNWL levels for the period 1994–2023 are higher** compared to those previously reported to the Danube Commission. This shift is primarily attributed to an increase in low flows (Q94%) by 14–24% and a decrease in high flows (Q1%) by 6–8% relative to the values used in earlier calculations. The hydrological recalibration of reference water levels reflects the evolving discharge regime in the Serbian–Croatian sector of the Danube River;
- The application of the Level of Service (LoS) concept and its integration with morphological assessment and historical hydrographic data resulting in the identification of **4 most critical navigation bottlenecks (Apatin, Čivutski/Židovski Rukavac, Drava Confluence and Staklar)**. In support of holistic system-based planning, the Consultant also recommends amending the current bottleneck list to include the **Aljmaš** sector, as the integrated modeling would provide improved foresight into river dynamics and navigation risks;

- A Multi-Criteria Analysis (MCA) framework has been employed to holistically evaluate alternative solutions. The classification of criteria into four domains—**navigation, environment, feasibility, and climate vulnerability**—ensured that recommended measures are technically effective, environmentally responsible, implementable, and resilient to future uncertainties. By assigning proportional weights to each category (40% navigation, 40% environment, 15% feasibility, 5% climate resilience), the MCA accommodates both operational mandates and sustainability objectives;
- The use of the Weighted Product Model and discrete scoring thresholds—anchored by a "Do-nothing" baseline—provides a transparent, evidence-based mechanism for ranking scenarios;
- The project identified key problematic areas where sediment accumulation and unstable morphology compromise the fairway. A suite of nature-inclusive structures—such as chevrons, detached groynes, sills, and opening of the sidearm channels—was proposed to restore flow dynamics while preserving ecological integrity. Evaluations indicated that these measures can enhance navigational efficiency, minimize maintenance costs, and minimize environmental impact and even create beneficial microhabitats for aquatic and riparian species.
- According to the adopted criteria and the corresponding scores, the scenario proposing new river training structures is considered optimal (Scenario 4 which includes 2 chevrons, 1 detached groyne and 6 sills). However, it should be taken into account that planning in the field of navigation must examine in more detail the connection between the main Danube channel and the floodplains, and thus the broader impact of the proposed measures on the environment. Therefore, in this project, the conclusions must be taken with caution, as this connection has only been considered indirectly (the impacts of the proposed solutions on lateral water and sediment transport and their effects on the ecosystem have been considered only indirectly). In this context, the necessity of intersectoral cooperation at the state level, as well as cooperation between countries within the Danube basin, is particularly emphasized.

Recommendations

It should be noted that both Serbia and Croatia are signatories to all relevant international agreements and actively participate in the implementation of international initiatives concerning inland waterways and inland navigation.

With respect to bilateral arrangements, Serbia and Croatia signed the Agreement on Navigation on Inland Waterways and their Technical Maintenance in 2010. However, the two countries have not yet concluded an interstate agreement regarding the delineation of the border along the Danube River.

To promote sustainable and effective inland navigation along the Danube River, a set of general recommendations has been developed. These address key environmental, operational, and governance challenges and provide a framework for responsible development that aligns with EU principles and regional cooperation priorities:

Holistic Development of Inland Navigation - Promote resilient and sustainable navigation infrastructure by integrating innovative solutions that protect and enhance the ecological integrity of the Danube River. River restoration and meandering should be included in holistic inland navigation development—**when they are ecologically justified, technically feasible, and strategically aligned** with broader EU and national objectives. The goal is not to compromise navigation, but to design infrastructure that supports both **resilient transport** and **healthy river ecosystems**.

Tailored Adaptive Measures - Apply a context-specific mix of structural, nature-based, and non-structural interventions to optimize navigation outcomes while minimizing environmental impact.

Integrated River Management - Address the interplay of physical, ecological, and social processes. Develop strategies that enhance coordinated river system management, mitigate potential conflicts, and support long-term sustainability.

Alignment with EU Principles - Ensure compliance with the Do No Significant Harm principle and the EU Taxonomy Regulation to maintain high standards of environmental and sustainability performance across all infrastructure planning activities.

Cross-Border Administrative Cooperation - Enhance coordination between Serbian and Croatian waterway authorities to jointly address and manage identified bottlenecks along their shared sector of the Danube River.

The following specific recommendations are organized by implementation horizon (short-, medium-, and long-term) and thematic focus, and include designated ownership to guide accountability and follow-up action.

I. Short-Term Actions (0–2 years)

Theme: Forwarding of Calculated LNWL and HNWL Data

- The calculated LNWL and HNWL data to be forwarded to the Croatian river administration and officially submitted to the Danube Commission to update the old records and incorporate the new data into regular use on the common Danube sector.

Ownership: National (Serbian) waterway authorities

Theme: Work of both river administration on the Bottleneck Catalogue at the shared sector of the Danube

- Both administrations to regularly update adopted Bottleneck Catalogue to ensure effective management and navigation improvements;

Ownership: Both waterway authorities

Theme: Delivery of the software and Targeted Training

- To provide technical justification and full documentation of selected modeling software.
- To provide targeted training on 1D and 2D hydrodynamic modelling to Serbian river administration staff—and to Croatian counterparts, in order to build internal capacity for scenario analysis, model interpretation, and adaptive river management;

Ownership: Consultant

Theme: Sustainable solutions

- Both administrations to explore opportunities to develop potential sustainable solutions for addressing navigational challenges in prioritized bottlenecks;
- Both administrations to adopt the MCA approach in the planning process with inclusion of relevant experts to ensure structured and effective decision-making;

- Application of the 2D model to serve as a capacity-building exercise and be integrated into regular planning operations for both administrations.

Ownership: Both waterway authorities

Theme: Decision Support and Environmental Integration

- Use ecological assessments and zero-state analysis to support preparation of the Environmental Impact Assessment (EIA).

Ownership: Both waterway authorities, national environmental authorities

II. Medium-Term Actions (2–5 years)

Theme: Hydrological data and services

- Coordination and cooperation of hydrometeorological services of Serbia and Croatia that would lead to harmonization in terms of measurements, data collection and data processing;
- Future studies assessing reference water levels should rely on hydrological stations with at least 30 years of continuous data records, in line with international best practices. As Croatian stations are expected to reach the 30-year threshold by 2030, a new reference level assessment can be scheduled for that time.

Ownership: Both waterway authorities and state hydrometeorological services of Serbia and Croatia

Theme: Monitoring and Mitigation Planning

- Design and propose an ecological monitoring Programme aligned with EU environmental directives.

Ownership: Both waterway authorities, national environmental authorities

III. Long-Term Actions (5+ years and beyond)

Theme: Implementation and Adaptive Management

- Develop long-term maintenance and adaptation plans based on 2D model outcomes and MCA prioritization;
- Embed climate resilience criteria into future infrastructure designs.

Ownership: Both waterway authorities supported by transport ministries

Theme: Monitoring

- Evaluate performance of nature-inclusive structures (if any established) (e.g., chevrons, sidearms) by establishing key monitoring indicators and benchmarks.

Ownership: Both waterway authorities.

Implications / next steps / Definition of the next steps for future investments

1. Consolidation of Strategic Inputs

- Review outcomes of available documentation and modeling analyses (1D/2D hydraulic results, sediment transport, ecological assessments).
- Confirm scenario selection through stakeholder endorsement or governing body decisions.
- Clarify regulatory context—particularly permitting frameworks, cross-border coordination, and environmental obligations.

2. Technical Scoping and Design Parameters

- Define the technical scope of interventions, including boundaries of works, performance objectives, and integration with existing infrastructure.
- Lock in design criteria, such as reference water levels (e.g., LNWL, HNWL), vessel classes, fairway dimensions, and roughness coefficients, with traceable justifications.
- Incorporate site-specific constraints, e.g., erosion-prone zones, ecological sensitivities, or navigational bottlenecks.

3. Data and Documentation Readiness

- Ensure geospatial and topographic datasets (e.g., bathymetry, riverbank geometry, sediment profiles) are accurate, complete, and quality-assured.
- Check hydrological and hydraulic modeling outputs to serve as design baselines.
- Secure all supporting reports and approvals from earlier project phases (e.g., stakeholder consultations, MCA results, environmental screening).

4. Institutional and Procedural Coordination

- Establish clear ownership of tasks, with identified technical leads, oversight bodies, and communication protocols.
- Coordinate with regulatory authorities to identify technical requirements for permitting (including environmental and navigational authorities).
- Validate compliance requirements, including national standards, Danube Commission guidelines, and EU directives (e.g., WFD, EIA, Birds & Habitats Directives).

5. Outline Documentation Structure

- Draft the structure and content map for the technical documentation (e.g., general design report, detailed design drawings, bill of quantities).
- Plan integration of complementary documents, such as risk assessments, cost estimations, and environmental mitigation strategies.
- Schedule internal reviews and agree on quality control checkpoints during preparation.

Limitations of the project and recommendations for future initiatives

Throughout the implementation of the project, several technical, organizational, and data-related constraints have emerged:

1. Technical Limitations
   - Incomplete floodplain data: Several Stakeholders forum meetings highlighted gaps in floodplain mapping, which hindered hydraulic modeling for high waters;
   - Modeling constraints: Limited calibration data for low-flow conditions and sediment transport reduced confidence in long-term morphological projections;
   - Infrastructure data gaps: Inconsistent input data for river structures (e.g. groynes, embankments) affected scenario reliability.
2. Organizational Limitations
   - Fragmented stakeholder coordination: Divergent stakeholder priorities—namely, a predominant focus on river restoration and the promotion of one-way navigation, while neglecting efforts to enhance overall navigation conditions—have diverged from the Terms of Reference and consequently delayed consensus on key project parameters;
   - The lack of a holistic approach—evidenced by the absence of active participation from Inland Waterway (IWW) experts in the Stakeholders Forum—limited the depth and balance of technical discussions and constrained the integration of navigation-specific perspectives into key project decisions;
3. Data-Related Limitations
   - Missing historical datasets: hydrological records were partially unavailable, limiting analysis;
   - Some relevant geospatial and bathymetric data were unavailable;
   - Inconsistent metadata standards: Variability in data formats and documentation complicated integration.
   - environmental datasets should be systematically incorporated into the modelling framework through interdisciplinary collaboration. This would support a MORE holistic and evidence-based approach, aligning hydraulic performance with ecological sustainability.

Recommendations for Future Initiatives

1. Capacity Building
   - Implement targeted training programs for institutional staff on hydraulic modeling, GIS integration, and environmental compliance;
   - Develop a stakeholder engagement framework to streamline coordination and feedback mechanisms.
2. Technical Enhancements
   - Invest in updated floodplain mapping using LiDAR and satellite imagery to close existing data gaps;
   - Expand model calibration datasets through coordinated field campaigns;

- Adopting a more collaborative and participatory approach in MCA would likely yield more balanced, transparent, and context-sensitive decisions. This method fosters shared ownership of outcomes, encourages diverse perspectives, and helps align technical feasibility with policy priorities and operational realities.

3. Procedural Improvements

- Introduce a pre-contract validation protocol to ensure all baseline data and stakeholder inputs are confirmed before project launch;

4. Strategic Planning

- Align future project phases with EU Green Deal and regional climate adaptation strategies to enhance funding eligibility.
- Integrate lessons learned into updated Terms of Reference for upcoming feasibility and design studies.

5. Strengthen Stakeholder Engagement

- Promote regular and meaningful engagement, with particular emphasis on underrepresented stakeholder groups to ensure balanced representation and inclusive decision-making;
- Engage external experts at the early stages to foster technical continuity, strengthen collaborative dynamics, and support informed project development across all phases.
- Clear articulation of shared objectives during early consultation phases;
- Transparent communication of the Consultant's scope and limitations;
- Mechanisms for adaptive collaboration, allowing stakeholder input to inform implementation without compromising contractual obligations.

6. Institutional Coordination

- Establish regular bilateral coordination meetings between national waterway authorities to facilitate continuous dialogue, streamline decision-making, and resolve transboundary operational issues;
- Form cross-sector technical working groups—covering disciplines such as hydrology, ecology, and navigation—to promote integrated planning, ensure technical cohesion, and align project outcomes with both environmental and navigational priorities.

Technical characteristics of the finally proposed variants

The study developed four distinct scenarios including different solutions:

Scenario 1 (Baseline) serves as a benchmark "do nothing" approach, modeling morphological changes using dominant discharge methodology to set reference natural river evolution without intervention.

Scenario 2 (Structural and Revitalization) introduces non-traditional structural measures emphasizing both navigation improvement and environmental protection, including chevrons in the Apatin sector and 60-meter wide sidearm channels in the Drava confluence and Aljmaš sectors.

Scenario 3 (Minimal Intervention) represents a business-as-usual approach focusing on fairway realignment without large-scale physical interventions, optimizing navigation through route adjustments.

Scenario 4 (Comprehensive Measures) combines traditional structural measures with nature-inclusive solutions, incorporating proposed structures included in Scenario 2 elements plus additional detached T-groynes and sills across multiple sectors.

The final design variants for river training structures along the Danube River comprise five types of solutions:

1. Chevron Structures

- The adopted chevron structures feature a distinctive horseshoe-shaped design constructed from crushed stone materials ranging from 15 to 45 cm in size.
- These structures maintain standardized dimensions with a crest width of 3 meters and asymmetrical slopes configured at 1:2 upstream and 1:3 downstream. The structural height is calibrated to the Low Navigation Water Level (LNWL) + 1 meter, ensuring optimal visibility during critical navigation periods.
- A significant engineering advantage lies in their construction methodology, as chevrons are typically built on existing sandbars, substantially reducing material requirements compared to conventional river training structures.
- The final design incorporates chevrons at river kilometers 1405.000 and 1404.50.

2. Sill Structures

- Proposed are stone sills with a maximum grain size of 45 cm, which will serve as submerged structures for flow redistribution and erosion control in affected zones.
- The structures maintain consistent geometric specifications with a crest width of 3 meters and slope configurations of 1:1.5 upstream and 1:3 downstream.
- The structural height varies with a maximum of approximately 7 meters, with dimensions calculated based on desired hydraulic effects.
- The final design encompasses sill structures across three critical sectors: Apatin, Drava confluence, and Staklar, with structures positioned at river kilometers 1401.000, 1400.600, 1382.800, 1382.600, 1375.600, and 1375.200.

3. Detached T-Groyne Structure

- The detached T-groyne represents an eco-friendly alternative to traditional groyne systems, featuring the characteristic T-shaped configuration. The design creates channels between riverbanks and structure that enable longitudinal connectivity for aquatic organisms.
- The structure maintains standardized dimensions with a crest width of 3 meters and slope ratios of 1:2 upstream and 1:3 downstream. The structural height follows the established standard of LNWL + 1 meter for optimal navigation safety.
- The construction employs a dual-material approach: the structural body utilizes smaller stone fractions of 15 cm, while the top protective layer incorporates stones up to 45 cm. The final design places this structure at river kilometer 1393.400.

4. Sidearm Channel Systems

- The sidearm channels constitute comprehensive revitalization measures that simultaneously address navigation requirements and ecological enhancement.
- The final design specifies a channel width of 60 meters, determined through extensive 2D modeling analysis that evaluated incremental widths from 15 to 60 meters.
- The channels feature trapezoidal cross-sections with 1:1 bank slopes and a longitudinal slope of 0.002.
- Construction methodology involves excavation through existing groyne systems, requiring complete removal of select existing groynes.
- Bank protection utilizes stones recovered from excavated groyne bodies, while channel bottoms remain natural with partial stone coverage from surplus groyne materials.
- The final implementation encompasses two primary sectors: Drava confluence and Aljmaš, with channels designed to follow the local riverbed slope of the main channel.

5. Fairway Realignment Specifications

- Apatin Sector Modifications: Three problematic locations underwent radius adjustments where geometrically feasible. At Location 1 (rkm 1408.200 – 1407.300) radius was reduced from 4,450 to 2,600 meters, while at Location 2 (1404.600 – 1402.500) radius increased from 9,010 to 9,150 meters.
- Čivutski Rukavac Constraints: Five critical locations were identified (rkm 1396.750-1396.000, 1395.450-1394.750, 1393.100-1392.600, 1390.950-1390.400, and 1390.000-1389.400), but no fairway realignment was possible due to constricted riverbed conditions.
- Drava Confluence Adjustments: Limited modifications were implemented at three locations, with radius changes from 2,050 to 1,900 meters at Location 1 (rkm 1386.00 – 1384.700), and complex multi-radius configuration (R1=1,000m, R2=3,000m, R3=1,700m) replacing the original 5,000-meter radius at Location 3 (rkm 1382.500 – 1381.000).
- Staklar Sector Modifications: There is one problematic location from the aspect of the width of the fairway. Since the location is also problematic from the aspect of the radius itself, the fairway realignment has not been proposed in this sector.

Definition of the next steps for future investments

To ensure the long-term impact of project outcomes, the following actionable next steps are proposed for the both waterway administration and relevant Ministries:

1. Investment Planning Framework

- Establish a detailed roadmap outlining priority infrastructure segments and investment needs;
- Conduct a gap analysis based on current project outputs and national development objectives;
- Define investment phasing and funding strategies to support future feasibility and implementation phases.

2. Feasibility and Environmental Assessment

- Initiate feasibility studies and updated environmental impact assessments for identified bottlenecks;
- Ensure these assessments are aligned with EU directives and national legislative frameworks.

3. Stakeholder Coordination

- Develop a coordination protocol with relevant ministries, local authorities, international financial institutions and all other interested parties.

4. Institutional Preparedness

- Review administrative procedures to ensure streamlined execution of upcoming projects.

5. Regulatory and Technical Alignment

- Harmonize design standards with EU navigation and environmental guidelines.

6. Monitoring and Evaluation Mechanism

- Establish a monitoring system with defined indicators for tracking future investment progress.

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ABBREVIATIONS

Abbr.	Meaning
1D	One dimensional (model, modeling)
2D	Two dimensional (model, modeling)
AD	Akcionarsko društvo (Joint-Stock Company)
AGN	European Agreement on Main Inland Waterways of International Importance
CA	Contracting Authority
CEF	Connecting Europe Facility
cm	centimeter
CS	Critical sector
DEM	Digital Elevation Model
DHMZ	State Hydro-meteorological Service of Croatia
DTM	Digital Terrain Model
EIA	Environmental Impact Assessment
EIB	European Investment Bank
ENR	Etiage navigable et de régularisation
EU	European Union
EUSDR	European Union Strategy for the Danube Region
FABDEM	Forest And Buildings removed Copernicus DEM
GIS	Geographic Information System
GNS	Guidelines Towards Achieving a Good Navigation Status
H	Stage (water level)
HEC-RAS	Hydrologic Engineering Center's River Analysis System
HNQ	Discharge at high navigation level
HNWL	High Navigation Water Levels
HRV	Croatia
IWT	Inland Waterway Transport
JS	Joint Statement on Guiding Principles for the Development of Inland Navigation and Environmental Protection in the Danube River Basin
km	Kilometer
LIDAR	Light Detection and Ranging
LNQ	Discharge at low navigation level
LNWL	Low Navigation Water Levels
m	Meter
m^3/s	Cubic meters per second
maAs	meters above Adriatic Sea
m.a.s.l.	Meters above sea level (Trieste/Adriatic See)
Max	Maximum
MCA	Multi-Criteria Analysis
Min	Minimum

Abbr.	Meaning
MoCTI	Ministry of Construction, Transport and Infrastructure
N/A	Not applicable
NAIADES	Action plan for boosting future-proof European inland waterway transport
PIANC	World Association for Waterborne Transport Infrastructure
PLATINA	PLATform for Implementation of NAiades
Q	Discharge
ref.	Reference (State or Value)
SEA	Strategic Environmental Assessment
SHDI	Shannon Diversity Index
SRB	Serbia
TBR MDD	The Transboundary Biosphere Reserve Mura-Drava-Danube
TEN-T	Trans-European Transport Network
TIN	Triangulated Irregular Network
ToR	Terms of Reference
UN	United Nations
UNFCCC	UN Framework Convention on Climate Change
WFD	Water Framework Directive
WWF	World Wildlife Fund

INTRODUCTION

The Contract "Data Collection, hydraulic and morphological modelling of the Danube River and the Sava River in the Republic of Serbia, Lot 1: Hydraulic and morphological modelling of the SRB-HRV common stretch of the Danube River" is financed by the European Union under the Connecting Europe Facility (CEF) Programme and the European Investment Bank, under the Finance Contract Serbian Inland Waterway Infrastructure between the European Investment Bank and the Republic of Serbia. The Contracting Authority (CA) is the Ministry of Construction, Transport and Infrastructure (MoCTI) of the Republic of Serbia. The service contract was concluded between the MoCTI and the Hidrozavod DTD AD Novi Sad (hereinafter referred to as the Consultant).

The overall objective of the project is to contribute to the creation of competitive transport system by the improvement of infrastructure alongside the Danube River, in accordance with the national policy and strategy provisions and with the respect of EU transport system development plans in order to ensure fast, safe, reliable and environmentally friendly transportation, smooth flow of freight and mobility of people. Integrated planning approach and inter-sectoral cooperation through the Stakeholders' Forum platform is planned throughout the process.

A key goal of the project is to support the **achievement of Good Navigation Status (GNS)** as required under the **EU's NAIADES Action Plan** and related national commitments. GNS ensures that the Danube River and its infrastructure are maintained at levels that guarantee efficient and reliable navigation. The project contributes to these goals by identifying and addressing **navigation challenges (bottlenecks)** in the common Croatian - Serbian stretch of the Danube River (river-km 1433.1 to 1295.5). These challenges, primarily caused by dynamic water level alteration, if not addressed properly, can negatively affect the overall navigation.

The project activities focus on developing hydrological and morphological models, reassessing Low and High Navigation Water Levels (LNWL/HNWL), analyzing critical navigational bottlenecks, preparing potential sustainable solutions to address the navigational challenges in prioritized bottlenecks, and promoting stakeholder collaboration. These actions align with the overarching transport-related objectives of improving connectivity, efficiency, and safety across the EU's inland waterway network, thus contributing to a seamless integration of the Danube Corridor into the broader Trans-European Transport Network (TEN-T).

Environmental objectives and considerations in the project are defined through the compliance with the EU Environmental Legislation (Habitats[1] and Birds[2] Directive) and Water Framework Directive[3], in particular, with the requirements of Article 4(7). The Project is in the core zone of the **UNESCO five-country Transboundary Biosphere Reserve Mura-Drava-Danube**, which spans Austria, Slovenia, Croatia, Hungary, and Serbia, promoting cross-border cooperation in sustainable river basin management and biodiversity conservation.

Furthermore, the project adheres to principles outlined in the Joint Statement on Guiding Principles for the Development of Inland Navigation and Environmental Protection in the Danube River Basin, ensuring a balanced approach between navigation improvement and environmental sustainability. By harmonizing navigational improvements with environmental objectives, the project supports integrated river basin management and contributes to broader goals of sustainable development.

The Activity 5 of the Contract deals with the elaboration of study on alternative solutions for the identified and prioritized bottlenecks, based on compilation of results from the Activity 1, Activity 2, Activity 3, and Activity 4, analyzing alternative solutions for improvement of navigations conditions during low water periods.

Chapter 1 of this study contains results of the performed 1D modeling. Chapter 2 deals with the update of reference water levels, mainly the ENRs. The content of the Chapter 3 is the updated catalogue of navigational bottlenecks on the SRB-HRV joint stretch of the Danube River. Chapter 4 of this study contains definition of the methodology for prioritization of navigational bottlenecks, as well as application of the defined methodology for prioritization. The subject of the Chapter 5 is definition of the MCA, commonly agreed among stakeholders prior to the application in the process of analysis of alternative solutions for the earlier prioritized navigational bottlenecks. Chapter 6 of this study deals with the definition of variants for prioritized bottlenecks. The subject of the Chapter 7 of the study is 2D modeling of alternative solutions and their evaluation through commonly agreed MCA, including conclusions.

Transparency of the whole process is ensured by the work of the multidisciplinary Stakeholders' Forum, documented by the Minutes of Meetings held during the period of implementation of the Contract, attached as Annex 1 to this study. Also stakeholders' feedback and the responses of the Consultant are available at the following ink: https://www.plovput.rs/pf2w-eng

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[1] Habitats Directive (Council Directive 92/ 43/ EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora)

[2] Birds Directive (Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds)

[3] Water Framework Directive (Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy)

CHAPTER 1. 1D MODELING

1.1. Introduction

1-D hydraulic modelling is envisioned as the first step in the navigational fairway analysis. Its purpose is to provide a mathematical and engineering framework for identifying bottlenecks along a 140 km common stretch of the Danube River between Serbia and Croatia.

The hydraulic model results should offer reliable prediction of the water surface elevation along this stretch and help determine the available boundaries for navigation fairways according to the Danube Commission's recommendations. In the project's second phase, river sequences within the observed stretch with outlines smaller than those recommended by the Danube Commission will be identified and further analyzed.

The Terms of Reference (ToR) initially foreseen developing a 1D (one-dimensional) hydraulic model that outputs a water stage elevation profile along the common stretch and average velocity at the analyzed cross-sections.

However, after conducting a comprehensive input data analysis and reviewing novel software capabilities, it was found that a **2D (two-dimensional) model of the entire stretch emerged as a more convenient approach**. Namely, all collected, processed and integrated data aggregated into the Digital Terrain Model are the baseline for the 1D and/or 2D hydraulic modelling. In terms of the time required for simulations, the consultant concluded that the application of a 2D flow model allows an acceptable runtime. At the same time, outcomes from the 2D model would be much valuable and concurrently 2D hydraulic model can meet the requirements set out by the ToR and offer additional insights, albeit at a different engineering level. The 2D approach also allows greater flexibility in calibration and more detailed analysis of the calculated velocities and water stages over time.

It is important to emphasize that preparation of the hydrodynamic model is separate activity from the hydrological analysis and update of ENRs, and these two activities will couple after the hydrodynamic model calibration and verification. Therefore, the issue of hydrological analysis and update of ENRs will not be part of the next chapter (– UPDATE OF ENRs).

1.2. Study and Model Area

The common stretch between Serbia and Croatia extends from km 1,433, near the tripoint border of Hungary, Serbia, and Croatia, to km 1,295, where the town of Bačka Palanka on the Serbian side and Ilok on the Croatian side are located. These two towns are interconnected by a bridge. The stretch which is subject of modelling is slightly shorter, since the data available for the modelling are available for the Bezdan/Batina and Bačka Palanka/Ilok gauging stations. The Consultant decided to focus on a Hydrologic Stations (GS) on a Croatian side and to use this data for modelling since the most input data related to bathymetry were obtained from Croatian partners, so the final extent of the project is from Batina at km 1,427 to Ilok at km 1,300.

A detailed map which embraces the whole stretch with topography, measured cross-sections by the single-beam, training works, chainage and location of the relevant Hydrologic Stations are shown in Figure 1.

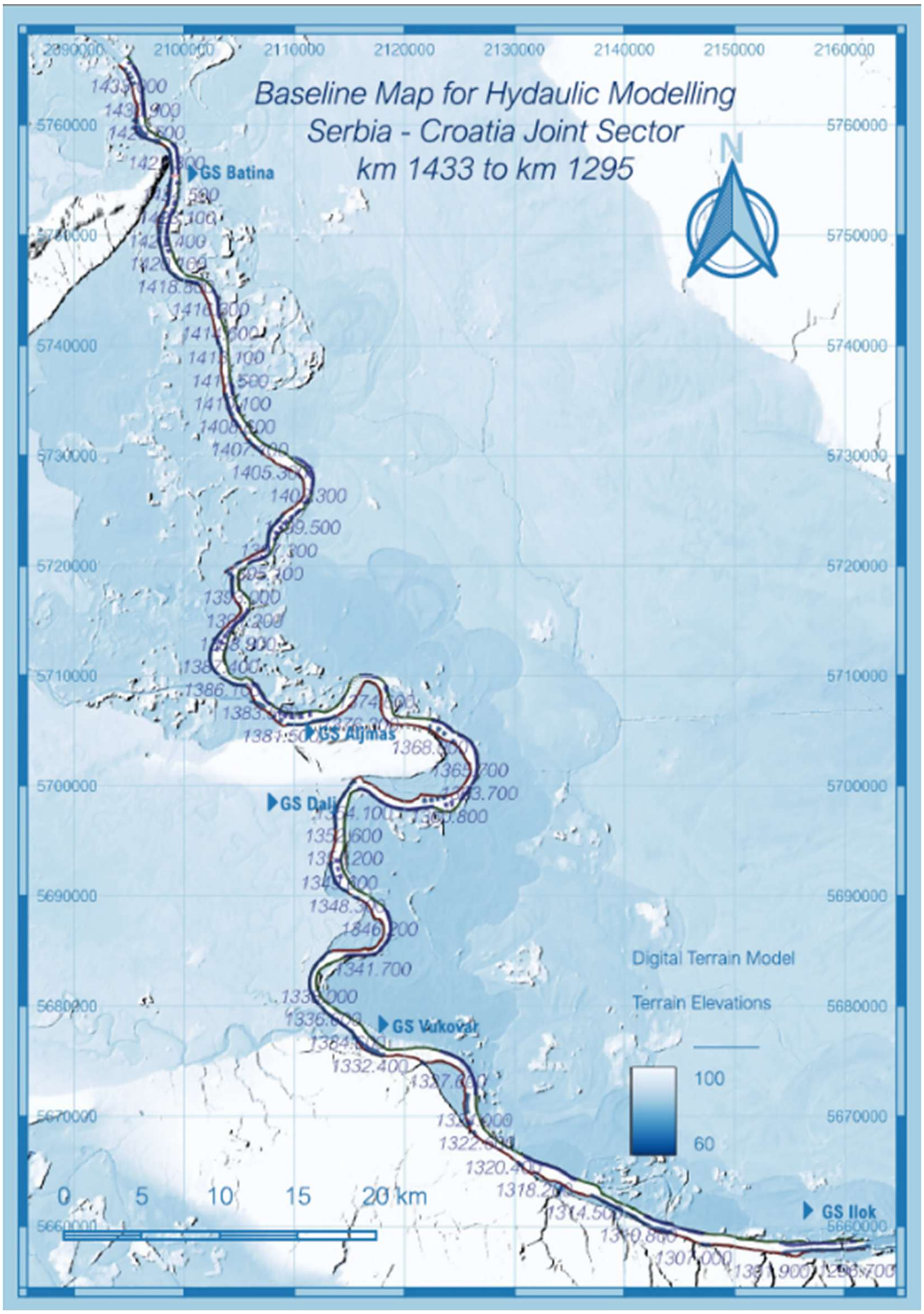


Figure 1: A detailed map of the analyzed stretch with topographic representations, location of the cross-sections, training works and location of relevant Hydrologic Stations

1.3. Model Setup

1.3.1. Data used for the Modelling

The hydraulic modelling process includes several steps: model preparation, review and selection of available hydrologic data suitable for model calibration, model calibration, selection of data for verification, verification, and finally, running the model to determine water surface elevations along the observed section of the Danube. These steps will be elaborated upon in the following text.

The model preparation involves collecting and integrating various data types into the modelling software to simulate and predict flow conditions along the watercourse. The required data can be categorized into two main groups: river geometry and hydrology.

1.3.1.1. River Geometry

Reconstructing river geometry is a challenging task that requires a multidisciplinary approach and the handling of vast amounts of data. These data often come in various formats, with differing levels of accuracy and resolution, and are typically difficult to process. The available data used for reconstructing the river geometry are listed in Table 1.

Table 1: List of available data for the digital definition of the Danube River geometry

Type of data	Format of data
Data collected by the single-beam survey equipment	X, Y, Z triplets and D, Z (distance from the left fixed point, elevation)
Data collected by the multi-beam survey equipment	X, Y, Z triplets in 2 x 2m grid arrangement
Data collected by the LIDAR	X, Y, Z triplets in 5 x 5m and 1 x 1m grid arrangement.
Data about the existing training structures	Data exchange file *.dxf and catalogue of all structures with coordinates, chainage, type of structure and photo.
Data about the pillars of the bridges	Data exchange file *.dxf with charted axes of the bridge and pillars

The quality, coverage, and consistency of the data will be discussed in the following paragraph.

1.3.1.1.1. Preliminary Analysis of Available Spatial Data

All collected data were shared as point cloud data or in a data exchange format. They can be processed as vector data (in the form of mesh), such as TIN (Triangulated Irregular Network), or as raster data, like TIFF (Georeferenced TIFF). Since HEC-RAS operates with raster data, processing the data in raster format is the most natural approach.

Single-Beam Data

The data collected using single-beam equipment are divided into 1,375 files - one file per cross-section. These data have already been processed and quality-controlled, ensuring that all data are aligned with the cross-sections without irregularities. However, the primary disadvantages of this dataset are the disproportion between the spacing of points within each cross-section and the spacing between cross-sections, as well as the lack of data near the riverbank. The point spacing disparity poses a technical challenge for triangulation, while the missing data, particularly along the riverbank, is a more critical issue. Figure 2 illustrates the triangulation problem (A) caused by the varying distances between points along the cross-section and between cross-sections, as well as the issue of missing data (B).

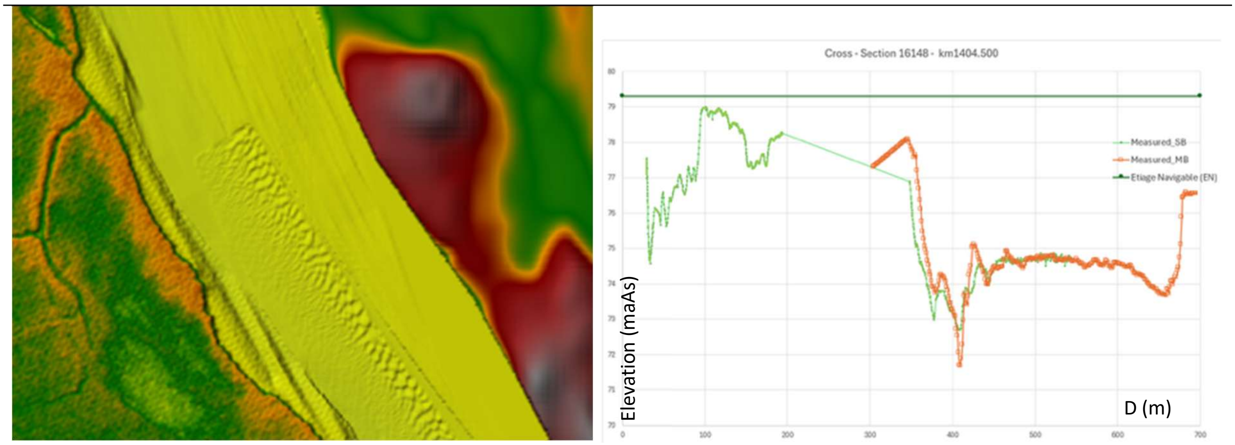


Figure 2: (A) segment of the riverbed composed of data collected by both single-beam and multi-beam methods. (B) Overlapped cross-sections generated from the single-beam and multi-beam data.

Multi-Beam Data

The data collected by the multi-beam equipment are extremely valuable, offering the most detailed representation of riverbed morphology. Segment (A) in Figure 2 demonstrates the significant differences between the surfaces generated from single-beam and multi-beam data and depicts how multi-beam measurements provide an extraordinary level of details (see the display of dunes on the riverbed). For this project, nine locations were surveyed using multi-beam technology. The list of these surveyed locations is provided in Table 2.

Table 2: List of sections surveyed by the multi-beam

Stretch	Chainage
Apatin	km 1,405 to 1,400
Borovo 1	km 1,348.3 to 1,343.8
Borovo 2	km 1,340.55 to 1,337.95
Mohovo	km 1,311.2 to 1,307.8
Sotin	km 1,325.2 to 1,320
Staklar	km 1,377 to 1,373.7
Vukovar	km 1,330 to 1,325.2
Židovski Rukavac	km 1,398 to 1,389
Ušće	km 1,383.5 to 1,381.6

Figure 3 shows the sections of the observed stretch covered by the multi-beam survey (A) and closer view on the section surveyed by the multi-beam with orange gradient colored covered area.

– Orange (darker) is the area that consecutive single-beam measurements cover. The coverage area is generated by connecting the endpoints of the charted cross-sections.

– Orange (gradient) is the area covered by the multi-beam measurement. The borderline is generated manually.

Figure 3: (A) The central part of the observed stretch of the Danube, showing five of the nine regions surveyed with multi-beam equipment. (B) A closer view of the Apatin stretch (the area surveyed by the multi-beam equipment is highlighted in an orange gradient).

The data collected using the multi-beam technique provide significantly better resolution of the riverbed compared to single-beam data. However, the weak point remains the inability to effectively survey shallow waters and areas near the riverbank, as noted in Figure 3. These imperfections, such as poorly surveyed shallow waters and the transition zones between the water surface and riverbanks, were supplemented with data from other sources, notably LIDAR.

LIDAR (Light Detection and Ranging)

The additional geometry data provided by partners as a LIDAR data, collected from aerial surveys, are primarily used for topographic data collection and can be combined with bathymetric data to create a Digital Elevation Model (DEM) of the surface, regardless of whether it is underwater or exposed. After processing, the triangulated LIDAR data the geographical coverage of the LIDAR data appears to be limited, encompassing only the right riverbank and riverbed. This issue relates to international borders, and it is beyond the scope of this project. Interestingly, the LIDAR data also captured information about the riverbed. A preliminary comparison between LIDAR data and data collected by traditional riverbed survey methods shows promising similarities, warranting further exploration of this topic.

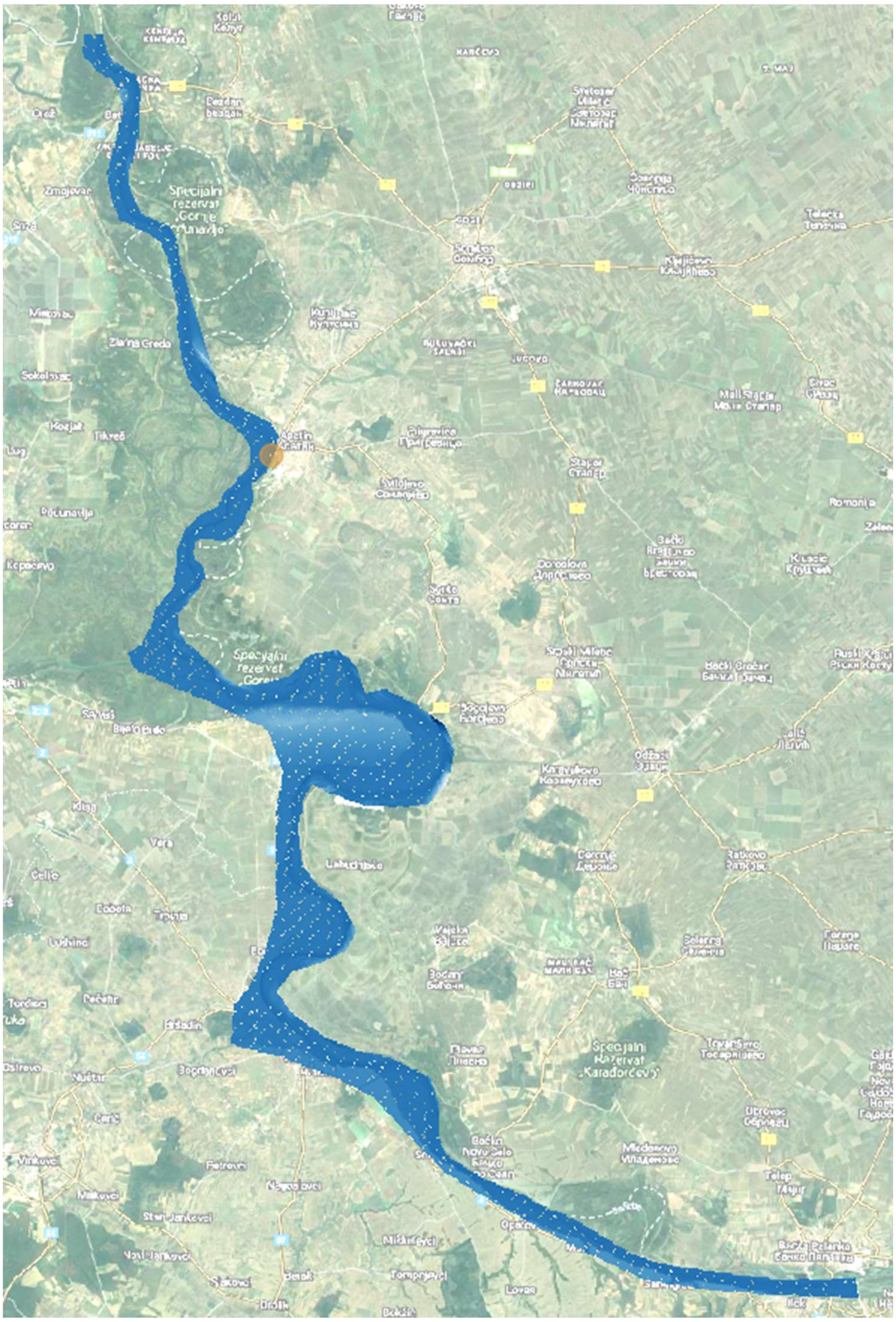


Figure 4: Geographic coverage of the LIDAR survey, showing that only the right riverbank and a portion of the Danube River were surveyed

In certain segments, the alignment between conventional bathymetric surveys and LIDAR-derived data was highly accurate, whereas in others, noticeable discrepancies were observed.

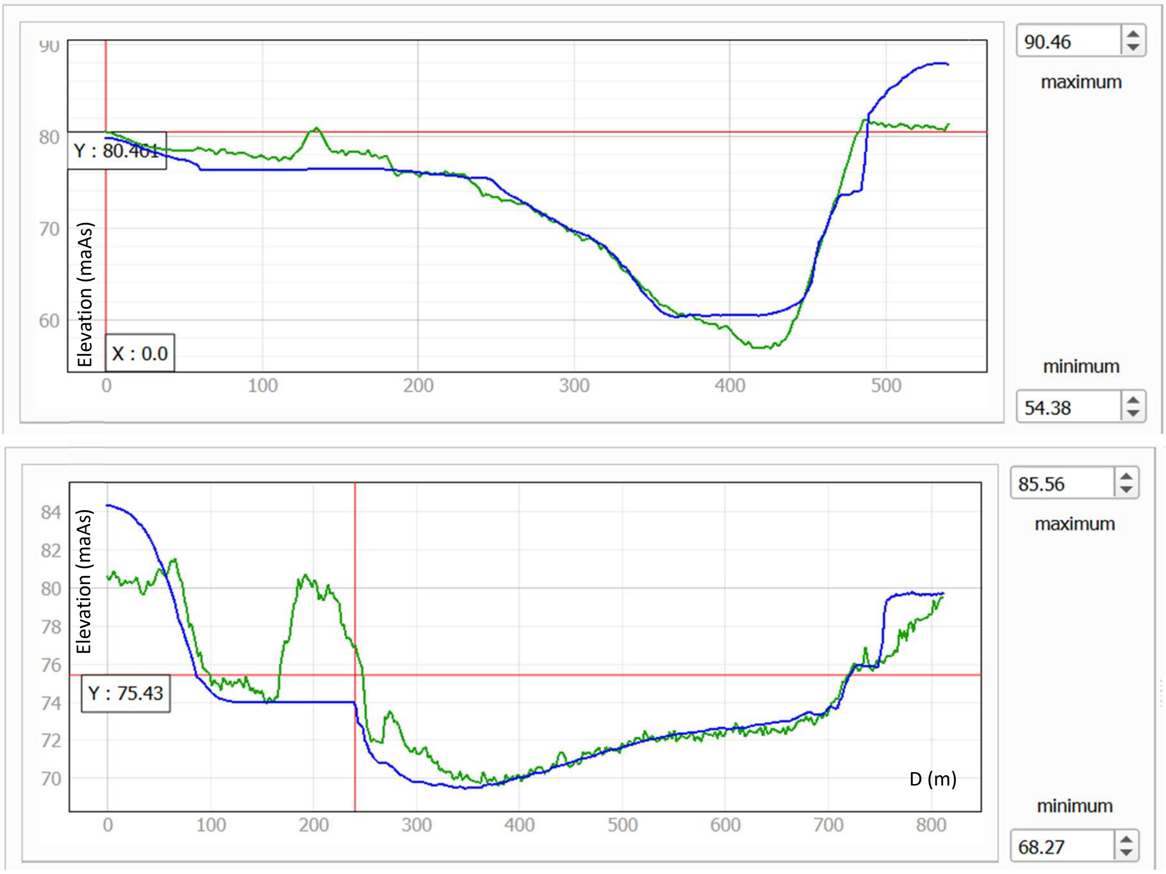


Figure 5: A comparison between two cross-sections is shown, where the green line represents the surface surveyed by LIDAR, and the blue line represents the cross-section through the hybrid model composed of the data described above

The comparison results are encouraging, indicating that LIDAR surveys could provide a valuable data set for an integrated Digital Terrain Model (DTM), given proper validation. When combined with 2D models, such data could offer innovative approaches to navigation information services and river management.

DTM (FABDEM)

To address missing topological data, reliable public sources were used. After thorough research, the FABDEM (Forest and Buildings removed Copernicus DEM) provided by the University of Bristol was identified as the most reliable source. The FABDEM, available at University of Bristol FABDEM, was imported as the background for the entire 137.5 km stretch of the Danube River, with all other collected data integrated as patches onto this DEM.

While the accuracy of the public source data is generally at least two classes lower compared to the collected data, it was the best available option, especially since these data were not critical to the core model. To ensure that the public data did not impact the overall model quality, numerous cross-checks were performed.

1.3.1.1.2. Verification of Hybrid DEM

The control and verification of the Hybrid Digital Elevation Model (Hybrid DEM) are illustrated in Figure 6. It is important to note that missing riverbank data were supplemented, making the Hybrid DTM suitable for river hydrodynamic modelling.

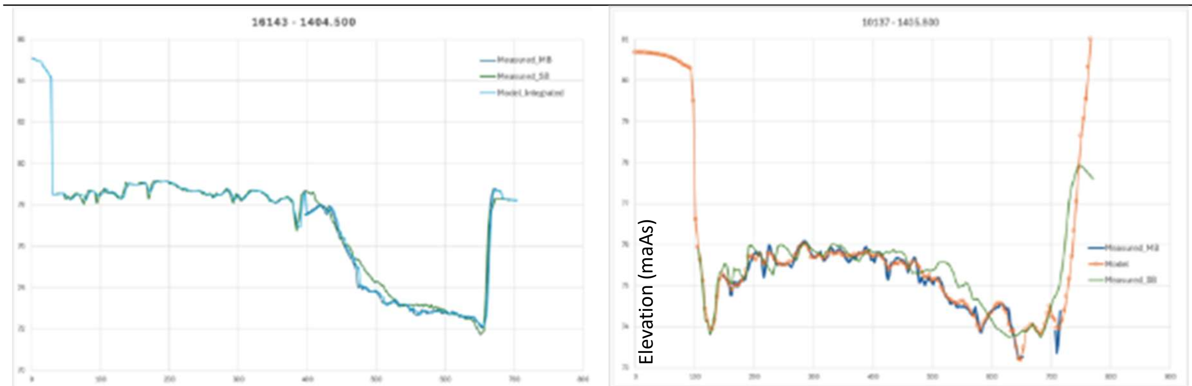


Figure 6: Cross-Section 16143 – 1404.5 and 10137 - 1405.8 Verification of the Hybrid DEM by the comparison between cross-sections: measured by the single-beam, measured by the multibeam and Hybrid DTM model

1.3.1.2. Hydrological Data for the Calibration and Verification of the Model

At this point, we need to separate the hydrological data into two groups. The first group consists of historically collected and statistically analyzed data for model exploitation, which will be discussed in a separate chapter. The second group includes hydrological data necessary for model calibration and verification. This chapter focuses on the calibration and verification data and how to utilize this data in the calibration and verification process.

The hydrological data were derived from two primary sources, the Serbian and Croatian Hydro-meteorological Services, which operate hydrological stations along the common stretch of the river. Additionally, the Danube HIS website, available at Danube HIS, was used as a source for daily and hourly data in some cases.

The hydrological study identified inconsistencies between datasets obtained from Serbian and Croatian gauging stations. As a result, it was concluded that calibration and verification datasets should be sourced exclusively from either the Serbian or Croatian side, since combining data from both may introduce uncontrolled biases that are difficult to mitigate. The modelled water surface elevations will be recurrently compared with values derived from the Rating Curves at each hydrological station to ensure satisfactory calibration results. To maintain consistency in the calibration process, this approach will rely on time-averaged values from Croatian gauging stations where Rating Curves are available.

1.3.2. Modelling Software

HEC-RAS (Hydrologic Engineering Center's River Analysis System) is hydraulic modelling software developed by the US Army Corps of Engineers. Its primary purpose is to simulate water flow, manage river hydraulics, and assess flood risks. HEC-RAS can model both one-dimensional steady and unsteady flow conditions, as well as two-dimensional unsteady flows. It supports the analysis of natural rivers, channels, and hydraulic structures. The software's flexibility and robustness make it highly recommended for detailed hydraulic analysis. Given the superior graphic user interface than other free packages (e.g. Telemac does not have integral Graphical user interface (GUI) for pre-processing, simulation setup and postprocessing) making it easier to set up, modify and run model simulations. Along with the aforementioned, HEC-RAS is an open-source software and it has a large user base with readily available support material.

HEC-RAS also features advanced GIS capabilities for terrain modelling and spatial data analysis, making it highly applicable for real-world scenario simulations. The model is built using river geometry data from various sources, combined into a comprehensive hybrid Digital Elevation Model (DEM). The underlying mathematical model is based on time and depth/cross-sectional averaged Navier-Stokes equations (2D/1D Saint Vennant equations). The 2D Saint-Vennant (so called "Full momentum") equations include components that model water turbulence and Coriolis effects. In this project simplified 2D flow model incorporated in HEC-RAS software as "Diffusion wave equation" option was used as this option is suitable for numerical simulations of gradually varying unsteady flow (integral 2D model). In that case, the results obtained from the application of Diffusive wave equations are not significantly different from the results of the simulations with "full momentum" equations, but Diffusive wave equations are computationally less demanding.

1.3.2.1. Model Inputs

The primary inputs for the modelling process include river geometry, the computational grid (with underlying Digital Terrain Model), boundary conditions based on hydrometric and analyzed data, and geospatial data required for calibrating Manning's coefficient.

River Geometry

The controlled and verified Hybrid DTM was imported as a basic layer for the river geometry definition. The bathymetry of the riverbed, river flow, meandering curves, training structures, river branches, tributaries etc. are determined and georeferenced on this layer. This layer represents the main foundation for all other layers which are associated with the river geometry layer. A representative section of the Hybrid Digital Terrain Model (DTM) is presented in Figure 7.

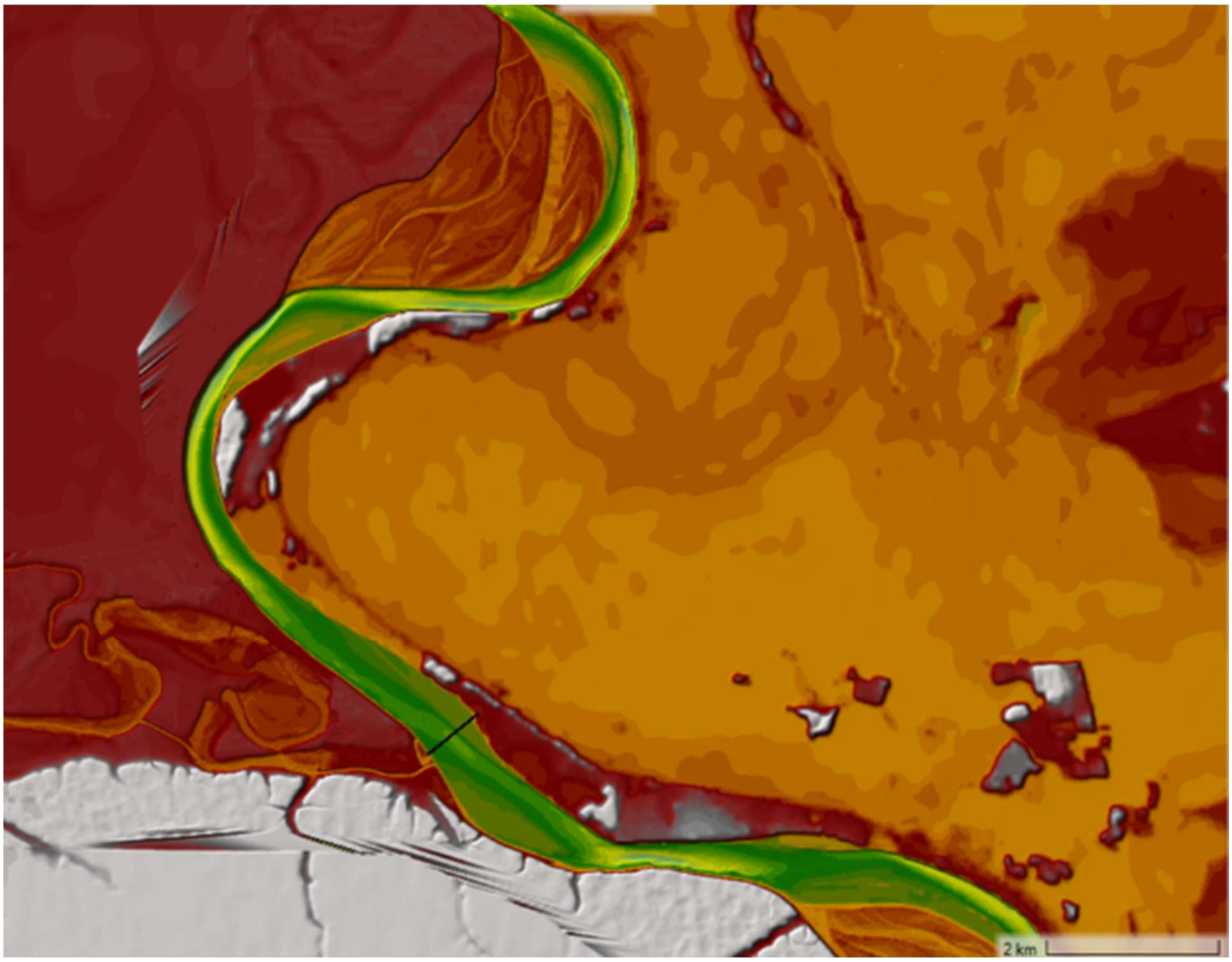


Figure 7: The segment of the Hybrid DEM with riverbed 3D model and terrain of the surrounding floodplain areas

The model of terrain includes the location and shape of the bridge pillars.

Hydrologic data input

The observed stretch of the Danube requires at least three key inputs to simulate natural conditions: the incoming flow from Hungary, the tributary inflow from the Drava River, and downstream boundary conditions corresponding to the imposed flow conditions (discharges).

Model calibration generally required filtered data to eliminate side effects caused by waves (generated by wind or vessels) or uncertainties related to the measurements itself. The aforementioned effects could make calibration impossible task since these effects are not taken into account by adopted hydraulic model. To meet this this requirement, the calculated water surface elevations for determining the optimal values of Manning coefficients were compared with the elevations from the rating curves for the Croatian hydrological stations (Figure 8). In this process, a constant discharge from the domain of low water discharge rates were set at the upstream boundaries of the model (for the same discharges, water surface elevations were read from the rating curves along the Danube as measured values since these values can be considered as filtered values). During the verification procedure, measured water surface elevations from Croatian hydrological stations were used, but a time series representing low-flow conditions without significant oscillations were selected (Figure 9).

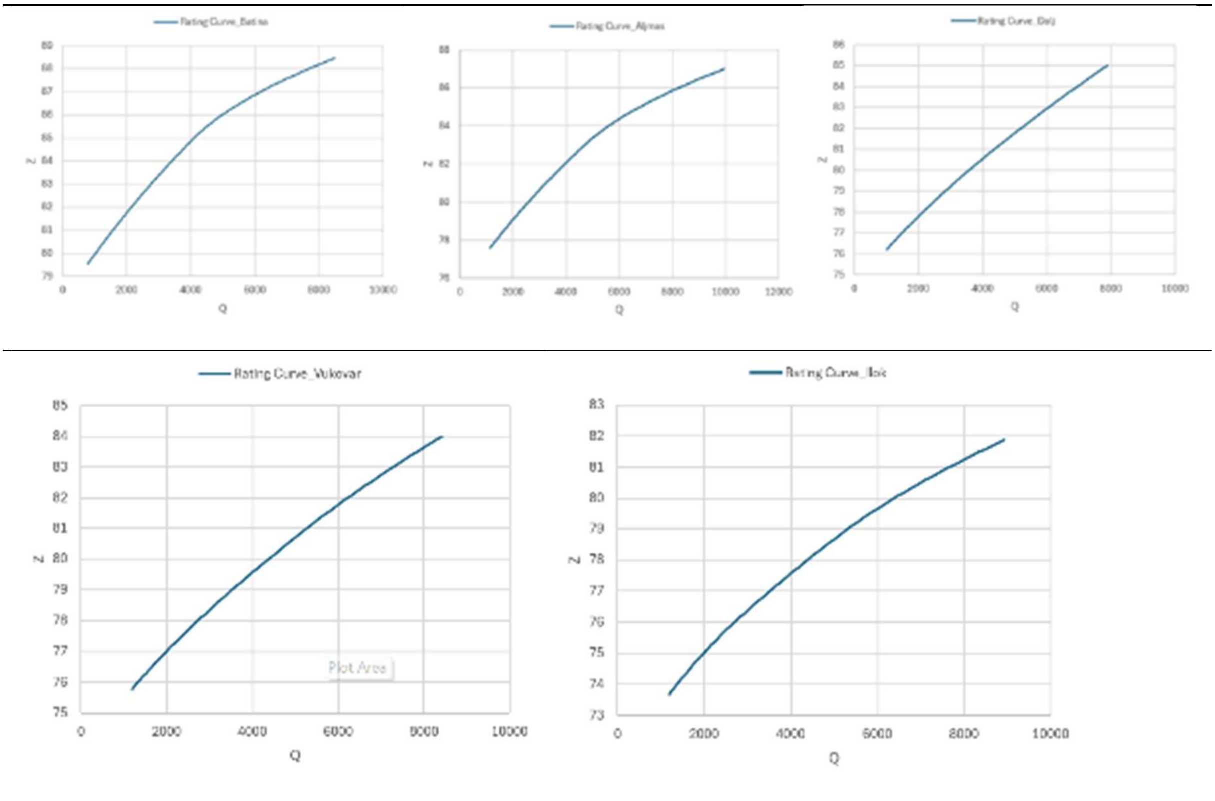


Figure 8: The Rating Curves for the Hydrographic Stations operated by the Croatian Meteorological Institute. Rating Curves respectfully: 1. Batina; 2. Aljmaš; 3. Dalj; 4. Vukovar and 5. Ilok (this rating curve is the boundary condition at the same time)

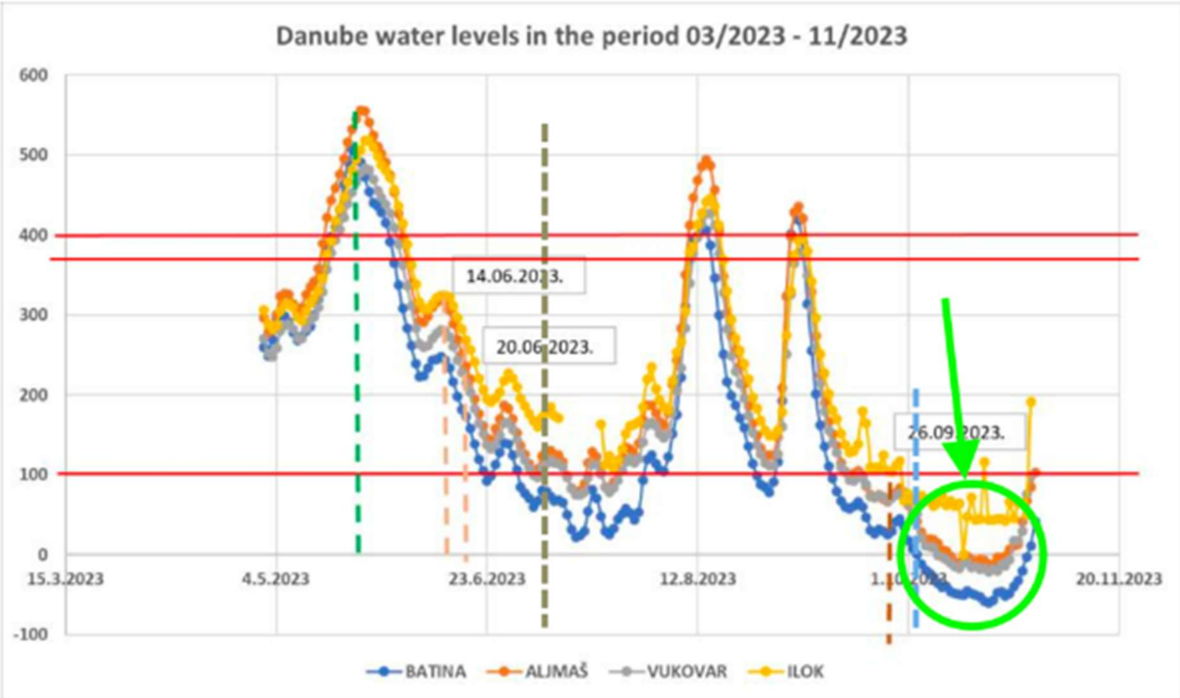


Figure 9: Recorded water elevations on the Danube in the period 03/2023-11/2023 with indicated measurement dates (a portion of time series encircled with green color were used for calibration)

1.3.2.2. Numerical Setup

Computational grid

The model setup process begins with the import and geo-referencing of the terrain data (Hybrid DTM). This terrain layer serves as the foundation for all other layers associated with the river geometry.

The model's perimeter is defined by a polygon that determines the flow domain, acting as a "glass wall" where no water can enter or exit. The model equations apply only within this perimeter. The perimeter polygon was constructed to follow the highest points in the floodplain area and is divided into a grid representing calculation volumes that cover the terrain.

For the river perimeter, a grid of 200x200m squares was applied. While this grid is relatively coarse and may introduce numerical instability, the riverbed was extracted and refined using a 30x30m grid to improve accuracy. The refined grid regions were aligned with the river flow, and break lines were introduced to separate the riverbed from the higher land that defines the floodplain.

Figure 10 illustrates the details of the numerical grid, including its alignment with the river flow and the computational points assigned to each volume (grid square).

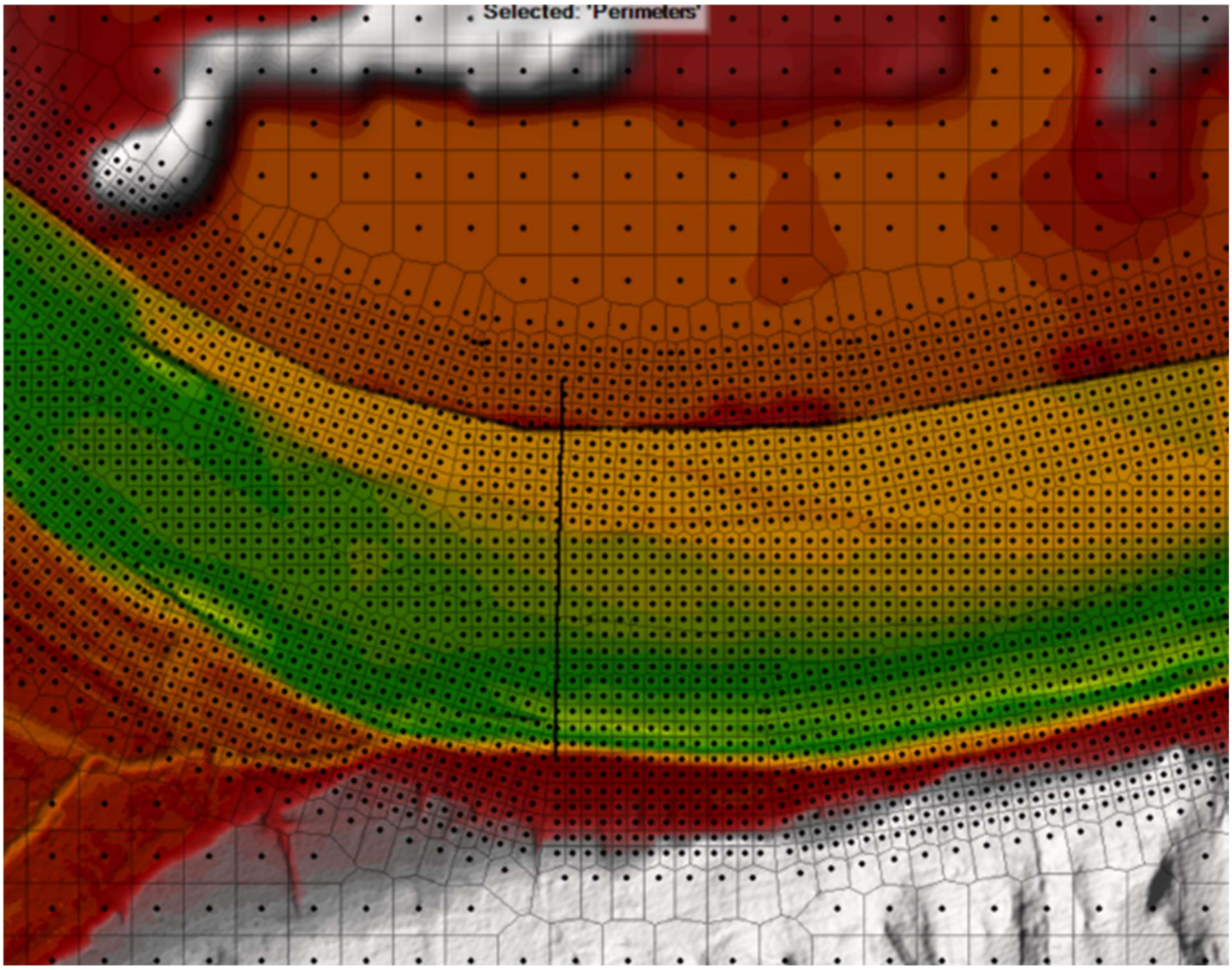


Figure 10: Digital Terrain Model underlined under the numerical grid with calculation points and perimeter border

The numerical grid covering the 140 km stretch of the Danube River comprised approximately 300,000 computational nodes. Manning's roughness coefficient was applied through calibration layers, which were adjusted to span the areas between consecutive hydrological stations. Each of these regions could have a distinct Manning's roughness coefficient, allowing for more precise calibration. Additionally, constructed training facilities were surveyed and incorporated into the Hybrid DEM (Figure 11).

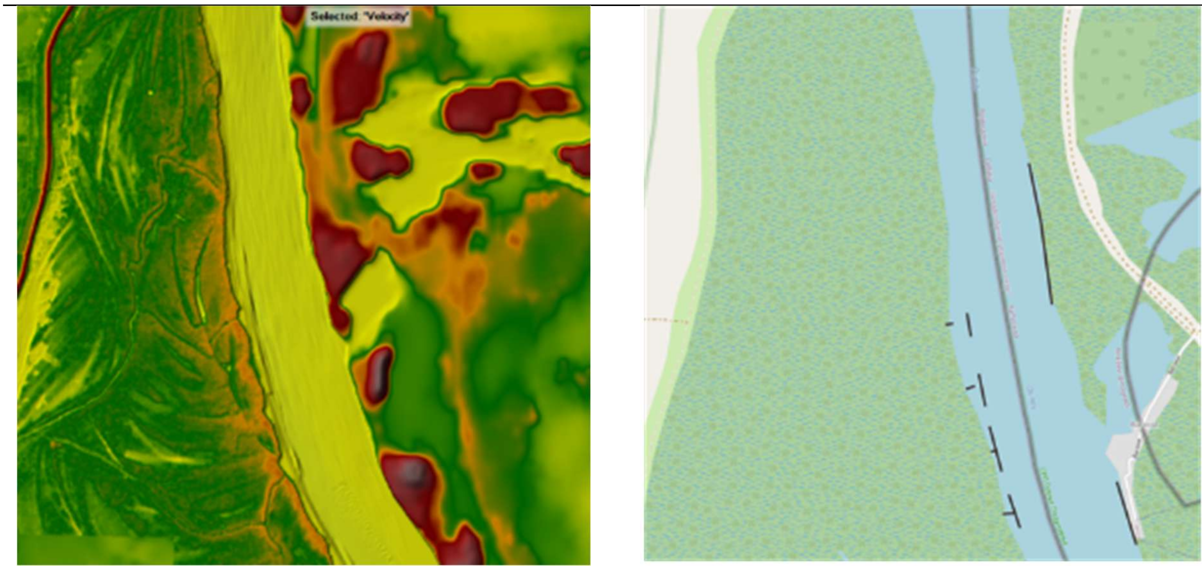


Figure 11: The array of four groynes arranged along the right riverbank

Boundary conditions

The model setup incorporates three boundary conditions (Figure 12). Inflows are provided as hourly hydrographs, while the downstream boundary condition is defined by the Ilok Rating Curve (Figure 13).

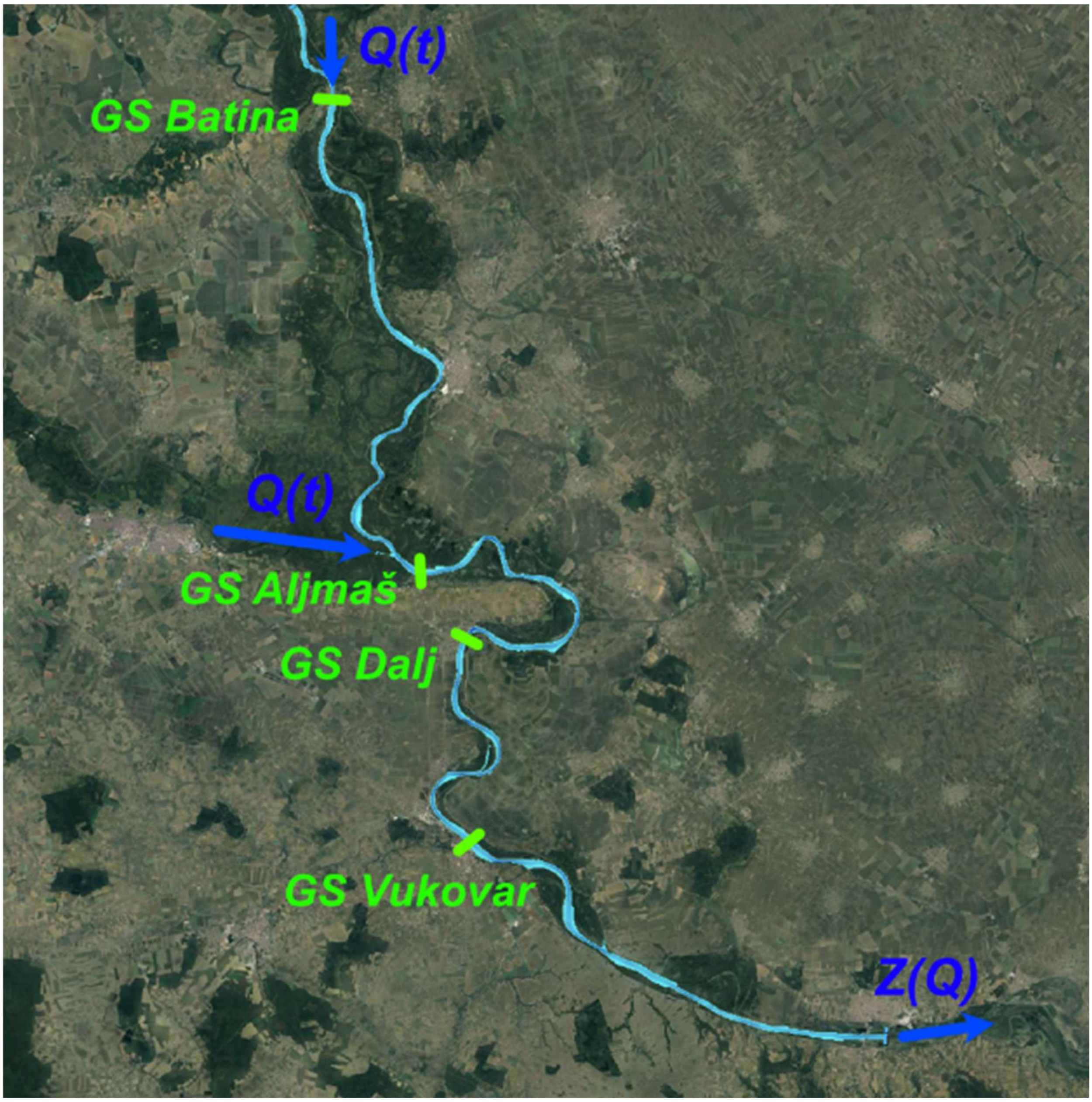


Figure 12: Locations of the boundary cross sections (the end of blue arrows) and Croatian gauging stations whose data were used for model calibration and verification (green lines)

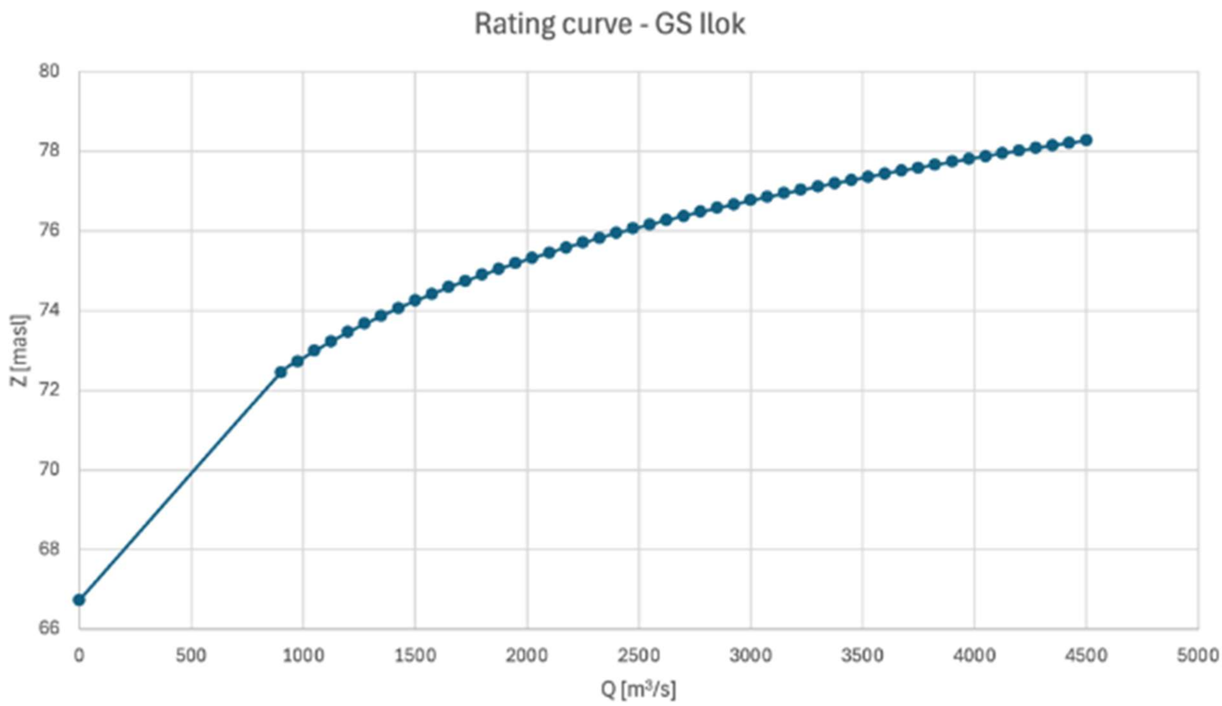


Figure 13: GS Ilok, Rating curve – Downstream boundary condition

In the calibration process, a steady-state flow conditions are considered because LNWLs (Low Navigation Water Levels) will be determined under the same conditions in the study. To achieve steady-state conditions, constant discharges (as hydrographs) are set at the two upstream ends, and the simulation is run long enough for all results to converge.

1.4. Model Calibration and Verification

Model calibration is an essential step in preparing a river flow simulation. This process ensures that the simulation's outputs will match the measured results. The process comprises repetitive simulations with different coefficients subjected to calibration. In this particular case, the value of Manning’s coefficient was alternated and calibrated.

In theory, the Manning coefficient will, among other factors, depend on depth (flow rate). Therefore, the value of this coefficient should decrease with increasing depth and vice versa. This would mean that the value of the coefficient needs to be determined for each flow discharge range. In this part of the study, the focus is primarily on low flows, so the model will be calibrated for this flow discharge range. For creating detailed 2D models of the critical sectors, the Manning coefficient values for mean flow and bankfull discharge will additionally be determined.

The optimal Manning values were determined such that, for the sections between Croatian hydrological stations (operated by DHMZ), by varying the Manning coefficient with a step of $0.0005 m^{-1/3} s$ (initial value is $0.0300 m^{-1/3} s$), the smallest differences between calculated water surface elevations and the elevations read from the flow curves at the cross sections of the gauging stations were obtained. For the purpose of calibration, only data from Croatian stations were used because, due to the identified inconsistency in water surface elevations between Serbian and Croatian stations, it is not reasonable to combine data from the stations of the two hydrometeorological services. Additionally, DHMZ (Croatian Meteorological and Hydrological Service) has a denser network of control cross-sections (gauging stations), allowing Croatian data to cover a greater degree of longitudinal variability in the Manning coefficient through calibration. Later in the text, it will be shown that the calibration results from the Croatian stations provide realistic values for the Manning coefficients.

After adopting the Manning coefficient values in the calibration process, the model was verified using recent time series of water levels from the low-flow domain. During verification, the calculated and recorded levels were visually compared throughout the entire time series, and the largest differences and their frequency were observed.

1.4.1. Model Calibration

It was explained why the model is calibrated for steady-state flow conditions and why water stage elevations from the rating curves are used instead of the recorded levels at the gauging stations. For the calibration simulations, a flow rate of 950m³/s was selected at the GS Batina cross section and 350m³/s at the upstream profile on the Drava River (near the confluence of the Drava). Manning coefficients are adopted for the sections between the Croatian stations on the Danube, and each combination of Manning coefficient values is checked by first establishing that the calculated hydraulic values across the entire computational domain have converged. Table 3 shows the water surface elevations from the rating curves and the calculated elevations for the adopted Manning coefficient values (the table shows these values applicable to the section downstream of the specified station).

Table 3: Comparison of observed (Z_{DHMZ}) and calculated (Z_{HECRAS}) elevations for adopted Manning's coefficients

	Vukovar	Dalj	Aljmaš	Batina
Z_{DHMZ} [m.a.s.l.]	75.96	76.70	77.88	79.86
Z_{HECRAS} [m.a.s.l.]	75.98	76.69	77.88	79.85
n [$m^{-1/3}s$]	0.0290	0.0300	0.0295	0.0325

It can be observed that the adopted values are close to the initial estimate and are expectedly somewhat higher in the upstream part of the common sector, which is physically justified given that lower flow rates occur along this reach of the Danube. In a way, this also confirms the values from the rating curves that correspond to the low flows range.

1.4.2. Model Verification

The inflow time series of discharges on the GS Batina from 01.10.2023 (00:00) to 15.10.2023 (00:00) was selected for verification (Figure 14). For the Drava River, the inflow data on the GS Belišće from the same period was selected and applied to the model (Figure 15). The measurement results from the Belišće GS were taken while this GS is the most downstream stations where rating curve is established, and it is not under the Danube's backwater influence. However, this station is 54 km upstream from the confluence of the Drava River, so, based on expert judgment, a time shift of 3 hours was applied when setting the discharge at the confluence itself.

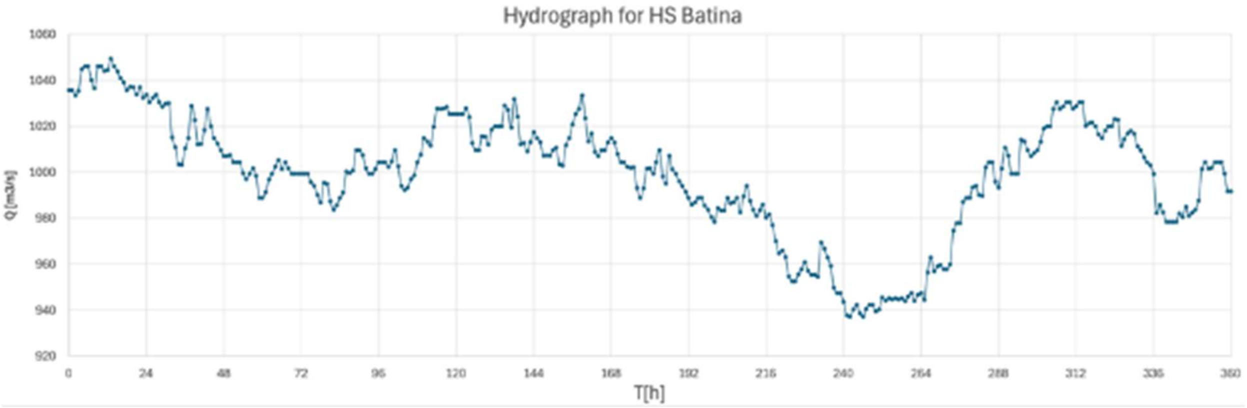


Figure 14: HS Batina (Danube), Time series for verification (discharges derived from recorded water surface elevations using the rating curve)

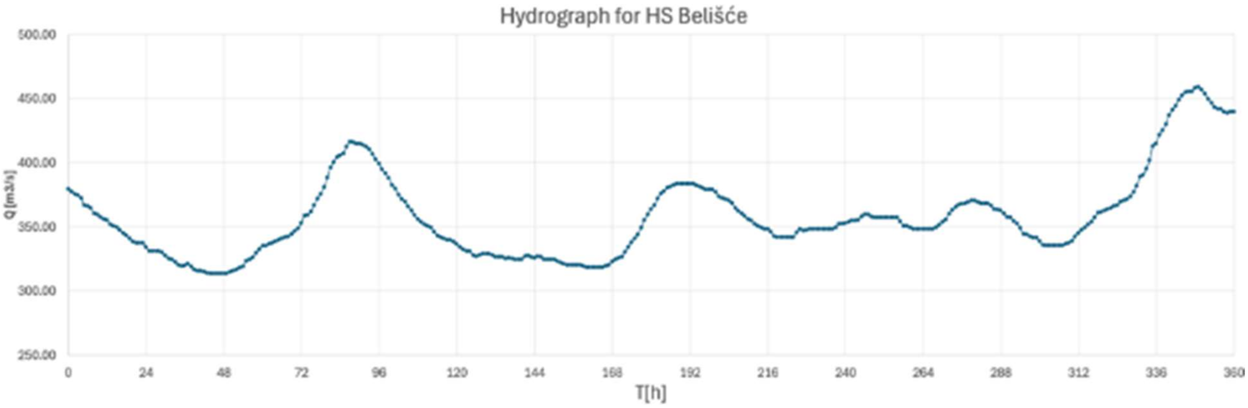


Figure 15: HS Belišće (Drava), Time series for verification (discharges derived from recorded water surface elevations using the rating curve)

The calculated water surface elevations were compared with the recorded elevations along the entire common sector (Figure 16, Figure 17, Figure 18). A visual inspection of the results shows that the simulation follows the observed trends, and the differences, except for the initial part of the simulation (at the very beginning of the simulation, the observed levels do not correspond to steady flow conditions, making the initial condition setting problematic), are at no point greater than 10cm. The largest deviations of the peak values are generally much smaller, only a few centimeters. A slight time lag is also noticeable in the occurrence of local maxima and minima, but this lag is consistent. Based on the observations, and considering the uncertainty regarding the inflow from the Drava River, these results can be considered satisfactory.

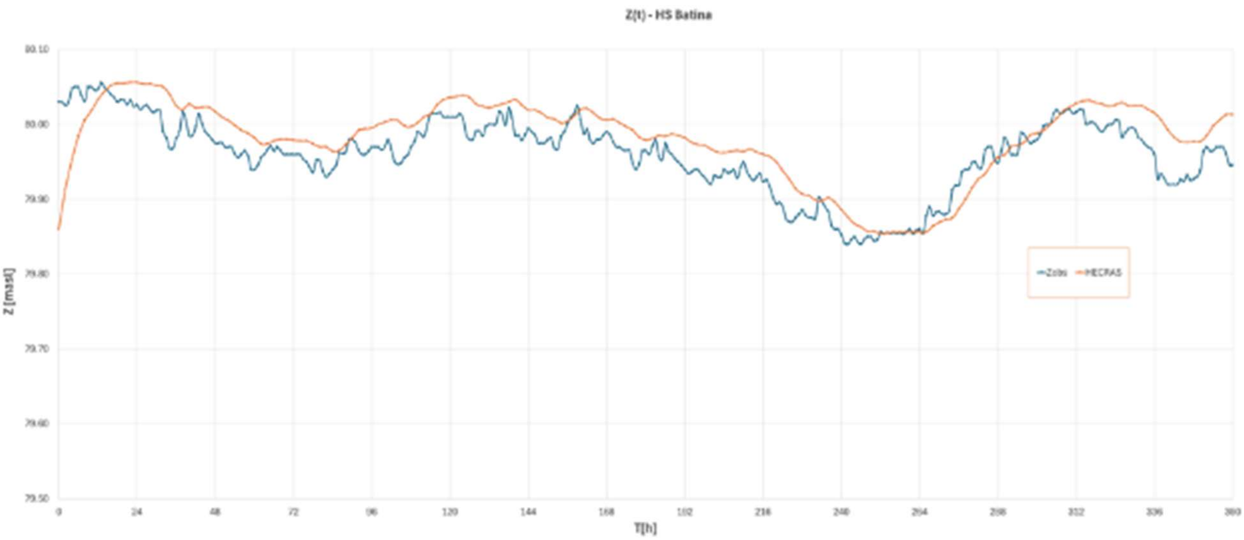


Figure 16: HS Batina (Danube), Comparison between Calculated (red line) and Observed elevations

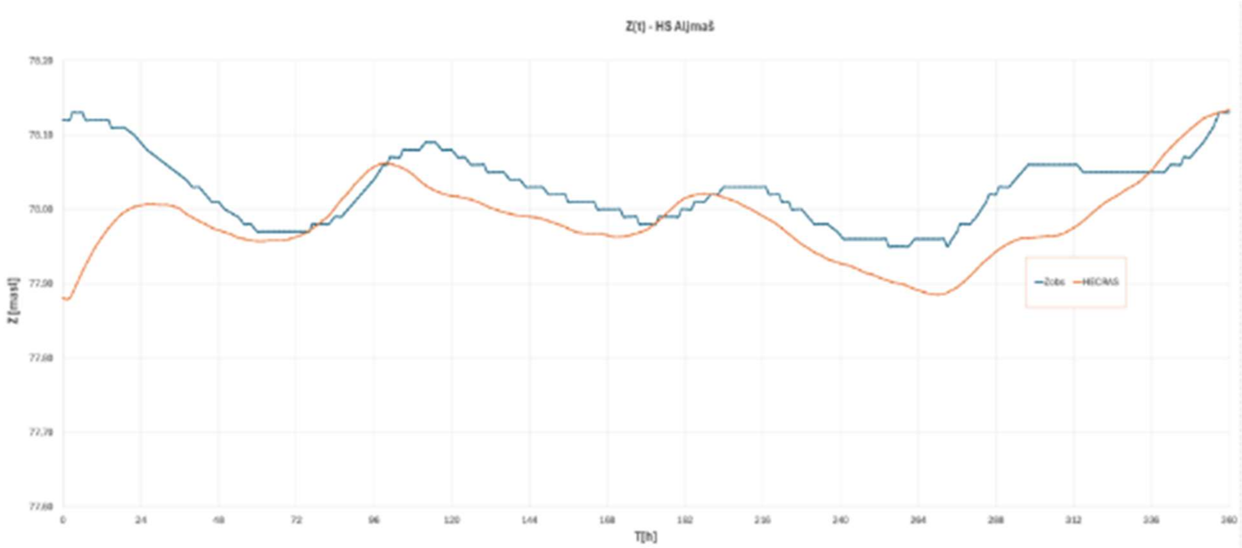


Figure 17: HS Aljmaš (Danube), Comparison between Calculated and Observed elevations

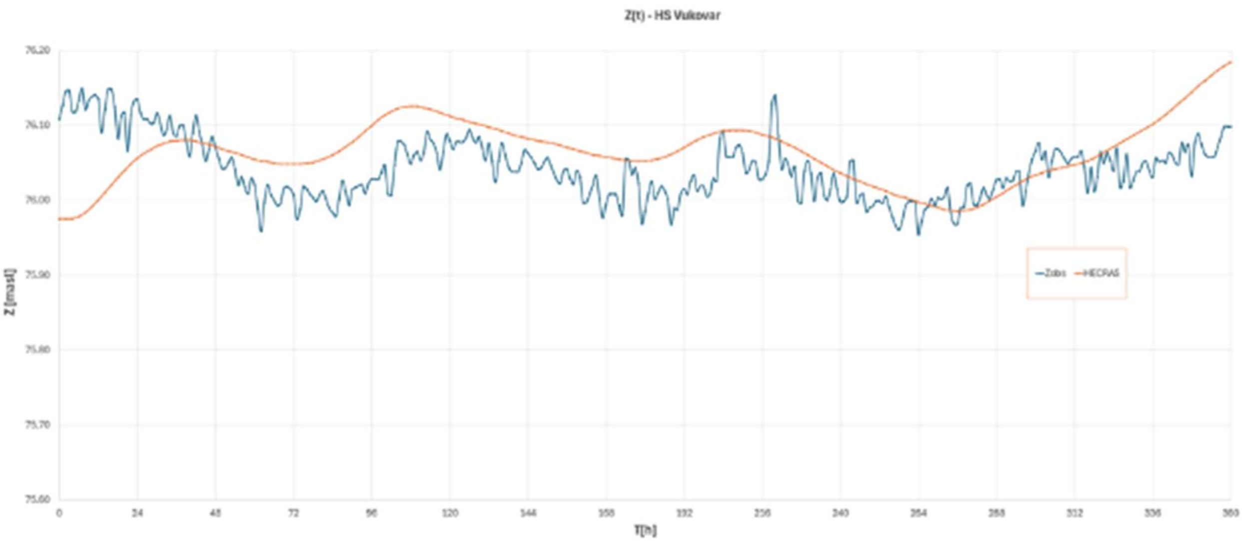


Figure 18: HS Vukovar (Danube), Comparison between Calculated and Observed elevations

1.5. Calculations of LNWLs (Steady flow simulation for $Q_{94\%}$)

The hydraulic model of the entire common stretch was created to calculate low navigation water levels. The model was previously calibrated for discharges upstream from the Drava confluence of 950m³/s and downstream from the confluence of 1,300m³/s, as these are the flow rates corresponding to the lowest discharges from the recent period, i.e., the period of riverbed survey. These flows are slightly lower than the $Q_{94\%}$ discharges (1,180m³/s and 1,435m³/s) from the previous study (Witteveen Bos, 2012), based on which the official low navigational water levels were adopted (for HS Bezdan and HS Bogojevo). However, based on the results of the hydrological study from this project, significantly higher values of the $Q_{94\%}$ discharges were adopted, 1,450m³/s (for sector upstream of Drava confluence including HS Batina) and 1,715m³/s (for sector downstream of Drava confluence including HSs Vukovar, Dalj and Aljmaš). Therefore, it was expected that the hydraulic calculations with the previously determined Manning coefficient values would indicate the need to adjust the values of the coefficient due to the higher relevant discharges (see upper table in Figure 19). Thus, an additional calibration for the newly adopted $Q_{94\%}$ discharges values was carried out in the same manner as described in the previous procedure.

$Q_{94\%}$

1st iteration	Vukovar	Dalj	Aljmaš	Batina
Z_{DHMZ} [masl]	76.60	77.36	78.60	80.61
Z_{HECRAS} [masl]	76.73	77.51	78.70	80.77
n [$m^{-1/3}s$]	0.0290	0.0300	0.0295	0.0325

Calibration

$Q_{94\%}$

5th iteration	Vukovar	Dalj	Aljmaš	Batina
Z_{DHMZ} [masl]	76.60	77.36	78.60	80.61
Z_{HECRAS} [masl]	76.59	77.36	78.60	80.61
n [$m^{-1/3}s$]	0.0270	0.0285	0.0290	0.0305

Figure 19: Results of calibration for $Q_{94\%}$

In the calibration process and later in the calculation of LNWLs (Low Navigational Water Levels), discharges of 1450m³/upstream of the Drava confluence and 1715m³/s downstream were used. For the entire downstream section, the discharge adopted was the one corresponding to the Aljmaš station, which represents the lowest $Q_{94\%}$ discharge downstream of the Drava confluence. This ensures water surface elevations that are on the "safe side" from the perspective of meeting navigational conditions. An additional reason for not adopting additional inflows in the downstream direction is that the discharges for downstream stations are not significantly different, which is understandable given that there are no tributaries on the section between the Aljmaš and Ilok (Bačka Palanka) hydrological stations.

The results of the additional calibration for the adopted $Q_{94\%}$ discharges predictably show slightly lower Manning coefficient values (lower table in Figure 19). As with the previous calibration, the highest values are obtained for the section upstream of the confluence of the Drava River, which can again be explained by the smaller discharge rate at the upstream end of the section.

In Figure 20 a profile of the water surface elevations for the entire sector is shown. The diagram shows the water surface levels and the riverbed bottom along the axis of the existing fairway axis. Since the 2D flow simulation provides a distribution of levels in the horizontal plane, it is easy to create a map showing the flow zones where the minimum navigational depth criterion (2.5m) is met. These maps are shown in the Figure 21 and Figure 22, respectively for the sectors Apatin and Staklar as examples.

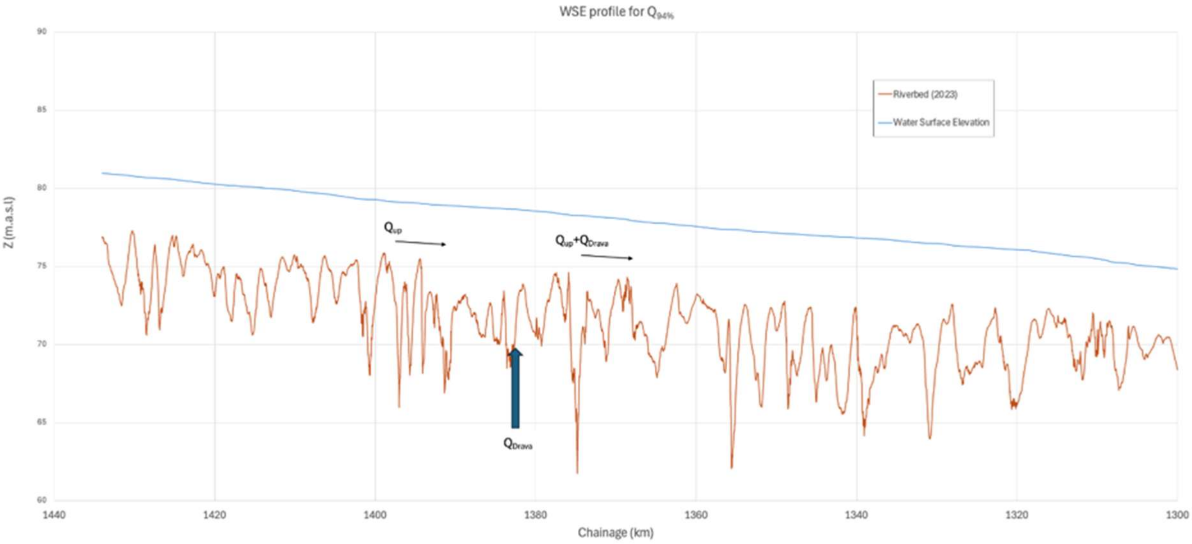


Figure 20: Water surface elevation profile for common stretch of the Danube River

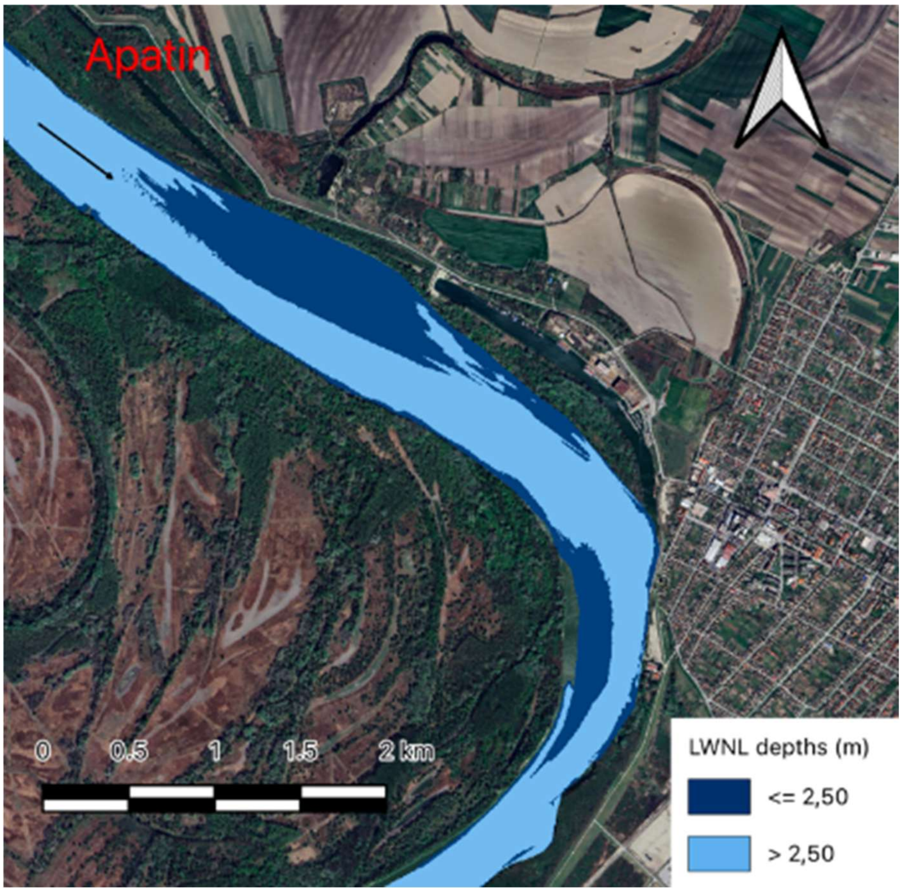


Figure 21: LNWL depth map for CS Apatin

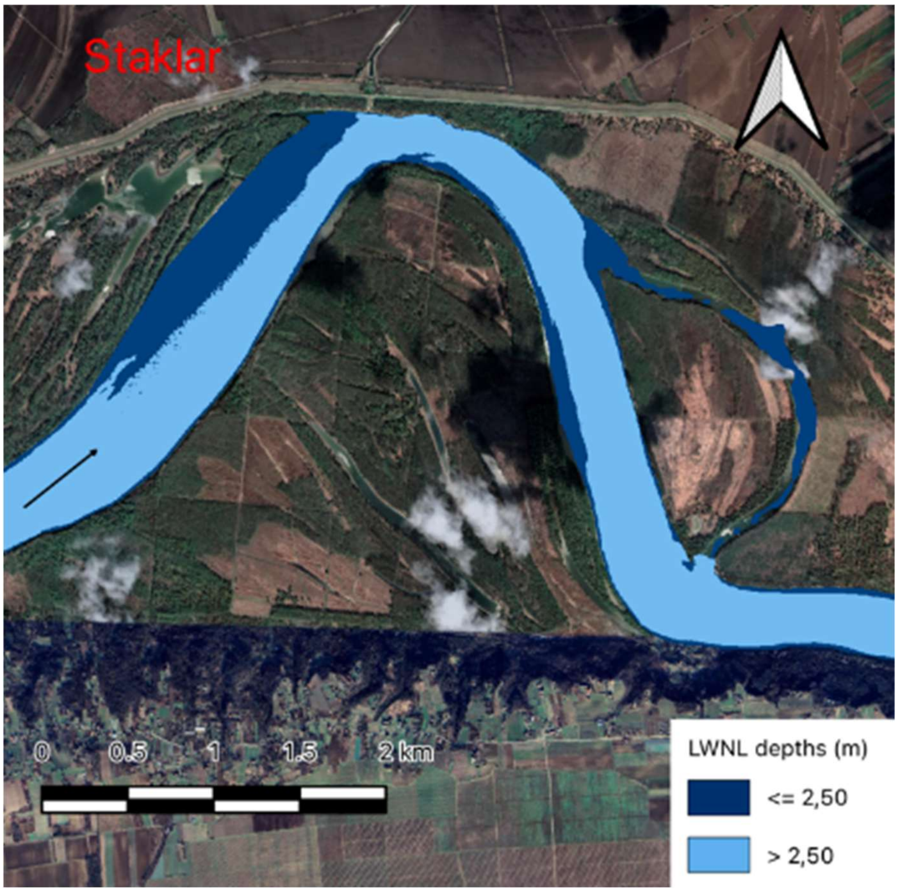


Figure 22: LNWL depth map for CS Staklar

Additional analysis can also determine the volumes of material from the riverbed that need to be removed to ensure the required minimum navigation depths (at 200m width of fairway) for the riverbed condition recorded in 2023. The results of this analysis are shown in Table 4. Taking into account navigability conditions (meeting the minimum fairway depth within the boundaries of the existing fairway and the curvature along the path of the existing navigation route), it was concluded that, based on the conducted hydraulic calculations, four sections (highlighted with green color in Table 4) can be excluded from the current list of critical sectors (also, there is no need for adding other sectors that were not previously indicated as critical). It should be noted here that the fairway realignment was not considered in the sectors that remain critical, and this will be further addressed in the next phase of the project, which will focus on measures to improve navigation conditions.

Table 4: Volume of sediment within the fairway of 2.5m depth at 200m fairway width

No	Sector	Chainage (rkm)	Volume of sediment within the fairway (m^3)
1	Bezdan	1429.0 - 1425.0	4,745
2	Siga Kazuk	1424.2 - 1414.4	1,016
3	Apatin	1408.2-1400.0	54,311
4	Čivutski Rukavac	1397.2-1389.0	52,977
5	Drava confluence	1388.8-1382.0	22,013
6	Aljmaš	1381.4-1378.2	0
7	Staklar	1376.8-1373.4	14,781
8	Erdut	1371.4-1366.4	0
9	Bogojevo	1366.2-1361.4	330
10	Dalj	1357.0-1351.0	244
11	Borovo 1	1348.6-1343.6	26,555
12	Borovo 2	1340.6-1338.0	40,353
13	Vukovar	1332.0-1325.0	2
14	Sotin	1324.0-1320.0	85
15	Opatovac	1315.4-1314.6	37
16	Mohovo	1311.4-1307.6	748
17	Ilok	1302.0-1300.0	0

In a dedicated section of the study (– PRIORITIZATION OF NAVIGATIONAL BOTTLENECKS), based on the results of the hydraulic calculation for the newly adopted $Q_{94\%}$ flow, an updated catalog of critical sectors will be presented. It will explain how the prioritization of critical sectors was conducted, i.e., how the determination of those critical sectors for which measures to improve navigation conditions will be proposed in this project was made.

1.6. Reflection to the general trend of river bed deepening observed in the literature

According to the Terms of Reference (ToR), one of the Consultant's objectives is to assess the results of the 1D (2D) modeling in relation to the observed trend of decreasing water levels. This decline is attributed to riverbed deepening caused by incision resulting from historical and ongoing river regulation, which has been estimated at approximately 1 meter over the past 70 years (see the presentation by E. Tamas, University of Budapest, at the 43rd IAD Conference in 2021). However, results of the hydrological study from this project shows different trend regarding discharges ($Q_{94\%}$ discharges are significantly higher, and consequently the LNWLs are higher).

The methodology outlined in the paper "Hydrological Indicators of Riverbed Incision Along the Free-Flowing Danube River Reach from Budapest to Slankamen," authored by Tamás, E.A., Đorđević, D., Kalocsa, B., and Vujanović, A., and presented at the 43rd IAD Conference on Rivers and Floodplains in the Anthropocene—Upcoming Challenges in the Danube River Basin, held from June 9-11, 2021, is based on annual time series data of minimum, mean, and maximum water levels across all gauging stations.

The time series data covering the 70-year period from 1950 to 2019 (Figure 23) clearly demonstrate a declining trend in all analyzed water levels along the stretch of the Danube River between Serbia and Croatia.

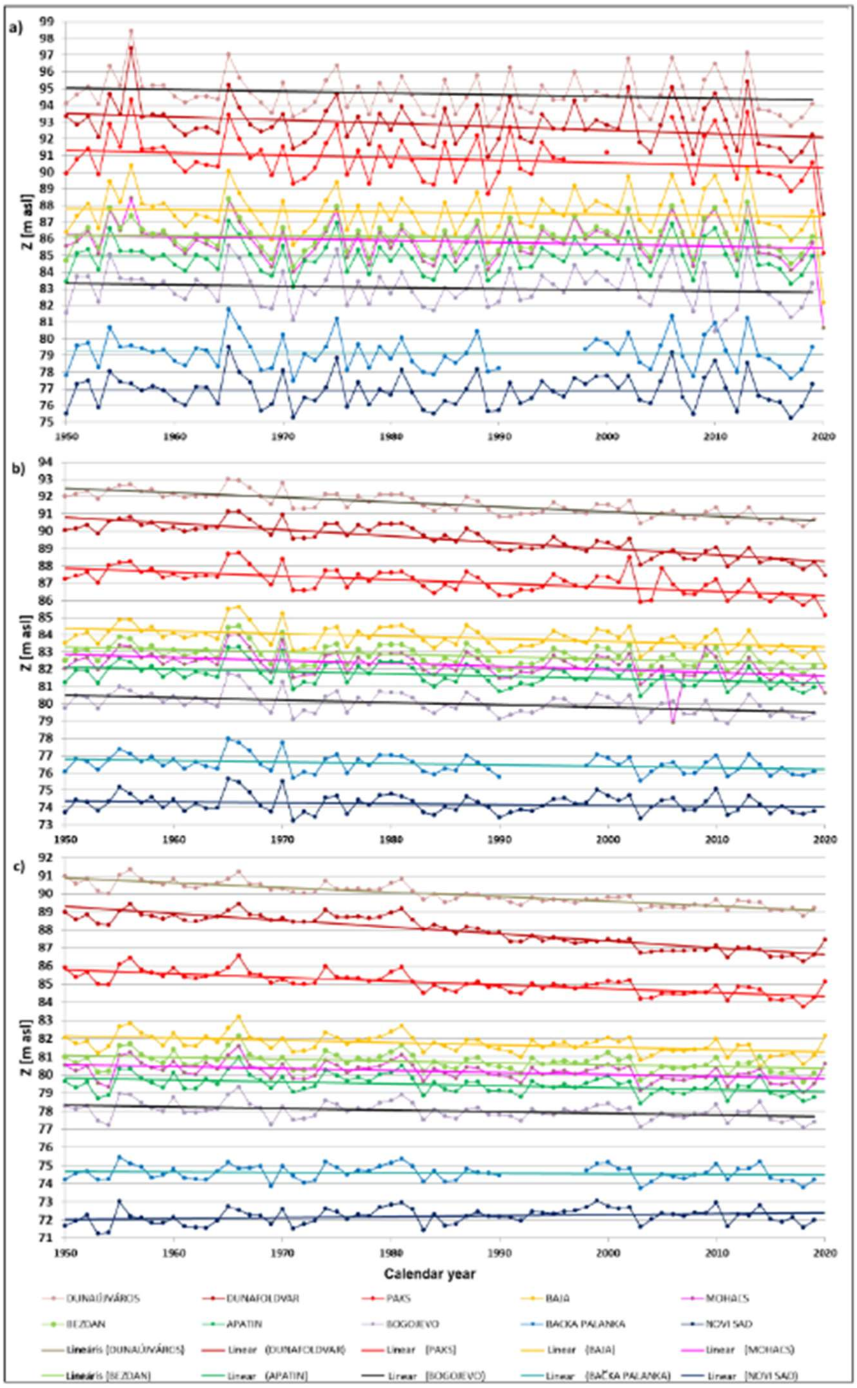


Figure 23: Annual a) maximum, b) mean and c) minimum water levels with linear trends (source "Hydrological indicators of the riverbed incision along the free-flowing Danube River reach from Budapest to Slankamen relevant for the lateral connectivity between the river channel and floodplains")

While the 1D(2D) modeling process in this Project, including the hydrological study, does not incorporate the annual minimum, mean, and maximum water levels, adding data from the 2020-2023 period to the existing 70-year dataset would not significantly alter the observed declining trends in water levels. The same applies to the discharge measurements.

Since the annual minimum, mean, and maximum discharges show no discernible trend (Figure 24)—remaining constant or nearly constant, as indicated by their parallel alignment to the time axis—the continuous decline in annual water levels can be attributed to riverbed incision. To better substantiate this conclusion, additional analyses are necessary. It should also be noted that riverbed incision can be significantly influenced by excessive dredging.

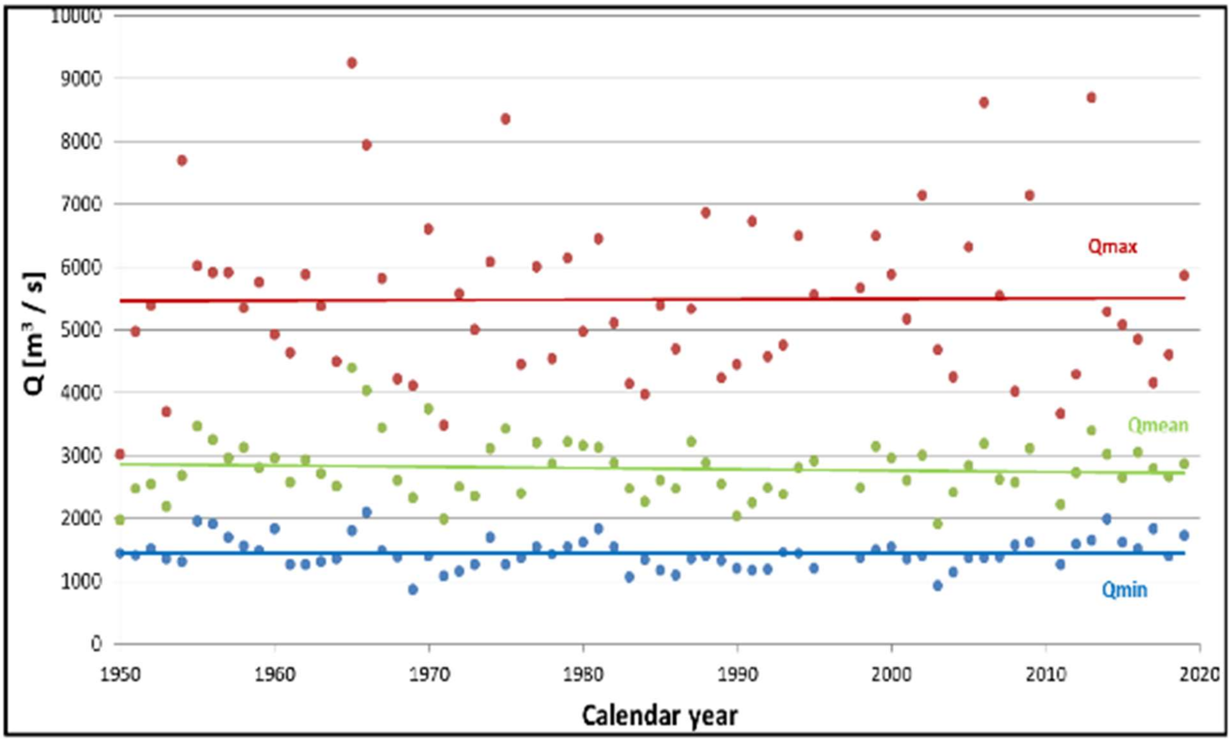


Figure 24: Annual maximum, mean and minimum discharges at Bogojevo gauging station (source "Hydrological indicators of the riverbed incision along the free-flowing Danube River reach from Budapest to Slankamen relevant for the lateral connectivity between the river channel and floodplains")

For instance, a morphological analysis of the characteristic cross-sections in all critical sectors along the Danube River stretch could be conducted. This type of analysis requires detailed calculations of the cross-sectional areas, as well as an assessment of whether these cross-sections are eroding, in dynamic balance, or accumulating sediment over time. However, this task falls outside the scope of this project, and data on sediment is also limited.

Nevertheless, since the focus is on reconnecting rivers with their floodplains and restoring wetlands in line with the EU Floods Directive—lateral connectivity is a crucial consideration. This aspect will be integral in proposing relevant options to address critical bottlenecks from a navigation perspective.

1.7. Conclusions on 1D Modeling

Based on conducted activities described in this report, the following key conclusions can be drawn:

- By creating an integral 2D (hybrid) hydraulic model for the entire stretch of the joint Serbian-Croatian sector, a tool has been developed that will be used for the revision of Low Navigation Water Levels (LNWLs), which will be consequently based on rating curves that, in a way, have been confirmed by hydraulic analysis in the low flows domain;
- The development of a hybrid river bed model provided an important foundation for a detailed 2D flow model for hydraulic analyses on the most critical sections. During the creation of the hybrid model, smaller areas of the main channel near the banks were observed, where reliable geometry estimation could not be obtained, so the geometry of these bed parts was defined based on interpolation using global terrain models;
- A need has been identified to improve the quality of hydrological data and to harmonize data between the Serbian and Croatian gauging stations;
- Despite the observed issues with topographic and hydrological data, satisfactory agreements between the calculated and recorded water surface levels were achieved in the low-flow domain. As part of developing a detailed 2D flow model of the most critical sectors, there will be a need for additional calibration of the Manning coefficient for the domain of mean flows and for bankfull discharge, but the methodology for this calibration has been developed through the activities described in this report.

CHAPTER 2. – UPDATE OF ENRs

2.1. Introduction

This chapter supports the preparation of hydrological inputs for developing the hydrodynamic model of the shared Serbian–Croatian section of the Danube River. Its primary objective is to characterize the water regime along this river stretch and define navigation conditions under low-flow, mean-flow, and flood-flow scenarios.

All analyses in this chapter are performed having in mind the requirements of ToR related to the assessment of low and high navigable water levels (LNWL and HNWL, respectively). More specifically, the Danube Commission (Glossary of the Danube navigation, 2015) defines LNWL as the water level having duration of 94% in a year that is computed from data on the observed river discharges over a period of 30 years, excluding the periods with presence of ice. Similarly, HNWL is defined as the water level with duration of 1%, based on the discharges observed during a period of 30 years, excluding the ice periods. Starting from this definition, the study is focusing on the hydrological data on discharges in the last 30 years (1994-2023).

The following section reviews data used in the hydrological analysis, followed by the section which provides preliminary considerations of the available data. This step was necessary in order to check consistency of data at twin Serbian and Croatian stations along the common stretch of the Danube River. After this preliminary analysis, the three aspects of water regime (low, mean, flood flows) are described. The final section provides hydrological assessment of low and high navigable water levels.

2.2. Data Used in the analysis

The common Serbian-Croatian reach of the Danube River between the Hungarian border and Bačka Palanka (chainage from km 1,433 to km 1,295) is covered by 4 hydrological stations operated by Republic Hydrometeorological Service of Serbia (RHMZ) and 9 stations operated by Croatian Meteorological and Hydrological Service (DHMZ). The stations are shown in Figure 25 and listed in Table 5. Of additional importance are the stations on the Drava River, which can help in assessing water balance before and after its confluence with the Danube River. These stations are also listed in Table 5.

Discharge is measured at 3 stations in Serbia and 5 stations in Croatia. Only two stations in Serbia (Bezdan and Bogojevo) have discharge records of 30 years or longer, while the Croatian stations generally have only 22 years of record. The length of record on stages (water levels) is generally longer.

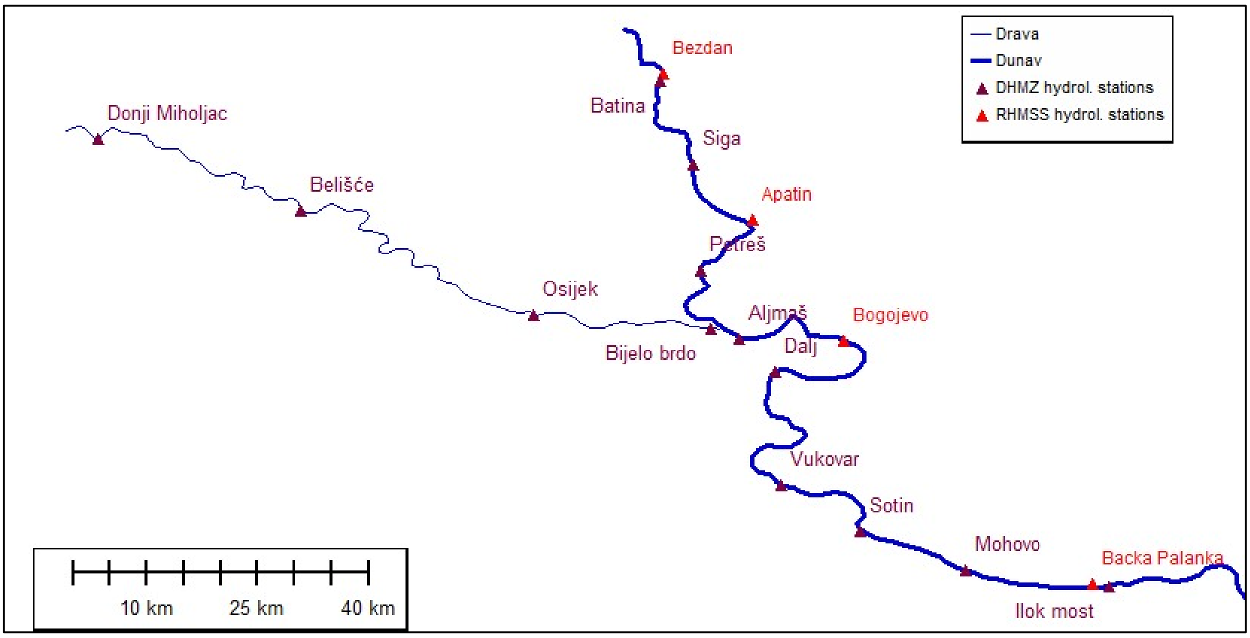


Figure 25: Hydrological stations in the study area

Table 5: Hydrological stations on the Danube River from rkm 1.433 to rkm 1.295 and on the Drava River

Hydrological station	Approx. chainage (rkm)	Year of establishment	Gauge zero (m)	Measurements (H – stage, Q – discharge)	Data available
Danube – Serbia					
Bezdan	1425.59	1856	80.64	H, Q	Yes
Apatin	1401.90	1876	78.84	H	Yes
Bogojevo	1367.25	1871	77.46	H, Q	Yes
Bačka Palanka	1298.56	1888	73.97	H, Q	Yes
Danube – Croatia					
Batina	1424.60	2001	80.45	H, Q	Yes
Siga	1412	2017	78.51	H	No
Petreš	1393	2017	77.275	H	No
Aljmaš	1380.25	1909	78.08	H, Q	Yes
Dalj	1353.7	1985	75.204	H, Q	Yes
Vukovar	1333.4	1856	76.188	H, Q	Yes
Sotin	1322	2017	74.021	H	No
Mohovo	1311	2017	73.912	H	No
Ilok / Ilok most	1298.70	1856	73.968	H, Q	Yes
Drava – Croatia					
Bijelo Brdo	1.0	1964	78.324	H	Yes
Osijek	18.96	1827	81.481	H	Yes
Belišće	53.8	1962	83.993	H, Q	Yes
Donji Miholjac	80.5	1988	88.57	H, Q	Yes

Source: internet sites of RHMZ and DHMZ

Note: Gauge zero elevations for all stations are according to the Adriatic Sea level

For the purpose of this analysis, the following data from 3 hydrological stations operated by RHMZ (Bezdan, Bogojevo, and Bačka Palanka) were requested and obtained from RHMZ:

- Daily water stages and flows for last 30 years (1994-2023);
- Annual minimum and maximum stage and flow for the complete observational record; and
- Data on ice phenomena for the complete observational record.

Data on rating curves for these stations were obtained from the relevant Serbian institutions.

The following data were made available for the stations operated by DHMZ:

- Daily water stages and flows for the period of record, ending with year 2022; and
- Stage-discharge rating curves.

Table 6 gives an overview of data from Serbian stations available for this study. The record of daily stages and discharges for Bezdan is continuous throughout the last 30 years, while the record for Bogojevo has gaps. Data for Bačka Palanka start only in 2013, and have a gap in 2015. Data on annual extremes of stage and discharge was obtained for the complete period of record to facilitate valid statistical analysis. The record of extremes is longer for stages (from 1894 at Bezdan and from 1921/1922 at Bogojevo and Bačka Palanka), while the extreme discharges are available from 1950 at Bezdan and Bogojevo and only from 2013 at Bačka Palanka. Data on ice phenomena have some gaps.

Table 6: Data from hydrological stations operated by RHMZ available for the study

Station	Data				
	Daily water levels	Daily discharges	Annual max/min water levels	Annual max/min discharges	Ice phenomena
Bezdan	1994-2023	1994-2023	1894-2023	1950-2023	1994-2023
Bogojevo	1994-28.2.2010, 1.3.2011-2023	1994-1995, 1998-2009, 1.3.2011-2023	1921-1940, 1943, 1946-2009, 2012-2023	1950-1995, 1998-2009, 2012-2023	1994-2023
Bačka Palanka	2013-31.5.2015, 7.7.2015-2023	2013-28.2.2015, 7.7.2015-2023	1922-1943, 1946-1988, 1990, 1999-2002, 2004-2014, 2016-2023	2013-2014, 2016-2023	1999-2023

Table 7 shows the availability of data at Croatian stations operated by DHMZ. Unfortunately, none of the Croatian stations has data that covers the complete 30-year period 1994-2023.

Table 7: Data from hydrological stations operated by DHMZ available for the study

Station	Data on daily water levels	Data on daily discharges
Batina	9.3.2001-2022	2002-2022
Aljmaš	1.7.1998-2022	2001-2022
Dalj	1.7.1998-2003, 2005-2022	2001-2003, 2005-2022
Vukovar	4.6.1998-8.7.2018, 10.10.2018-2022	2001-8.7.2018, 10.10.2018-2022
Ilok	1.7.1998-2022	2001-2022
Bijelo Brdo	1964-2013	
Osijek	1946-2023	
Belišće	1962-2022	1962-2022
Donji Miholjac	1993-2022	1994-2022

2.3. Preliminary Analysis of Available Data

Hydrological analyses in this study are based on data from the latest 30 years, focusing on the 1994-2023 period. However, due to different lengths of time series at Serbian and Croatian stations, the results of various statistical analyses in this study may not be directly comparable among the stations. For this reason, it was necessary to perform preliminary analysis of data in a common period with available data and to get an insight into possible uncertainties stemming from using short data series.

To understand relative magnitudes of discharges at the stations, a 10-year period of 2013-2022 with data available at all stations (with smaller gaps at Bačka Palanka and Vukovar) is considered. Box plots showing distributions of daily discharges at all stations over 2013-2022 are given in Figure 26, together with mean flows in the same period. The figure shows that the measurements at stations Bezdan and Batina, which are virtually at the same chainage, are in good agreement, except for the lowest flows which are lower at Batina. Mean flows over 2013-2022 at these two stations differ by about 2%. Distributions of discharges at two stations located downstream of the confluence of the Danube and Drava, Aljmaš and Bogojevo, also show good agreement except for the lowest flows. Mean flow at Bogojevo for 2013-2022 is slightly lower (by 2.5%) than the mean flow at Aljmaš despite being a downstream station. At the end of the common sector, stations Ilok and Bačka Palanka (located at the same chainage) show similar ranges and their mean flows over 2013-2022 differ by 2.5%.

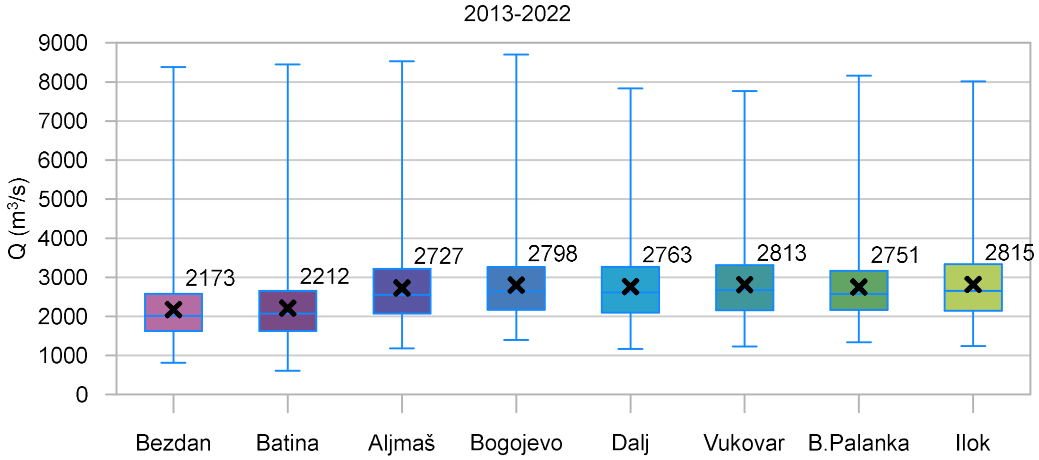


Figure 26: Ranges and distribution quantiles of daily flows (box-plots) and mean flows (black crosses) for 2013-2022

Overall comparison of mean flows for 2013-2022 shows slight inconsistencies at the stations downstream from the Drava confluence since they do not systematically increase in downstream direction. Despite the small differences in mean flows (about 2%), much greater differences may arise during specific periods. An example is given in Figure 27, which shows significant divergence of discharges at Bačka Palanka and Ilok during the low-flow season in 2018, while the water level measurements are in agreement.

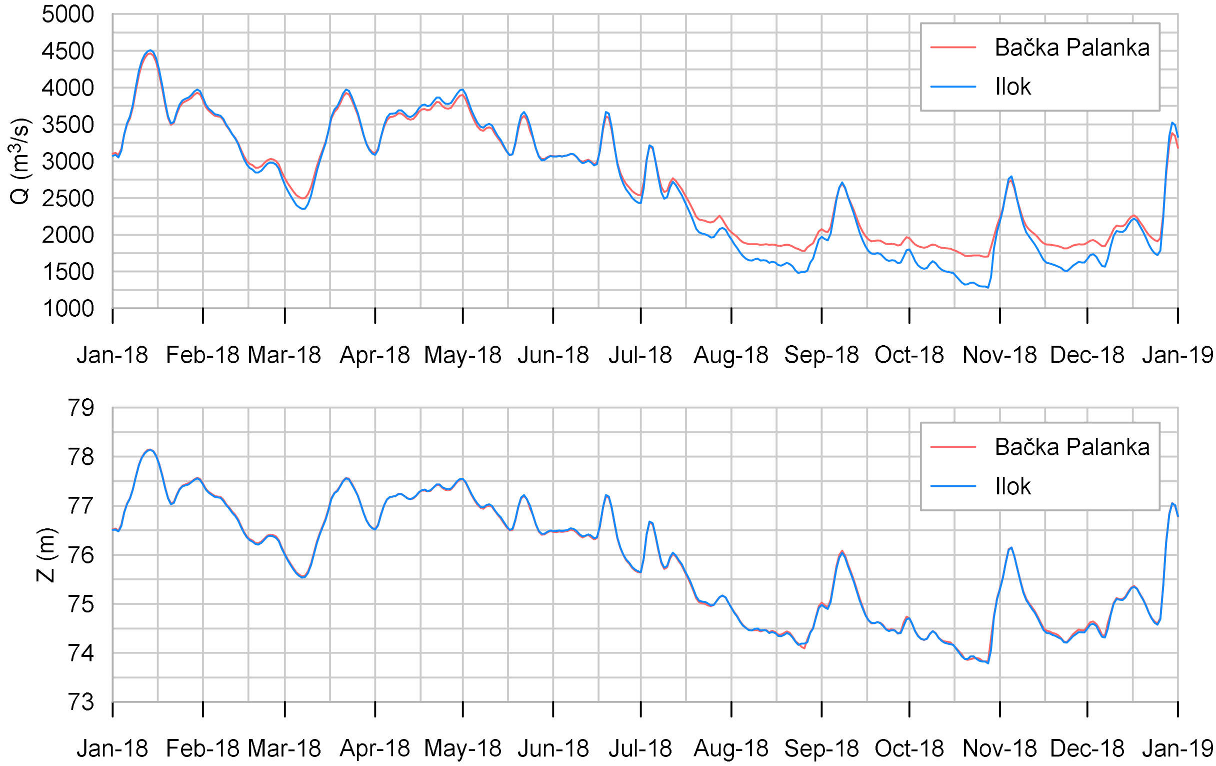


Figure 27: Annual hydrograph (top: discharges, bottom: water levels) at Bačka Palanka and Ilok for 2018, showing significant differences in estimated river discharges during the low-flow season

By comparing discharges at twin stations, it was found that the greatest differences are attributed to low flows and below-average flows in general (Figure 28). Differences in discharges can generally originate from discrepancies in either water level measurements, or in stage-discharge relationships employed by RHMZ and DHMZ to convert measured stage into discharges. Differences in water level measurements at twin stations are mostly small or reasonable, but in few cases are substantial, indicating some kind of error (Figure 29).

On the other hand, stage-discharge relationships at twin stations are different in a complex manner (Figure 30). For the same water level, they produce discharges that could be either greater or smaller than those at the twin station. It should be noted that stage-discharge curves for Croatian stations were obtained from DHMZ in a functional form of quadratic regression, while the curves for the Serbian stations were reconstructed from the simultaneous data on stages and discharges.

From this preliminary analysis, it is obvious that there are two main factors that bring uncertainties into the hydrological analyses: short records and inconsistencies in measurements and data processing techniques at Serbian and Croatian stations. Having in mind that one of the goals of this study is to define low and high navigable water levels by analyzing the discharges, the uncertainties related to discharges at twin stations have to be understood and taken into account.

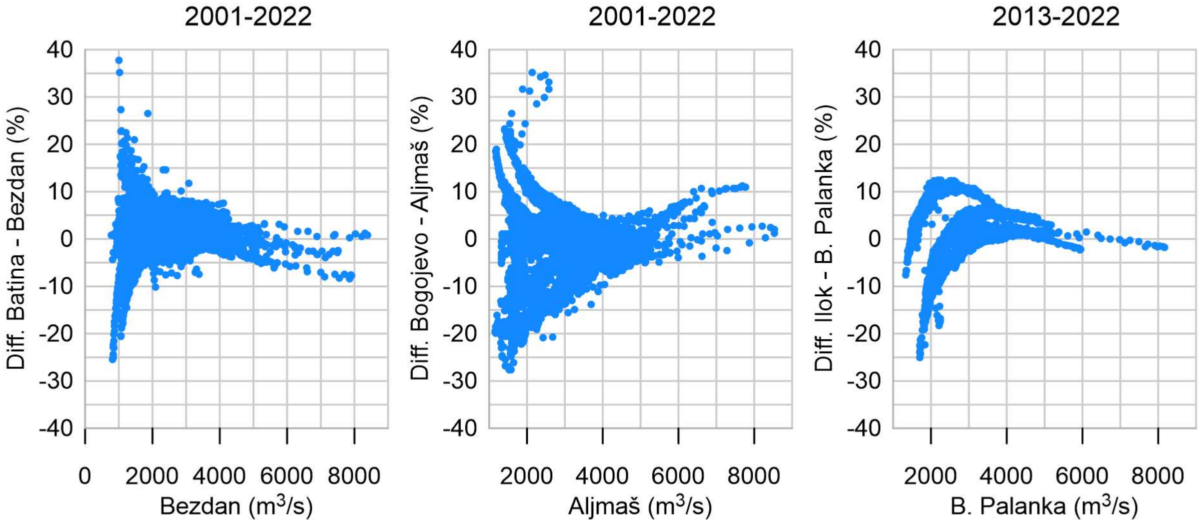


Figure 28: Percentage differences in daily discharges measured at twin stations (left: Bezdan and Batina, middle: Aljmaš and Bogojevo, right: Bačka Palanka and Ilok) in relation to the magnitude of discharge

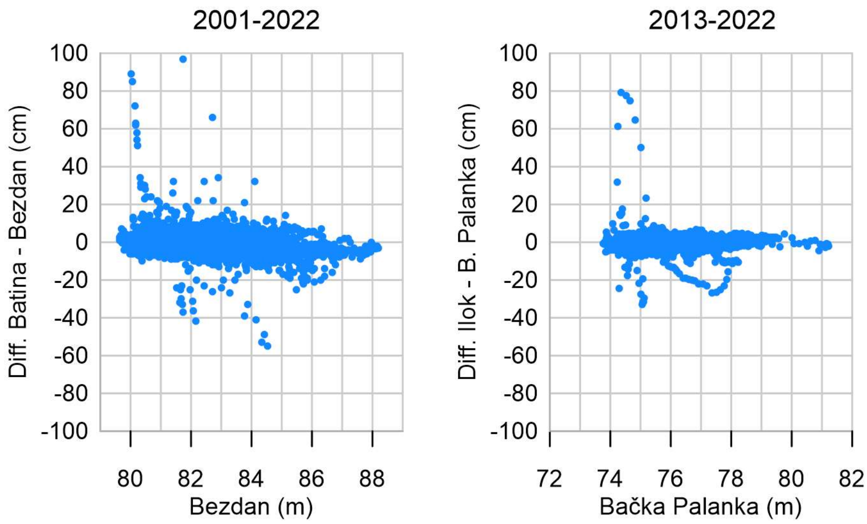


Figure 29: Differences in daily water levels measured at twin stations (left: Bezdan and Batina, right: Bačka Palanka and Ilok)

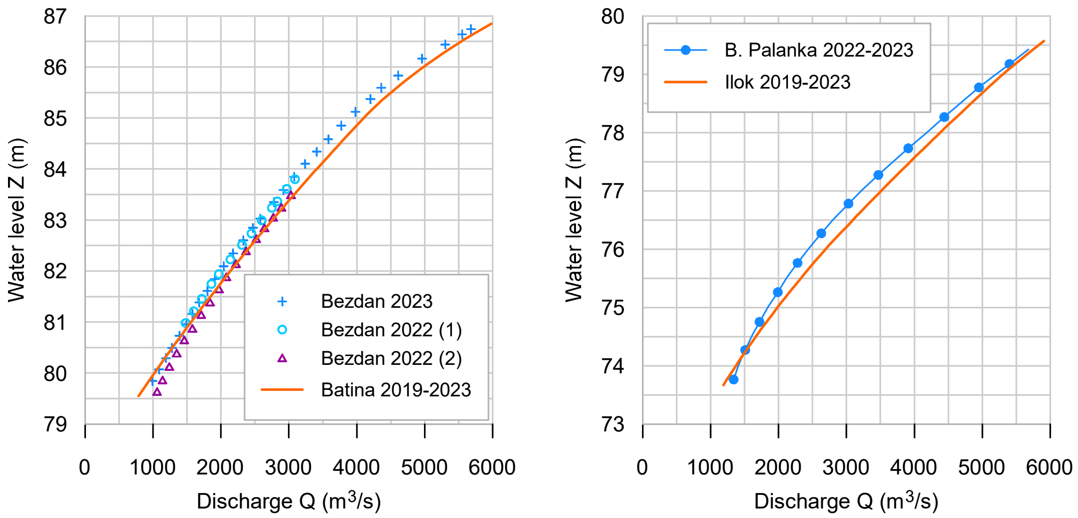


Figure 30: Stage-discharge curves at twin stations (left: Bezdan and Batina, right: Bačka Palanka and Ilok)

2.4. Mean Flows

2.4.1. Mean Flows for 1994-2023

Characteristic discharges at hydrologic stations along the Danube are computed for all stations with discharge data regardless of the series length within the 1994-2023 period. This is justified by small differences (up to 5%) in mean flows over 1994-2023 and over 2013-2022 at stations having (almost) complete record, thus confirming an assumption that the partial records may be used for the assessment of mean flows at stations with incomplete data.

Frequency distributions of daily discharges at all stations along the common sector of the Danube River during 1994-2023 are shown in Figure 31. Table 8 shows average discharge and maximum and minimum observed discharges at each station. For Serbian stations, absolute minimum and maximum discharges are shown, while the minimum and maximum daily discharges are shown for the Croatian stations. Figure 32 shows the evolution of the mean flows with the chainage along the Danube.

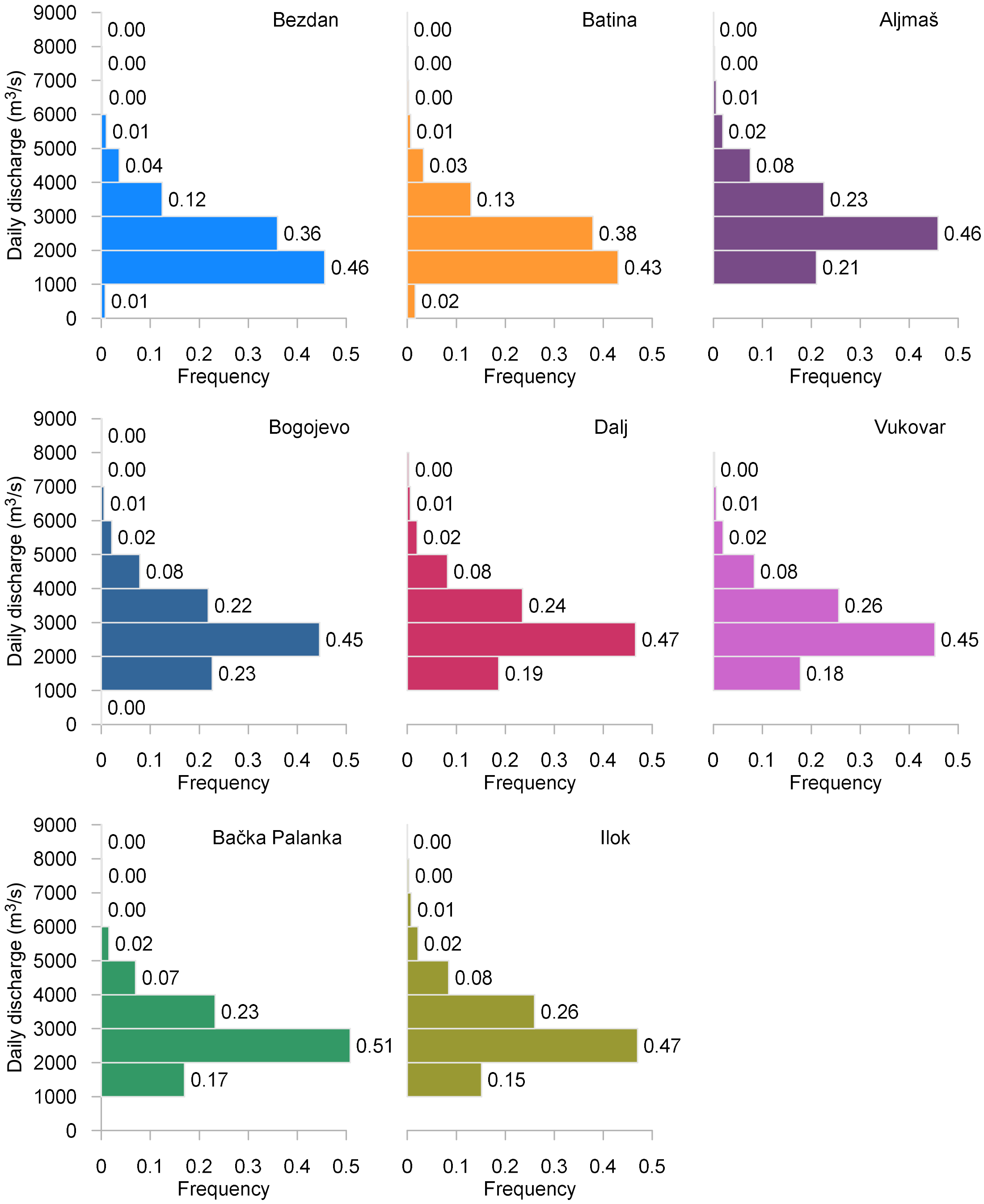


Figure 31: Frequencies of daily discharges of the Danube at hydrological stations for 1994-2023

Table 8: Range of discharges of the Danube and Drava at hydrological stations for 1994-2023

Station	Years with complete data	1994-2023		
		Mean flow (m^3/s)	Minimum observed flow (m^3/s)	Maximum observed flow (m^3/s)
Danube				
Bezdan	30	2280	784 (2003)	8410 (2013)
Batina	21	2274	609 (2018)	8450 (2013)
Aljmaš	22	2775	1149 (2003)	8531 (2013)
Bogojevo	26	2756	915 (2003)	8710 (2013)
Dalj	21	2822	1168 (2022)	7832 (2013)
Vukovar	21	2844	1029 (2003)	7770 (2013)
Ilok	22	2887	1192 (2003)	8015 (2013)
Bačka Palanka	10	2755	1340 (2022)	8180 (2013)
Drava				
Donji Miholjac	29	508	175 (2022)	2166 (2014)
Belišće	20	516	205 (2002)	2017 (2014)

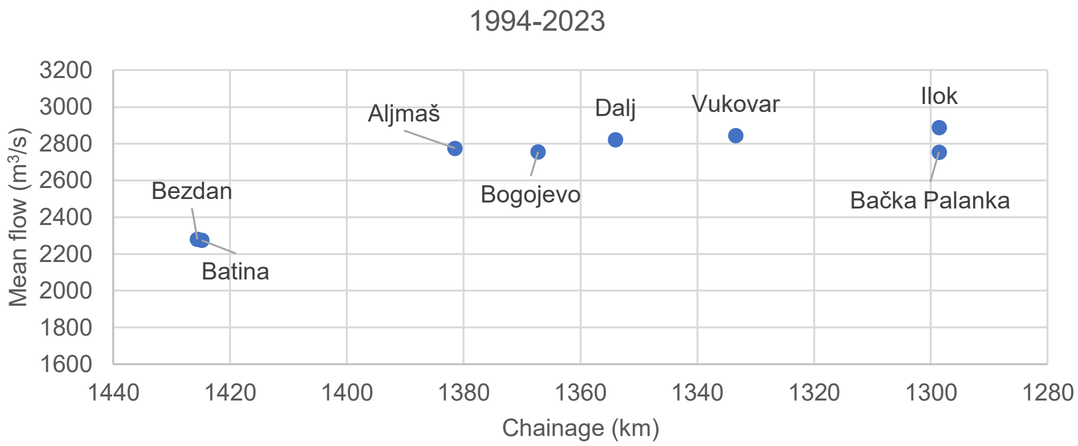


Figure 32: Mean flows at hydrological stations along the common sector of the Danube River

2.4.2. Annual Flows

Figure 33 shows the series of annual discharges at all stations for the last 30 years (1994-2023). Data on annual discharges for Serbian stations Bezdan and Bogojevo are available from 1950 and these long-term series are shown in Figure 34. The long-term series indicate that the Danube regime along this stretch after 1980 is less variable than before 1980. Both the lowest and the highest annual discharges were recorded before 1980. Since this study is based on the data from the last 30 years (1994-2023), the series of mean annual discharges at Bezdan and Bogojevo was tested for homogeneity with a break point in 1994, i.e., periods 1950-1993 and 1994-2023 were compared. Several parametric and non-parametric homogeneity tests were applied (t-test and Mann-Whitney test for means, F-test for variances). The results shown in Table 9 indicate that the variance of the mean annual discharges is significantly different in the second period compared to the first period (as per F-test at 5% significance level). Change in mean discharge from one period to another is not significant (t-test for means with unequal variances and Mann-Whitney test at 5% significance level). Trend in the mean annual discharge series was not detected (non-parametric Mann-Kendall test and parametric test for significance of the slope of linear regression).

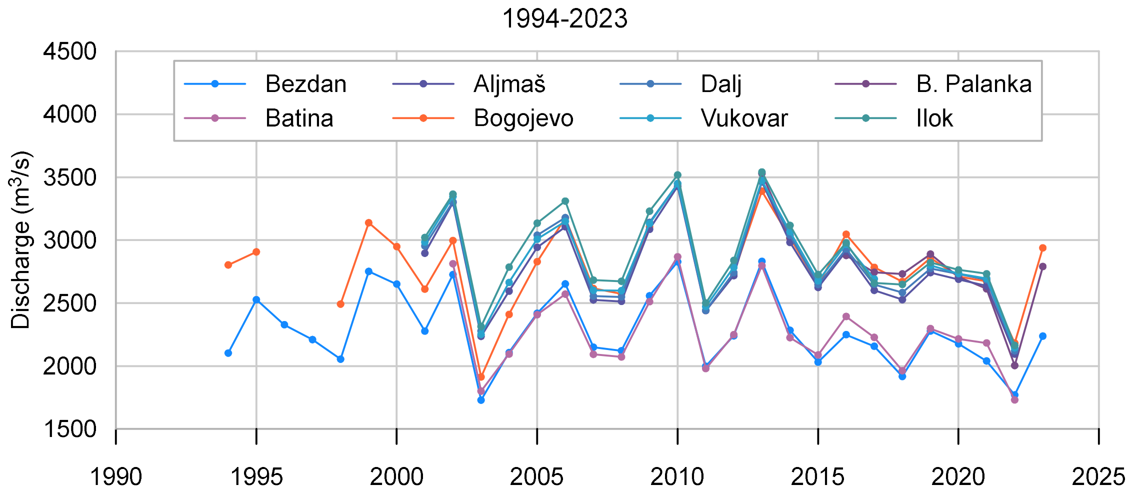


Figure 33: Mean annual discharges of the Danube for 1994-2023

Table 9: Results of statistical tests on homogeneity and presence of trend for the series of mean annual discharges

Station	**Bezdan**		**Bogojevo**	
Period	1950-1993	1994-2023	1950-1993	1994-2023
No. of data	44	30	44	26
Mean	2255	2280	2806	2776
Stand. dev.	463	296	525	316
F-test	F statistic = 2.445 p-value = 0.007 < 0.05 H_0 (equal variances) rejected		F statistic = 2.769 p-value = 0.004 < 0.05 H_0 (equal variances) rejected	
t-test	t statistic = -0.278 p-value = 0.782 > 0.05 H_0 (equal means) not rejected		t statistic = 0.301 p-value = 0.764 > 0.05 H_0 (equal means) not rejected	
Mann-Whitney test	t statistic = -0.859 p-value = 0.390 > 0.05 H_0 (equal means) not rejected		t statistic = -0.352 p-value = 0.724 > 0.05 H_0 (equal means) not rejected	
Mann-Kendall test	z statistic = -0.056 p-value = 0.955 > 0.05 H_0 (absence of trend) not rejected		Test cannot be applied due to gaps	
Linear regression slope test	Correlation coefficient = -0.066 t statistic = -0.560 p-value = 0.577 > 0.05 H_0 (absence of trend) not rejected		Correlation coefficient = -0.086 t statistic = -0.708 p-value = 0.481 > 0.05 H_0 (absence of trend) not rejected	

Long-term variability of mean annual discharges at Bezdan and Bogojevo was also examined by means of moving average with an 11-year window (Figure 34). Smoothed series indicate almost two cycles of long-term periodicity (the first one ending in the beginning of 1990s, while the second one is not finished). The length of the cycles could roughly be estimated at about 40 years. Figure 35 shows normalized cumulative periodogram for Bezdan resulting from spectral analysis. It does not reveal any significant harmonics in the series of annual discharges, but the harmonic with the greatest amplitude (accounting for about 11% of total series variance) has frequency of 1/37 years^{-1}, what corroborates visual identification of the 40-year cycles. The above conclusion is important for consideration of discharges of the Danube River at the given stretch over the last 30-year period, which obviously belongs to an unfinished cycle that is expected to end within the next decade.

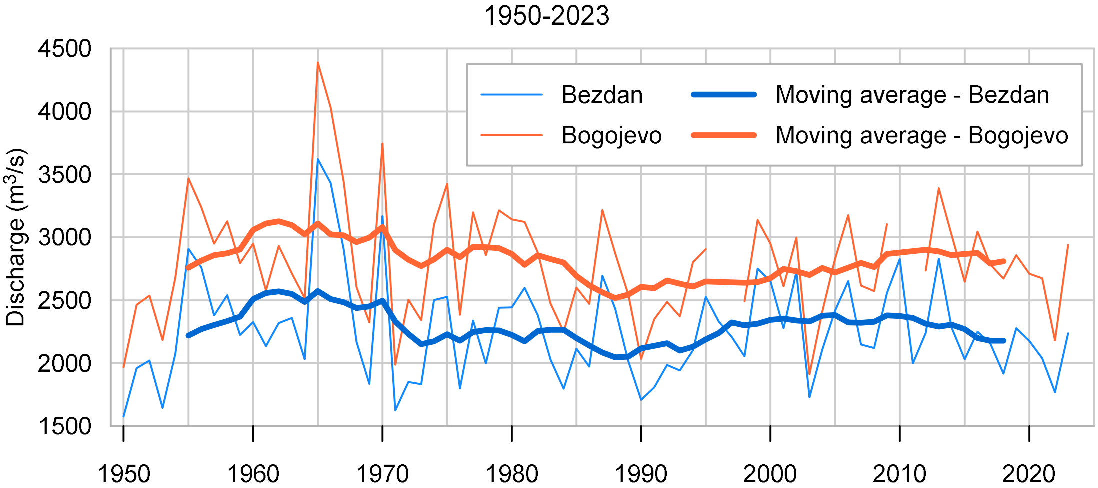


Figure 34: Long-term series of mean annual discharges of the Danube at Bezdan and Bogojevo with 11-year moving average

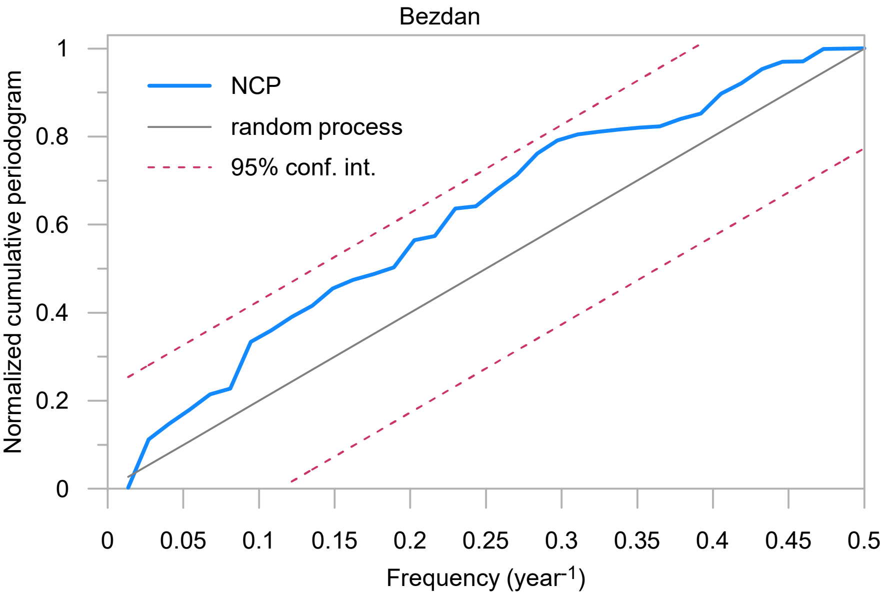


Figure 35: Normalized cumulative periodogram (NCP) for the series of annual discharges at Bezdan

To get an insight into the influence of the Drava River on the Danube discharges upstream and downstream of the confluence, Figure 36 shows normalized mean annual discharges at Bezdan, Bogojevo and Donji Miholjac (discharges are normalized in respect to the long-term means for 1950-2023). This figure also shows 11-year moving averages for the three stations, suggesting that the relative contribution of the Drava River between 1995 and 2010 was lower than in other periods. This resulted in somewhat different relative average discharges upstream and downstream of the Drava confluence, with Bezdan having discharge slightly above the long-term mean and Bogojevo exhibiting average discharges slightly below the long-term mean.

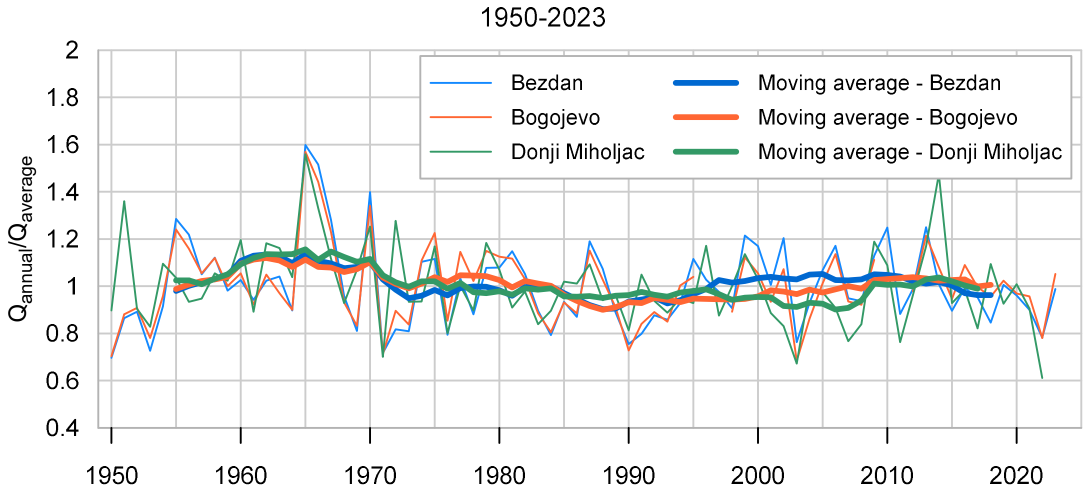


Figure 36: Long-term series of normalized mean annual discharges of the Danube at Bezdan, Bogojevo, and Drava at Donji Miholjac with 11-year moving average

Figure 37 and Table 10 provide the results of frequency analysis of long-term series of annual discharges at Bezdan and Bogojevo. For both stations, log-Pearson type 3 distribution is used to fit empirical distribution. The analysis was not performed for the short series at Bačka Palanka and at Croatian stations.

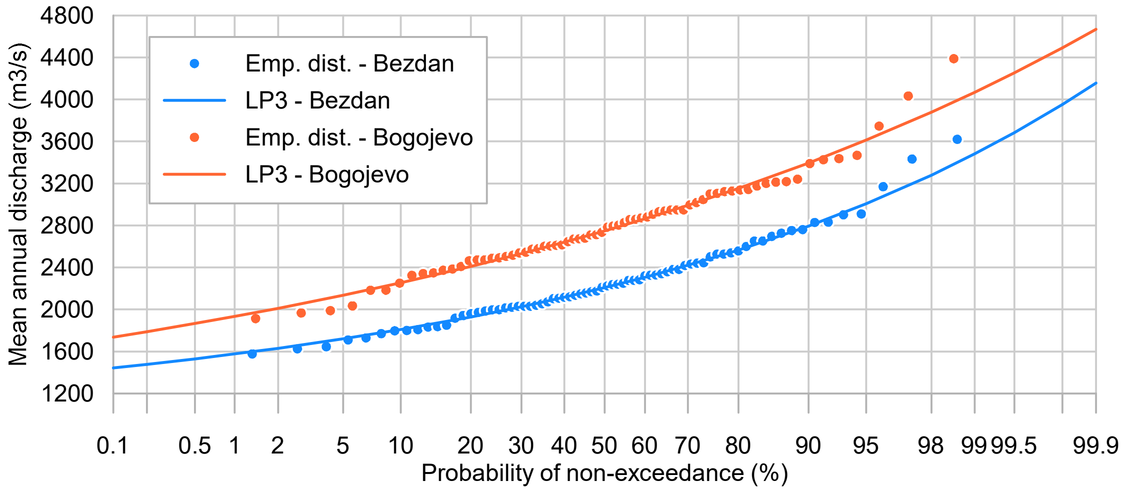


Figure 37: Distributions of mean annual discharges at Bezdan and Bogojevo: empirical distribution and log-Pearson type 3 (LP3) fit based on the complete record 1950-2023

Table 10: Mean annual discharges at Bezdan and Bogojevo for characteristic probabilities

Station	Probability of non-exceedance										
	0.1%	1%	5%	10%	20%	50%	80%	90%	95%	99%	99.9%
Discharge (m^3/s)											
Bezdan	1445	1577	1720	1809	1930	2208	2566	2794	3007	3481	4156
Bogojevo	1737	1933	2135	2254	2410	2749	3153	3395	3612	4068	4668

2.4.3. Seasonal Distribution

Seasonal (intra-annual) distributions of discharges are shown in Figure 38 for stations Bezdan and Bogojevo, which have the longest record and provide representative results. On average, the highest water at Bezdan and Bogojevo occur in May, and the lowest in October and November. Figure 38 also shows the 90% confidence interval for the seasonal distribution for Bezdan and Bogojevo.

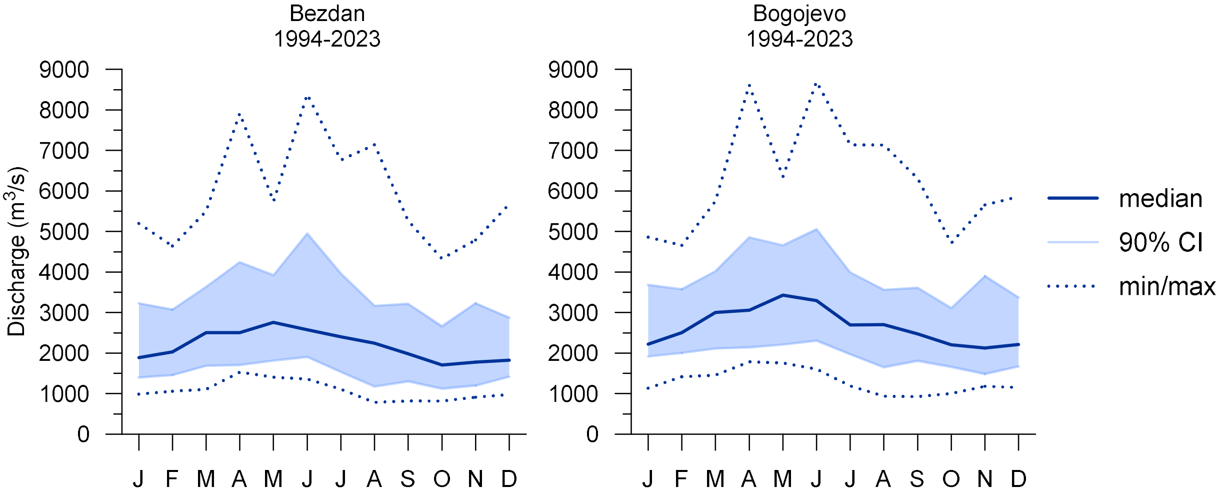


Figure 38: Seasonal distribution of flow (monthly discharges) at Serbian stations, showing long-term median (thick line), 90% confidence interval (shaded area) and envelopes of minimum and maximum monthly discharges (dashed line)

Due to short records, other stations exhibit similar but somewhat more variable pattern of the seasonal regime (Figure 39). Table 11 provides mean monthly discharges for all stations.

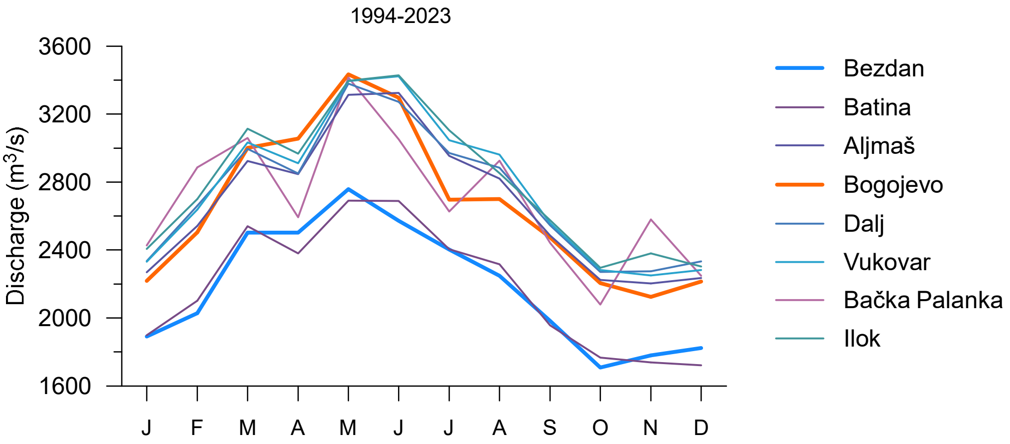


Figure 39: Median seasonal distribution of flow (monthly discharges) over 1994-2023 at all hydrological stations, computed for available record lengths

Table 11: Mean monthly discharges at Bezdan and Bogojevo

Station	Mean monthly discharges (m^3/s)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bezdan (1994-2023)	2067	2166	2509	2724	2796	2891	2432	2132	2056	1781	1894	1915
Batina (2002-2022)	2165	2254	2531	2614	2694	2954	2379	2188	2059	1795	1824	1851
Aljmaš (2001-2022)	2574	2674	2964	3157	3279	3548	2915	2684	2571	2277	2331	2333
Bogojevo (1994-2023)	2489	2644	3007	3297	3370	3440	2867	2543	2498	2204	2387	2331
Dalj (2001-2022)	2646	2734	3022	3181	3322	3551	2933	2743	2627	2329	2385	2396
Vukovar (2001-2022)	2626	2746	3045	3240	3341	3588	2998	2778	2647	2331	2384	2388
Bačka Palanka (2013-2023)	2642	2896	2938	2812	3334	3520	2626	2617	2540	2267	2481	2479
Ilok (2001-2022)	2688	2805	3118	3344	3396	3629	3020	2768	2641	2373	2432	2443

2.4.4. Duration Curves

Computation of flow duration curves in this study is performed having in mind the requirements related to the assessment of low and high navigable water levels (LNWL and HNWL, respectively) by the Danube Commission (Glossary of the Danube navigation, 2015). LNWL is defined as the water level having duration of 94% in a year that is computed from data on the observed river discharges over a period of 30 years, excluding the periods with presence of ice. Definition of HNWL is analogous except it is related to the discharge having duration of 1%.

To serve the purpose of determining LNWL and HNWL in line with the above definition, flow duration curves are assessed from daily discharge records during the last 30 years (1994-2023) with the periods with ice excluded from the record. This kind of assessment of flow duration was possible only for Serbian stations for which data on ice phenomena was available.

It should be noted that excluding ice days results in less than 365 (366) daily discharges per year. This means that it is not possible to estimate flows with durations longer than the number of non-ice days in a year. For this reason, duration is treated as the relative time ranging from 0 to 100% over non-ice period in each separate year.

In this chapter, flow duration curves are assessed using the so-called annual framework, meaning that duration curves are computed for each year of the record separately. This approach provides duration curves that are less sensitive to the choice of the period at the extreme tails than the period-of record approach, and also provides a possibility to quantify the hydrological uncertainties (Vogel and Fennessey, 1994). Duration curves for the Danube stations are therefore computed for each year in the 1994-2023 period (except for years with data gaps). Based on all duration curves within the given period, mean duration curve is derived as well as the 90% confidence interval. This confidence interval shows the range where possible variation of discharges for a given duration (or variation of duration for a given discharge) can be found with probability of 90%. For example, discharge at Bezdan having 94% duration has mean (expected) value of 1344m^3/s, but based on the last 30 years it is expected to be in the range between 1025 and 1634m^3/s with probability of 90%. Figure 40 shows mean flow duration curves for Bezdan and Bogojevo with the 90% confidence intervals, and Table 12 shows discharges at these two stations for some characteristic durations.

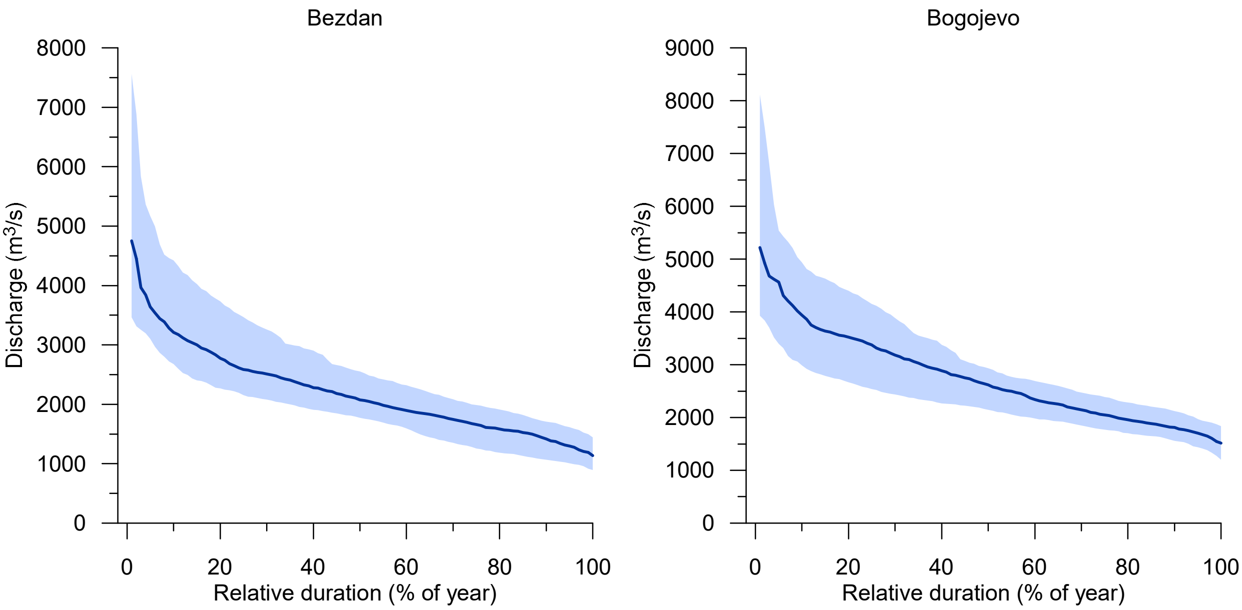


Figure 40: Flow duration curves for Bezdan and Bogojevo for 1994-2023 based on non-ice periods: long-term median (thick line) and 90% confidence interval (shaded area)

Table 12: Mean discharges with 90% confidence intervals at Bezdan and Bogojevo for characteristic durations for 1994-2023 based on non-ice periods

Duration (%)	Discharge at Bezdan (m^3/s)			Discharge at Bogojevo (m^3/s)		
	Mean	90% Conf. int.		Mean	90% Conf. int.	
		Lower limit	Upper limit		Lower limit	Upper limit
1	4920	3465	7565	5395	3925	8119
2	4576	3313	6885	5130	3836	7491
5	3902	3101	5175	4507	3395	5540
10	3406	2678	4426	4051	2989	4942
20	2927	2269	3736	3546	2668	4398
30	2621	2079	3261	3180	2437	3887
40	2348	1908	2903	2874	2268	3377
50	2105	1771	2555	2592	2146	2934
60	1901	1593	2321	2351	1981	2693
70	1729	1353	2086	2153	1852	2471
80	1580	1183	1913	1978	1702	2287
90	1422	1066	1709	1805	1558	2120
94	1344	1025	1634	1707	1455	2020
95	1316	1010	1615	1685	1437	1972
98	1231	960	1526	1584	1331	1900
99	1193	917	1495	1543	1272	1871
100	1153	894	1446	1501	1203	1839

Flow duration curves for other stations with shorter records were computed based on the available data. Due to the lack of data on ice phenomena for Croatian stations, some preliminary analysis was conducted to address the following two questions: (1) are there significant differences between the estimates of flow duration when estimated by excluding or including days with ice phenomena, and (2) are there significant differences when the flow duration is estimated from the 30-year record or a shorter one? To answer these questions, mean flow duration curves for Bezdan and Bogojevo are computed by both excluding and including ice days, and also computed for complete record 1994-2023 and for two shorter periods, 2001-2022 (period of available data at Croatian stations) and 2013-2023 (period of available data at Bačka Palanka). The results have shown (Figure 41) that the flow duration curves differ slightly when computed with ice days included or excluded. However, the differences in computed mean duration curves may be more significant if the record shorter than 30 years is used. The differences are the most pronounced for the high extremes (high flow with 1% duration), but can also be noticeable for the low extremes (low flow with 94% duration).

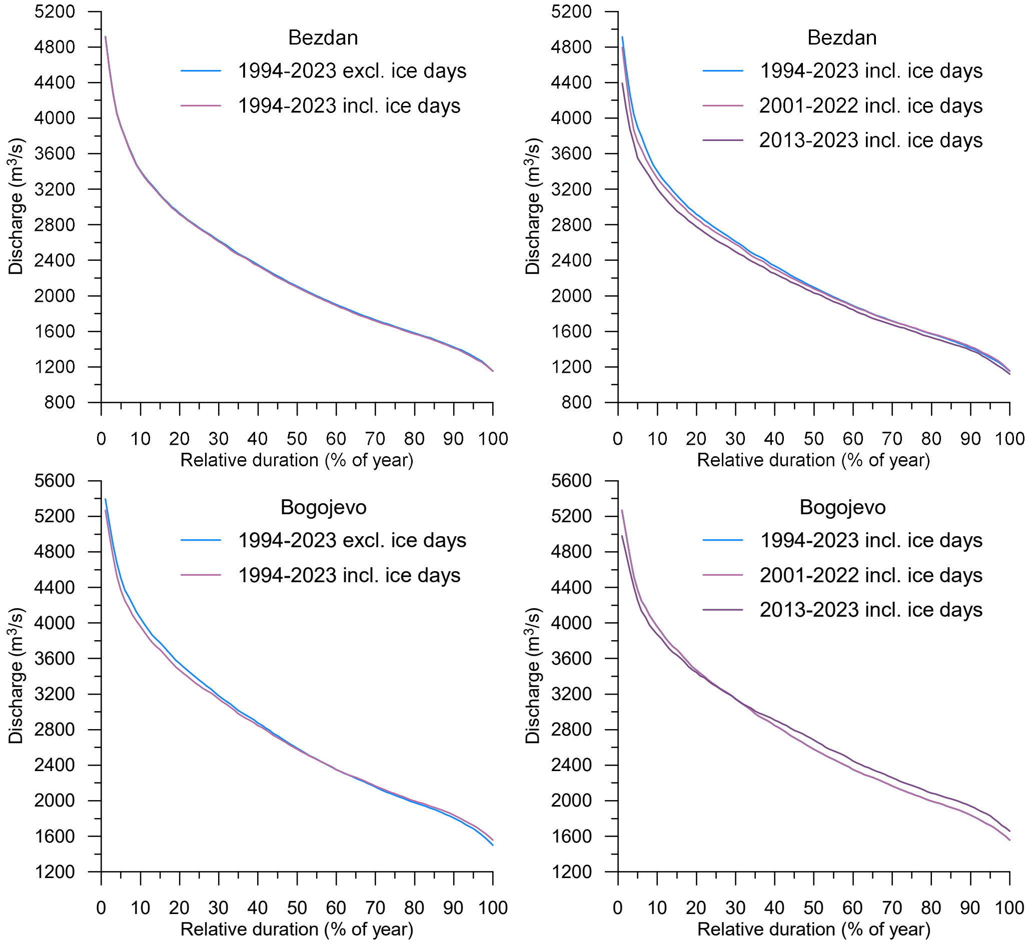


Figure 41: Mean flow duration curves for Bezdan and Bogojevo computed with excluding/including days with ice (left panels) and for different subperiods (right panels)

Based on these conclusions and also having in mind the sources of uncertainties identified in the preliminary analysis of data, it is concluded that the flow duration curves for stations having record shorter than 30 years should be adjusted in order to get comparable results along the given Danube sector. Adjusting flow duration curves based on short records to represent longer periods is recommended by US Geological Survey (Searcy, 1959) because such duration curves are considered unreliable for predicting the future pattern of flow.

For each station with short record, a transfer function between discharges at that station and a neighboring station with longer record is defined. This transfer function is aimed at adjusting the discharges of given duration from a shorter period to the 1994-2023 period. The transfer function is derived on the basis of mean flow duration curves for the station with shorter record and the station with the longer record, but for the timeframe corresponding to the shorter record. Because all the stations with shorter records are located downstream of the Drava confluence, Bogojevo is selected as the station with complete record over 1994-2023. Since the flow duration curve for Bogojevo is computed by excluding data on ice days, the transfer function effectively adjusts the flow duration curves from Croatian stations not only for shorter record but also for including ice days in computation. The transfer functions are defined by creating a regression relationship between the discharges at the two stations having duration from 1% to 100% in steps of 1% (total of 100 discharges). Transfer functions were developed for stations Aljmaš, Dalj, Vukovar, Ilok and Bačka Palanka (Figure 42). The regressions obtained are shown in Table 13.

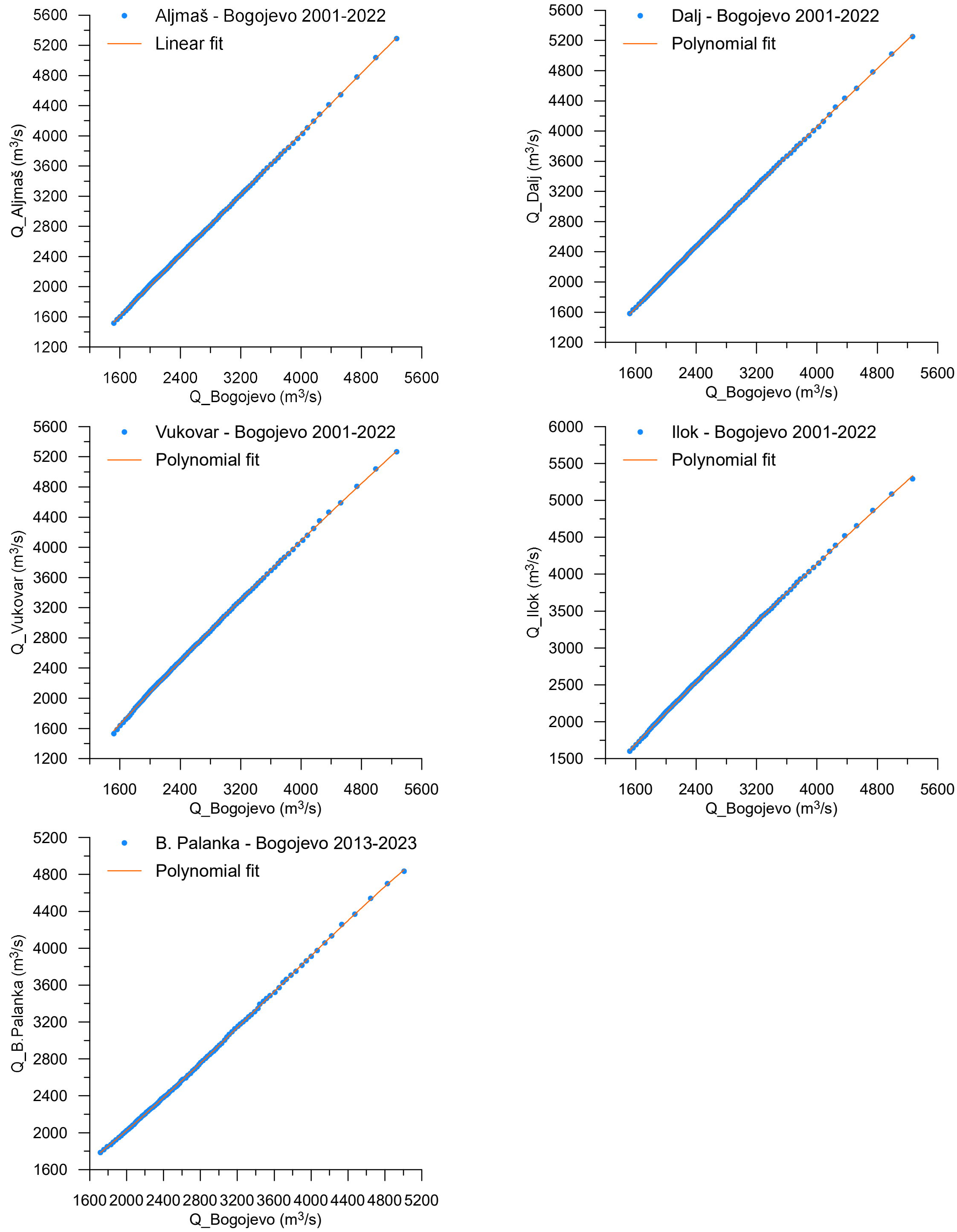


Figure 42: Transfer functions to adjust flow duration curves at stations with short record

Table 13: Regression fits used as transfer functions for adjustment of flow duration curves (Y denotes discharge for given duration at the station with short record, and X denotes discharge for the same duration at Bogojevo; both X and Y are in m^3/s)

Station	Regression equation	Coefficient of determination
Aljmaš	$Y = 1.00655 \cdot X$	$R^2 \approx 1$
Dalj	$Y = -13.6 + 1.0625 \cdot X - 1.12 \cdot 10^{-5} \cdot X^2$	$R^2 = 0.99993$
Vukovar	$Y = -101.88 + 1.13 \cdot X - 2.1 \cdot 10^{-5} \cdot X^2$	$R^2 = 0.99982$
Ilok	$Y = -52.74 + 1.126 \cdot X - 1.97 \cdot 10^{-5} \cdot X^2$	$R^2 = 0.99986$
Bačka Palanka	$Y = 728.9 + 0.366 \cdot X + 0.000173 \cdot X^2 + 1.64 \cdot 10^{-8} \cdot X^3$	$R^2 = 0.99991$

For each station with the short record, discharges having duration 1% and 94% ($Q_{1\%}$ and $Q_{94\%}$, respectively) are adjusted by using the transfer function with the discharge of given duration at Bogojevo over the complete 1994-2023 period as the input variable. Table 14 shows the results and compares them with corresponding values before the adjustment. It can be seen that, after the adjustment, low flows $Q_{94\%}$ mostly have consistent values along the Danube stretch of interest. On the other hand, this is not the case with flood flows $Q_{1\%}$, but this kind of inconsistency is expected having in mind well-known inherent uncertainties in stage-discharge curves during floods. However, to have consistent input for hydrodynamic modelling, low flows $Q_{94\%}$ at Aljmaš and Ilok are adopted to have the same values as at Bogojevo and Bačka Palanka respectively, while high flows $Q_{1\%}$ between Aljmaš and Vukovar are adopted to have the same value as at Bogojevo (as shown in Table 14).

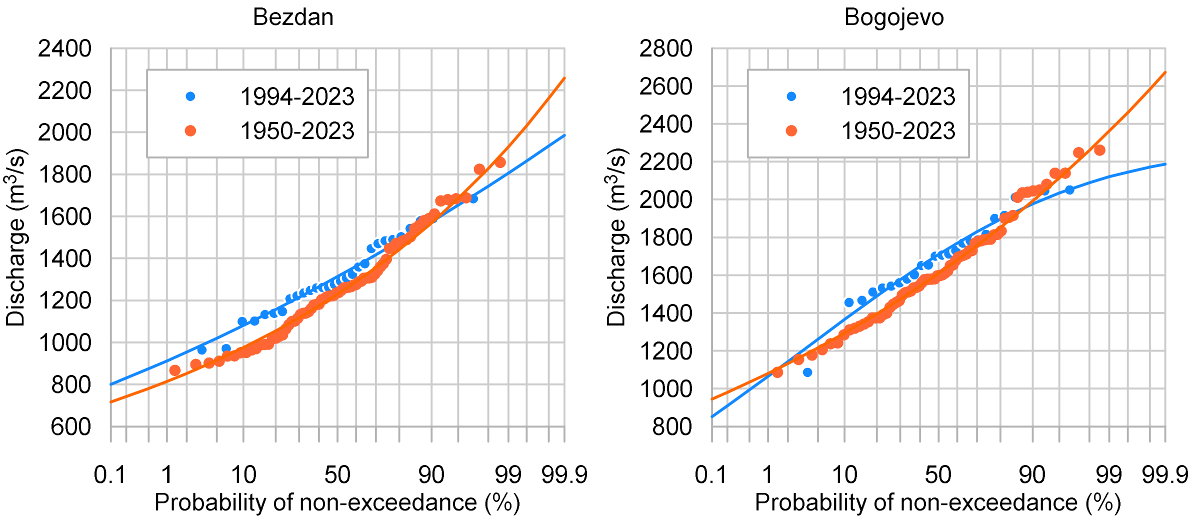
Table 14: Comparison of characteristic discharges assessed from flow duration curves, before and after the adjustment with the transfer function

Station	$Q_{94\%}$ (m^3/s)			$Q_{1\%}$ (m^3/s)		
	Before adjustment	After adjustment	Adopted	Before adjustment	After adjustment	Adopted
Bezdan	1344	–	1344	4920	–	4920
Batina	1316	1349	1349	4817	4940	4940
Aljmaš	1735	1719	1707	5290	5430	5395
Bogojevo	1707	–	1707	5395	–	5395
Dalj	1791	1768	1768	5252	5392	5395
Vukovar	1774	1769	1769	5266	5391	5395
Ilok	1821	1813	1778	5292	5449	5449
Bačka Palanka	1897	1778	1778	4835	5173	5449

2.5. Low Flows

The regime of low flows is considered by undertaking frequency analysis of annual minimum discharges with durations of 1, 7, 10, 20 and 30 days. For this analysis, data on daily discharges during the 1993-2024 period are used to establish the series of annual minima for all durations. The resulting series are shorter than 30 years, especially at the Croatian stations. After preliminary analysis, log-Pearson type III distribution was selected as the best fit for all annual minima series.

Short series are known to bring high uncertainty into frequency analysis. The degree to which the short series could affect the results of frequency analysis was analyzed for stations Bezdan and Bogojevo, for which long term data was available. Figure 43 shows that the probability distributions of 30-day annual minimum discharges at these two stations differ significantly for shorter and longer record.



Note: dots: empirical distribution, lines: log-Pearson type III distribution fit

Figure 43: Frequency analysis of 30-day annual minimum discharges for 1994-2023 vs. 1952-2023

When focusing on the 1994-2023 period only, the concerns about the uncertainty are even more emphasized for the Croatian stations, for which only 21 or 22 years of record are available. After computing low flows for characteristic probabilities at all Serbian and Croatian stations, inconsistencies in the results arise along the joint Danube sector. Figure 44 shows a considerable difference in results for Bezdan and Batina stations (with 30 and 21 years of record, respectively), as well as illogical ratio between Aljmaš and Bogojevo (with 22 and 26 years of record, respectively). For the latter pair of stations, it was already discussed that the differences in stage-discharge rating curves also contribute to the significant differences in discharges at these two stations.

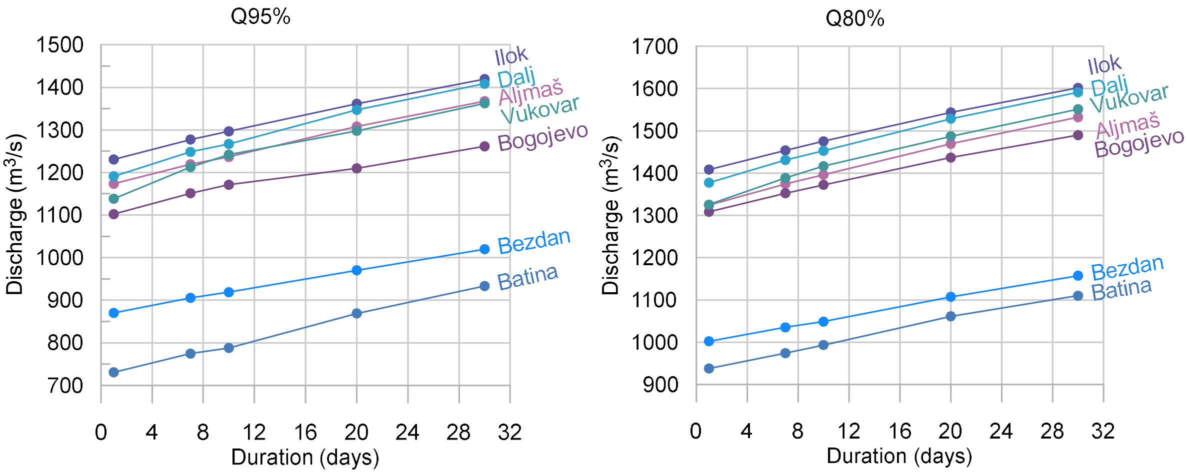


Figure 44: Relationship between low flows with 95% probability of exceedance and duration for the stations along the joint Danube sector (results for 1994-2023)

Having the above in mind, it can be concluded that the frequency analysis of short records, combined with inconsistencies in rating curves, cannot provide reliable information for the low flow analysis. Therefore, the results are shown here only for the long-term period at Bezdan and Bogojevo (Table 15).

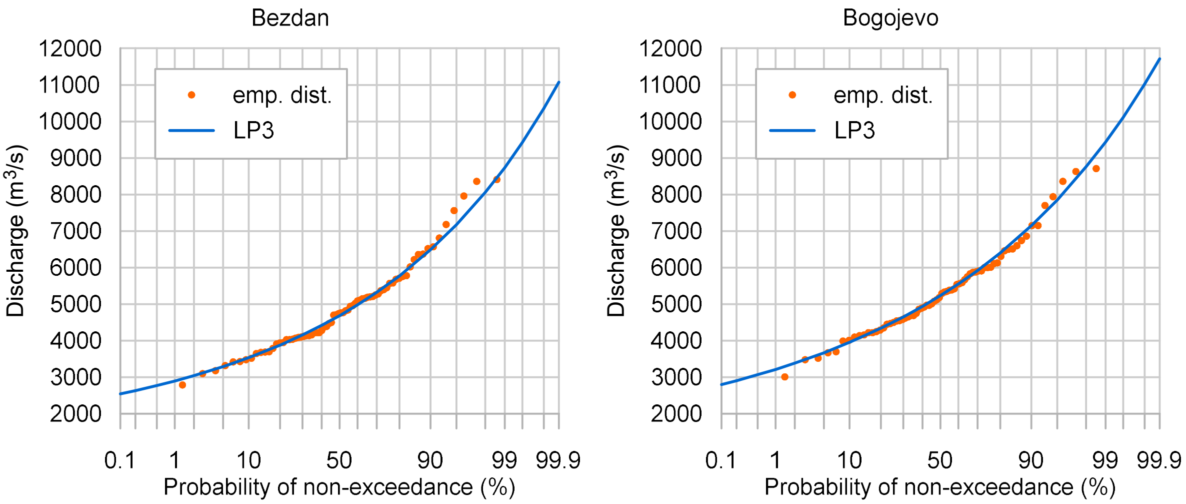
Table 15: Comparison of characteristic discharges assessed from flow duration curves, before and after the adjustment with the transfer function

Duration (days)	Probability of exceedance				
	99%	98%	95%	90%	80%
	Low flows at Bezdan (m^3/s)				
1	728	762	816	869	938
7	751	785	841	894	965
10	760	795	851	905	977
20	789	825	884	941	1017
30	814	853	915	975	1055
	Low flows at Bogojevo (m^3/s)				
1	965	1014	1090	1162	1254
7	1003	1050	1126	1196	1287
10	1016	1063	1138	1209	1300
20	1041	1092	1172	1247	1345
30	1080	1133	1216	1294	1395

2.6. Flood Flows

Flood flows are characterized through the frequency analysis of annual maximum flows. Discharge records at Bezdan and Bogojevo from 1952-2023 are used to estimate floods for a range of probabilities.

The observed data are fitted with the log-Pearson type III distribution, which was selected as the best fit for both stations (Figure 45). The flood quantiles are also shown in Table 16.



Note: dots: empirical distribution, lines: log-Pearson type III distribution fit

Figure 45: Frequency analysis of annual maximum discharges for 1952-2023

Table 16: Flood flows at Bezdan and Bogojevo from flood frequency analysis

Return period (years)	Probability of exceedance	Bezdan (m^3/s)	Bogojevo (m^3/s)
2	50%	4,689	5,235
5	20%	5,775	6,401
10	10%	6,488	7,148
20	5%	7,171	7,853
50	2%	8,062	8,758
100	1%	8,739	9,435
200	0.5%	9,425	10,114
500	0.2%	10,355	11,021
1000	0.1%	11,078	11,718

2.7. Navigable Water Levels

Low and high navigable water levels (LNWL and HNWL, respectively), as critical indicators for inland navigation, represent reference water levels at which the full functionality of the waterway is available for navigation (Muilerman et al., 2018). The Danube Commission (2013, 2015a) has defined LNWL as the water level having duration of 94% in a year that is computed from data on the observed river discharges over a period of 30 years, excluding the periods with presence of ice. HNWL is defined as the water level with duration of 1%, based on the discharges observed during a period of 30 years, excluding the ice periods. Danube Glossary (Danube STREAM project, 2019) defines LNWL further by specifying that it represents the water level derived from the stage-discharge rating curve based on the discharge having 94% duration over the 30-year period, on days without ice (and similarly for HNWL).

With flow duration curves computed as described in section 2.3.4, with an adjustment that accounts for lengths of record shorter than 30 years during 1994-2023, it is possible to define LNWLs and HNWLs at hydrological stations by converting the characteristic discharges $Q_{94\%}$ and $Q_{1\%}$ (with duration 94% and 1%, respectively) into corresponding levels by means of the stage-discharge rating curves.

The stage-discharge curves for Croatian stations were obtained from DHMZ in a functional form of quadratic relationship between the water levels and discharges. According to DHMZ, the functional rating curves are valid from 2019 to 2024. Stage-discharge curves for Serbian stations were not delivered directly by RHMSS, but were obtained unofficially from “Plovput”.

Reference LNWLs and HNWLs are obtained from the stage-discharge curves for the mean values of $Q_{94\%}$ and $Q_{1\%}$, and the results are shown in Table 17 and in Figure 46. Slight differences present at twin stations are not unexpected having in mind the disagreement of stage-discharge relationships for these stations. However, the reference levels resulting from the hydrological analysis should further be validated by hydrodynamic simulations, leading to the final adoption of the low and high navigable water level.

Table 17: Water levels corresponding to the discharges of duration of 94% and 1% at hydrological stations along the Serbian-Croatian common stretch of the Danube River

Station	Chainage (km)	Duration 94%		Duration 1%	
		Water level (m)	Stage (cm)	Water level (m)	Stage (cm)
Bezdan	1425.59	80.63	-1	86.12	548
Batina	1424.60	80.62	17	85.96	551
Aljmaš	1380.25	78.58	50	83.79	571
Bogojevo	1367.25	77.73	27	83.01	555
Dalj	1353.70	77.43	223	82.23	703
Vukovar	1333.40	76.68	49	81.14	495
Ilok	1298.70	74.68	71	79.15	518
Bačka Palanka	1298.56	74.87	90	79.23	526

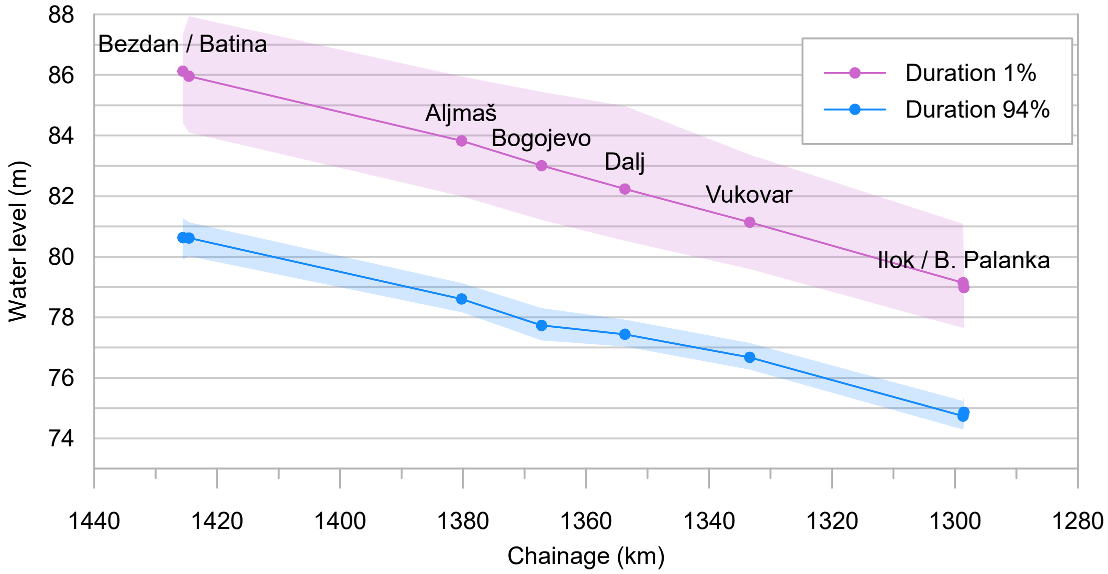


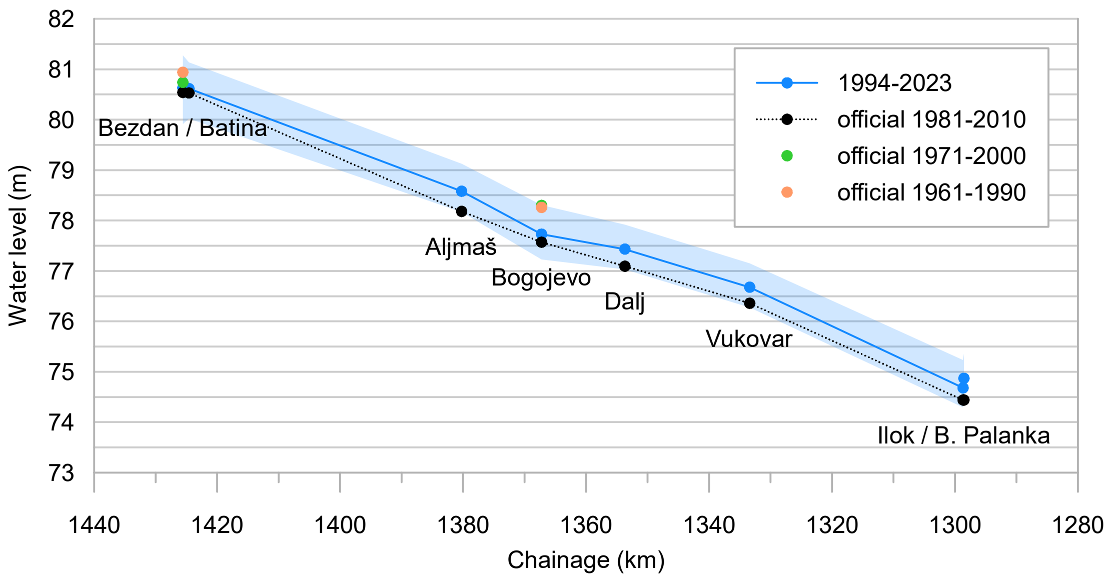
Figure 46: Water levels corresponding to discharges of 1% and 94% duration at hydrological stations along the Serbian-Croatian common stretch of the Danube River, with 90% confidence intervals (shaded areas)

Comparison of the reference water levels from this study with the official levels reported to the Danube Commission for the previous 30-year periods is given in Table 18. The official levels for 1961-1990, 1971-2000 and 1981-2010 are retrieved from the publications of the Danube Commission (1995, 2007, 2015b). For 1961-1990 and 1971-2000 the levels are available only for Serbian stations. The levels were not reported for the period 1991-2020, neither for Serbian nor for Croatian stations. All reference levels are also shown in Figure 47 and Figure 48. The comparison shows that the LNWLs in this project are higher than the corresponding levels for 1981-2010, but still lower than in earlier periods 1971-2000 and 1961-1990. On the other hand, reference HNWLs for 1994-2023 are lower than in previous calculations. The differences are less pronounced at Bezdan and Batina then at the stations downstream of the Drava confluence.

Table 18: Comparison of the results of this study with the official high and low navigable water levels reported to the Danube Commission

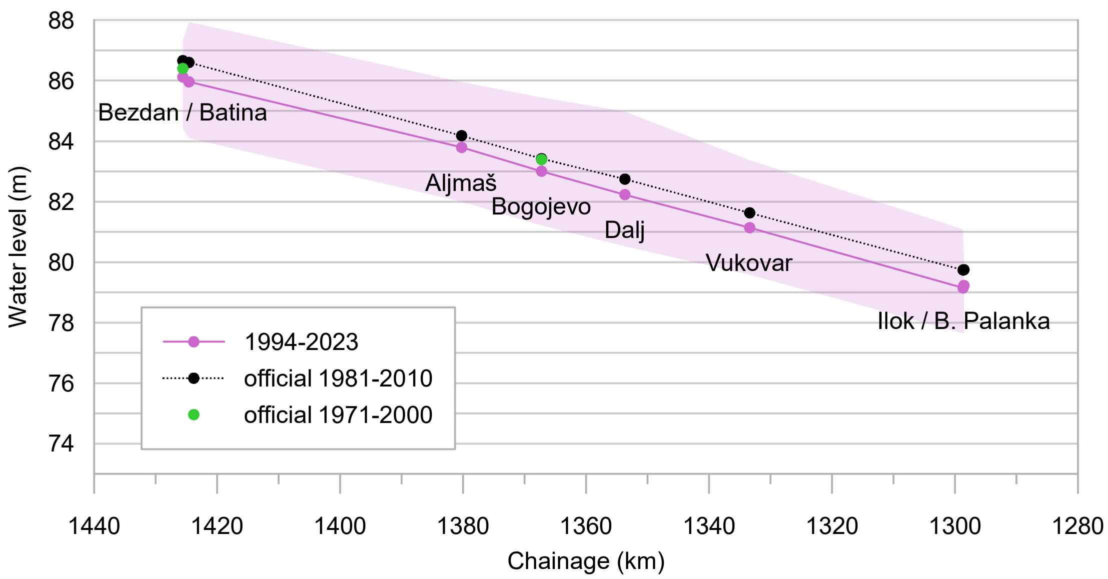
Station	Chainage (km)	Gauge zero (m)	Period	LNWL			HNWL		
				Q (m³/s)	H (cm)	Z (m)	Q (m³/s)	H (cm)	Z (m)
Bezdan	1425.59	80.64	1961-1990	1150	30	80.94	–	–	–
			1971-2000	1140	10	80.74	5048	576	86.40
			1981-2010	1180	-10	80.54	5280	602	86.66
			1994-2023	1344	-1	80.63	4920	548	86.12
Batina	1424.60	80.45	1961-1990	–	–	–	–	–	–
			1971-2000	–	–	–	–	–	–
			1981-2010	1180	8	80.53	5280	615	86.60
			1994-2023	1349	17	80.62	4940	551	85.96
Aljmaš	1380.25	78.08	1961-1990	–	–	–	–	–	–
			1971-2000	–	–	–	–	–	–
			1981-2010	1435	10	78.18	5850	610	84.18
			1994-2023	1707	50	78.58	5395	571	83.79
Bogojevo	1367.25	77.46	1961-1990	1530	80	78.26	–	–	–
			1971-2000	1480	84	78.30	5720	593	83.39
			1981-2010	1435	11	77.57	5850	596	83.42
			1994-2023	1707	27	77.73	5395	555	83.01
Dalj	1353.70	75.20	1961-1990	–	–	–	–	–	–
			1971-2000	–	–	–	–	–	–
			1981-2010	1435	189	77.09	5850	754	82.74
			1994-2023	1768	223	77.43	5395	703	82.23
Vukovar	1333.40	76.19	1961-1990	–	–	–	–	–	–
			1971-2000	–	–	–	–	–	–
			1981-2010	1435	17	76.36	5850	544	81.63
			1994-2023	1769	49	76.68	5395	495	81.14
Ilok / Ilok most	1298.70	73.97	1961-1990	–	–	–	–	–	–
			1971-2000	–	–	–	–	–	–
			1981-2010	1435	47	74.44	5850	577	79.74
			1994-2023	1778	71	74.68	5449	518	79.15
Bačka Palanka	1298.56	73.97	1961-1990	–	–	–	–	–	–
			1971-2000	–	–	–	–	–	–
			1981-2010	1435	47	74.44	5850	578	79.75
			1994-2023	1778	90	74.87	5449	526	79.23

Note: Q is reference discharge, H is stage, and Z is water level



Note: shaded area represents 90% confidence interval for 1994-2023

Figure 47: Comparison of LNWLs from previous official calculations



Note: shaded area represents 90% confidence interval for 1994-2023

Figure 48: Comparison of HNWLs from previous official calculations

The main cause of different reference water levels are different reference discharges. Low flows $Q_{94\%}$ at hydrological stations are greater in this study than the previous calculation by 14-24%, and the high flows $Q_{1\%}$ are lower by 6-8% than in the previous calculation.

The shift in low flows from 1981-2010 to 1994-2023 can also be seen by comparing the distributions of daily discharges in these two periods at Bezdan and Bogojevo, presented in Figure 49. This figure shows that the distribution changed from one period to another. The change is especially visible in the domain of low flows. Discharges below 1500m^3/s at Bezdan, and below 2000m^3/s at Bogojevo, are much less frequent in the latter period then during 1981-2010. At the same time, about-average discharges (discharges between 1500 and 3000m^3/s at Bezdan, and between 2000 and 3500m^3/s at Bogojevo) are more frequent during 1994-2023. This explains the shift in $Q_{94\%}$ from 1180 to 1344m^3/s at Bezdan, and from 1435 to 1707m^3/s at Bogojevo.

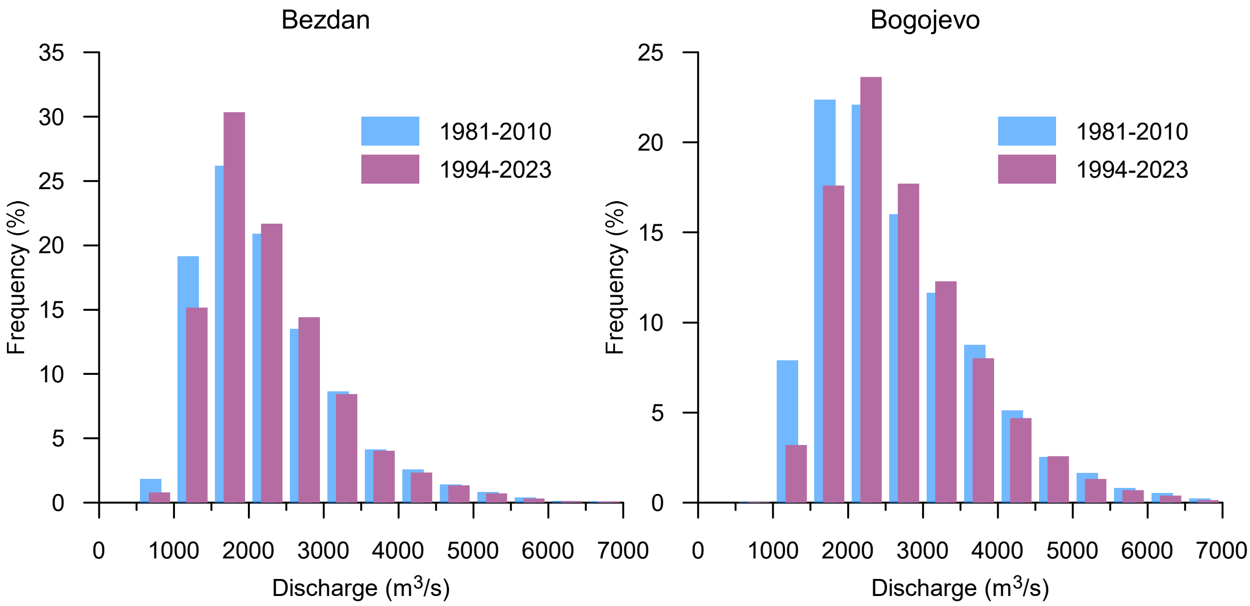


Figure 49: Comparison of distributions of daily discharges from two 30-year periods

This observation-based evidence on the increase of low flows at this stretch of the Danube does not support projected low flow trends anticipated by the climate models for the middle Danube basin in the update of the Danube Study by ICPDR (LMU, 2018). Conclusions from this study indicated that low flow conditions would be expected to increase in duration and intensity, with a reduction of low flows by 25-50% by mid-21st century. On the other hand, more recent projections (Probst and Mauser, 2023) show an expected increase in low flows in the near future (2031-2060) under two extreme climate change scenarios RCP 2.6 (very optimistic scenario) and RCP 8.5 (very pessimistic scenario). In the work of Probst and Mauser (2023; Fig. 14), climate simulations for Bezdan indicate an upward shift in the low-flow domain of flow duration curves in the future, compared to the historical 1971-2000 period. This means that a given discharge value would be exceeded in the future in more days in a year, or that a higher discharge would correspond to a given duration.

To conclude, although there is a certain reservation about the accuracy of the measurements and stage-discharge rating curves on the common Serbian-Croatian stretch of the Danube, the observations are clearly showing increased low flows in the last 30 years. This increase may be attributed to climate change as the observations support the most recent findings from Probst and Mauser (2023). However, this increase may also originate from the water management practices in the regulated upstream sections of the Danube and its tributaries, but this statement cannot be made without collecting further information on such practices.

2.8. Conclusions and Recommendations on Updated ENRs

Based on the available hydrological data at 8 hydrological stations, this hydrological study delivers information on hydrological regime of the Danube River along the common Danube stretch from the Hungarian border to Bačka Palanka. All aspects of water regime are covered (mean, low and flood flows).

Analysis of the consistency of data across the stations (and especially at twin Serbian/Croatian stations) has shown that the data are generally consistent, but that there are occasional significant discrepancies that weaken the confidence in the results of the analysis. Consequently, there is a strong need for coordination and cooperation of hydrometeorological services of Serbia and Croatia that would lead to harmonization in terms of measurements, data collection and data processing.

The analysis has also shown that it is not possible to treat data from hydrological stations with shorter records (Croatian stations and Bačka Palanka) equally as the stations with longer records within the selected 30-year period. It is therefore recommended that similar future studies involving the assessment of reference water levels should be based on records from stations with complete records over 30 years. Eventually, Croatian stations would reach 30 years of records in 2030, when the new assessment can be performed.

The reference discharges $Q_{94\%}$ and $Q_{1\%}$ needed for the estimation of reference water levels (low and high navigable water levels) are estimated from duration analysis of observed discharges, with a necessary adjustment to compensate for the shortness of the records and lack of information on ice phenomena at some stations. Converting these discharges to water levels using the most recent stage-discharge rating curves resulted in different reference levels than those calculated previously for the 1981-2010 period. This difference is due to the less frequent occurrence of low flows in this stretch of the Danube.

The results for the reference water levels obtained in this hydrological study will be further used and validated in hydrodynamic simulations that would lead to final adoption of the reference levels.

As presented in Table 18, all new LNWL levels observed during the period from 1994 to 2023 are higher and all new HNWL levels observed during the period from 1994 to 2023 are lower compared to those reported to the Danube Commission in earlier periods. The main cause is greater low flows $Q_{94\%}$ by 14-24%, and the lower high flows $Q_{1\%}$ by 6-8% than in the previous calculation.

The calculated LNWL and HNWL data should be forwarded to the Croatian river administration and officially submitted to the Danube Commission to update the old records and incorporate the new data into regular use.

CHAPTER 3. – BOTTLENECKS CATALOGUE

3.1. Introduction

Based on the results of the CHAPTER 1 - 1D MODELING, including the CHAPTER 2 – UPDATE OF ENRs, the Consultant calculated new reference water levels (Etiage navigable et de régularisation – ENR, or Low Navigation Water Levels - LNWL) for the entire project area (common sector of the Danube River). Following application of the official designed fairway axis, as provided by the Contracting Authority, the Consultant applied a design fairway depth of 2.5 m and varying fairway widths—100 m, 120 m, 150 m, and 200 m—in accordance with the Level of Service (LoS) approach. This approach reflects varying service quality levels offered by waterway administrations to users, whereby higher fairway dimensions correspond to a higher level of navigational service, and vice versa. These fairway parameters were systematically applied across the entire common Serbian–Croatian stretch of the Danube River. Additionally, the Consultant incorporated historical hydrographic data, also supplied by the Contracting Authority, to provide further insight into the morphological evolution of the identified sectors.

3.2. Analyzed navigation bottlenecks

A list of analyzed navigation bottlenecks—defined as river stretches with potentially constrained fairway conditions during low water periods—is presented in Table 19.

Table 19: List of Analyzed navigation bottlenecks

No.	Sector	Chainage (from km to km)	Quantity of sediment (m^3) within fairway of 2.5m depth &			
			Width 100m	Width 120m	Width 150m	Width 200m
1	**Bezdan / Batina**	1,429.0 – 1,425.0	0	0	0	4,745
2	**Siga Kazuk**	1,424.2 – 1,414.4	0	0	0	1,106
3	**Apatin**	1,408.2 – 1,400.0	7,035	14,635	26,821	54,311
4	**Čivutski Rukavac / Židovski Rukavac**	1,397.2 – 1,389.0	343	1,494	8,164	52,977
5	**Drava Confluence**	1,388.8 – 1,382.0	0	441	4,221	22,013
6	**Aljmaš**	1,381.4 – 1,378.2	0	0	0	0
7	**Staklar**	1,376.8 – 1,373.4	733	1,571	3,823	14,781
8	**Erdut**	1,371.4 – 1,366.4	0	0	0	0
9	**Bogojevo**	1,366.2 – 1,361.4	0	0	0	330
10	**Dalj**	1,357.0 – 1,351.0	0	0	0	344
11	**Borovo 1**	1,348.6 – 1,343.6	0	415	5,431	26,555
12	**Borovo 2**	1,340.6 – 1,338.0	0	346	6,863	40,353
13	**Vukovar**	1,332.0 – 1,325.0	0	0	0	2
14	**Sotin**	1,324.0 – 1,320.0	0	0	0	85
15	**Opatovac**	1,315.4 – 1,314.6	0	0	0	37
16	**Mohovo**	1,311.4 – 1,307.6	93	177	368	748
17	**Bačka Palanka / Ilok**	1,302.0 – 1,300.0	0	0	0	0

Figure 50: Analyzed navigation bottlenecks

Compared to the existing list of bottlenecks identified by the Serbian and Croatian authorities a decade ago, the updated list of bottlenecks contains 13 sectors. This means that 4 sectors from the previous list — **Aljmaš**, **Erdut**, **Vukovar**, and **Ilok**— are no longer considered critical for navigation, as the full fairway parameters are now available. The updated list of navigation bottlenecks is presented in the Table 20.

Table 20: Updated list of navigation bottlenecks

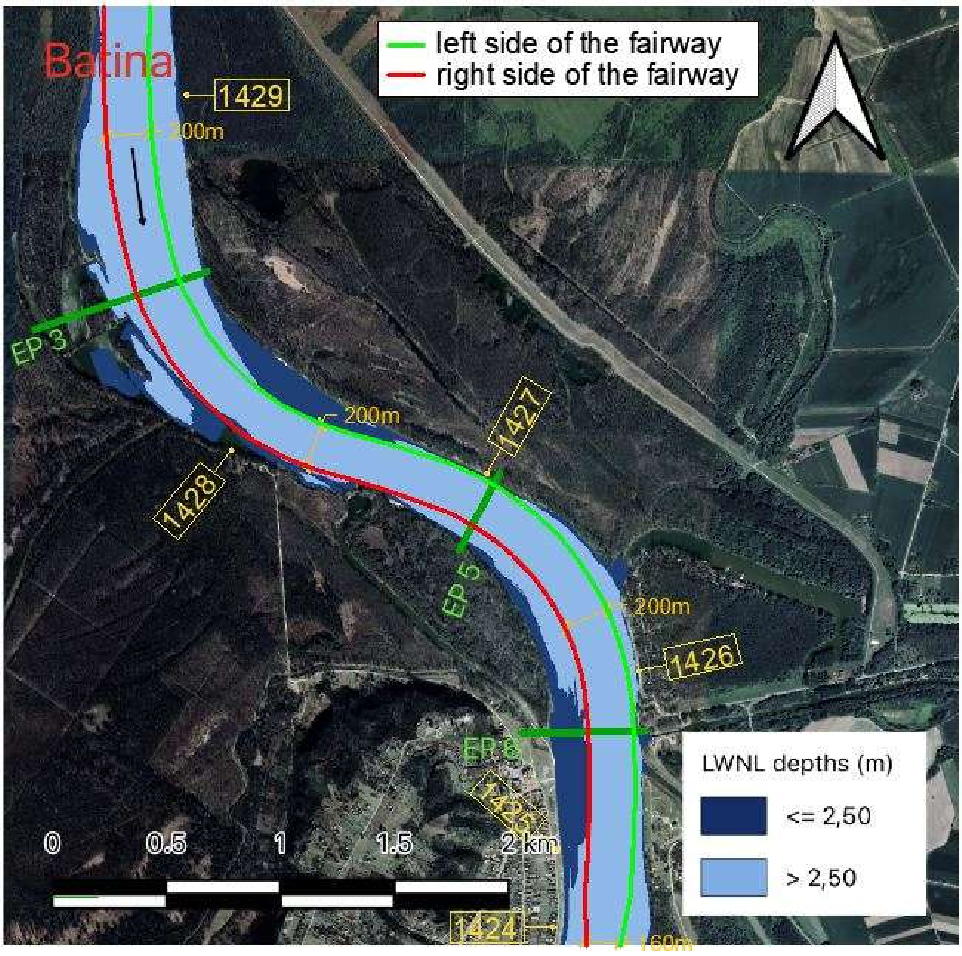
No.	Sector	Chainage (from km to km)	Quantity of sediment within the fairway of 2.5m depth &			
			Width 100m	Width 120m	Width 150m	Width 200m
1	**Batina/Bezdan**	1,429.0 – 1,425.0	0	0	0	4,745
2	**Siga Kazuk**	1,424.2 – 1,414.4	0	0	0	1,106
3	**Apatin**	1,408.2 – 1,400.0	7,035	14,635	26,821	54,311
4	**Židovski/Čivutski Rukavac**	1,397.2 – 1,389.0	343	1,494	8,164	52,977
5	**Drava Confluence**	1,388.8 – 1,382.0	0	441	4,221	22,013
7	**Staklar**	1,376.8 – 1,373.4	733	1,571	3,823	14,781
9	**Bogojevo**	1,366.2 – 1,361.4	0	0	0	330
10	**Dalj**	1,357.0 – 1,351.0	0	0	0	344
11	**Borovo 1**	1,348.6 – 1,343.6	0	415	5,431	26,555
12	**Borovo 2**	1,340.6 – 1,338.0	0	346	6,863	40,353
14	**Sotin**	1,324.0 – 1,320.0	0	0	0	85
15	**Opatovac**	1,315.4 – 1,314.6	0	0	0	37
16	**Mohovo**	1,311.4 – 1,307.6	93	177	368	748

To ensure traceability, the Consultant maintained the original numbering system established by the Serbian and Croatian authorities across all tables in this and related reports. For consistent presentation of the identified navigation bottlenecks, a standardized template was developed. This template includes essential location details, visual representations of each bottleneck, information on navigational constraints and limitations, relevant historical context (i.e. whether the location was previously recognized as a bottleneck or newly identified), and key ecological and hydrological characteristics.

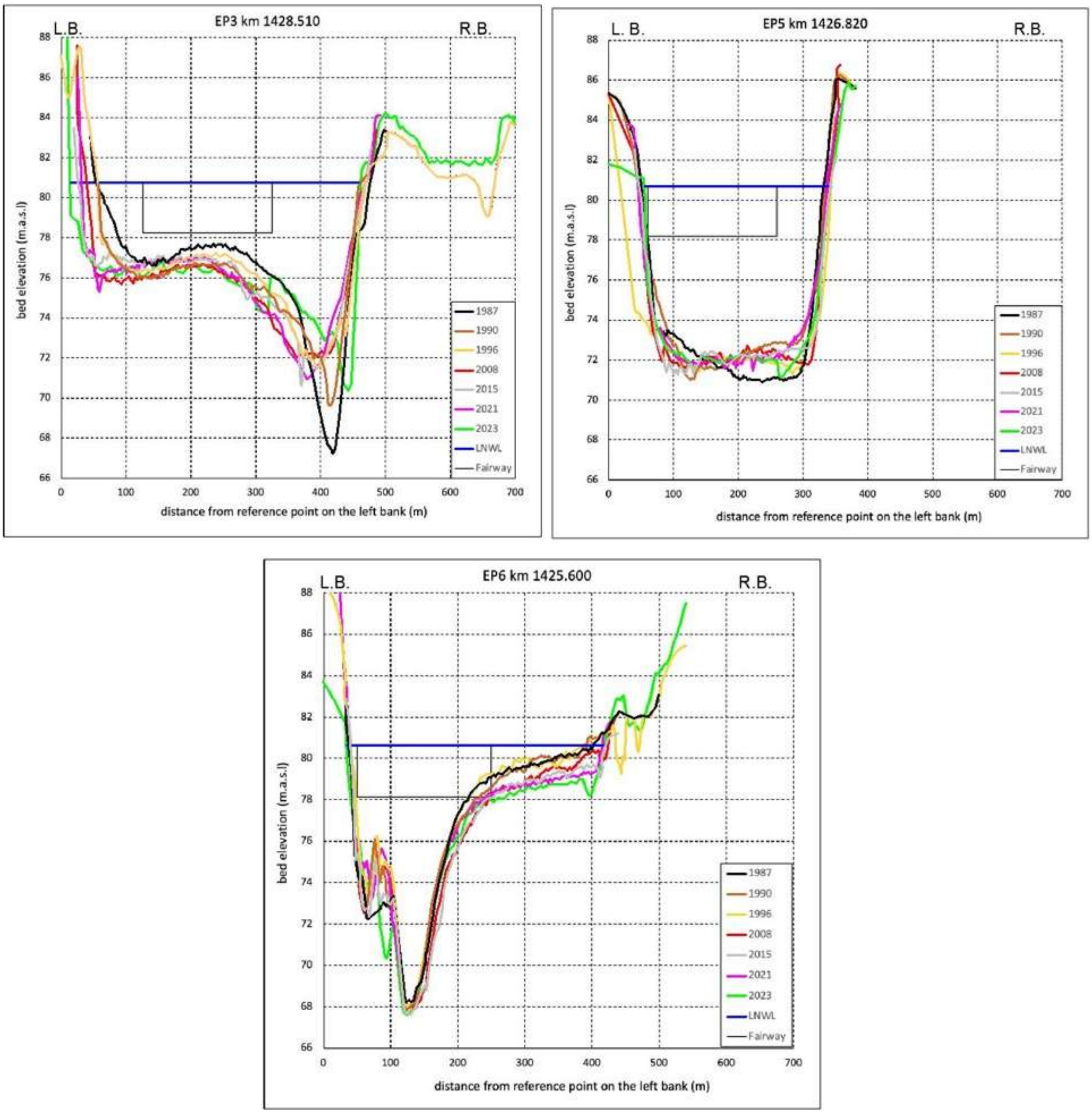
3.3. Bezdan

Basic location info			
Name of the bottleneck	**Bezdan**	Alternative name	**Batina**
Waterway	Danube River	Waterway class (AGN)	VI
From (km upstream)	1,429.00	To (km downstream)	1,425.00
Total length (km)	4,00	River bed	sand

Visualization



Layout view of the critical sector



Cross sections of the critical sector

Basic information on the navigation obstacle(s)			
☐ depth	☒ width	☐ radius	☐ height
☐ other (to be specified if selected)			

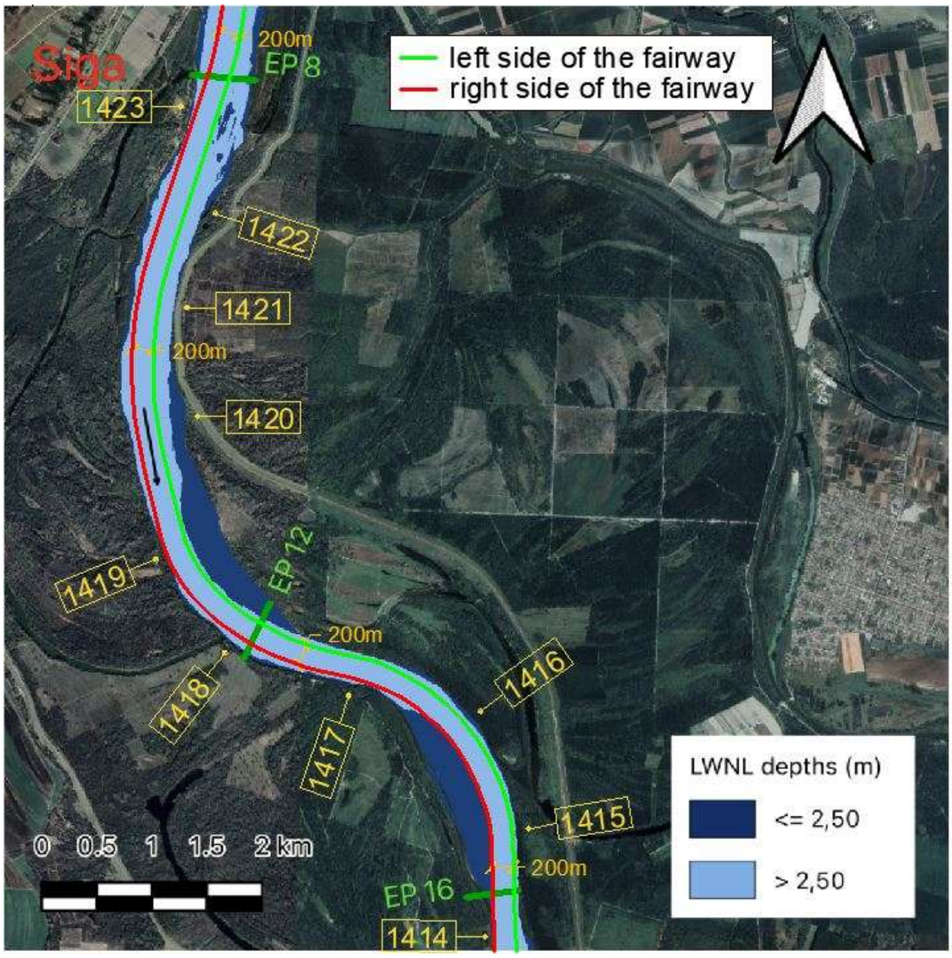
Historical information				
☒ The location is known as the navigation bottleneck from before			☐ The location is newly identified navigation bottleneck	
Basic ecological information				
Overall ecological status of the water body (ICPDR, Danube River Basin Management Plan, Update 2021, Annex 9)				
☐ high	☐ good	☒ moderate	☐ poor	☐ bad
Protected areas information: - The Transboundary Biosphere Reserve Mura-Drava-Danube - Danube north from Kopački rit (HR2001309) Natura 2000 site - Special Nature Reserve Gornje Podunavlje - Gornje Podunavlje (RS000001) Emerald site				
Basic hydrological information				
Name of the reference gauging station			Bezdan	
Year of the establishment of the gauging station			1856	
Location of the gauging station			km 1.425,59	
Distance to the (center of the) bottleneck			1.41 km	
Period for the calculation of the reference levels			*1981-2010*	
ENR (LNWL)	*80.54 m.a.s.l.*	*-10 cm*	*LNQ*	*1.180 m^3/s*
HNWL	*86.66 m.a.s.l.*	*602 cm*	*HNQ*	*5.280 m^3/s*
Period for the calculation of the reference levels			1994-2023	
ENR (LNWL)	80.63 m.a.s.l.	-1 cm	LNQ	1.344 m^3/s
HNWL	86.13 m.a.s.l.	549 cm	HNQ	4.920 m^3/s
Name of the reference gauging station			Batina	
Year of the establishment of the gauging station			2001	
Location of the gauging station			km 1.424,60	
Distance to the (center of the) bottleneck			2.40 km	
Period for the calculation of the reference levels			*1981-2010*	
ENR (LNWL)	*80.53 m.a.s.l.*	*8 cm*	*LNQ*	*1.180 m^3/s*
HNWL	*86.60 m.a.s.l.*	*615 cm*	*HNQ*	*5.280 m^3/s*
Period for the calculation of the reference levels			1994-2023*	
ENR (LNWL)	80.62 m.a.s.l.	17 cm	LNQ	1.349 m^3/s
HNWL	85.96 m.a.s.l.	551 cm	HNQ	4.940 m^3/s

Note: m.a.s.l. here and elsewhere in the document is with reference to the Trieste zero.

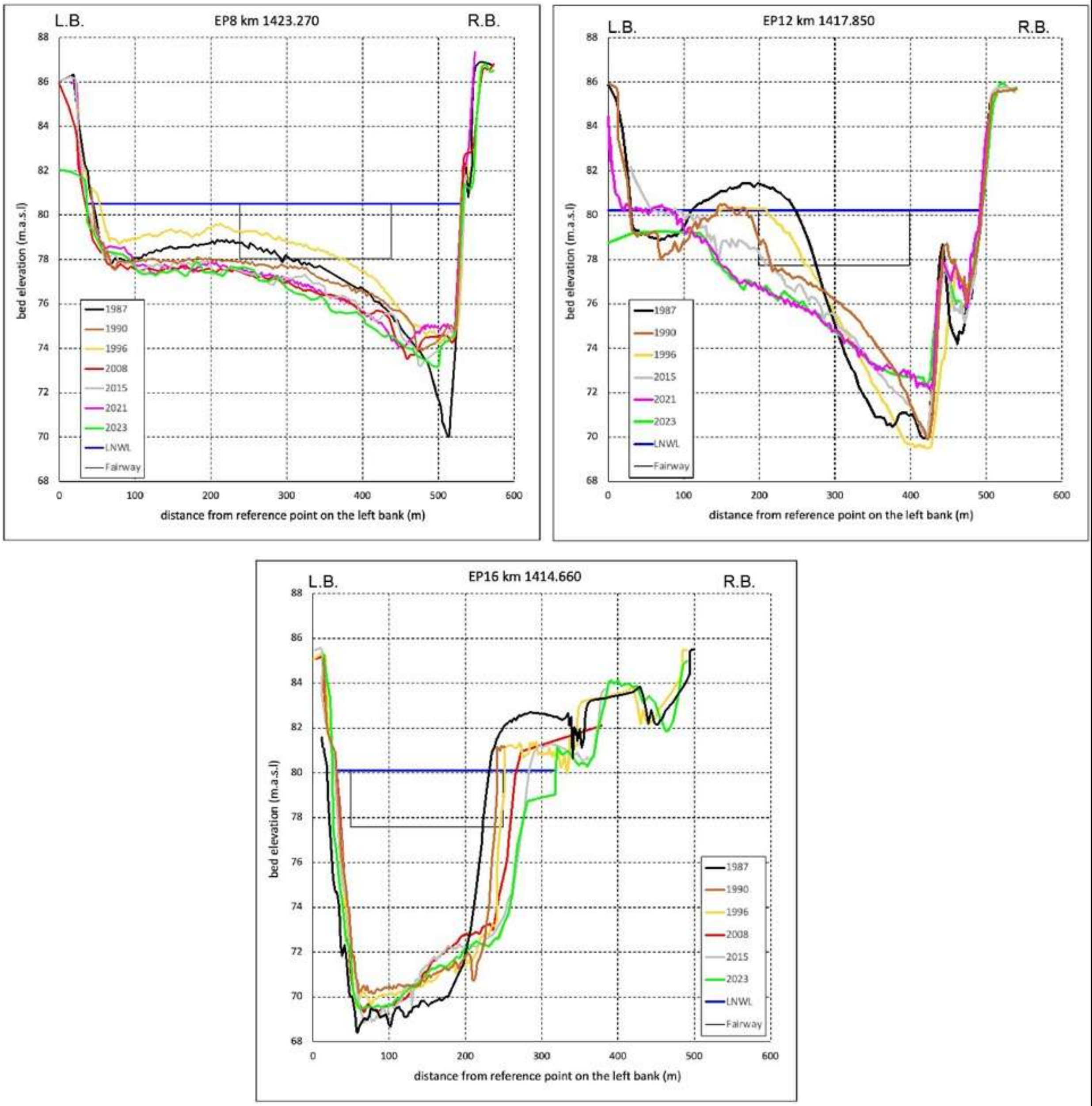
3.4. Siga Kazuk

Basic location info			
Name of the bottleneck	**Siga Kazuk**	Alternative name	N/A
Waterway	Danube River	Waterway class (AGN)	VI
From (km upstream)	1,424.20	To (km downstream)	1,414.40
Total length (km)	9,80	River bed	sand

Visualization



Layout view of the critical sector



Cross sections of the critical sector

Basic information on the navigation obstacle(s)			
☐ depth	☒ width	☐ radius	☐ height
☐ other (to be specified if selected)			

Historical information	
☒ The location is known as the navigation bottleneck from before	☐ The location is newly identified navigation bottleneck

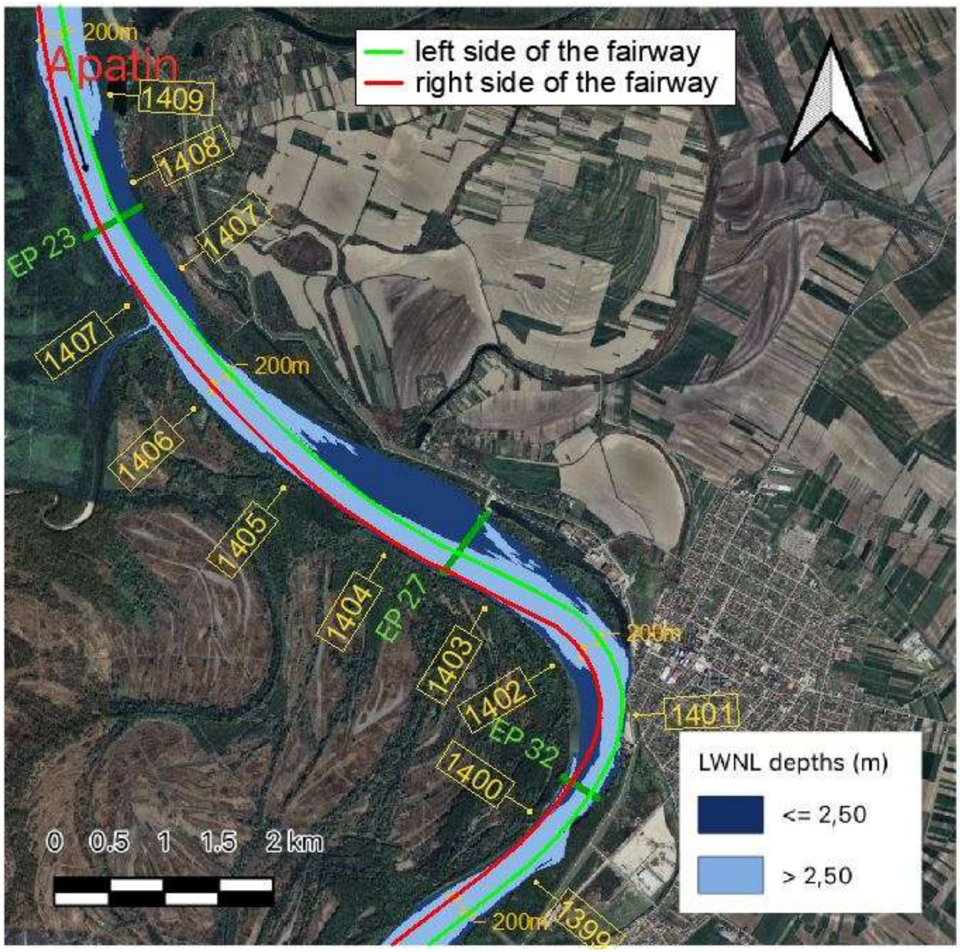
Basic ecological information				
Overall ecological status of the water body (ICPDR, Danube River Basin Management Plan, Update 2021, Annex 9)				
☐ high	☐ good	☒ moderate	☐ poor	☐ bad
Protected areas information: - The Transboundary Biosphere Reserve Mura-Drava-Danube - Danube north from Kopački rit (HR2001309) Natura 2000 site - Special Nature Reserve Gornje Podunavlje - Gornje Podunavlje (RS000001) Emerald site				

Basic hydrological information				
Name of the reference gauging station			Bezdan	
Year of the establishment of the gauging station			1856	
Location of the gauging station			km 1.425,59	
Distance to the (center of the) bottleneck			6.29 km	
Period for the calculation of the reference levels			1981-2010	
ENR (LNWL)	80.54 m.a.s.l.	-10 cm	LNQ	1.180 m^3/s
HNWL	86.66 m.a.s.l.	602 cm	HNQ	5.280 m^3/s
Period for the calculation of the reference levels			1994-2023	
ENR (LNWL)	80.63 m.a.s.l.	-1 cm	LNQ	1.344 m^3/s
HNWL	86.13 m.a.s.l.	549 cm	HNQ	4.920 m^3/s
Name of the reference gauging station			Batina	
Year of the establishment of the gauging station			2001	
Location of the gauging station			km 1.424,60	
Distance to the (center of the) bottleneck			5.30 km	
Period for the calculation of the reference levels			*1981-2010*	
ENR (LNWL)	*80.53 m.a.s.l.*	*8 cm*	*LNQ*	*1.180 m^3/s*
HNWL	*86.60 m.a.s.l.*	*615 cm*	*HNQ*	*5.280 m^3/s*
Period for the calculation of the reference levels			1994-2023*	
ENR (LNWL)	80.62 m.a.s.l.	17 cm	LNQ	1.349 m^3/s
HNWL	85.96 m.a.s.l.	551 cm	HNQ	4.940 m^3/s

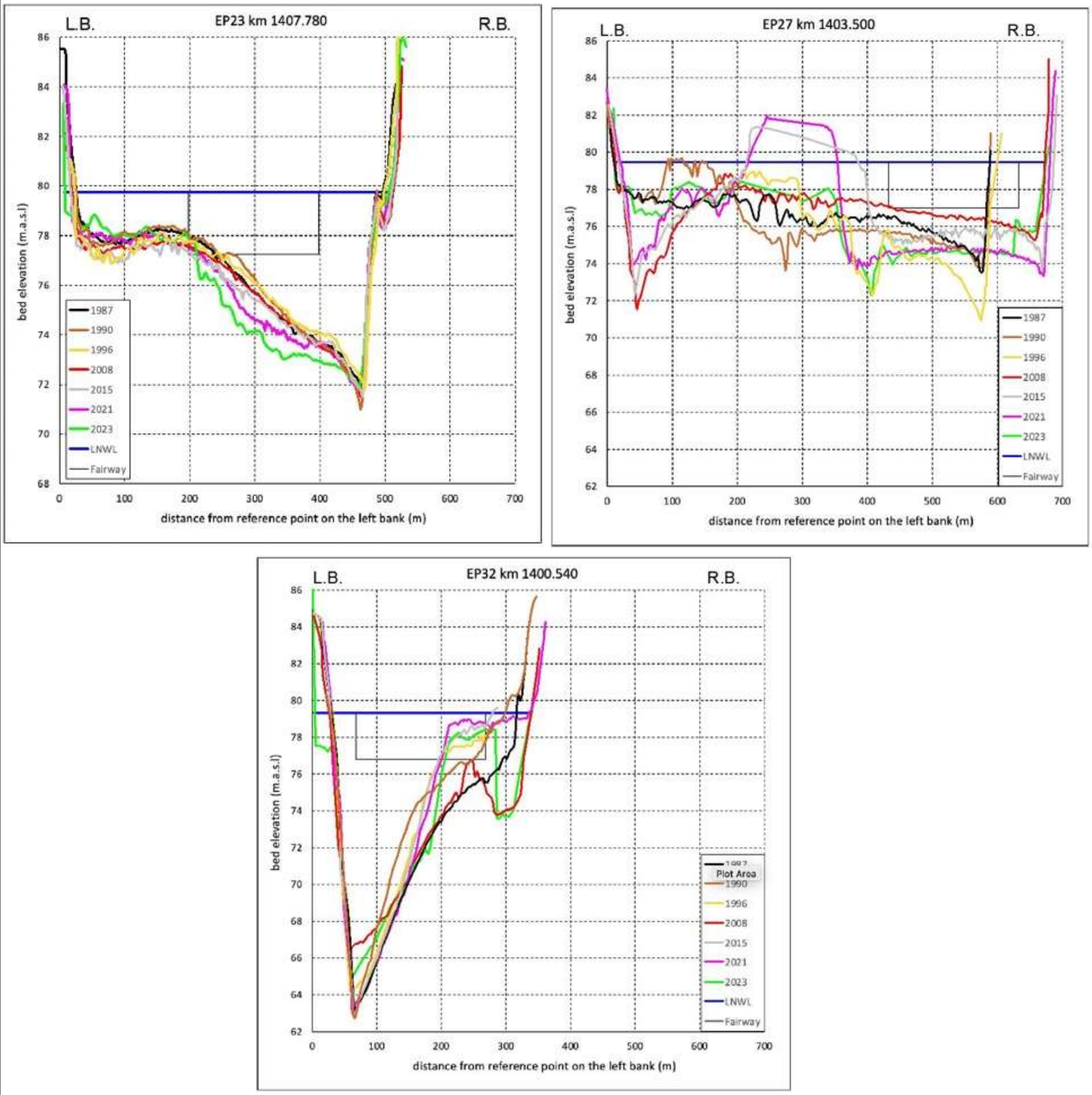
3.5. Apatin

Basic location info			
Name of the bottleneck	**Apatin**	Alternative name	N/A
Waterway	Danube River	Waterway class (AGN)	VI
From (km upstream)	1,408.20	To (km downstream)	1,400.00
Total length (km)	8,20	River bed	sand

Visualization



Layout view of the critical sector



Cross sections of the critical sector

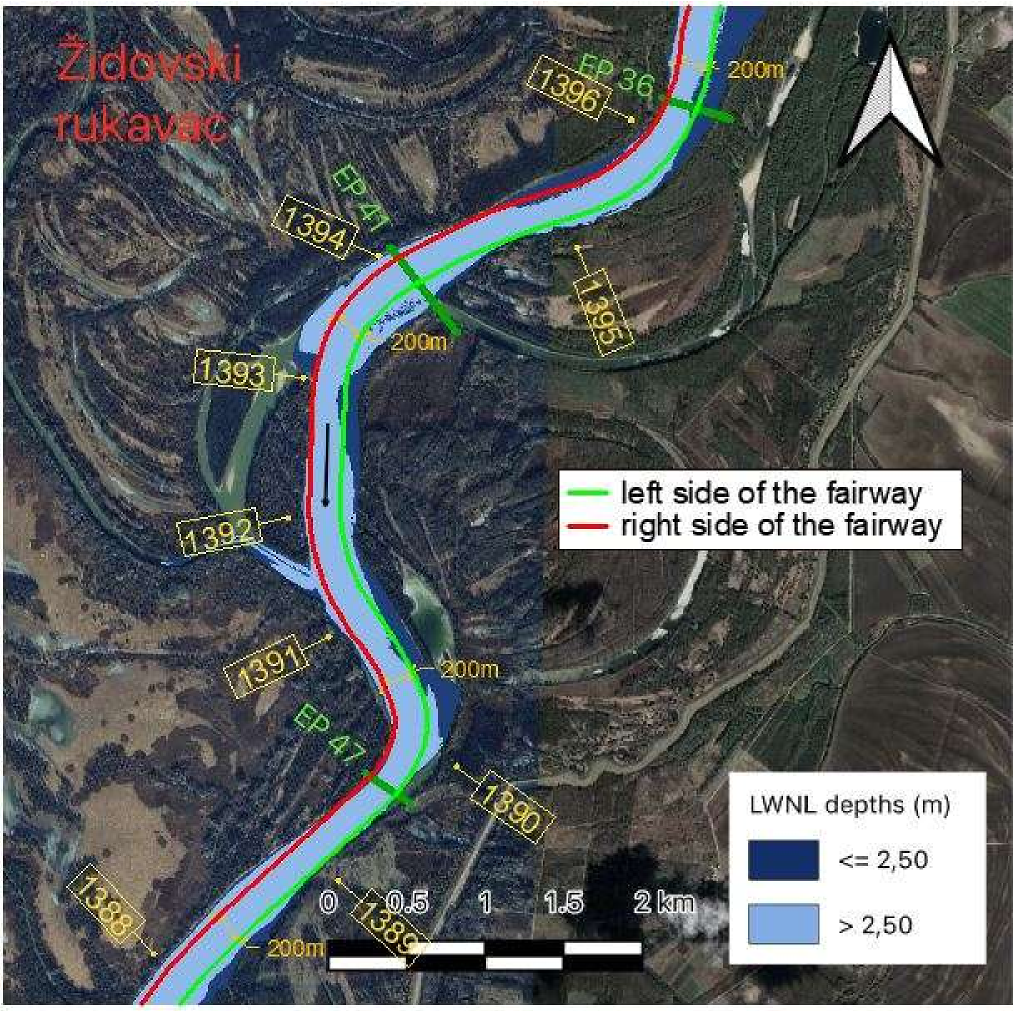
Basic information on the navigation obstacle(s)			
☒ depth	☒ width	☐ radius	☐ height
☐ other (to be specified if selected)			

<table>
<tr><th colspan="6">Historical information</th></tr>
<tr><td colspan="3">☒ The location is known as the navigation bottleneck from before</td><td colspan="3">☐ The location is newly identified navigation bottleneck</td></tr>
<tr><td colspan="6"></td></tr>
<tr><th colspan="6">Basic ecological information</th></tr>
<tr><td colspan="6">Overall ecological status of the water body (ICPDR, Danube River Basin Management Plan, Update 2021, Annex 9)</td></tr>
<tr><td>☐ high</td><td>☐ good</td><td colspan="2">☒ moderate</td><td>☐ poor</td><td>☐ bad</td></tr>
<tr><td colspan="6">Protected areas information:
- The Transboundary Biosphere Reserve Mura-Drava-Danube
- Special Nature Reserve Gornje Podunavlje
- Kopački rit Nature Park
- Kopački rit (HR2000394) Natura 2000 site</td></tr>
<tr><td colspan="6"></td></tr>
<tr><th colspan="6">Basic hydrological information</th></tr>
<tr><td colspan="3">Name of the reference gauging station</td><td colspan="3">Apatin</td></tr>
<tr><td colspan="3">Year of the establishment of the gauging station</td><td colspan="3">1876</td></tr>
<tr><td colspan="3">Location of the gauging station</td><td colspan="3">km 1.401,90</td></tr>
<tr><td colspan="3">Distance to the (center of the) bottleneck</td><td colspan="3">2.20 km</td></tr>
<tr><td colspan="3">Period for the calculation of the reference levels</td><td colspan="3">1981-2010</td></tr>
<tr><td>ENR (LNWL)</td><td>79.31 m.a.s.l.</td><td>47 cm</td><td colspan="2">LNQ</td><td>1.180 m³/s</td></tr>
<tr><td>HNWL</td><td>85.58 m.a.s.l.</td><td>674 cm</td><td colspan="2">HNQ</td><td>5.280 m³/s</td></tr>
<tr><td colspan="3">Period for the calculation of the reference levels</td><td colspan="3">1994-2023</td></tr>
<tr><td>ENR (LNWL)</td><td>N/A</td><td>N/A</td><td colspan="2">LNQ</td><td>N/A</td></tr>
<tr><td>HNWL</td><td>N/A</td><td>N/A</td><td colspan="2">HNQ</td><td>N/A</td></tr>
<tr><td colspan="4">Name of the reference gauging station</td><td colspan="2">Batina</td></tr>
<tr><td colspan="4">Year of the establishment of the gauging station</td><td colspan="2">2001</td></tr>
<tr><td colspan="4">Location of the gauging station</td><td colspan="2">km 1.424,60</td></tr>
<tr><td colspan="4">Distance to the (center of the) bottleneck</td><td colspan="2">20.50 km</td></tr>
<tr><td colspan="4">Period for the calculation of the reference levels</td><td colspan="2">1981-2010</td></tr>
<tr><td>ENR (LNWL)</td><td>80.53 m.a.s.l.</td><td colspan="2">8 cm</td><td>LNQ</td><td>1.180 m³/s</td></tr>
<tr><td>HNWL</td><td>86.60 m.a.s.l.</td><td colspan="2">615 cm</td><td>HNQ</td><td>5.280 m³/s</td></tr>
<tr><td colspan="4">Period for the calculation of the reference levels</td><td colspan="2">1994-2023*</td></tr>
<tr><td>ENR (LNWL)</td><td>80.62 m.a.s.l.</td><td colspan="2">17 cm</td><td>LNQ</td><td>1.349 m³/s</td></tr>
<tr><td>HNWL</td><td>85.96 m.a.s.l.</td><td colspan="2">551 cm</td><td>HNQ</td><td>4.940 m³/s</td></tr>
</table>

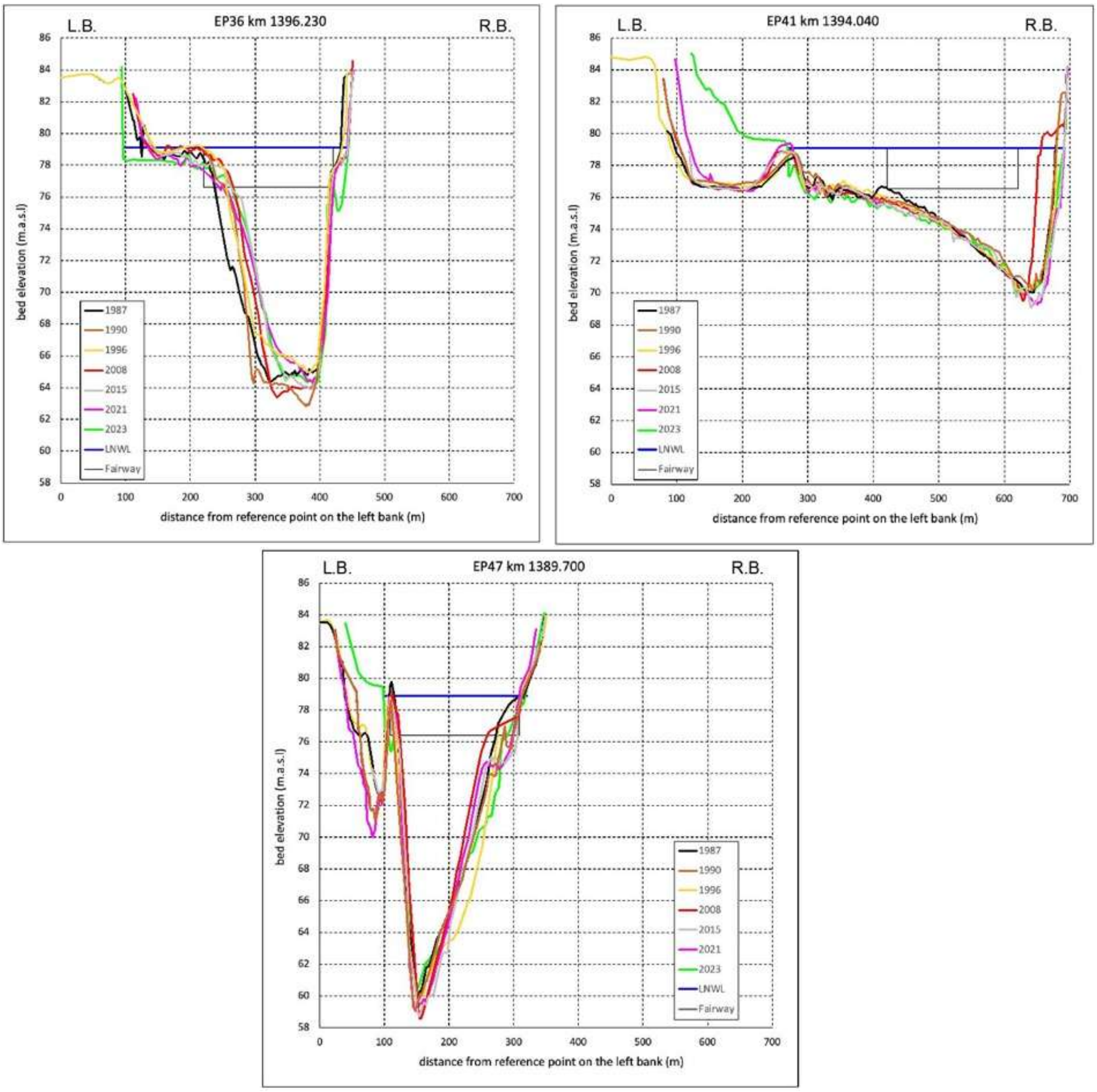
3.6. Čivutski Rukavac

Basic location info			
Name of the bottleneck	**Čivutski Rukavac**	Alternative name	**Židovski Rukavac**
Waterway	Danube River	Waterway class (AGN)	VI
From (km upstream)	1,397.2	To (km downstream)	1,389.0
Total length (km)	8,20	River bed	sand

Visualization



Layout view of the critical sector



Cross sections of the critical sector

Basic information on the navigation obstacle(s)			
☒ depth	☒ width	☐ radius	☐ height
☐ other (to be specified if selected)			

Historical information	
☒ The location is known as the navigation bottleneck from before	☐ The location is newly identified navigation bottleneck

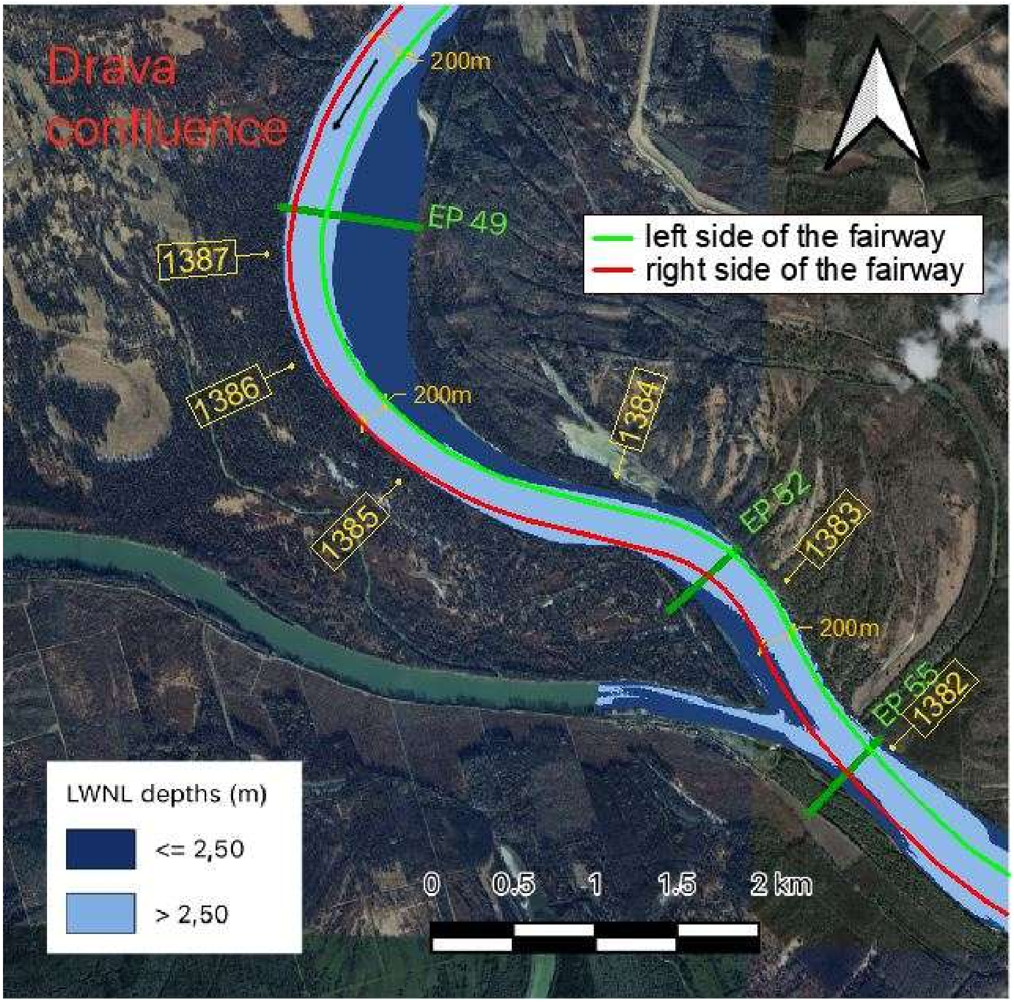
Basic ecological information				
Overall ecological status of the water body (ICPDR, Danube River Basin Management Plan, Update 2021, Annex 9)				
☐ high	☐ good	☒ moderate	☐ poor	☐ bad
Protected areas information: - The Transboundary Biosphere Reserve Mura-Drava-Danube - Special Nature Reserve Gornje Podunavlje - Kopački rit Nature Park - Kopački rit (HR2000394) Natura 2000 site - Gornje Podunavlje (RS000001) Emerald site				

Basic hydrological information				
Name of the reference gauging station			Apatin	
Year of the establishment of the gauging station			1876	
Location of the gauging station			km 1.401,90	
Distance to the (center of the) bottleneck			8.80 km	
Period for the calculation of the reference levels			1981-2010	
ENR (LNWL)	79.31 m.a.s.l.	47 cm	LNQ	1.180 m^3/s
HNWL	85.58 m.a.s.l.	674 cm	HNQ	5.280 m^3/s
Period for the calculation of the reference levels			1994-2023	
ENR (LNWL)	N/A	N/A	LNQ	N/A
HNWL	N/A	N/A	HNQ	N/A
Name of the reference gauging station			Aljmaš	
Year of the establishment of the gauging station			1909	
Location of the gauging station			km 1.380,25	
Distance to the (center of the) bottleneck			12.85 km	
Period for the calculation of the reference levels			*1981-2010*	
ENR (LNWL)	*78.18 m.a.s.l.*	*10 cm*	*LNQ*	*1.435 m^3/s*
HNWL	*84.18 m.a.s.l.*	*610 cm*	*HNQ*	*5.850 m^3/s*
Period for the calculation of the reference levels			1994-2023*	
ENR (LNWL)	78.58 m.a.s.l.	50 cm	LNQ	1.707 m^3/s
HNWL	83.79 m.a.s.l.	571 cm	HNQ	5.395 m^3/s

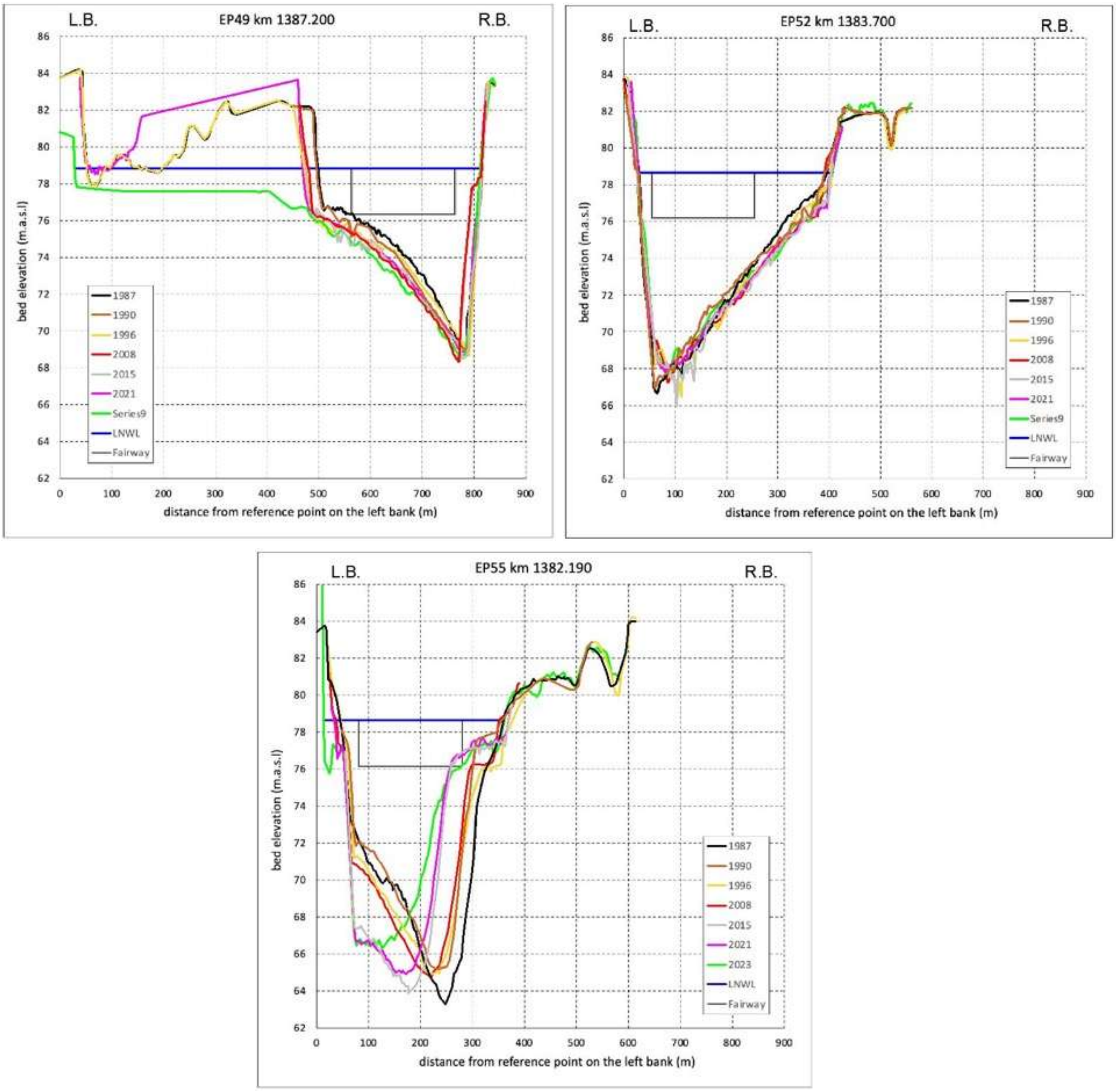
3.7. Drava Confluence

Basic location info			
Name of the bottleneck	**Drava Confluence**	Alternative name	N/A
Waterway	Danube River	Waterway class (AGN)	VI
From (km upstream)	1,388.8	To (km downstream)	1,382.0
Total length (km)	6,80	River bed	sand

Visualization



Layout view of the critical sector



Cross sections of the critical sector

Basic information on the navigation obstacle(s)			
☒ depth	☒ width	☐ radius	☐ height
☐ other (to be specified if selected)			

Historical information	
☒ The location is known as the navigation bottleneck from before	☐ The location is newly identified navigation bottleneck

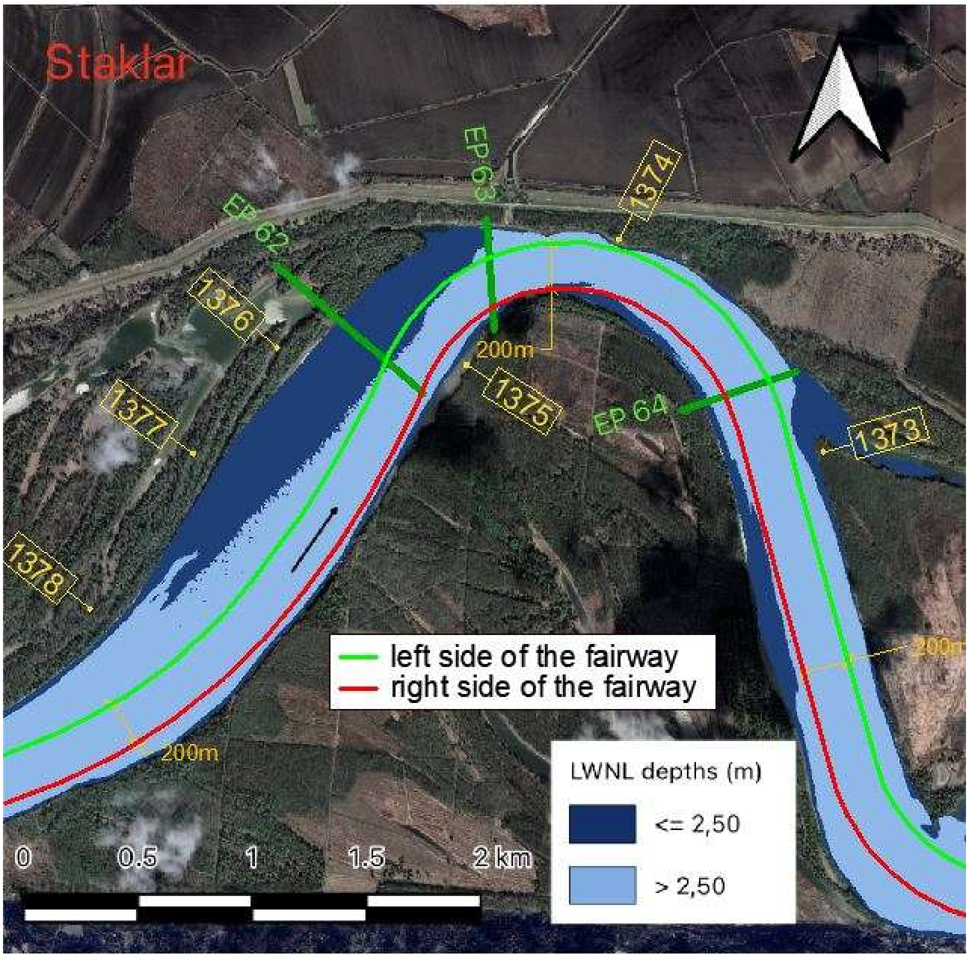
Basic ecological information				
Overall ecological status of the water body (ICPDR, Danube River Basin Management Plan, Update 2021, Annex 9)				
☐ high	☐ good	☒ moderate	☐ poor	☐ bad
Protected areas information: - The Transboundary Biosphere Reserve Mura-Drava-Danube - Special Nature Reserve Gornje Podunavlje - Kopački rit Nature Park - Kopački rit (HR2000394) Natura 2000 site - Gornje Podunavlje (RS000001) Emerald site				

Basic hydrological information				
Name of the reference gauging station			Apatin	
Year of the establishment of the gauging station			1876	
Location of the gauging station			km 1.401,90	
Distance to the (center of the) bottleneck			16.50 km	
Period for the calculation of the reference levels			1981-2010	
ENR (LNWL)	79.31 m.a.s.l.	47 cm	LNQ	1.180 m^3/s
HNWL	85.58 m.a.s.l.	674 cm	HNQ	5.280 m^3/s
Period for the calculation of the reference levels			1994-2023	
ENR (LNWL)	N/A	N/A	LNQ	N/A
HNWL	N/A	N/A	HNQ	N/A
Name of the reference gauging station			Aljmaš	
Year of the establishment of the gauging station			1909	
Location of the gauging station			km 1.380,25	
Distance to the (center of the) bottleneck			5.15 km	
Period for the calculation of the reference levels			*1981-2010*	
ENR (LNWL)	*78.18 m.a.s.l.*	*10 cm*	*LNQ*	*1.435 m^3/s*
HNWL	*84.18 m.a.s.l.*	*610 cm*	*HNQ*	*5.850 m^3/s*
Period for the calculation of the reference levels			1994-2023*	
ENR (LNWL)	78.58 m.a.s.l.	50 cm	LNQ	1.707 m^3/s
HNWL	83.79 m.a.s.l.	571 cm	HNQ	5.395 m^3/s

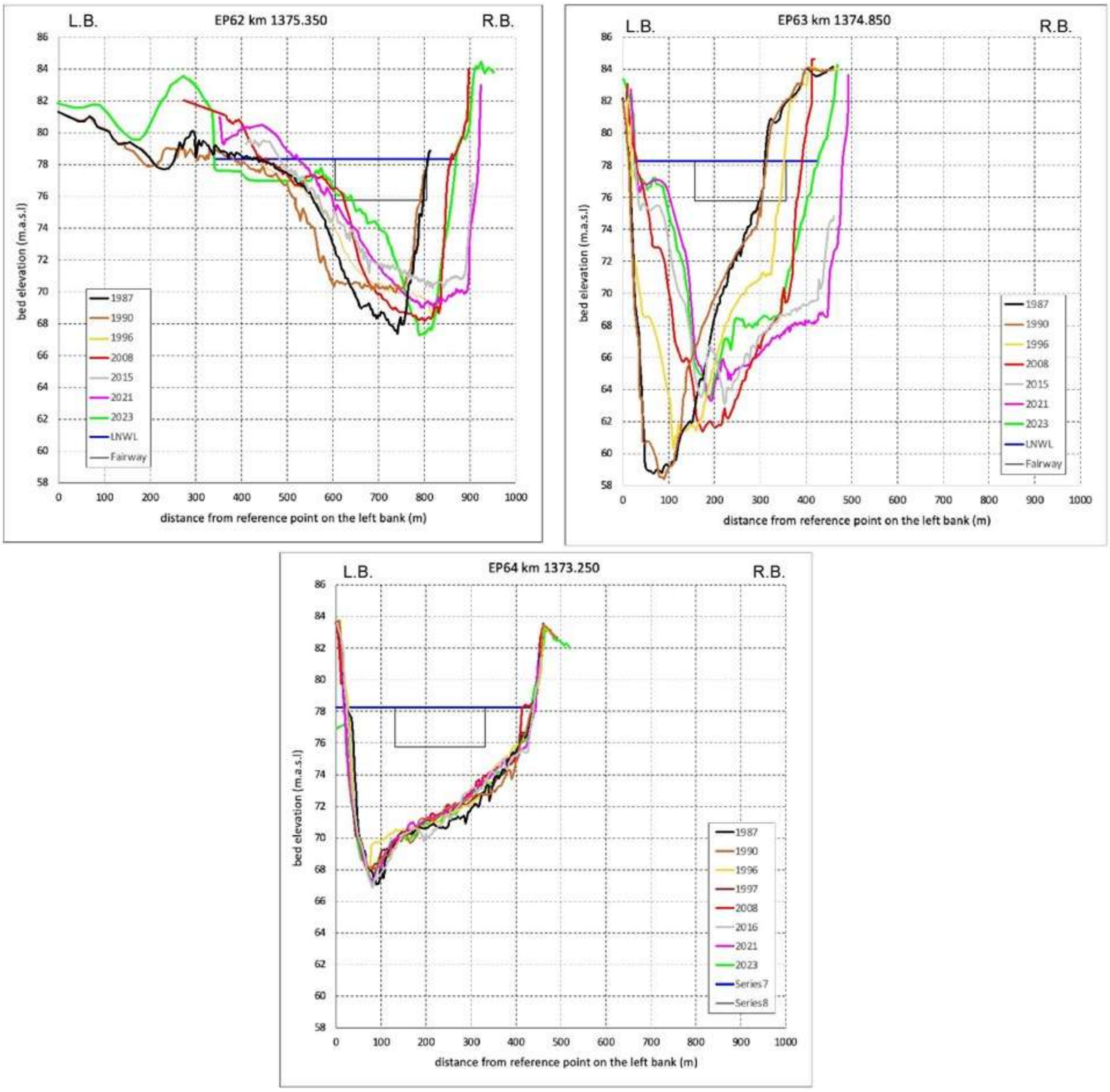
3.8. Staklar

Basic location info			
Name of the bottleneck	**Staklar**	Alternative name	N/A
Waterway	Danube River	Waterway class (AGN)	VI
From (km upstream)	1,376.8	To (km downstream)	1,373.4
Total length (km)	3,40	River bed	sand

Visualization



Layout view of the critical sector



Cross sections of the critical sector

Basic information on the navigation obstacle(s)			
☒ depth	☒ width	☐ radius	☐ height
☐ other (to be specified if selected)			

Historical information

☒ The location is known as the navigation bottleneck from before	☐ The location is newly identified navigation bottleneck

Basic ecological information

Overall ecological status of the water body (ICPDR, Danube River Basin Management Plan, Update 2021, Annex 9)

☐ high	☐ good	☒ moderate	☐ poor	☐ bad

Protected areas information:
- The Transboundary Biosphere Reserve Mura-Drava-Danube
- Special Nature Reserve Gornje Podunavlje
- Danube - Vukovar (HR2000372) Natura 2000 site
- Gornje Podunavlje (RS000001) Emerald site

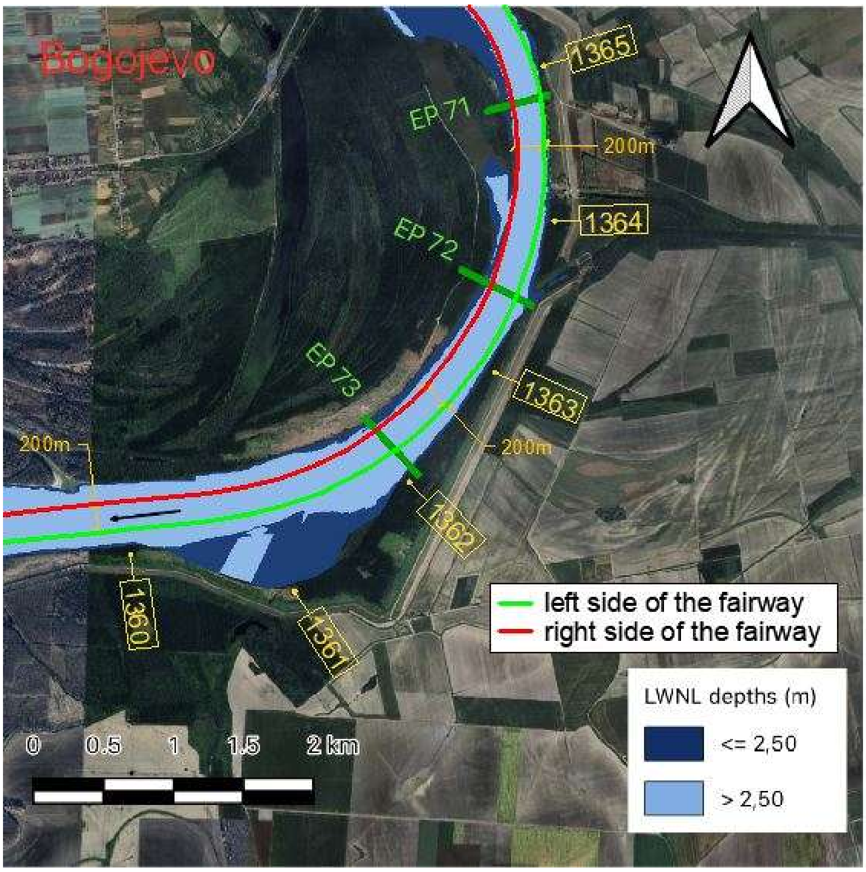
Basic hydrological information

Name of the reference gauging station			Bogojevo	
Year of the establishment of the gauging station			1871	
Location of the gauging station			km 1.367,30	
Distance to the (center of the) bottleneck			7.80 km	
Period for the calculation of the reference levels			1981-2010	
ENR (LNWL)	77.57 m.a.s.l.	11 cm	LNQ	1.435 m^3/s
HNWL	83.42 m.a.s.l.	596 cm	HNQ	5.850 m^3/s
Period for the calculation of the reference levels			1994-2023	
ENR (LNWL)	77.73	27 cm	LNQ	1.707 m^3/s
HNWL	83.01 m.a.s.l.	555 cm	HNQ	5.395 m^3/s
Name of the reference gauging station			Aljmaš	
Year of the establishment of the gauging station			1909	
Location of the gauging station			km 1.380,25	
Distance to the (center of the) bottleneck			5.15 km	
Period for the calculation of the reference levels			*1981-2010*	
ENR (LNWL)	*78.18 m.a.s.l.*	*10 cm*	*LNQ*	*1.435 m^3/s*
HNWL	*84.18 m.a.s.l.*	*610 cm*	*HNQ*	*5.850 m^3/s*
Period for the calculation of the reference levels			1994-2023*	
ENR (LNWL)	78.58 m.a.s.l.	50 cm	LNQ	1.707 m^3/s
HNWL	83.79 m.a.s.l.	571 cm	HNQ	5.395 m^3/s

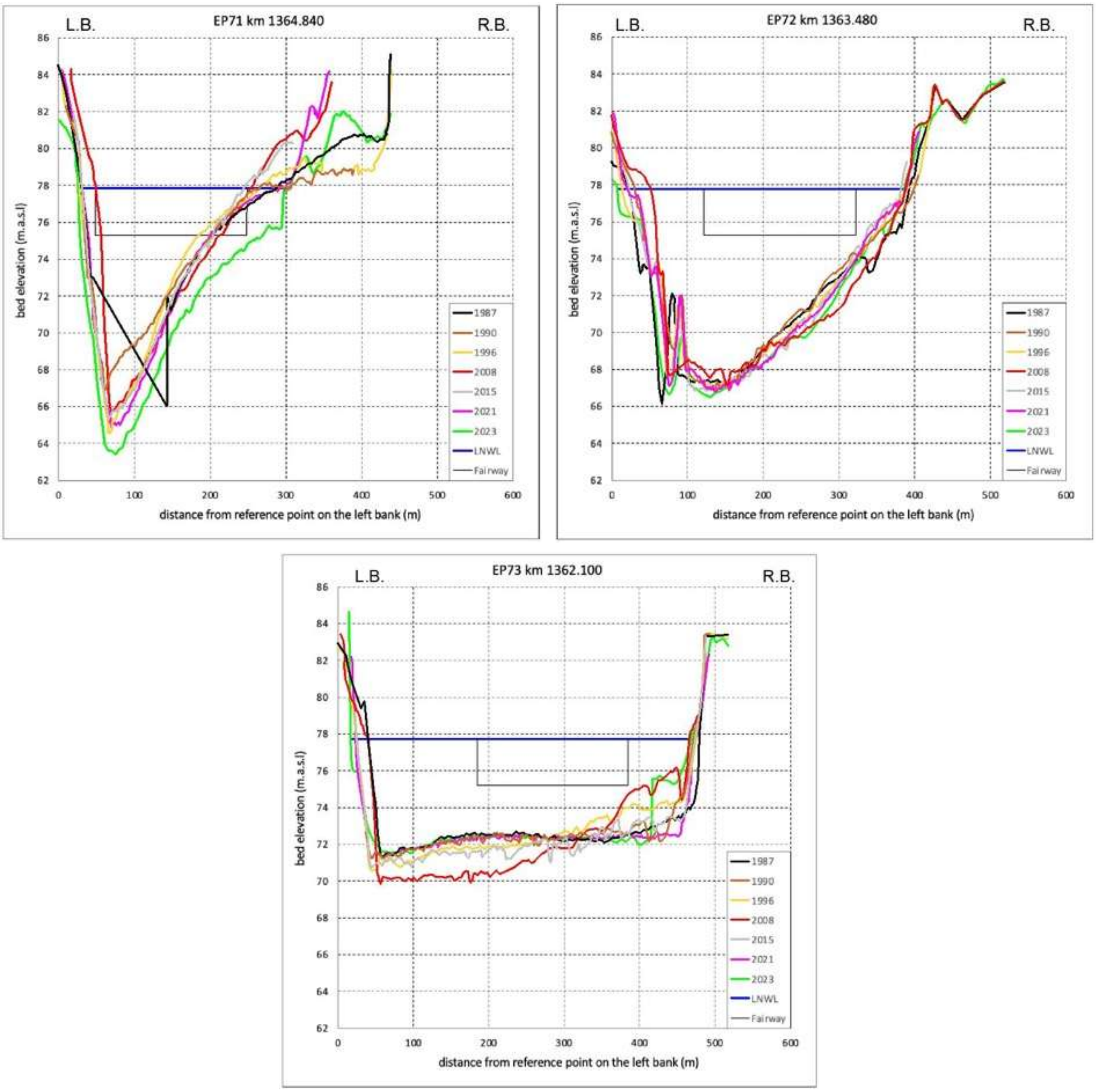
3.9. Bogojevo

Basic location info			
Name of the bottleneck	**Bogojevo**	Alternative name	N/A
Waterway	Danube River	Waterway class (AGN)	VI
From (km upstream)	1,366.2	To (km downstream)	1,361.4
Total length (km)	4,80	River bed	sand

Visualization



Layout view of the critical sector



Cross sections of the critical sector

Basic information on the navigation obstacle(s)			
☐ depth	☒ width	☐ radius	☐ height
☐ other (to be specified if selected)			

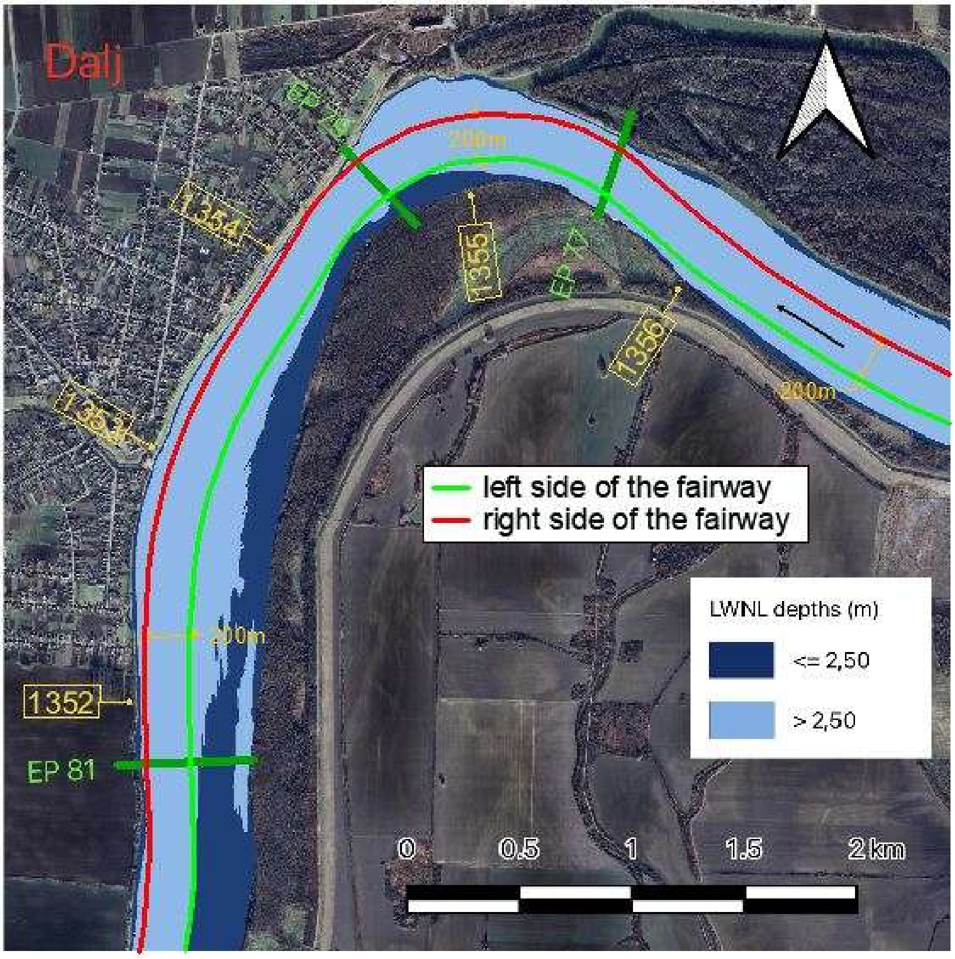
Historical information	
☒ The location is known as the navigation bottleneck from before	☐ The location is newly identified navigation bottleneck

Basic ecological information				
Overall ecological status of the water body (ICPDR, Danube River Basin Management Plan, Update 2021, Annex 9)				
☐ high	☐ good	☒ moderate	☐ poor	☐ bad
Protected areas information: - The Transboundary Biosphere Reserve Mura-Drava-Danube - Danube - Vukovar (HR2000372) Natura 2000 site				

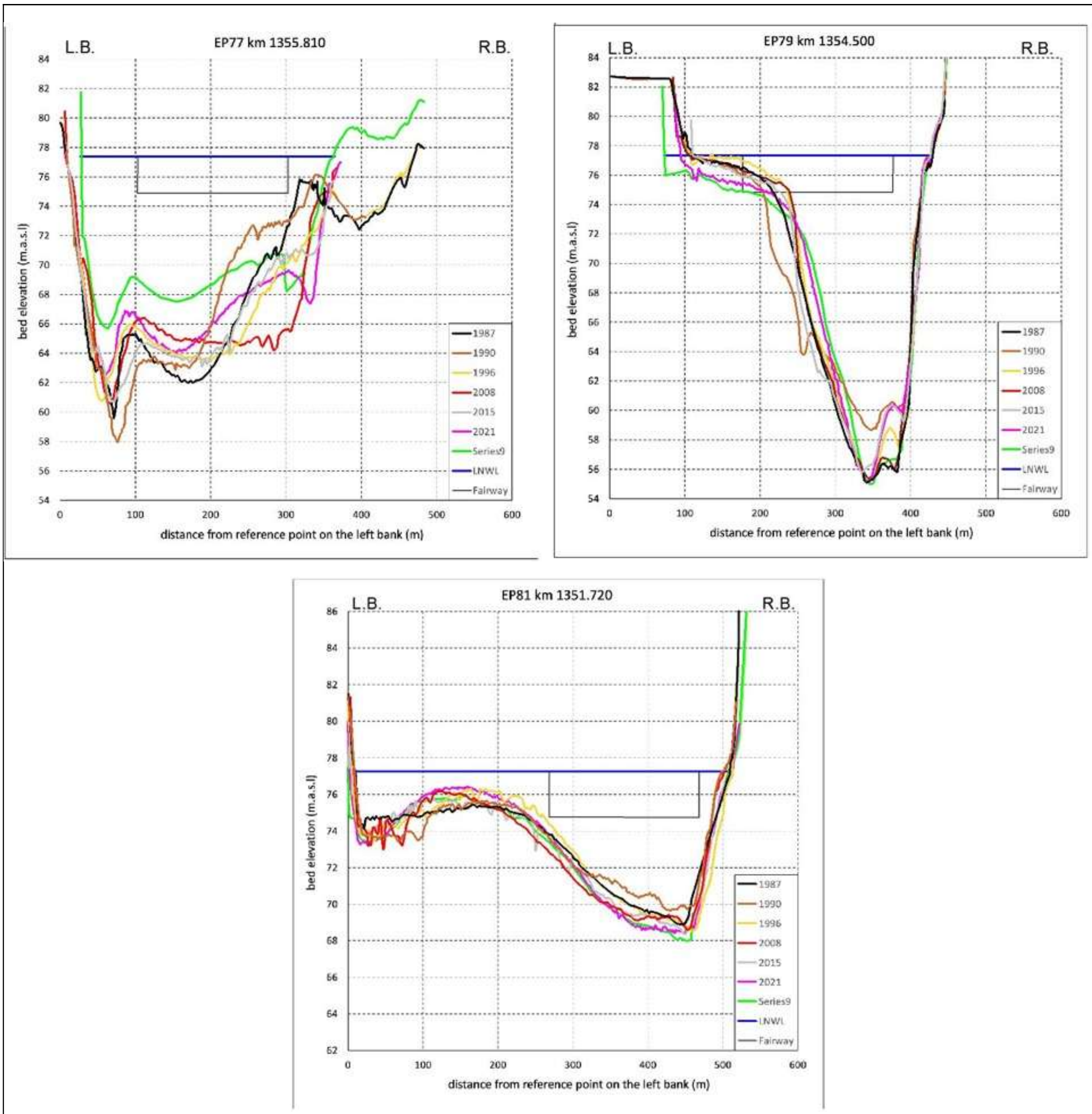
Basic hydrological information				
Name of the reference gauging station			Bogojevo	
Year of the establishment of the gauging station			1871	
Location of the gauging station			km 1.367,30	
Distance to the (center of the) bottleneck			4.00 km	
Period for the calculation of the reference levels			1981-2010	
ENR (LNWL)	77.57 m.a.s.l.	11 cm	LNQ	1.435 m^3/s
HNWL	83.42 m.a.s.l.	596 cm	HNQ	5.850 m^3/s
Period for the calculation of the reference levels			1994-2023	
ENR (LNWL)	77.73	27 cm	LNQ	1.707 m^3/s
HNWL	83.01 m.a.s.l.	555 cm	HNQ	5.395 m^3/s
Name of the reference gauging station			Dalj	
Year of the establishment of the gauging station			1985	
Location of the gauging station			km 1.353,70	
Distance to the (center of the) bottleneck			10.10 km	
Period for the calculation of the reference levels			*1981-2010*	
ENR (LNWL)	*77.09 m.a.s.l.*	*189 cm*	*LNQ*	*1.435 m^3/s*
HNWL	*82.74 m.a.s.l.*	*754 cm*	*HNQ*	*5.850 m^3/s*
Period for the calculation of the reference levels			1994-2023*	
ENR (LNWL)	77.43 m.a.s.l.	223 cm	LNQ	1.768 m^3/s
HNWL	82.23 m.a.s.l.	703 cm	HNQ	5.395 m^3/s

3.10. Dalj

Basic location info			
Name of the bottleneck	**Dalj**	Alternative name	N/A
Waterway	Danube River	Waterway class (AGN)	VI
From (km upstream)	1,357.0	To (km downstream)	1,351.0
Total length (km)	6,00	River bed	sand
Visualization			



Layout view of the critical sector



Cross sections of the critical sector

Basic information on the navigation obstacle(s)			
☐ depth	☒ width	☐ radius	☐ height
☐ other (to be specified if selected)			

Historical information	
☒ The location is known as the navigation bottleneck from before	☐ The location is newly identified navigation bottleneck

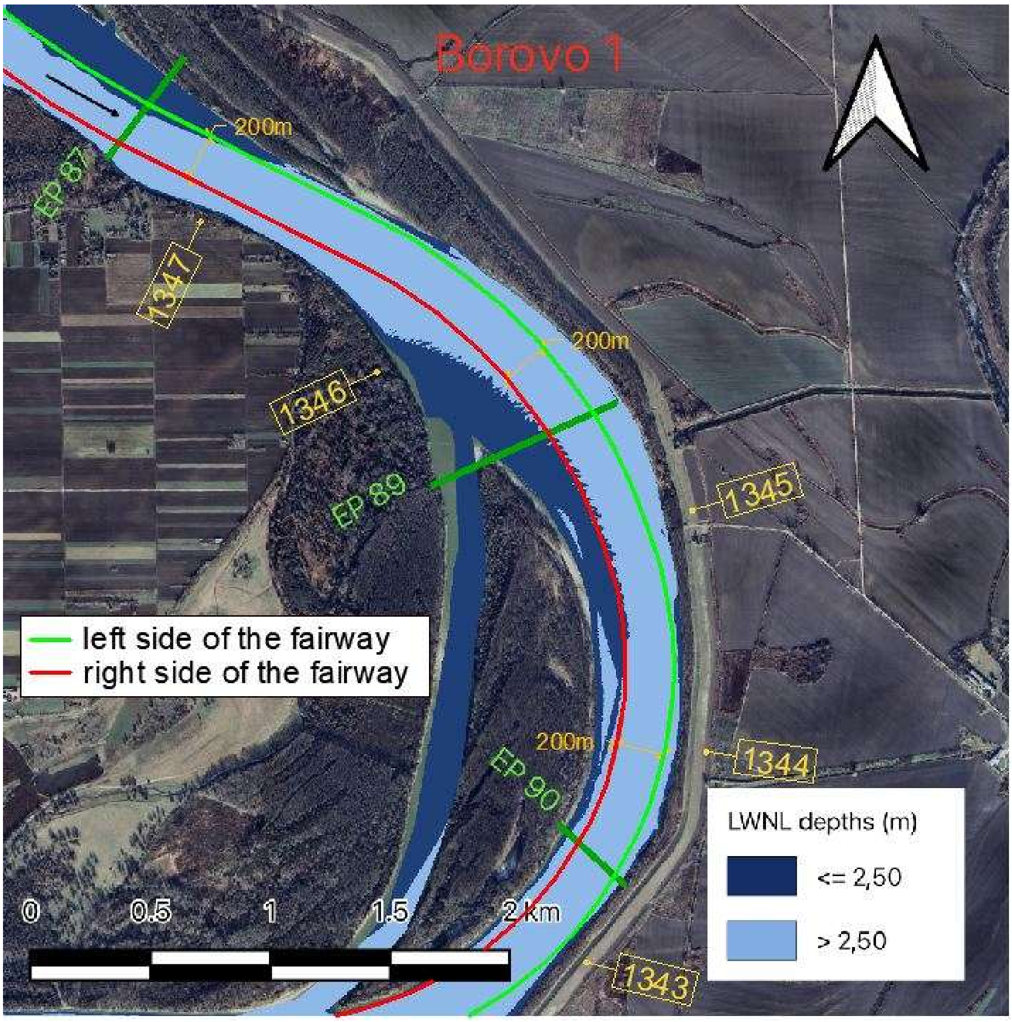
Basic ecological information				
Overall ecological status of the water body (ICPDR, Danube River Basin Management Plan, Update 2021, Annex 9)				
☐ high	☐ good	☒ moderate	☐ poor	☐ bad
Protected areas information: - The Transboundary Biosphere Reserve Mura-Drava-Danube - Danube - Vukovar (HR2000372) Natura 2000 site				

Basic hydrological information				
Name of the reference gauging station			Bogojevo	
Year of the establishment of the gauging station			1871	
Location of the gauging station			km 1.367,30	
Distance to the (center of the) bottleneck			13.30 km	
Period for the calculation of the reference levels			1981-2010	
ENR (LNWL)	77.57 m.a.s.l.	11 cm	LNQ	1.435 m^3/s
HNWL	83.42 m.a.s.l.	596 cm	HNQ	5.850 m^3/s
Period for the calculation of the reference levels			1994-2023	
ENR (LNWL)	77.73	27 cm	LNQ	1.707 m^3/s
HNWL	83.01 m.a.s.l.	555 cm	HNQ	5.395 m^3/s
Name of the reference gauging station			Dalj	
Year of the establishment of the gauging station			1985	
Location of the gauging station			km 1.353,70	
Distance to the (center of the) bottleneck			0.30 km	
Period for the calculation of the reference levels			*1981-2010*	
ENR (LNWL)	*77.09 m.a.s.l.*	*189 cm*	*LNQ*	*1.435 m^3/s*
HNWL	*82.74 m.a.s.l.*	*754 cm*	*HNQ*	*5.850 m^3/s*
Period for the calculation of the reference levels			1994-2023*	
ENR (LNWL)	77.43 m.a.s.l.	223 cm	LNQ	1.768 m^3/s
HNWL	82.23 m.a.s.l.	703 cm	HNQ	5.395 m^3/s

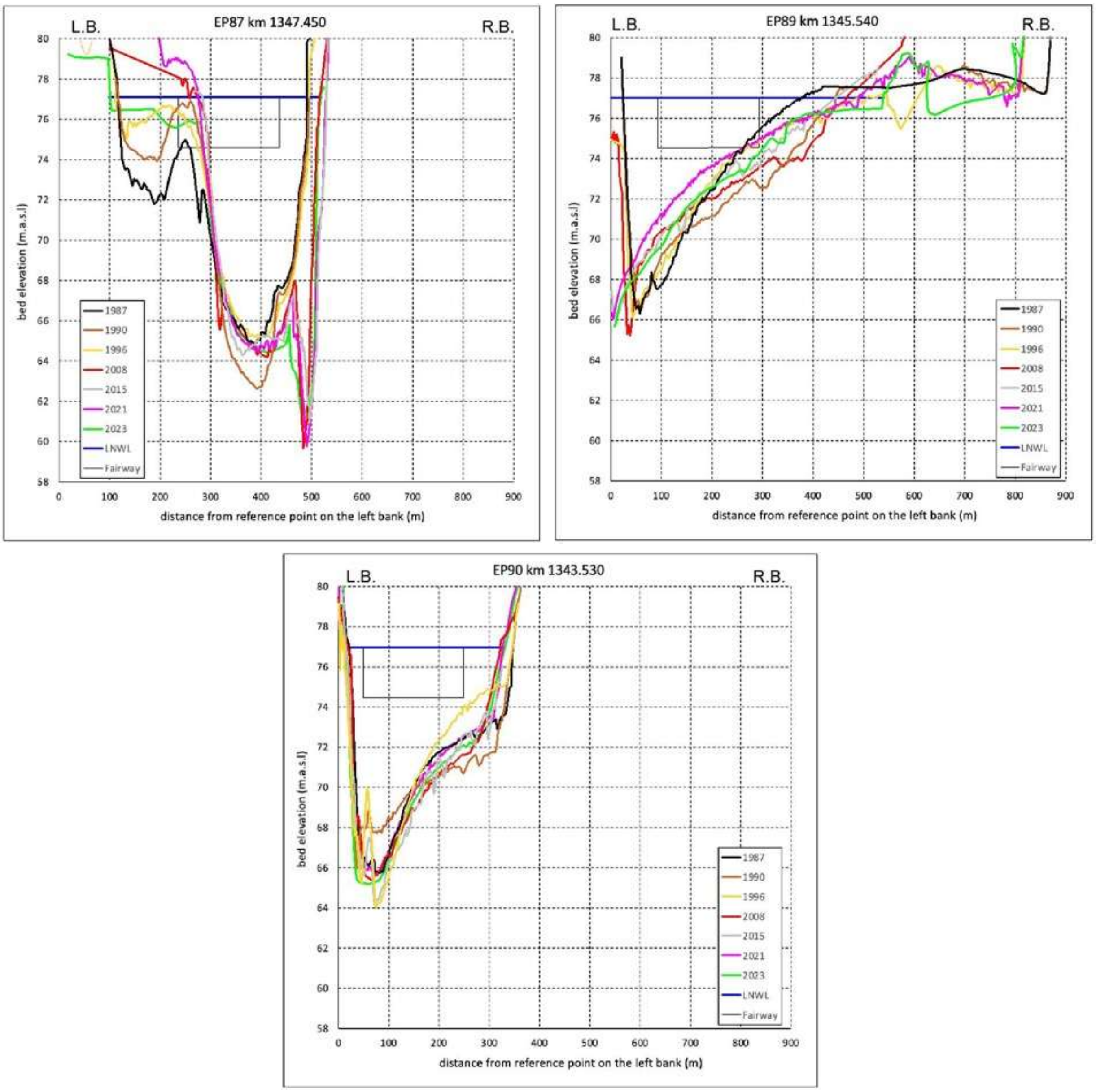
3.11. Borovo 1

Basic location info			
Name of the bottleneck	**Borovo 1**	Alternative name	N/A
Waterway	Danube River	Waterway class (AGN)	VI
From (km upstream)	1,348.6	To (km downstream)	1,343.6
Total length (km)	5,00	River bed	sand

Visualization



Layout view of the critical sector



Cross sections of the critical sector

Basic information on the navigation obstacle(s)			
☒ depth	☒ width	☐ radius	☐ height
☐ other (to be specified if selected)			

Historical information	
☒ The location is known as the navigation bottleneck from before	☐ The location is newly identified navigation bottleneck

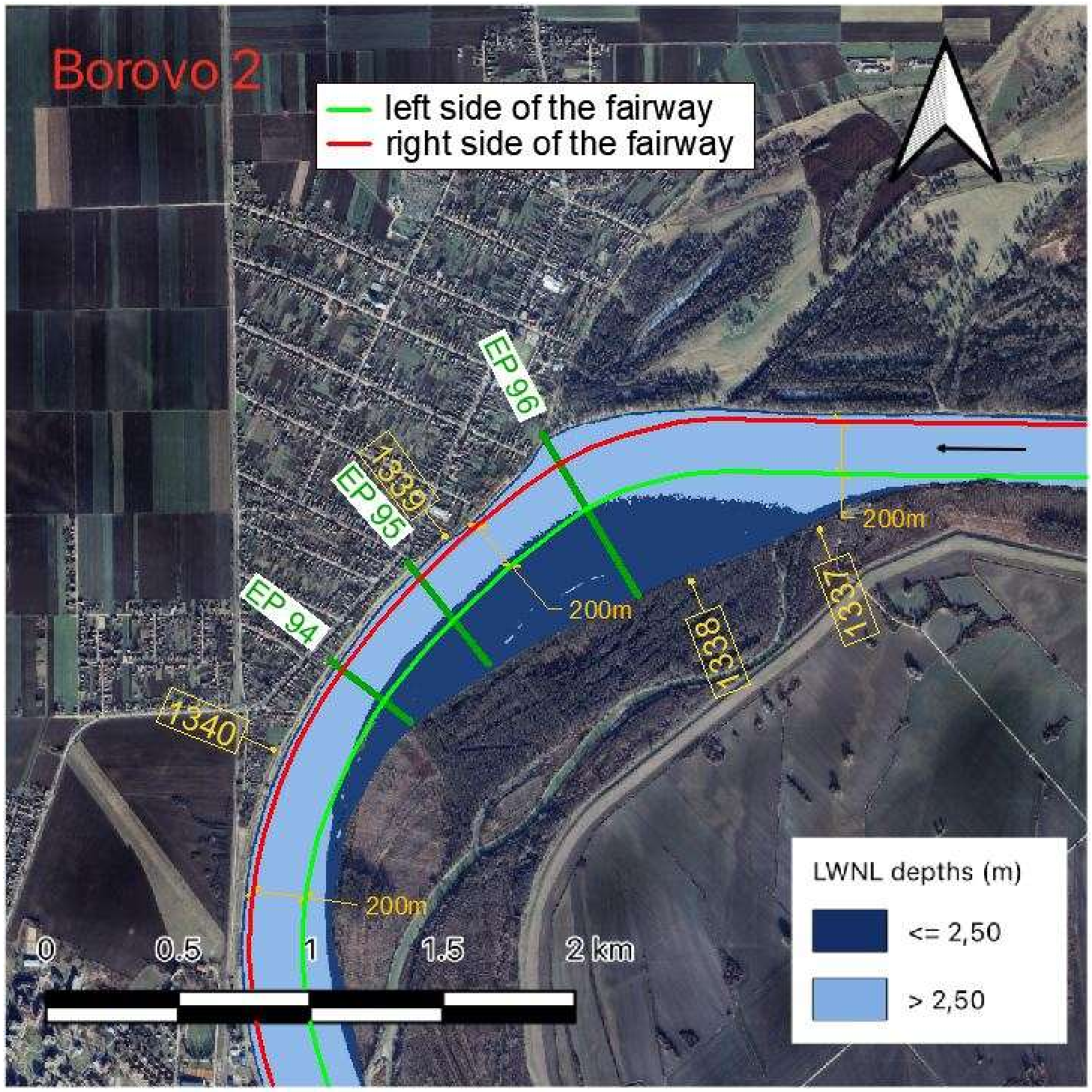
Basic ecological information				
Overall ecological status of the water body (ICPDR, Danube River Basin Management Plan, Update 2021, Annex 9)				
☐ high	☐ good	☒ moderate	☐ poor	☐ bad
Protected areas information: - The Transboundary Biosphere Reserve Mura-Drava-Danube - Danube - Vukovar (HR2000372) Natura 2000 site				

Basic hydrological information				
Name of the reference gauging station			Bogojevo	
Year of the establishment of the gauging station			1871	
Location of the gauging station			km 1.367,30	
Distance to the (center of the) bottleneck			21.20 km	
Period for the calculation of the reference levels			1981-2010	
ENR (LNWL)	77.57 m.a.s.l.	11 cm	LNQ	1.435 m^3/s
HNWL	83.42 m.a.s.l.	596 cm	HNQ	5.850 m^3/s
Period for the calculation of the reference levels			1994-2023	
ENR (LNWL)	77.73	27 cm	LNQ	1.707 m^3/s
HNWL	83.01 m.a.s.l.	555 cm	HNQ	5.395 m^3/s
Name of the reference gauging station			Dalj	
Year of the establishment of the gauging station			1985	
Location of the gauging station			km 1.353,70	
Distance to the (center of the) bottleneck			7.60 km	
Period for the calculation of the reference levels			*1981-2010*	
ENR (LNWL)	*77.09 m.a.s.l.*	*189 cm*	*LNQ*	*1.435 m^3/s*
HNWL	*82.74 m.a.s.l.*	*754 cm*	*HNQ*	*5.850 m^3/s*
Period for the calculation of the reference levels			1994-2023*	
ENR (LNWL)	77.43 m.a.s.l.	223 cm	LNQ	1.768 m^3/s
HNWL	82.23 m.a.s.l.	703 cm	HNQ	5.395 m^3/s

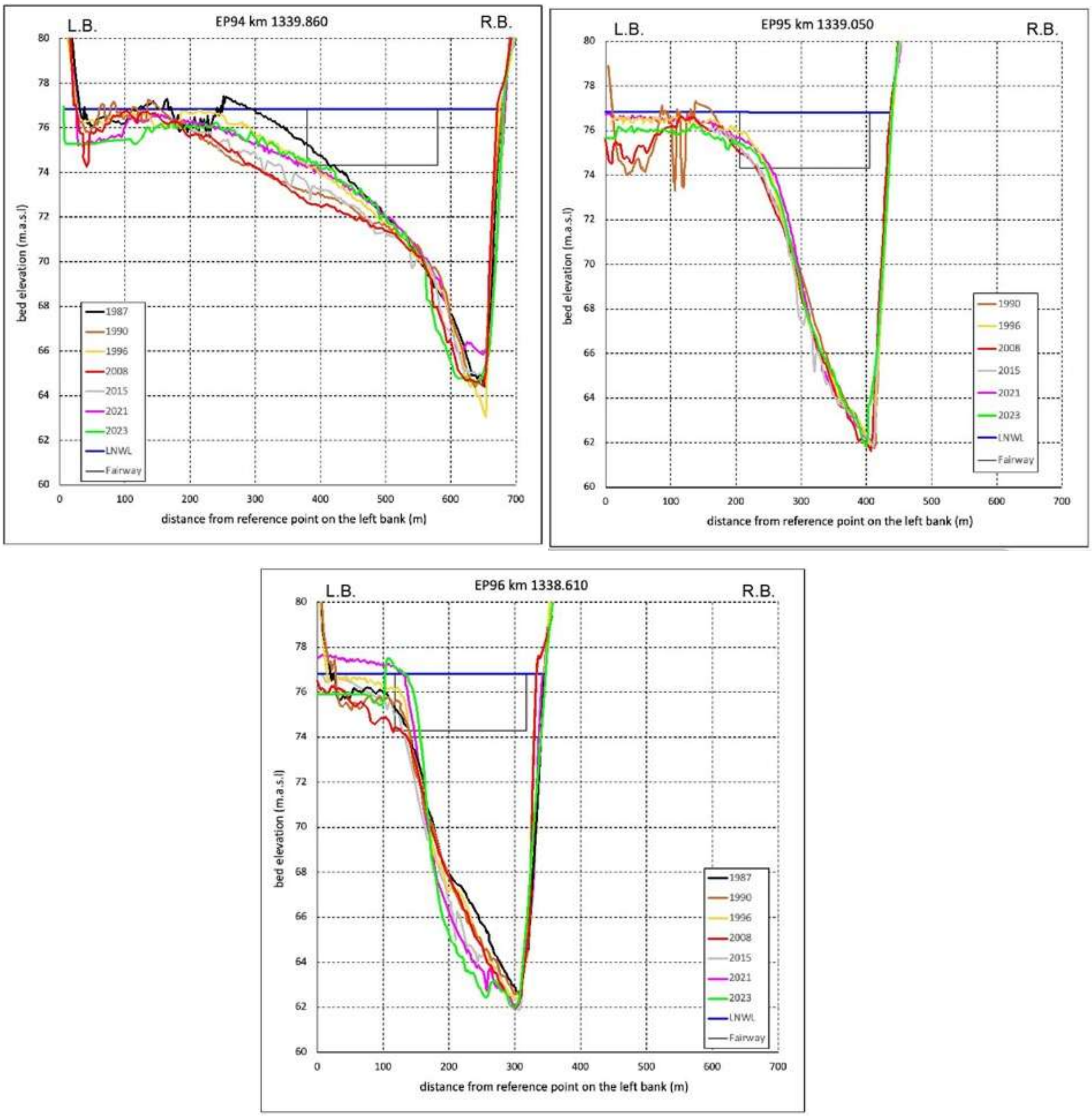
3.12. Borovo 2

Basic location info			
Name of the bottleneck	**Borovo 2**	Alternative name	N/A
Waterway	Danube River	Waterway class (AGN)	VI
From (km upstream)	1,340.6	To (km downstream)	1,338.0
Total length (km)	2,60	River bed	sand

Visualization



Layout view of the critical sector



Cross sections of the critical sector

Basic information on the navigation obstacle(s)			
☒ depth	☒ width	☐ radius	☐ height
☐ other (to be specified if selected)			

Historical information	
☒ The location is known as the navigation bottleneck from before	☐ The location is newly identified navigation bottleneck

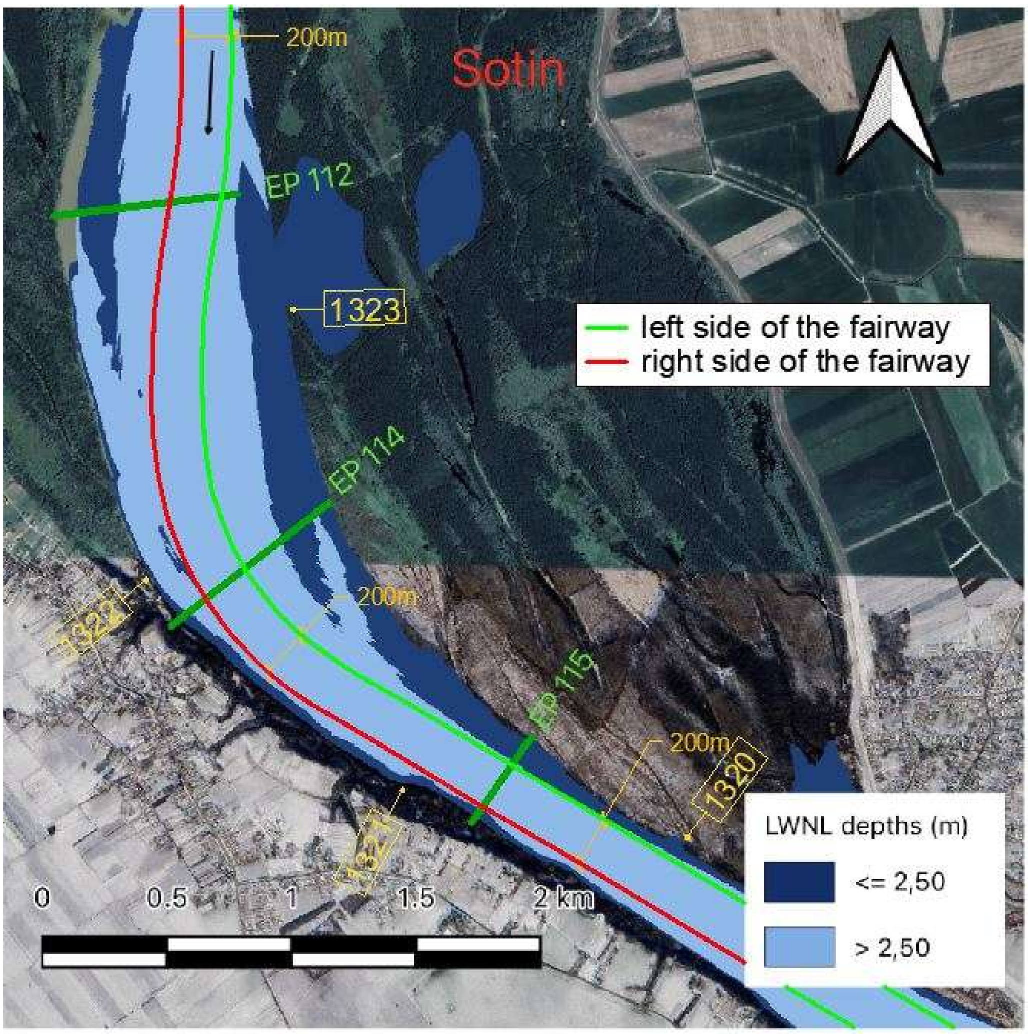
Basic ecological information				
Overall ecological status of the water body (ICPDR, Danube River Basin Management Plan, Update 2021, Annex 9)				
☐ high	☐ good	☒ moderate	☐ poor	☐ bad
Protected areas information: - The Transboundary Biosphere Reserve Mura-Drava-Danube - Danube - Vukovar (HR2000372) Natura 2000 site				

Basic hydrological information				
Name of the reference gauging station			Bogojevo	
Year of the establishment of the gauging station			1871	
Location of the gauging station			km 1.367,30	
Distance to the (center of the) bottleneck			28.00 km	
Period for the calculation of the reference levels			1981-2010	
ENR (LNWL)	77.57 m.a.s.l.	11 cm	LNQ	1.435 m^3/s
HNWL	83.42 m.a.s.l.	596 cm	HNQ	5.850 m^3/s
Period for the calculation of the reference levels			1994-2023	
ENR (LNWL)	77.73	27 cm	LNQ	1.707 m^3/s
HNWL	83.01 m.a.s.l.	555 cm	HNQ	5.395 m^3/s
Name of the reference gauging station			Vukovar	
Year of the establishment of the gauging station			1856	
Location of the gauging station			km 1.333,40	
Distance to the (center of the) bottleneck			5.90 km	
Period for the calculation of the reference levels			*1981-2010*	
ENR (LNWL)	*76.36 m.a.s.l.*	*17 cm*	*LNQ*	*1.435 m^3/s*
HNWL	*81.63 m.a.s.l.*	*544 cm*	*HNQ*	*5.850 m^3/s*
Period for the calculation of the reference levels			1994-2023*	
ENR (LNWL)	76.68 m.a.s.l.	49 cm	LNQ	1.769 m^3/s
HNWL	81.14 m.a.s.l.	495 cm	HNQ	5.395 m^3/s

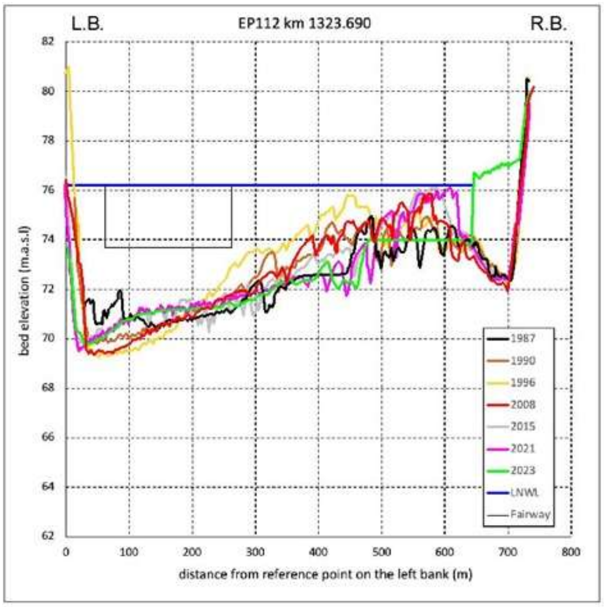
3.13. Sotin

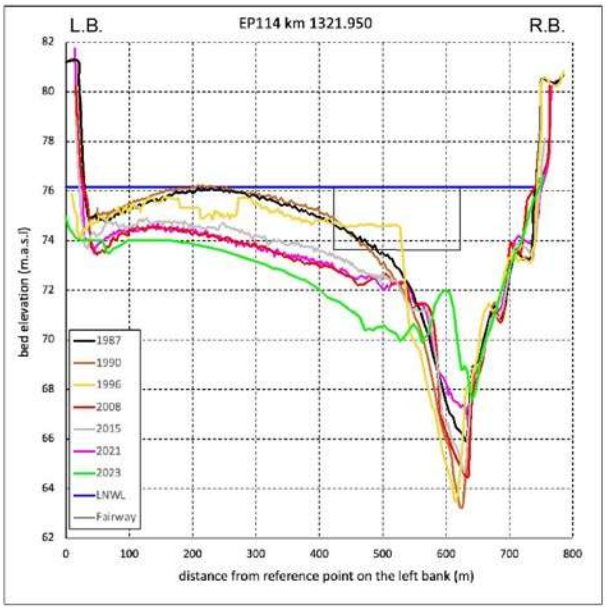
Basic location info			
Name of the bottleneck	**Sotin**	Alternative name	N/A
Waterway	Danube River	Waterway class (AGN)	VI
From (km upstream)	1,324.0	To (km downstream)	1,320.0
Total length (km)	4,00	River bed	Sand

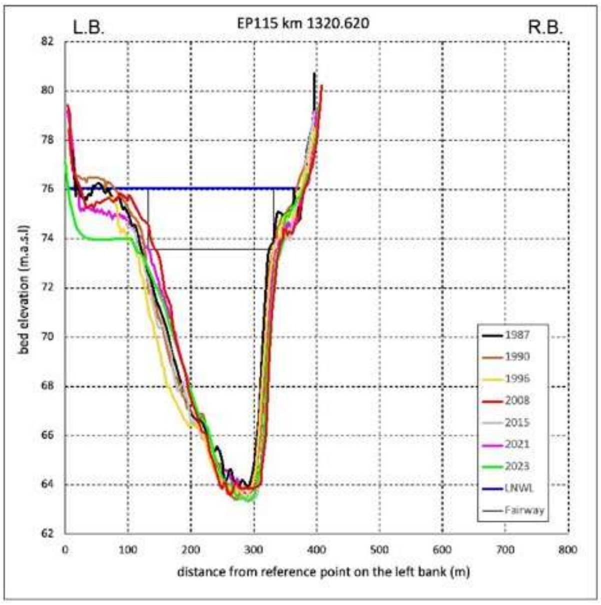
Visualization



Layout view of the critical sector







Cross sections of the critical sector

Basic information on the navigation obstacle(s)			
☐ depth	☒ width	☐ radius	☐ height
☐ other (to be specified if selected)			

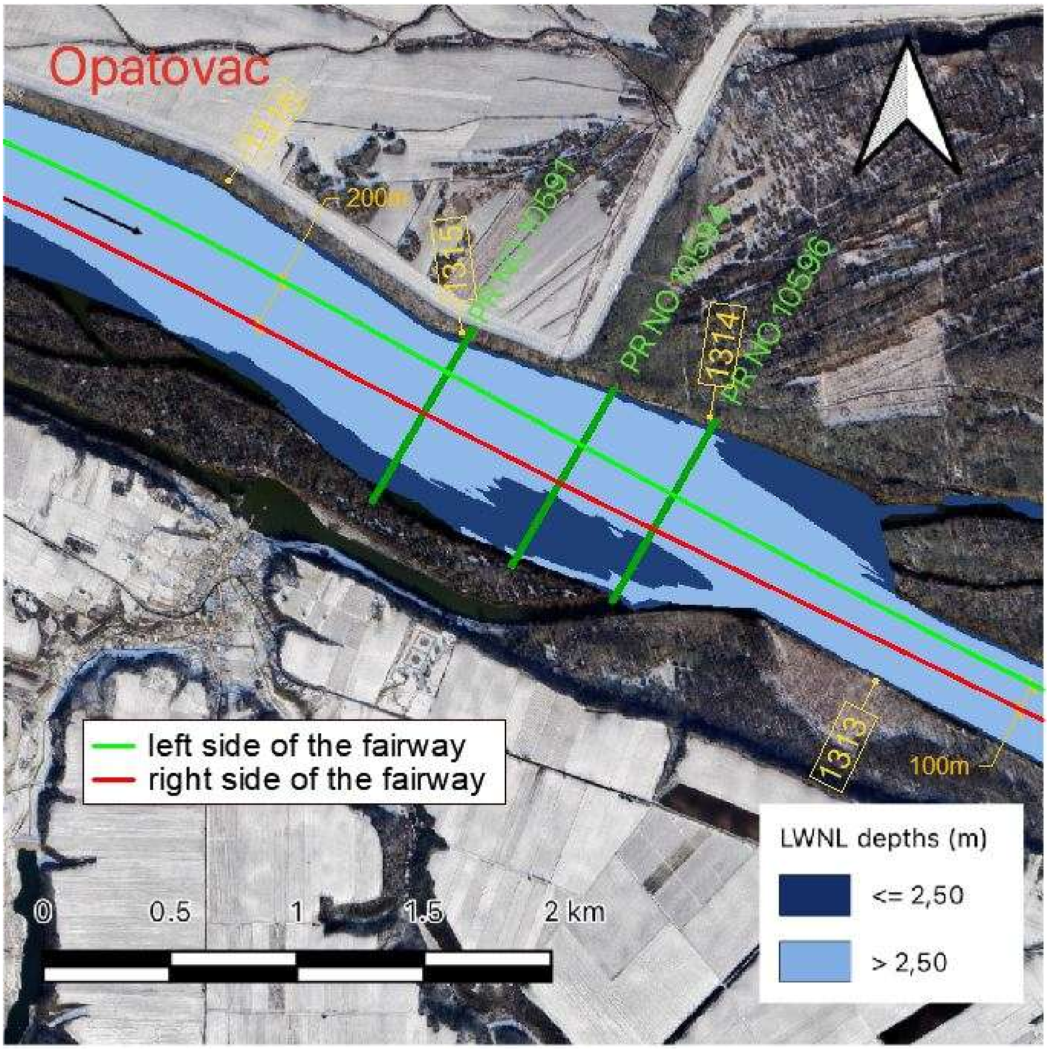
Historical information	
☒ The location is known as the navigation bottleneck from before	☐ The location is newly identified navigation bottleneck

Basic ecological information				
Overall ecological status of the water body (ICPDR, Danube River Basin Management Plan, Update 2021, Annex 9)				
☐ high	☐ good	☒ moderate	☐ poor	☐ bad
Protected areas information: - The Transboundary Biosphere Reserve Mura-Drava-Danube - Danube - Vukovar (HR2000372) Natura 2000 site				

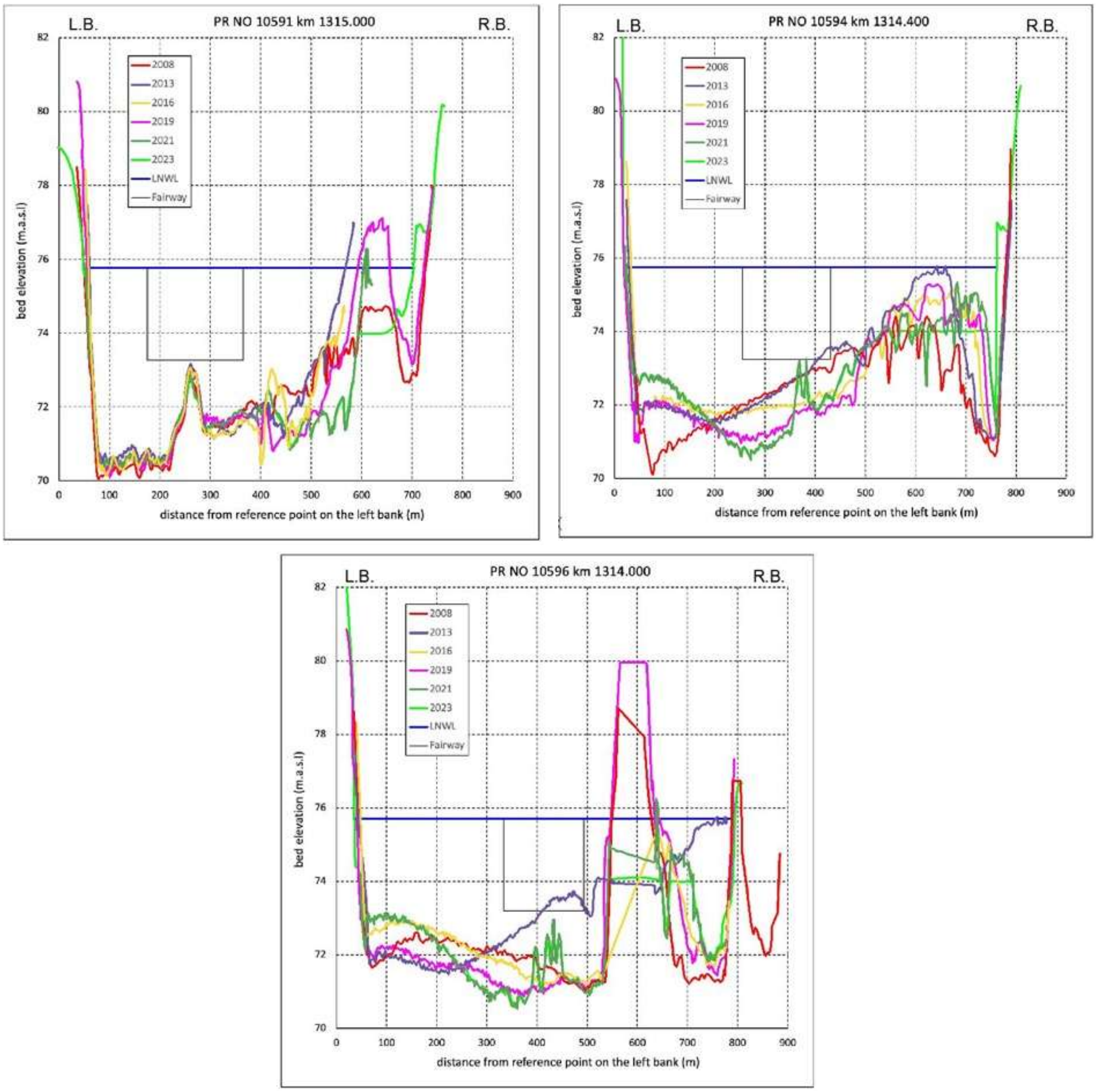
Basic hydrological information				
Name of the reference gauging station			Bačka Palanka	
Year of the establishment of the gauging station			1888	
Location of the gauging station			km 1.298,60	
Distance to the (center of the) bottleneck			23.40 km	
Period for the calculation of the reference levels			1981-2010	
ENR (LNWL)	74.44 m.a.s.l.	47 cm	LNQ	1,435 m^3/s
HNWL	79.75 m.a.s.l.	578 cm	HNQ	5,850 m^3/s
Period for the calculation of the reference levels			1994-2023	
ENR (LNWL)	74.86	89 cm	LNQ	1,778 m^3/s
HNWL	78.98 m.a.s.l.	501 cm	HNQ	5,173 m^3/s
Name of the reference gauging station			Vukovar	
Year of the establishment of the gauging station			1856	
Location of the gauging station			km 1.333,40	
Distance to the (center of the) bottleneck			11.40 km	
Period for the calculation of the reference levels			*1981-2010*	
ENR (LNWL)	*76.36 m.a.s.l.*	*17 cm*	*LNQ*	*1.435 m^3/s*
HNWL	*81.63 m.a.s.l.*	*544 cm*	*HNQ*	*5.850 m^3/s*
Period for the calculation of the reference levels			1994-2023*	
ENR (LNWL)	76.68 m.a.s.l.	49 cm	LNQ	1.769 m^3/s
HNWL	81.14 m.a.s.l.	495 cm	HNQ	5.395 m^3/s

3.14. Opatovac

Basic location info			
Name of the bottleneck	**Opatovac**	Alternative name	N/A
Waterway	Danube River	Waterway class (AGN)	VI
From (km upstream)	1,315.4	To (km downstream)	1,314.6
Total length (km)	0,80	River bed	Gravel
Visualization			



Layout view of the critical sector



Cross sections of the critical sector

Basic information on the navigation obstacle(s)			
☐ depth	☒ width	☐ radius	☐ height
☐ other (to be specified if selected)			

Historical information	
☒ The location is known as the navigation bottleneck from before	☐ The location is newly identified navigation bottleneck

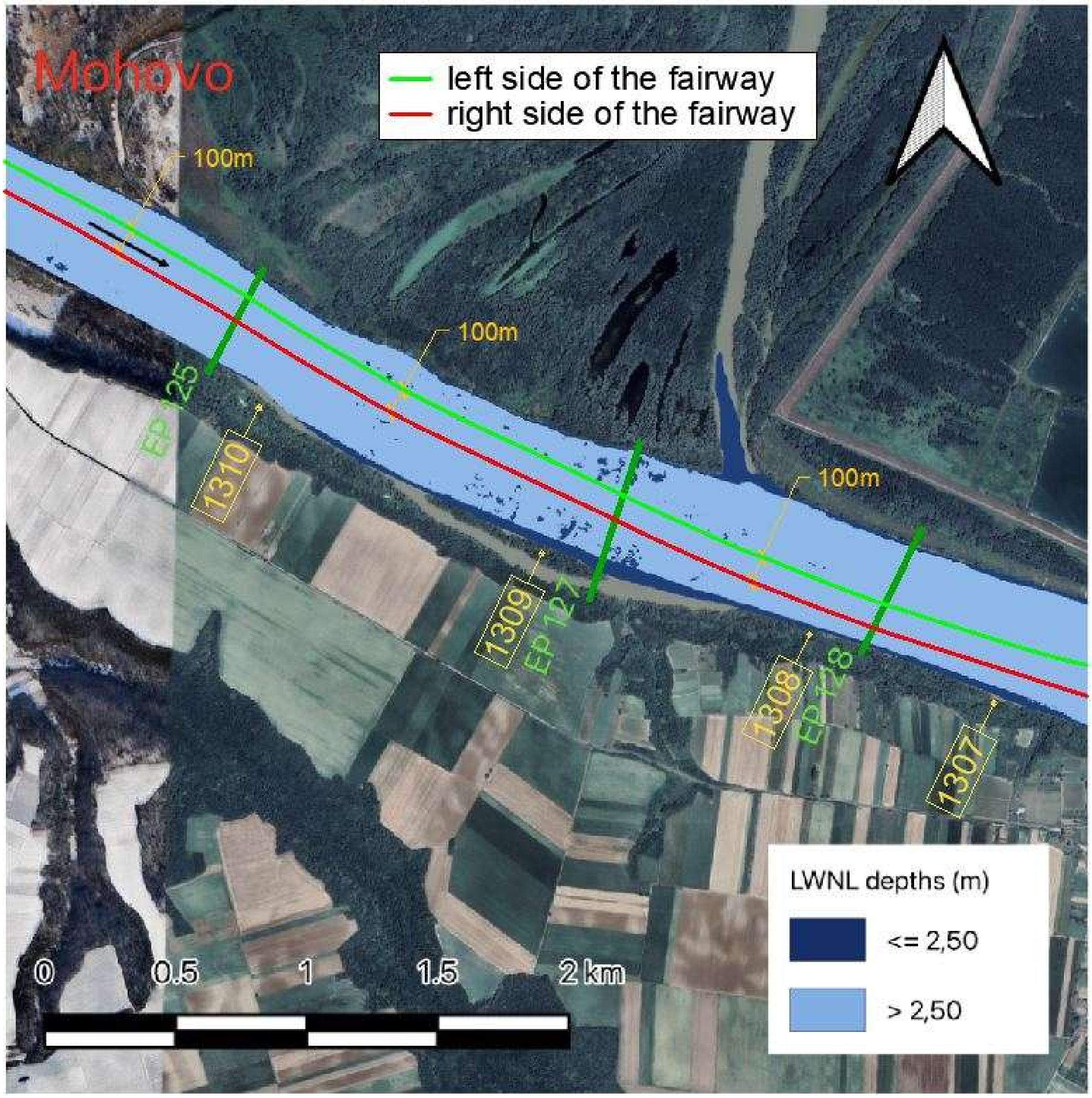
Basic ecological information				
Overall ecological status of the water body (ICPDR, Danube River Basin Management Plan, Update 2021, Annex 9)				
☐ high	☐ good	☒ moderate	☐ poor	☐ bad
Protected areas information: - The Transboundary Biosphere Reserve Mura-Drava-Danube - Danube - Vukovar (HR2000372) Natura 2000 site				

Basic hydrological information				
Name of the reference gauging station			Bačka Palanka	
Year of the establishment of the gauging station			1888	
Location of the gauging station			km 1.298,56	
Distance to the (center of the) bottleneck			16.40 km	
Period for the calculation of the reference levels			1981-2010	
ENR (LNWL)	74.44 m.a.s.l.	47 cm	LNQ	1,435 m^3/s
HNWL	79.75 m.a.s.l.	578 cm	HNQ	5,850 m^3/s
Period for the calculation of the reference levels			1994-2023	
ENR (LNWL)	74.86	89 cm	LNQ	1,778 m^3/s
HNWL	78.98 m.a.s.l.	501 cm	HNQ	5,173 m^3/s
Name of the reference gauging station			Ilok / Ilok most	
Year of the establishment of the gauging station			2019	
Location of the gauging station			km 1.298,70	
Distance to the (center of the) bottleneck			16.30 km	
Period for the calculation of the reference levels			*1981-2010*	
ENR (LNWL)	*74.44 m.a.s.l.*	*47 cm*	*LNQ*	*1.435 m^3/s*
HNWL	*79.74 m.a.s.l.*	*577 cm*	*HNQ*	*5.850 m^3/s*
Period for the calculation of the reference levels			1994-2023*	
ENR (LNWL)	74.68 m.a.s.l.	71 cm	LNQ	1.778 m^3/s
HNWL	79.15 m.a.s.l.	518 cm	HNQ	5.449 m^3/s

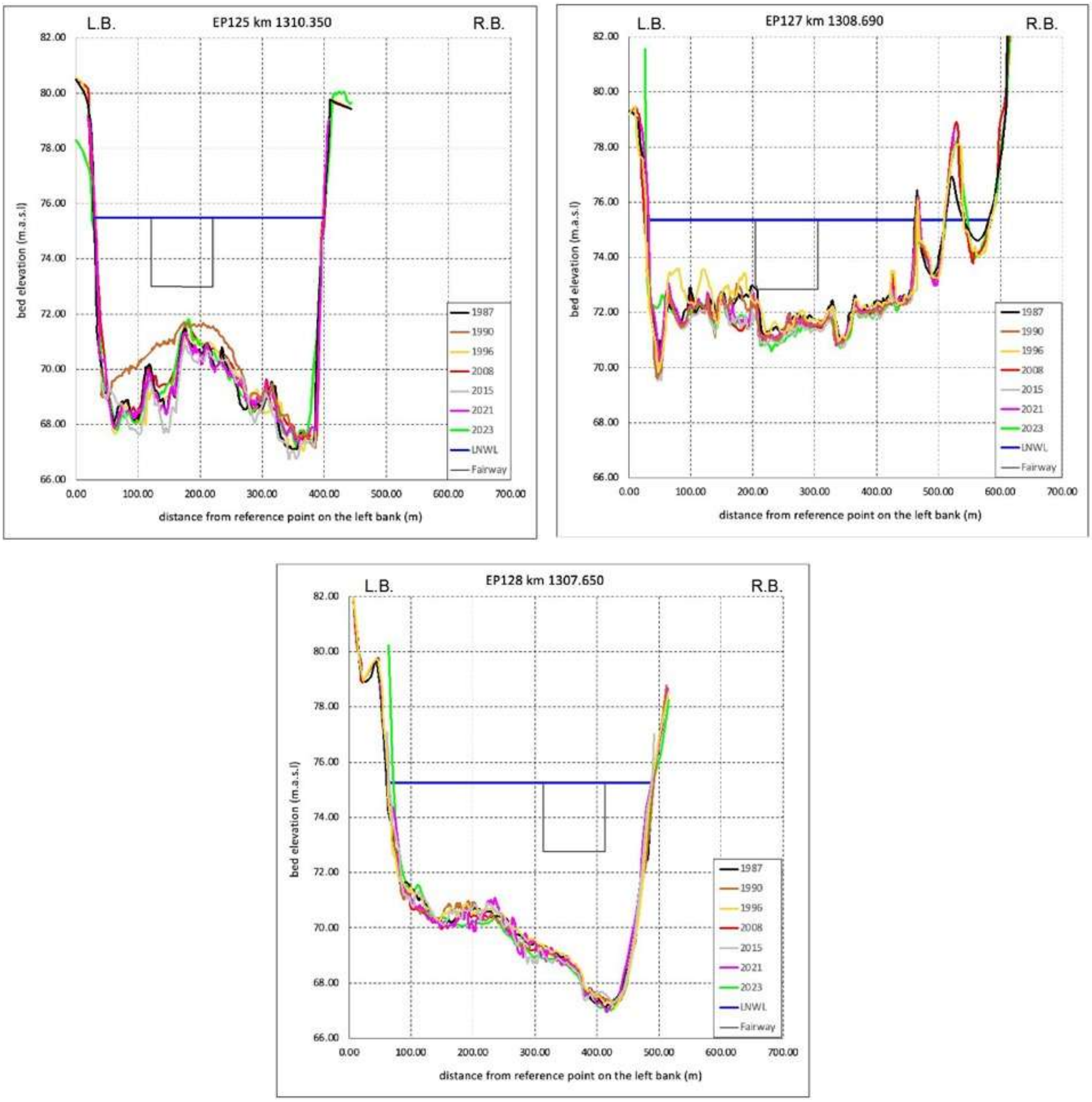
3.15. Mohovo

Basic location info			
Name of the bottleneck	**Mohovo**	Alternative name	N/A
Waterway	Danube River	Waterway class (AGN)	VI
From (km upstream)	1,311.4	To (km downstream)	1,307.6
Total length (km)	3,80	River bed	Gravel, rock

Visualization



Layout view of the critical sector



Cross sections of the critical sector

Basic information on the navigation obstacle(s)			
☐ depth	☒ width	☐ radius	☐ height
☐ other (to be specified if selected)			

Historical information				
☒ The location is known as the navigation bottleneck from before		☐ The location is newly identified navigation bottleneck		
Basic ecological information				
Overall ecological status of the water body (ICPDR, Danube River Basin Management Plan, Update 2021, Annex 9)				
☐ high	☐ good	☒ moderate	☐ poor	☐ bad
Protected areas information: - The Transboundary Biosphere Reserve Mura-Drava-Danube - Special Nature Reserve Karađorđevo - Danube - Vukovar (HR2000372) Natura 2000 site - Karađorđevo (RS0000038) Emerald site				
Basic hydrological information				
Name of the reference gauging station			Bačka Palanka	
Year of the establishment of the gauging station			1888	
Location of the gauging station			km 1.298,60	
Distance to the (center of the) bottleneck			10.90 km	
Period for the calculation of the reference levels			1981-2010	
ENR (LNWL)	74.44 m.a.s.l.	47 cm	LNQ	1,435 m^3/s
HNWL	79.75 m.a.s.l.	578 cm	HNQ	5,850 m^3/s
Period for the calculation of the reference levels			1994-2023	
ENR (LNWL)	74.86	89 cm	LNQ	1,778 m^3/s
HNWL	78.98 m.a.s.l.	501 cm	HNQ	5,173 m^3/s
Name of the reference gauging station			Ilok / Ilok most	
Year of the establishment of the gauging station			2019	
Location of the gauging station			km 1.298,70	
Distance to the (center of the) bottleneck			10.80 km	
Period for the calculation of the reference levels			*1981-2010*	
ENR (LNWL)	*74.44 m.a.s.l.*	*47 cm*	*LNQ*	*1.435 m^3/s*
HNWL	*79.74 m.a.s.l.*	*577 cm*	*HNQ*	*5.850 m^3/s*
Period for the calculation of the reference levels			1994-2023*	
ENR (LNWL)	74.68 m.a.s.l.	71 cm	LNQ	1.778 m^3/s
HNWL	79.15 m.a.s.l.	518 cm	HNQ	5.449 m^3/s

3.1. Conclusions

The application of the Level of Service (LoS) approach marks an advancement in defining the navigability conditions of the Serbian–Croatian section of the Danube River.

The identification of 13 navigation bottlenecks—together with the declassification of four previously critical sectors—reflects morphological changes in the past decade.

The use of a unified bottleneck presentation template enhances consistency, traceability, and comparability across national reporting lines.

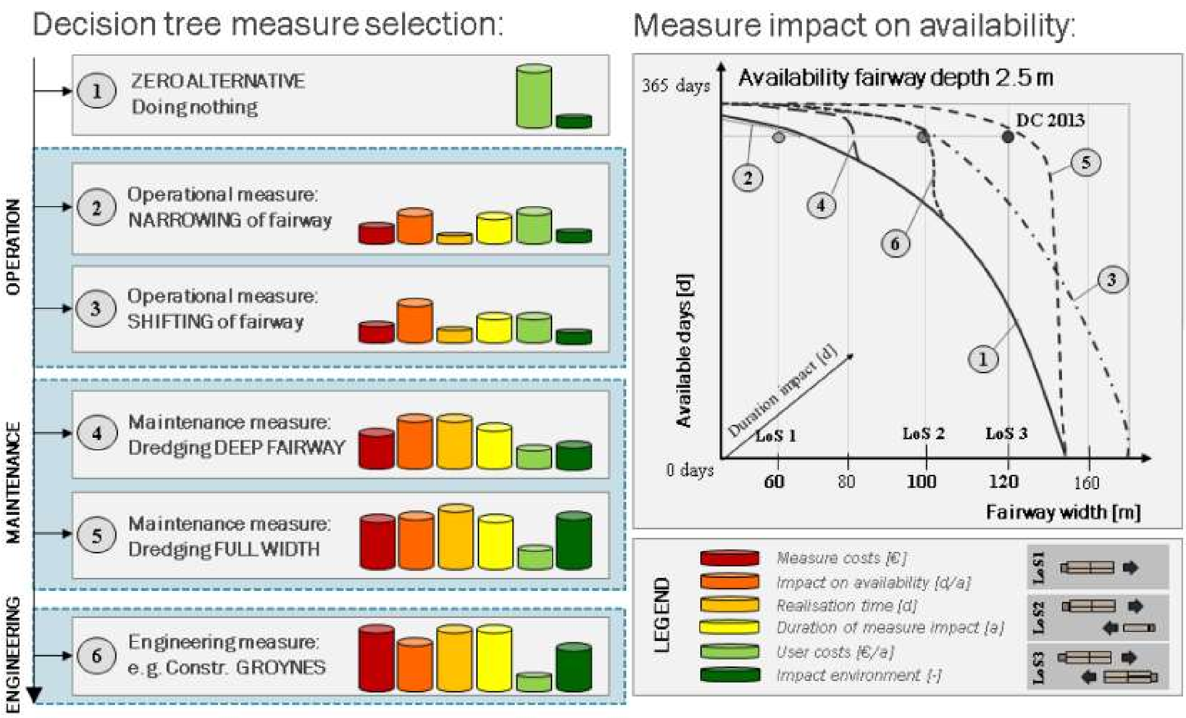
CHAPTER 4. – PRIORITIZATION OF NAVIGATIONAL BOTTLENECKS

4.1. Introduction

Navigation bottlenecks—also referred to as critical navigation sectors—are river stretches where fairway parameters, such as depth and width, are significantly reduced during low-flow periods. These constraints can compromise the continuity and safety of inland navigation, particularly under drought or seasonal low water conditions. However, the severity of impact varies across the identified bottlenecks. Some sectors exhibit only marginal reductions in fairway parameters with limited influence on vessel passage, while others present substantial navigational constraints that may pose safety risks or operational disruptions. Accordingly, each bottleneck must be evaluated not only by its physical characteristics but also by its operational significance within the broader waterway network.

4.2. Methodology for prioritization of navigation bottlenecks

In this light, link can be made to the Good Practice Manual on Inland Waterway Maintenance (MOVE/FP7/321498/PLATINA II, 2016) and example of different measures applicable to identified navigation bottlenecks (Figure 51). Similar approach can be found under the Guidelines Towards Achieving a Good Navigation Status – the GNS study (2018) as well.



Source: Good Practice Manual on Inland Waterway Maintenance, MOVE/FP7/321498/PLATINA II, 2016, p. 86; based on NEWADA duo (2014): Feasibility Study for a Waterway Maintenance Management System (WMMS) for the Danube, Network of Danube Waterway Administrations – data and user orientation, Final Report, NEWADA duo project deliverable O.6.4.9

Figure 51: Example of visualization of results of evaluation of different measures (from do nothing through O&M to engineering measure)

In accordance with this approach, the first step is to assess whether soft measures—such as narrowing or realignment (shifting) of the fairway—can be feasibly applied. If these options prove insufficient, the next step involves evaluating whether maintenance dredging activities could enhance navigation conditions. Should neither of these measures yield viable improvements, the development and potential implementation of river training structures should be considered as a final alternative.

4.3. Application of the methodology for prioritization of navigation bottlenecks

As the initial step in applying the previously defined methodology for prioritizing navigation bottlenecks, the fairway width was reduced from 200 m to 150 m. This narrowing resulted in the removal of the following sectors from the list of bottlenecks: **Bezdan, Siga Kazuk, Bogojevo, Dalj, Sotin, and Opatovac**. The Consultant notes that the sediment volumes identified within the defined fairway at Bogojevo, Dalj, Sotin, and Opatovac are relatively small and may also be influenced by the specific method of hydrographic surveying applied. The updated list of navigation bottlenecks, following this narrowing step, is provided in Table 21.

Table 21: List of navigation bottlenecks after application of operation measures

No.	Sector	Chainage (from km to km)	Quantity of sediment within the fairway of 2.5m depth &			
			Width 100m	Width 120m	Width 150m	Width 200m
3	**Apatin**	1,408.2 – 1,400.0	7,035	14,635	26,821	54,311
4	**Čivutski Rukavac**	1,397.2 – 1,389.0	343	1,494	8,164	52,977
5	**Drava Confluence**	1,388.8 – 1,382.0	0	441	4,221	22,013
7	**Staklar**	1,376.8 – 1,373.4	733	1,571	3,823	14,781
11	**Borovo 1**	1,348.6 – 1,343.6	0	415	5,431	26,555
12	**Borovo 2**	1,340.6 – 1,338.0	0	346	6,863	40,353
16	**Mohovo**	1,311.4 – 1,307.6	93	177	368	748

It should be noted that predicting the long-term sustainability of the proposed measures is not feasible. Accordingly, all relevant sectors should be subject to continuous monitoring by the competent Serbian and Croatian authorities, with appropriate interventions implemented based on prevailing conditions and observed morphological trends.

As a subsequent step, a combination of further fairway narrowing and, where necessary, maintenance dredging may be considered for the **Borovo 1** and **Borovo 2** sectors, both of which currently exhibit relatively favorable morphological dynamics.

Finally, it was noted that certain sectors (such as the Mohovo) present distinct challenges. In this case, the riverbed is marked by fixed rocky outcrops, introducing a fundamentally different dimension to navigation safety. Such conditions cannot be addressed through routine maintenance dredging or standard river training structures. Moreover, the limited volume of sediment identified within the fairway does not accurately reflect the extent of navigational constraints posed. Due to the immovable nature of these rocky features, hydraulic and morphological modelling offers limited value. Physical removal of the rock formations is required to restore safe and reliable fairway parameters.

After this step, the list of navigation bottlenecks after application of possible fairway operation and maintenance measures is presented at the Table 22.

Table 22: List of prioritized navigation bottlenecks

No.	Sector	Chainage (from km to km)	Quantity of sediment within the fairway of 2.5m depth &			
			Width 100m	Width 120m	Width 150m	Width 200m
3	**Apatin**	1,408.2 – 1,400.0	7,035	14,635	26,821	54,311
4	**Čivutski Rukavac**	1,397.2 – 1,389.0	343	1,494	8,164	52,977
5	**Drava Confluence**	1,388.8 – 1,382.0	0	441	4,221	22,013
7	**Staklar**	1,376.8 – 1,373.4	733	1,571	3,823	14,781

In close coordination with both Serbian and Croatian river administrations, as expressed during SHFM09, the Consultant recommends revising the current list to include the **Aljmaš** sector, which is not presently classified as critical for navigation (see Table 23). This recommendation is based on the sector's strategic location between two prioritized sectors—Drava Confluence (upstream of Aljmaš) and Staklar (downstream)—with which it shares similar hydro-morphological characteristics. The Consultant considers that integrated modeling of these adjacent sectors may offer a more comprehensive understanding of potential hydro-morphological developments in this area.

Table 23: List of prioritized navigation bottlenecks to be the subject of 2D modeling

No.	Sector	Chainage (from km to km)	Quantity of sediment within the fairway of 2.5m depth &			
			Width 100m	Width 120m	Width 150m	Width 200m
3	**Apatin**	1,408.2 – 1,400.0	7,035	14,635	26,821	54,311
4	**Čivutski Rukavac**	1,397.2 – 1,389.0	343	1,494	8,164	52,977
5	**Drava Confluence**	1,388.8 – 1,382.0	0	441	4,221	22,013
6	**Aljmaš**	1,381.4 – 1,378.2	0	0	0	0
7	**Staklar**	1,376.8 – 1,373.4	733	1,571	3,823	14,781

4.4. Conclusions

The identification and prioritization of navigation bottlenecks along the common Serbian–Croatian stretch of the Danube River underscore the strategic importance of adaptive and tiered riverbed management practices. The application of the Level of Service (LoS) methodology, together with hydro-morphological analysis and historical survey data, has allowed for a classification of critical navigation sectors according to both physical constraints and their operational relevance within the waterway network.

The preliminary narrowing of the fairway from 200 m to 150 m served as an effective soft measure, eliminating several sectors from the bottleneck list and demonstrating the utility of minimal interventions in specific contexts. However, the variable sediment volumes and survey-related uncertainties observed in some areas—such as Bogojevo and Opatovac—highlight the need for cautious interpretation of bathymetric data.

Notably, site-specific challenges—Mohovo sector—reveal the limitations of conventional maintenance strategies. The presence of immobile rocky bottom not only worsens navigation risks but also negates the utility of typical hydraulic modeling, necessitating direct structural interventions such as rock removal. These cases illustrate that physical and morphological constraints must be addressed with context-specific technical solutions beyond standardized river training.

Given the complexity and variability of the conditions observed, long-term sustainability of individual measures cannot be reliably predicted. Consequently, a robust monitoring regime, supported by the joint engagement of Serbian and Croatian authorities, is essential to inform timely and proportional responses to evolving riverbed conditions.

In support of holistic system-based planning, the Consultant also recommends amending the current bottleneck list (Apatin, Čivutski/Židovski Rukavac, Drava Confluence and Staklar) to include the Aljmaš sector. Although not presently identified as critical, its hydro-morphological alignment with neighboring priority sectors suggests that integrated modeling would yield improved foresight into river dynamics and navigation risks.

CHAPTER 5. – DEFINITION OF MCA

5.1. Introduction

A key feature of the project is the use of a structured multi-criteria analysis (MCA) to assess proposed intervention scenarios against a diverse set of indicators. These are grouped into four main categories—navigation, environmental sustainability, technical and financial feasibility, and vulnerability to climate change—reflecting the broad range of considerations necessary in navigation planning. Each scenario, including a "Do-nothing" baseline scenario, is subjected to both qualitative and quantitative assessment based on modeled hydromorphological responses, ecological impacts, and economic viability, using 2D sediment transport simulations as a primary modeling tool. The weighting and scoring structure of the MCA have been designed to reflect both project-specific goals and best practices from comparable EU initiatives.

Through this holistic methodology, the project seeks not only to rank intervention options according to their performance across multiple domains, but to establish a transparent, traceable decision-making framework that supports long-term planning and cooperation between the two riparian states.

5.2. MCA framework

The multi-criteria analysis (MCA) for selecting the optimal scenario for each sector is structured to evaluate and rank alternative solutions aimed at improving navigation conditions along the shared Serbian–Croatian sector of the Danube River. This includes comparison with a "Do-nothing" scenario, which represents a baseline condition without any structural, non-structural, operational, or maintenance interventions. The "Do-nothing" scenario serves as the reference point against which the performance and added value of alternative scenarios are assessed.

Within this evaluation framework, specific navigation and ecological criteria require demonstrable improvement over the baseline condition. To ensure this, minimum performance thresholds will be introduced in the scoring system, such that proposed scenarios must exceed the navigational and ecological standards defined under the "Do-nothing" option over their projected lifespans and in alignment with established ecological objectives.

All proposed alternatives will adhere to applicable international, EU, and national legislative requirements. This includes compliance with the EU Water Framework Directive (WFD), the Birds and Habitats Directives (BHD), the EU Taxonomy Regulation, recommendations of the Danube Commission, documentation of the International Commission for the Protection of the Danube River (ICPDR), and the relevant legislation of both Serbia and Croatia.

5.3. MCA methodology

The criteria defined in the MCA for this project are categorized into four groups: navigation, environment, feasibility and climate change vulnerability. Alternative scenarios will be ranked using the **Weighted product model** of Multi Criteria Analysis. For each sub-criterion, the indicator values for alternative scenarios and the "Do-nothing" scenario will be compared. These indicator values pertain to the estimated condition after implementing measures (either under alternative scenarios or "Do-nothing" scenario), using numerical simulations of 2D sediment transport.

"Do-nothing" scenario serves as the reference with a score of 1 in the multi-criteria analysis. If an alternative scenario receives a final score (obtained by multiplying scores across all criteria) less than 1, it indicates that this scenario is "worse" than the "Do-nothing" scenario. Conversely, if a measure under alternative scenarios receives a score greater than 1, it can be recommended for implementation. Naturally, the scenario with the highest score represents the "best" scenario under the current project.

The final scoring expression is defined as follows:

$$Total\ score = N_1^{0.30} \cdot N_2^{0.05} \cdot N_3^{0.05} \cdot E_1^{0.15} \cdot E_2^{0.05} \cdot E_3^{0.05} \cdot E_4^{0.05} \cdot E_5^{0.05} \cdot E_6^{0.05} \cdot F_1^{0.05} \cdot F_2^{0.10} \cdot C^{0.05}$$

Where the terms denoted with *N, E, F* and *C* represent the scores for navigational (3 criteria), ecological (6 criteria), economic (2 criteria) and climate change aspects (1 criterion), respectively. The exponents in the expression are the weight coefficients assigned to each sub-criterion. All components of the product are adopted in the analysis based on expert judgment combined with quantitative data where available, which is explained through calculated values for quantitative indicators or assigned values for qualitative indicators related to the corresponding criteria. Summarized scores are given for criteria that encompass multiple indicators. The scores for criteria are provided based on expert consideration, as the indicators may overlap to a certain extent. Therefore, indicators within the same group do not have to be independent. The same applies to different criteria, for example, there is a relationship between the diversity of morphological forms and biodiversity (hydro-morphological indicators and indicators for living organisms are dependent).

Discrete values can be adopted for all variables: 0 – an unacceptable value that causes the entire solution to be rejected, so these solutions will not be ranked; 0.25 - a value indicating the least acceptable solution 0.5 – a value indicating moderate but acceptable deterioration compared to the “Do-nothing” scenario; 1 – a value indicating an unchanged state compared to the “Do-nothing” scenario; 1.5 – indicating moderate improvement; and 2 – significant improvement. Considering the specific navigational and ecological goals, for all criteria, minimum acceptable values of 1 or higher are introduced (this will be explained in more detail in the description of the criteria).

5.4. Justification of Weighting Coefficients in the MCA Framework

The selection of weighting coefficients within the multi-criteria analysis (MCA) framework reflects a deliberate alignment with the strategic priorities and objectives of the project. The assigned weights capture the relative importance of each evaluation domain—navigation performance, environmental sustainability, technical and financial feasibility, and climate change vulnerability—based on a synthesis of expert judgment, lessons learned from comparable projects, and stakeholder input, including direct consultation with relevant authorities and decision-makers.

The rationale for each weighting category is as follows:

40% for navigation related criteria

- Reasoning: Improvement of navigational conditions is the primary focus in this activity, ensuring the safety, efficiency, and reliability of transportation. The criteria within this category (depth requirements, maneuverability, and safety) directly impact the usability of the waterway for vessels and are based on the recommendations of the Danube Commission (DC), European legislation and international treaties.
- Why 40%? This relatively high weight indicates the importance placed on improving and maintaining navigation standards, reflecting the countries' obligation to ensure Good Navigation Status. Projects in similar contexts likely prioritized navigation heavily due to its role in economic and logistic terms, and the whole EU transport policies, where the inland waterway transport is considered as environmentally friendly mode of transport. The high weighting for DC recommendations (0.30) reflect the critical role of physical waterway parameters for navigation. Lower weights for maneuverability (0.05) and safety (0.05) acknowledge their importance but subordinate them to channel dimensions.

40% for environment related criteria

- Reasoning: Environmental sustainability is a critical component of modern waterway projects, aligning with EU directives and global efforts to mitigate ecological impacts. The criteria include hydro-morphology, naturalness, sediment quality, and impacts on fauna and flora.
- Why 40%? Equal weight with navigation suggests a balanced approach where environmental considerations are as significant as navigation needs. This ensures that interventions are not only functional but also ecologically responsible. The higher weight for hydro-morphology (0.15) stems from its broad influence on ecosystem health and waterway stability. Equal weights (0.05) for naturalness, sediment quality, and biological aspects indicate a more balanced but less dominant consideration compared to hydro-morphology.

15% for feasibility criteria

- Reasoning: Feasibility, encompassing technical and financial aspects, is crucial for determining whether a proposed solution can be realistically implemented. Cost-effectiveness and execution capability are key to successful project delivery.
- Why 15%? While important, feasibility is secondary to the core objectives of navigation and environmental protection. However, it still carries substantial weight, as impractical solutions would undermine the project's viability. The higher weight for financial aspects (0.10) emphasizes cost considerations in decision-making. Technical aspects (0.05) are vital but often constrained by financial and environmental considerations.

5% for climate change vulnerability

- Reasoning: Climate change vulnerability addresses the adaptability and resilience of proposed measures in response to future climatic conditions. This is relatively new but growing focus in waterway management.
- Why 5%? Although essential, this criterion carries less weight than the others due to its more specific scope. Decision-makers may have prioritized immediate navigation and environmental needs over long-term climate adaptivity in this instance.

In Table 24, Table 25, Table 26 and Table 27 proposed criteria, indicators, acceptable scores and weighting coefficients are provided. The coefficients were proposed based on values previously applied in similar projects and communication with decision-makers.

Table 24: Criteria related to navigation

Code	Criteria	Indicators	Acceptable Score	Weighting coefficient
N_1	Maximal DC recommendations	Quantitative - Water depth ratio (width of 200 m used as reference value), Width ratio (water depth of 2.5m used as reference value), Curve radius ratio	1.5 - 2	0.30
N_2	Maneuverability	Quantitative - Velocity ratio Qualitative - Hindrance	0.25 - 2	0.05
N_3	Safety	Qualitative - Visibility of the structures	0.25 - 1	0.05

Table 25: Criteria related to environment

Code	Criteria	Indicators	Acceptable Score	Weighting coefficient
E_1	Hydro-morphology	Quantitative - Riverbed volume ratio, SHDi ratio, Length of low flow channels ratio, Bankfull discharge water level difference, Near bank velocity ratio, bank erosion length ratio	0.25 - 2	0.15
E_2	Physical naturalness of solution	Quantitative - Number of structures difference and level of nature protection	0.25 - 2	0.05
E_3	Sediment and water quality	Quantitative - Dredging volume Qualitative - Effects on physical, chemical and biological parameters of water quality	0.25 - 2	0.05
E_4	Bird population	Qualitative - Aspects of nesting, wintering and foraging	1 - 2	0.05
E_5	Fish population	Qualitative - Aspects of spawning, migration, wintering habitats, growing and living	1 - 2	0.05
E_6	Flora and habitats	Qualitative - Creation of new areas for distribution	1 - 2	0.05

Table 26: Criteria related to feasibility

Code	Criteria	Indicators	Acceptable Score	Weighting coefficient
F_1	Technical aspects	Quantitative - Execution of works and Response time	0.25 - 1	0.05
F_2	Financial aspects	Quantitative - Investment and maintenance costs/avoided users costs as benefit	0.25 - 2	0.10

Table 27. Climate change related criterion

Code	Criteria	Indicators	Acceptable Score	Weighting coefficient
C	Climate change vulnerability	Qualitative - Aspects of exposure, sensitivity and resilience	0.25 - 2	0.05

In the following text, the presented criteria will be described in more detail, and examples of scores for scenarios involving structural and non-structural measures will be provided. It is important to note that the examples offer only indicative expected scores, which evaluate the impact of a certain type of structure on the analyzed indicators. These scores should not be generalized, as the impact of a solution depends not only on the type of structure but also on its dimensions and spatial position.

5.4.1. Navigation criteria

Alternative solutions presented should enable safe and secure navigation, formally demonstrated by meeting navigability conditions within the adopted fairway limits of each sector, according to the criteria of the Danube Commission. However, some aspects of navigation cannot be formally evaluated through these conditions, so additional criteria are introduced into the MCA (Multi-Criteria Analysis) that directly or indirectly relate to additional recommendations concerning safe and unobstructed navigation.

The criteria used to demonstrate the achievement of navigation-related objectives are divided into three groups based on the possible range of acceptable values in the MCA (Multi-Criteria Analysis).

Maximal DC recommendations (N1): The first group includes criteria related to the recommendations of the Danube Commission in terms of navigation conditions. The ratings for this criterion N1 should be greater than 1.0. Namely, considering that the primary goal of the project is to propose and analyze alternative solutions to improve navigation conditions, the score for this sub-criterion should be higher than 1. However, the project will also analyze the effects of measures aimed at enhancing naturalness, i.e., renaturalization measures, which will not necessarily address navigation conditions. In this sense, the MCA analysis, tailored to fit the project's modeling framework, will take on a broader significance.

Maneuverability (N2): The second group relates to hydrodynamic parameters that may make vessel maneuvering more difficult or easier. Ratings for this criterion (N2) may be less or greater than 1, depending on the occurrence of certain flow patterns. For example, changes in maximum velocities (higher or lower) compared to the reference state ('Do-nothing') or the occurrence (presence or absence) of sudden changes in flow pattern can influence navigability, thus being considered key obstacles or enablers for navigation.

Safety (N3): Finally, the third sub-criterion, for which a score N3 is given, concerns the expert evaluation of the risk of vessels colliding with structures (if they are part of the solution), and in the best-case scenario, this score can be 1 (meaning that additional risks are absent or negligible). A score of 0.5 for this criterion would indicate minimal risks and value of 0.25 the least acceptable risks.

5.4.1.1. Maximal DC Recommendations

Water depth ratio

The primary indicator of navigability is the water depth at the low water navigation level (defined for the $Q_{94\%}$ discharge) within the fairway. To assess navigability, water depths within the fairway limits pre-adopted for each sector at the low navigation level after the implementation of measures are compared to the corresponding depths in the 'Do-nothing' scenario. The water depth ratio will be the ratio of the average minimum depths along the fairway for the alternative and the 'Do-nothing' scenarios. The minimum depths will be averaged based on the longitudinal profile of minimum depths in cross-sections.

Width ratio

Satisfying the minimum navigable depth at the low water navigation level (which is 2.5m for the joint sector) can also be achieved outside the limits of the existing fairway. To evaluate this 'reserve,' a width ratio is introduced, which represents the ratio of the width where this depth requirement is continuously met for the alternative solution (at the low water navigation level) to the correspondingly defined width for the 'Do-nothing' scenario. As with depths, the average widths from the longitudinal profile will be compared.

Curve radius ratio

The curvature of the fairway is a parameter analyzed in scenarios where changes to the axis of the existing fairway are planned. The curve radius ratio will represent the ratio of the minimum designed radius to the existing radius in the sector.

5.4.1.2. Maneuverability

Velocity ratio

The flow velocity affects the maneuverability of the vessel, and consequently, the safety of navigation. The velocity ratio represents the relationship between the maximum calculated water velocity for the condition after implementing measures and the do-nothing condition. Maximum velocities will be checked within the range of the low, average and high-water navigation levels.

Hindrance

Within this criterion, the flow patterns that may facilitate or hinder navigation will be considered. The presence of changes in flow pattern will be examined, and an expert assessment based on results of numerical simulations will be made regarding how these flow patterns can affect the maneuverability of the vessel.

5.4.1.3. Safety

Visibility of the structures

This criterion takes into account the reduction of navigation safety due to the construction of river training structures. This risk, although minimal, is inevitably introduced by the construction of structures, even if they must be properly marked and registered in the river information system. Depending on the level of risk assessed by expert judgment, it may have a greater or lesser impact on navigation safety.

5.4.2. Environmental criteria

The proposed Multi-Criteria Analysis (MCA) builds on prior work in the navigation projects in Serbia (Consortium Witteveen Bos, 2013), in which criteria were divided into three groups (navigation, environment and feasibility) with more weight given to the first two groups (navigation and environment – 40% each). The suggested criteria, indicators, and weighting coefficients are based on values applied in similar projects and communication with experts, including those from Stakeholder Forum, and decision-makers.

Multi-criteria analysis of hydro-morphological alterations of a critical sector of the Danube and their impact on biota (fish, birds, flora) will give the most adequate and appropriate solution. Existing environmental documentation is collected and used. Regarding ecological status of this common sector of the Danube is estimated based on abiotic and biotic quality parameters as moderate according to WFD (Liška, Wagner, & Sengl, 2019).

The impact of the proposed solutions on the environment is assessed by evaluating the considered scenarios using the criteria related to:

- Hydro-morphology;
- Naturalness of solutions
- Sediment and water quality;
- Fish population;
- Bird population;
- Flora.

In this group of criteria, there are also indicators for which alternative scenarios must not receive scores lower than those for the "Do-nothing" scenario. For the group of indicators that directly relate to wildlife (fish, birds, and flora), a score lower than the reference score (1.0) is not acceptable. For all other groups of indicators, scores ranging from 0.25 to 2.0 are possible.

5.4.2.1. Hydro-morphology indicators

Riverbed volume ratio

Using a coupled 2D model of free surface flow and sediment transport, the change in the geometry of the Danube riverbed will be simulated for the selected sectors. As a result of the numerical simulations, the change in riverbed volume (defined as volume bounded by provisional horizontal plane beneath the riverbed and the riverbed itself) will be obtained and compared for each alternative solution with the riverbed volume change in the "Do-nothing" scenario. Based on this comparison, the impact of the proposed measures on morphological changes will be assessed. Previous studies (including study conducted by Hidroing and Danube sediment study) indicate a trend of erosion in the joint sector; however, without an integrated assessment of the water and sediment regime, it is difficult to conclude to what extent this is the result of river training structures along the common sector, controlled (or even uncontrolled) sediment extraction or water regime changes influenced by management decision or climate changes.

River training structures aimed at deepening the riverbed improve navigational conditions through bed erosion but have negative ecological impacts by removing sediment from the riverbed, decreasing the habitat variability in the river, lowering the surface and ground water levels in the floodplain etc. which is vital for aquatic life. This clearly creates a conflict between navigation needs and ecological concerns. However, sediment transport must also be viewed integrally from an ecological perspective, as sediment nourishes downstream areas. For instance, on the Danube section downstream of the joint Serbian-Croatian sector (Serbian free-flow sectors), erosion is even more pronounced. If measures to retain sediment were implemented solely within the joint sector, it would increase sediment deficits downstream. Considering the local nature of this project, it is recommended to positively evaluate measures that minimize changes in the riverbed volume and their impact on sediment regime alterations. This approach addresses not only ecological concerns but also the broader conflict of interest between navigation and ecology (Ausili et al., 2022). According to this approach, solutions that result in low values of riverbed volume changes compared to the "Do-nothing" scenario will be considered as favorable solutions since it will not have a significant impact on the sediment regime.

SHDi ratio

The Shannon diversity index is a measure of spatial unevenness of a certain attribute. When considering the riverbed in a horizontal plane, and assessing the presence of specific river forms, this index will reflect morphological diversity (Kidová, Radecki-Pawlik, Rusnák, & Plesiński, 2021), which is important for biodiversity. The SHDi index will be determined for low-flow conditions in each analyzed scenario, for the state after riverbed adjustment as a result of modelling. At low-flow levels, the following characteristic areas will be identified in the horizontal plane: areas under active flow, areas of stagnant water, river bars, and areas potentially covered by vegetation (areas that are not submerged during higher water levels). An example of the identification of these areas for two fictitious scenarios is given in Figure 52 and Figure 53.

The Shannon index will be calculated as follows:

$$SHDi = -\sum_{i=1}^{4} p_i \ln p_i$$

Where pi is proportion of each area class in river main channel planform (as shown in figures, 4 area classes are used). Pi is the proportion of each area class relative to the total area. The sum is taken over all 4 classes.

Higher values of this index indicate greater diversity of the analyzed forms and represent a more desirable outcome from the ecological perspective.

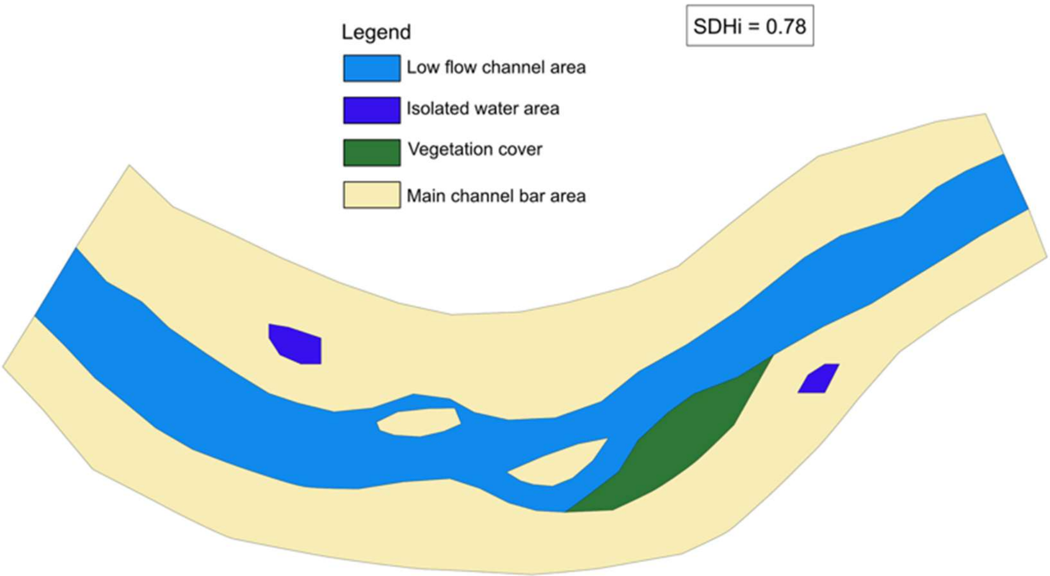


Figure 52: Characteristic areas after 2D sediment transport simulation for channel forming discharge (fictitious "Do-nothing" scenario)

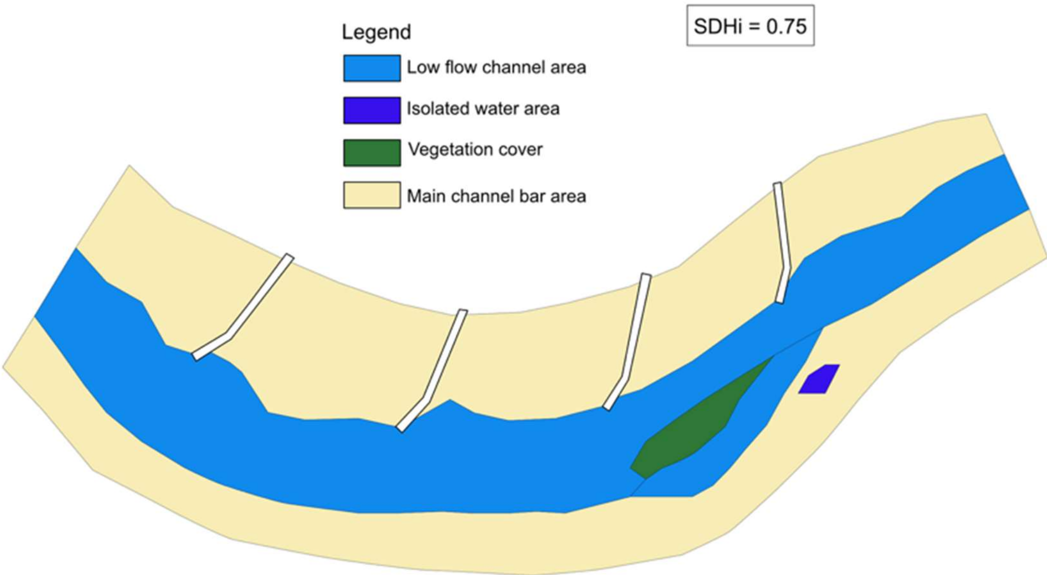


Figure 53: Characteristic areas after 2D sediment transport simulation for channel forming discharge (fictitious alternative solution with groynes)

In the example from the figures, a visual inspection suggests that the morphological diversity is greater for the “Do-nothing” scenario, which is also reflected in a higher SHDi value. Thus, in this case, due to the SHDi ratio, the assessment indicates a moderate negative change for the alternative scenario from a morphological perspective. Considering the importance of this indicator, the overall criterion for the alternative solution must receive a score of less than 1.0.

Length of low flow channels ratio

Given the ecological significance of low-flow conditions, an additional indicator is introduced to specifically evaluate the effect of the proposed solutions on the change in channel length under environmental flow, which can be determined based on input data used in hydrological study (e.g. GEP method can be used as obligatory method in Serbia). The value of the indicator is calculated as the ratio of the channel axis length for the alternative solution compared to the reference solution.

Water stage elevation difference for bankfull discharge

Due to the lack of input data for simulating river flow during flood events (as these analyses would exceed the scope of the project), the impact of the proposed measures on the high-water domain is assessed indirectly by comparing the calculated water surface elevations at bankfull discharge for the alternative and "Do-nothing" scenarios (at the upstream end of the critical sector modelled).

For a predefined discharge that approximately fills the main channel of the Danube (to be determined later as a result of numerical flow simulations), water levels for the "Do-nothing" scenario and alternative scenarios will be compared. Although the measures are not expected to have a significant effect within this discharge domain, an increase in water levels will be positively evaluated—considering the ecological importance of periodic flooding—as an indicator of a slight increase in the frequency of flooding.

Near bank velocity ratio

The previous indicator indirectly relates to sediment input into floodplains through advection. To also account for sediment transport via dispersion, albeit indirectly, a new indicator is introduced.

Generally, the lateral sediment inflow is proportional to the transverse gradient of velocities (and depths) in the channel during high water (Figure 54). This means that the inflow of sediment from the main channel to the floodplains will be greater if the differences in velocities in the main channel and floodplains are larger (same is valid for depth ratio). If these velocity differences decrease—e.g., by constructing groynes that reduce the depth in vicinity of the banks— then the velocity gradients will also decrease, leading to an expected reduction in sediment inflow and, consequently, lower sedimentation in the floodplains (Instead of sediment being transported into the floodplains, it may settle in groyne fields, reducing the sediment that reaches the floodplain). Given that the project does not have complete data on the geometry of the floodplain, the impact of alternative solutions on lateral sediment exchange can only be assessed indirectly. Therefore, based on the results of hydraulic analyses, flow velocities (and depths) along the banks will be compared for conditions after the implementation of alternative solutions and for the reference state ("Do-nothing") at bankfull discharge (the flow corresponding to the state just before water overflows from the main channel).

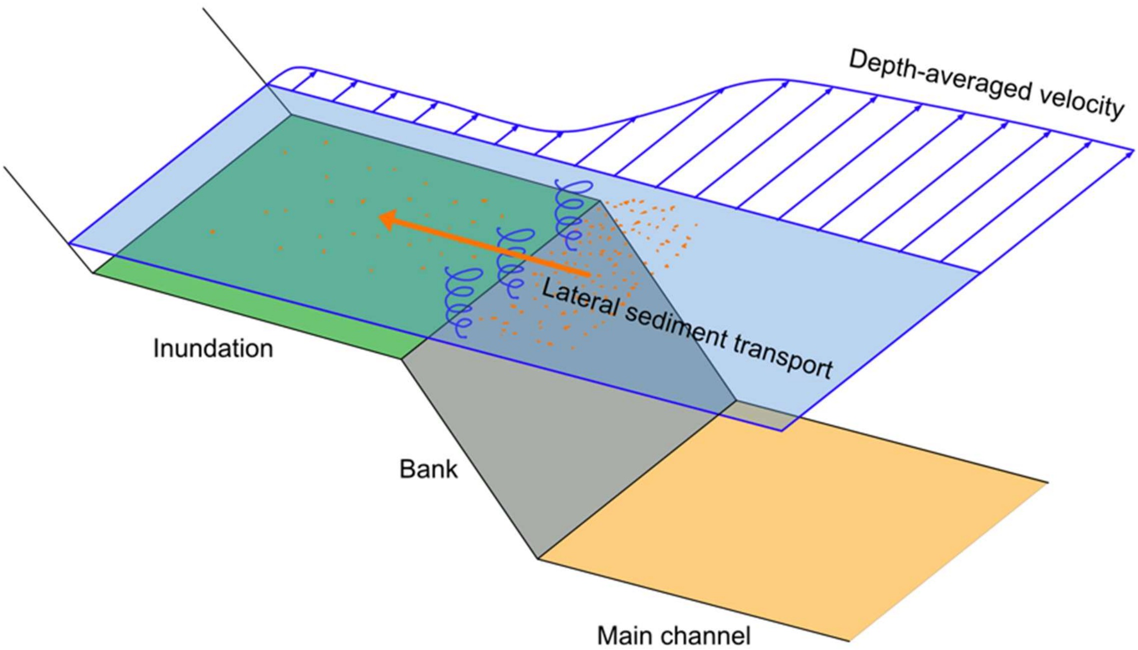


Figure 54: Lateral sediment exchange between main channel and floodplain

The length of the erodible bank ratio

An important aspect of lateral connectivity is the link between the main channel and the floodplains, which is expressed through river meandering. Since meandering can be modeled in the sediment transport simulation model to be used in the project, it will be assessed based on the length of the riverbank where meandering occurs in the numerical simulation. An increase in this length compared to the baseline scenario will be positively evaluated.

5.4.2.2. Physical naturalness of solution

Number of structures difference

As a specific indicator of the natural appearance of the riverbed, an additional indicator is introduced to evaluate the presence of river training structures. A reduction in the number of structures compared to the baseline scenario is positively assessed.

This indicator can also be linked to another aspect of the connectivity between floodplains and the main channel, manifested through aquatic-terrestrial fluxes that are not directly a result of flooding. River training structures may have a negative ecological impact by disrupting these fluxes (Figure 55).

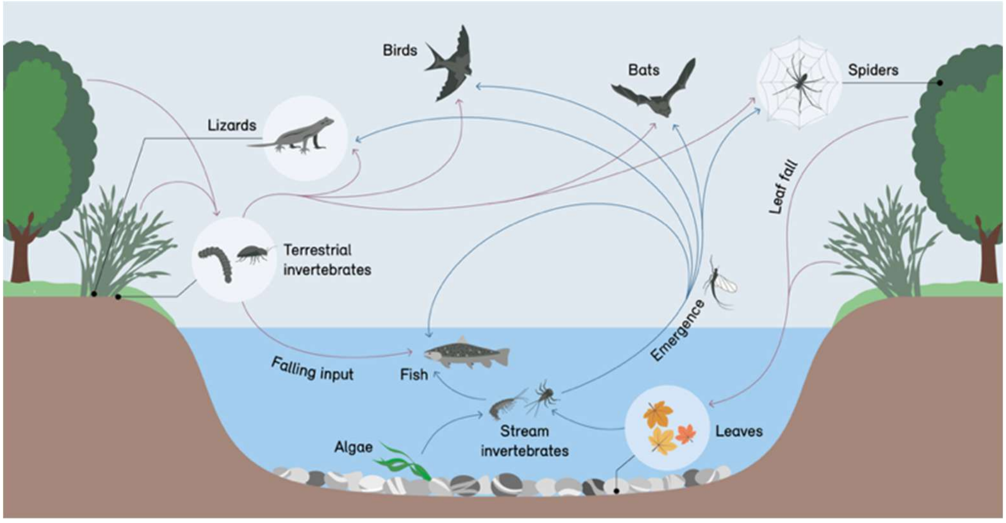


Figure 55: Illustration for aquatic-terrestrial fluxes (Baxter, Fausch and Saunders 2005)

Level of nature protection

This indicator complements the previous one as it considers the specificity of the area where interventions are proposed, i.e., it accounts for the change in the number of structures from the perspective of ecosystem protection. This means that the change in the number of structures will have a greater impact on the evaluation (positive or negative, depending on whether the number decreases or increases) if the area where the measures are proposed is designated as a zone of special significance from the perspective of nature protection.

5.4.2.3. Sediment and water quality indicators

Dredging volume

Dredging is a measure that is standardly applied as part of the maintenance of fairways. However, although this measure ensures the required dimensions of the fairway, it introduces certain ecological risks due to direct destruction of fish habitat areas or the mobilization of pollutants. Additionally, since the geometry of the flow is altered, the degree of implementation of this measure can have a greater or lesser (additional) impact on the sediment regime. In the MCA (Multi-Criteria Analysis), the necessity of including this measure in the solution (scenario) is negatively evaluated and removal from river system will be considered as unacceptable. The negative contribution to the score for the category "Sediment and water quality" will be assessed based on expert evaluation, considering the volume of material to be dredged.

Water quality parameters

The project does not include mathematical modeling of the impact of solutions on water quality parameters, but all aspects of water quality will be considered, and a qualitative assessment of this impact will be provided based on expert evaluation. In the assessment, other indicators used in the MCA (primarily hydro morphological) will be taken into account, as well as the characteristics of river training structures if they are part of the solution.

5.4.2.4. Bird population indicators

Considering both ecological indicators in bird population (nesting, wintering and foraging), negative effect of some hydro-morphological alterations can be manifested through the lack of connection of habitat with the surrounding environment. Some changes in river morphology can be characterized as positive, by establishment of shelters for certain bird species.

The scores for the impact of the solutions on the bird's population will be:

- the "do-nothing" scenario has the value 1;
- with improvement (expert judgment combined with quantitative data where available) the value increases from 1 to 2;
- any deterioration disqualifies the solution (the solution needs modification).

Nesting

During nesting, all bird species related to the Danube banks and floodplains, all representatives of the orders Anseriformes, Charadriformes, Ciciniformes, and from birds of prey the white-tailed eagle will be taken into account (Table 28).

Table 28: Selected bird species for MCA in terms of nesting

	Nesting
Waterfowls	Anseriformes (Aythya ferina, Aythya fuligula, Anas crecca, Tadorna tadorna, Branta leucopsis, Cygnus cygnus)
Cormorants	Suliformes fam. Phalacrocoracidae (Phalacrocorax carbo, Microcarbo pygmaeus)
Herons, storks and ibises	Ciconiformes fam. Ardeidae (Ardea cinere, Ardea alba, Arde purpurea, Ardeola ralloides, Nicticorax nicticorax, Ixobiychus minutus, Egretta garzetta, Botaurus stellaris), Ciconiidae (Ciconia nigra)
Wader	Charadriformes fam. Charadriidae
Rails	Gruiformes fam. Rallidae
Roller, bee-eater, kingfisher and sand martin	Coraciformes (Alcedo athis, Merops apiaster), Passeriformes (Riparia riparia)
Birds of prey	Falconiformes Accipitriformes (Haliaeetus albicilla, Milvus migrans)

Wintering

For the winter period, the impacts on the Anseriformes that live on the Danube and the white-tailed eagle will be analyzed (Table 29).

Table 29: Selected bird species for MCA in terms of wintering

	Wintering
Waterfowls	Anseriformes
Herons, storks and ibises	Ciconiformes fam. Ardeidae
Cormorants	Suliformes fam. Phalacrocoracidae
Rails	Gruiformes fam. Rallidae
Birds of prey	Accipitriformes (Haliaeetus albicilla)

Foraging

In addition to the nesting and wintering season, the Danube and surrounding floodplain areas represents an important feeding area for a large number of birds (up to 20,000), primarily waterfowls, during spring and autumn migration. This aspect will also be taken into account.

	Foraging
Waterfowls	Anseriformes
Herons, storks and ibises	Ciconiformes fam. Ardeidae, Ciconiidae, Threskiornithidae
Wader, gulls and sandpiper	Charadriformes fam. Charadriidae, Laridae, Scolopacidae,
Rails	Gruiformes fam. Rallidae
Birds of prey	Accipitriformes (Haliaeetus albicilla, Milvus migrans, Circus spp.)

5.4.2.5. Fish population indicators

The fish population was selected as a reliable environmental criterion for MCA and the conservation status was the criterion for selection and analyses. Regarding the fish population which is present in the investigated sector of the Danube the numbered ecological indicators in MCA analysis takes in account fish species with high categories in threat status (IUCN, 2023), (EU Habitat directive, Croatian and Serbian legislations) recorded in critical sector of the Danube (OIKON, Hidroing, VPB, 2024).

Recorded fish species in critical sector of the Danube are classified according to ecological characteristics (habitat preference, feeding habits, and living) into 3 groups: Rheophils, Litophils and Limnophils & phytophils (Table 30).

Rheophils – fish species best adapted for living in flowing water, in current of water;

Litophils – fish species adopted for living on a hard river bottom (ruffe, balon`s ruffe, sander, schrätzer, gobies;

Limnophils & phytophils – fish species best adopted for living in slow and stagnant water.

T The most sensitive ecological indicators are spawning, migration and wintering. Any hydrological alteration or construction will impact fish population. Some can be positive, having in mind the possibilities that solutions will make suitable and good environment for certain fish species, mostly rheophils (physical diversity, compensation). On the other hand, some construction may have negative impact, by destruction or disappearance of habitats that are suitable for spawning, wintering or migration.

The scores for the impact of the solutions on the fish population will be given in the same way as for birds:

- the "do-nothing" scenario has the value 1;
- with improvement (expert judgment) the value increases from 1 to 2;
- any deterioration disqualifies the solution (the solution needs modification).

Table 30: Selected fish species for MCA

Species name	Latin name	Status (IUCN)	Status (SRB)	Status (HR)	EU Habitat Directive
Asp (R)	*Aspius aspius*	LC	P	LC	Annex II, V
Common barbel (R)	*Barbus barbus*	LC	P	LC	Annex V
Balkan loach (L&Ph)	*Cobitis elongata*	LC	SP	VU	Annex II
Loach (L&Ph)	*Cobitis elongatoides*	LC	SP	VU	Annex II
Danube bleak (R)	*Alburnus sava*	LC	SP	LC	
Balon's ruffe (L)	*Gymnocephalus baloni*	LC	SP	VU	Annex II, IV
Schreaetzer (L)	*Gymnocephalus schraetser*	LC	P	CR	Annex II, V
Ide (L&Ph)	*Leuciscus idus*	LC	P	VU	
Common chub (R)	*Squalius cephalus*	LC	P	VU	
Cactus roach (R)	*Rutilus virgo*	LC	P	NT	Annex II, V

(Legend: (R) – rheophils; (Li) – lithophils; (L&Ph) - Limnophils & phytophils)

5.4.2.6. Flora indicators

The evaluation of the solution in terms of its impact on flora will be conducted primarily by assessing morphological changes in the riverbed, which will be estimated based on the results of 2D flow and sediment transport simulations. An expert assessment will be provided regarding the potential for creating new areas for distribution.

Registered species of the flora that will be analyzed along critical sectors are:

- 91E0* Alluvial forests - Alnus glutinosa and Fraxinus excelsior (Alno-Padion, Alnion incanae, Salicion albae) - Populus alba, Populus nigra, Salix alba, Rubus caesius, Carex elata, Carex remota, Carex riparia, Galium palust, Polygonum hydropiper, Rumex sanguineus;
- 3130 Oligotrophic to mesotrophic standing waters with vegetation - Lindernia dubia, Eleocharis acicularis, Cyperus michelianus, Lythrum portula;
- 3150 Natural eutrophic lakes with Hydrocharition or Magnopotamion type vegetation - Lemna spp., Spirodela polyrhiza, Utricularia vulgaris, Azolla filiculoides, Salvinia natans (emerged plants);

- 3270 Rivers with muddy banks - Bidens frondosa, Bidens tripartitus, Polygonum hydropiper, Potentilla supina.

The scores for the impact of the solutions on the flora will be given in the same manner as for fish and birds:

- the "do-nothing" scenario has the value 1;
- with improvement (creating new areas for distribution) the value increases from 1 to 2;
- any deterioration disqualifies the solution (the solution needs modification).

Listed habitat types NATURA 2000, with regard to its ecological characteristics, is a list of typical and indicator species that were recorded along the critical sections of the Danube. NATURA 2000 floodplains are sensitive to changes in the water level and the natural river hydro-morphological dynamics. The flora of the Natura 2000 habitat types was included in these analyses.

5.4.3. Feasibility criteria

The project considers the technical and economic feasibility of the solutions. In terms of technical aspects, the time needed for a solution to show its effects and the difficulty of implementing the measures are evaluated. For the economic feasibility of the project, the ratio of economic benefits to costs is considered. As with other criteria, the assessments are based on indicators through which alternative solutions are compared with the "Do-nothing" scenario.

5.4.3.1. Technical aspects

Construction of works

Within the technical aspects, the score will be further reduced for structural measures whose execution is complex (precise positioning of the structure, underwater construction, use of different types of materials (Consortium Witteveen Bos, 2013). If any structural solutions are complex in this regard, the score for that solution will be further reduced, meaning the scenario being considered will receive a score of 0.25 for the technical aspects.

Response time

The evaluation of measures cannot be based solely on their effects, as the time required for these effects to manifest (or be proven) can vary significantly and influence many indicators of project success. Therefore, in this project, measures are assessed according to this time factor. The highest score of 1.0 is given to the zero alternative and those non-structural measures that do not require complicated implementation procedures (e.g., fairway realignment). Structural measures require a series of steps, including the development of technical documentation and the construction of structures. An additional issue is the inability to predict the time after which river structures will show their effects (with uncertainty in estimating the effects themselves). Since this time is significantly longer for structural measures in any case, all scenarios involving such measures will receive a score no higher than 0.5 for the Technical aspects criterion group.

5.4.3.2. Financial aspects

Investment and maintenance costs/avoided users costs as benefit

The financial aspects of the alternative solutions will be compared with the financial indicators of the "Do-nothing" scenario. Through analysis of all alternative solutions, the difference between the benefits and the costs of the measures will be assessed. Benefits will be calculated as the avoided costs for fairway users due to the extended navigation period (if it is estimated to be extended) compared to the "Do-nothing" scenario. In this way, positive values of the benefit-cost difference will indicate solutions that are financially better than "Do-nothing," and such scenarios will be evaluated with a score of 1 or even 2. Conversely, scores between 0.25 and 1.0 may be given.

5.4.4. Climate change vulnerability

The impact of climate change on changes in the water and sediment regime is beyond the scope of the project, but the vulnerability of navigation and ecosystems to climate change will be qualitatively addressed, taking into account aspects of exposure (through the identification of affected categories), sensitivity and resilience across all scenarios, considering the vulnerability assessment of the "Do-nothing" scenario as the reference state. The sensitivity of the solutions to climate change will be evaluated based on the analysis of the sensitivity of the effects of the solutions to changes in hydrological inputs, while resilience will be assessed based on the potential for modifications to the solutions over time.

5.5. Numerical Example of MCA

The scenarios mentioned—"Do nothing," "Groyne system," and "Fairway realignment"—are **not preselected or definitive choices for the project**. Instead, they represent an initial framework or examples of potential scenarios to be assessed during the project's evaluation phase.

The project aims to comprehensively explore a range of options to address the objectives and challenges. These scenarios serve as examples to improve understanding of how MCA works. It is the starting point to frame the discussion and analysis, while ensuring that a variety of strategies are considered, including innovative or hybrid solutions. In this context, the **mentioned scenarios are merely illustrative**.

Scores for the criteria - Navigation

Scenario / Indicators - Subcriteria	"Do-nothing" (Reference values/state)	Groyne system (Indicators -> **Score**)	Fairway realignment (Explanation -> **Score**)
Water depth	ref. value: $\overline{H}$ = 2.45m *Comment: DC recommendation is not met*	*ratio* = 1.08 ($\overline{H}$ = 2.65m)	*ratio* = 1.04 ($\overline{H}$ = 2.55m)
Width	ref. value: $\overline{B}$ = 170m *Comment: DC recommendation is not met*	*ratio* = 1.10 ($\overline{B}$ = 187m)	*ratio* = 1.07 ($\overline{B}$ = 182m)
Curve radius	ref. value: $\overline{R}$ = 1300m	*ratio* = 1.00 ($\overline{R}$ = 1300m)	*ratio* = 0.95 ($\overline{R}$ = 1240m)
N_1 - Maximal DC Recommendations	**1.0**	**2.0**	**1.5**
Velocity	ref. value: $\overline{V_{max}}$ = 1.70m/s	*ratio* = 1.03 ($\overline{V_{max}}$ = 1.75m/s)	*ratio* = 1.00 ($\overline{V_{max}}$ = 1.70m/s)
Hindrance	ref. state: No sudden change in flow pattern	proj. state: No sudden change in flow pattern	proj. state: Moderate changes in flow pattern
N_2 - Maneuverability	**1.0**	**1.0**	**0.5**
Visibility of the structures	ref. state: There are four groynes on the sector with same crest level = DLNL + 1m	proj. state: Additional four groynes with crest level = DLNL + 1m (slightly increased risk of accidents)	New marking works will be conducted
N_3 - Safety	**1.0**	**0.5**	**1.5**

Environment

Scenario / Indicators - Sub criteria	"Do-nothing" (Reference values/state)	Groyne system on convex side of the bend (Indicators -> **Score**)	Fairway realignment (Explanation -> **Score**)
River bed volume	ref. value: $V = -88500m^3$	*diff.* = -7000m^3 ($V = -95500m^3$)	*diff.* = 0 ($V = -88500m^3$)
SHDi	ref. value: $SHDi = 0.78$	*ratio* = 0.96 ($SHDi = 0.75$) Negative impact on biodiversity (living organisms negatively affected including macroinvertebrate)	*ratio* = 1.0 ($SHDi = 0.78$)
Length of LF channels ref. value/ratio	ref. value: L_{lf} = 250m	*ratio* = 0.84 (L_{lf} = 210m)	*ratio* = 1.0 (L_{lf} = 250m)
$Z(Q_{bankfull})$	ref. value: Z = 90.00m.a.s.l.	*diff.* = 1cm (Z = 90.01m.a.s.l.)	diff. = 0m (Z = 90.00 m.a.s.l.)
Near bank velocity ratio	ref. value: V_b = 1.4m/s	*ratio* = 0.64 (V_b = 0.9m/s)	*ratio* = 1.0 (V_b = 1.4m/s)
Bank erosion length ratio	ref. value: L_{be} = 2050m	*ratio* = 0.95	*ratio* = 1.0 (L_{be} = 2050m)
E$_1$ - Hydro-morphology	**1.0**	**0.25**	**1.0**
Number of structures difference	ref. value: 10	difference = +4 (aquatic-terrestrial fluxes can be disturbed with all 4 structures)	difference = 0
Level of protection	ref. state	5-Country biosphere reserve	*no changes*
E$_2$ - Naturalness of solution	**1.0**	**0.25**	**1.0**
Dredging volume	n.a.	n.a.	n.a.
Water quality parameters	n.a.	slightly negative effects since local stagnant water introduced	*n.a.*
E$_3$ - Sediment and Water quality	**1.0**	**0.5**	**1.0**
Nesting	ref. state	no changes if groyne system is proposed along shallow banks / negative effect for steep banks	*no changes*
Wintering	ref. state	n.a.	*no changes*
Foraging	ref. state	n.a.	*no changes*

Scenario / Indicators - Sub criteria	"Do-nothing" (Reference values/state)	Groyne system on convex side of the bend (Indicators -> **Score**)	Fairway realignment (Explanation -> **Score**)
E_4 - Birds	1	**1 / 0**	**1**
Spawning	ref. state	n.a.	*no changes*
Migration	ref. state	n.a.	*no changes*
Growing	ref. state	sheltered	*no changes*
Living	ref. state	negative due to siltation	*no changes*
Wintering habitats	ref. state	n.a.	*no changes*
E_5 - Fish	**1.0**	**0.5**	**1.0**
Creation of new areas for distribution	ref. state	no significant change	*no changes*
E_6 - Flora	**1.0**	**1.0**	**1.0**

Feasibility

Scenario / Indicators - Subcriteria	"Do-nothing" (Reference values/state)	Groyne system (Indicators -> **Score**)	Fairway realignment (Explanation -> **Score**)
Response time ref. value/ratio	*no response time*	*long period*	*short period*
Execution of works	without execution works	moderate difficulty	improving marking system (simple implementation)
F_1 - Technical aspects	**1.0**	**0.25**	**1.0**
CBA ref. value/ratio	<0	*significantly higher B-C*	*higher B-C*
F_2 - Financial aspects	**1.0**	**2.0**	**1.5**

Climate change

Scenario / Indicators - Subcriteria	"Do-nothing" (Reference values/state)	Groyne system (Indicators -> **Score**)	Fairway realignment (Explanation -> **Score**)
Aspect of sensitivity	ref. state	*moderate sensitivity*	*no changes regarding reference state*
Aspect of resilience	ref. state	*moderate adaptivity*	*no changes regarding reference state*
C - Climate change vulnerability	**1.0**	**0.5**	**1.0**

Total score

	Group score for navigation	Group score for environment	Group score for feasibility	Group score for climate change	**Total Score**
"Do-nothing"	1.00	1.00	1.00	1.00	**1.00**
Groyne system	1.19	0.71	1.00	0.97	**0.81**
Fairway realignment	1.11	1.00	1.04	1.00	**1.16**

The solutions ranked by total score:

1. Fairway realignment
2. "Do-nothing"
3. Groyne system

5.6. Conclusions

The development of a transparent and balanced decision-making framework for improving navigation along the common Serbian–Croatian section of the Danube River reflects a proactive and methodological approach to inland waterway management. A multi-criteria analysis (MCA) is designed to identify the most suitable alternative scenarios for enhancing navigation conditions while adhering to environmental safeguards and feasibility constraints rooted in international, EU, and national regulatory obligations.

The classification of evaluation criteria into four distinct yet interrelated groups—navigation, environment, feasibility, and climate change vulnerability—ensures a holistic assessment of proposed interventions. Assigning equal weight (40%) to navigation and environmental criteria reinforces the project's dual commitment to maintaining transport functionality and ecological integrity. Simultaneously, the inclusion of feasibility (15%) and climate resilience (5%) criteria acknowledges the operational realities and forward-looking dimensions of infrastructure planning.

The application of the Weighted Product Model, with scenario scores benchmarked against a "Do-nothing" reference scenario, introduces a comparative structure. This enables decision-makers to evaluate the relative merits of each alternative not solely on technical outputs but on their alignment with long-term navigational goals, ecological improvement targets, and financial viability. The use of discrete scoring thresholds further enhances this comparability by clearly delineating acceptable performance baselines, eliminating solutions that underperform across critical domains.

By favoring navigation depth and hydro-morphology within their respective groups, the MCA structure ensures that pivotal physical and environmental parameters are appropriately emphasized without undermining the role of complementary indicators such as biodiversity, sediment quality, and implementation feasibility.

Importantly, the MCA framework promotes adaptive, goal-oriented planning. It recognizes the dynamic nature of river morphology and the need for continuous re-evaluation in response to hydrological, ecological, and climatic changes. The incorporation of climate change vulnerability as a dedicated criterion underscores the recognition that infrastructure planning must extend beyond present-day challenges toward future-proofing solutions for a changing river system.

Ultimately, this MCA-driven process does not merely prioritize a single "optimal" solution; it equips stakeholders with an understanding of synergies between competing objectives. The resulting study therefore provides not just a decision-making tool, but a platform for informed dialogue among river navigation managers, engineers, and ecological stakeholders across both countries.

CHAPTER 6. – DEFINITION OF BOTTLENECKS VARIANTS

6.1. Introduction

The chapter sets the foundation for a comprehensive re-evaluation of river training approaches on the common sector of the Danube River. By coupling traditional hydraulic techniques with modern, nature-inclusive designs, the proposed measures aim to enhance navigability while preserving the river's ecological integrity. The 2D hydraulic modelling plays a main role in quantifying the effects of the interventions, resolving uncertainties, and refining the risk analysis. A sufficient number of scenario-based model simulations were conducted to ensure that the proposed solutions attain a level of technical and analytical quality acceptable to all involved parties.

Proposed Measures and Modelling Approach

A range of structural intervention measures is introduced, including chevrons, sills, detached groynes, and sidearm channels. Each measure is conceptualized to stabilize the fairway and enhance the natural sediment dynamics and improve habitat connectivity along the river. These measures underwent detailed evaluation using advanced two-dimensional hydraulic modeling, designed to simulate the complex interactions between flow dynamics, sediment transport, and morphological evolution under the proposed scenarios.

Risk Analysis and Uncertainties

While comprehensive risk assessments depend on the outcomes of the forthcoming modeling results, the current preliminary analysis has identified several key areas of uncertainty that warrant further investigation:

- **Hydraulic and Sediment Transport Variability:** There is inherent uncertainty in forecasting how flow dynamics will adjust following the introduction of structural measures. Potential risks include unintended acceleration of currents, irregular sediment deposition, and localized erosion. Sensitivity analyses incorporated within the 2D hydrodynamic model will help isolate the parameters with the greatest influence on these responses;
- **Structural Performance Under Variable Conditions:** Although the proposed interventions are anticipated to improve navigability, their structural performance may be sensitive to extreme discharge events and future climate variability. These risks underscore the need for detailed model calibration and validation using historical flow and sediment data;
- **Ecological Impacts:** Although the proposed interventions are designed with ecological sustainability in mind—aiming to restore more natural flow conditions and enhance habitat diversity—there is still a risk of short-term disturbance during construction and potential long-term changes in habitat connectivity and quality. An adaptive monitoring program should be designed to verify that ecological impacts remain within acceptable limits and that mitigation measures are effective over time;
- **Implementation Uncertainties:** Given that the measures are still under the planning phase, factors such as construction feasibility, cost-effectiveness, and regulatory approvals also pose a degree of uncertainty. These aspects will be addressed in subsequent phases after the 2D modelling phase has provided a clear indication of expected outcomes.

6.2. Scope of the river training works analysis

As outlined in the preceding chapter, the priority navigation bottlenecks have been identified along the river stretch between rkm 1408.2 and rkm 1373.4 (refer to Table 31 and Figure 58 for detailed information).

Table 31 - Prioritized bottlenecks

No.	Sector	Chainage	Quantity of sediment within the fairway of 2.5m depth &			
		(from rkm to rkm)	Width 100m	Width 120m	Width 150m	Width 200m
3	**Apatin**	1,408.2 - 1,400.0	7,035.00	14,635.00	26,821.00	54,311.00
4	**Čivutski Rukavac**	1,397.2 - 1,389.0	343.00	1,494.00	8,164.00	52,977.00
5	**Drava Confluence**	1,388.8 - 1,382.0	-	441.00	4,221.00	22,013.00
7	**Staklar**	1,376.8 - 1,373.4	733.00	1,571.00	3,823.00	14,781.00

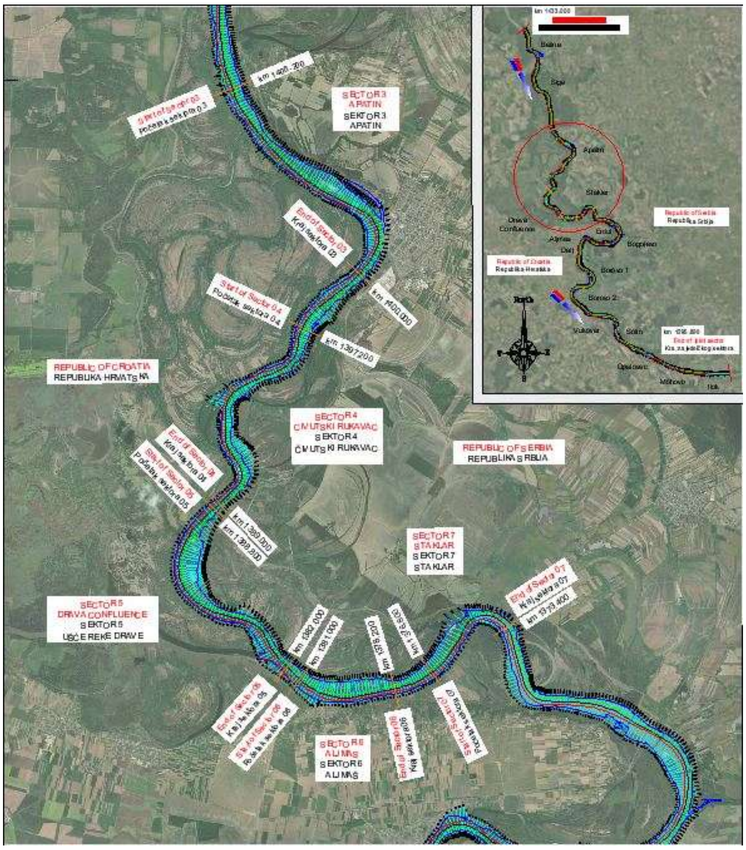


Figure 56 - The map of the common stretch, designated as a stretch with the priority bottlenecks

6.3. Importance of Environmental and Morphological Considerations

Particular attention is given to the following key aspects, which are considered critical to the definition of bottlenecks variants:

- Restoring and maintaining the required 200-meter fairway width;
- Minimizing ecological deterioration while addressing structural shortcomings;
- Incorporating nature-inclusive engineering solutions that balance navigational efficiency with habitat preservation.

This approach seeks to balance the objectives of enhanced navigation performance with the imperative to preserve environmental integrity:

- **Habitat Preservation:** Prioritize designs that maintain or restore natural habitats (e.g., fish spawning grounds, floodplain connectivity) to support biodiversity;
- **Sediment Dynamics:** Avoid over-stabilization; allow natural sediment transport to sustain geomorphological processes and reduce riverbed erosion which leads to the lowering of the water surface;
- **Soft Engineering:** To minimize ecological degradation, favor non-structural measures (e.g., bioengineering, fairway realignment, bedload management) over hard infrastructure.

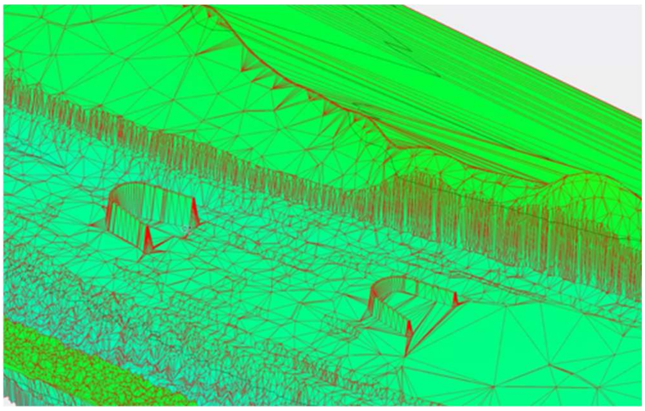
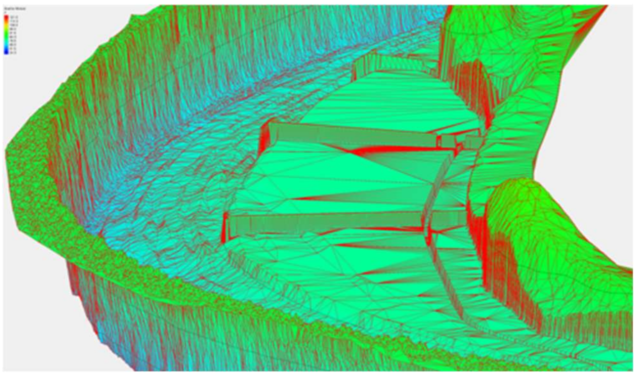
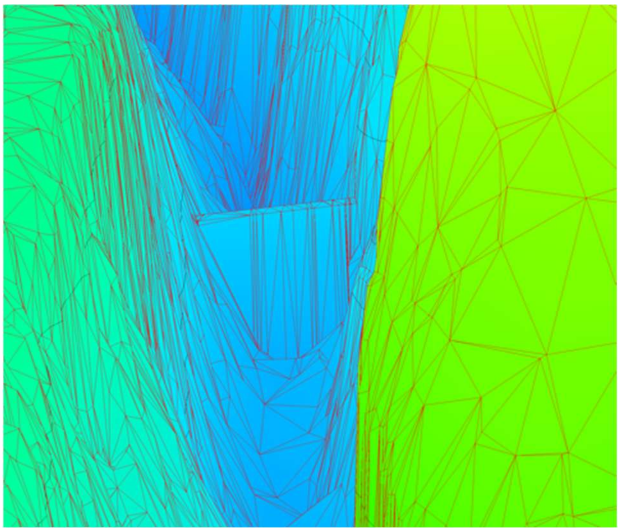
The collaborative approach and engagement of environmental experts ensures compliance with the EU Water Framework Directive (WFD) goals, the Habitat Directive and national regulations.

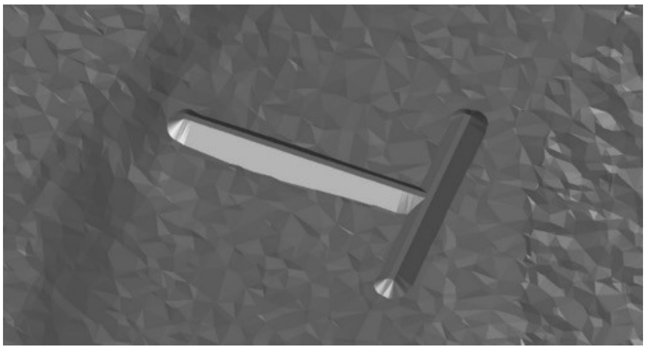
Equally, the proposed and analyzed solutions in the project are based on nature-inclusive solutions, presented in the next chapter.

6.4. Eco-friendly structural nature-inclusive solutions

One of the proposed scenarios emphasizes soft engineering measures that are not subject to direct numerical modeling. While some interventions are structural in nature, they integrate nature-based design principles aimed at enhancing ecological compatibility. Within this framework, the Consultant has explored a variety of environmentally sensitive structures, assessing their potential benefits and associated risks from both navigational and ecological standpoints, in close consultation with relevant stakeholders. A comprehensive overview of the eco-friendly structures considered during scenario development is presented in Table 32.

Table 32 - Breakdown of the structures used in the scenario development

Structure	3D presentation in model
Chevron	
Sidearm channel	
Submerged bottom sill	

Structure	3D presentation in model
Detached Groyne	

Nature-inclusive structures are engineered to simultaneously improve navigational parameters—particularly the definition and stability of fairway outlines—while supporting more sustainable ecological dynamics within the intervention zone. These interventions aim to integrate hydraulic functionality with ecological value, minimizing adverse impacts on river habitats and, where possible, fostering habitat enhancement.

A comparative analysis between traditional groynes and alternative chevron structures illustrates the ecological advantages associated with shifting toward softer, more adaptive design solutions. While conventional groynes are typically rigid transverse structures that constrict flow and induce sediment deposition, they can disrupt lateral connectivity and create local scouring. In contrast, chevrons, due to their angled and deflective geometry, tend to maintain navigability by redirecting flow energy while allowing partial throughflow that benefits habitat complexity. Their alignment can promote sediment sorting, reduce shear stress along sensitive banks, and support spawning grounds or benthic habitats.

This functional differentiation underscores the value of incorporating ecological design principles into navigation infrastructure, particularly in river stretches where habitat diversity and resilience are critical to meeting the obligations of the EU Water Framework Directive and other environmental legislation.

Chevrons offer significant navigational benefits. They stabilize fairway without creating abrupt flow disruptions, resulting in a safer and more predictable navigation environment compared to the turbulence induced by traditional groynes. Unlike groynes, which tend to accumulate debris and require frequent dredging, chevrons are less prone to blockage and siltation, thereby reducing maintenance costs.

Similarly, sidearm openings serve as an effective mitigation measure by diminishing erosion and sedimentation in the main riverbed near the channel. Additionally, sidearm channels enhance the river's capacity to erode downstream sediments, which benefits the overall channel stability and self-adjustment over long stretches. They also provide:

1. **Restoration of Natural Hydro-morphology** - Sidearms help restore a more natural multi-channel structure, improving overall river ecosystem health;
2. **Habitat Diversity & Refuge Creation** - They create low-flow zones that provide refuge for fish, amphibians, macroinvertebrates, and aquatic vegetation, especially during high-flow events;

3. **Improved Spawning and Nursery Habitats** - Sidearms often have shallower, calmer waters ideal for fish spawning and juvenile development;
4. **Enhanced Biodiversity** - The variety of flow conditions and sediment types supports a greater diversity of flora and fauna;
5. **Riparian Zone Revitalization -** Reconnecting floodplain features through sidearms supports riparian vegetation growth and wetland formation.

The observed common stretch of the Danube is characterized by a naturally narrow riverbed, which has been further constricted by existing hydro-technical structures. In sharply curved sections such as Apatin and Staklar, intensive erosion has deepened the channel to depths of 15–20 meters—an unusual condition for the Danube River. Consequently, the use of submerged sills has been evaluated, with consideration given to both their positive and adverse effects on the river ecosystem. The following details potential ecological benefits of the sills:

1. **Habitat Creation & Enhancement** - Submerged sills can create microhabitats (e.g., pools upstream and riffles downstream), enhancing aquatic species' habitat diversity. They often provide shelter and feeding grounds for fish, especially in low-flow conditions;
2. **Sediment Retention and Bed Stabilization** – The sills are helping in stabilizing or even enhancing the low water table, reducing riverbed incision, increasing shear stress on shallow areas close to the main channel, and better distribution of flow over the riverbed (navigation channel). By reducing flow velocities, sills help retain sediments, benefiting aquatic vegetation and benthic organisms. Stabilized beds mitigate the risk of habitat degradation caused by excessive erosion or sediment transport.

Sill's utilization also has certain drawbacks, reflected as a barriers to aquatic organisms, which may be the consequence of poorly designed sills, may hinder fish migration and movement of aquatic species, especially for weaker swimmers or during low-flow periods.

6.5. Methodology

The 136-kilometre area along the Danube, from km 1433 to km 1297, has been thoroughly examined to address navigational challenges while considering ecological sustainability as a key aspect. Divided into four sections, this common sector contains eight critical locations where the fairway fails to achieve the required 200m width at Low Navigation Water Level. These bottlenecks were analyzed using a comprehensive approach that balances navigational needs with environmental protection.

From a navigational standpoint, the document concentrates on the assessment of hydraulic conditions, fairway maintenance needs, and the evaluation of potential structural interventions, including groynes, chevrons, and sills. Dredging was considered solely as a secondary measure to address urgent navigational constraints, with primary emphasis placed on sustainable, long-term interventions. On the ecological front, the analysis drew upon prior environmental screening studies conducted by Croatian experts, placing particular focus on habitat conservation and the preservation of natural sediment transport dynamics.

Historical cross-sectional data (EP) were employed in the morphological analysis, while available DEMs served as the basis for both 1D and 2D modelling. The engineering assessment followed a three-stage process:

- **Review of Existing Conditions:** Using GIS mapping and conceptual analysis, we conducted a detailed examination of the current morphological state, including the impact of historical river structures and operational measures, e.g. dredging (even if the latter was not applied for many years);
- **Stakeholder Engagement:** The initial scenarios were presented and discussed in forums with stakeholders, where feedback was used to refine potential solutions;
- **Regulatory Coordination:** Finally, the relevant authorities in Serbia and Croatia discussed and approved the proposed measures, ensuring alignment with national and EU waterway and environmental policies.

6.6. Existing Conditions and Bottleneck Analysis

6.6.1. Identification of critical locations

The priority bottleneck sectors listed in Table 23 were analyzed using a Digital Elevation Model (DEM) developed for 1D modelling and data on Low Navigation Water Levels (LNWL) obtained from a hydrologic study. These data sets were integrated within GIS software to produce a 2D map, which is color-coded based on a 25-dm contour line. Areas where the riverbed is shallower than 25 dm are shown in dark blue, while deeper areas appear in light blue (Figure 57). Additionally, a 200-meter-wide navigational fairway—with a centerline and chainage marks at every 100 m—was overlaid on the map. The left side of the fairway is displayed in green and the right side in red.

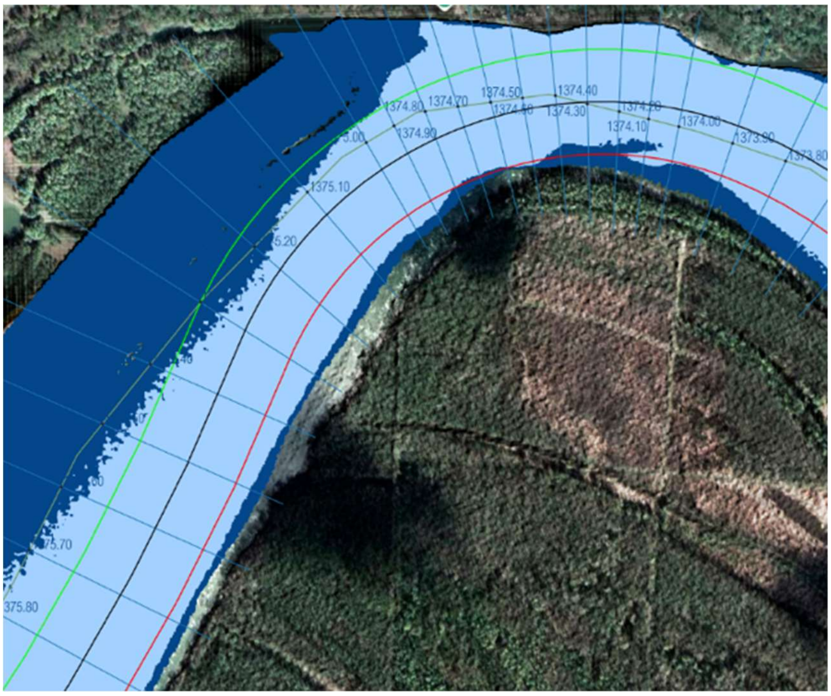
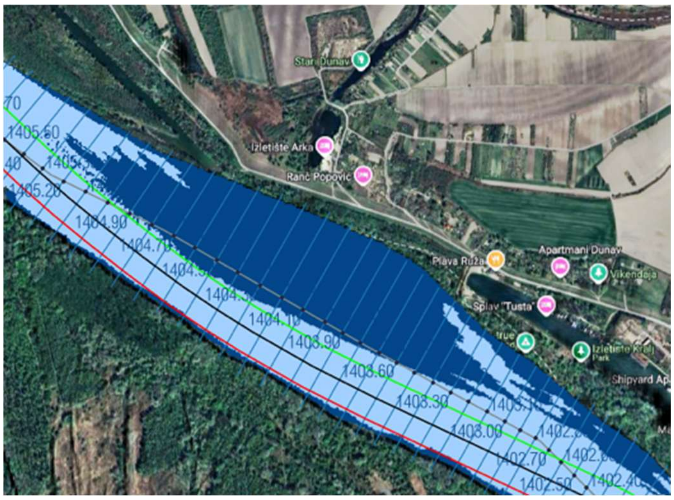
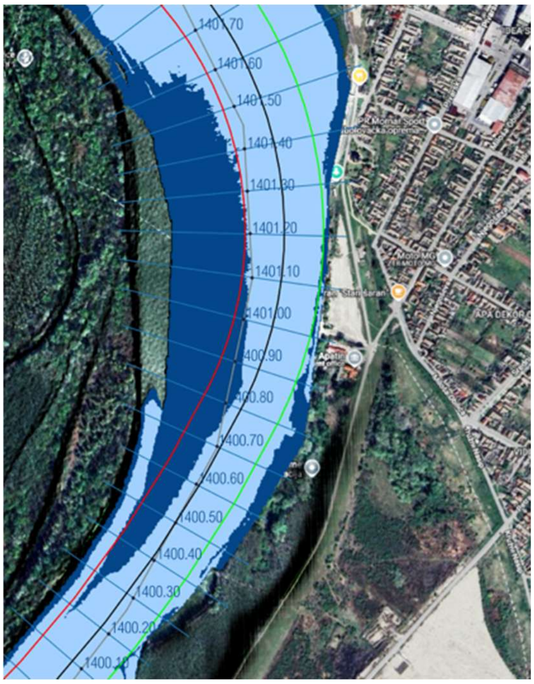


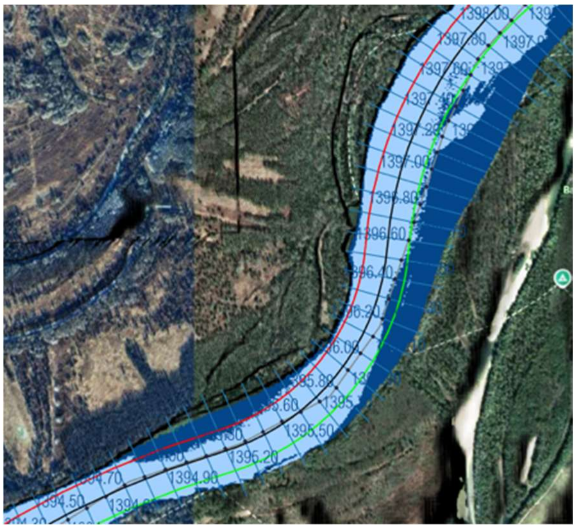
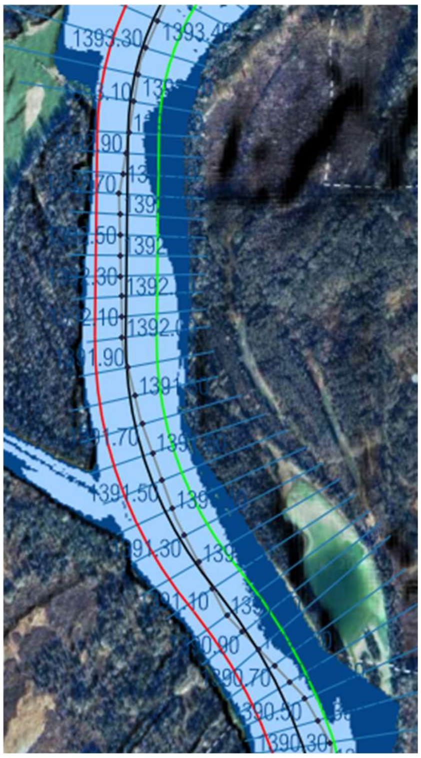
Figure 57 - An example of the map developed for the analysis of the critical locations along the section with priority bottlenecks

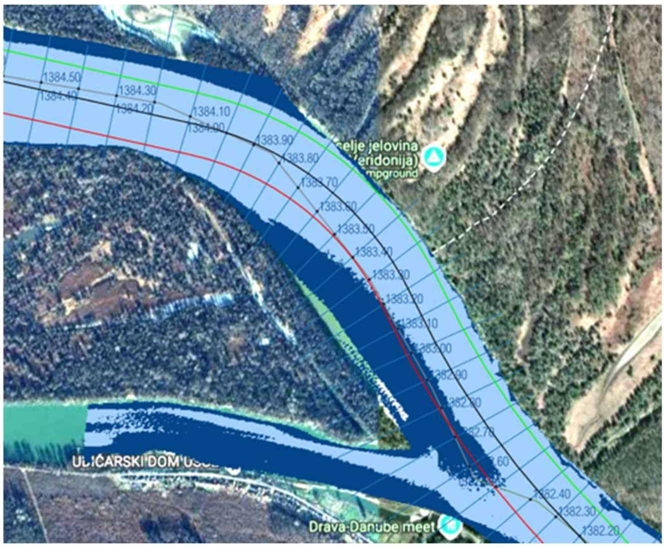
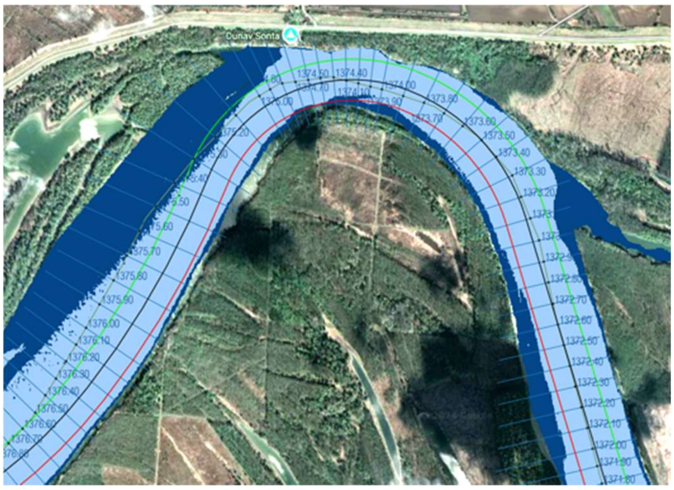
The locations where the fairway limits crosses the dark blue areas (areas shallower than 25dm) are pinpointed as "critical locations"; as such, they are comprehensively analyzed in the next chapter.

The list of the pinpointed critical locations is given in Table 33.

Table 33 - The list of identified locations

No.	Chainage	Sector	Map
1.	rkm 1405.4 - rkm 1403.0	Apatin	
2.	rkm 1401.7 - rkm 1400.2	Apatin	

No.	Chainage	Sector	Map
3.	rkm 1397.2 - rkm 1394.7	Čivutski / Židovski rukavac	
4.	rkm 1393.2 – rkm 1390.5	Čivutski / Židovski rukavac	

No.	Chainage	Sector	Map
5	**rkm 1383.7 – rkm 1382.3**	**Drava confluence**	
6	**rkm 1376.8 – rkm 1373.4**	**Staklar**	

6.6.2. Assessment of current issues (navigation, sedimentation, erosion, ecological impacts)

6.6.2.1. Apatin rkm 1,408.2 – 1,400.0 – Sector 3

As indicated in Table 33, the Apatin sector contains two critical locations. The first—located between km 1405.4 and km 1403.0—does not precisely fit the established criteria (the navigational fairway edge intersects the 25-dm contour). Nevertheless, this location has historically been a neuralgic point for navigation, and therefore, it is designated as critical. Figure 58 illustrates the historical development of cross-section EP27 at km 1403.5, corroborating the assertion of the area's inherent volatility. The critical sandbar was formed at the beginning of the 21st century in the middle of the river bed. At this time, the growing structure slowly shifted downstream and closed the entire cross-section. The navigation was temporarily redirected along the left riverbank with severe limits on available widths. The EP 27 shows the development of the observed sandbar, where it is notable that in 2021, a significant amount of sand reduced the cross-section area and split the water flow into two branches. The present position of the sandbar is favorable and it would be useful from the navigation perspective to remain there.

The Apatin sector has experienced relatively little structural intervention over time. Specifically, only four short groynes, constructed after 2000 on the Croatian side, are present (see Figure 58).

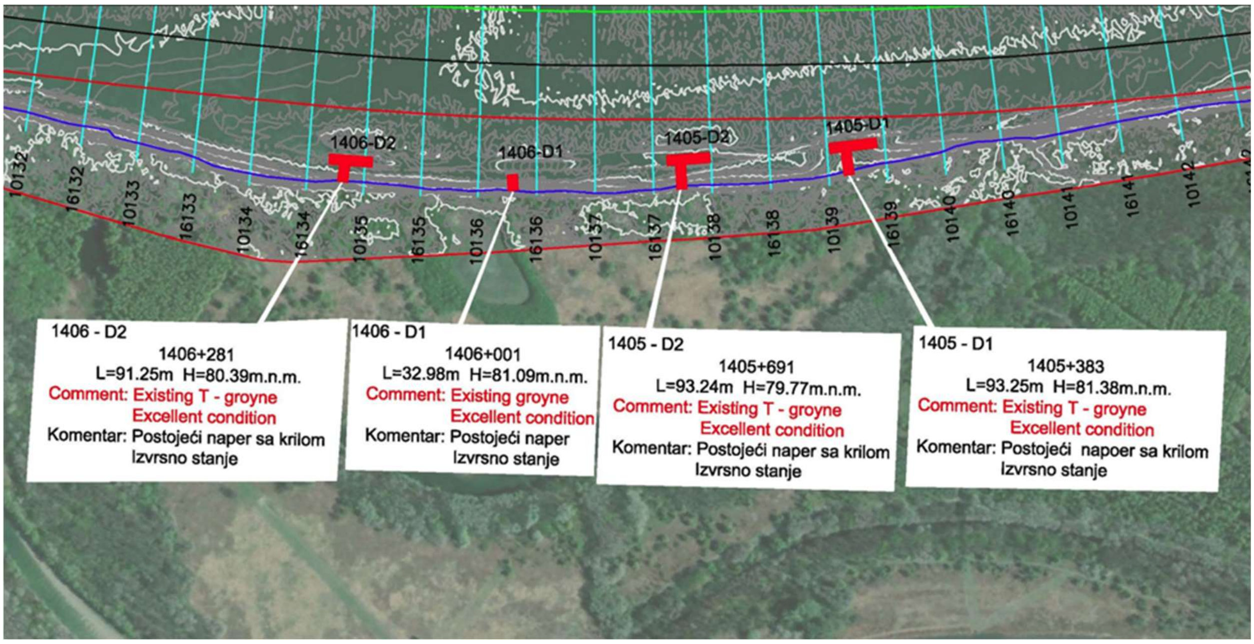


Figure 58 - The map of the existing t groynes on the Croatian side located between km 1406.281 and km 1405.383 with legend and condition

As indicated in Table 3, the Apatin sector contains two critical locations. The first—located between rkm 1405.4 and rkm 1403.0—does not exactly match the established criteria (since the navigational fairway edge intersects the 25-dm contour), yet it has historically been a neuralgic point for navigation. Accordingly, this location is designated as critical. Figure 4 illustrates the historical development of cross-section EP27 at rkm 1403.5, corroborating the area's inherent volatility.

Furthermore, the Apatin sector has experienced relatively few structural interventions over time; only four short groynes, constructed after 2000 on the Croatian side, are present (see Figure 58).

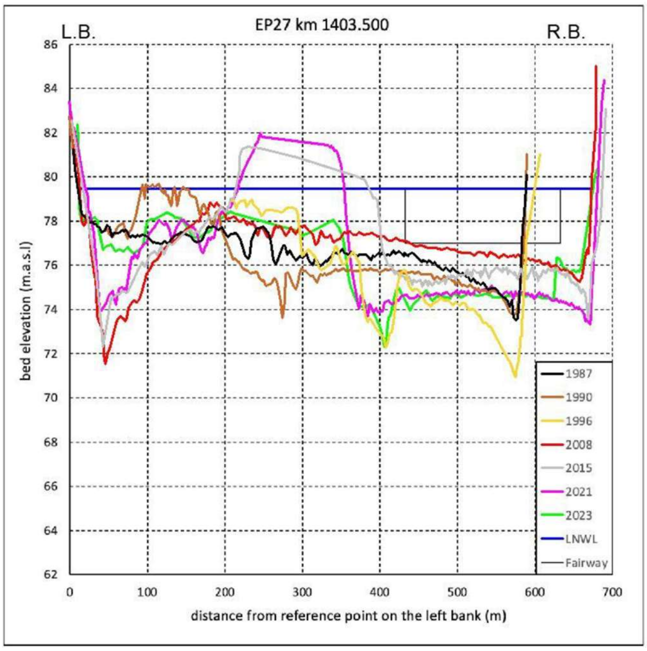


Figure 59 - EP 27, rkm 1403.5 – Volatile nature of the observed stretch and intensive riverbed alternations over time

In this case, the consultant faces a challenging task: to propose a solution that requires minimal intervention to correct the sandbar while minimizing ecological impact.

The second critical location, as noted in Table 33, is more straightforward since it represents the narrowest part of the fairway along the entire common stretch between Serbia and Croatia. Here, the available navigational outline is approximately 120 meters, located in a sharp bend that generates adverse turbulence due to the curved channel. The cross-section of this stretch exhibits a typical triangular shape, with the left riverbank composed of solid rock that remains stable over time. Consequently, secondary turbulences erode the riverbed, deepening it to between 15 and 20 meters relative to the LNWL. Simultaneously, helicoidal turbulence deposits the eroded material onto the concave right riverbank, further suppressing the fairway and impeding navigation. Figure 59, which presents a cross-section EP 32, clearly corroborates the morphological and flow analyses.

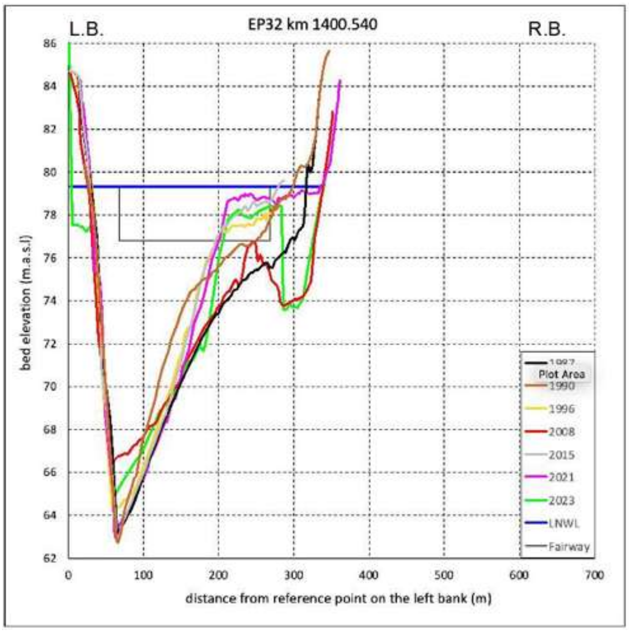


Figure 60 - EP 32, rkm 1400.540 – historical development, shows extreme depths along the left river bank and fixed position of the left riverbank over time

From an environmental perspective, the Apatin stretch lies within ecologically important and legally protected areas on both sides of the Danube. This includes the Serbian Gornje Podunavlje Special Nature Reserve and the Croatian Kopački Rit Nature Park, as well as the Mura-Drava-Danube Transboundary Biosphere Reserve and the Kopački Rit Natura 2000 site (HR2000394).

Species of conservation interest in this area include the white-tailed eagle (Haliaeetus albicilla), the black kite (Milvus migrans), the kingfisher (Alcedo atthis), and the sand martin (Riparia riparia). These species rely on the natural structure of riverbanks and riparian habitats for nesting and foraging. Although construction works and modifications to river morphology can temporarily alter local habitat conditions, careful planning and the implementation of mitigation measures—such as preserving key vegetation zones and scheduling works outside sensitive breeding periods—can help reduce disturbances and maintain ecological balance.

Figure 61 - Apatin sector and Natura 2000 protected zones

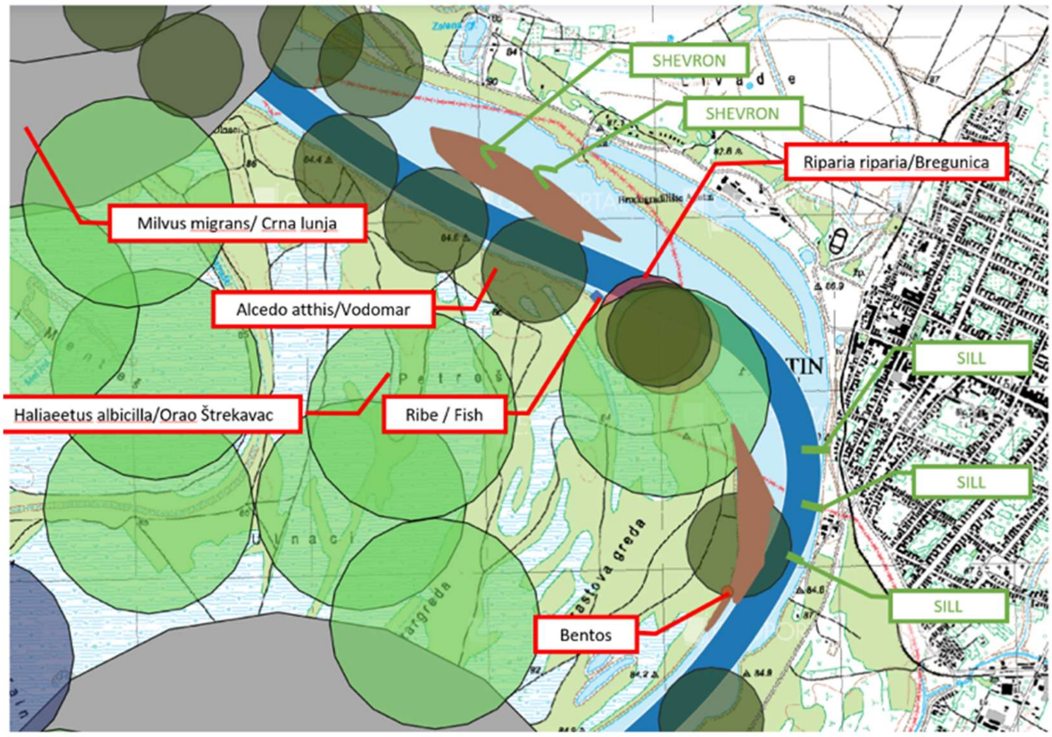


Figure 62 - Apatin - Screenshot of the GIS map with results of the environmental screening

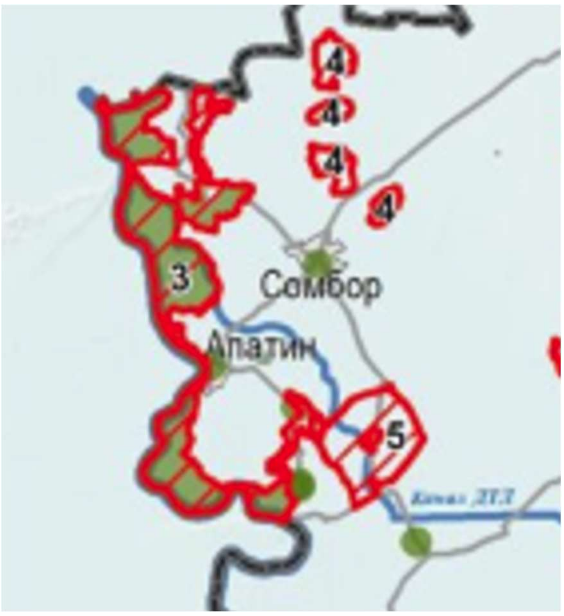


Figure 63 - Ecological Network map of the protected areas in Serbia

6.6.2.2. Čivutski/Židovski Rukavac (km 1397.2 – 1389.0) – Sector 4

Čivutski/Židovski Rukavac ranks second after Apatin in terms of the volume of material that must be removed to achieve the required fairway dimensions, according to the methodology employed for prioritizing critical sectors. Along this stretch, four distinct locations are identified as critical. Information from Croatian authorities indicates that the Čivutski Rukavac sector requires continuous monitoring and maintenance, as even small amounts of deposited material can disrupt navigation given this section's narrow configuration relative to other Danube segments.

Figure 64 illustrates how the morphology of this sector was analyzed using three available cross-sections with historical data.

Čivutski/Židovski Rukavac ranks second after Apatin regarding the volume of material that must be removed to achieve the required fairway dimensions (based on the methodology used for critical sector prioritization). Along this stretch, four different locations are marked as critical. According to the information from the Croatian authorities, Čivutski rukavac Sector permanently requires monitoring and maintenance. The map shows that the stretch is very narrow compared to other stretches on the Danube, and small deposited amounts may cause navigation issues.

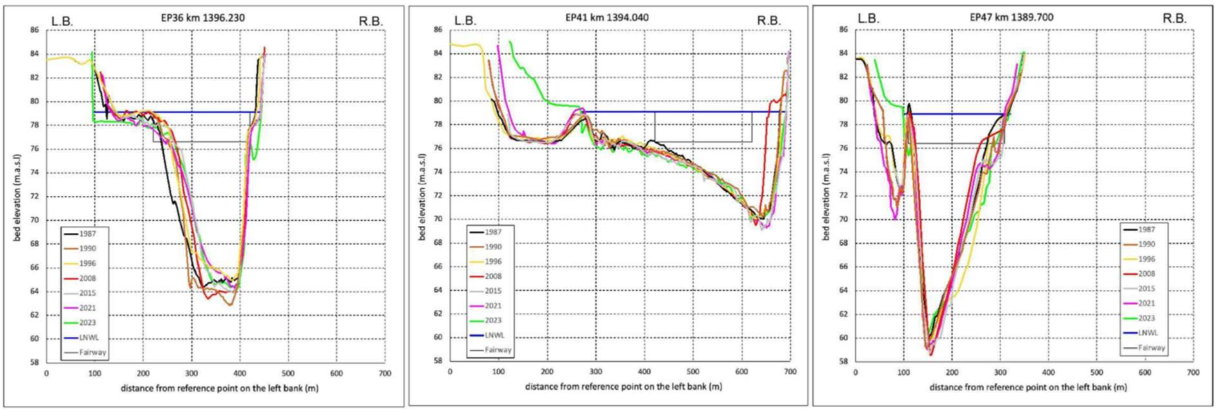


Figure 64 -EP 36 km 1396.230, EP 41 km 1394.040 and EP 47 km 1389.700 - The chronology of changes in the representative cross-sections

The conclusions which flow out of the morphological analysis are showing that:

1. The cross-section has remained stable over time. The riverbed width and depth at this location are fixed, with no indications for significant future changes.
2. The riverbed is relatively narrow (in some sections, as little as 200m), but this is compensated by depths reaching 20m, likely due to convenient geological conditions.
3. Bottlenecks and sand deposits have formed in areas where previous river training works were implemented. Two possible explanations for this behavior are:
    a. The designed fairway width may have been miscalculated, leading to material deposition in already narrowed sections.
    b. The river carries large amounts of sediment, so any discontinuity creates bedload deposition and sedimentation conditions.

These conclusions should be carefully considered during the design of structural measures.

Figure 65 - The contractions in the Čivutski / Židovski rukavac sector on km 1394.6 and 1389.5

Additionally, natural contractions are observed downstream of the identified bottlenecks. The first contraction occurs at rkm 1394.6, where the riverbed narrows to 200 m, while the second contraction, at rkm 1389.7, is even more pronounced, with a width of less than 200 m. These constrictions produce a local backwater effect that slows the water current and promotes sediment deposition (see Figure 65).

Historically, the Čivutski/Židovski Rukavac stretch has been critical for navigation. This is evidenced by the multiple existing training structures in the sector. Figure 66 clearly shows the location of these structures as detailed in Table 34.

Table 34 - Čivutski/Židovski Rukavac - The list of the existing structures on a Right and Left riverbank

Republic of Serbia – Left Riverbank					Republic of Croatia – Right Riverbank				
No.	Station (rkm)	Object type	Length (m)	Label	Station	Object type	Length (m)	Height (m.a.s.l.)	Label
13	1396+720	Groyne	115.44	\					
14	1395+420	Sills	153.7	\					
15	1395+300	Sills	81.64	\					
16					1393+691	Sills	72.97	80.09	1393-D2
17					1393+117	Sills	262.05	79.2	1393-D1
18	1389+880	Groyne	153.7	\					
19	1389+810	Groyne	81.64	\					
20	1389+525	Groyne	150.33	\					

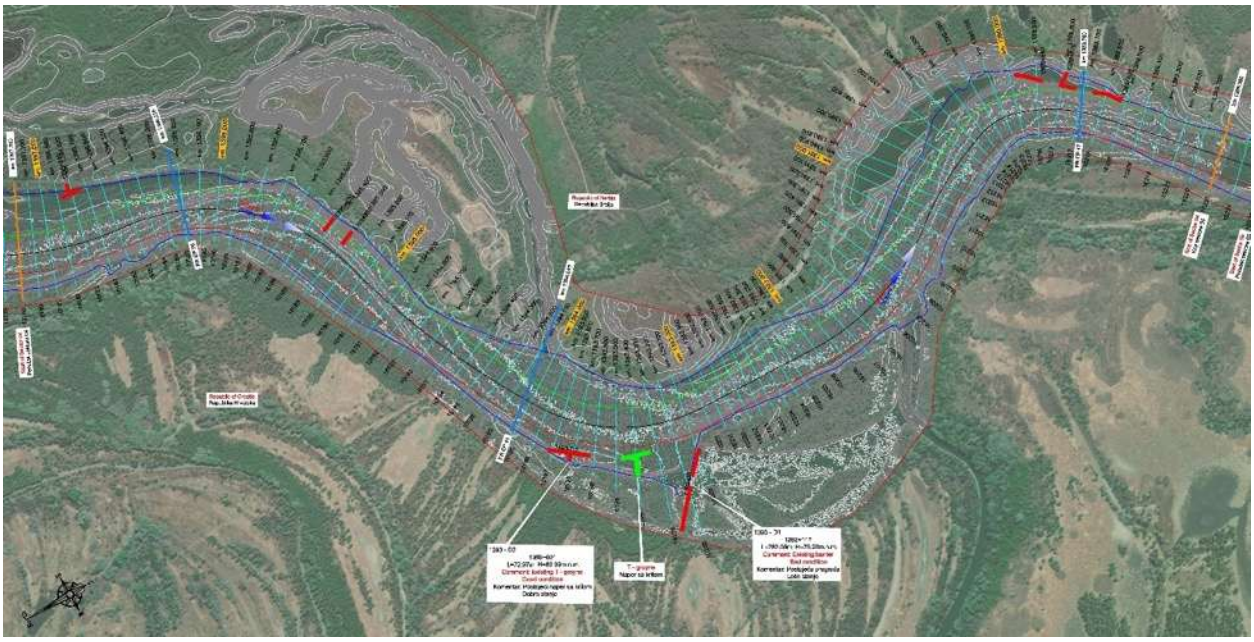


Figure 66 - ČIVUTSKI/ŽIDOVSKI RUKAVAC – map of the sector with locations of the existing structures (red color)

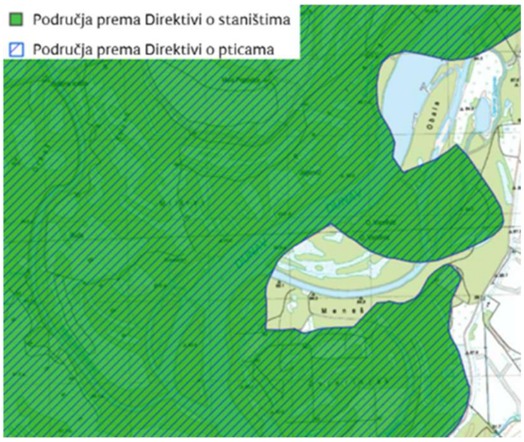


Figure 67 - Čivutski/Židovski rukavac - Natura 2000 protected zones

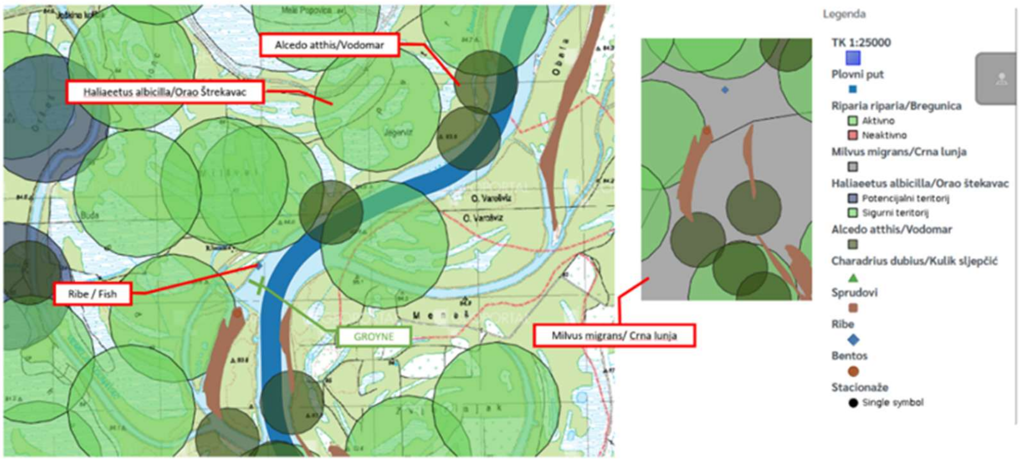


Figure 68 - Čivutski/Židovski rukavac Screenshot of the GIS map with results of the environmental screening

The sector Čivutski/Židovski Rukavac river sector is in the nature-protected areas. On the Serbian side- the protected area is Gornje Podunavlje Special Nature Reserve, and on the Croatian side is - Kopački Rit Nature Park, as well as the Mura-Drava-Danube Biosphere Reserve and the Kopački rit Natura 2000 site (HR2000394), (Figure 67 and Figure 68).

6.6.2.3. Drava Confluence (rkm 1388.8 – 1382.0) – Sector 5

The Drava confluence is a typical river confluence where two significant water flows meet, creating complex hydraulic conditions. One of the key effects observed in this area is the backwater effect, which slows the flow and leads to intensive bedload deposition in zones of reduced velocity.

There are two cross-sections with a historic array of surveys for the morphological analysis. One cross-section EP 52, rkm 1383.700 is upstream of the confluence, and the second EP 55 rkm 1382.190 is downstream (Figure 69).

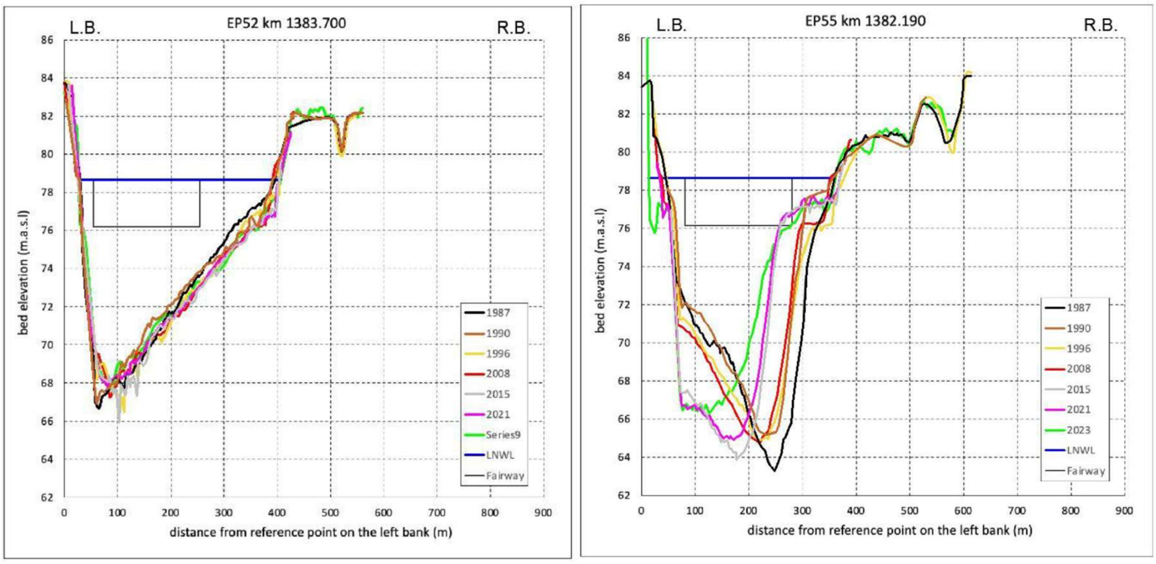


Figure 69 - EP 52 rkm 1383.700 and EP 55 1382.190 - The chronology of changes

Deposited material suppresses the navigational fairway, and variations in the Danube and Drava discharges cause the sandbar to change its shape, thereby affecting navigation. Cross-section EP 52 demonstrates a high degree of stability over time, while EP 55 shows notable instability in the riverbed area, although the riverbanks remain stable and fixed. The list of activities related to the training works is provided in Table 35.

Table 35 - Drava Confluence - The list of the existing structures on a left and right riverbank

Republic of Serbia – Left Riverbank					Republic of Croatia – Right Riverbank				
No.	Station (rkm)	Object type	Length (m)	Label	Station	Object type	Length (m)	Height (m.a.s.l.)	Label
21	1388+640	Groyne	123.1	\					
22	1388+325	Groyne	63.37	\					
23	1387+910	Groyne	98.46	\					
					1382+557	Groyne	37.06	80.03	1382-D2

As shown in Table 36, the recorded activities in the past were not related to the confluence but to the upstream sector. The stability of EP 52 demonstrates that the upstream groynes at rkm 1388 have successfully stabilized the riverbed. The location of the structures in the sector Drava confluence is shown in Figure 70 in red.

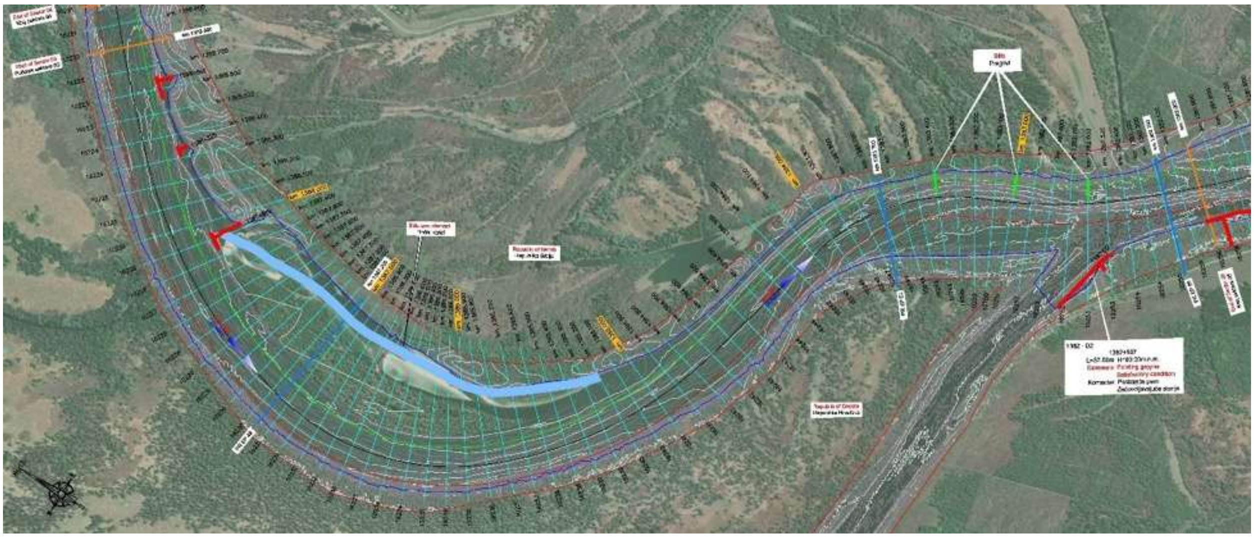


Figure 70 - Drava Confluence Map with existing training structures (red color)

The sites proposed for intervention are located within protected areas (Figure 71 and Figure 72) in both Serbia and Croatia, including the Gornje Podunavlje Special Nature Reserve, the Kopački Rit Nature Park, the Mura-Drava-Danube Transboundary Biosphere Reserve and the Natura 2000 site Dunav_Vukovar (HR2000372).

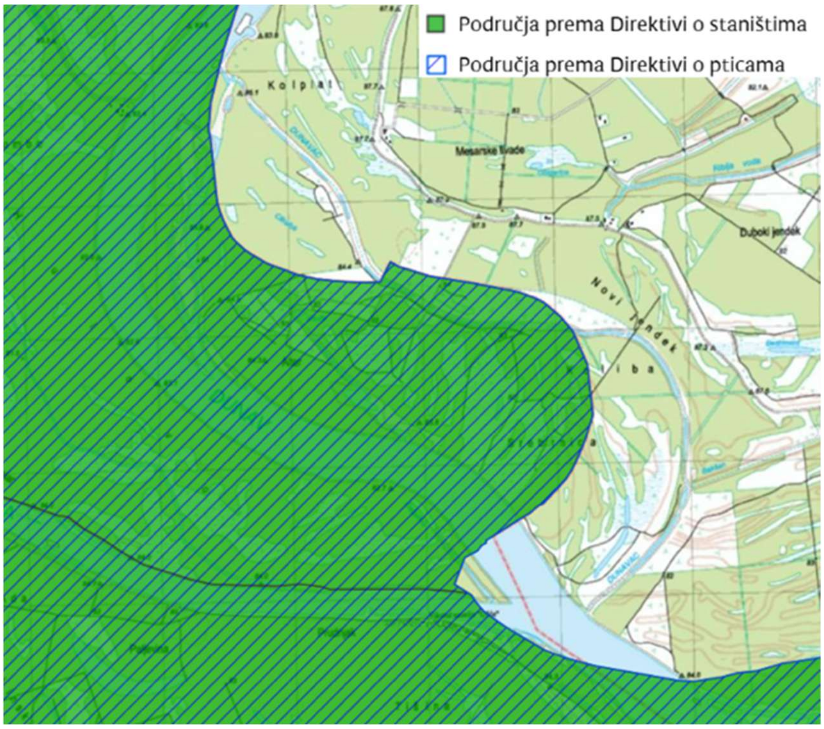


Figure 71 -Drava Confluence - Natura 2000 protected zones

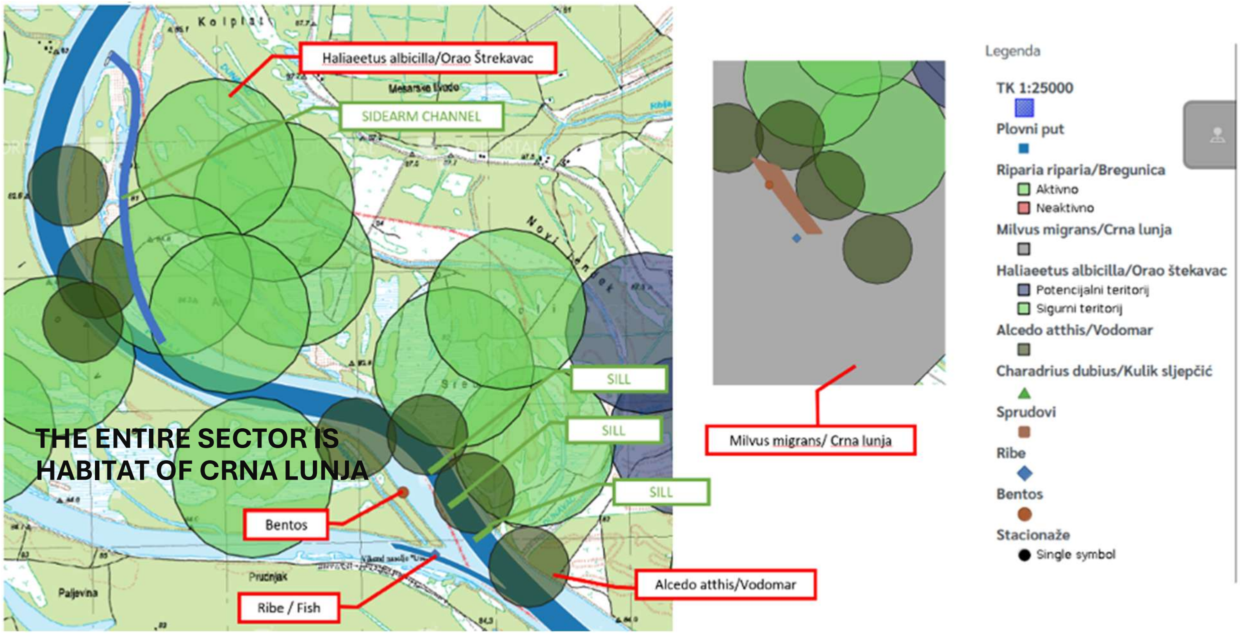


Figure 72 -Drava Confluence - Screenshot of the GIS map with results of the environmental screening

6.6.2.4. Staklar rkm 1376.8 to 1373.4 – Sector 6

Staklar is a sector characterized by a long, sharp curve. A navigation bottleneck occurs at the sector entrance, where a large sandbar has formed, restricting the fairway width and impacting navigation safety. The cross-sections in Figure 73 show the unstable nature of the riverbed geometry in the zone before the deflection and the stable riverbed after.

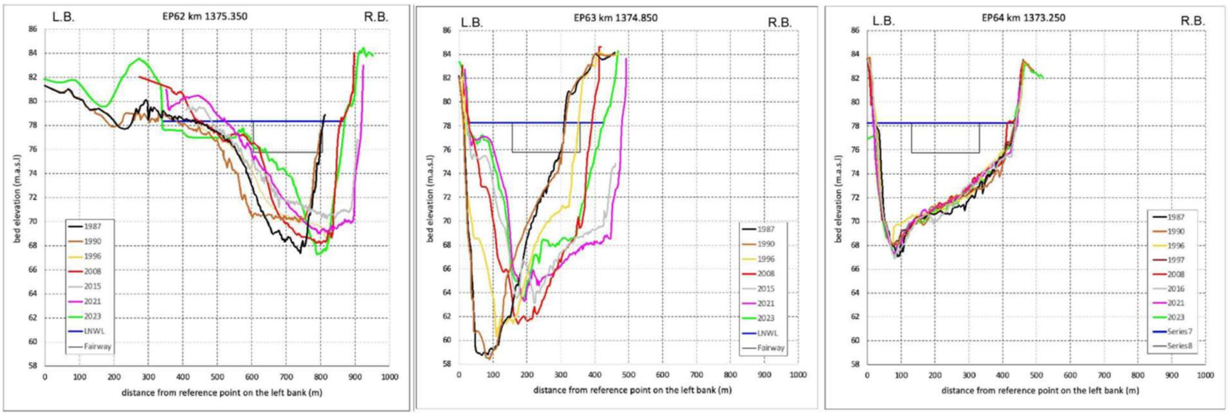


Figure 73 - EP 62 rkm 1375.350, EP 63 Km 1374.850 and EP 64 rkm 1373.250

The analysis of historical river structures (Table 36) and cross-section development confirms that the implemented sills have significantly contributed to downstream stability, effectively securing the riverbed over time. This positive impact serves as a foundation for the bottleneck resolving strategy.

Table 36 - Staklar - The list of the existing structures on a Right and Left riverbank

Republic of Serbia – Left Riverbank					Republic of Croatia – Right Riverbank				
No.	Station (rkm)	Object type	Length (m)	Label	Station	Object type	Length (m)	Height (m.a.s.l.)	Label
34	1374+200	Sills	70.50/63.8	73.0/66.0					
35	1373+980	Sills	46.50	65.5					
36	1373+890	Sills	56.00	66.0					
37	1373+790	Sills	34.50	65.0					
38	1373+700	Sills	46.5/18	73.0/64.0					

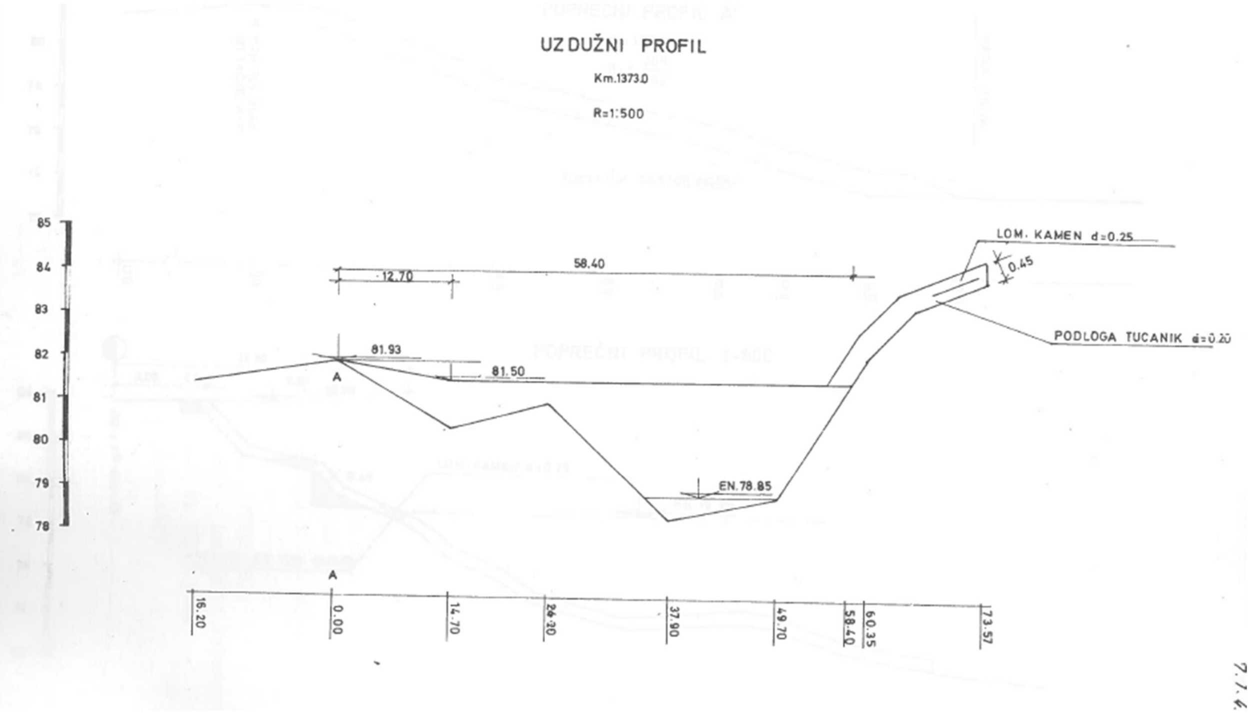


Figure 74 - Longitudinal cross-section of the submerged sill on the Staklar sector

The location of the sills is given on the sector map – Figure 75.

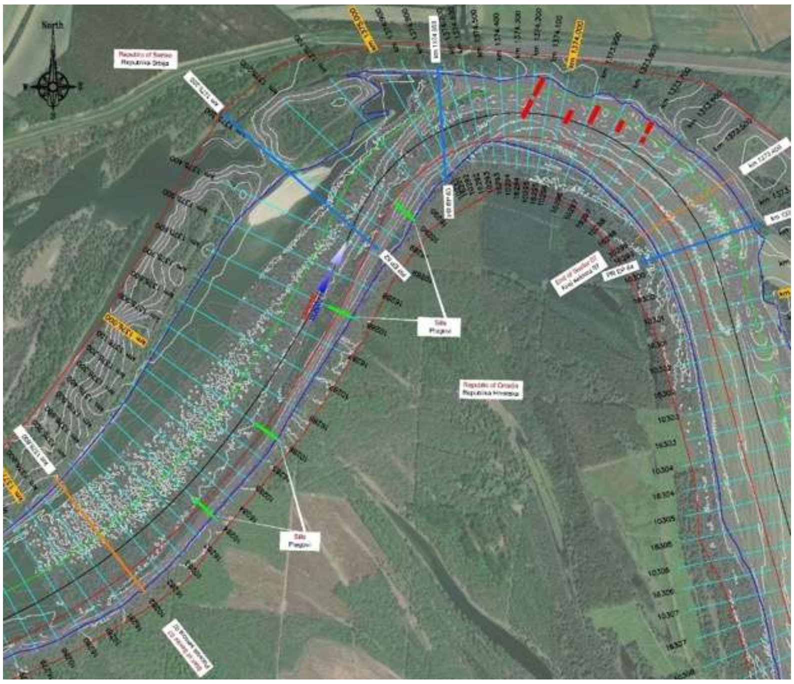


Figure 75 - Staklar – map of the sector with location of the sills

The site proposed for the structural measures is located within protected areas in Serbia and Croatia (Figure 76 and Figure 77), including the Gornje Podunavlje Special Nature Reserve and the Natura 2000 site Dunav_Vukovar (HR2000372).

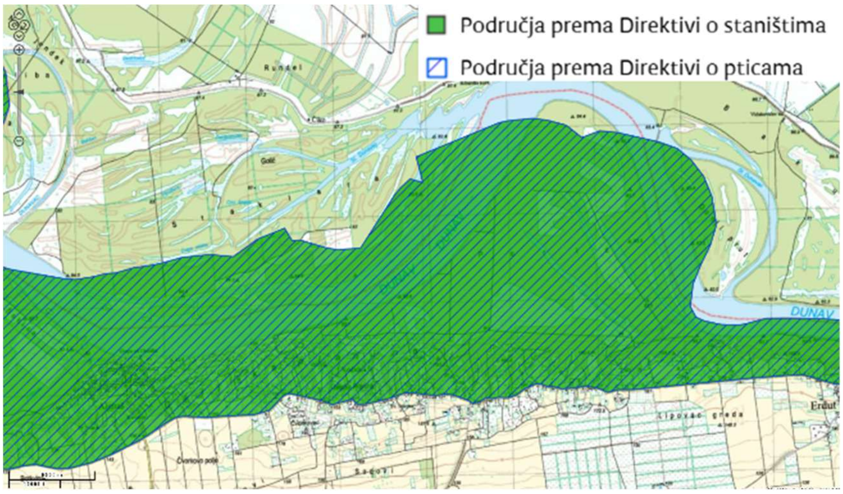


Figure 76 - Staklar – Natura 2000 protected zones

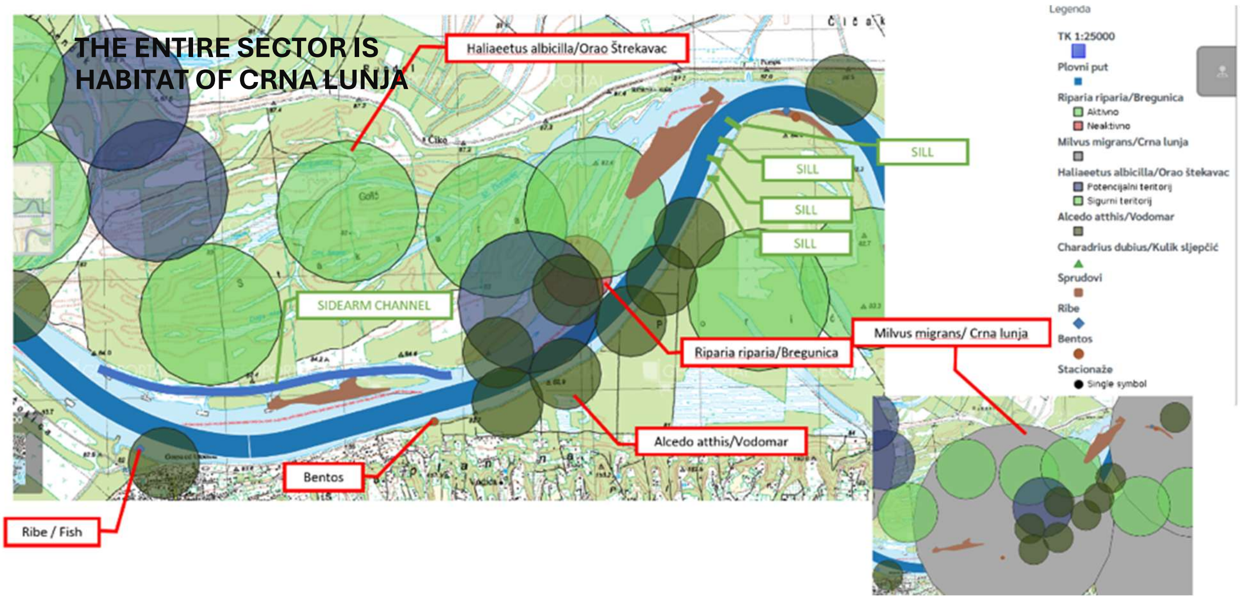


Figure 77 - Staklar - Screenshot of the GIS map with results of the environmental screening

6.7. Proposed River Training Structures and Solutions

6.7.1. Description of suitable structures and solutions per location

6.7.1.1. Apatin rkm 1,408.2 – 1,400.0 – Sector 3

As detailed in a previous chapter, the Apatin sector presents two critical locations. The first features a restless, permanently active sandbar that periodically disrupts navigation. The second is a highly narrow stretch along the river band, characterized by a sandbar forming along the concave right riverbank. Both locations lie within sensitive, nature-protected areas and require carefully selected measures to improve flow conditions and sediment transportation, while minimizing adverse impacts on the natural environment.

Chapter 1.4 elaborates on the importance and distinctions between traditional and contemporary river training approaches. It also highlights the positive and adverse impacts of the nature-inclusive structures under consideration. Accordingly, the consultant presents a balanced assessment of the chosen measures, outlining their respective pros and cons regarding navigation and environmental performance.

For the sandbar between km 1405.4 and km 1403.0, the proposed structural intervention comprises a combination of two chevrons placed on the sandbar (see Figure 78). This nature-inclusive approach is favored over traditional groynes, which are typically used in such situations.

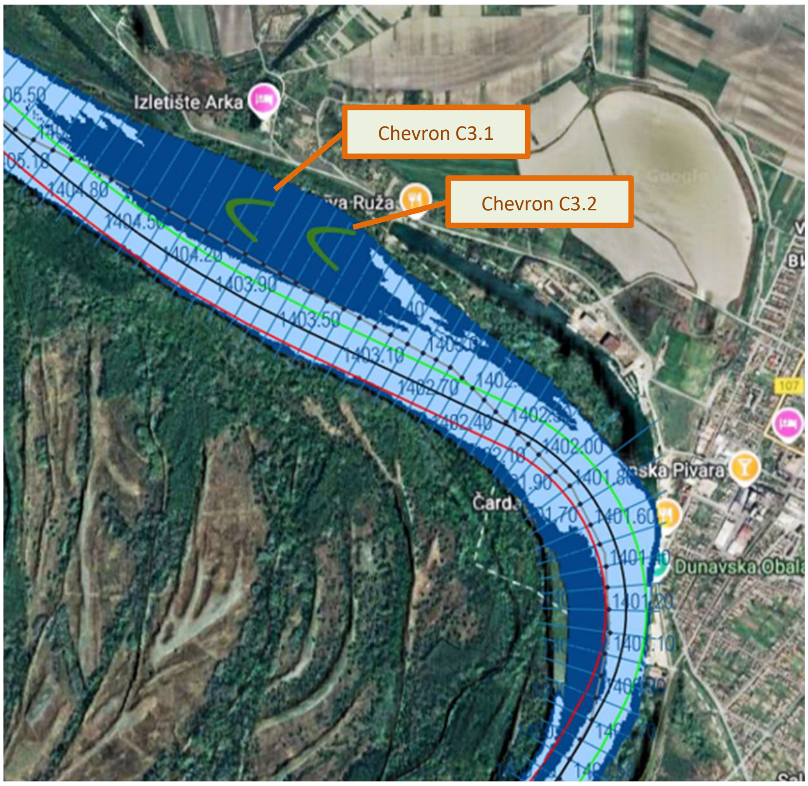


Figure 78 - Apatin rkm 1405.4 and rkm 1403.0 combination of two chevrons envisaged for stabilization of the sandbar and improvement of navigational conditions

The chevron is a relatively new river training structure on the Danube. Over the past ten years, several chevrons have been constructed on the Serbian stretch of the river; however, comprehensive studies evaluating their long-term efficiency and impact remain limited.

One of the most notable chevron structures was built near Futog between 2018 and 2019. Figure 79 presents a satellite view of this chevron, highlighting its layout and seamless integration into the river system.

Figure 79 - Chevron top view constructed in sector Futog, Serbia

Despite limited historical data, chevrons are emerging as a promising alternative thanks to their ability to:

- Influence flow patterns, thereby enhancing navigation conditions;
- Promote beneficial sediment deposition behind the structure;
- Reduce environmental impacts compared to traditional groynes.

Further monitoring and detailed modelling efforts will be essential to quantify their effectiveness and optimize their design and implementation in future river training projects.

The second critical location on the Apatin stretch is a sandbar positioned along the right riverbank. This sandbar, known as a Bentos zone, plays a crucial role for the microflora, fauna, and other organisms inhabiting the riverbed. To eliminate bottlenecks and ensure a stable fairway in this area, structural measures have been proposed. While dredging might provide optimal navigational conditions, it would significantly harm the benthic habitat. Therefore, the solution consists of installing a series of sills along the thalweg (the line of maximum depths) to facilitate sandbar transformation and widen the navigation channel (Figure *80*) illustrates the analysed positions for the three sills' disposition. In addition to the variant with three sills, a variant with two sills was also modeled, which was adopted (two structures on the right in Figure *81*) because, in terms of channel alterations, there was no significant difference, omitting the most upstream of the three shown in Figure *80*. Also, in addition to varying the number of sills, different sill heights were considered. As with the number of sills, the minimum height (7 meters) that resulted in significant deepening of the riverbed in critical zones was adopted.

The dredging route, if deemed necessary later, will be determined after the sills have been in place for at least six months, allowing sufficient time to assess their impact. Given the sandbar's vulnerability and the sensitivity of the entire stretch, these measures must be carefully planned in collaboration with environmental experts.

In addition to river training structures for addressing navigation issues in the Apatin sector, the project also analyzed the possibility of altering the fairway position. The proposed solution is to relocate the fairway in the critical sections from km 1408.200 – 1407.300 and from km 1404.600 – 1402.500. At the upstream most point of this sector, the fairway alignment has undergone moderate modifications (Figure *82*). The original curvature radius was 4450 meters, with the length of the curve segment being L = 1362.5 meters. After realignment, the radius has been reduced to 2600 meters, and the length of the curve segment is now 1373.8 meters. In the middle of this sector, the fairway alignment has undergone minor modifications (Figure *83*). The original curvature radius was 9010 meters, with the length of the curve segment being L = 1921.3 meters. After realignment, the radius increased to 9150 meters, while the length of the curve segment became 1920.7 meters.

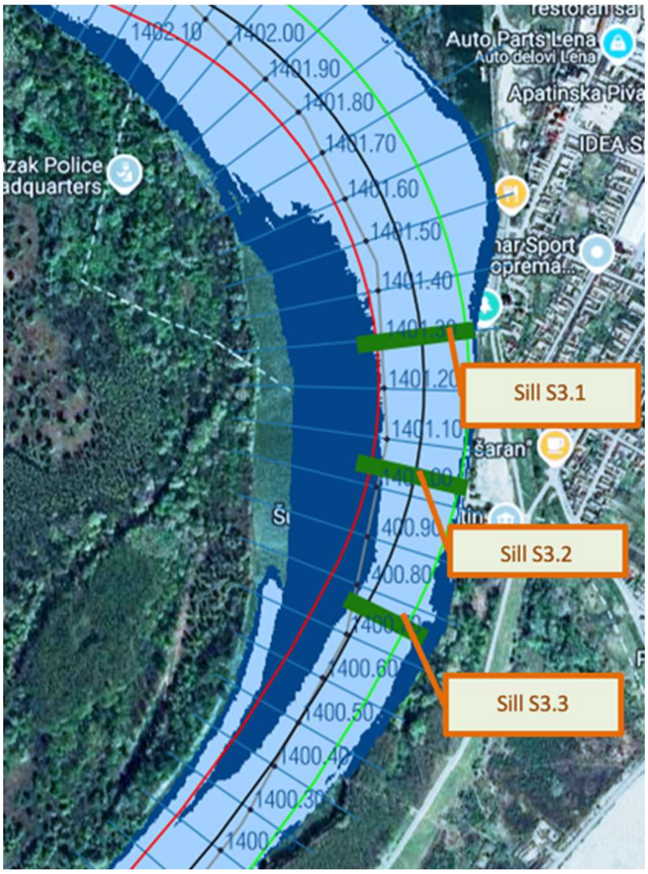


Figure 80 - Analysed position for the variant with three sills on Apatin sector: S3.1, S3.2 and S3.3

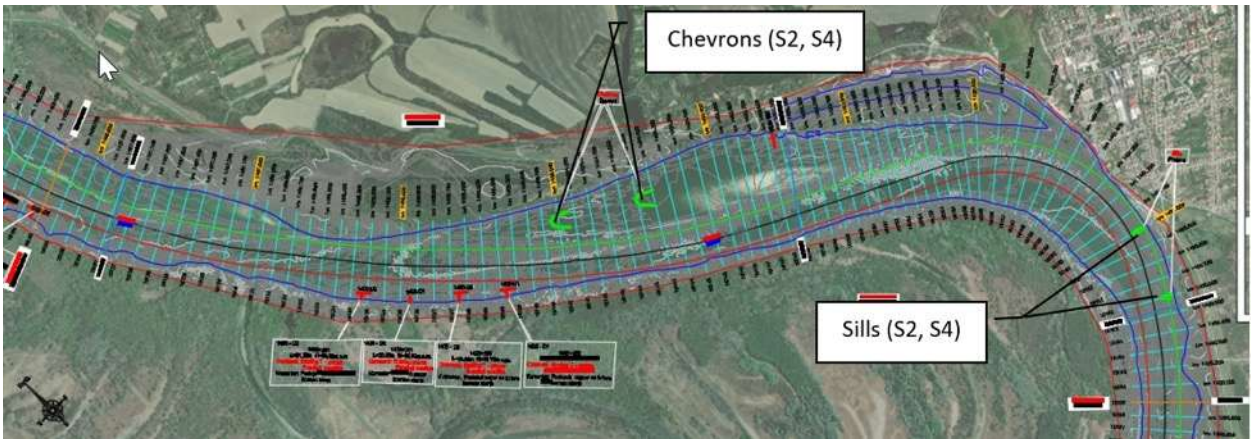


Figure 81. Positions of adopted structures (green color) along Apatin sector in Scenarios 2 and 4

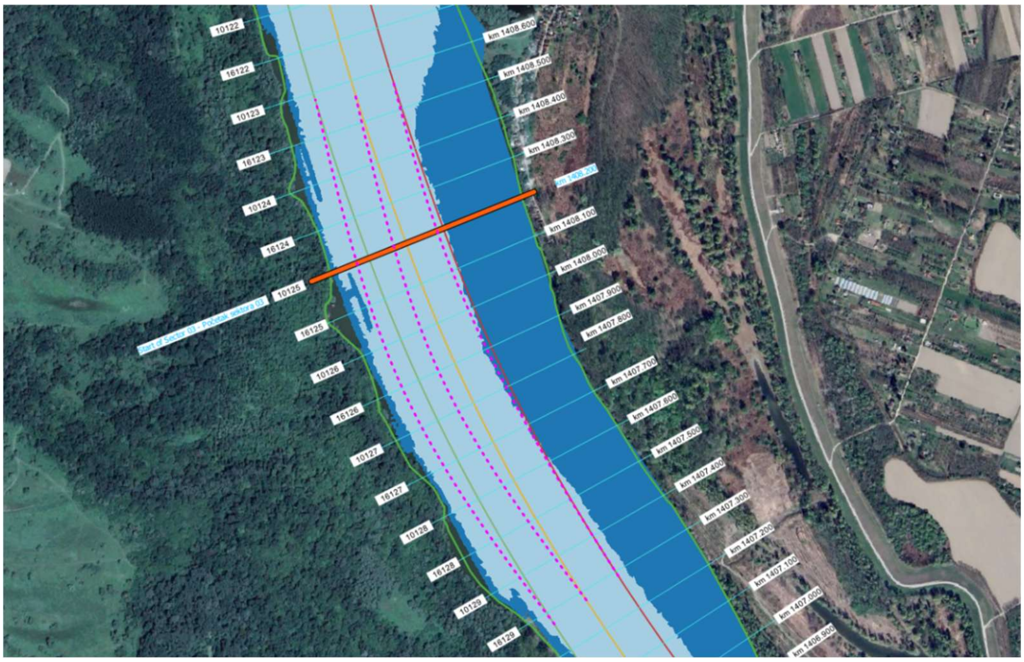


Figure 82. Fairway realignment at the critical section from rkm 1408.200 - 1407.300

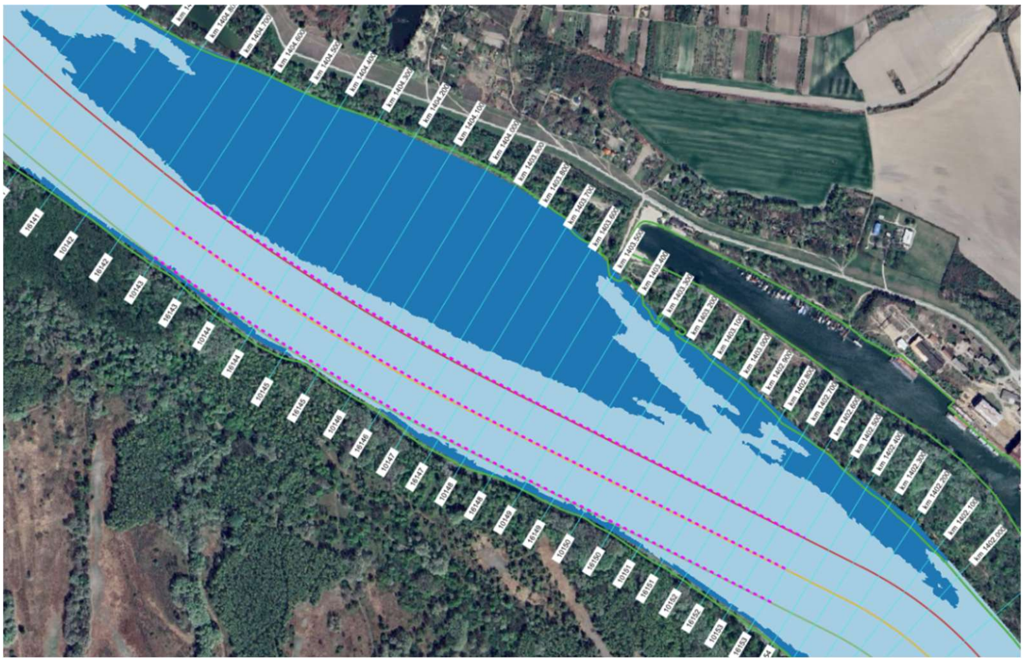


Figure 83. - Fairway realignment at the critical section from rkm 1404.600 – 1402.500

6.7.1.1.1. Chevron Structure – Design and Construction

The typical shape of a chevron resembles a horseshoe. This structure is primarily composed of crushed stone and has sizes ranging from 15 to 45 cm.

Technical Characteristics

The general characteristics of both adopted chevrons are shown in

Table *37*.

Table 37 - Technical characteristics of adopted chevrons

Crest Width:	3 m
Slopes:	Upstream face slope: 1:2 Downstream face slope: 1:3
Height (crest level):	As with the groyne, the crest elevation of the chevron is set to be 1 meter higher than the low navigation level, ensuring visibility at this characteristic water level.

One key advantage of chevrons is that they are often constructed on sandbars. This reduces the amount of material required for construction compared to other river training structures.

In Figure 84 and Figure 85 3D views, typical cross-sections and horizontal views of two chevron structures as adopted in the project are presented.

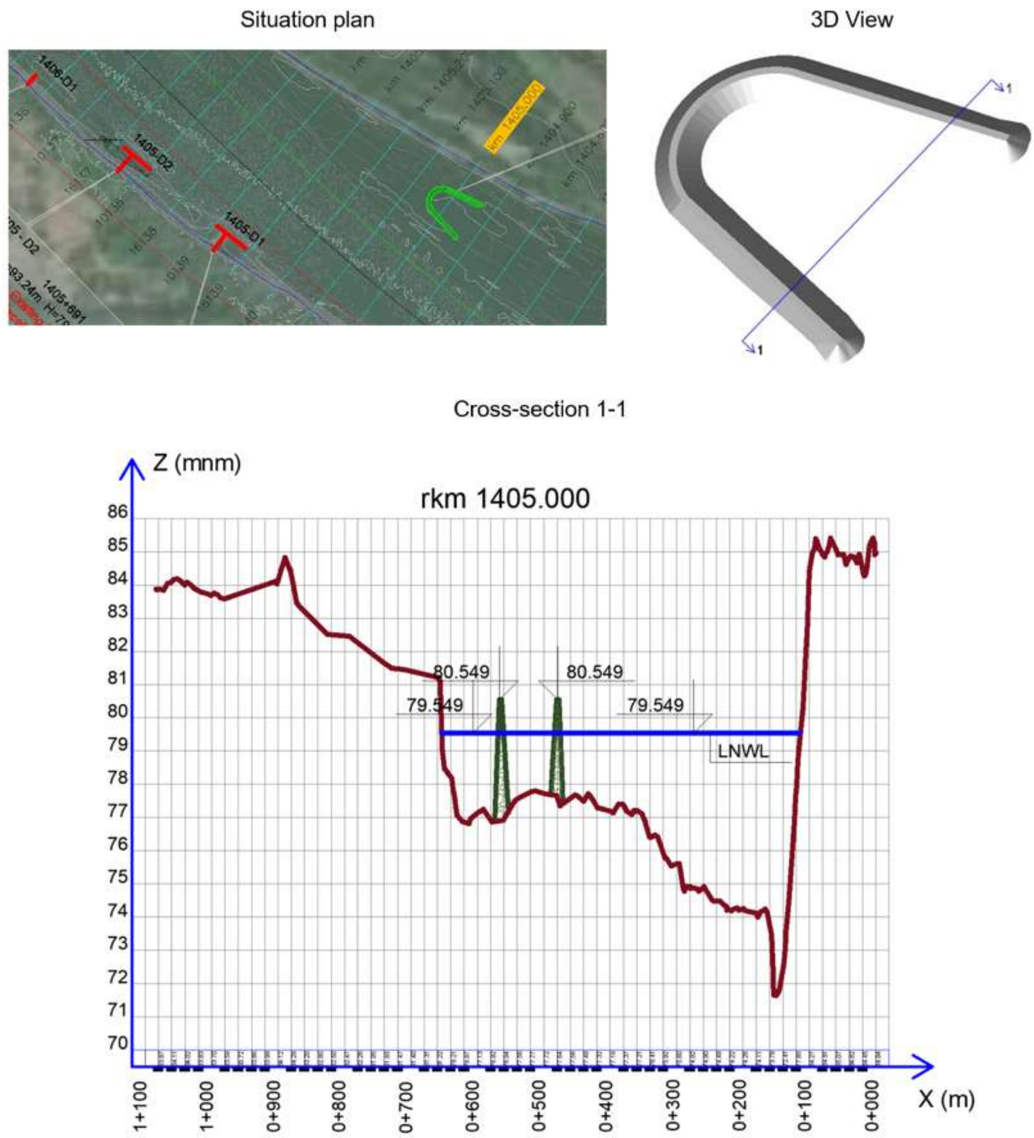


Figure 84. Different views of the adopted chevron in Scenarios 2 and 4 (rkm 1405.000)

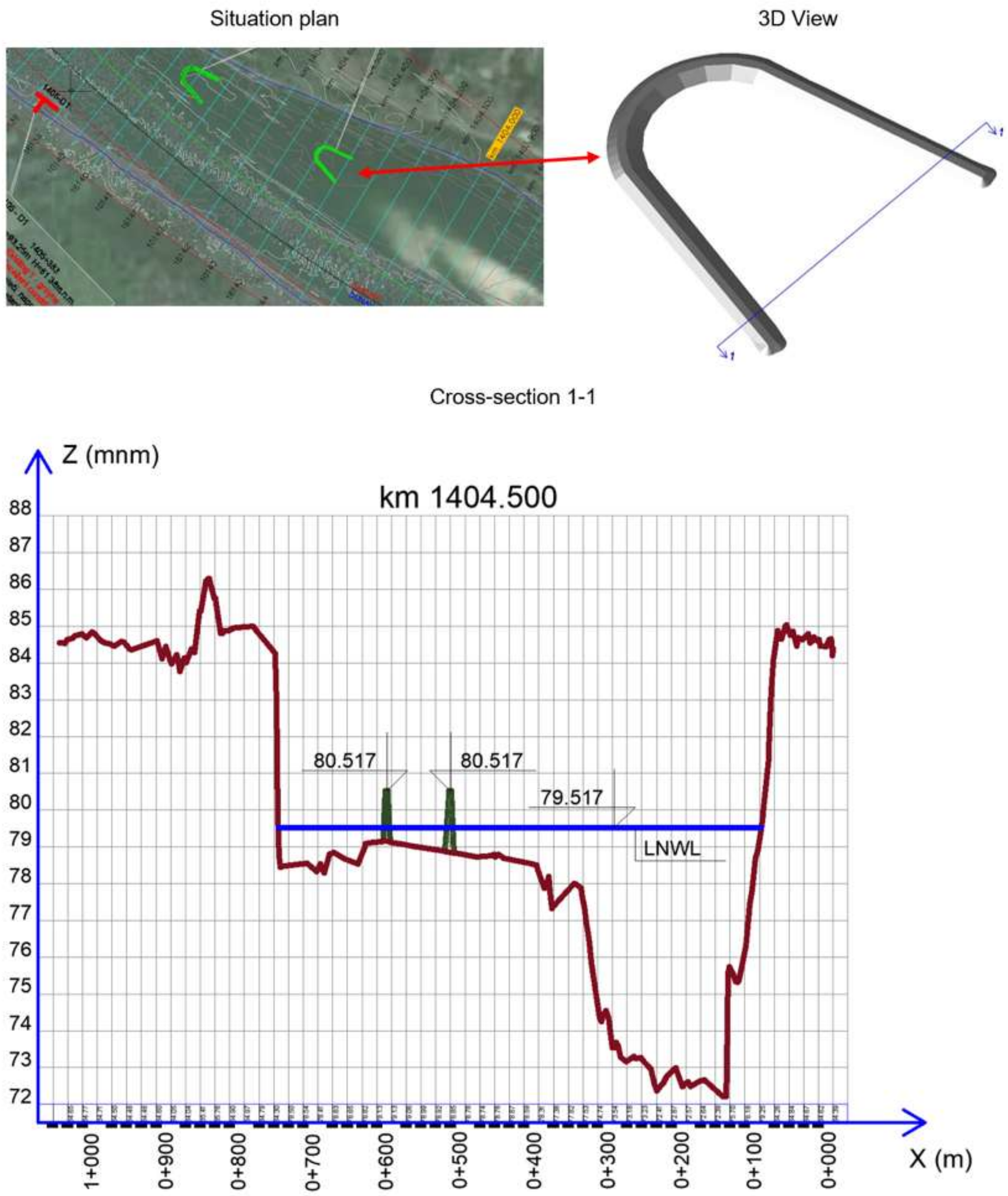


Figure 85. Different views of the adopted chevron in Scenarios 2 and 4 (rkm 1404.500)

6.7.1.1.2. Sill Structures along Apatin sector – Design and Construction

A sill is a submerged hydro-technical structure designed explicitly for river regulation. Depending on its intended function, a sill can serve a dual role. Traditionally, sills were used as barriers in shallow branches to hinder river flow at certain levels, thereby promoting distribution of flow through alternative channels. Additionally, they function to prevent deepening scours in the riverbed and to redistribute water across the channel. When placed in deeper sections, sills help prevent further erosion and adjust the shape of the cross-section in the affected zone. The application of sills increases water velocities locally, which can lead to lateral erosion and a widening of the riverbed, which is a desired morphological effect.

Because a sill is submerged, its height is not predetermined but rather calculated based on the requirements for water redistribution, the specific characteristics of the river system, and the desired hydraulic effects. The common characteristics of both adopted sills are provided in Table 38, while Figure 86 and Figure 87 show characteristic views of the sills in the Apatin sector.

Table 38. Technical characteristics of adopted sills along Apatin sector

Crest Width:	3 m
Slopes:	Upstream face slope: 1:1.5 Downstream face slope: 1:3
Height:	Max. ~7m

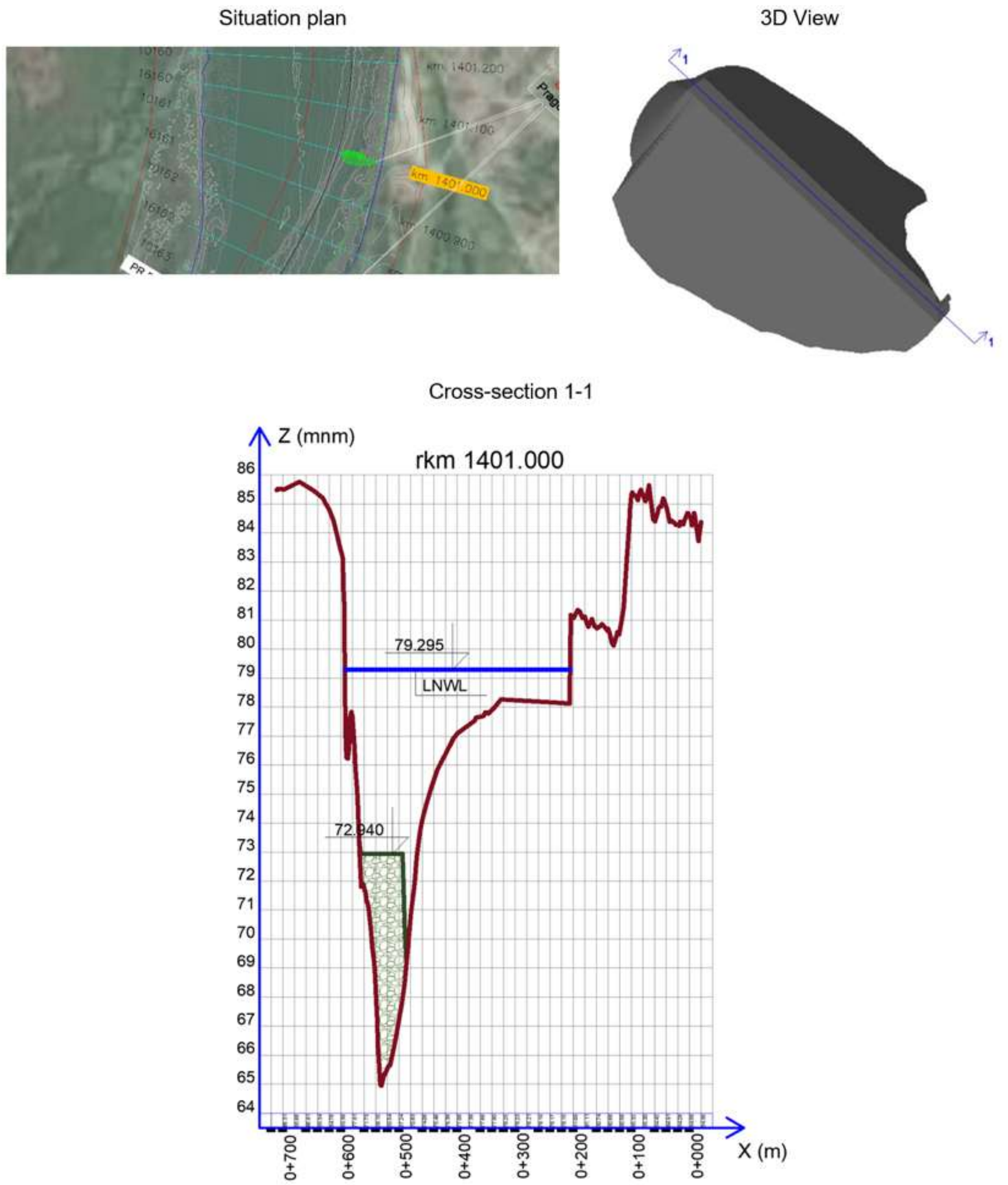


Figure 86. Different views of the adopted sill in Scenarios 2 and 4 (rkm 1401.000)

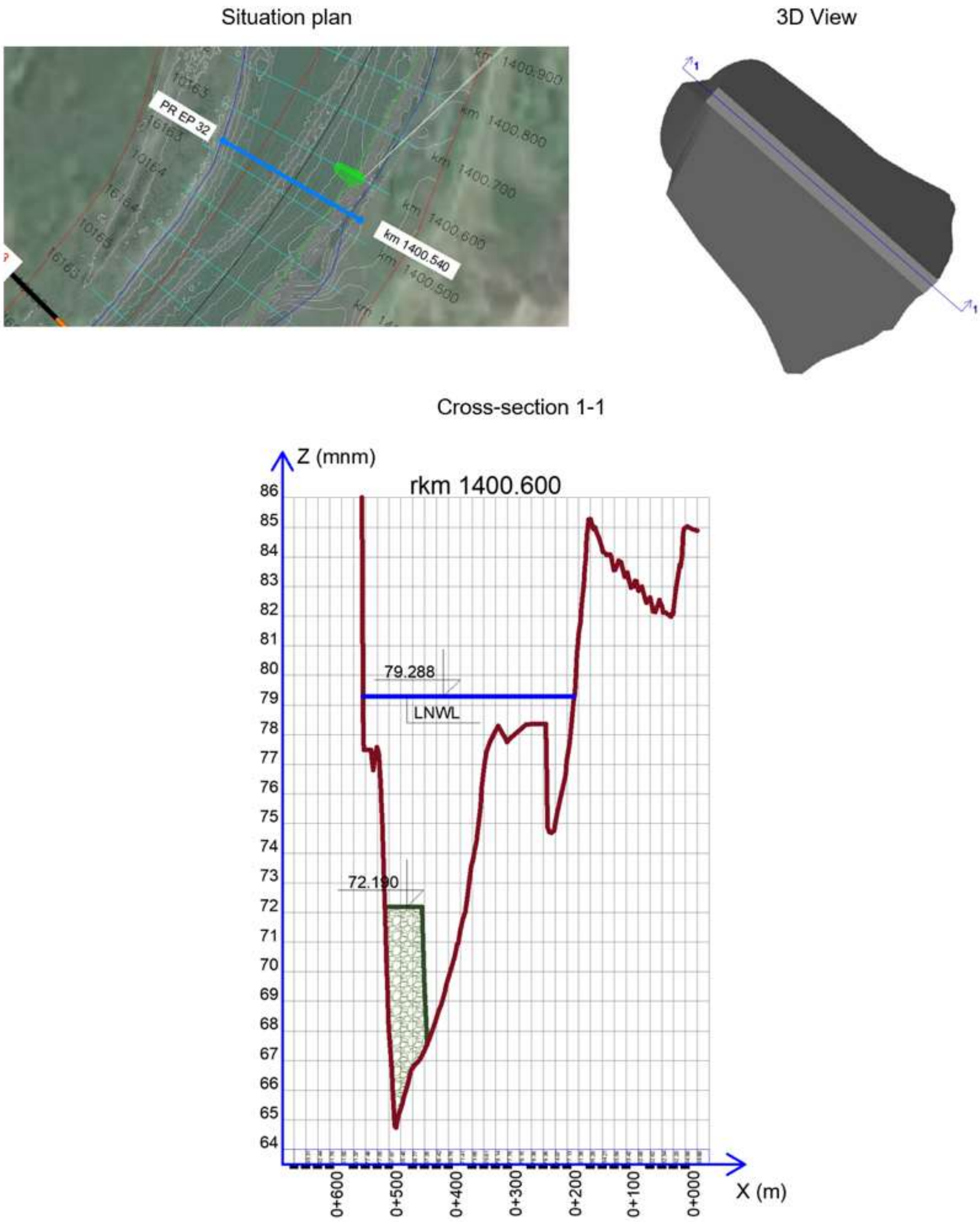


Figure 87. Different views of the adopted sill in Scenarios 2 and 4 (rkm 1400.600)

6.7.1.2. Čivutski/Židovski Rukavac (km 1397.2 – 1389.0) – Sector 4

As outlined in previous sub-chapter, Assessment of Current Issues, the Čivutski/Židovski rukavac stretch is characterized by a narrow riverbed and persistent sandbars that create navigation bottlenecks at four critical locations. From a river engineering perspective, this presents a complex challenge, further compounded by the environmental constraints inherent in a nature-protected area. Consequently, the proposed measures must simultaneously satisfy both navigational and ecological requirements. To address these challenges, the consultant has identified three possible engineering strategies to mitigate the bottlenecks:

- **Bedload Management:** Reducing suspended bedload from the upstream flow before it reaches the critical bottleneck zone;
- **Flow Concentration:** Constructing structural elements to concentrate the flow and consequently increase shear stress within the bottleneck area and,
- **Riverbed Widening:** Expanding the riverbed in the contraction zone to reduce local flow concentration (a standard measure under such conditions and objectives).

After thorough analysis and discussions with waterway administrations, it was decided to test a detached groyne in the river band where the water flow disperses. The current sediment transport balance has created four convenient locations for bedload deposition, which led the consultant to propose and prepare for modeling a detached groyne at km 1393.45, specifically designed to facilitate bedload transport (Figure 88).

It should be noted that the possibility of altering the fairway alignment was also analyzed, but due to spatial constraints, this option was not found to be feasible at any location within the sector.

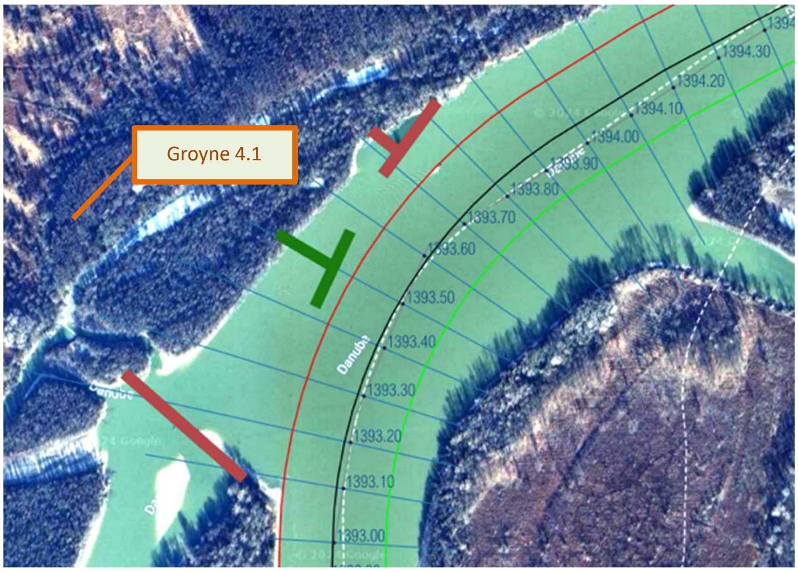


Figure 88 - The Danube River km 1393.5 – location of the newly proposed groyne (green) between two existing structures (red)

6.7.1.2.1. Detached Groyne Structure – Design and Construction

Groynes are the most used hydraulic structures on the Danube. When viewed from above, they are typically T-shaped, as shown in Figure 89.

Key characteristics of groynes are that they are always constructed in groups of two or more. This arrangement maximizes their functionality and the river's water, sediment, and ice transport capacity.

Figure 89 - Satellite image of the groyne field

To address rising ecological concerns, the engineers recently developed detached groynes, which are more nature-inclusive and eco-friendly. The trenched channel on the back of the groyne enables the genesis of small, connected ponds between the riverbank and sand deposits in the groyne fields. In this way, the barrier for aquatic organisms is removed, and new spawning and nursery habitats are created. Over time, the sedimented groyne fields will become a benthic zone for aquatic flora and fauna.

In the numerical model of sediment transport, four groyne variants were analysed: rooted and detached groynes, each with and without a wings. As a solution that balances the navigation requirements (ensuring navigability without significantly hindering maneuverability near the structure) and environmental considerations (allowing water flow along the bank), a detached T-groyne was adopted (in Scenario 2).

The structure's body is built using smaller stone fractions (15 cm), while the top layer is finished with stones up to 45 cm. The height of groynes on the Danube corresponds to the Low Navigation Water Level (LNWL) + 1m. These measures are based on safety requirements which are prescribed for incised riverbeds. The height of the structures is related to their visibility during the periods when the water surface elevation is close to the LNWL (As shown in the Table 39 listing the basic geometric characteristics of the groyne). Characteristic views of the adopted type of groyne in Scenario 2 are shown in Figure 90.

Table 39 Summary of the technical characteristics of the detached T-groyne

Crest Width:	3 m
Slopes:	Upstream face slope: 1:2 Downstream face slope: 1:3
Height (Crest level):	Low Navigation Water Level (LNWL) +1m.

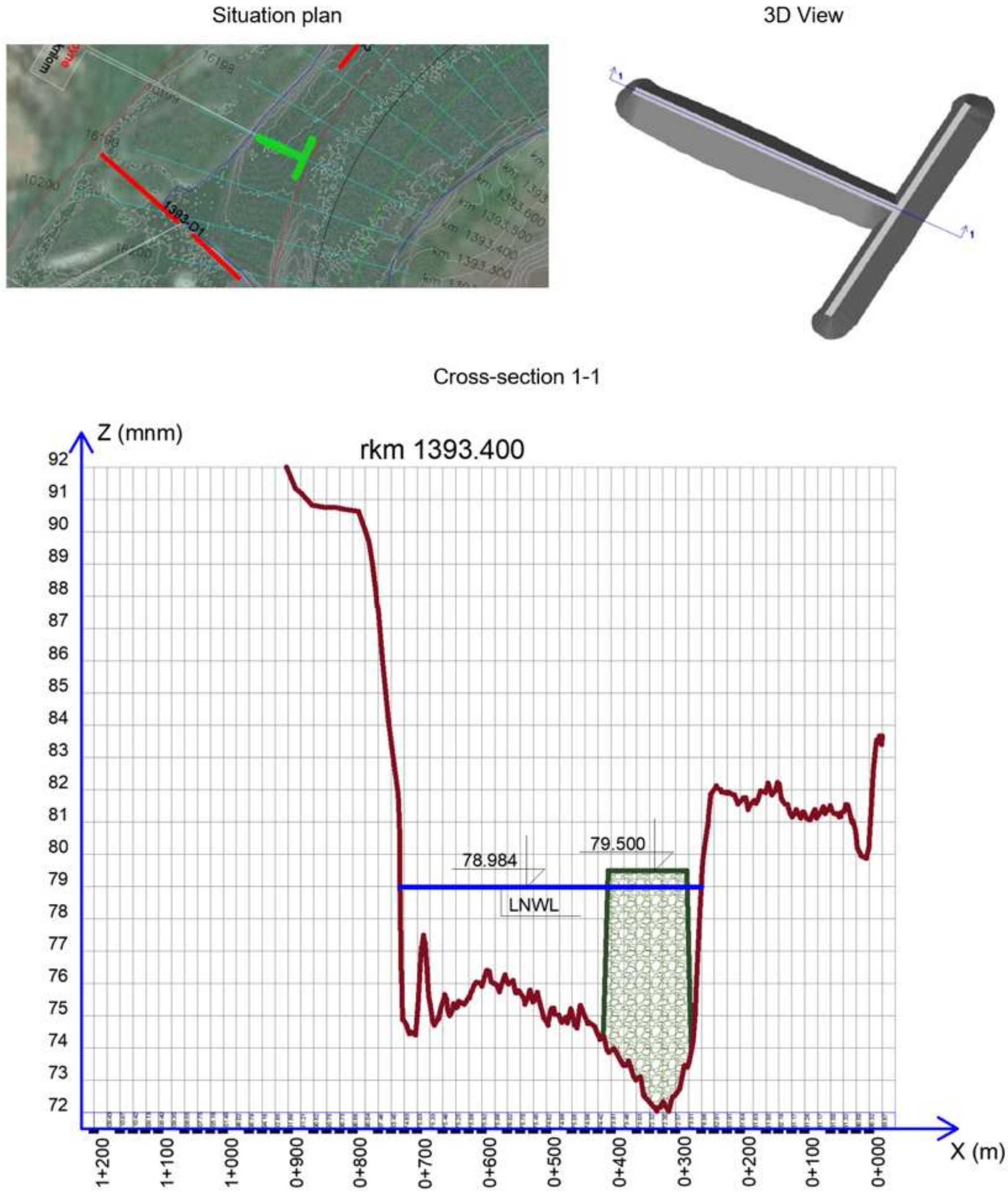


Figure 90. Different views of the adopted detached T-groyne in Scenario 2 (rkm 1393.400)

6.7.1.3. Drava Confluence (rkm 1388.8 – 1382.0) – Sector 5

The engineering strategies developed for Čivutski/Židovski Rukavac are also applicable to the Drava Confluence, although the hydraulic complexity at the confluence necessitates a combined approach.

The proposed solution integrates two measures addressing different physical mechanisms in bedload transport. Figure 91 illustrates the analysed interventions for the Drava Confluence sector, which include a sidearm channel along the left riverbank (from km 1387.8 to km 1385.65) paired with the construction of three sills upstream of the confluence. In this sector as well, the dimensions of the structures were varied. The channel width was increased until an effect on enhancing the sediment transport capacity was observed in the downstream reach of the riverbed. As in the case of the Apatin sector, the number of sills was reduced to two, and approximately the same maximum structure height was adopted. The adopted layout of structures in Scenarios 2 (channel) and 4 (sills) is shown in Figure 92.

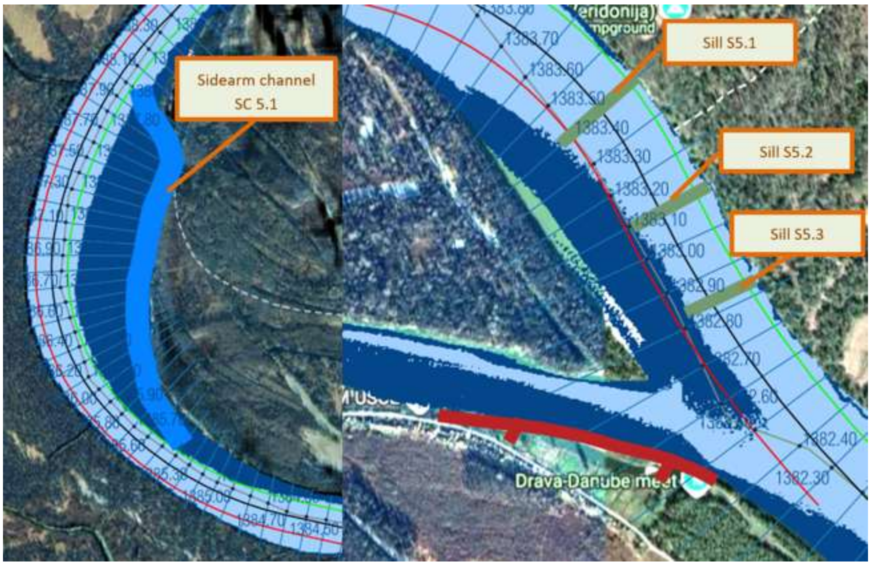


Figure 91 - The map of the structural measures analyzed along the Drava Confluence Sector – Sidearm channel 5.1 and Sills 5.1, 5.2 and 5.3

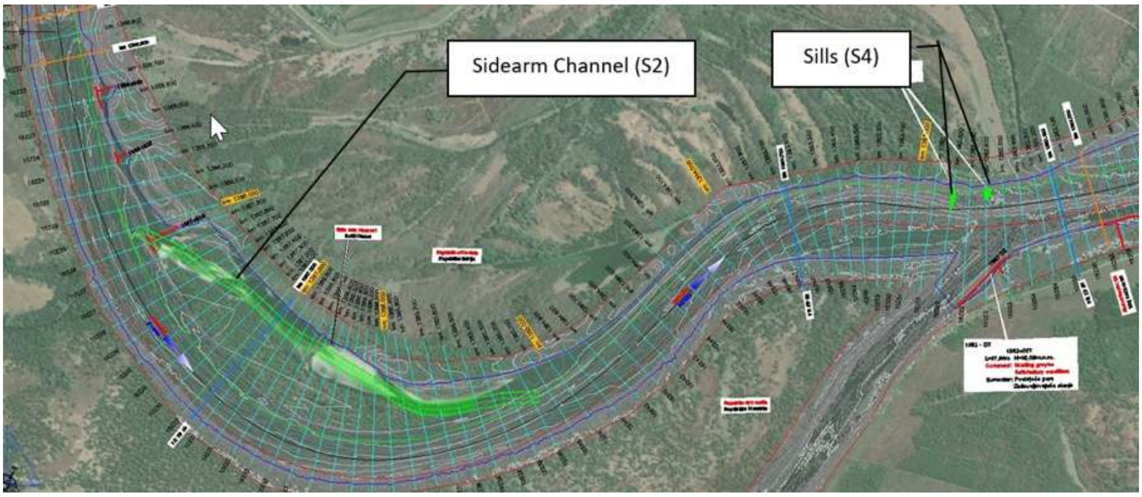


Figure 92. The adopted layout of proposed structures (green color) in Scenarios 2 and 4

In this sector, the option of altering the fairway alignment was also analyzed as a solution for improving navigation conditions.The proposed solution is to realign the fairway at the critical sections from km 1386.00 – 1384.700 and from km 1382.500 – 1381.000.

At the first location, the original curvature radius was 2050 meters, with the length of the curve segment being L = 1366.9 meters. After realignment, the radius is 1900 meters, and the length of the curve segment is 1375.1 meters. The modification of the fairway is shown in Figure *93*.

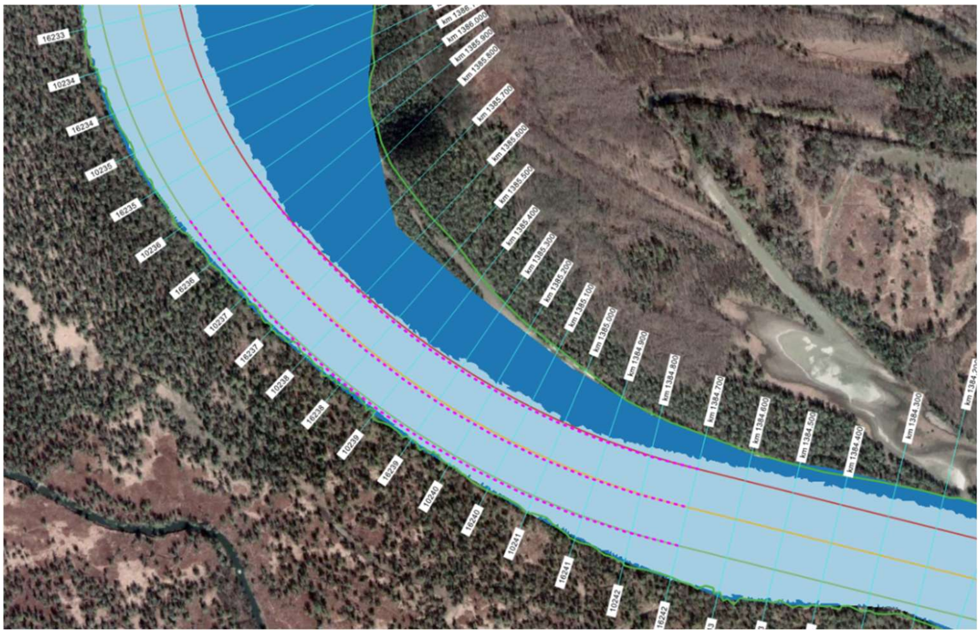


Figure 93 - The fairway realignment at the critical section from rkm 1386.000 - 1384.700

Location 3 is the downstreammost point of this sector, where the fairway alignment has undergone moderate modifications. The original curvature radius was 5000 meters, with the length of the curve segment being L = 1040.9 meters. After realignment, the fairway was modified to include three different radii:

R1= 1000m, L= 824.7m.

R2= 3000m, L= 605.7m.

R3= 1700m, L= 768.9m.

The modification of the fairway is shown in Figure 94.

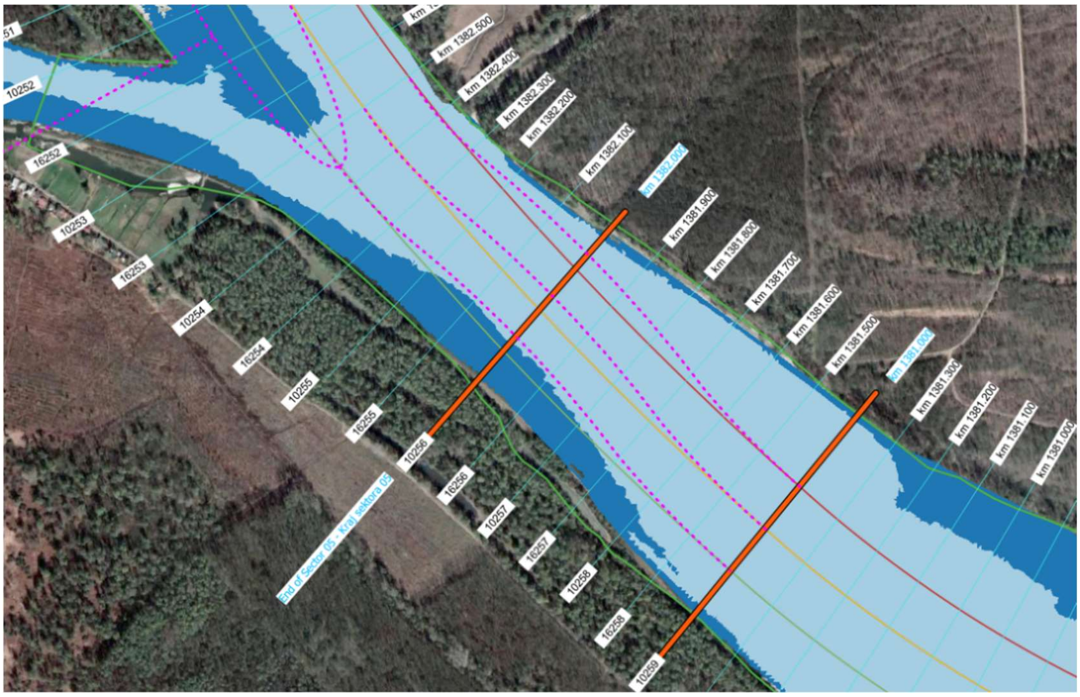


Figure 94 - The fairway realignment at the critical section from rkm 1382.500 - 1381.000

6.7.1.3.1. The Sidearm channel along Drava confluence sector – Design and Construction

The sidearm channel is one of the proposed revitalization measures that affects both navigation conditions and ecology. It is proposed to construct the channel by excavating through the existing groyne system (see Figure 95), whereby one existing groyne would be completely removed.

The basic technical characteristics of the solution are given in Table 40.

Table 40: Summary of technical characteristics of the sidearm channel

Channel Width:	The model will calculate the channel width. 60m is the initial value
Channel Bank Slopes:	1:1
Channel slope	0.002
Channel Bank Protection	The channel bank slopes will be protected by the stones, dominantly by the stones taken over from the groynes;

At this level of documentation development, trapezoidal cross-section is analyzed with side slopes 1:1. The longitudinal slope of the channel will approximately follow local slope of the riverbed in the main channel. The slopes of the sidearm channel will be protected with stones excavated from the groynes bodies. The channel bottom will be natural, partially covered by the surplus stones from the groynes. The channel width was varied in increments of 15 meters in the 2D transport model. In the initial variant with a width of 15 meters, no positive effect on increasing the sediment transport capacity downstream of the channel in the Drava confluence zone was observed, so the width was increased up to 60 meters, at which point these effects were noted and the final width was adopted. For this adopted sidearm channel geometry (in Scenario 2), cross-sections at both ends are provided in Figure 96.

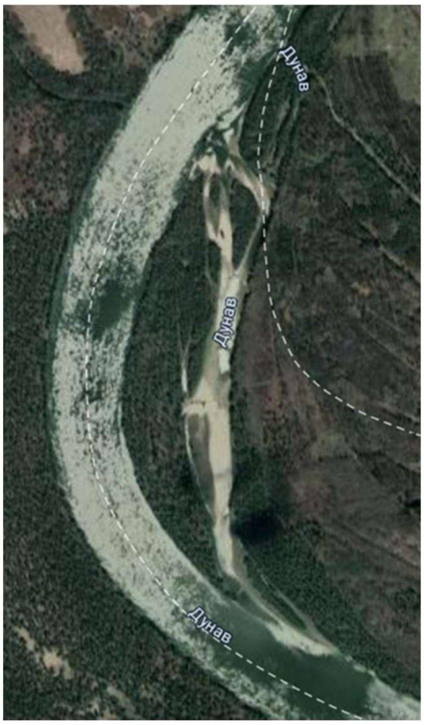


Figure 95: The Groyne field envisaged for restoration

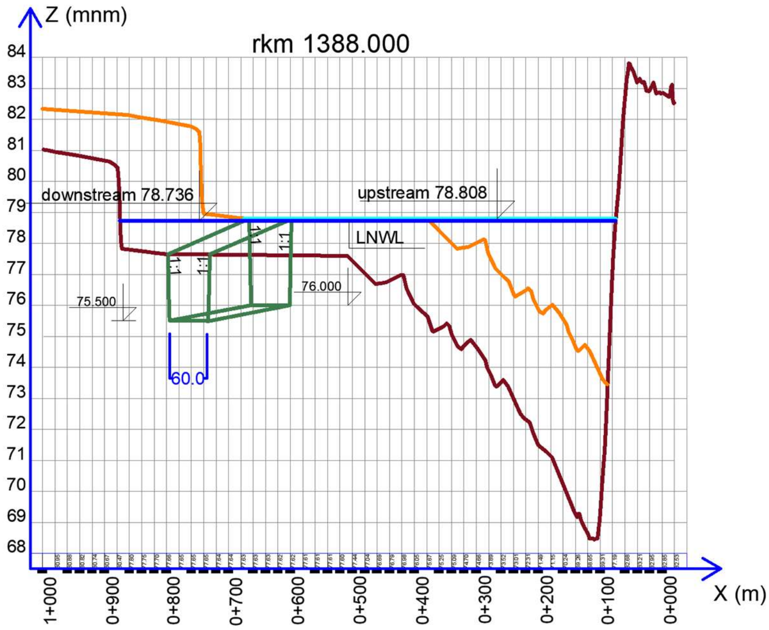


Figure 96. Cross-sections of the Danube riverbed and the proposed sidearm channel at both ends of the channel (Drava confluence sector)

6.7.1.3.2. Sill Structures along Drava confluence sector – Design and Construction

The sills along the Drava confluence sector have the same general technical characteristics (slopes and crest width) as the other proposed sills in the common Danube stretch. The change in (maximum) heights can be approximately observed in the cross-sections of the two adopted sills in Scenario 4, which are shown in Figure *97* and Figure *98*.

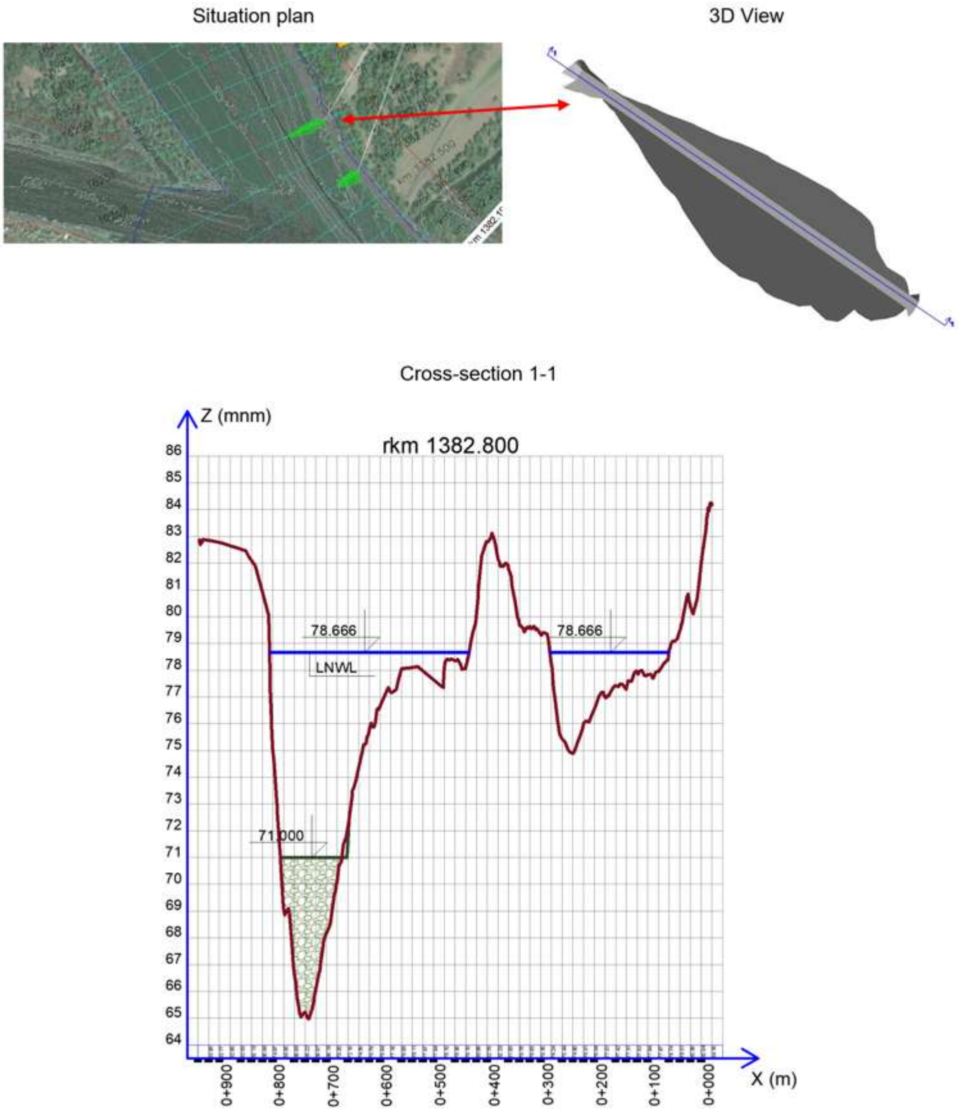


Figure 97. Different views of the adopted sill in Scenario 4 (rkm 1382.800)

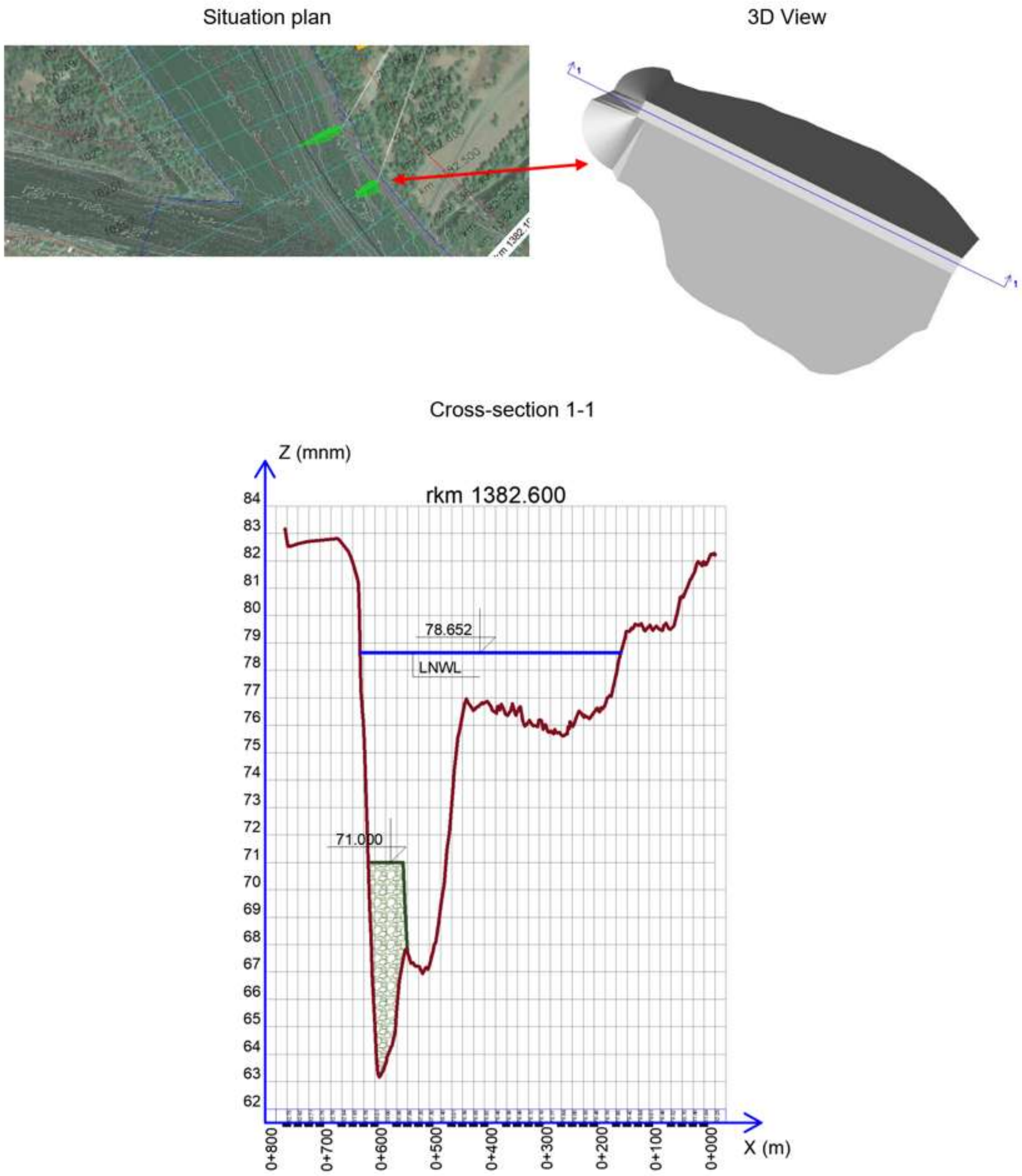


Figure 98 - Different views of the adopted sill in Scenario 4 (rkm 1382.600)

Staklar km 1376.8 to 1373.4 – Sector 6

The historical analysis of river structures and the development of cross-sections confirm that the implemented sills have significantly contributed to downstream stability, effectively stabilizing the riverbed over time. This positive performance underpins the overall bottleneck resolution strategy.

In terms of bedload management, a sidearm channel has been designed along the Aljmaš sector as solution for Staklar sector (the proposed solution addressing physical mechanism in bedload transport in the same manner as in the case of the sidearm channel proposed along the Drava confluence sector), while sills have been placed at the Staklar river band entrance to concentrate and redistribute water flow. The initial locations for the proposed measures - sidearm channel and the sills, are shown in Figure 99. It should be noted that, as in the case of the Čivutski rukavac sector, no possibility was found here either to carry out a fairway realignment.

Figure 99 - The locations envisaged for the sidearm channel trenching and construction of the sills on the Staklar section

The final layout in Scenario 4, adopted through modeling, includes two sills (Figure 100), as is the case in other sectors where the same solution has been applied.

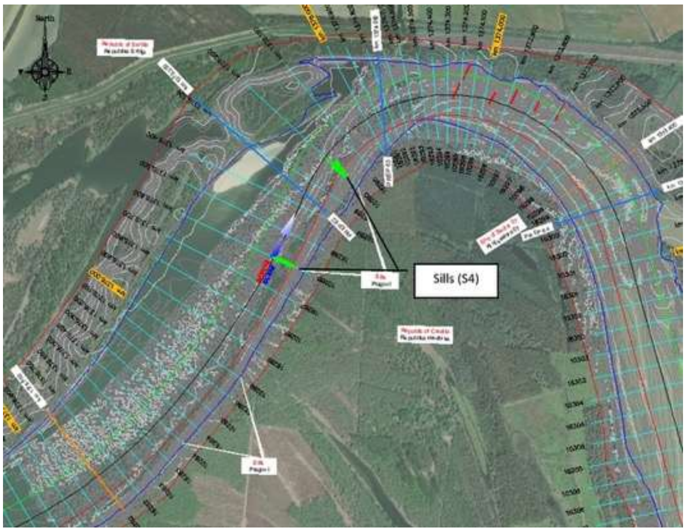


Figure 100 - Positions of adopted sills (green color) along Staklar sector in Scenario 4

6.7.1.3.3. The Sidearm channel solution for Staklar sector – Design and Construction

The technical details of the sills and the sidearm channel are practically the same as for the same types of structures in the Drava confluence sector, so only characteristic views are provided.

As in the case of the channel along the Drava confluence sector, based on the results of 2D modeling, a width of 60 meters was adopted for the sidearm channel along the Aljmaš sector. As shown in Figure 101, in this sector as well, the excavation of the channel involves the complete removal of two existing groynes.

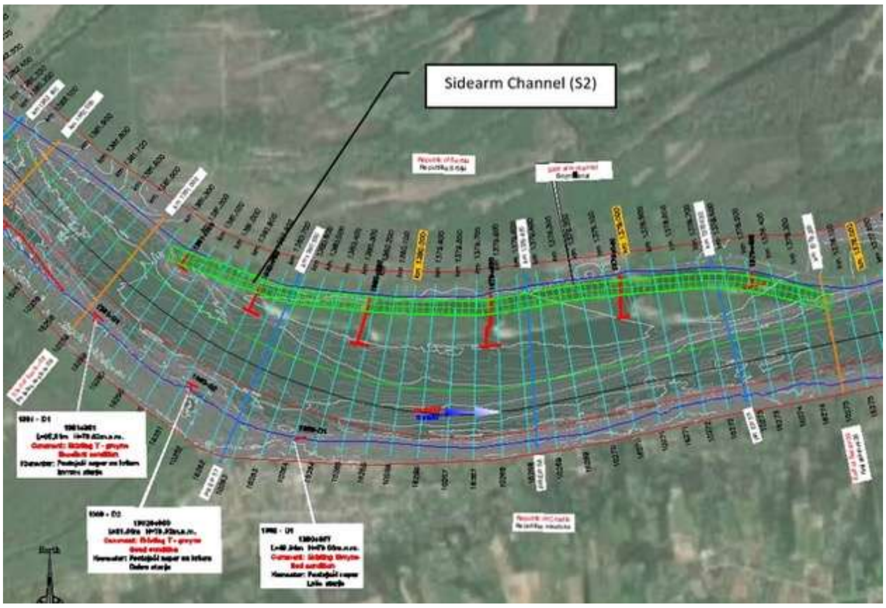


Figure 101 - Layout of the sidearm channel in the Aljmaš sector (in green), together with the locations of the existing groynes (in red)

The cross-sections at the ends of the sidearm channel along Aljmaš sector are shown in Figure *102*.

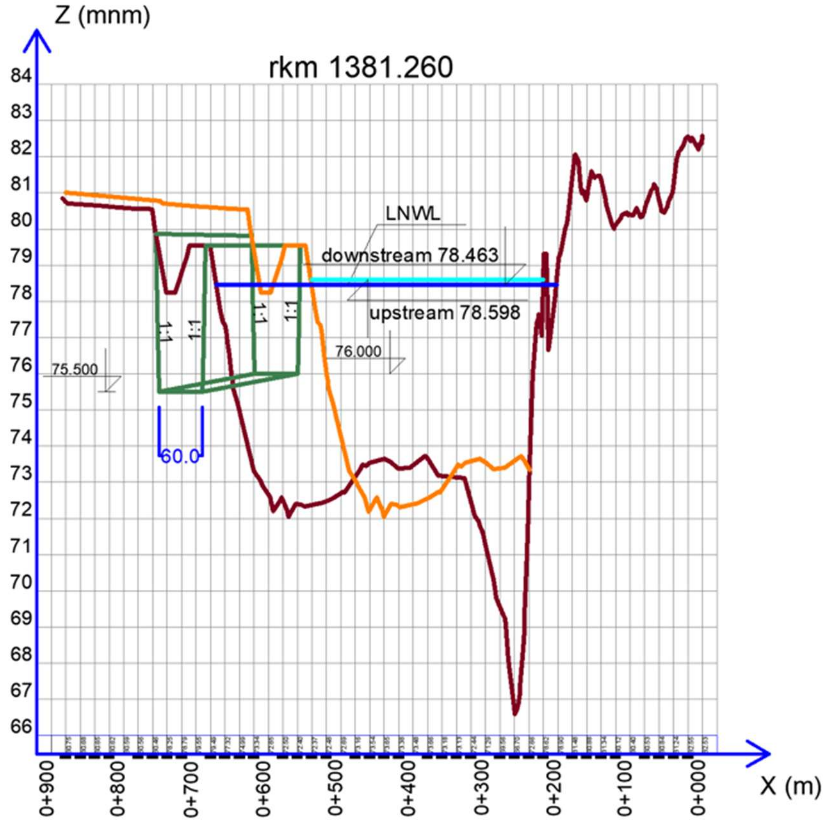


Figure 102. Cross-sections of the Danube riverbed and the proposed sidearm channel at both ends of the channel (Aljmaš sector)

6.7.1.3.4. Sill Structures along Staklar sector – Design and Construction

In addition to the general characteristics of the sills, which were adopted from other sectors, modeling has determined similar required structure heights to achieve a significant effect regarding morphological changes in navigation-critical zones along the Staklar sector. Characteristic representations for the adopted solution are shown in Figure *103* and Figure *104*.

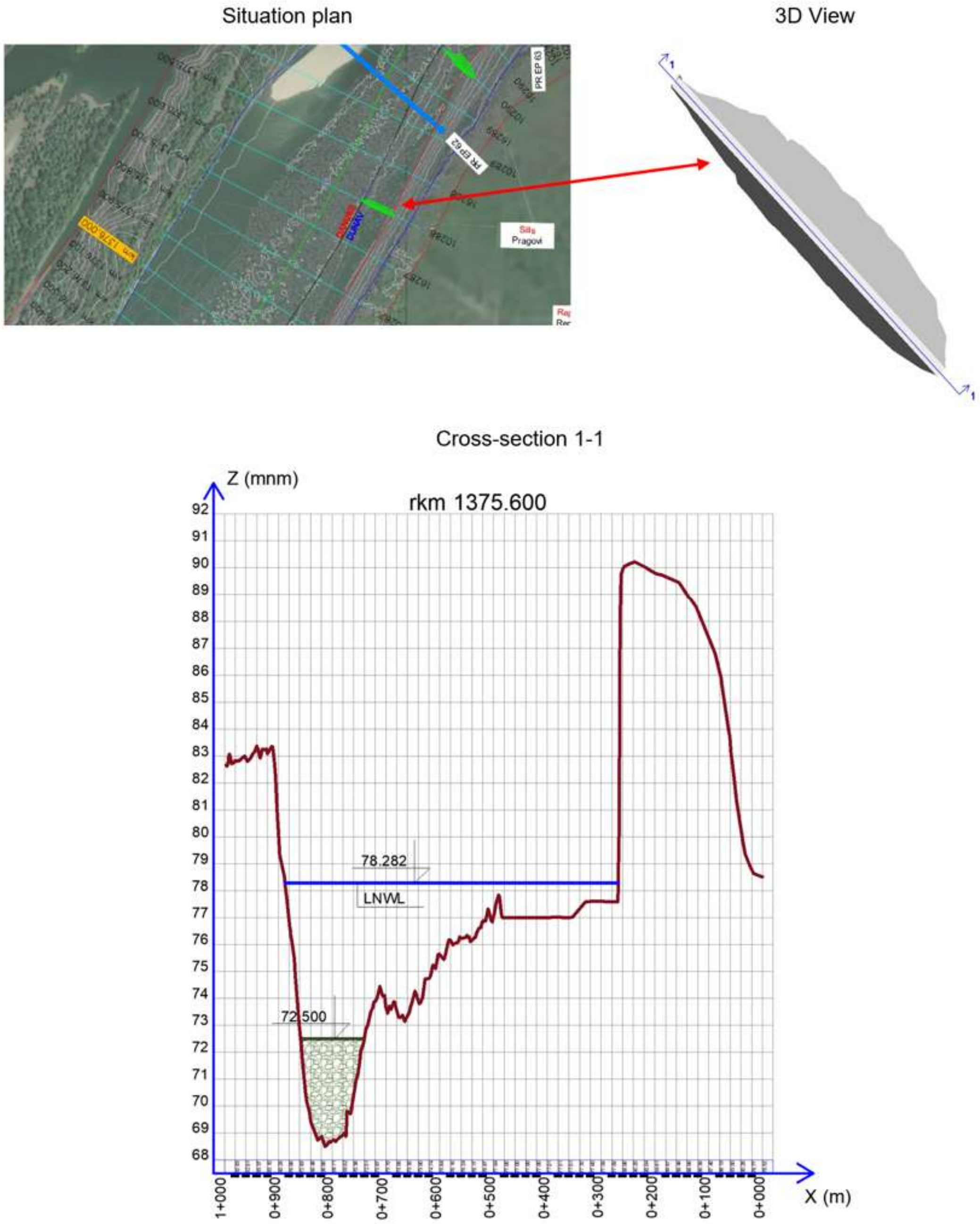


Figure 103. Different views of the adopted sill in Scenario 4 (rkm 1375.600)

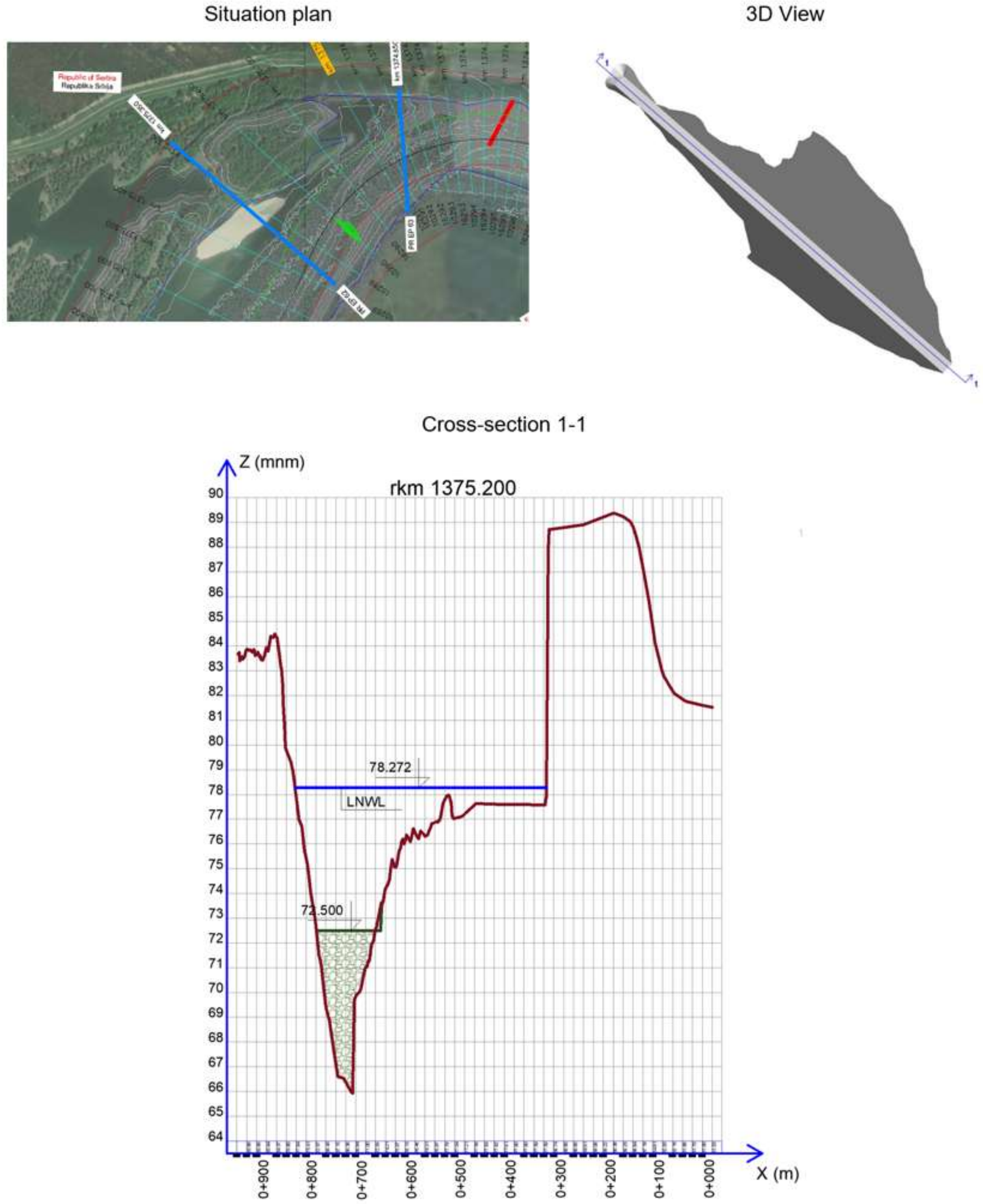


Figure 104. Different views of the adopted sill in Scenario 4 (rkm 1375.200)

6.7.2. Justification for each measure (environmental, morphological)

6.7.2.1. Apatin km 1,408.2 – 1,400.0 – Sector 3

The purpose of the envisaged chevrons is to smoothly redirect water into the main channel and stabilise the sandbar. Concurrently, part of the water flow will be directed towards the riverbank, making a river branch.

The expected result of this structural intervention from the navigational perspective are:

- Widening of the main channel where is the navigational fairway;
- Stabilization of the sandbar and preventing further alternations.

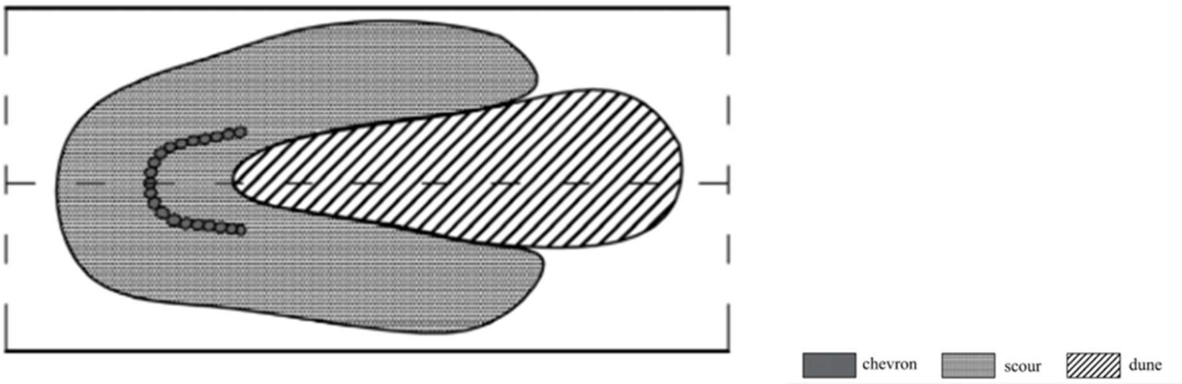


Figure 105 - The expected effects of placing the chevron in the riverbed with riverbed composed of the material which is mixture of the silk and fine sand

From an environmental perspective, the primary goal of the proposed measures is to minimize habitat destruction. This approach aims to sustain natural sediment dynamics that foster spawning and nursery habitats, as well as safe refuge zones.

In the long term, constructing chevrons may promote the formation of new river islands and shelters, thereby creating diverse habitats that benefit species such as herons, cormorants, and other waterfowl. These new hydraulic features could present both challenges and opportunities for aquatic biota. For example, fish species—including Aspius aspius, Barbus barbus, Chondrostoma nasus, and Squalius cephalus—often rely on varying flow conditions for spawning and feeding. The increased flow heterogeneity provided by well-designed chevrons and sills may create additional microhabitats that support different life stages of fish.

Moreover, ecological considerations are integrated into the design by ensuring riverine connectivity, maintaining shallow water zones, and avoiding uniform channelization. These measures not only support improved navigation but also promote long-term ecological health. It is essential to also restrict construction activities during the spawning season of protected and strictly protected species such as Aspius aspius, Gymnocephalus balonii, Leuciscus idus, and Squalius cephalus, to prevent undue disturbances.

6.7.2.2. Čivutski/Židovski Rukavac (rkm 1397.2 – 1389.0) – Sector 4

From an engineering perspective, the proposed detached groyne is intended to reshape the sediment transportation balance and generate additional shear forces. Its primary goal is to address the bottlenecks at km 1390.9 by increasing pressure on the sandbars in that zone, thereby improving navigational conditions. While the exact outcome of this intervention remains uncertain, the Čivutski/Židovski rukavac sector has experienced numerous navigational challenges, and the navigation authorities would welcome any effective measure to alleviate these issues.

From an environmental standpoint, the area targeted for the detached groyne is identified as a critical fish habitat (see Figure 106). This designation underscores the need for careful ecological consideration throughout the design and implementation process to ensure that any intervention does not adversely affect the local aquatic biodiversity.

Figure 106 - The fragment from the GIS prepared by the Croatian consortia related to the Čivutski/Židovski rukavac and wild populations, which are captured in this zone

The planned construction of an additional groyne on the right bank of the Čivutski Rukavac section, situated between two existing structures, is aimed at improving local navigation conditions by stabilizing the riverbank and optimizing the water flow. This area holds high ecological value—it serves as an important wintering site for diverse waterfowl and functions as a breeding area for various bird species, similar to the upstream sector. However, the construction activities, as well as the temporary disturbance they cause, could potentially impact the local bird populations. To mitigate these short-term effects, it is advisable to schedule construction outside the breeding season and the main winter months, while also maintaining undisturbed zones in close proximity to the work area.

From an ichthyological perspective, the sector's unique hydro-morphological characteristics support both rheophilic (current-loving) and limnophilic (still water-preferring) fish species. The installation of the groyne is expected to modify local hydraulic conditions by increasing flow velocity in its immediate vicinity and creating zones of lower flow within the groyne field. This hydrodynamic variability can enhance habitat diversity and support different life stages of fish—from spawning to juvenile development. For rheophilic species, improved flow velocity can enhance oxygenation and the availability of spawning substrates, while limnophilic species may benefit from the calmer, shallow waters provided by the groyne field as refuges or nursery areas.

To ensure that the new groyne contributes positively to both navigation and biodiversity, ecological considerations should be integrated into the design. This includes accounting for sediment deposition patterns to promote the formation of natural islands and shallow habitats. Additionally, continuous monitoring of bird and fish populations both before and after construction will be essential for adaptive management, ensuring that any environmental impacts are identified and mitigated promptly to maintain the ecological integrity of this sensitive and valuable section of the Danube River.

6.7.2.3. Drava Confluence (rkm 1388.8 – 1382.0) – Sector 5

The proposed sidearm channel is designed to split the water course into two streams. The existing riverbed becomes the main channel, which remains the same size, but the sidearm channel takes over the amount of water and decreases the discharge and velocities in the main riverbed. This action reduces the discharge and velocities in the main channel and consequently stimulates bedload sedimentation. The negative consequences of this measure might be the sidearm siltation, particularly in the zones of the channel mouth and its confluence to the main channel. The generated sediment thresholds may severely affect the channel function and envisaged siltation mechanism.

The reduction in suspended load enhances the water's ability to erode downstream deposits, which is the primary objective of this measure. To support this process, additional sills have been designed to redistribute the flow in the main channel and reshape the sandbar along the right riverbank.

While mixing of the two water flows at the channel confluence generates continuous riverbed morphology changes this effect is common in most confluences. However, hydraulic modelling remains essential to assess the impacts on:

- Flow patterns
- Sediment transport
- Riverbed morphology changes

From an environmental perspective, the sidearm channel trenching is considered a restoration measure that benefits both navigation and the ecosystem. The intervention, which involves breaching existing groynes (Figure 34) to reopen the side channel upstream of the Drava estuary combined with the installation of new sills on the left bank, aims to improve navigation through enhanced flow distribution and fairway stability.

Ecologically, reopening the side channel can reestablish the lateral connection between the main river and its tributaries, improving habitat diversity. This connectivity is particularly beneficial for fish species such as Rutilus virgo, Chondrostoma nasus, Squalius cephalus, and Cobitis elongatoides, which depend on side channels for spawning, feeding, or refuge during high water levels. Restoring natural flow in these channels may also reduce stagnation and enhance water quality, thereby supporting aquatic invertebrates and macrophytes that form the base of the food web.

Nevertheless, the modification of existing groynes and addition of sills could temporarily alter local hydraulic conditions, sediment transport, and flow regimes. Such changes might impact habitats used by certain fish species and waterbirds, especially if construction occurs during sensitive periods such as spawning or breeding seasons. By incorporating ecological considerations during planning—such as preserving shallow water zones, ensuring gentle gradients, and maintaining continuous flow paths—the structures can be designed to promote both improved navigation and biodiversity. In the long term, these measures may create new microhabitats and establish better conditions for both rheophilic and limnophilic species, contributing to a dynamic and resilient river ecosystem.

6.7.2.4. Staklar km 1376.8 to 1373.4 – Sector 6

The issues concerning the Staklar band and the sandbar along the left riverbank have already been described, and proposed measures have been outlined. This chapter will further elaborate on the anticipated effects of these measures, including their advantages and potential drawbacks.

Since submerged sills have proven effective in downstream areas, the approach will be extended by constructing additional sills. The idea behind this is to increase sediment transport capacity in the upstream portion of the river bend. Additionally, on the Aljmaš sector, rkm 1382.3 to rkm 1376.8, one more sidearm channel is designed as an upstream intervention with the goal of reducing bedload availability, and minimizing sedimentation along the sandbar, and lowering the demand for transport capacity. The effectiveness of these measures was assessed in the modelling activities.

The expected effects on the surrounding nature are considered and analyzed. In order to improve navigation conditions in the Danube section near Aljmaš, the proposed measures focus on non-structural interventions— in particular the partial removal of existing groynes and the reactivation of a sidearm channel. In contrast to the construction of new structures, these measures aim to restore more natural hydro-morphological dynamics by improving the flow distribution and restoring the lateral connection between the main channel and its floodplain.

From an ecological point of view, these measures can have a particularly positive impact on the local wildlife. The opening of the sidearm channel can improve the diversity of aquatic habitats and provide valuable spawning, feeding and refuge areas for various fish species, including both rheophilic (*Alburnus sava, Aspius aspius*) and limnophilic species (*Esox lucius, Cobitis elongata*). Increased water exchange and greater current variability can improve water quality and oxygen levels, promoting a richer benthic community and healthier fish populations. The reconnected side channel can also attract bird species, particularly waterfowl and waders, as it provides undisturbed shallow water zones ideal for foraging and resting.

In addition, the removal or modification of existing groynes can help to reduce current stagnation and sediment accumulation in certain areas, creating more dynamic habitat conditions that benefit a wider range of aquatic organisms. As these interventions are consistent with the principles of natural river restoration, they offer a rare opportunity to improve navigation while enhancing ecological functions — provided that implementation is carefully planned and timed to avoid sensitive periods such as fish spawning and bird breeding seasons.

At the Staklar site, which is located in the uppermost part of a pronounced bend in the Danube, a series of four sills have already been constructed along the left bank to improve navigation by stabilizing the navigation channel and controlling sediment transport. As an additional measure, the construction of three more sills is proposed on the right bank, directly upstream of the bend, is proposed. It is expected that these measures will optimize the concentration of the current and the alignment of the navigation channel, which is essential for safe and efficient navigation in this dynamic section of the river.

From an ecological perspective, the sills will not benefit a local biota, particularly. The sills present a local discontinuity for the fish swimming upstream in its migration. We assume that this discontinuity will affect some fish species and that they will easily adapt to the new modified habitat. Also, the sill creates a zone with intensive turbidity in the downstream zone that will be used by fish species for wintering habitats and feeding as well. On the other hand, the local turbulence will affect the benthic aquatic organisms, mostly aquatic insect larvae, while other representatives will recover in some extent. The birds and other biodiversity elements would not be affected by this measure.

6.8. Definition of Scenarios

6.8.1. Scenario 1: Baseline ("Do Nothing")

This scenario is the benchmark for evaluating the effectiveness of all other scenarios. Generally speaking, the "do nothing" scenario show how morphological changes develop starting from the current state without any activities (measures). It will be modelled as all other scenarios to understand the future trajectory of the observed stretch without modifications. However, as it is practically impossible to predict long-term changes in boundary conditions for a numerical sediment transport model, in practice, long-term predictions of morphological changes are performed using the so-called dominant discharge, which is considered to be the flow that has the dominant influence on changes in channel geometry. In numerical simulations, a constant discharge is used, and the deformation of the channel is examined under this flow. Given that the transport model is calibrated based on a limited set of data, the trends in morphological changes obtained as a result of numerical simulations cannot be taken for granted. On the other hand, the numerical model is based on validated equations that describe the phenomenon of sediment transport and, in a relative sense, can provide assessments of the effects of different measures; that is, they can be used to compare the effects of various interventions.

6.8.2. Scenario 2: structural and revitalization measures

This scenario focuses on the non-traditional structural measures to address the bottlenecks in key sectors like Apatin and Drava Confluence. This scenario considers non-traditional structural measures that place equal focus on improving indicators related to navigation and environmental protection criteria. In this scenario, the following structures have been proposed:

- **Chevrons in the Apatin sector** – Two chevrons have been adopted, while a variant with only one chevron was also considered. However, the single-chevron option did not provide satisfactory deepening of the riverbed along the left bank of the Danube near the chevron (the goal was to achieve greater non-uniformity of depths).
- **Sidarm channels in the Drava confluence and Aljmaš sectors** – The bottom width was varied, and in both sectors, a width of 60 meters was adopted as the width at which the desired effects occur.

6.8.3. Scenario 3: Navigational fairway realignment (minimal intervention approach)

Scenario 1 - "Do nothing" is designed as a benchmark scenario without intervention. Scenario 3 is envisioned as a business-as-usual scenario, comprising adjustments in the fairway over time. This scenario aims to optimize fairway without large-scale physical interventions.

6.8.4. Scenario 4: Full structural intervention (comprehensive measures)

This scenario includes only structural measures. It will consider more traditional structural measures combined with the nature-inclusive measures proposed in Scenario 2. In addition to Scenario 2, Scenario 4 contains the structural measures envisioned for Čivutski/Židovski rukavac and for sector Staklar. By sector, the following measures have been adopted in this scenario:

- **Chevrons and sills in the Apatin sector** – Two chevrons and two thresholds have been adopted, identical to those in Scenario 2.
- **Detached T-Groyne in the Čivutski rukavac sector** - One groyne has been adopted that will not be rooted to allow for a secondary flow. A groyne with a wing is proposed to reduce the impact on maneuverability in the section of the navigable waterway where this measure is suggested.
- **Sills in the Apatin, Drava confluence, and Staklar sectors** – For all sectors, two sills with maximum depths of around 7 meters have been adopted. Increasing the number of weirs did not significantly improve navigability at critical points to justify the construction of additional structures.

6.9. Conclusion

In conclusion, this study has comprehensively assessed the critical navigational bottlenecks along the joint Serbian-Croatian stretch of the Danube River, integrating both engineering and environmental perspectives. The analysis identified key problematic areas where sediment accumulation and unstable channel morphology compromise the required 200-meter fairway. A suite of nature-inclusive structures—such as chevrons, detached groynes, sills, and sidearm channels— was proposed to restore flow dynamics while preserving ecological integrity. Preliminary evaluations indicate that these measures can enhance navigational efficiency, minimize maintenance costs, and minimize environmental impact and even create beneficial microhabitats for aquatic and riparian species. The study's multi-scenario approach, detailed in Table 41, presents a baseline "Do Nothing" scenario alongside scenarios for structural and revitalization measures, fairway realignment, and full structural intervention.

Table 41 - Summary all four scenarios and training structures envisaged for analysis

Scenario	Apatin	Čivutski rukavac	Drava Confluence	Aljmaš	Staklar
Scenario 1 (S1) – Do nothing	-	-	-	-	-
Scenario 2 (S2) – Structural and revitalization measures	2 Chevrons, 2 sills	-	Sidearm channel	Sidearm channel	-
Scenario 3 (S3) – Fairway realignment	-	-	-	-	-
Scenario 4 (S4) – Only structural measures	2 Chevrons, 2 sills	1 Groyne	2 sills	-	2 sills

These scenarios encapsulate a range of interventions aimed at optimally balancing sediment management with ecological preservation through targeted hydraulic modifications. Robust hydraulic modeling, using both 1D and 2D techniques, will be essential to further test these hypotheses and assess their long-term performance.

Continuous monitoring and adaptive management will help ensure that potential short-term ecological disturbances are minimized and that the implemented solutions remain effective over time. The integration of stakeholder input and environmental regulations shall support the credibility and practical relevance of the proposed measures. Ultimately, by reconciling navigational requirements with sustainable environmental practices, the project paves the way for a resilient and dynamic river system that supports both safe navigation and rich biodiversity.

CHAPTER 7. – 2D MODELING AND APPLICATION OF MCA

7.1. Introduction

Finding the optimal scenario for resolving navigability issues while considering environmental protection criteria on the considered section of the joint Serbian-Croatian stretch of the Danube, from Apatin to Staklar, will be determined according to the adopted methodology for Multi-Criteria Analysis (MCA). The primary tool used in this analysis is a 2D sediment transport model. This model enables numerical simulations of changes in the Danube riverbed geometry under different boundaries and initial conditions. In other words, the model can be used to analyze the impacts of measures that alter the flow pattern on morphological changes, and consequently on navigability and ecology.

This report will first briefly describe the adopted numerical model, followed by the presentation of the results of numerical simulations for the analyzed scenarios, involving either the implementation of different measures to improve navigability or the absence of measures ("Do nothing" scenario). The scenarios with measures were defined in the previous report, where variant solutions were proposed. Therefore, this report will present the procedure for defining the final scenarios. As previously explained, these final scenarios will be ranked at the end of the report according to the adopted MCA methodology.

7.2. Model description

For the purposes of the 2D sediment transport numerical simulations, a model implemented within the software package BASEMENT is used. The model is based on the combined solution of the 2D flow equations (the hydraulic part of the model) and the sediment transport equations using the finite volume method. The model domain covers the section of the Danube from sector Apatin to sector Staklar, specifically from station rkm 1410.0 at the upstream end of the model to station rkm 1368.5 at the downstream end (Figure 107). In all scenarios, the model consists of about 700,000 computational cells (volumes) with triangular shapes in the horizontal plane (Figure 108). For the calibration and verification purposes, however, a shortened model was used, covering the section from station rkm 1389.0 to the downstream end of the entire section (Figure 109).

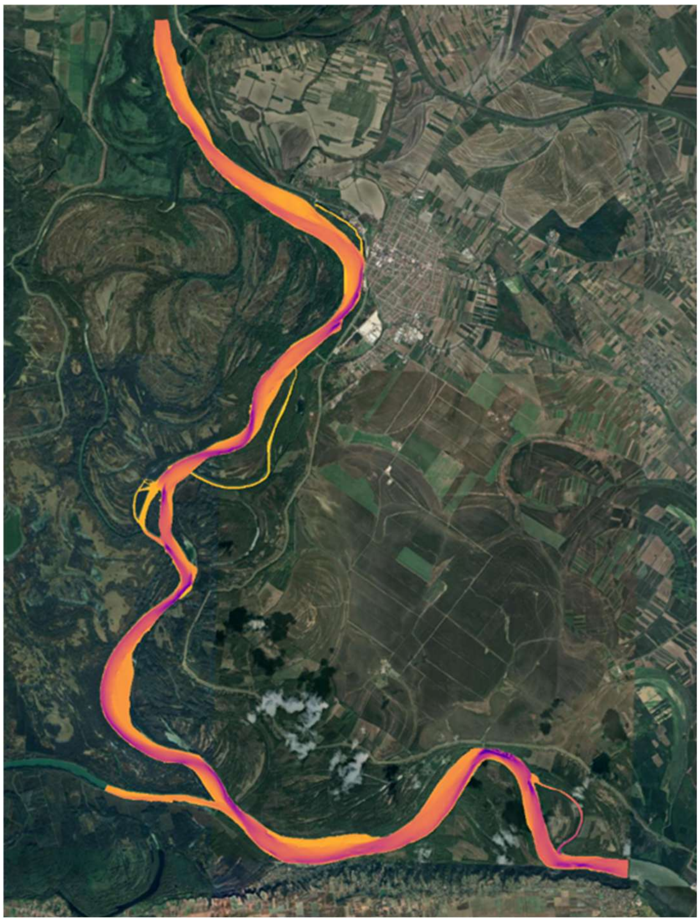


Figure 107: Computational domain for numerical simulations (with DEM for Scenario 1)

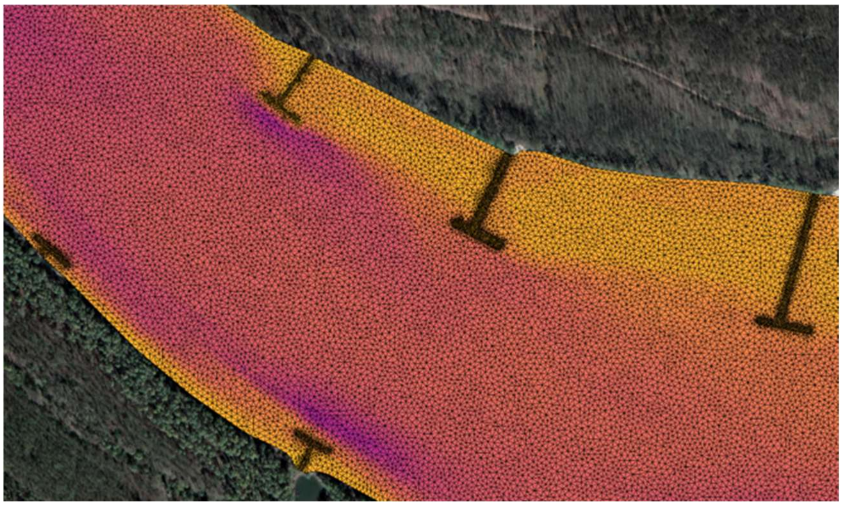


Figure 108: Computational mesh (portion of the sector Aljmaš)

For the hydraulic part of the model, a 2D flow mathematical model is applied, based on depth-averaging of the 3D flow equations and time-averaging the effects of turbulence (Reynolds equations). Unsteady flow equations are used, but for the initial condition for the sediment transport calculation, the solution of the previous steady flow simulation is employed.

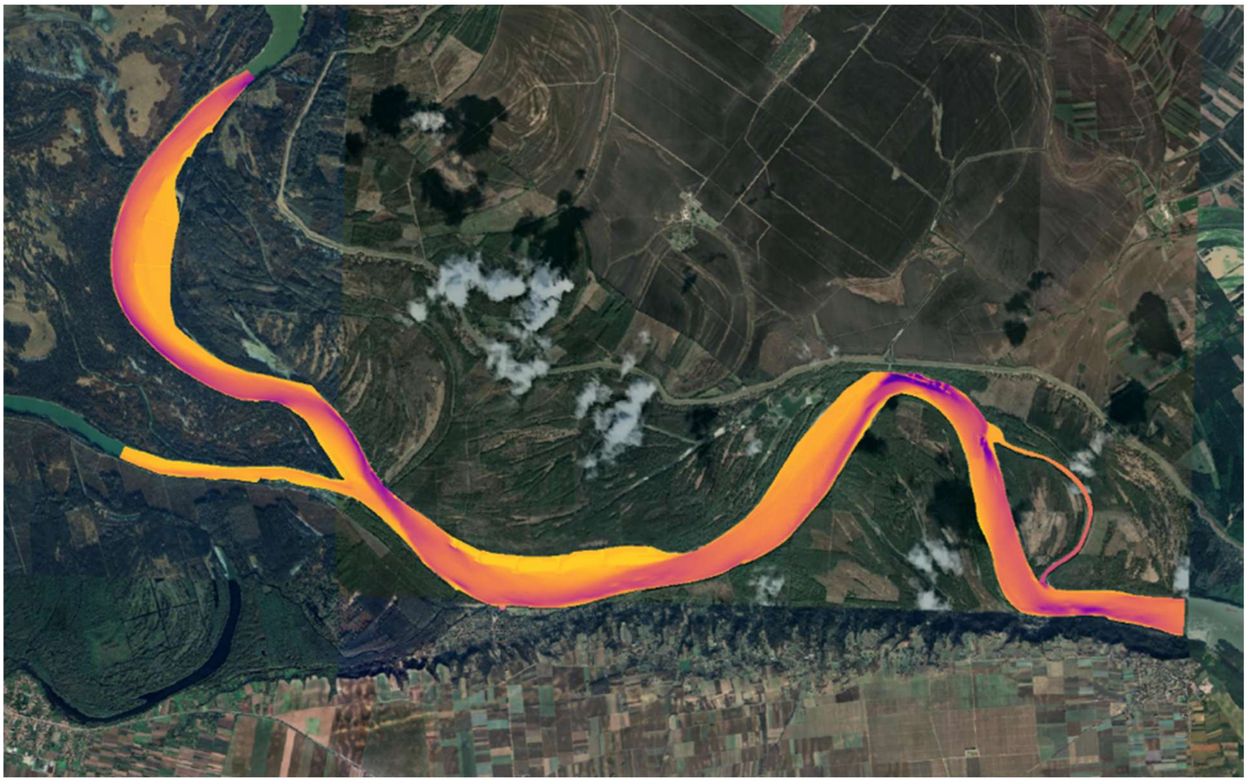


Figure 109: Computational domain for calibration (with DEM)

Thus, once the initial conditions for the riverbed deformation calculation are obtained, alongside the flow equations, the sediment continuity equation is solved, taking into ac-count the movement of sediment grains either in suspension or as bedload transport. Based on the difference between the sediment inflow and outflow in the control volume of the riverbed, the change in the bed elevation is determined. The conceptual sequence of sub-steps within one simulation step in sediment transport model is shown in Figure 110.

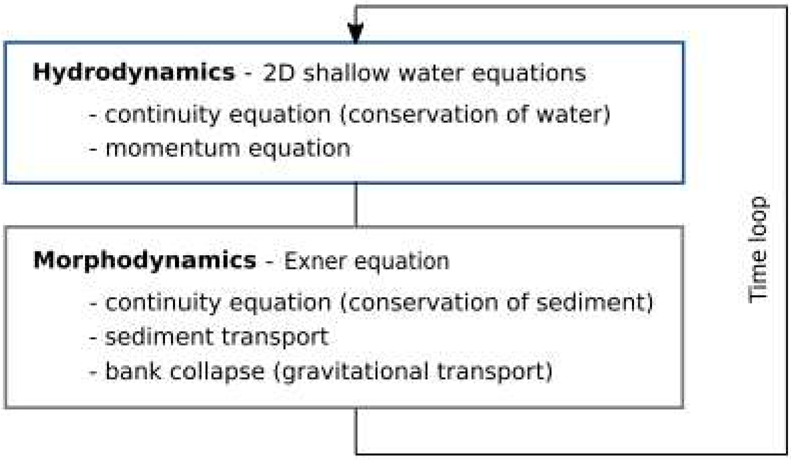


Figure 110: Overview of the Basement numerical model (Basement, System manual)

7.2.1. Boundary and initial condition

In order to account for the effects of the flow upstream and downstream of the considered domain in the numerical simulations, boundary conditions must be defined. At the up-stream end, in all simulations, a hydrograph (flow variation over time) is prescribed for the hydraulic part of the model, with a final value corresponding to the desired discharge, maintained long enough to establish steady flow. Similarly, at the downstream end, a stage hydrograph with a final value of the desired water level is prescribed. This water level value is adjusted to match the rating curve at the Aljmaš gauging station (HS Aljmaš) or, during the calibration process, with the recorded water level at the Bogojevo gauging station (HS Bogojevo).

For the "morphological" part of the model, the upstream sediment inflow and the down-stream sediment transport are defined for both bedload and suspended load. For bedload transport, transport capacities are prescribed for both boundary conditions. The upstream boundary condition for suspended load is specified as an influx correlated with previous measurements of suspended sediment, while at the downstream end, a zero-gradient condition for sediment concentration is applied.

7.2.2. Parameters for hydraulic part of the model

The main parameters of the flow model are the friction resistance coefficients and the kinematic turbulent viscosity coefficient. Changes in the value of the first coefficient significantly affect the longitudinal variation of the water level, while changes in the second coefficient influence the velocity distribution. For the calculation of friction resistance, the Chézy formula was used, incorporating an effective roughness (which is also influenced by the shape of sediment formations on the riverbed). This roughness was determined during the model calibration process. Regarding the effects of turbulence, an approach was adopted where a constant turbulent viscosity is assumed, which was also determined through calibration.

7.2.3. Parameters for morphological part of the model

The primary parameter for sediment transport is the sediment grain size. In the model, the granulometry is represented by a representative grain size, determined as the mean diameter of the sediment granulometric composition (approximately 0.25 mm) collected from the riverbed, with this grain size also having a significant presence in the granulometry of the suspended sediment (Figure 111). The justification for this approach lies in the fairly uniform granulometric curves of the sampled sediment from riverbed.

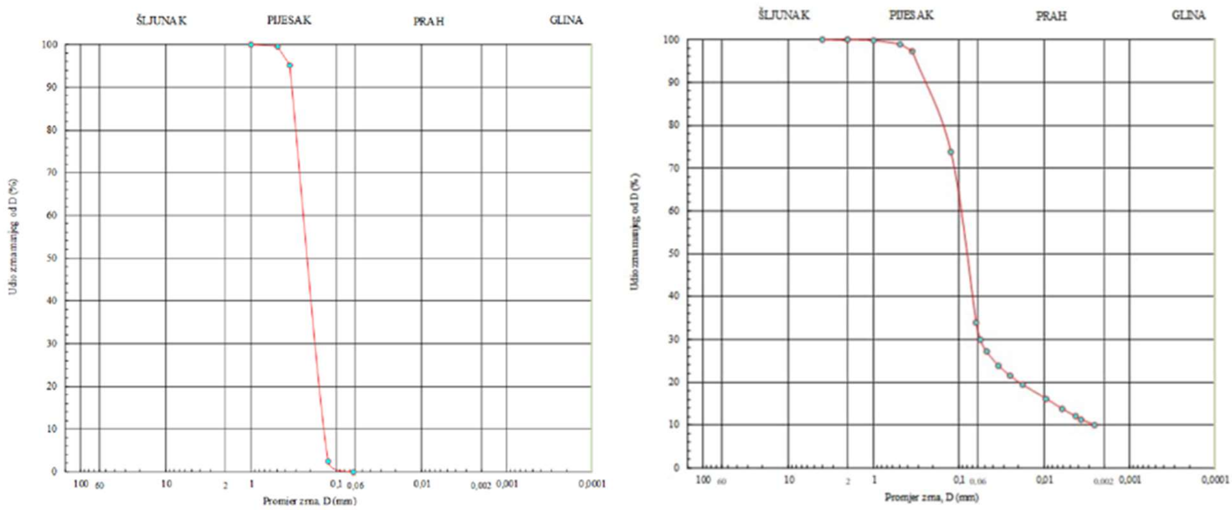


Figure 111: a) Granulometric curve of the sampled material from the Danube riverbed bedload (left) and b) suspended sediment curve (Hidroing & GF Zagreb, 2023) (right)

The second most important parameters are the critical shear stresses for initiating grain movement from the riverbed and for lifting sediment into suspension, the shear stress correction factor (which accounts for the relationship between the representative grain size and the effective roughness, considering the size of bedforms), and the diffusion coefficient for suspended sediment, which influences the degree of transverse and longitudinal mixing of suspended sediment due to concentration gradients. The values of these parameters were determined according to the procedure explained below.

7.2.4. Calibration and verification

For model calibration, velocity and sediment transport data collected in 2023 by Hidroing and Faculty of Civil engineering Zagreb were available. The measurements were conducted only in the Drava confluence zone. The results of velocity and sediment transport measurements from September 2023 were used, as these correspond to the period for which the bathymetry in the model is valid. The calculated values of velocity vector magnitudes are shown in Figure 112 (left distribution), while the distribution of measured velocities from the measurement campaign conducted in September is presented in Figure 112 (right distribution).

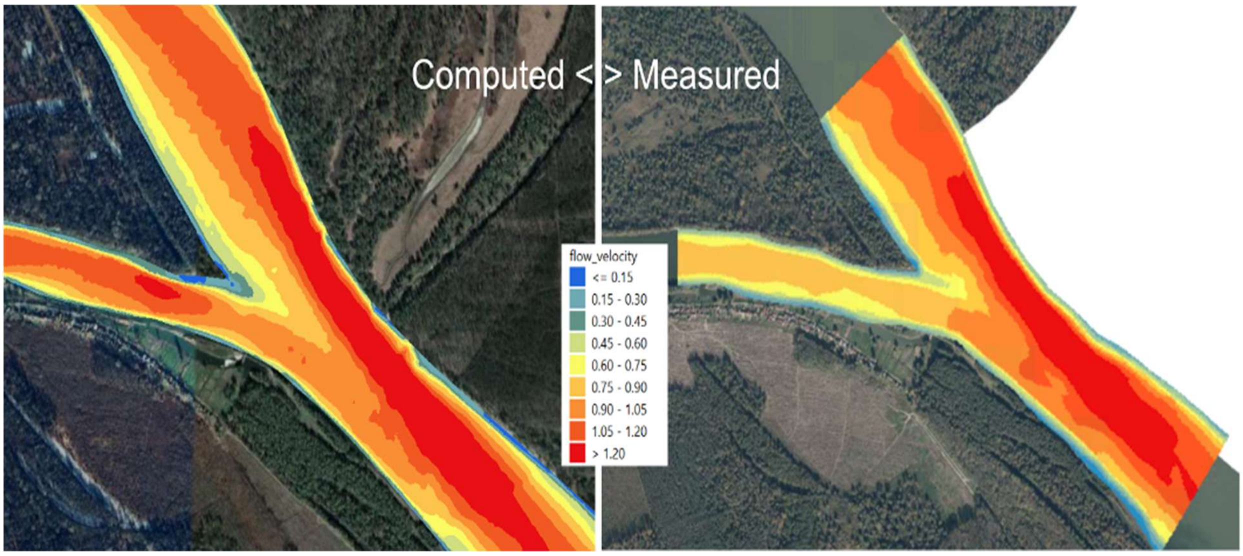
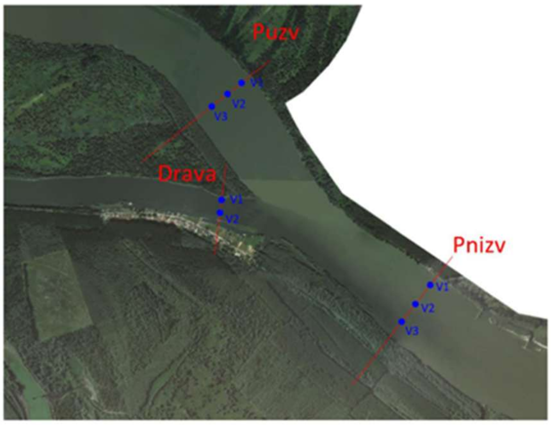


Figure 112: Comparison of Calculated and Measured Velocity Distribution in the Drava Confluence Sector (Hidroing, 2023)

Due to significant variations in geometry within the confluence zone even over the period of a single year, the possibilities for model verification are limited. However, assuming that during flows higher than those in the low-water domain, bathymetric changes have a lesser impact, measurements from May 2023 were used for model verification. For this measurement campaign, somewhat larger deviations were obtained, as expected, compared to the fourth campaign from September 2023. However, no significant differences were observed in a qualitative sense.

Given that discrepancies in the velocity distribution along the Drava were observed in the hydraulic part of the model — likely due to significant changes in the Drava riverbed geometry over a short period that were not monitored — special attention was paid, during the determination of sediment transport parameters, to achieving agreement with the measured values of bedload and suspended sediment transport at the upstream Danube cross-section (Figure 113). Additionally, qualitative agreement in the distribution of suspended and bedload sediment across the river width was also considered.

From Figure *113*, a difference in discharges during the measurements can be observed (the downstream discharge is not equal to the sum of the two upstream discharges). This difference can generally be explained by the unsteady flow conditions and the fact that the measurements were not conducted simultaneously, i.e., at the same time in all profiles.



Mjerenje	Profil	Q [m³/s]	Q_{VN} [kg/s]	Q_{SN} [kg/s]
m01	Puzv	4009	10.5	134.8
	PDrava	1336	4.4	47.1
	Pniz	5373	5.1	188.6
m02	Puzv	1963	8.5	61.1
	PDrava	531	7.9	18.0
	Pniz	2797	5.0	90.4
m03	Puzv	1348	5.0	42.3
	PDrava	363	10.2	12.9
	Pniz	1863	3.4	62.7

Figure 113: Results of Bedload (QVN) and Suspended Load (QSN) Transport Measurements in the cross-sections Puzv (upstream section on the Danube), Pniz (downstream section on the Danube), and Drava (section on the Drava) - the results from measurement campaign labeled m03 were used for calibration (Hidroing & GF Zagreb, 2023)

7.3. Numerical results

A set of measures or the absence thereof is considered as a scenario for which the initial channel geometry, subject to changes, is adopted. Numerical simulation is used to monitor changes in this initial geometry, and by comparing these changes, the scenarios are evaluated in the MCA.

The results for all scenarios will be presented by sectors of the fairway. This method of presenting the results was chosen to facilitate easier comparison of the effects of different solutions (scenarios) along each sector. The results are provided in the form of simulated velocity distributions and riverbed deformations in the horizontal plane under dominant dis-charge conditions. In short, the dominant discharge is the flow that has the greatest (dominant) influence on the formation of the riverbed geometry. According to this concept, if the riverbed is subjected to a constant dominant discharge over a certain period, it will result in riverbed geometry alterations that correspond to the long-term effects of varying flow and sediment transport characteristic of the natural water and sediment regime. For this discharge, a value of 2488 m^3/s was adopted for the upstream part of the Danube model (upstream of the Drava confluence), and 3039 m^3/s for the downstream part. The dominant discharge was obtained from an updated flow duration curve (Plavšić, 2024), using the duration value of 34% adopted in the study from 2013 (Consortium Witteeven+Boss).

7.3.1. Sector Apatin

The Apatin sector (from rkm 1,408.2 to 1,400.0 rkm) is the most upstream part of the computational domain. The main issue from the navigation perspective is the right downstream part of the river bend, where the survey cross-section EP 32 is located (Figure 114). In this area (at the EP32 cross-section) and under Scenario 1 ("Do nothing"), sediment deposition occurs. Another identified issue within the sector is the unstable sandbar at cross-section EP 27, where, according to simulations for Scenario 1 under dominant discharge, sedimentation also occurs. However, the problem concerning the stability of the sandbar —

specifically its movement both vertically and horizontally — requires attention, and countermeasures have been analyzed in this study.

With the proposed solution in Scenarios 2 and 4, portion of the flow in the river bend near Apatin is redirected toward the right bank, which can be indirectly observed by comparing velocity distributions in Figure *115* and Figure *116* (and directly in Figure *117*), where increased flow velocities are clearly noticeable in this area. This increase in velocity also explains the erosion near cross-section EP32 in the scenarios with measures, which, according to the simulation model, results in improved navigation conditions. Increased erosion compared to Scenario 1 along the right bank of the bend near Apatin is directly observed in the Figure 120 showing the differences in bed elevations after morphological changes.

The proposed solution for the second issue in the sector consists of two chevrons placed upstream of cross-section EP 27, between the fairway and the left bank. As shown in the velocity distribution figures, the chevrons create an area of lower flow velocities, thereby establishing hydraulic conditions favorable for sediment deposition. This is confirmed by the sediment transport simulation results, which show increased sediment accumulation in the problematic sandbar zone (Figure 118, Figure *119* and Figure 120). Additionally, the chevrons enhance flow along the left bank, and according to the simulations, create conditions for erosion in this area — leading to the development of flow zones that can remain submerged even at significantly lower discharges. Combined with the stabilization of the sandbar, this will create additional channel for low-flow conditions which would lead to more diverse river morphology.

Based on the presented results, it can be concluded that the proposed measures are expected to have positive effects on navigation and potentially on ecology, which is discussed in more detail in the chapter describing the MCA.

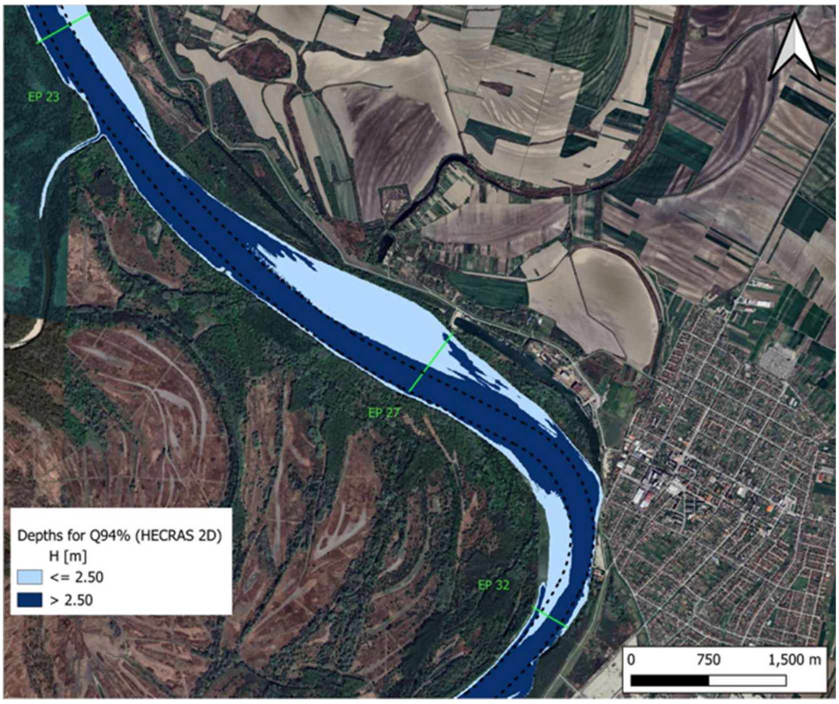


Figure 114: Depths at low navigable water levels for Apatin sector

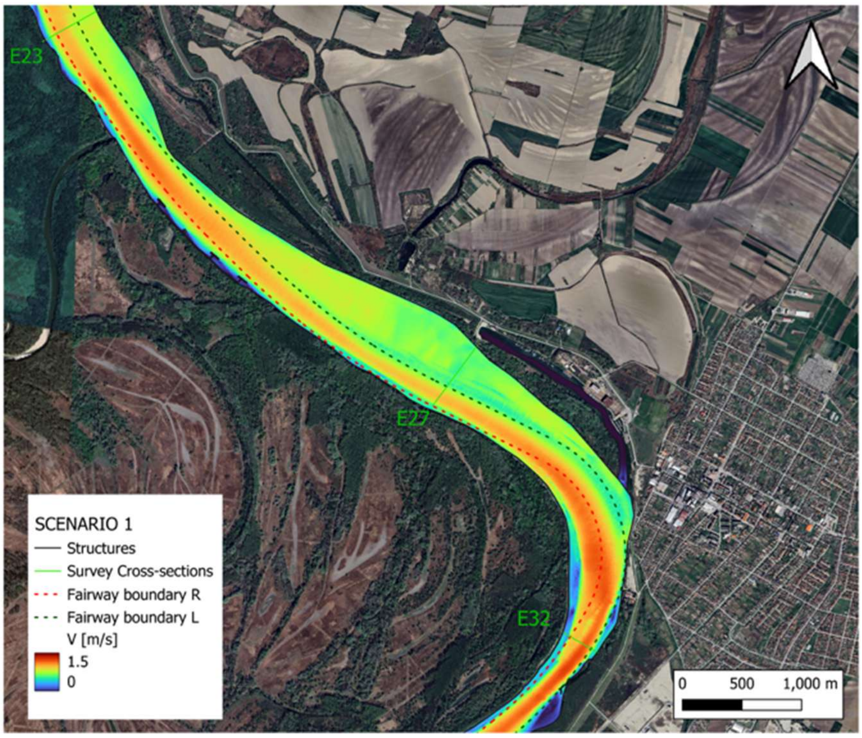


Figure 115: Distribution of depth-averaged velocities in the Apatin Sector for Scenario 1

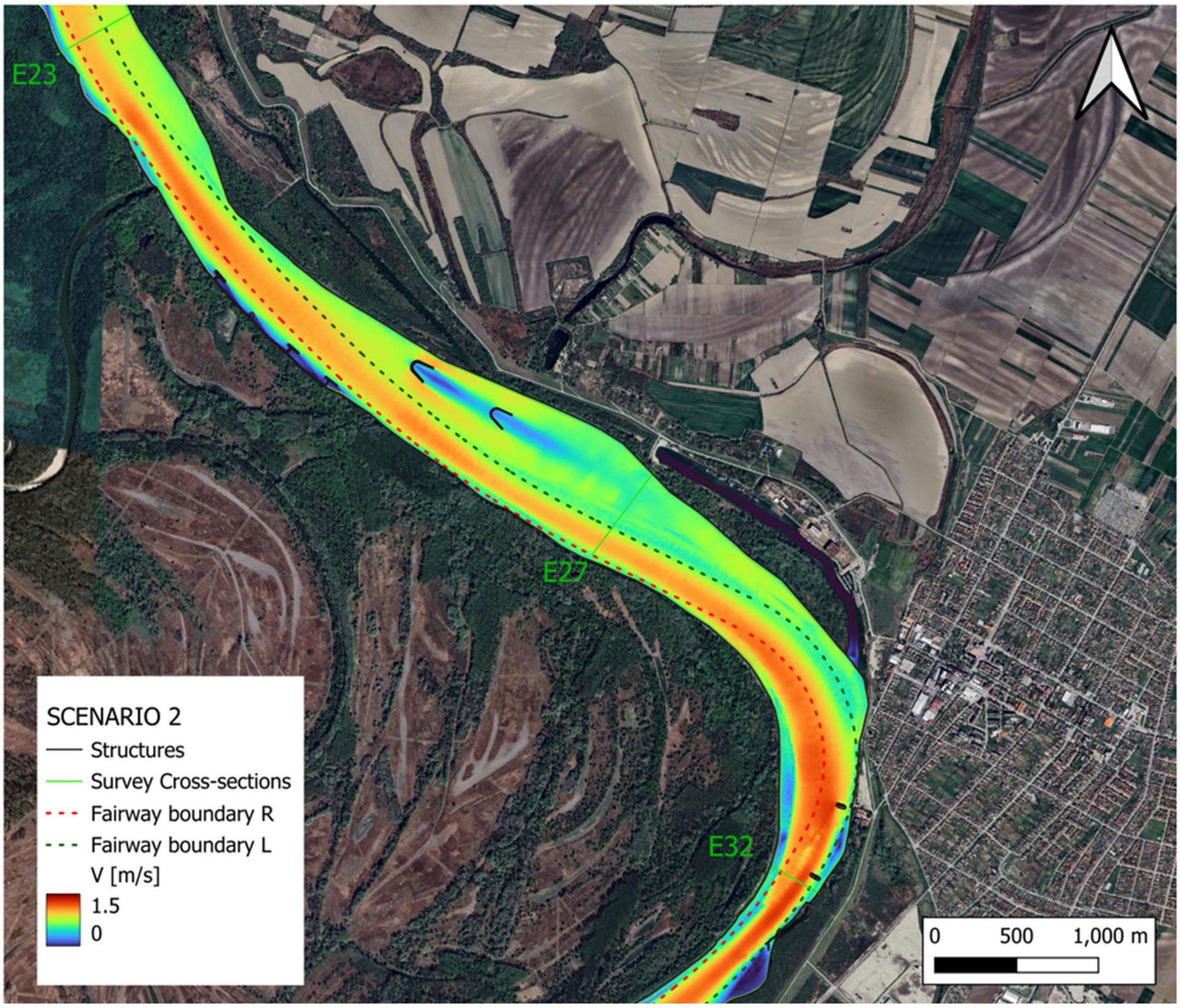


Figure 116: Distribution of depth-averaged velocities in the Apatin Sector for Scenarios 2 (almost identical results are valid for Scenario 4)

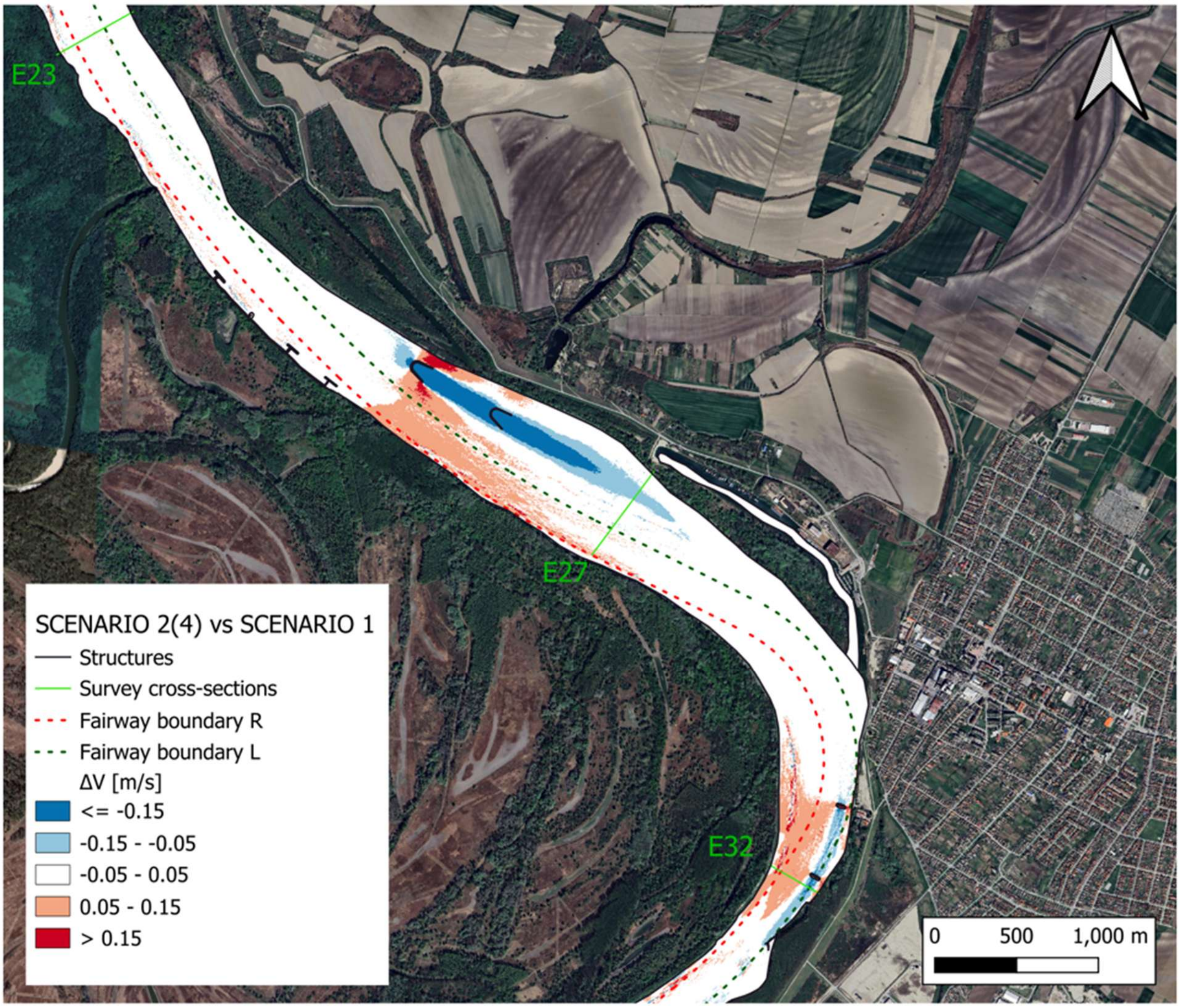


Figure 117: Differences in velocities between Scenario 2
(almost identical results for Scenario 4 and Scenario 1)

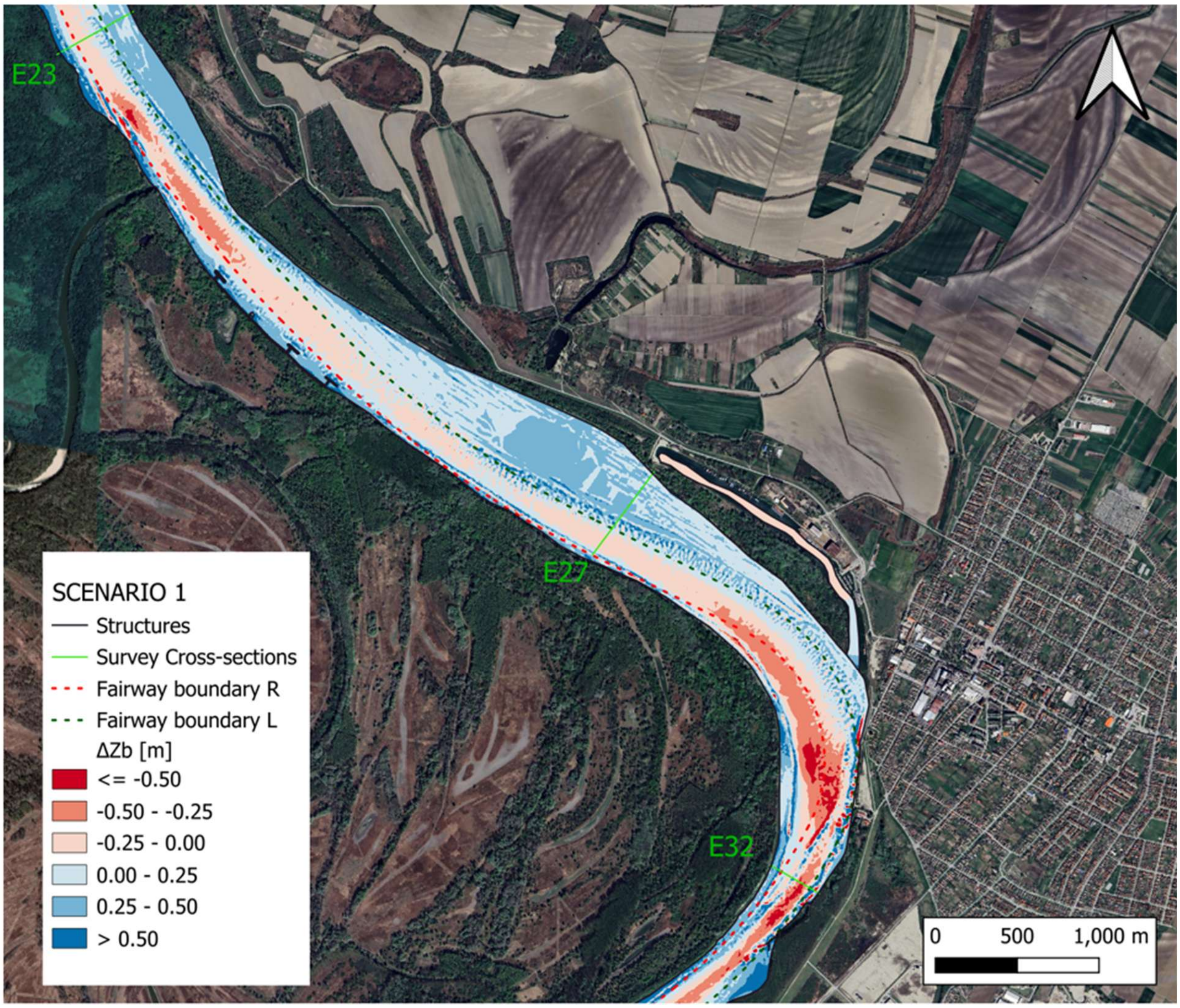


Figure 118: Riverbed vertical alterations in Apatin sector for Scenario 1

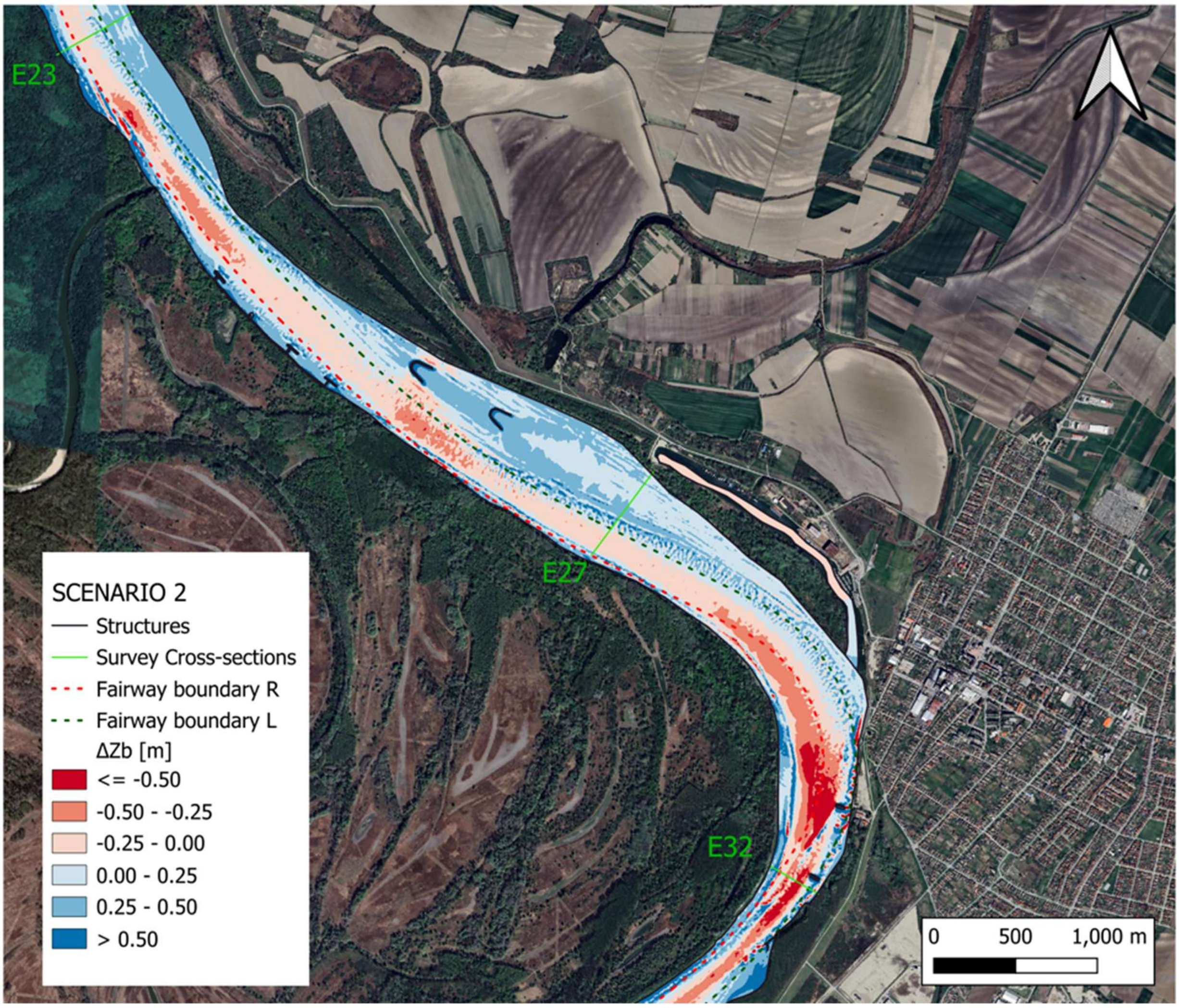


Figure 119: Riverbed vertical alterations in Apatin sector for Scenarios 2 (almost identical results for Scenario 4)

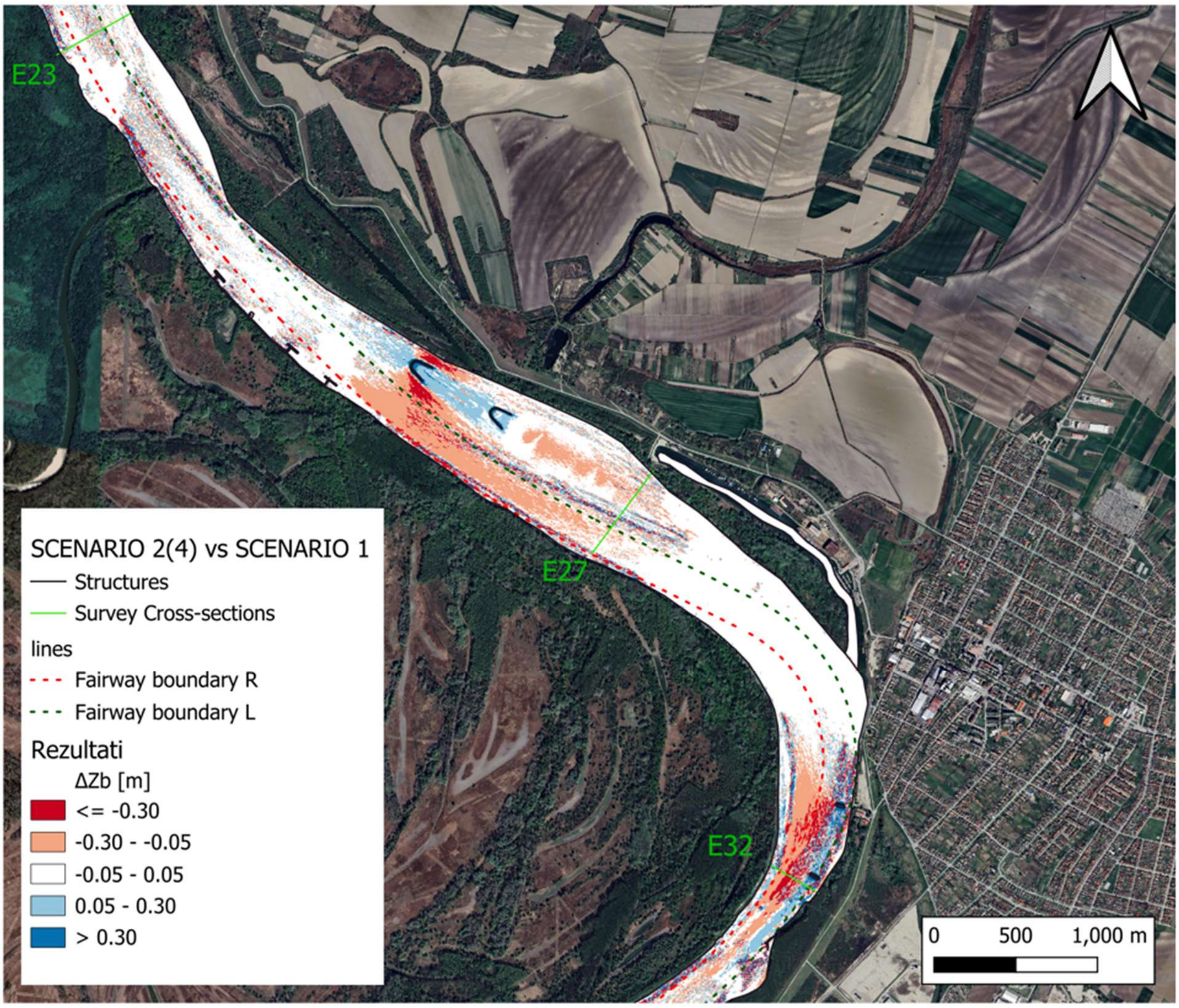


Figure 120: Differences in bottom elevations between Scenario 2 (almost identical results for Scenario 4) and Scenario 1 (end of simulation state)

7.3.2. Sector Čivutski rukavac

The downstream sector adjacent to the Apatin sector has also been identified as critical. The Čivutski rukavac sector (from 1,397.2 rkm to 1,389.0 rkm) is a section where, due to the narrower river width and existing structures, there was very limited space for proposing new measures. Therefore, in this study, only one location was selected where a single river training structure is considered in Scenario 4. This structure primarily addresses the issue of insufficient depths along the right edge of the fairway between cross-sections EP 41 and EP 47 (Figure 120).

The results of the analysis considering different types of groynes (shortened model) are presented first. The calculated flow velocity distribution for the entire sector is shown in Figure 121.

The idea behind the river training structure in this sector is to redirect part of the flow from the side channels downstream of cross-section EP 41 toward the main river course (the fairway), thereby ensuring greater depths. The construction of several types of groynes was analyzed, located 580 meters downstream of cross-section EP 41 along the left bank of the Danube. Both rooted and detached groynes, with and without wings, were considered — resulting in a total of four types of groyne variants.

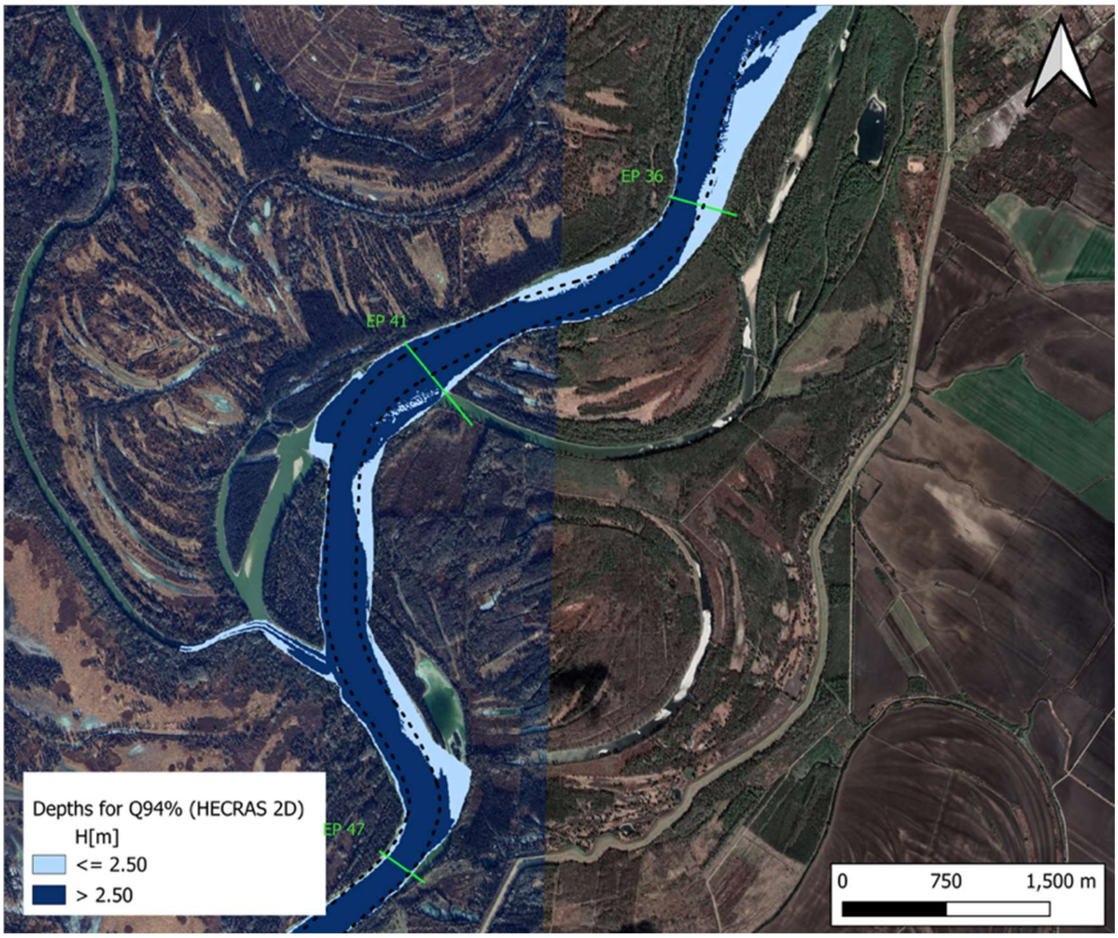


Figure 121: Depths at low navigable water levels for Čivutski rukavac sector

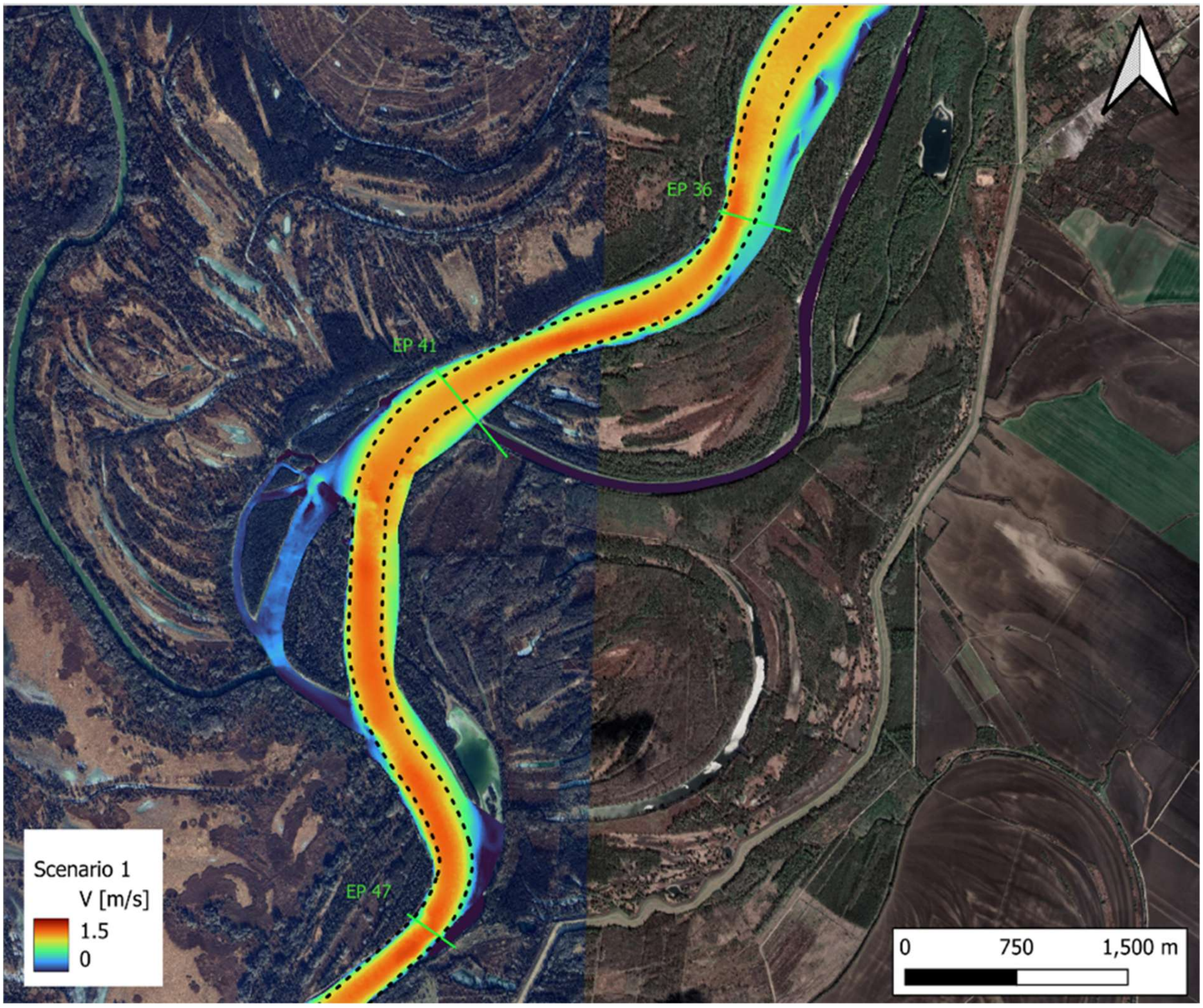


Figure 122: Distribution of depth-averaged velocity in Čivutski rukavac sector for Scenario 1

The hydraulic effects of the analyzed groyne types are shown in Figure 122, Figure 123, Figure 124 and Figure 125, which present the velocity distributions under dominant discharge conditions. As expected, in all variants, the groynes increase flow velocities in the main channel at the expense of reduced flow in the area downstream of the structure. Consequently, greater erosion occurs in the main channel downstream of the groyne compared to Scenario 1 (Figure 126, Figure 127, Figure 128, Figure 129 and Figure 130). In the case of detached groynes, the portion of flow between the groynes and the bank does not cause significant changes in velocities or riverbed deformations compared to the standard groynes, which makes them preferable, primarily due to their ecological benefits.

A separate analysis was conducted to examine the differences between groynes with wing (T-groyne) and without wing (both rooted). Under dominant discharge conditions, there were again no significant differences, so the comparison was supplemented with numerical flow simulations at $Q_{94\%}$ discharge — the discharge rate used to define low navigable water levels. Figure 131 and Figure 132 show the calculated velocities in the groyne zone at this discharge, for groynes with and without wings, respectively. The most notable difference is observed immediately downstream of the groyne, where the standard groyne creates a recirculation zone with significantly higher velocities. Given that the T-groyne variant (as expected) causes less disturbance to the velocity field and therefore represents a safer solution, this type of groyne is recommended.

Therefore, considering primarily the significant differences in terms of ecology and safety, the variant with a non-rooted T-groyne is adopted in Scenario 4.

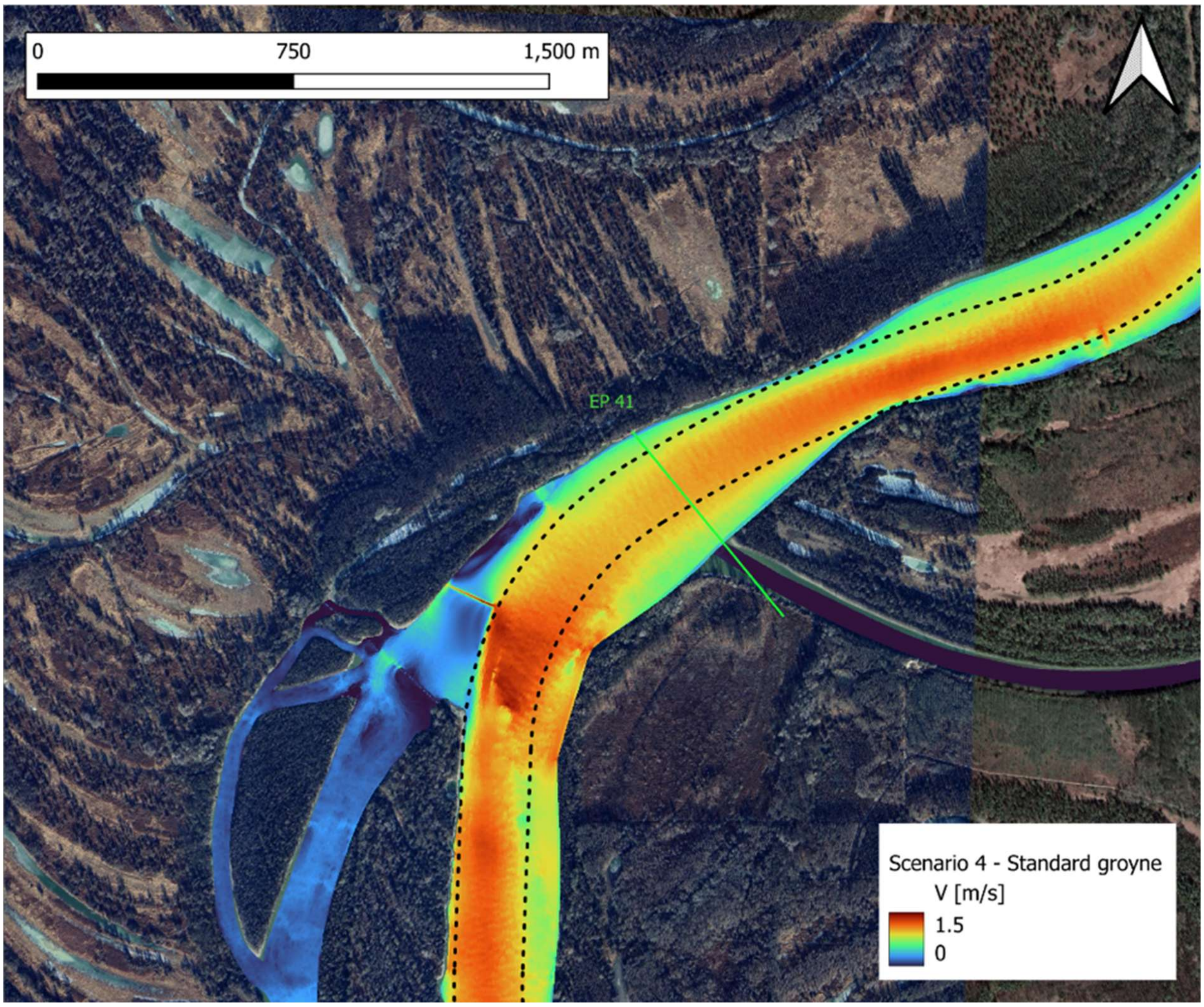


Figure 123: Velocity distribution at dominant discharge in the groyne zone of the Čivutski rukavac sector - Variant with rooted groyne without wings

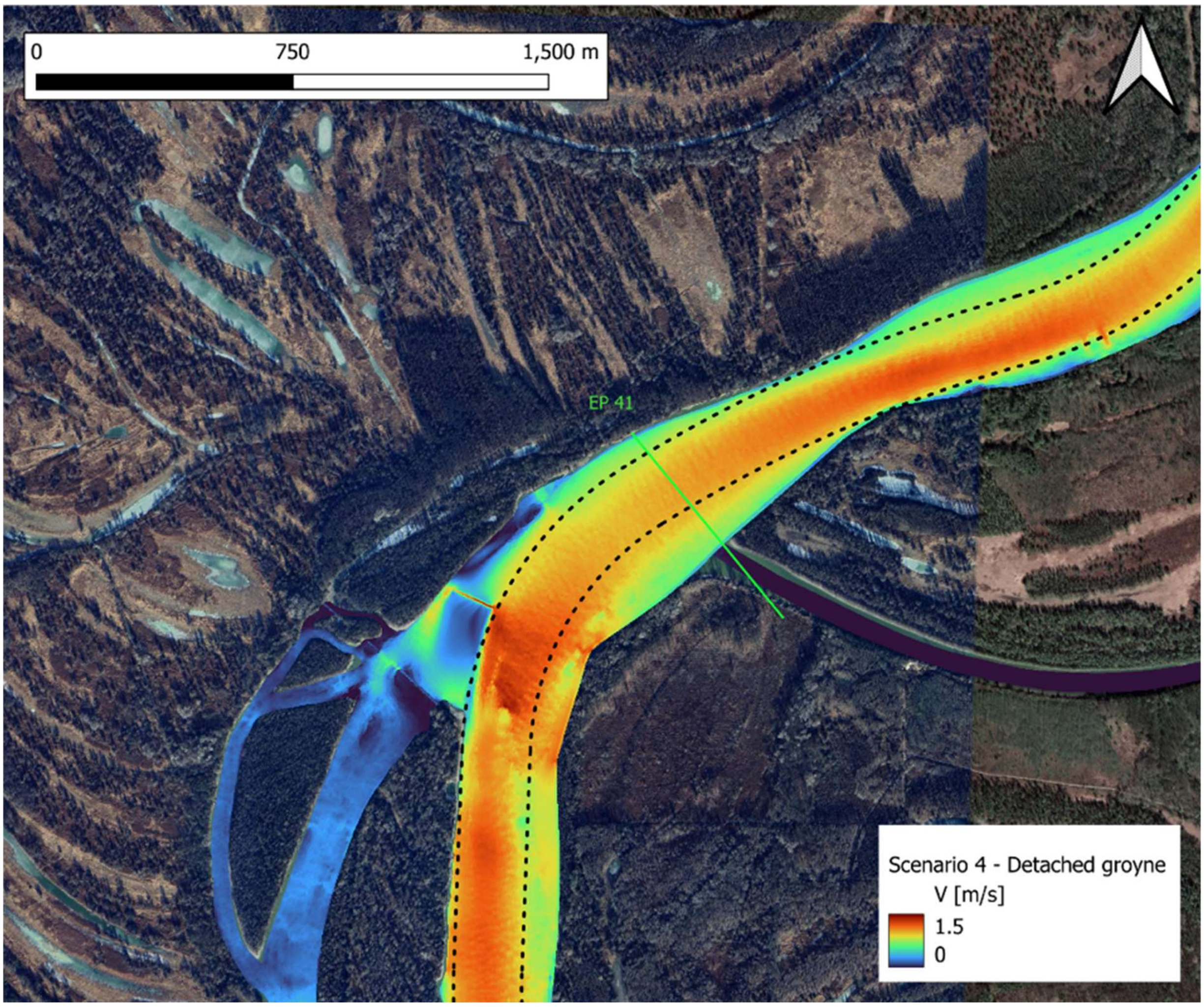


Figure 124: Velocity distribution at dominant discharge in the groyne zone of the Čivutski rukavac sector - Variant with detached groyne without wings

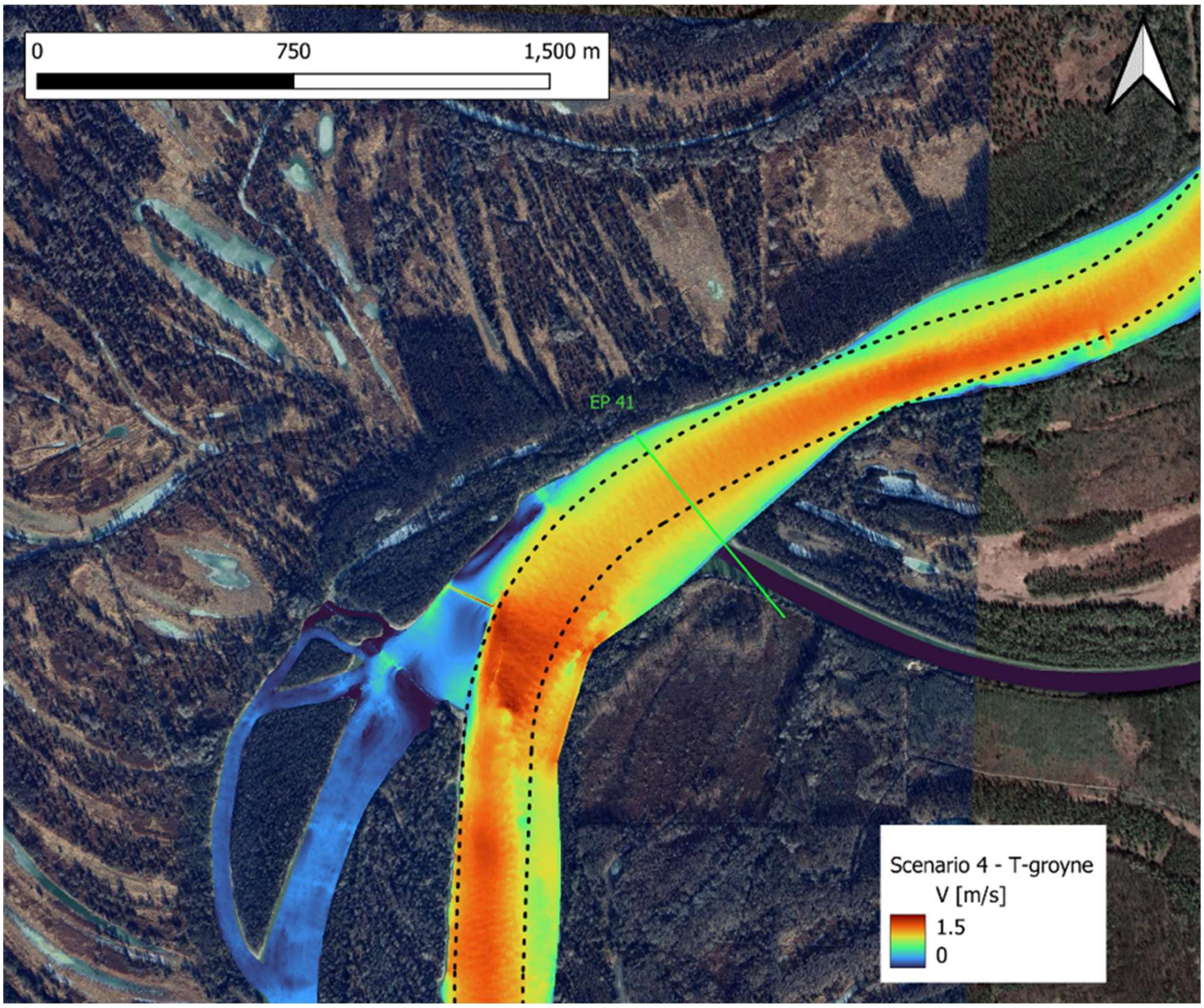


Figure 125: Velocity distribution at dominant discharge in the groyne zone of the Čivutski rukavac sector - Variant with rooted T-groyne

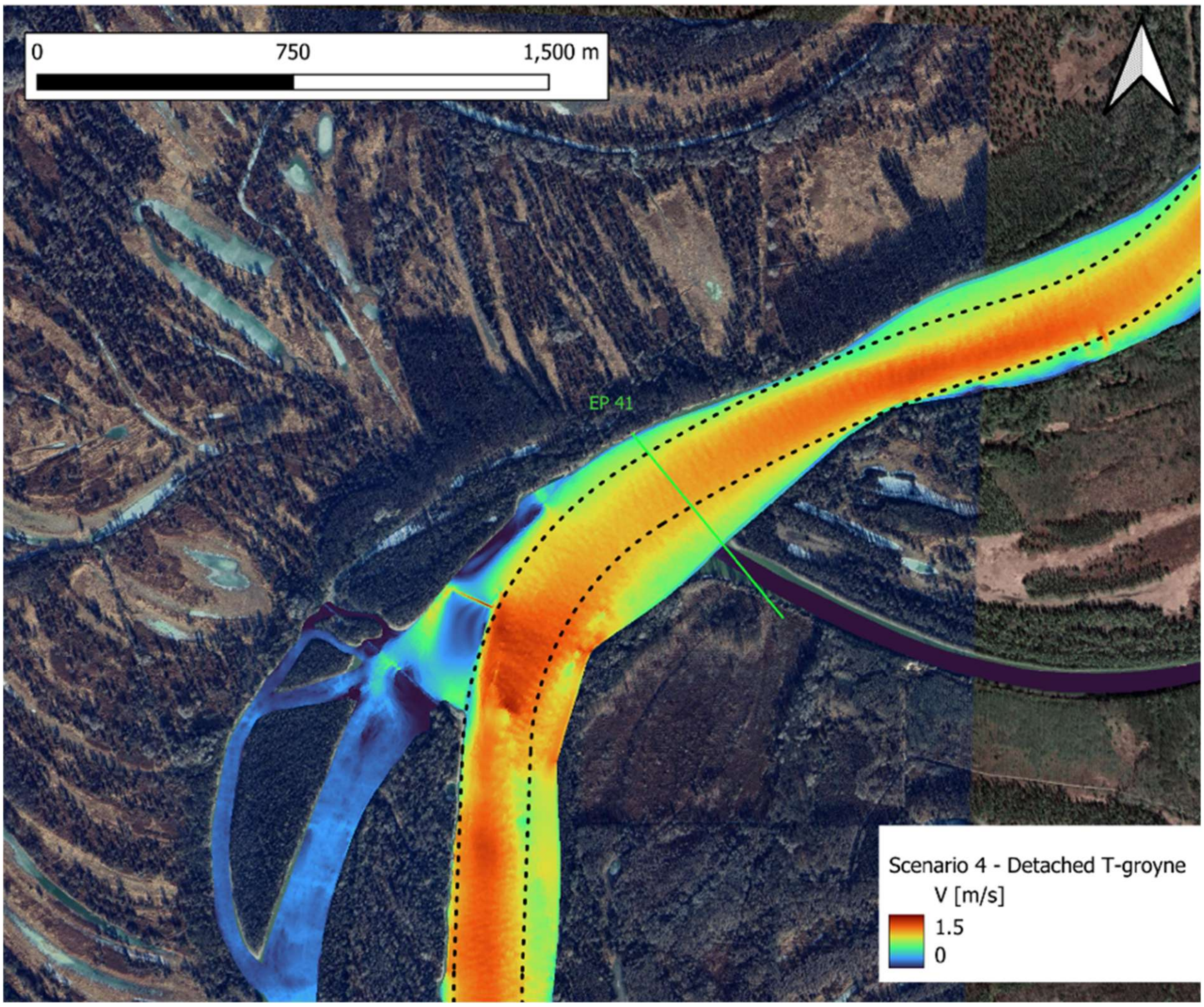


Figure 126: Velocity distribution at dominant discharge in the groyne zone of the Čivutski rukavac sector - Variant with detached T-groyne

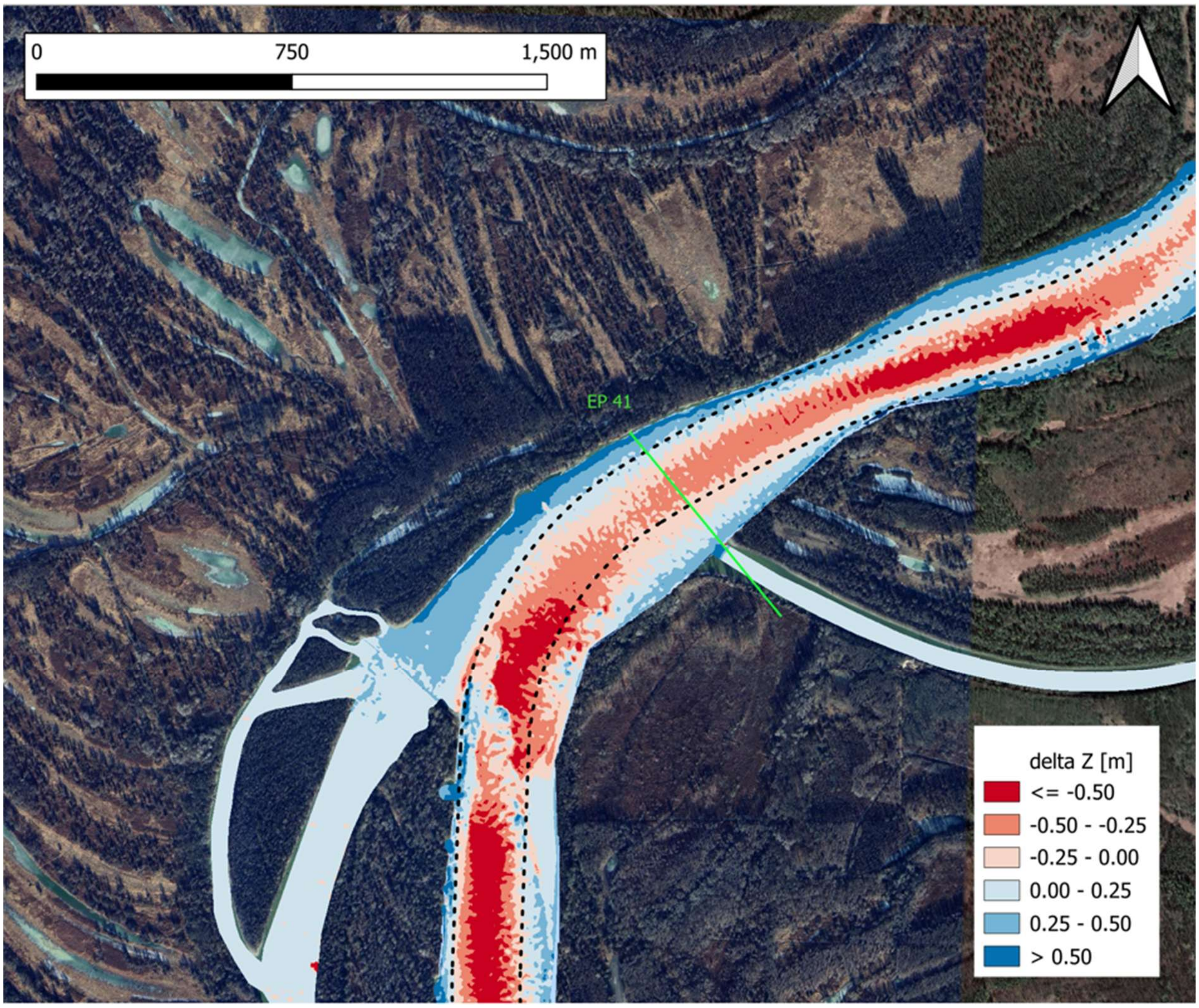


Figure 127: Riverbed vertical alterations at dominant discharge in the groyne zone of the Čivutski rukavac sector for Scenario 1

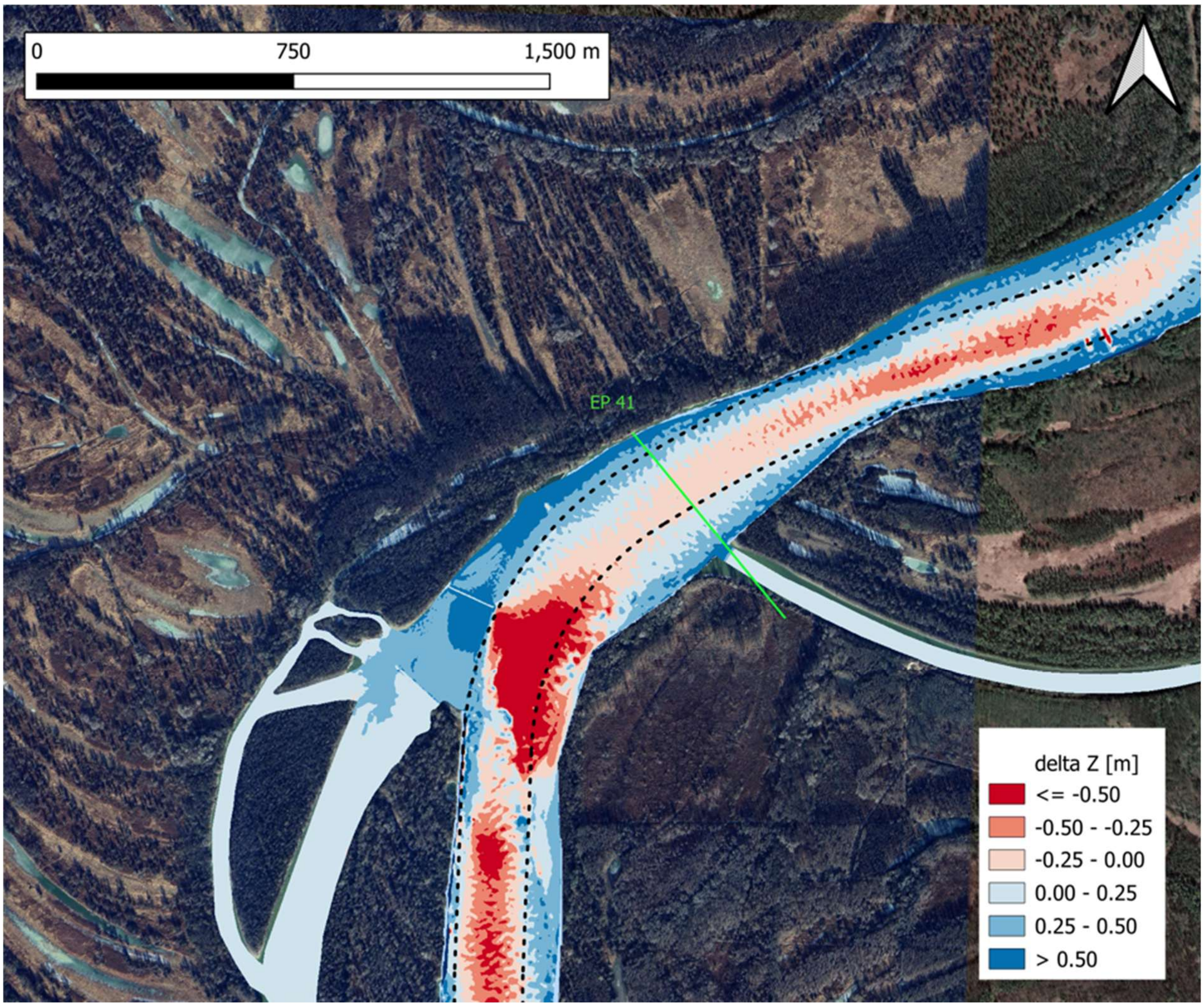


Figure 128: Riverbed vertical alterations at dominant discharge in the groyne zone of the Čivutski rukavac sector - Variant with rooted groyne without wings

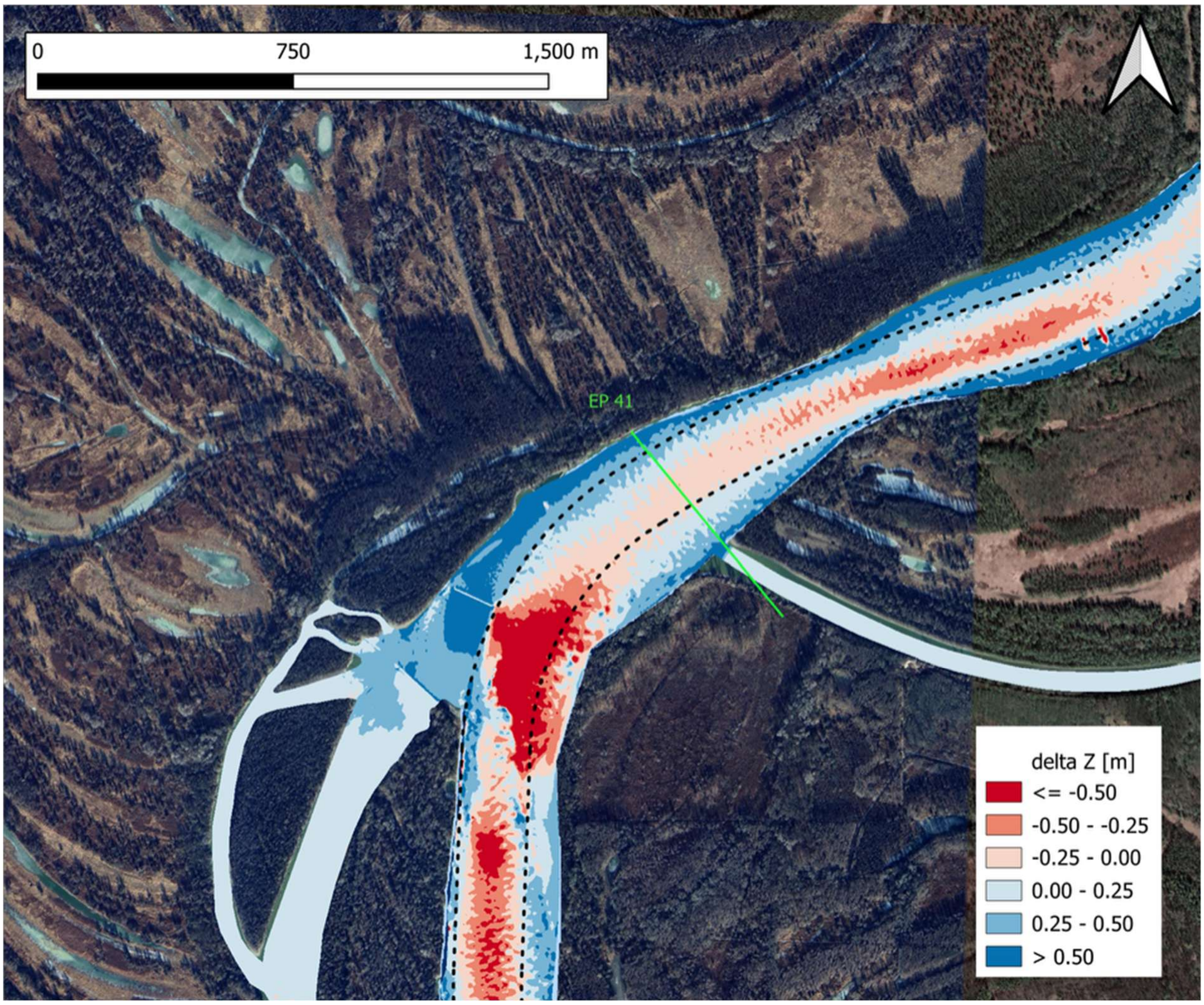


Figure 129: Riverbed vertical alterations at dominant discharge in the groyne zone of the Čivutski rukavac sector - Variant with detached groyne without wings

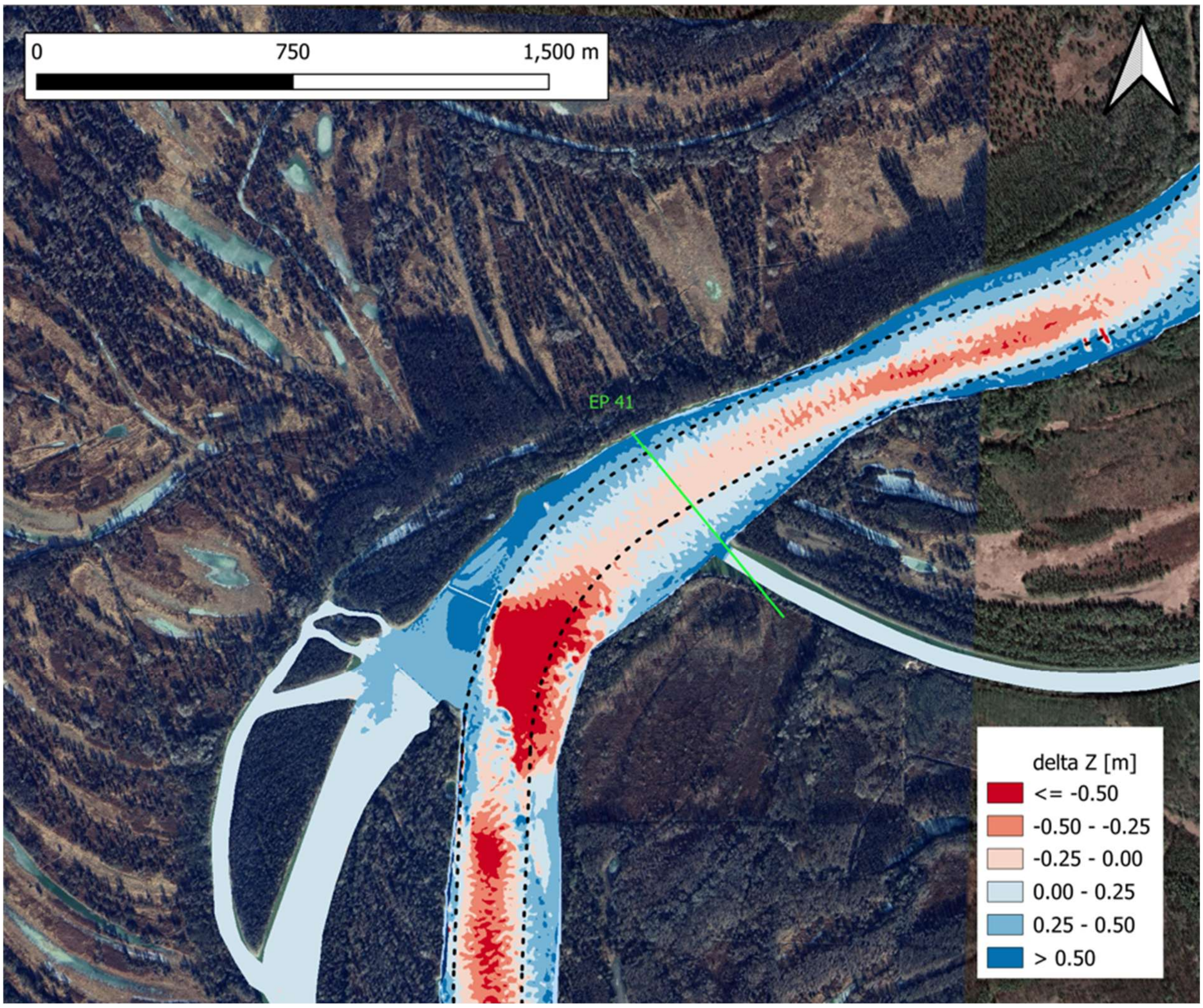


Figure 130: Riverbed vertical alterations at dominant discharge in the groyne zone of the Čivutski rukavac sector - Variant with rooted T-groyne

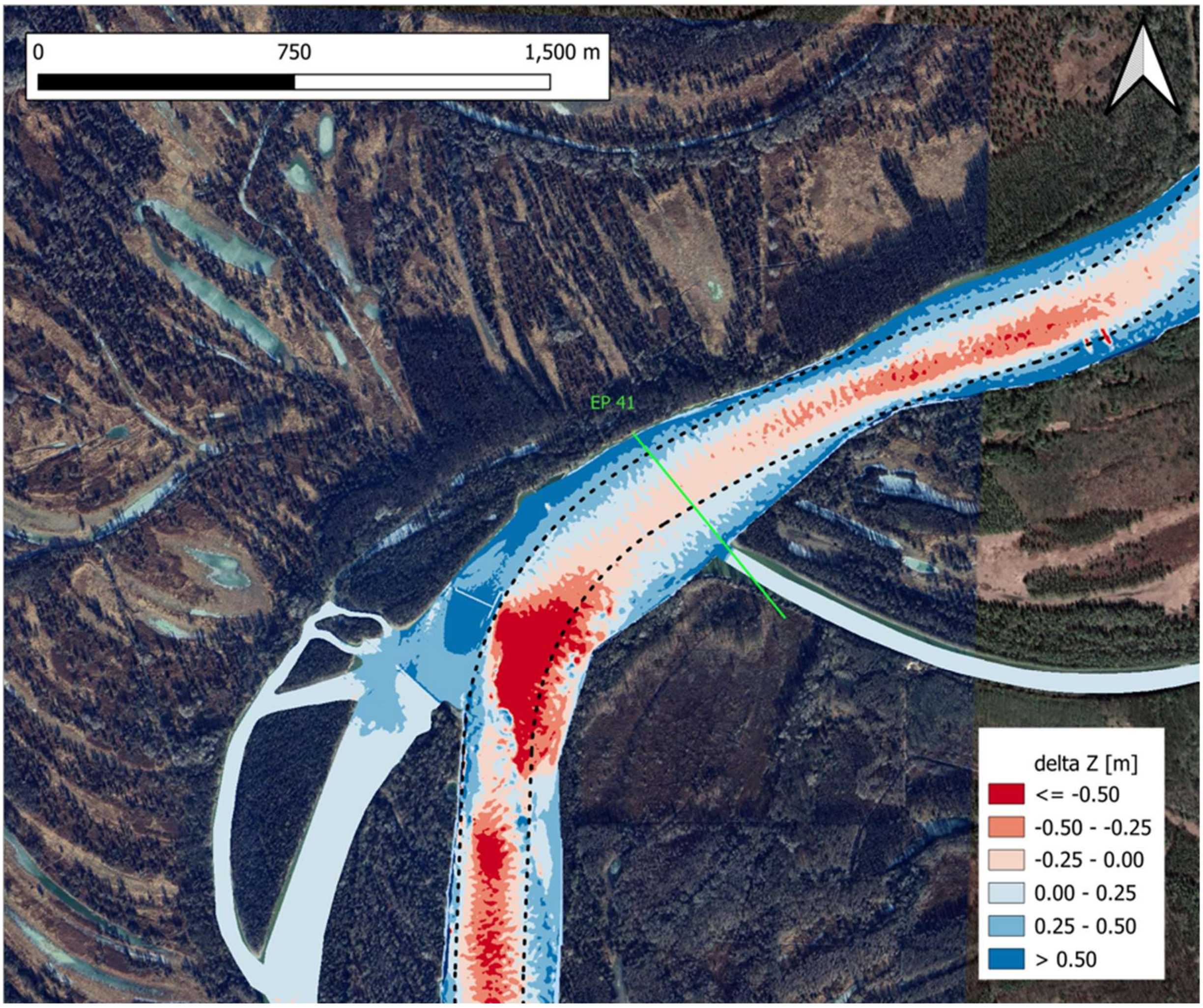


Figure 131: Riverbed vertical alterations at dominant discharge in the groyne zone of the Čivutski rukavac sector - Variant with detached T-groyne

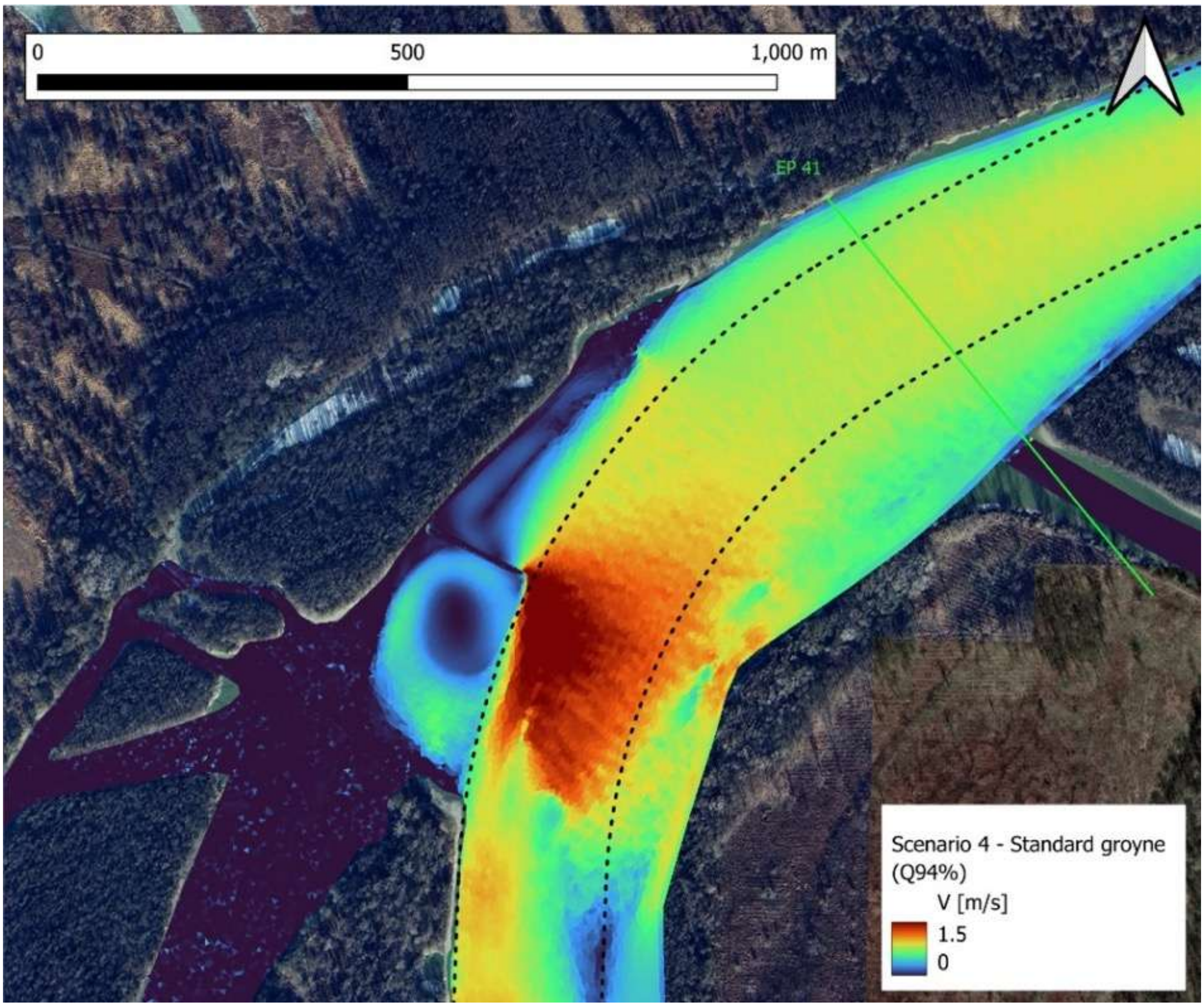


Figure 132: Velocity distribution at $Q_{94\%}$ discharge in the groyne zone of the Čivutski rukavac sector - Variant with groyne without wings

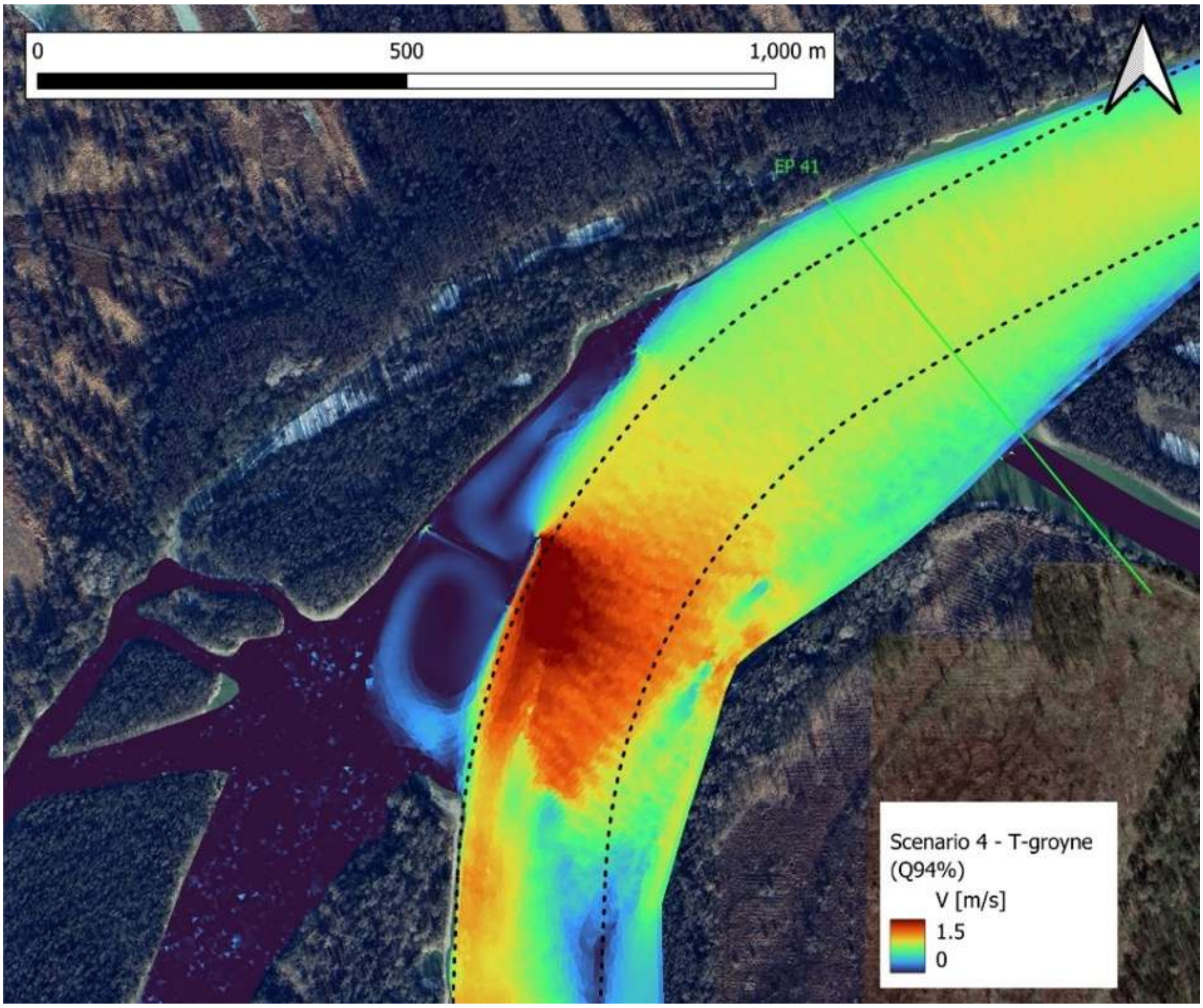


Figure 133: Velocity distribution at $Q_{94\%}$ discharge in the groyne zone of the Čivutski rukavac sector - Variant with T-groyne

The previous analysis served to determine the type of groyne to be used in the integrated model of the entire river section. The differences between the partial and integrated models, similar to the case of Apatin, are not significant, so only the differences in the calculated flow velocities and bed elevations after the riverbed deformation simulation will be presented. These differences are shown in Figure 134 and Figure 135, only between Scenarios 4 and 1, given that no significant differences were observed between Scenarios 2 and 1.

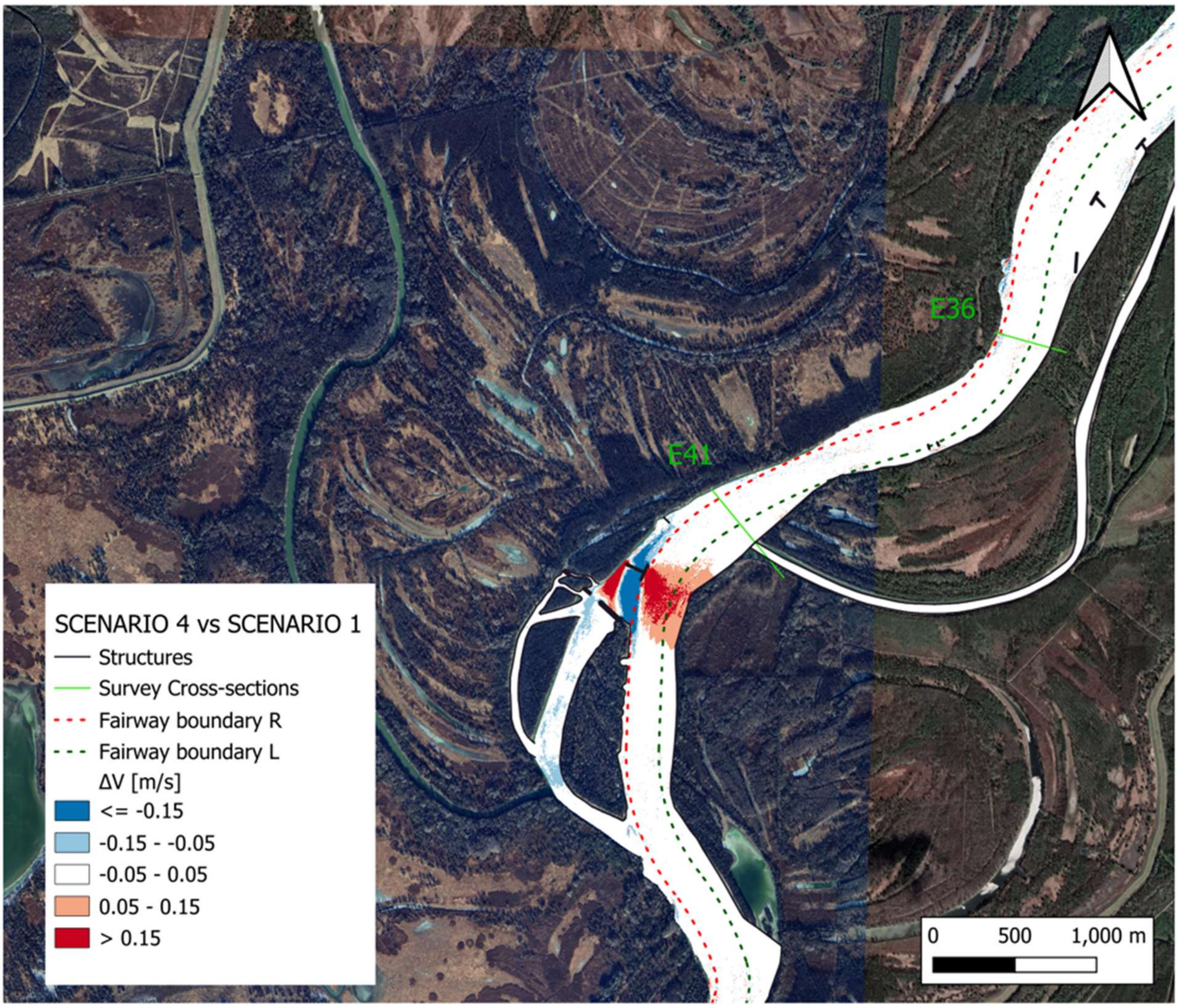


Figure 134: Differences in velocities between Scenario 4 and Scenario 1 (Sektor Čivutski rukavac)

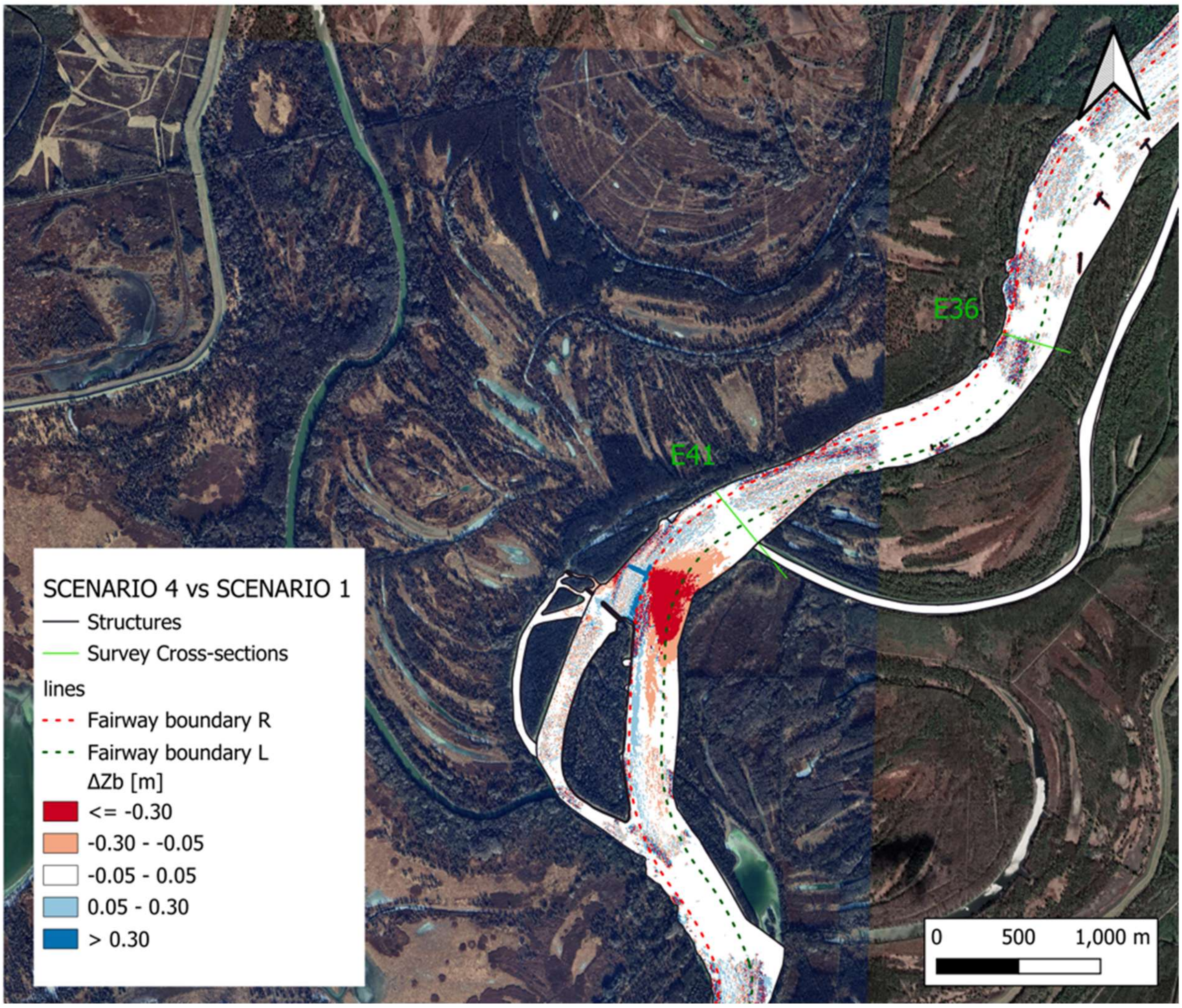


Figure 135: Differences in bottom elevations between Scenario 4 and Scenario 1 (Sector Čivutski rukavac)

7.3.3. Sector Drava confluence

In the sector Drava Confluence (from rkm 1,388.8 to 1,382.0 rkm), there is a common issue of dynamic changes in the river bed geometry in the flow area at the confluence of Drava and Danube rivers. The dominant phenomenon is the deposition of sediments along the tip formed by the right bank of the Danube and the left bank of the Drava (Figure 136).

This study examines two scenarios, in addition to the "Do nothing" scenario, with measures whose impacts have been simulated using the 2D sediment transport model. Under Scenario 2, the construction of a channel through the groyne fields is proposed for the section upstream of the confluence and cross-section EP 52. In Scenario 4, the construction of bottom sills between cross-sections EP 52 and EP 55 is planned. It should be emphasized that these measures primarily address the fairway zone of the Danube, but additional measures for the navigational connection with the Drava River should also be considered (which is not addressed in this study).

In Scenario 2, several channel geometries were analyzed, with widths of 30, 45, and 60 meters, taking care to avoid significant deformation along the channel while ensuring downstream effects (although minimal) at the confluence of the Drava. As a result, a channel width of 60 meters was determined to be necessary and was ultimately adopted. It should be noted that the depth within the channel was not considered as a parameter, which should be addressed in a more detailed analysis of the environmental impacts of this solution, along with further optimization of the design. In this project, only the channel width was varied, based on the condition related to morphological changes and the requirement for the channel to remain active during low flow conditions. This additionally increases the flow path length at lower water levels—an indicator linked to environmental impact.

The hydraulic effects of the solution, under dominant discharge conditions, can be assessed by comparing the velocity distributions for Scenarios 1, 2, and 4 presented in Figure 137, Figure 138 and Figure 139. Direct comparison is enabled by calculating the differences in velocity magnitudes. The velocity difference between Scenario 2 and Scenario 1 is shown in Figure 140, while the comparison between Scenario 4 and Scenario 1 is presented in Figure 141. Figure 142, Figure 143, and Figure 144 also show the simulated riverbed geometry alterations for the same scenarios. Similar to the case of velocities, the comparisons between the scenarios are shown in Figure 145 and Figure 146.The effects, in terms of deepening the riverbed in the fairway, can be barely observed in Scenario 2 but it is pronounced in the scenario with bottom sills (Scenario 4).

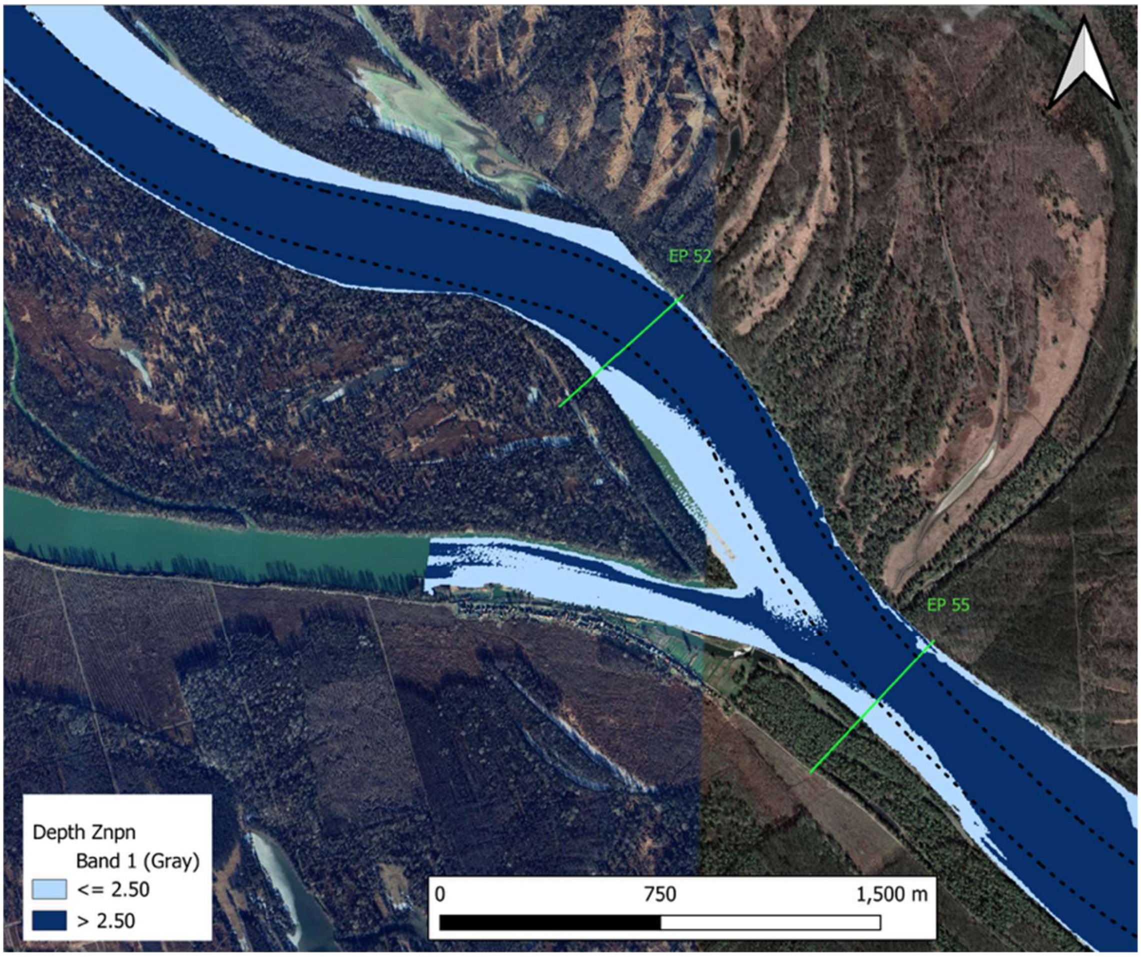


Figure 136: Depths at low navigable water levels for Drava confluence sector

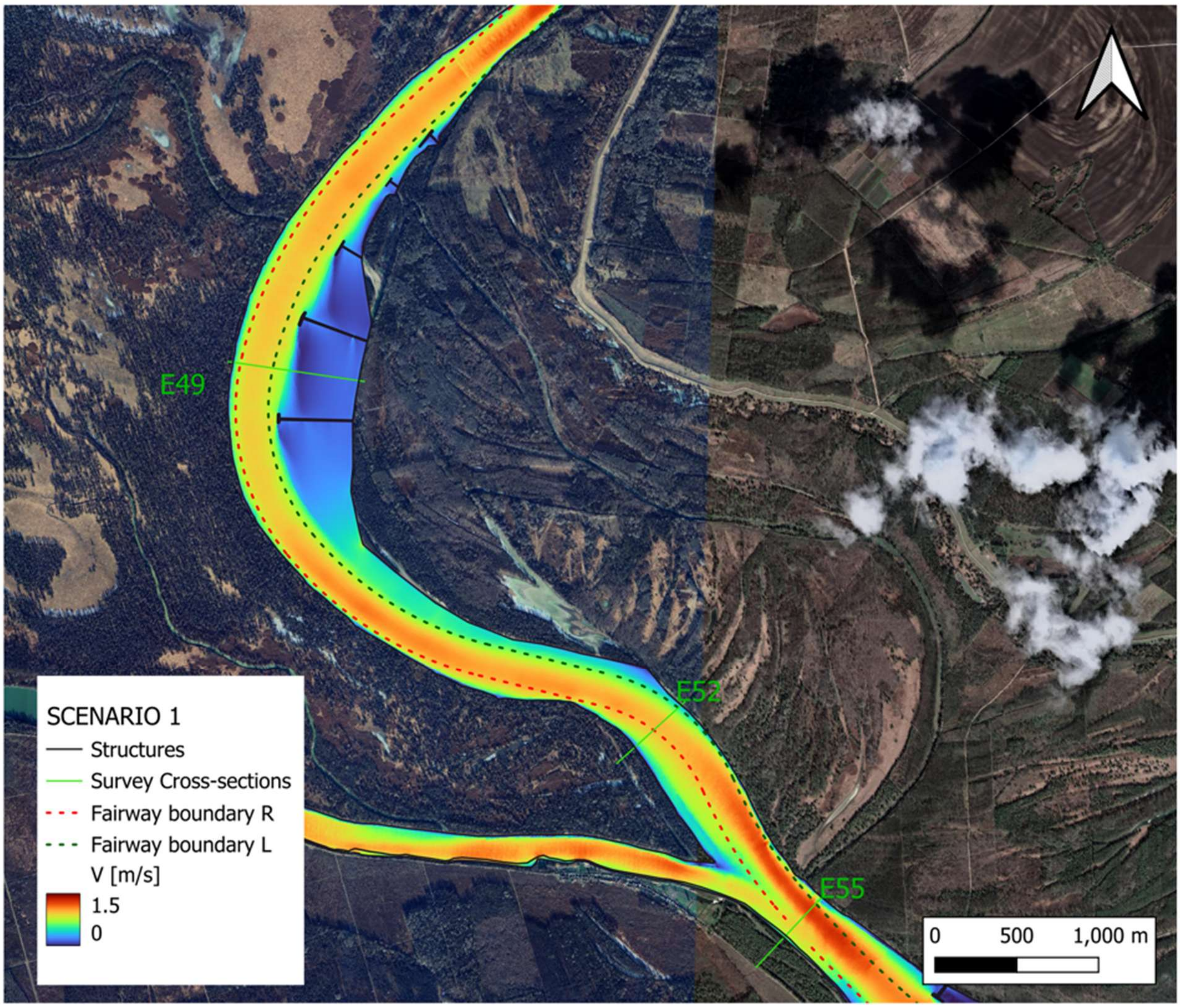


Figure 137: Distribution of depth-averaged velocity in Drava confluence sector for Scenario 1

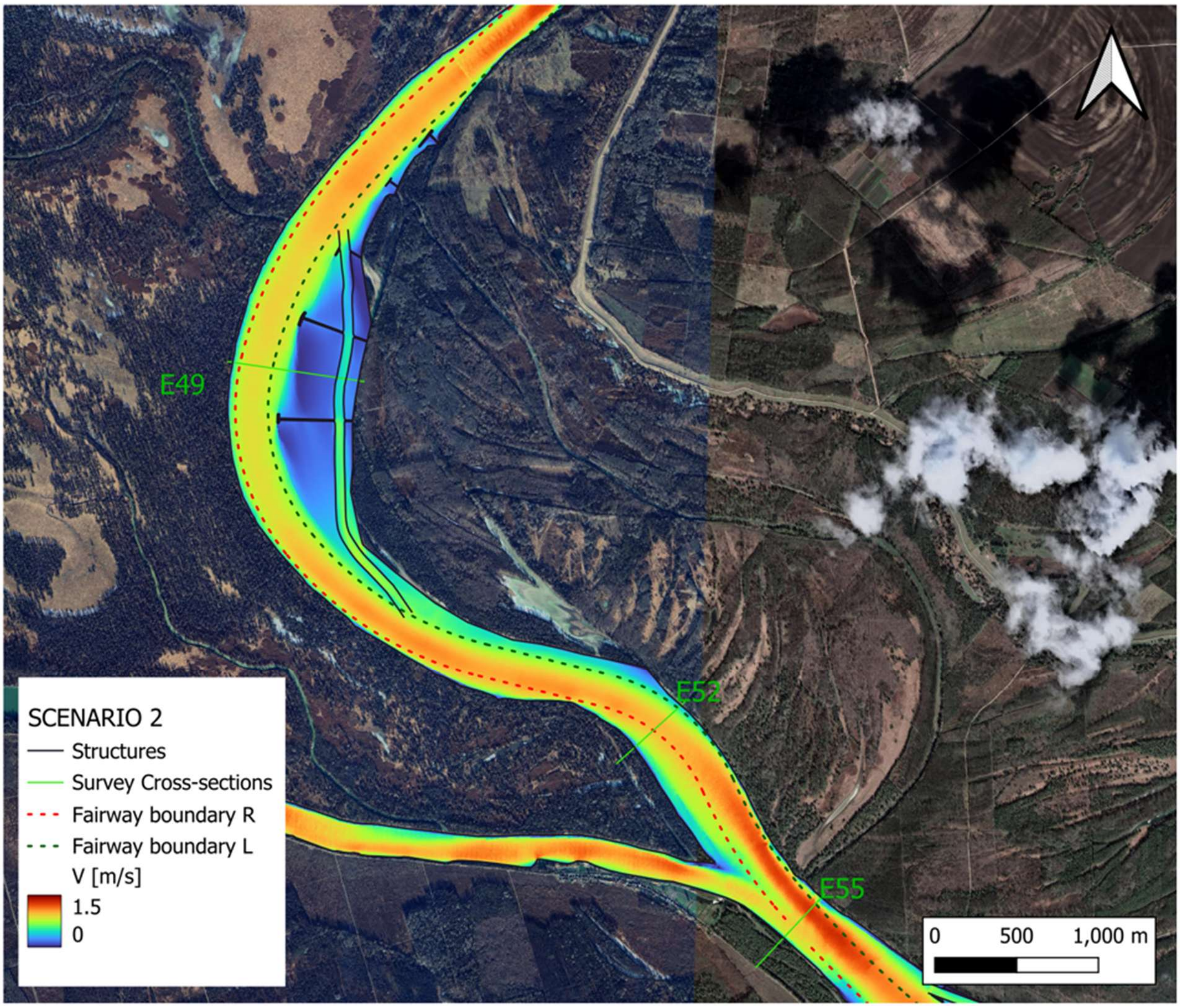


Figure 138: Distribution of depth-averaged velocity in Drava confluence sector for Scenario 2

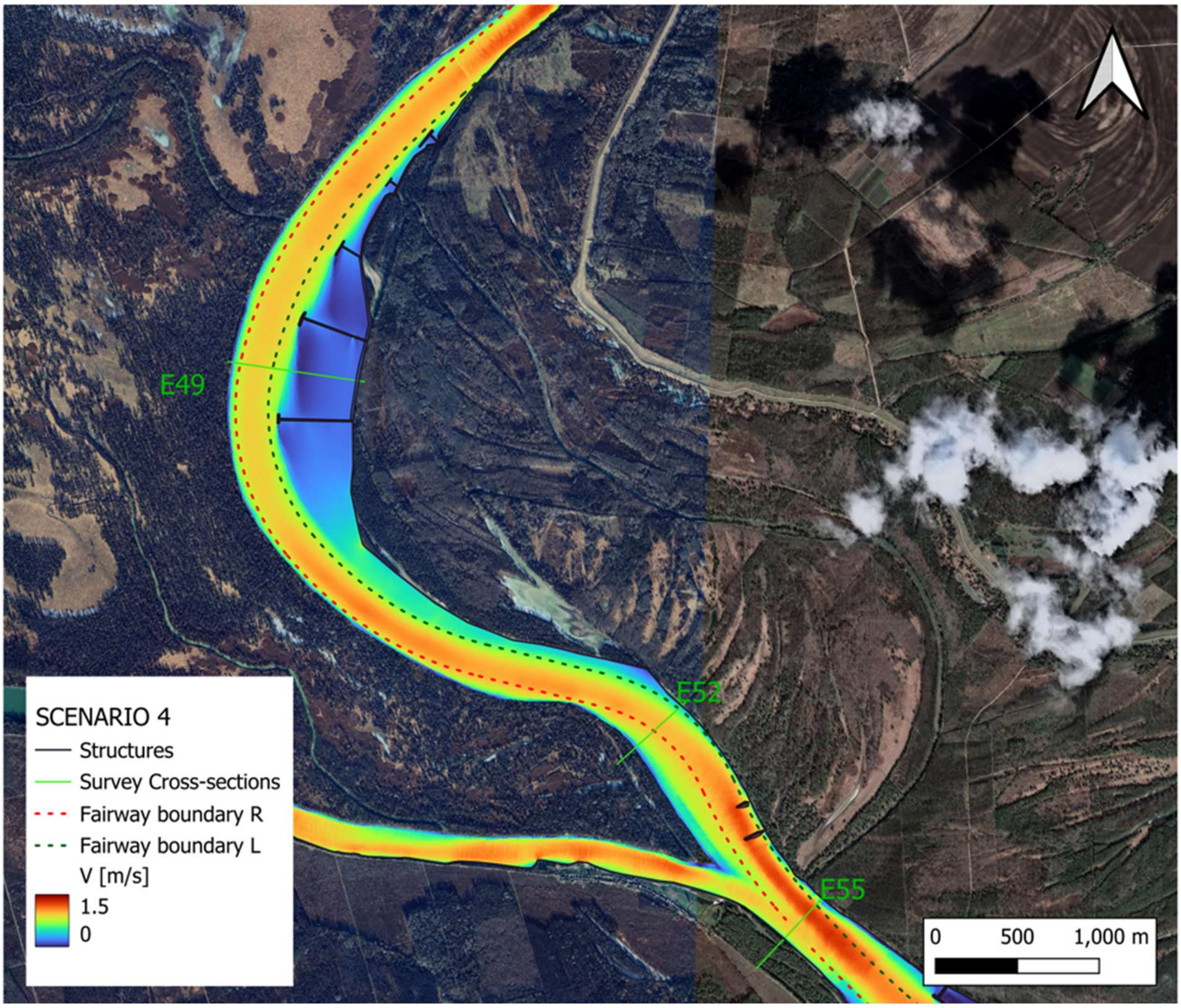


Figure 139: Distribution of depth-averaged velocity in Drava confluence sector for Scenario 4

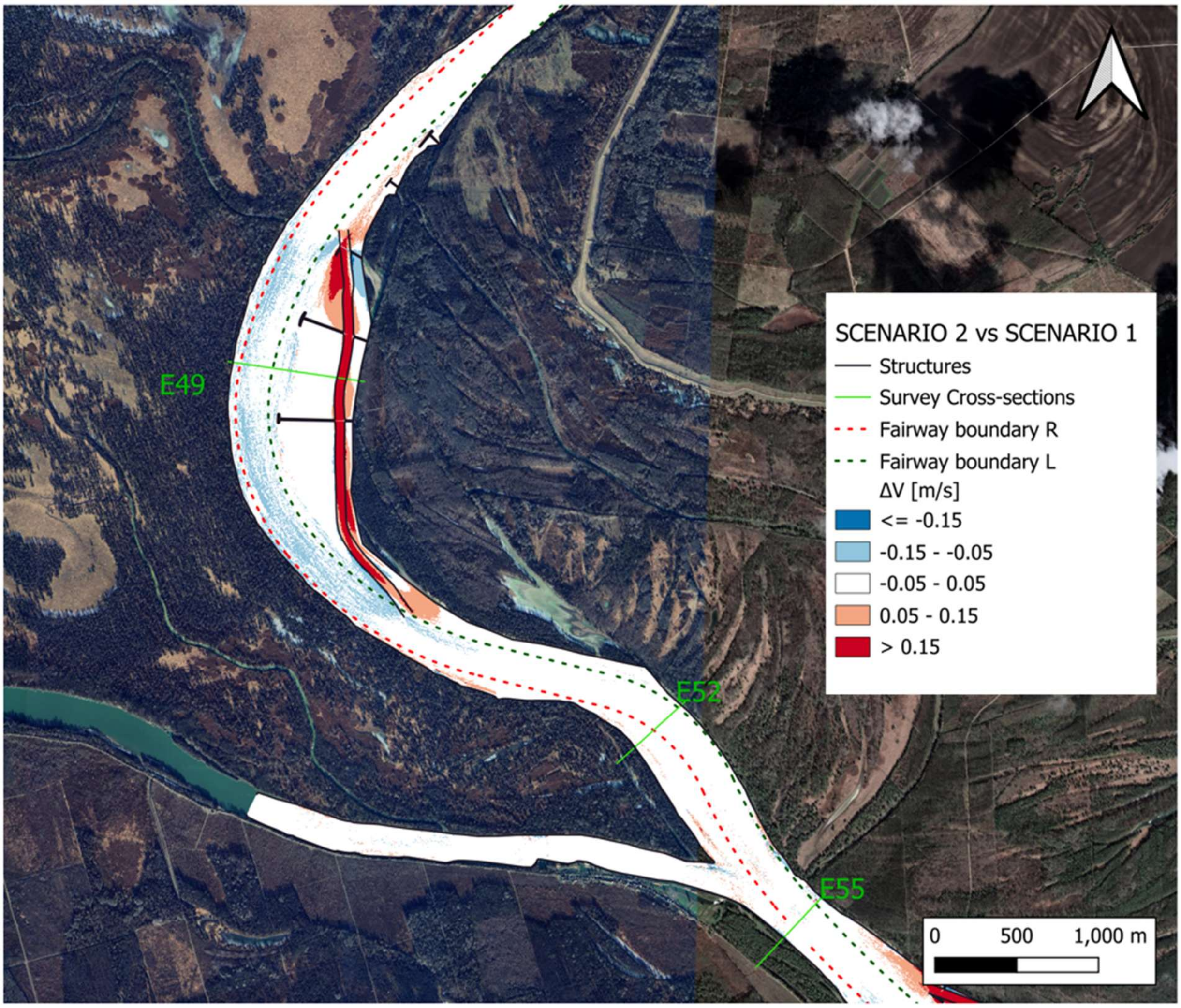


Figure 140: Differences in bottom elevations between Scenario 2 and Scenario 1 (Sector Drava confluence)

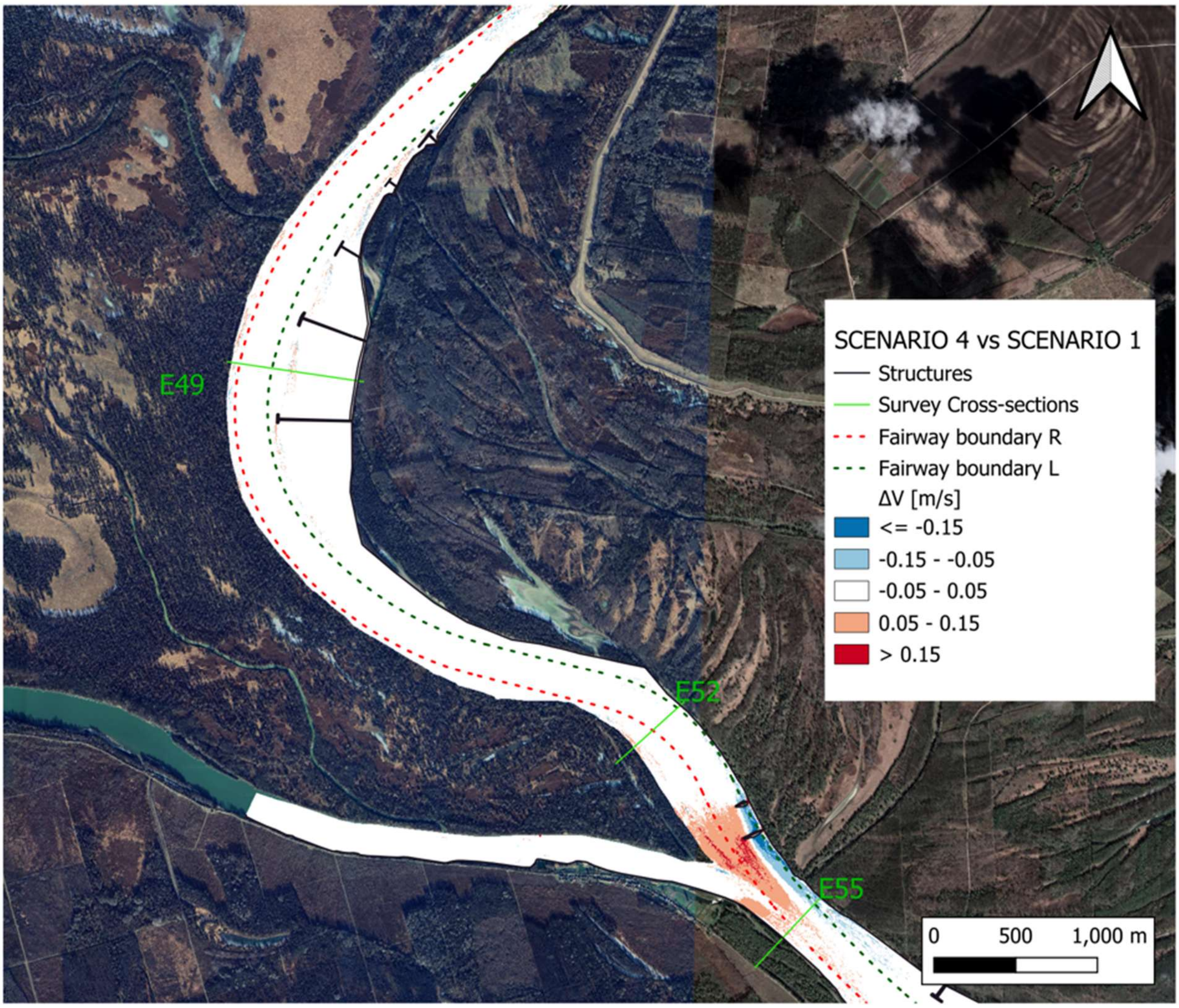


Figure 141: Differences in velocities between Scenario 4 and Scenario 1 (Sector Drava confluence)

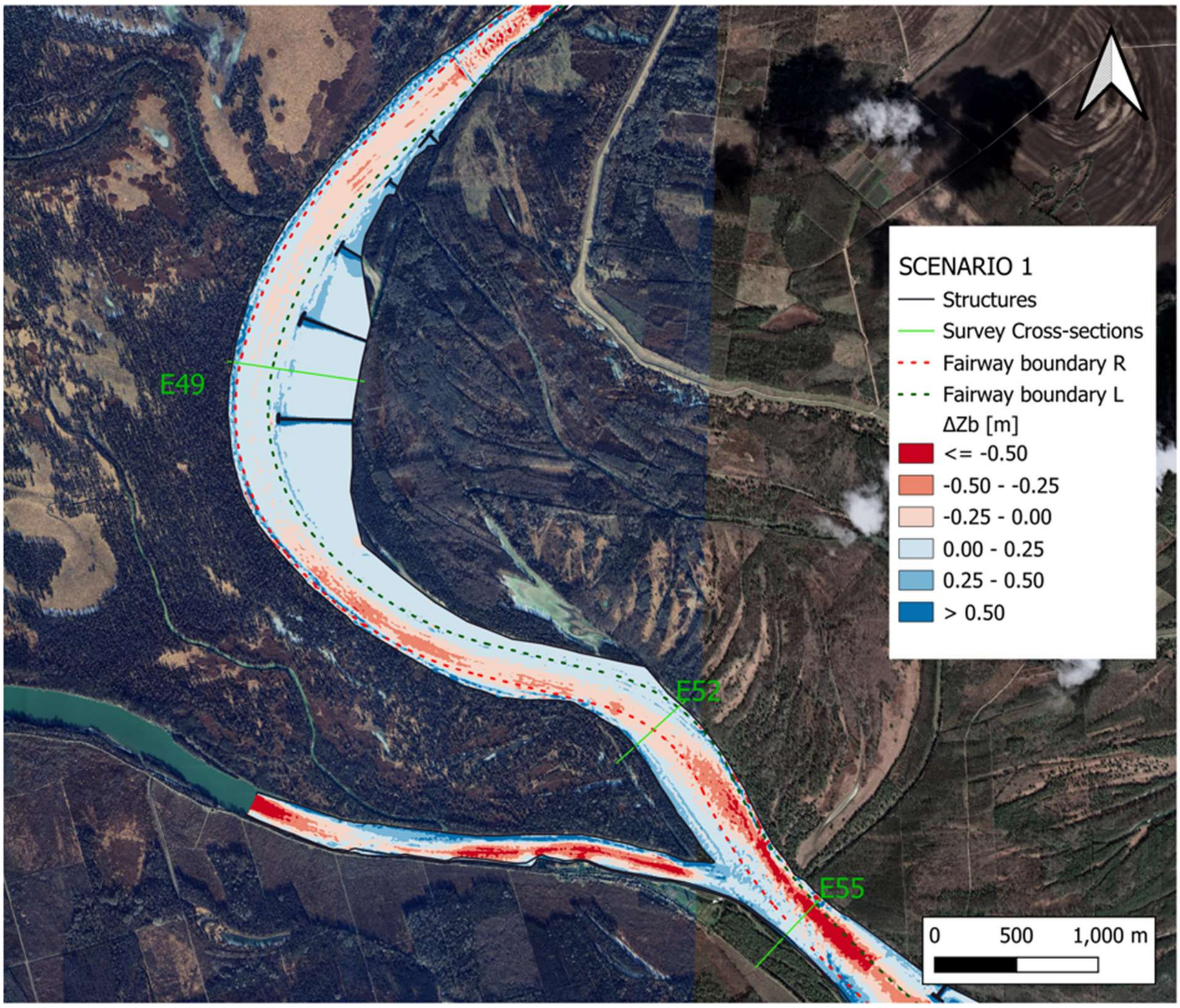


Figure 142: Riverbed vertical alterations in Drava confluence sector for Scenario 1

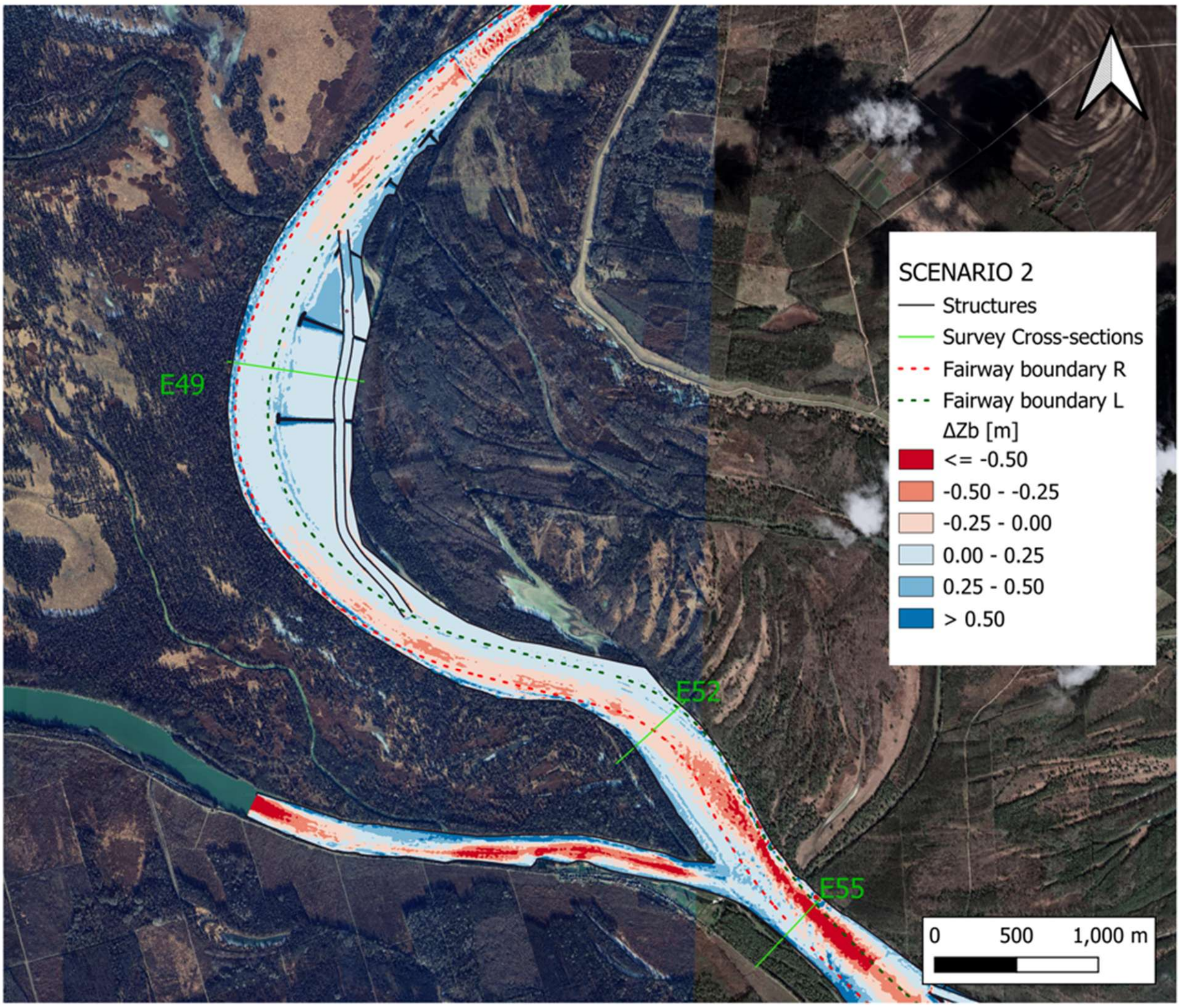


Figure 143: Riverbed vertical alterations in Drava confluence sector for Scenario 2

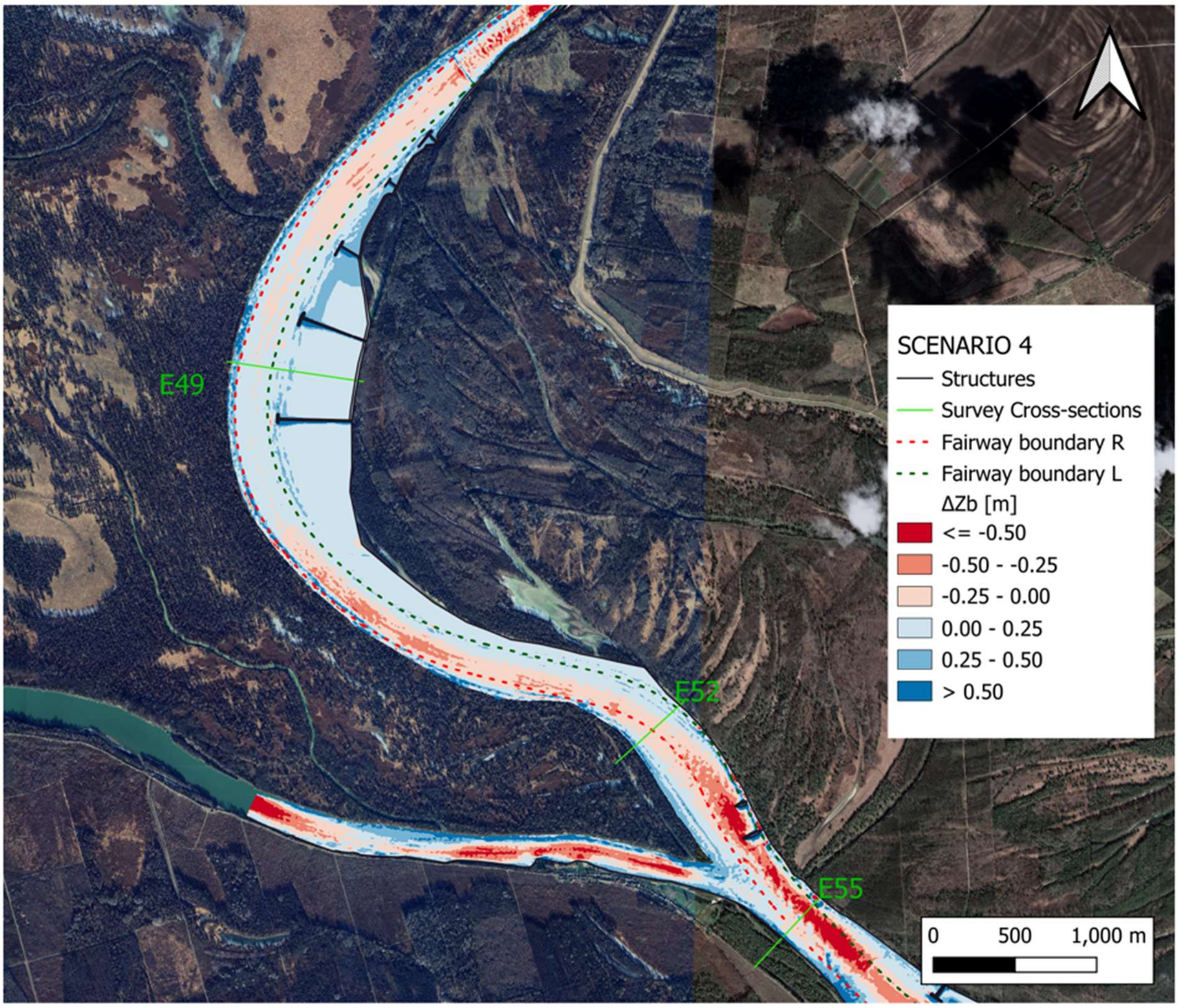


Figure 144: Riverbed vertical alterations in Drava confluence sector for Scenario 4

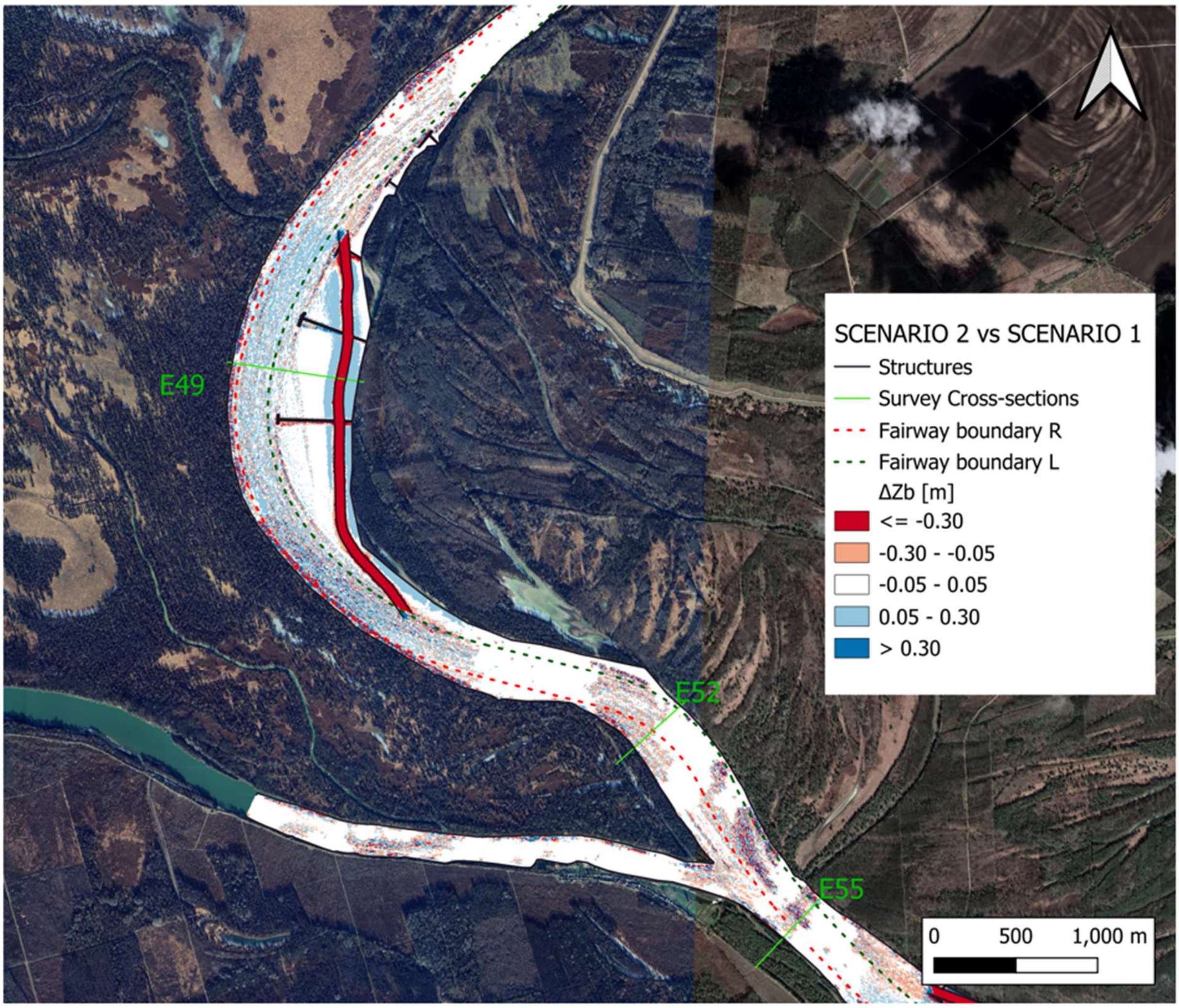


Figure 145: Differences in bottom elevations between Scenario 2 and Scenario 1
(Sector Drava confluence)

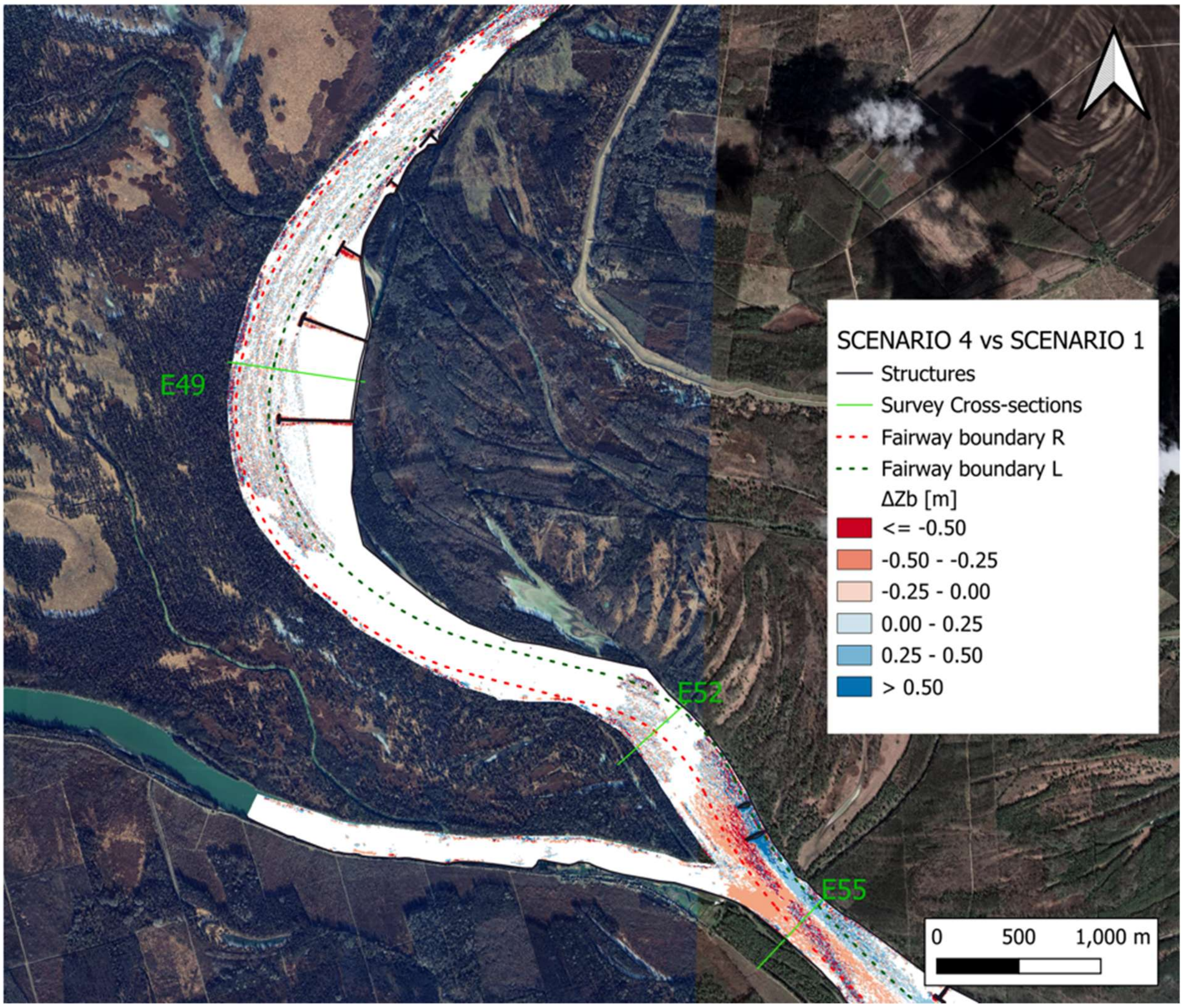


Figure 146: Differences in bottom elevations between Scenario 4 and Scenario 1 (Sector Drava confluence)

7.3.4. Sector Aljmaš

Aljmaš is the only sector (from rkm 1,381.4 to rkm 1,378.2) along the Danube reach from Apatin to Staklar that has not been identified as critical. However, the effects of proposed river training structures can be felt both upstream and downstream, so this sector was also analyzed in this study within the one simulation domain. An additional reason is that Scenario 2 considers the construction of a channel in this sector, similar to the one upstream from the confluence of the Drava River, with the goal of retaining sediment in this sector to create conditions for erosion in the downstream critical sector of Staklar.

As in the case of the confluence of the Drava River, in Scenario 2, the effects became noticeable only with a channel width of 60 meters (widths of 30 and 45 meters were also tested here). What can be observed in the figures showing the velocity distribution for all the modeled scenarios is that, in addition to the expected effect of the channel in reducing velocities (Figure 147, Figure 148 and Figure 150) along the fairway and thus promoting reducing of the erosion (Figure 152, Figure 153 and Figure 155, the effects of the sills planned for the upstream and downstream sectors in Scenario 4 are also felt in this sector (Figure 151 and Figure *156*).

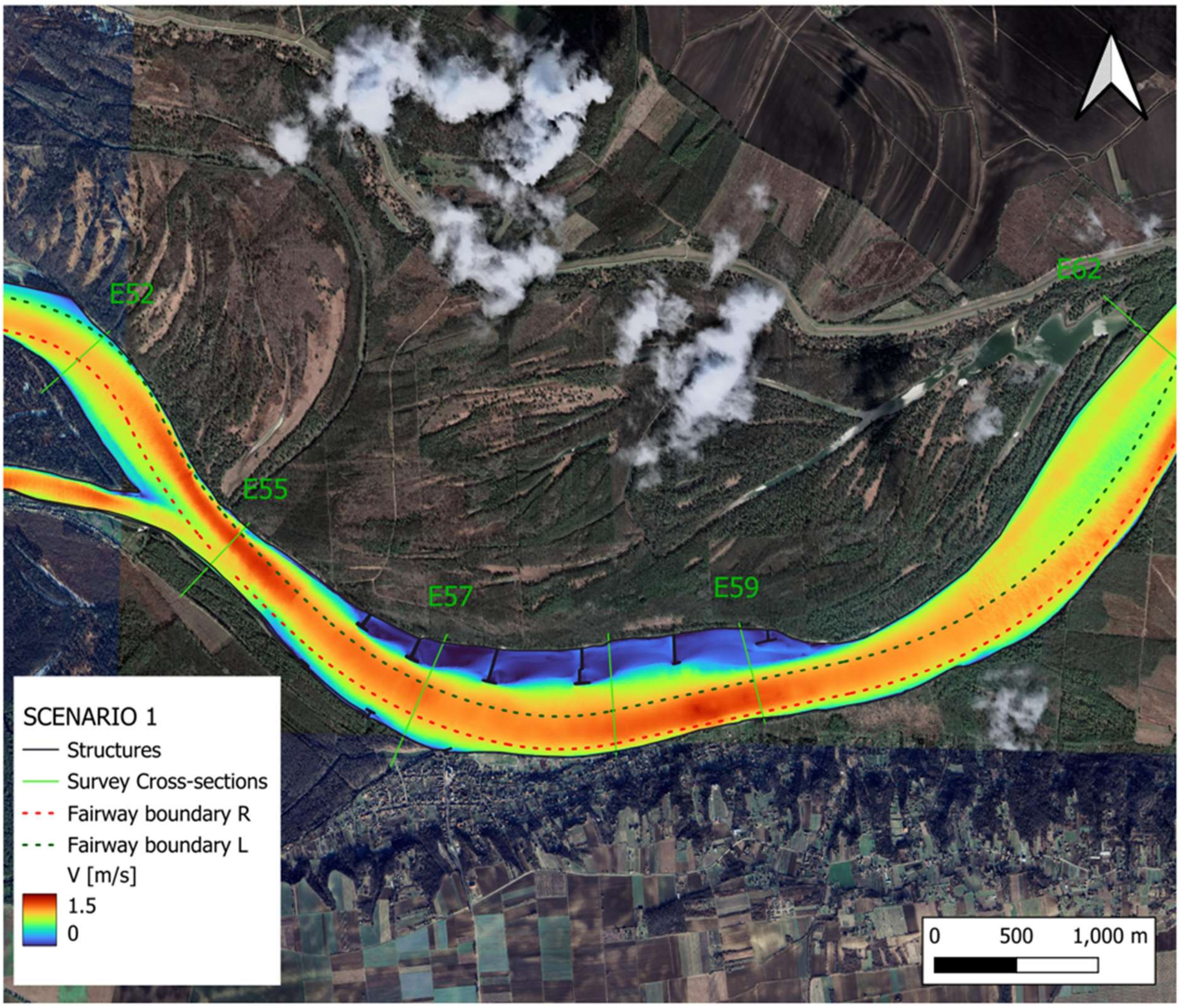


Figure 147: Distribution of depth-averaged velocity in Aljmaš sector for Scenario 1

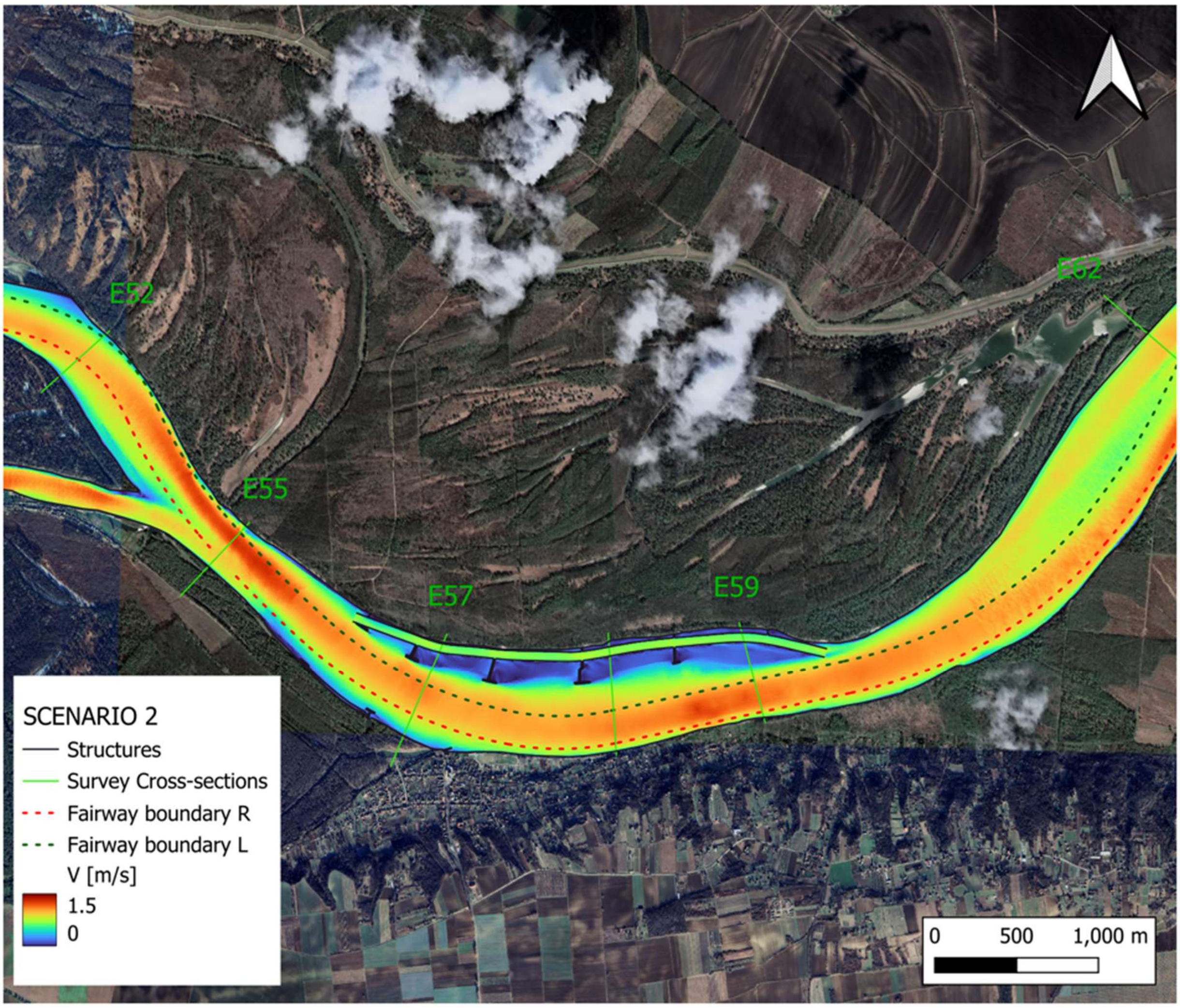


Figure 148: Distribution of depth-averaged velocity in Aljmaš sector for Scenario 2

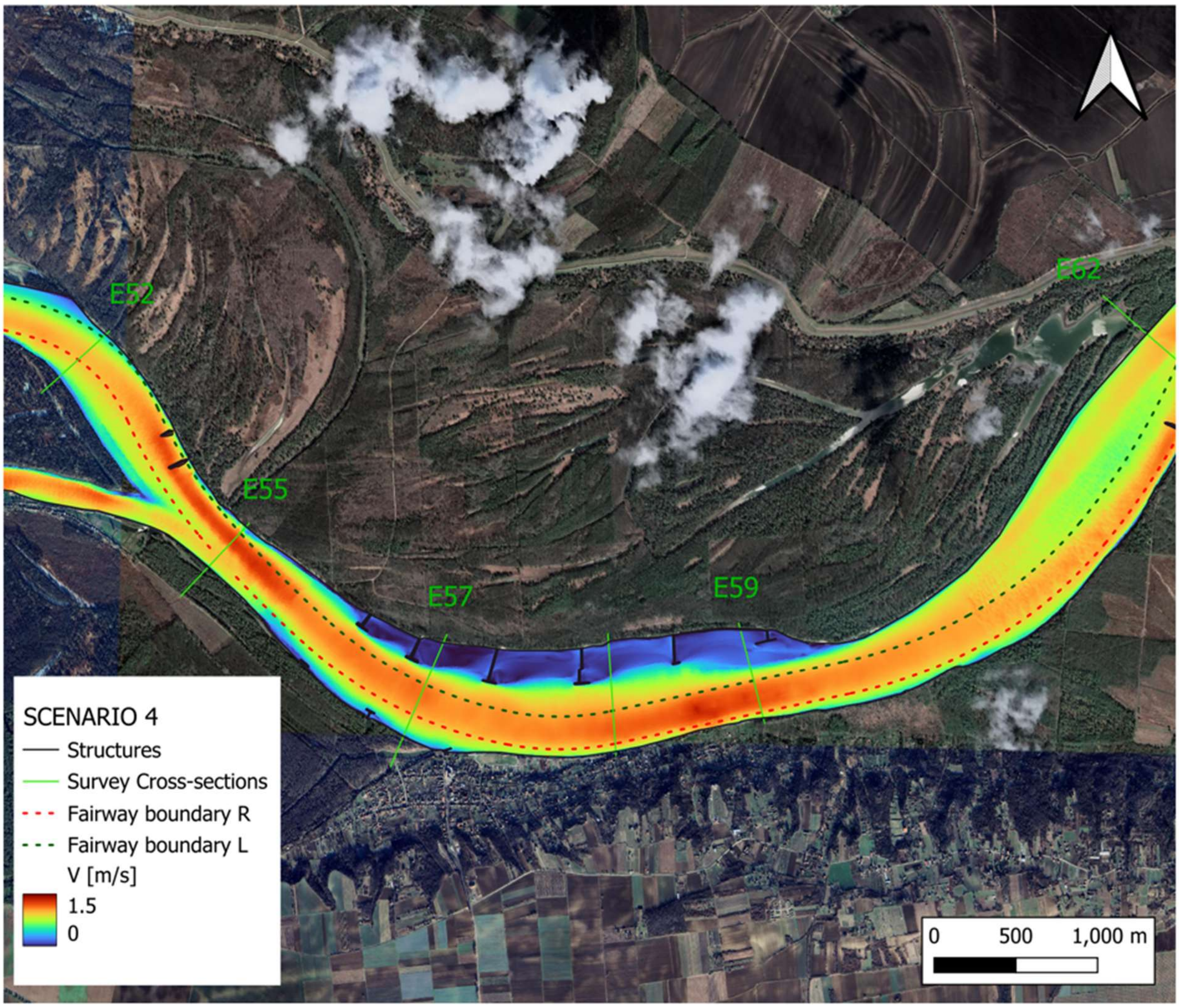


Figure 149: Distribution of depth-averaged velocity in Aljmaš sector for Scenario 4

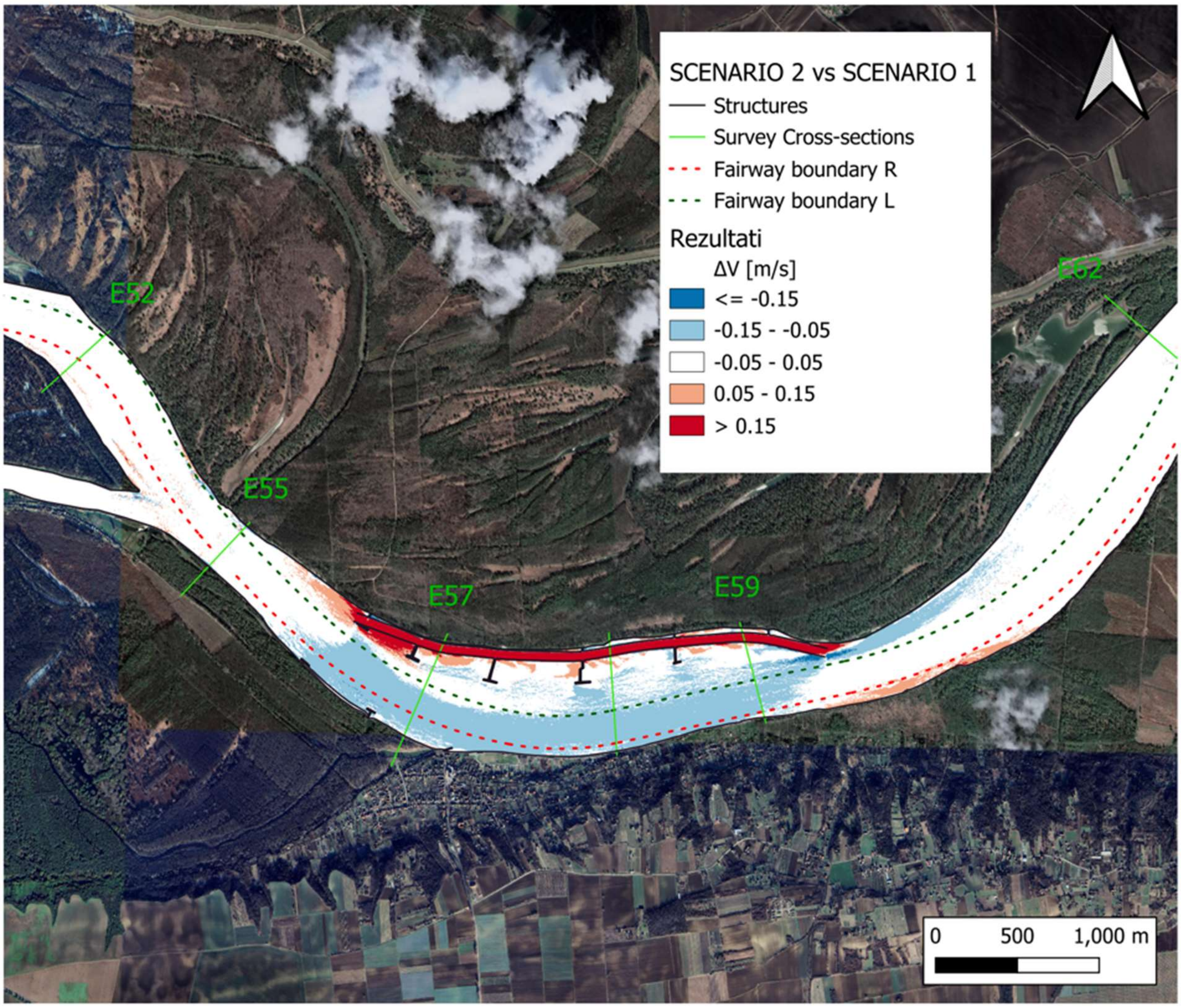


Figure 150: Differences in velocities between Scenario 2 and Scenario 1 (Sector Aljmaš)

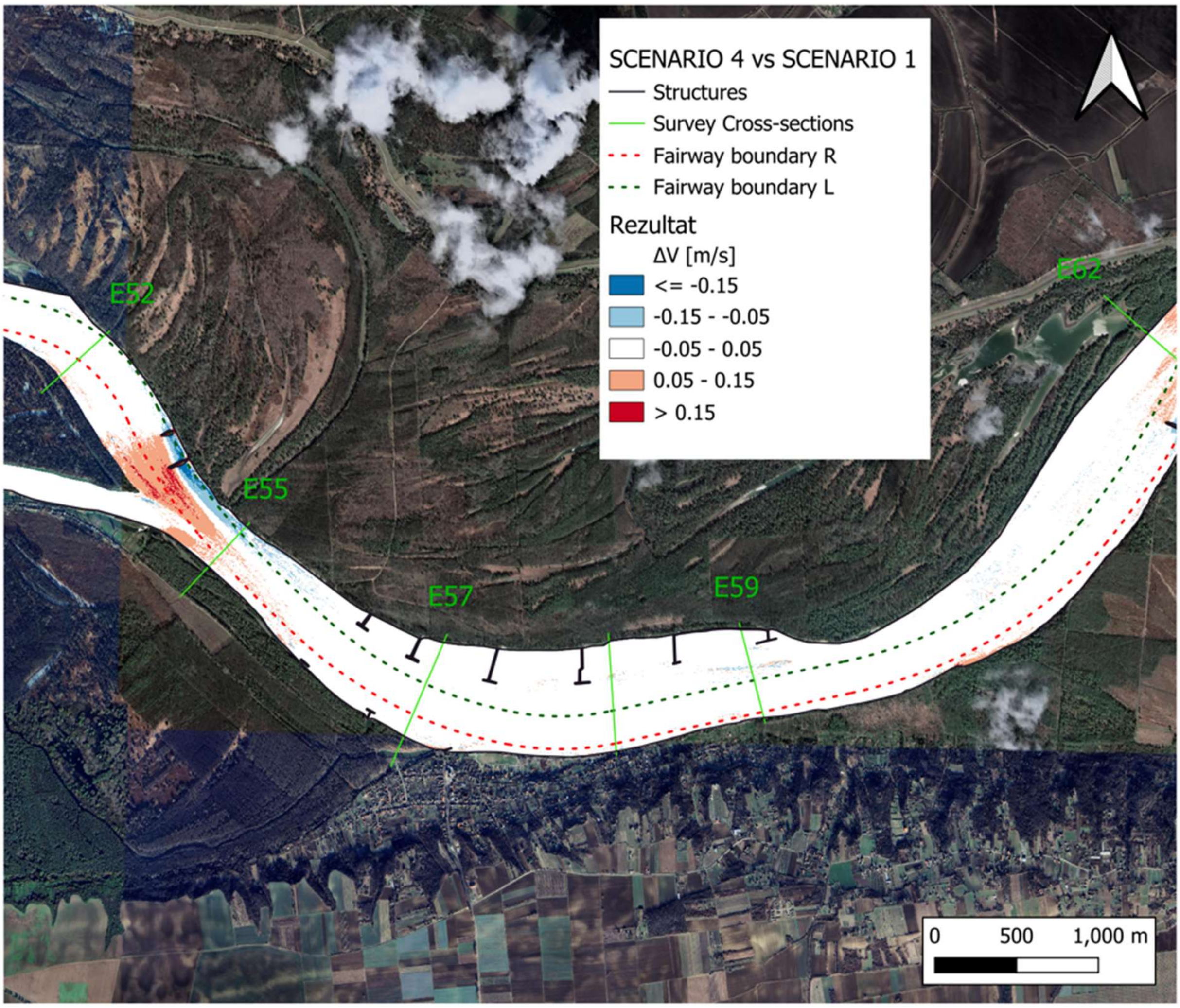


Figure 151: Differences in velocities between Scenario 4 and Scenario 1 (Sector Aljmaš)

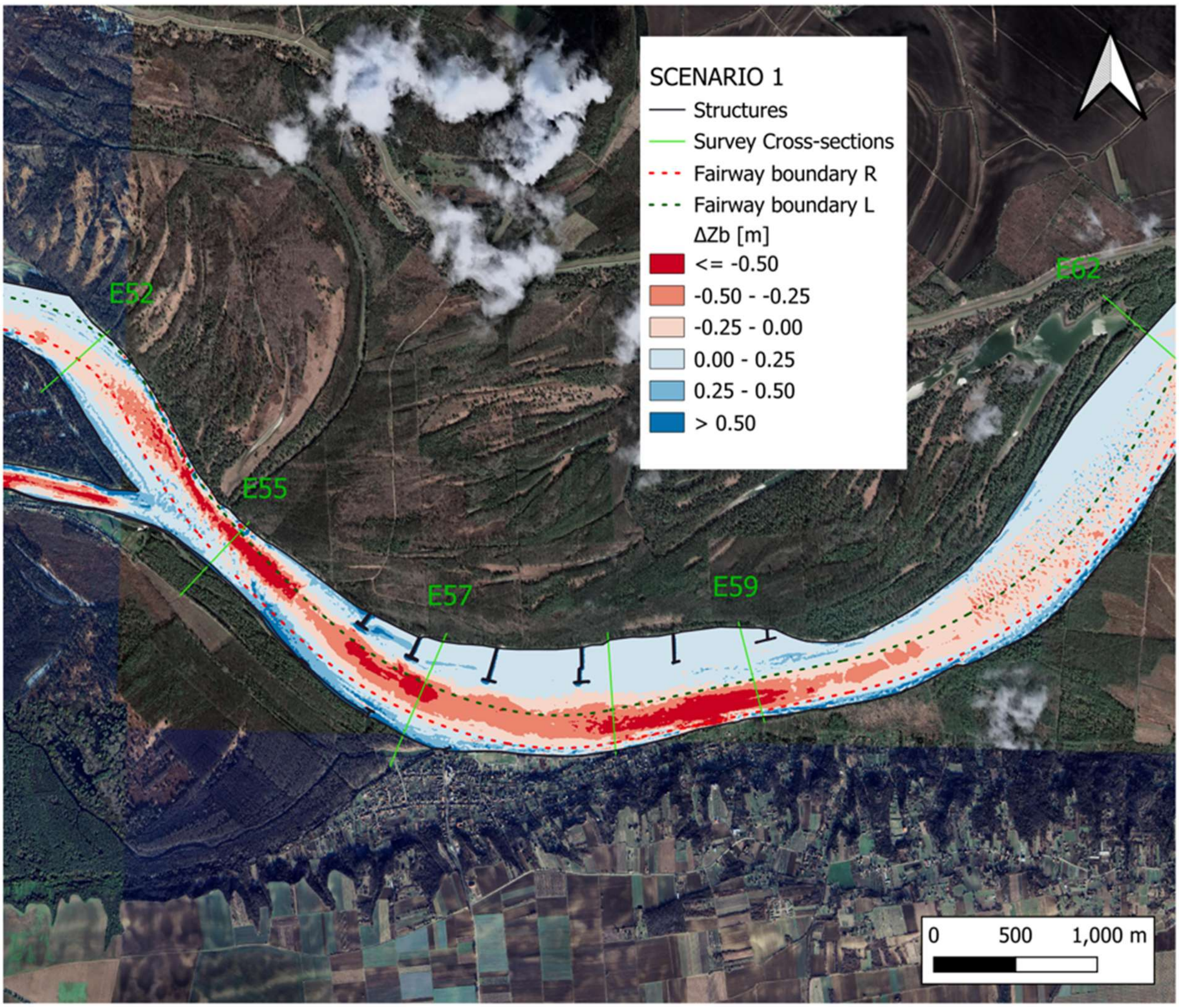


Figure 152: Riverbed vertical alterations in Aljmaš sector for Scenario 1

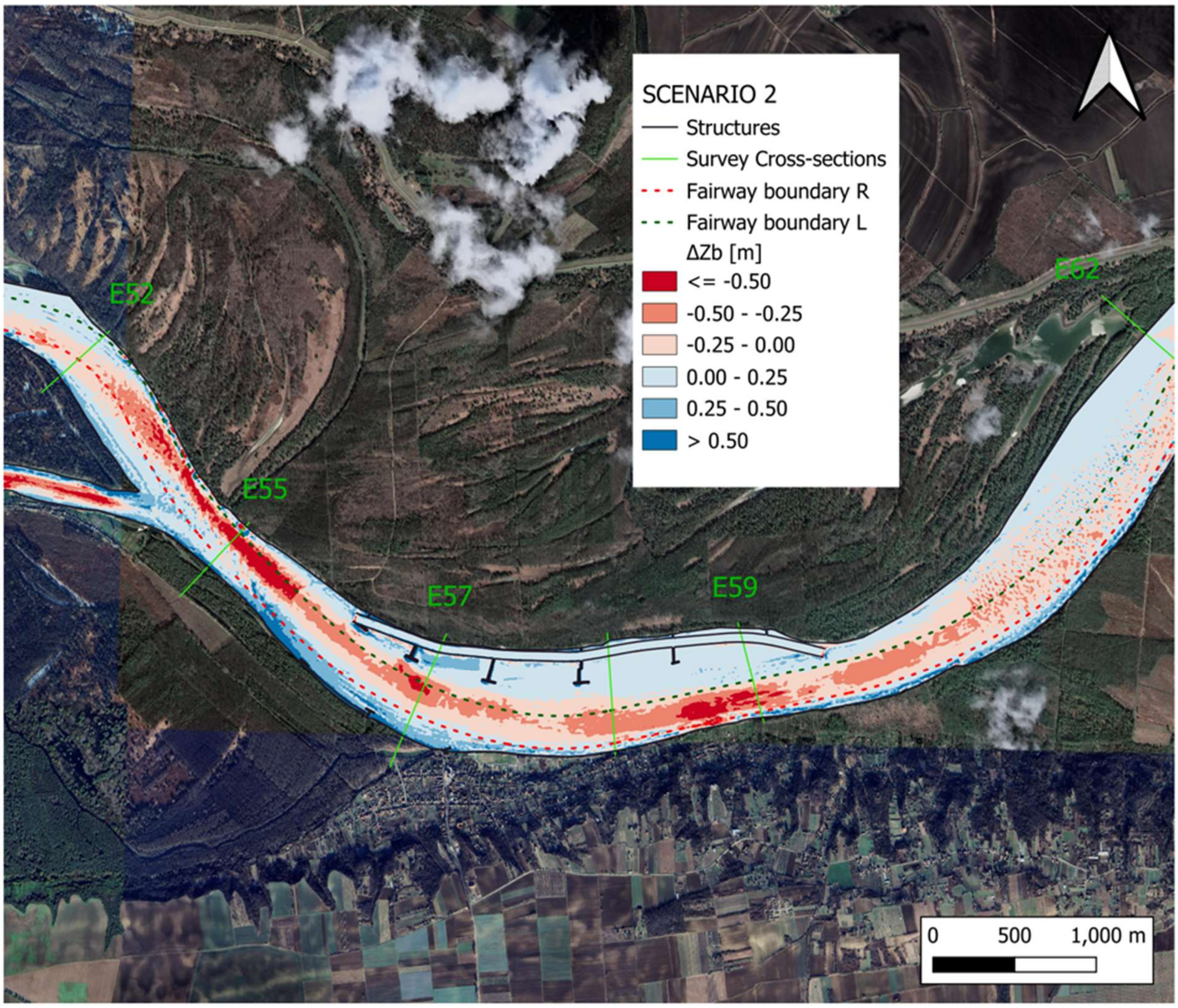


Figure 153: Riverbed vertical alterations in Aljmaš sector for Scenario 2

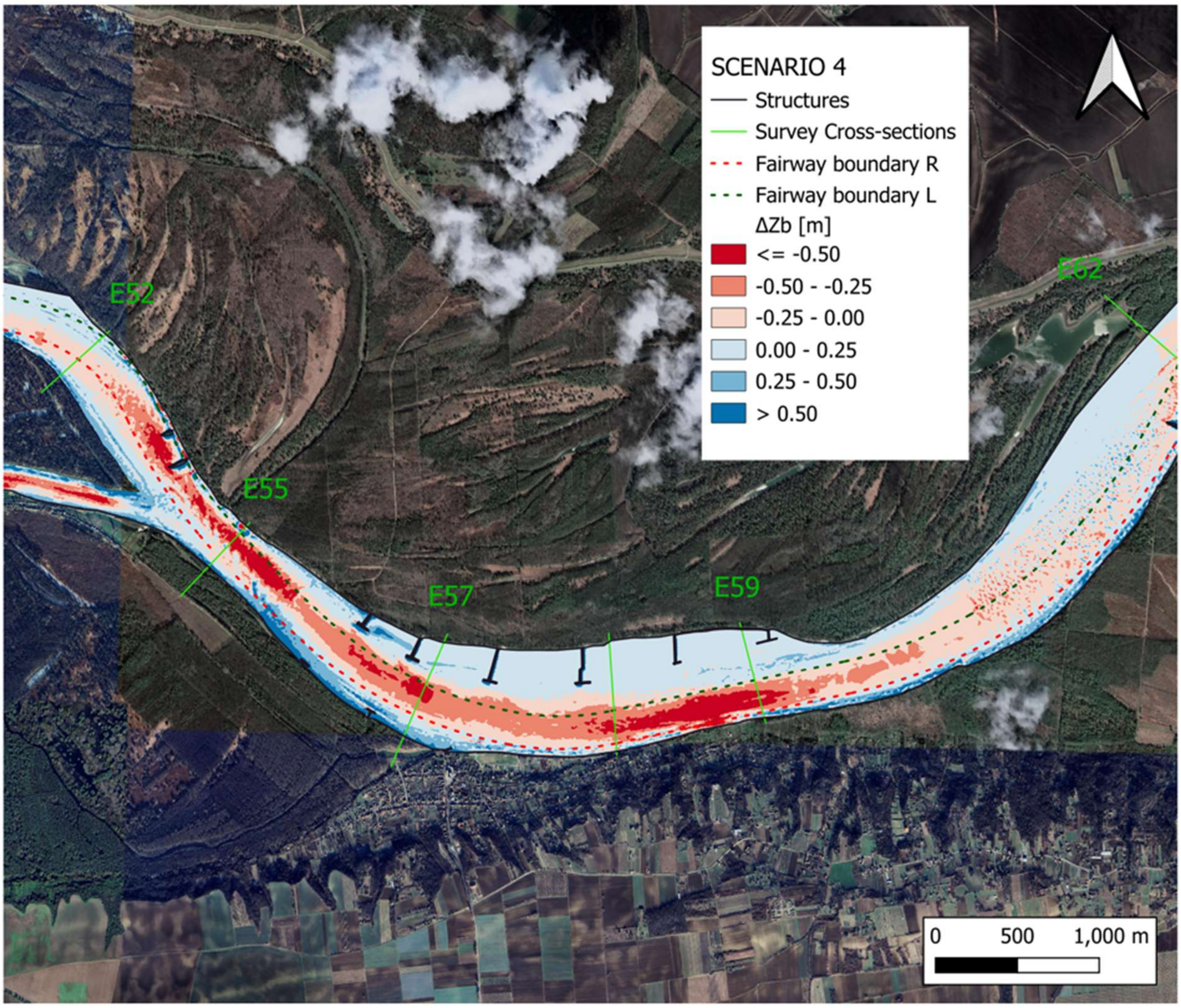


Figure 154: Riverbed vertical alterations in Aljmaš sector for Scenario 4

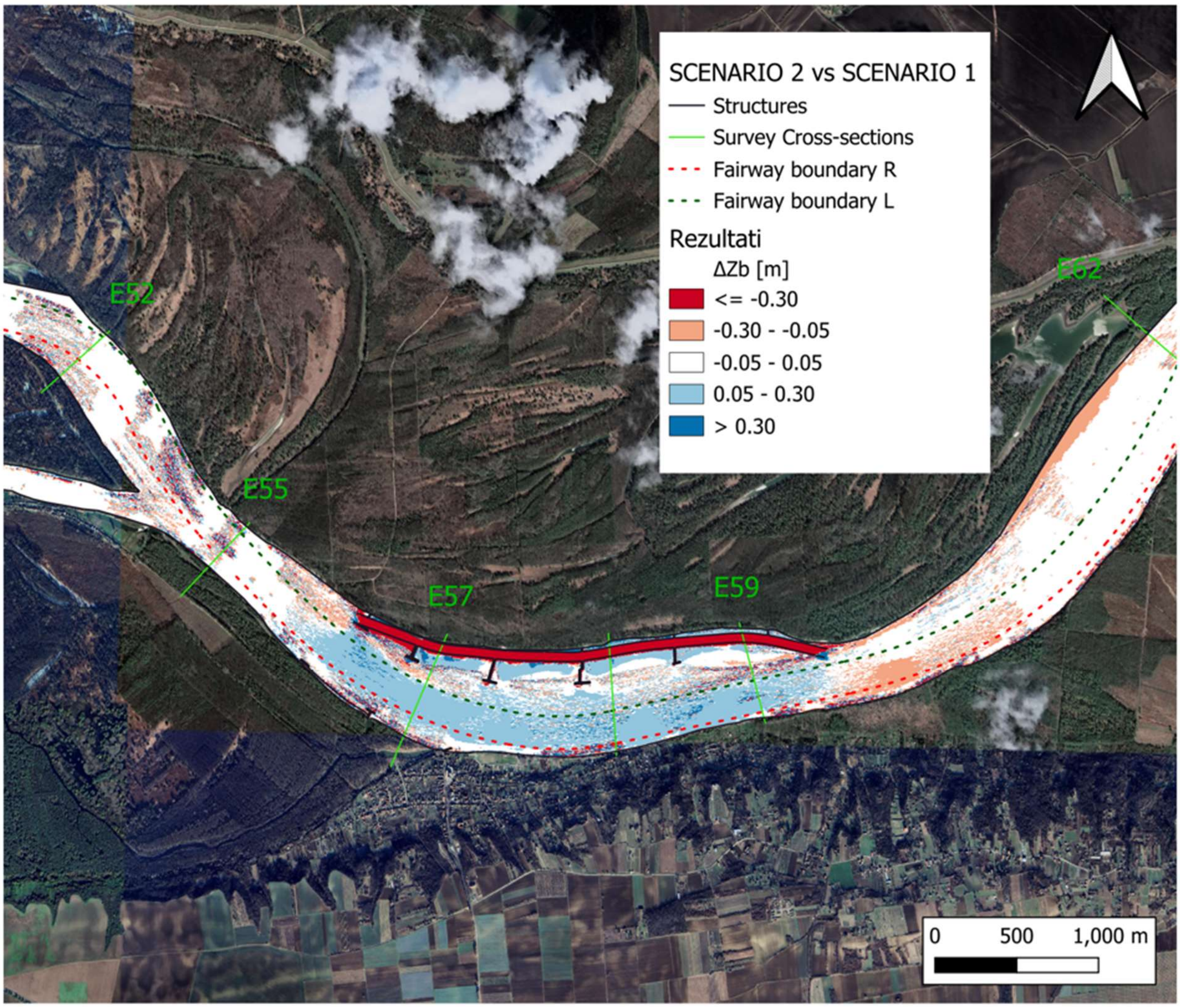


Figure 155: Differences in bottom elevations between Scenario 2 and Scenario 1 (Aljmaš)

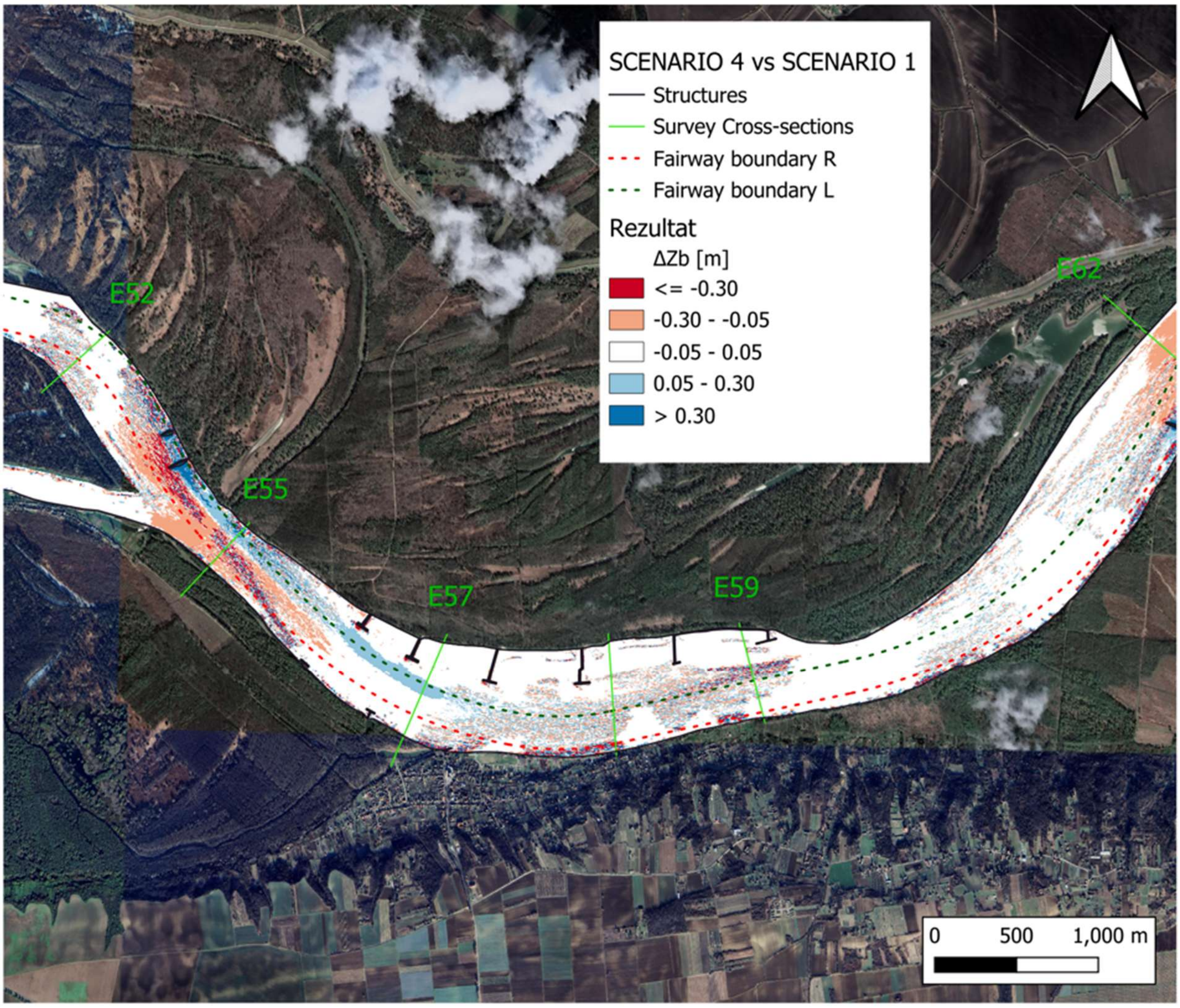


Figure 156: Differences in bottom elevations between Scenario 4 and Scenario 1 (Aljmaš)

7.3.5. Sector Staklar

In the Staklar sector (the section of the Danube from 1,376.8 rkm to 1,373.4 rkm), the most significant navigational problem occurs along the left edge of the fairway between cross-sections EP 62 and EP 63 (Figure 157). The solutions analyzed in the numerical simulations include the construction of a channel under Scenario 2 and bottom sills at the upstream end of the river bend. As subvariants for Scenario 4, configurations with four and two sills at the upstream end of the channel were analyzed, with variations in sills dimension to determine the heights at which the effects of the structures become evident.

The simulation results for Scenario 1 are shown in Figure 158 (velocity distribution for entire sector) and Figure 163 (riverbed vertical alterations for entire sector). According to this scenario, the model results confirm the problem in the critical zone along the left side of the fairway in the upstream part of the river bend. Interestingly, in the central part of the bend, along the right edge of the fairway, where a smaller area with insufficient depth was identified at $Q_{94\%}$ discharge, conditions for riverbed erosion exist under dominant discharge conditions. This is an area where sills were previously constructed, so it is likely that the simulation model reflects the effects of these structures (this assumption has not been verified by removing the sills in the model).

In both scenarios with riverbed regulation, the effects in terms of deepening the riverbed are visible, with the effect being more pronounced in Scenario 4. These differences will be evaluated in the chapter with the MCA analysis. The results for these scenarios are shown in Figure 159, Figure 161, Figure 164 and Figure 166 for Scenario 2, and in Figure 160, Figure 162, Figure 165 and Figure 167 for Scenario 4. Primarily based on Figure 166 and Figure 167, it can be said that Scenario 2 exhibits moderately "better" conditions for erosion along the central and upstream parts of the bend partially including the problematic area for navigation, while increased erosion (and reduced deposition) in Scenario 4 occurs precisely in the zone of the riverbed section where problems with meeting the minimum depth of 2.5m exist.

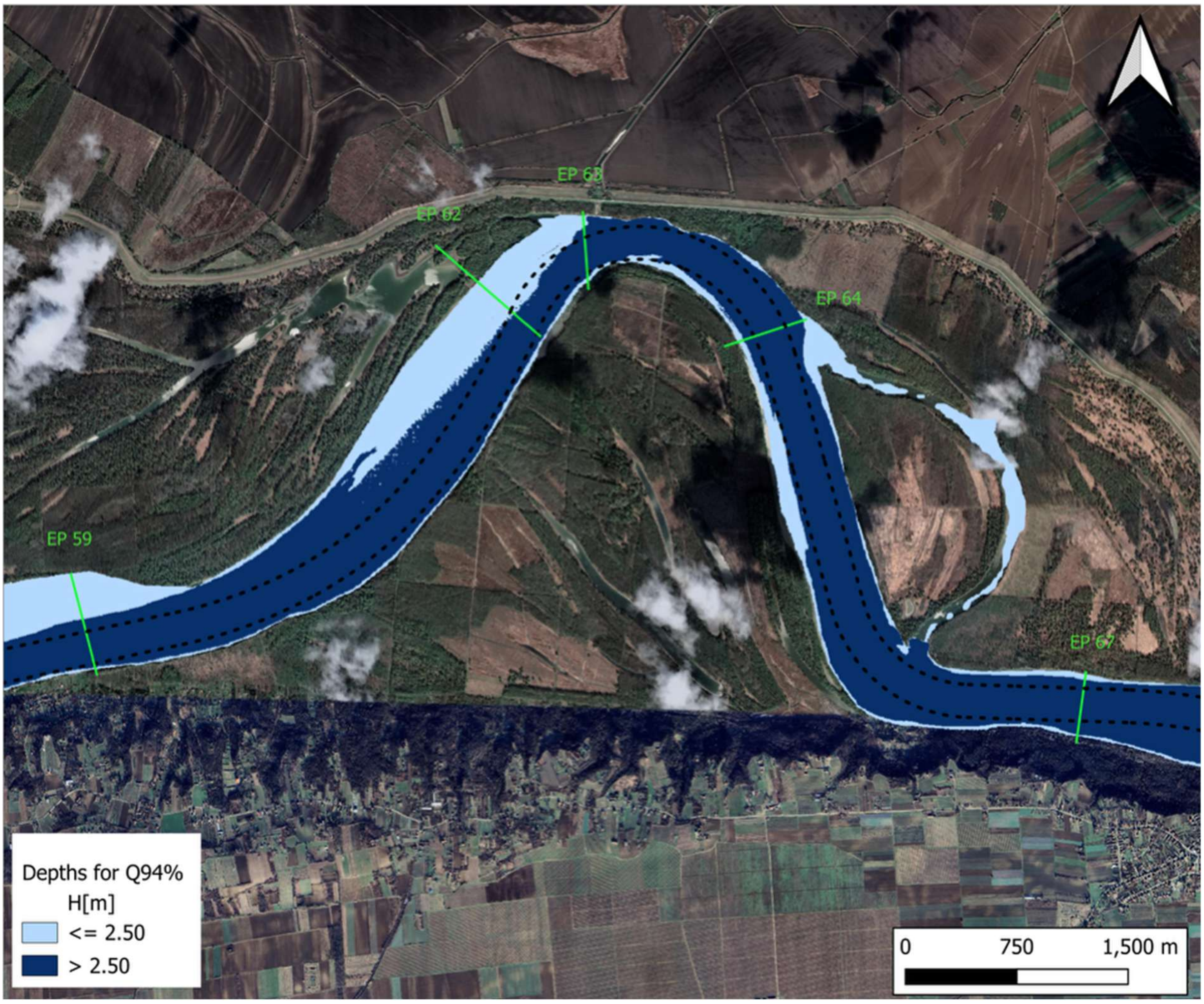


Figure 157: Depths at low navigable water levels for Staklar sector

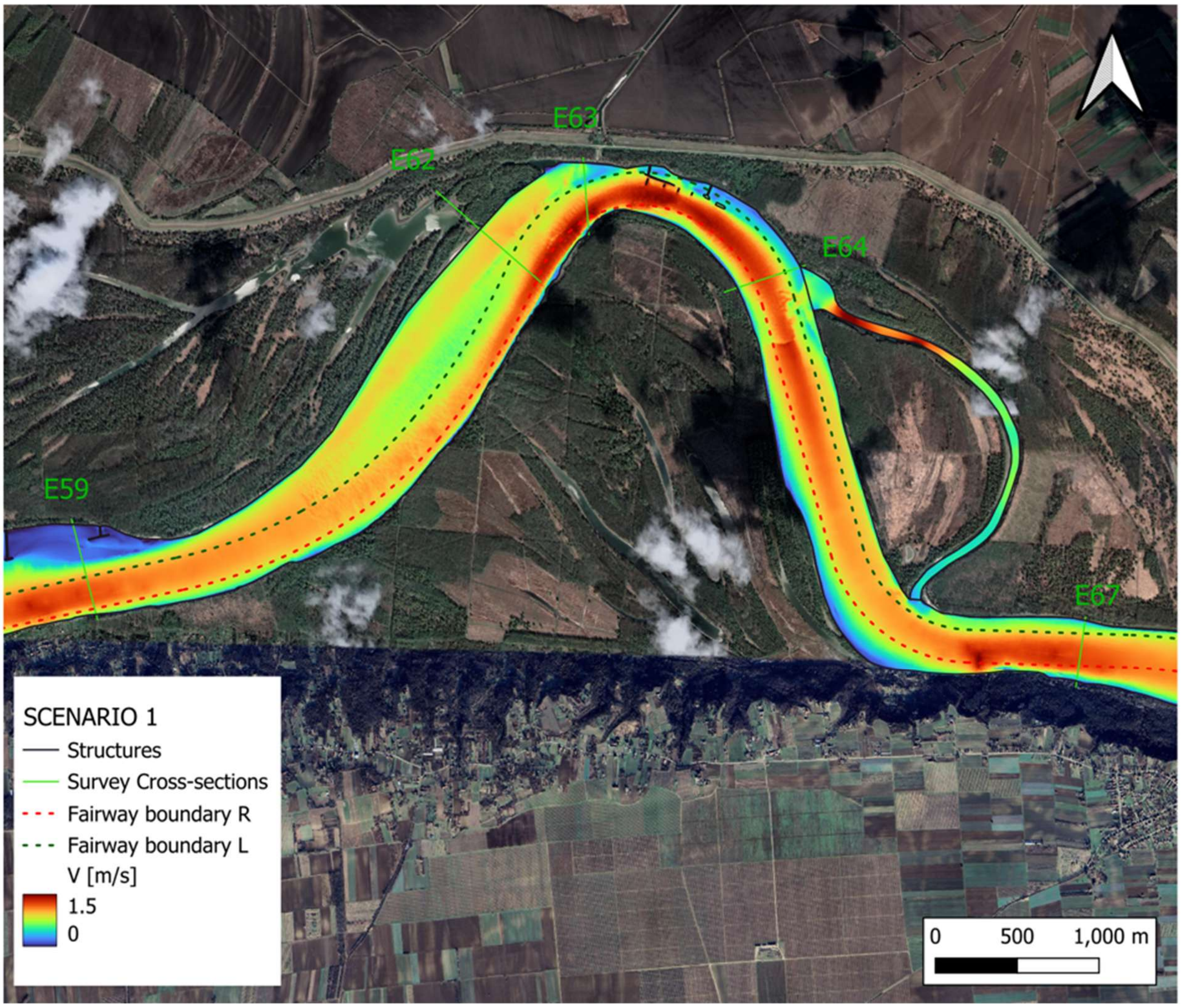


Figure 158: Distribution of depth-averaged velocity in Staklar sector for Scenario 1

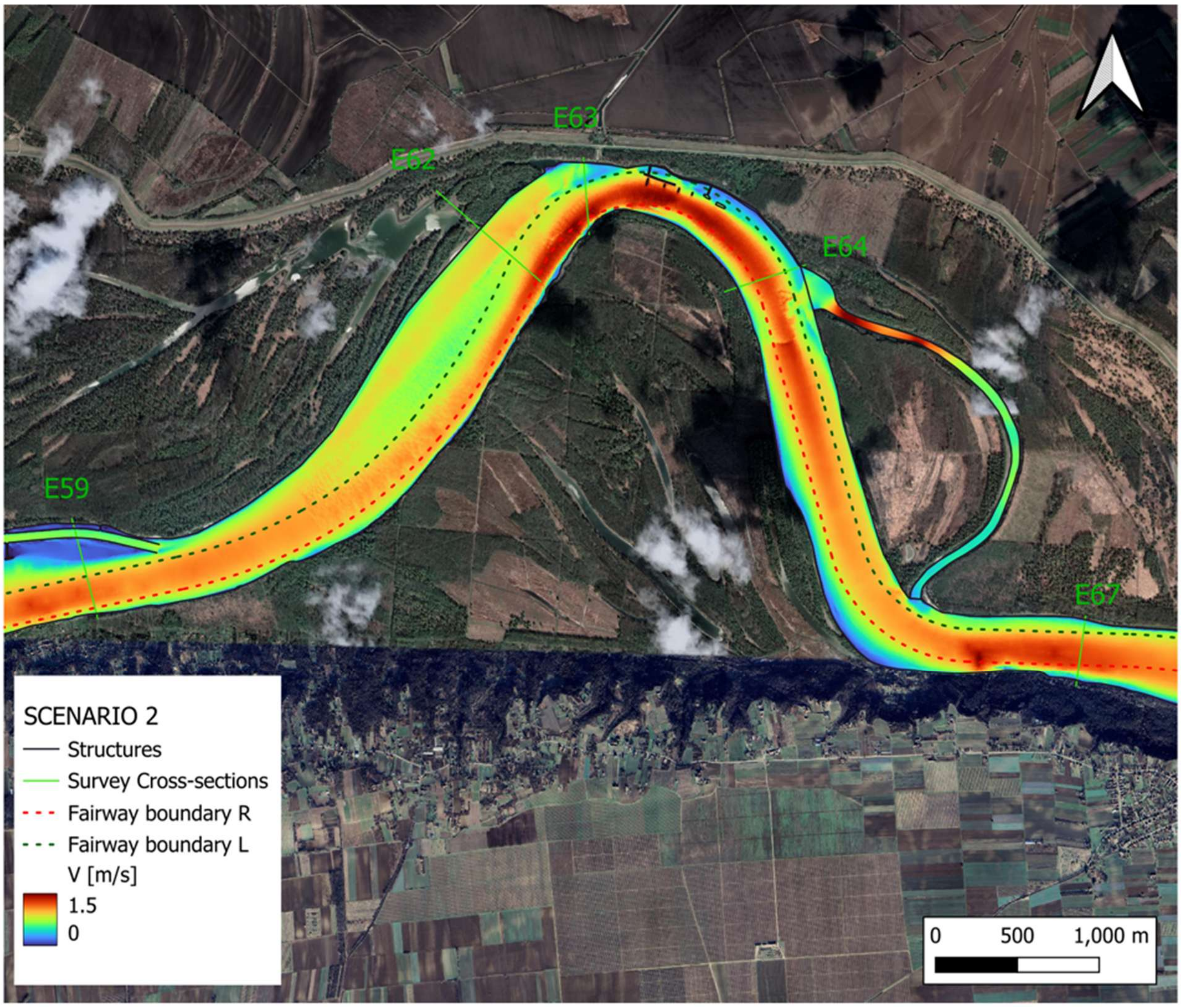


Figure 159: Distribution of depth-averaged velocity in Staklar sector for Scenario 2

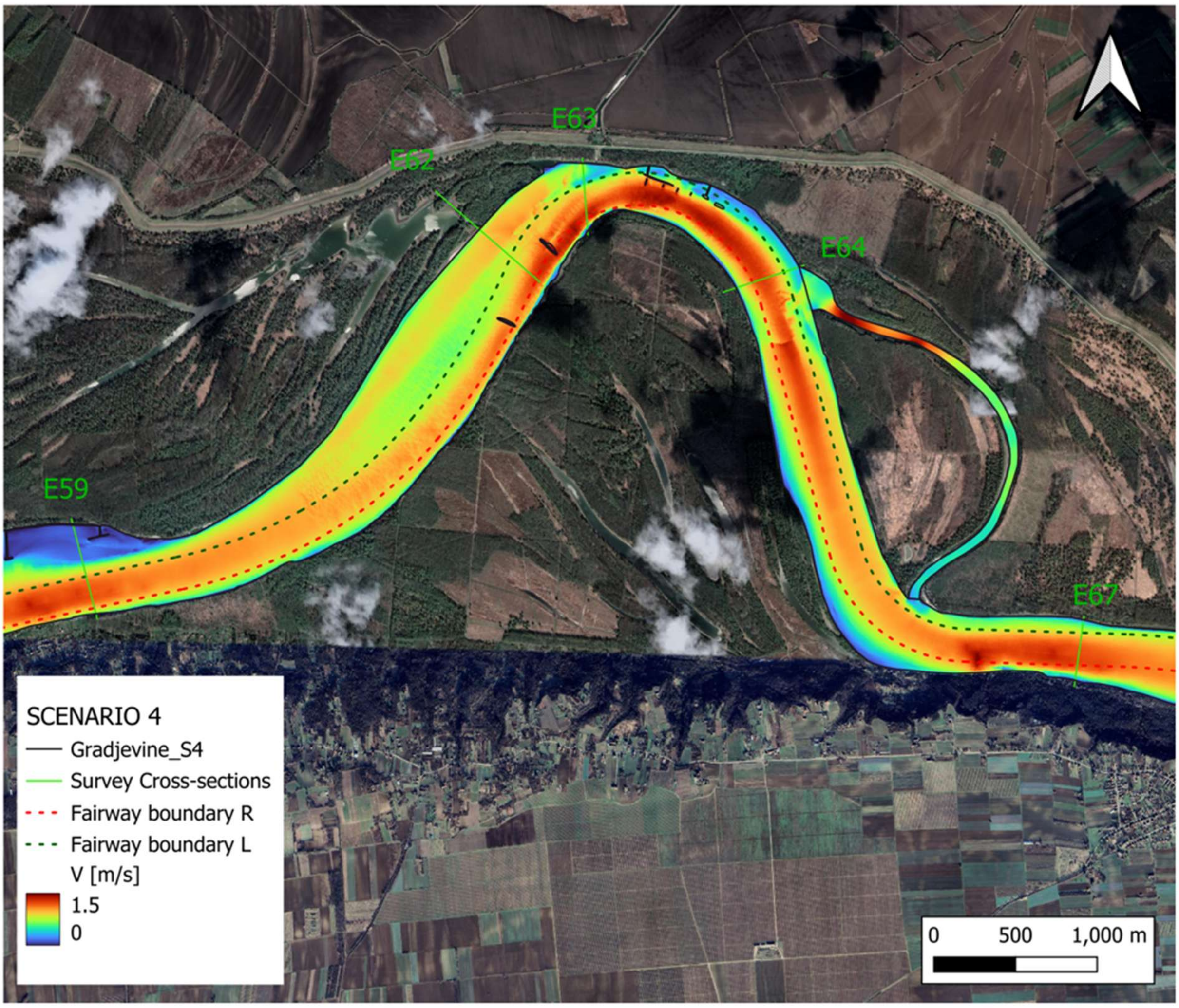


Figure 160: Distribution of depth-averaged velocity in Staklar sector for Scenario 4

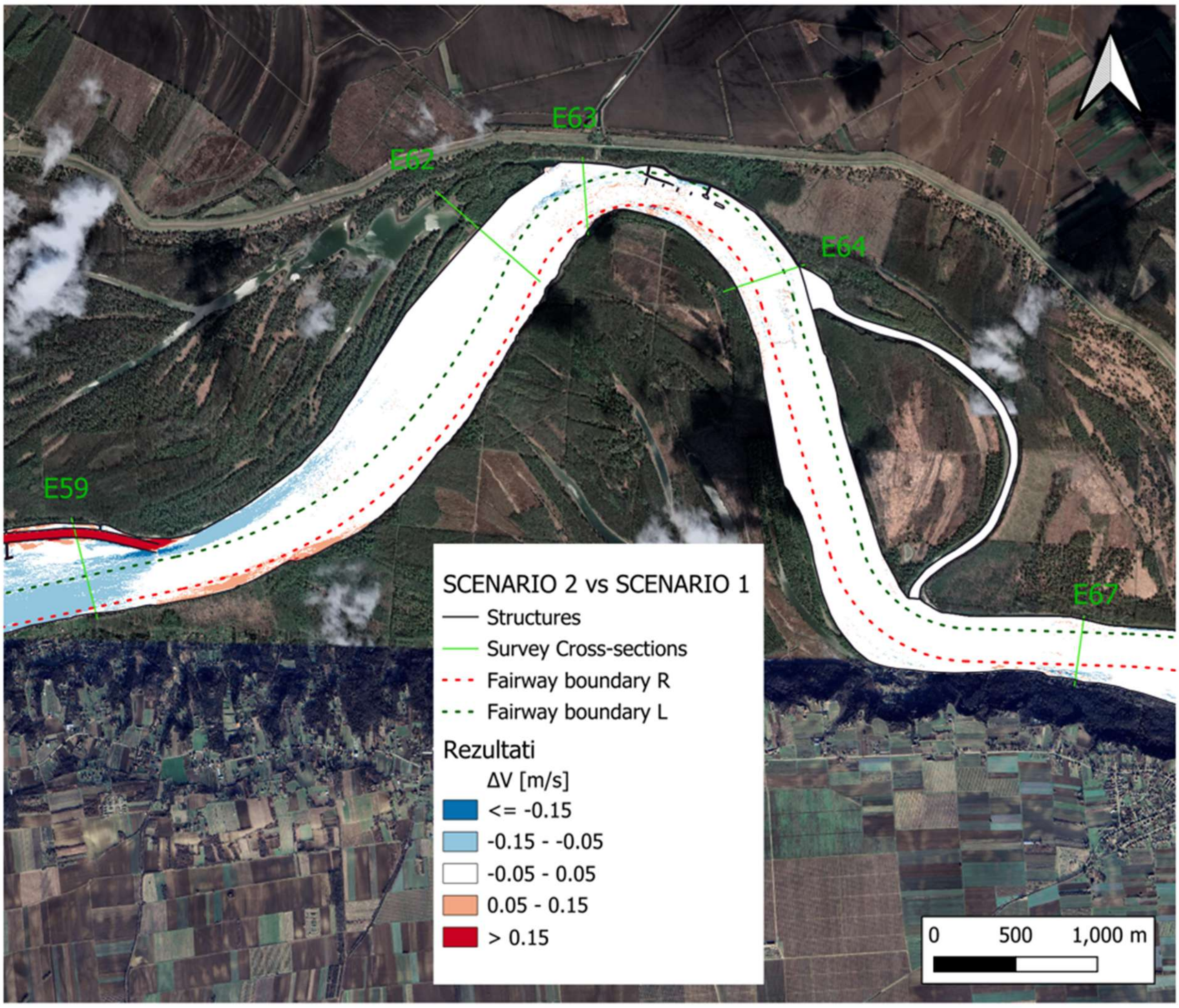


Figure 161: Differences in velocities between Scenario 2 and Scenario 1 (Sector Staklar)

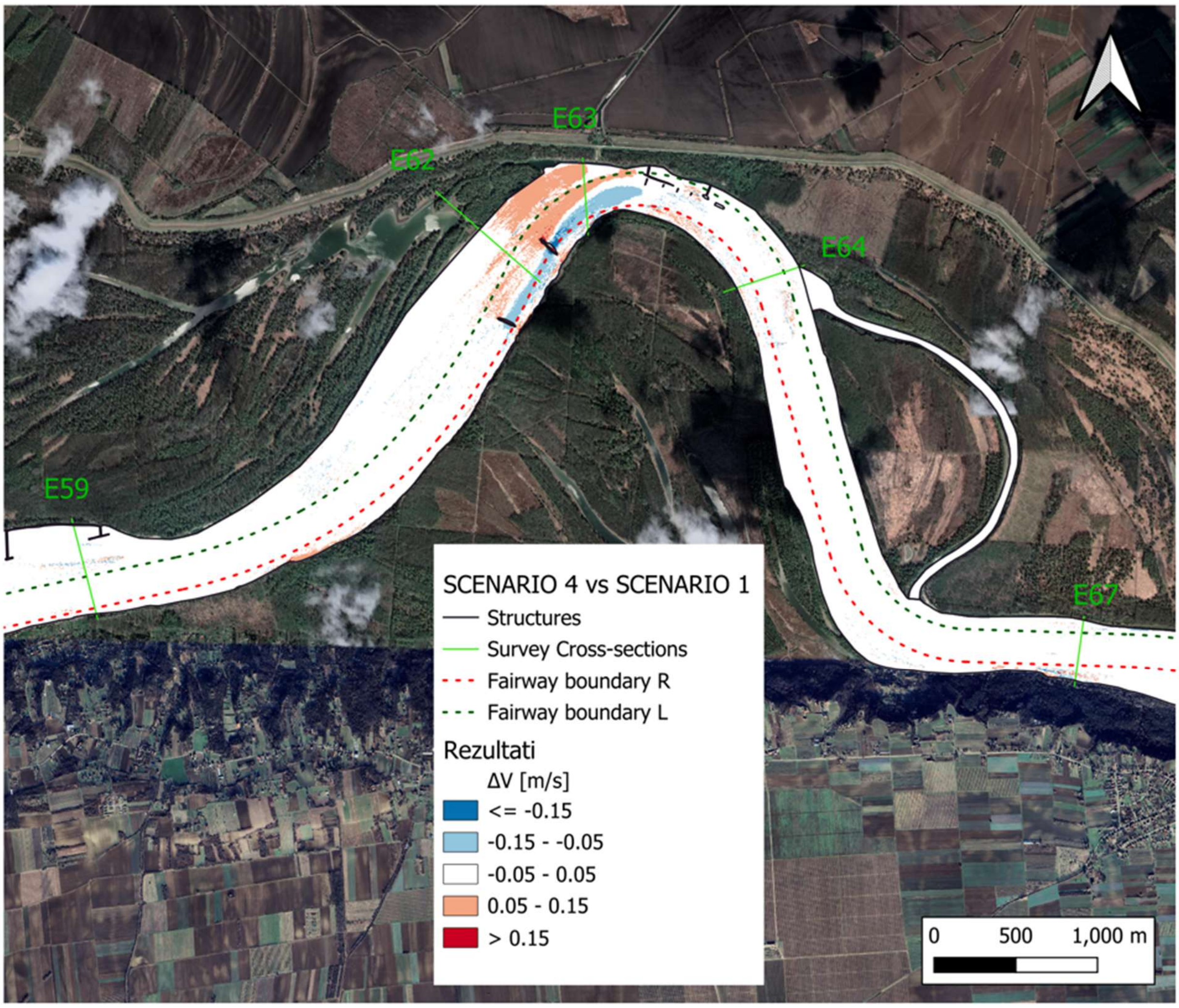


Figure 162: Differences in velocities between Scenario 4 and Scenario 1 (Sector Staklar)

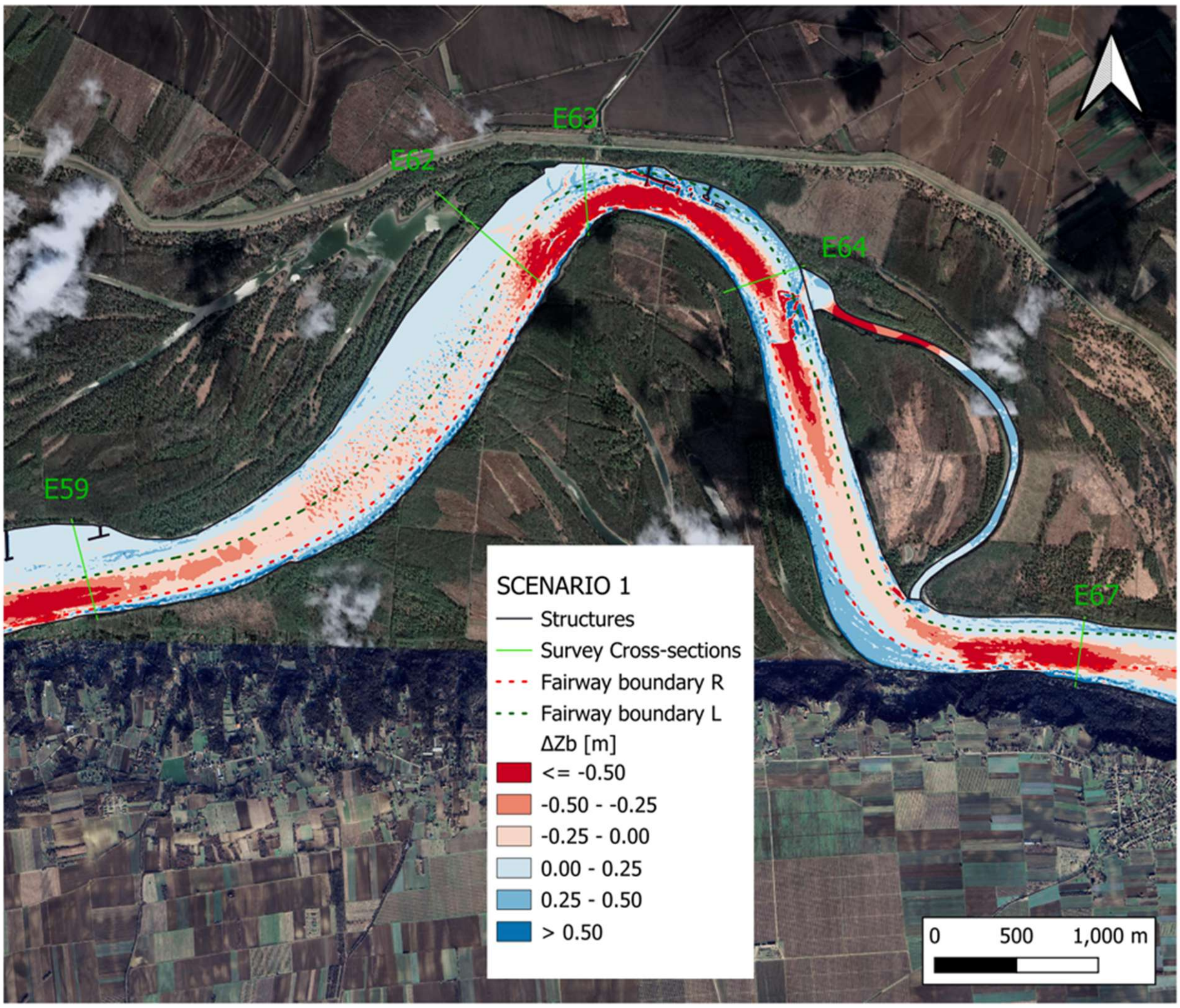


Figure 163: Riverbed vertical alterations in Staklar sector for Scenario 1

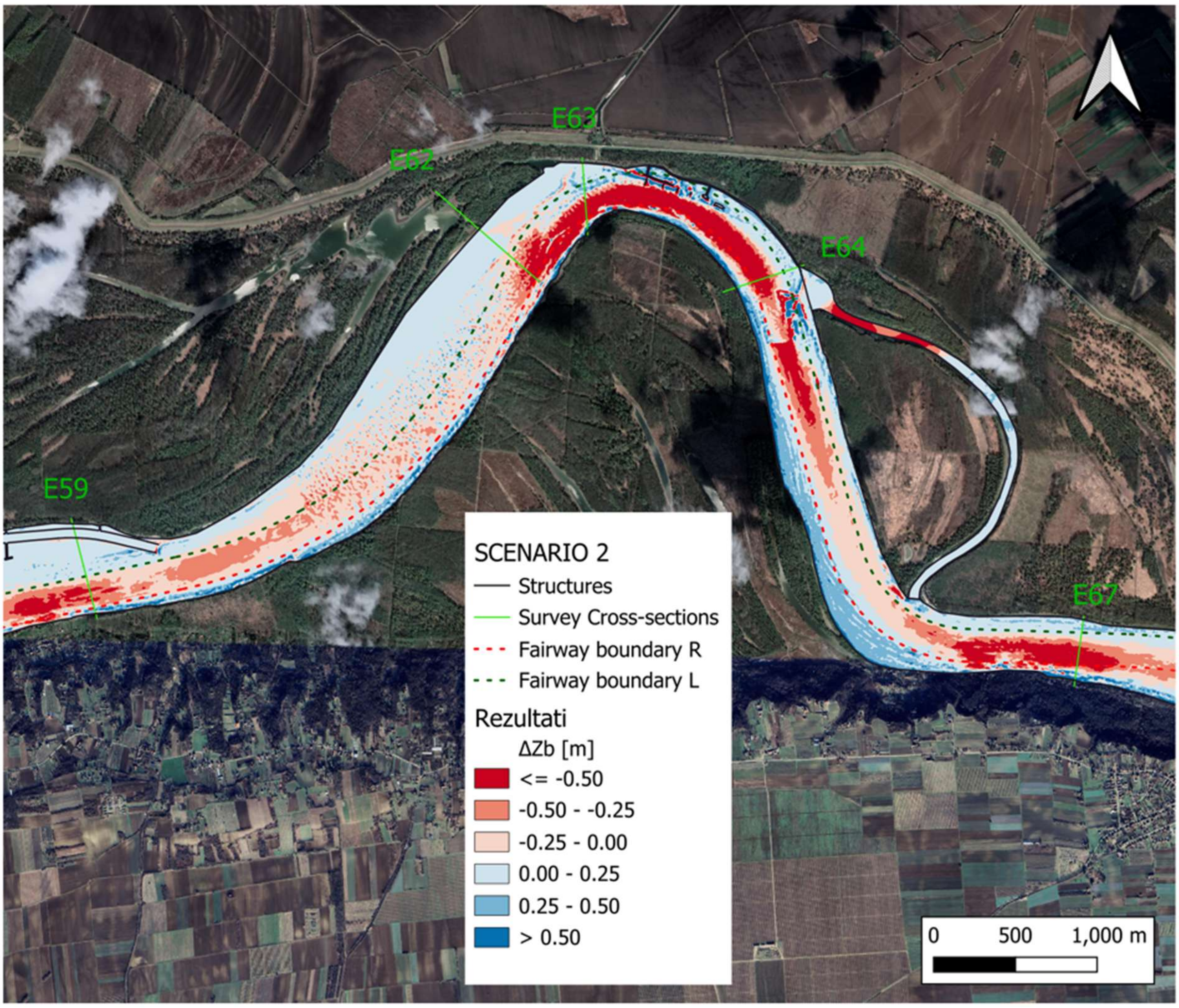


Figure 164: Riverbed vertical alterations along river bend in Staklar sector for Scenario 2

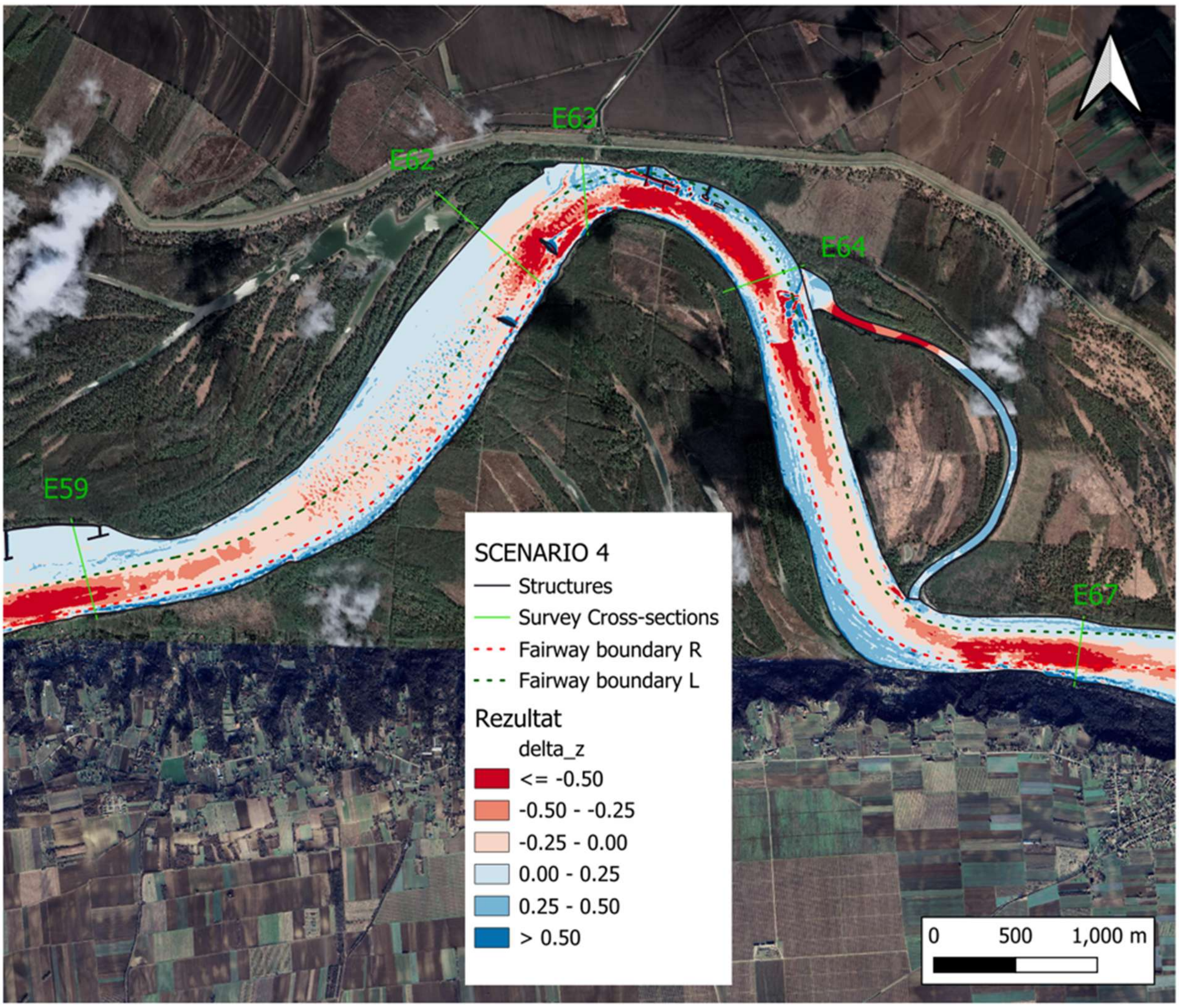


Figure 165: Riverbed vertical alterations in Staklar sector for Scenario 4

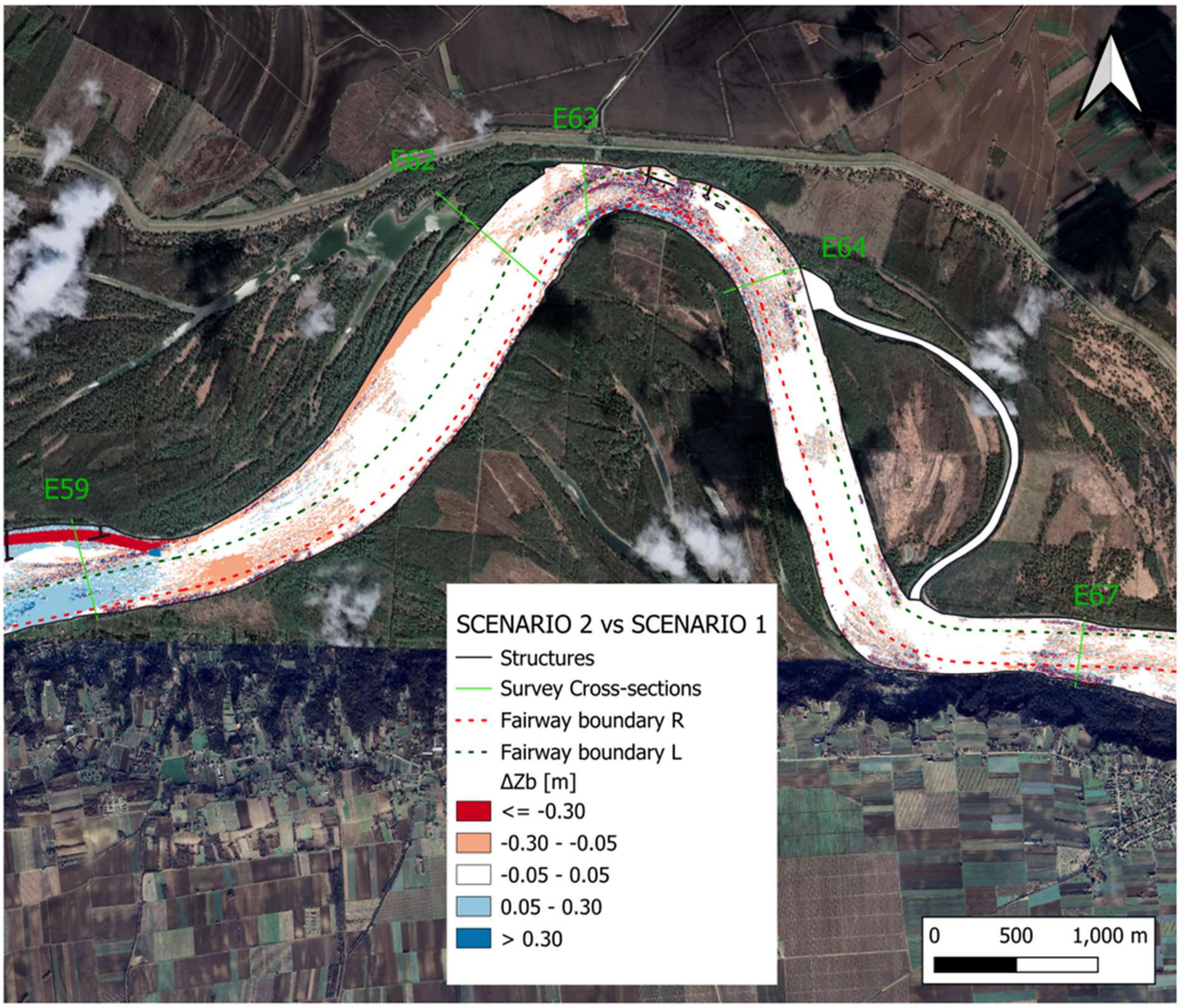


Figure 166: Differences in bottom elevations between Scenario 2 and Scenario 1 (Sector Staklar)

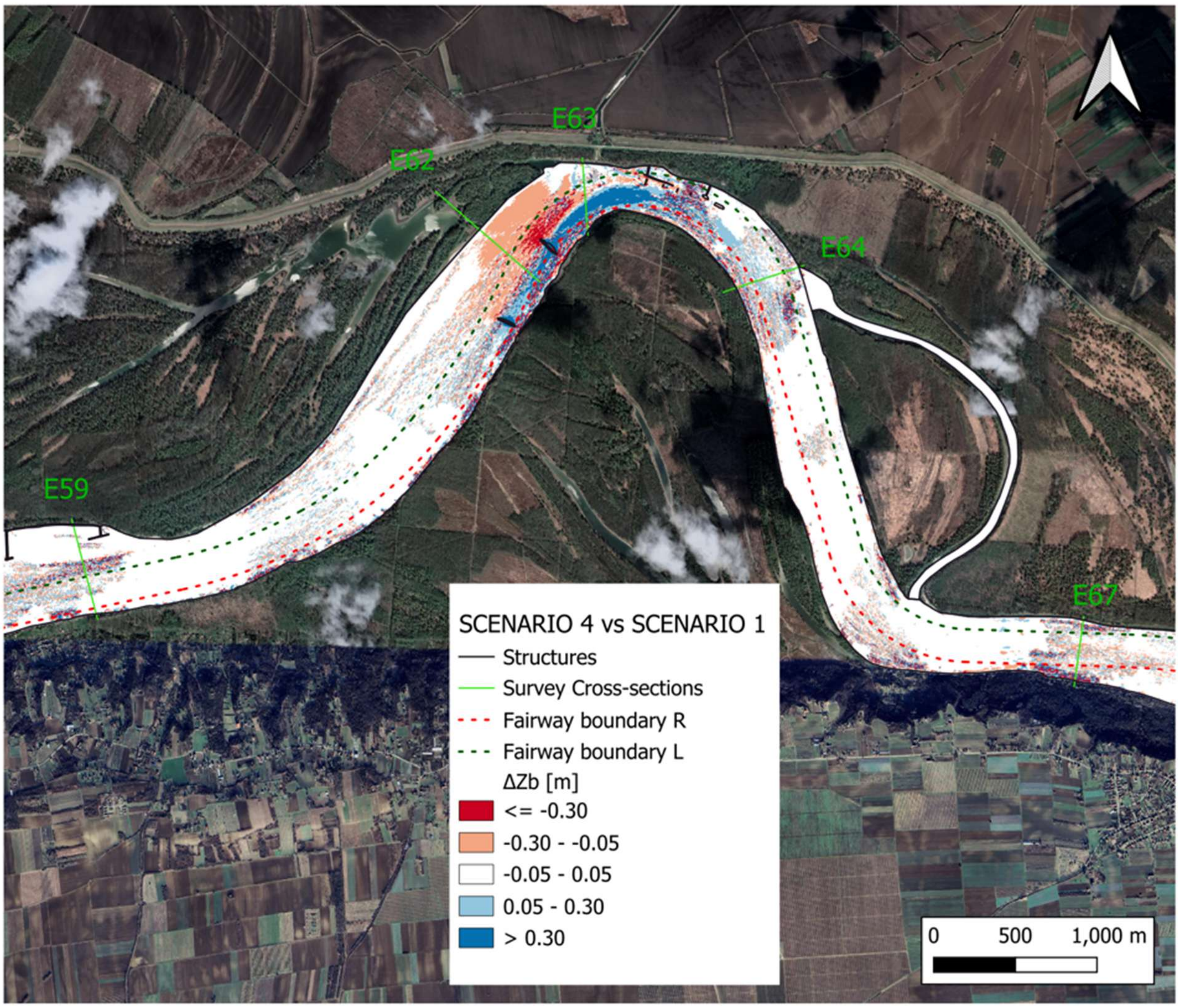


Figure 167: Differences in bottom elevations between Scenario 4 and Scenario 1 (Sector Staklar)

7.4. MCA Application

Based on the adopted methodology for multi-criteria analysis, four scenarios will be ranked, each corresponding to the application of different measures or the absence of measures for improving navigation conditions on the joint Danube sector. Most of the indicators used to assign scores according to different criteria were obtained from the results of 2D sediment transport simulations for the section of the Danube that includes all sectors from Apatin to Staklar.

The final outcome of the simulation process is the assessment of riverbed morphology after the implementation of measures. These riverbed states are compared from different perspectives in order to evaluate whether the measures lead to improvements or deteriorations (according to various criteria) in relation to "Do nothing" scenario. In addition to the numerical simulations described in the previous section, supplementary 2D river flow simulations were also conducted for the riverbed states after deformation, in order to assess the hydraulic effect of different solutions both in the low-flow domain and in the domain of flows confined within the main riverbed.

7.4.1. Navigation

The criteria used for evaluating navigation conditions are divided into three groups. The first group relates to addressing the recommendations of the Danube Commission. These criteria reflect the requirements for safe navigation, but they are of a general nature. Therefore, it was necessary to introduce additional criteria to rank the different solutions according to the degree to which they fulfill this requirement. For this reason, two new criteria were introduced, both inherently linked to the same requirement for safe navigation, taking into account the number of structures as well as their hydraulic effects on navigation.

7.4.1.1. Criteria and indicators for Navigation

The quantitative indicators used to evaluate the scenarios in terms of their impact on navigation refer to the longitudinal variation of extremes (minimum or maximum values) within the fairway zone. For this purpose, cross-sections were established at 100-meter intervals (Figure 168), in which minimum depths at a flow rate of $Q_{94\%}$ were determined, as well as the widths where the depth continuously exceeds 2.5 meters at the same flow rate. Additionally, for flows within the range that fills the riverbed (a flow slightly lower than the one corresponding to the high navigation level), the maximum velocities within the fairway were determined, which relate to criterion N2 (maneuverability).

Figure 168: Profiles used in the Apatin sector to determine the longitudinal distribution of minimum depths for Scenario 1 (Different shades of blue indicate depths within the fairway at $Q_{94\%}$)

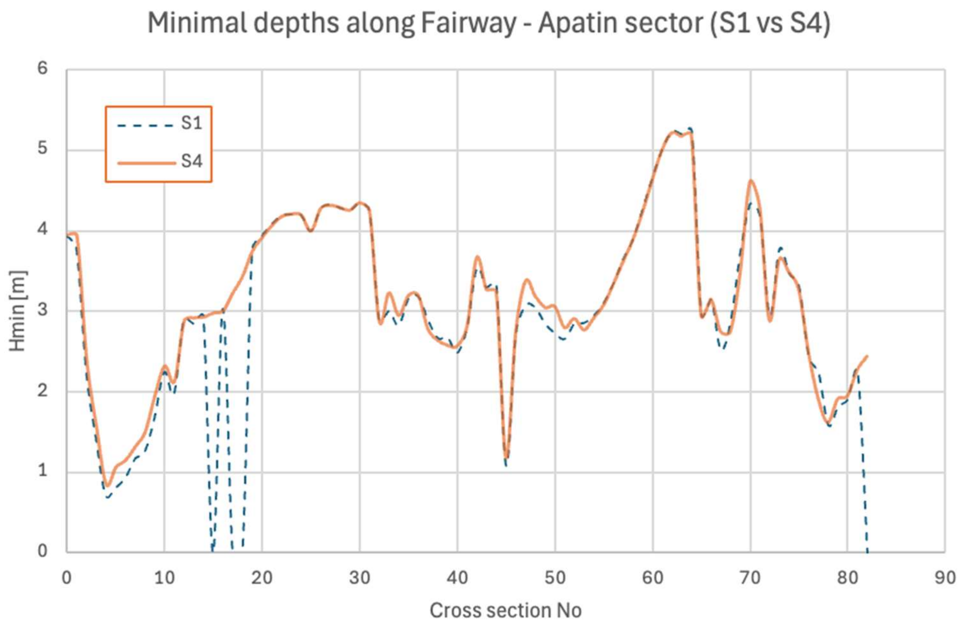


Figure 169: Minimum depths at a flow rate of $Q_{94\%}$ (Scenarios 1 and 4 after morphological alterations)

The evaluation tables present the average values of these extremes for all scenarios. Based on the average values, Scenarios 2, 3, and 4 were compared by presenting the ratios of their longitudinally averaged extreme values relative to those of Scenario 1.

In addition to the values presented in the MCA evaluation tables, a separate Table 42 is provided to assess the effects of the measures, showing the volumes that, based on the results of numerical simulations, would need to be dredged in order to achieve a depth of 2.5 meters over a width of 200 meters along each sector. It should be noted that these figures represent the total volumes for the entire sector, not just for the areas specifically targeted by the measures (meaning that the percentages in the tables would be higher if the volumes were compared only for the areas primarily targeted by the measures).

Table 42: Dredging volumes by scenario and percentage reduction in volume compared to Scenario 1

		S1	S2	S2_ΔV	S3	S3_ΔV	S4	S4_ΔV
		m^3	m^3	[-]	m^3	[-]	m^3	[-]
3	Apatin	49807	37922	23.9%	46313	7.0%	39171	21.4%
4	Čivutski	47905	48088	-0.4%	47905	0.0%	47318	1.2%
5	Drava	24011	23793	0.9%	17443	27.4%	19127	20.3%
6	Aljmaš	0	0	0.0%	0	0.0%	0	0.0%
7	Staklar	11742	11346	3.4%	11742	0.0%	8011	31.8%

Given the particular importance of navigation in this project, the evaluations in this segment will be presented by sector, so that the overall ratings for the entire section can be justified based on these sector-specific assessments.

7.4.1.2. Scores for Navigation

The presentation of indicator values or comments regarding qualitative indicators in the following tables for each sector serves as justification for the adopted scores assigned to the scenarios for each group of sub-criteria. The scores for the entire river stretch, i.e. the overall scores of each scenario for all three criteria (N1, N2, and N3), is calculated as the geometric mean. For navigation purposes, these overall scores are presented in Table 43.

7.3.1.2.1. Scores for Apatin sector

Scenario / Subcriteria	S1	S2	S3	S4
Water depth	ref. value: $\overline{H}$ = 2.98 m	*ratio* = 1.05 ($\overline{H}$ = 3.12 m)	*ratio* = 1.09 ($\overline{H}$ = 3.25 m)	*ratio* = 1.06 ($\overline{H}$ = 3.16 m) larger avoided dredging
Width	ref. value: $\overline{B}$ = 192.8 m	*ratio* = 1.00 ($\overline{B}$ = 193.0 m)	*ratio* = 1.01 ($\overline{B}$ = 194.4 m)	*ratio* = 1.00 ($\overline{B}$ = 193.1 m)
Curve radius	ref. value: $\overline{R}$ = 7718 m	*ratio* = 1.00 ($\overline{R}$ = 7718 m)	*ratio* = 0.90 ($\overline{R}$ = 6419 m >> recommended value)	*ratio* = 1.00 ($\overline{R}$ = 7718 m)
N_1 - Maximal DC Recommendations	**1.0**	**1.5**	**1.5**	**2.0**
Velocity	ref. value: $\overline{V_{max}}$ = 1.23 m/s	*ratio* = 1.02 ($\overline{V_{max}}$ = 1.25 m/s)	*ratio* = 1.00 ($\overline{V_{max}}$ 1.23 = m/s)	*ratio* = 1.02 ($\overline{V_{max}}$ = 1.25 m/s)
Hindrance	ref. state: No sudden change in flow pattern	proj. state: Moderate changes in flow pattern	ref. state: No sudden change in flow pattern	proj. state: Moderate changes in flow pattern
N_2 - Maneuverability	**1.0**	**0.5**	**1.0**	**0.5**
Visibility of the structures	ref. state	proj. state: There are no additional structures that could significantly increase the risk of accidents.	New marking works will reduce "existing" risk of accidents	proj. state: There are no additional structures that could significantly increase the risk of accidents.
N_3 - Safety	**1.0**	**1.0**	**1.5**	**1.0**

7.3.1.2.2. Scores for Čivutski rukavac sector

Subcriteria \ Scenario	S1	S2	S3	S4
Water depth	ref. value: $\overline{H}$ = 3.05 m	*ratio* = 1.00 ($\overline{H}$ = 3.06 m)	*ratio* = 1.00 ($\overline{H}$ = 3.05 m)	*ratio* = 1.01 ($\overline{H}$ = 3.08 m)
Width	ref. value: $\overline{B}$ = 190.5 m	*ratio* = 1.00 ($\overline{B}$ = 190.5 m)	*ratio* = 1.00 ($\overline{B}$ = 190.5 m)	*ratio* = 1.00 ($\overline{B}$ = 190.5 m)
Curve radius	ref. value	*ratio* = 1.00 (R = ref. value)	*ratio* = 1.00 (R = ref. value)	*ratio* = 1.00 (R = ref. value)
N_1 - Maximal DC Recommendations	**1.0**	**1.0**	**1.0**	**1.5**
Velocity	ref. value: $\overline{V_{max}}$ = 1.41 m/s	*ratio* = 1.01 ($\overline{V_{max}}$ = 1.42 m/s)	*ratio* = 1.00 ($\overline{V_{max}}$ = 1.41 m/s)	*ratio* = 1.01 ($\overline{V_{max}}$ = 1.42 m/s)
Hindrance	ref. state: No sudden change in flow pattern	proj. state: No sudden change in flow pattern	proj. state: No sudden change in flow pattern	proj. state: No sudden change in flow pattern
N_2 - Maneuverability	**1.0**	**1.0**	**1.0**	**1.0**
Visibility of the structures	ref. state	There are no additional structures that could increase the risk of accidents.	New marking works will reduce risk of accidents	Negligible increase in collision risk
N_3 - Safety	**1.0**	**1.0**	**1.5**	**1.0**

7.3.1.2.3. Scores for Drava confluence sector

Subcriteria \ Scenario	S1	S2	S3	S4
Water depth	ref. value: $\overline{H}$ = 3.53 m	*ratio* = 1.03 ($\overline{H}$ = 3.62 m)	*ratio* = 1.07 ($\overline{H}$ = 3.77m)	*ratio* = 1.04 ($\overline{H}$ = 3.67 m)
Width	ref. value: $\overline{B}$ = 194.9 m	*ratio* = 1.00 ($\overline{B}$ = 194.7 m)	*ratio* = 1.01 ($\overline{B}$ = 195.9 m)	*ratio* = 1.00 ($\overline{B}$ = 195.1 m)
Curve radius	ref. value: $\overline{R}$ = 3325 m	*ratio* = 1.00 ($\overline{R}$ = 3325 m)	*ratio* = 0.57 ($\overline{R}$ = 1900 m)	*ratio* = 1.00 ($\overline{R}$ = 3325 m)
N_1 - Maximal DC Recommendations	**1.0**	**1.0**	**2.0**	**2.0**
Velocity	ref. value: $\overline{V_{max}}$ = 1.30 m/s	*ratio* = 0.98 ($\overline{V_{max}}$ = 1.28 m/s)	*ratio* = 1.00 ($\overline{V_{max}}$ = 1.30 m/s)	*ratio* = 1.01 ($\overline{V_{max}}$ = 1.31 m/s)
Hindrance	ref. state	No sudden change in flow pattern	Sudden change in flow pattern due additional bend	Moderate changes in flow pattern
N_2 - Maneuverability	**1.0**	**1.0**	**0.25**	**0.5**
Visibility of the structures	ref. state	proj. state: One groyne removed	New marking works will reduce risk of accidents	proj. state: There are no additional structures that could increase the risk of accidents.
N_3 - Safety	**1.0**	**1.5**	**1.5**	**1.0**

7.3.1.2.4. Scores for Aljmaš sector

Scenario / Subcriteria	S1	S2	S3	S4
Water depth	ref. value: $\overline{H}$ = 5.20 m	*ratio* = 0.98 ($\overline{H}$ = 5.08 m)	*ratio* = 1.00 ($\overline{H}$ = 5.20 m)	*ratio* = 1.00 ($\overline{H}$ = 5.19 m)
Width	ref. value: $\overline{B}$ = 200.0 m	*ratio* = 1.00 ($\overline{B}$ = 200.0 m)	*ratio* = 1.00 ($\overline{B}$ = 200.0 m)	*ratio* = 1.00 ($\overline{B}$ = 200.0 m)
Curve radius	ref. value	*ratio* = 1.00 (R = ref. value)	*ratio* = 1.00 (R = ref. value)	*ratio* = 1.00 (R = ref. value)
N_1 - Maximal DC Recommendations	**1.0**	**1.0**	**1.0**	**1.0**
Velocity	ref. value: $\overline{V_{max}}$ = 1.34 m/s	*ratio* = 0.98 ($\overline{V_{max}}$ = 1.31 m/s)	*ratio* = 1.00 ($\overline{V_{max}}$ = 1.34 m/s)	*ratio* = 1.00 ($\overline{V_{max}}$ = 1.34 m/s)
Hindrance	ref. state: No sudden change in flow pattern	proj. state: No sudden change in flow pattern	proj. state: No sudden change in flow pattern	proj. state: No sudden change in flow pattern
N_2 - Maneuverability	**1.0**	**1.0**	**1.0**	**1.0**
Visibility of the structures	ref. state: There are four groynes on the sector with same crest level = DLNL + 1m	proj. state: Two groynes removed	New marking works will reduce risk of accidents	proj. state: There are no additional structures that could increase the risk of accidents.
N_3 - Safety	**1.0**	**1.5**	**1.5**	**1.0**

7.3.1.2.5. Scores for Staklar sector

Scenario / Subcriteria	S1	S2	S3	S4
Water depth	ref. value: $\overline{H}$ = 3.37 m	*ratio* = 0.99 ($\overline{H}$ = 3.35 m)	*ratio* = 1.04 ($\overline{H}$ = 3.49 m)	*ratio* = 1.04 ($\overline{H}$ = 3.52 m)
Width	ref. value: $\overline{B}$ = 189.4 m	*ratio* = 1.00 ($\overline{B}$ = 189.1 m)	*ratio* = 1.02 ($\overline{B}$ = 192.7m)	*ratio* = 1.03 ($\overline{B}$ = 195.3 m)
Curve radius	ref. value: $\overline{R}$ = ref. state	*ratio* = 1.00 ($\overline{R}$ = ref. state)	*ratio* = 1.00 ($\overline{R}$ = ref. state)	*ratio* = 1.00 ($\overline{R}$ = ref. state)
N_1 - Maximal DC Recommendations	**1.0**	**1.0**	**1.0**	**2.0**
Velocity	ref. value: $\overline{V_{max}}$ = 1.42 m/s	*ratio* = 1.00 ($\overline{V_{max}}$ = 1.42 m/s)	*ratio* = 1.00 ($\overline{V_{max}}$ = 1.42 m/s)	*ratio* = 0.99 ($\overline{V_{max}}$ = 1.41 m/s)
Hindrance	ref. state: No sudden change in flow pattern	proj. state: No sudden change in flow pattern	proj. state: No sudden change in flow pattern	proj. state: Moderate changes in flow pattern
N_2 - Maneuverability	**1.0**	**1.0**	**1.0**	**0.5**
Visibility of the structures	ref. state	proj. state: There are no additional structures that could increase the risk of accidents.	New marking works will reduce risk of accidents	proj. state: There are no additional structures that could increase the risk of accidents.
N_3 - Safety	**1.0**	**1.0**	**1.5**	**1.0**

Table 43: Overall Scores for Navigation group of criteria

Scenario / Criteria	S1	S2	S3	S4
N_1 - Maximal DC Recommendations	1.000	1.084	1.246	1.644
N_2 - Maneuverability	1.000	0.871	0.758	0.660
N_3 - Safety	1.000	1.176	1.500	1.000
Total score $(N1^{0.30} \cdot N2^{0.05} \cdot N3^{0.05})$	**1.000**	**1.026**	**1.075**	**1.137**

Based on the presented indicator values and the final overall ratings, it can be concluded that, as expected in terms of achieving improved navigability of the given river section, Scenario 4 has the most positive impact. However, with the introduction of six bottom sills this improvement comes at the cost of slightly worsened maneuvering conditions. On the other hand, the somewhat safer Scenario 3 receives a slightly lower score, as the relocation of the riverbed to achieve greater navigable depths is practically feasible on only two sectors. In any case, this scenario is more favorable than Scenario 2 which also results in an improvement. So, from the perspective of navigation, all scenarios can be recommended for further analysis.

7.4.2. Ecology

The second group of criteria evaluates the impact of the measures on the environment. As with the other criteria, the impact is assessed relative to the no-measures scenario (Do nothing). For all sub-criteria in groups E1 (Hydro-morphology), E2 (Naturalness of the solution), and E3 (Sediment and Water Quality), the ratings are based on aggregated (averaged) indicators for all sectors, which are considered as a single river reach. In contrast, for E4 (Fish), E5 (Birds), and E6 (Flora), the ratings will be adopted by sector, as was done in the case of navigation.

7.4.2.1. Hydro-morphology

All indicators related to the criteria from the hydro-morphology group are based on quantitative indicators described in the Definition of the MCA methodology. Here, additional explanation will be provided on how certain numerical values were obtained.

7.4.2.1.1. River bed volume

During the sediment transport simulation, the riverbed elevation changes. Along the river course, zones of erosion and deposition alternate (in the limiting case, there are no morphological changes). To assess these changes globally for the entire river section (the project area), the total river bed volume is calculated for each scenario by integrating the riverbed elevations (e.g., assuming a reference plane at Z = 0 meters above sea level). In the volume calculation, the difference in volume resulting from the implementation of the measures was omitted. As an indicator in the scenario assessment, the relative change in channel volume is used, compared to the post-deformation volume in Scenario 1.

Based on the calculated change in channel volume, it can be concluded that both Scenarios 2 and 4 cause, on a global scale, greater sedimentation compared to Scenarios 1 and 3. This can be explained by the backwater effect generated by the proposed structures (see the computed water level profiles in Chapter 2 of this report). Since smaller changes in channel volume relative to Scenario 1 are evaluated more positively, it can be stated that, after Scenarios 1 and 3, the most favorable option is Scenario 4, which results in an average riverbed aggradation of 1 mm compared to Scenario 1.

7.4.2.1.2. SHDI

The diversity of channel planforms, represented by four types - active channel, sandbars, vegetated areas, and inactive parts of the flow was quantified using the Shannon Geodiversity Index. For the purpose of calculating this index, hydraulic analyses were conducted for low-flow conditions corresponding to $Q_{95\%}$ (a flow rate that may be considered an estimate of environmental flow). The values of the Shannon Index for this case are presented in the indicator summary tables. The Figure 170 and Figure 171 illustrate the types of planform areas used in the SHDI calculation for the Apatin sector.

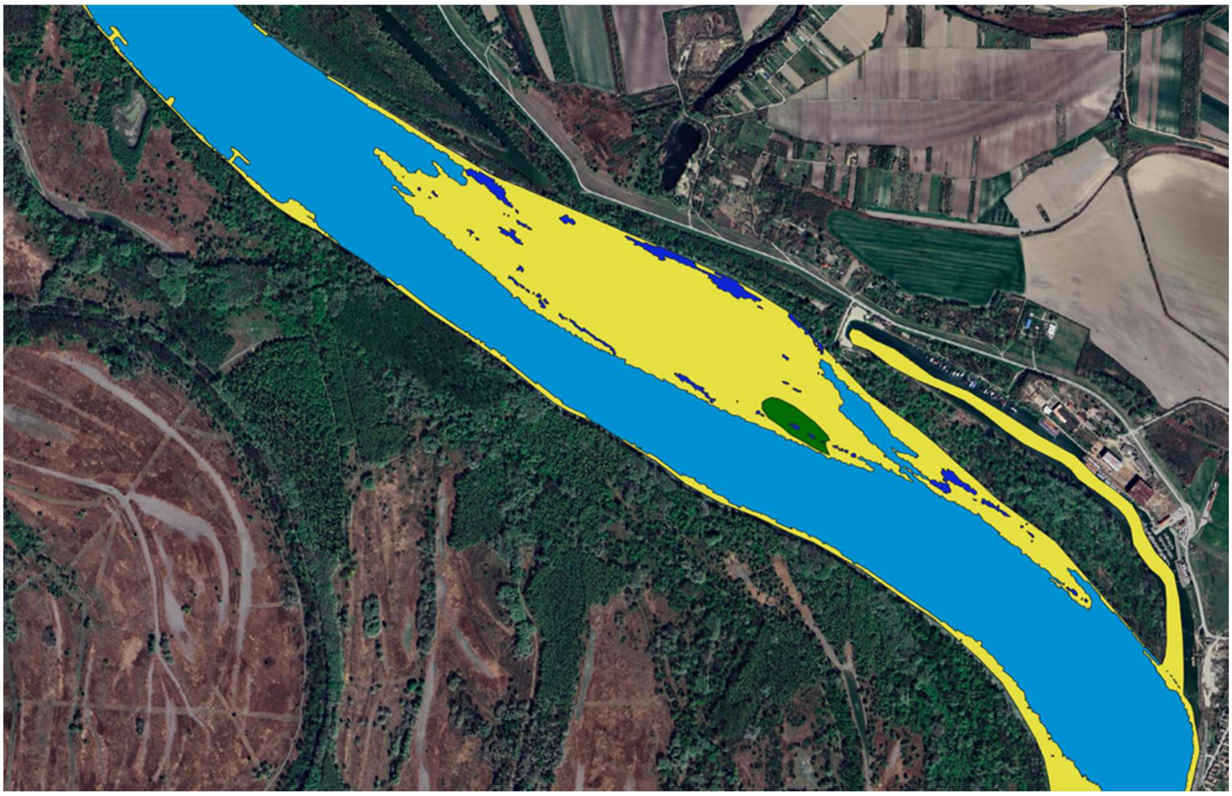


Figure 170: Different channel planforms at low water levels – Scenario 1 (yellow indicates sandbars; light and dark blue represent, respectively, the active and inactive parts of the flow; and green indicates areas covered with vegetation)

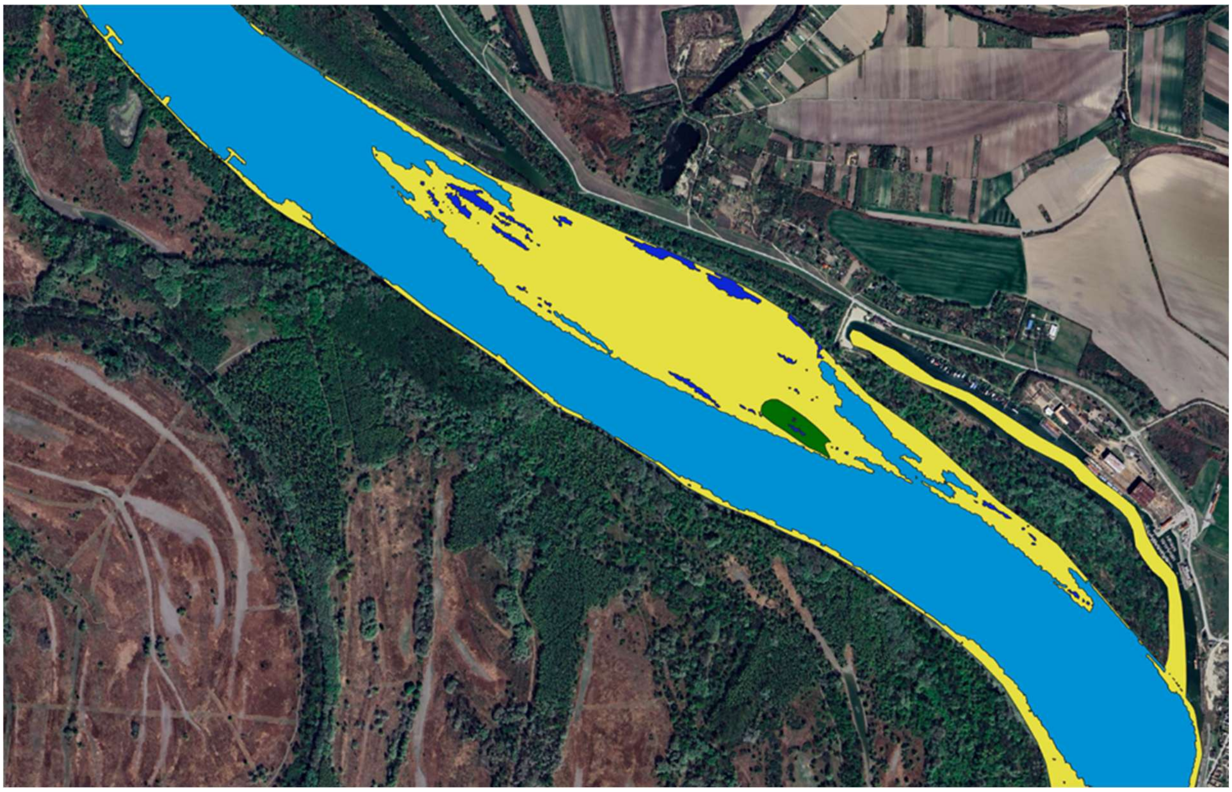


Figure 171: Different channel planforms - Scenario 4 (similar to Scenario 2)

It should be noted that depth variability at low flow conditions was additionally analyzed along the entire considered Danube sector. This variability is particularly pronounced in the Apatin sector, where Scenarios 2 and 4 propose the construction of chevrons (Figure 172), as well as in the Drava and Aljmaš sectors, where the construction of channels through the existing groyne fields is proposed. The same index used to assess channel planform types was also applied to depth distribution, and, as expected, higher index values were obtained for scenarios involving structural measures. Accordingly, the highest depth variability is observed, as expected, in Scenario 2, while Scenario 4 also yields a higher index value compared to Scenario 1.

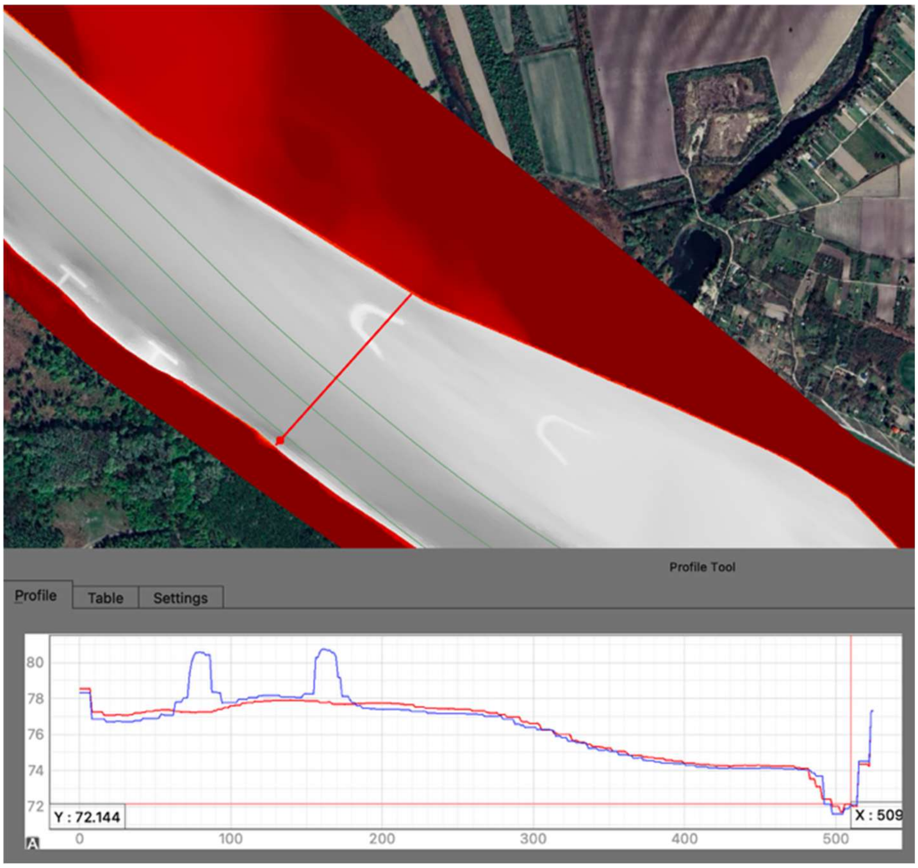


Figure 172: Comparison of cross-sections for Scenario 1 (red line in the lower graph) and Scenario 4 (blue line) at the location of the proposed upstream chevron

7.4.2.1.3. Length of the channels for low flow conditions

As with the Shannon Index, the total flow path length at low water was analyzed for the $Q_{95\%}$ discharge. For this flow rate, the ratios of total flow lengths between Scenario 2 and Scenario 1, as well as between Scenario 4 and Scenario 1, were determined. For the same reasons as in the case of depth variability, the greatest differences in these ratios for both Scenarios 2 and 4 were observed in the Apatin sector (flow path lines used in the calculation are shown in red in Figure 173 and Figure 174), and for Scenario 2 only, in the Drava and Staklar sectors.

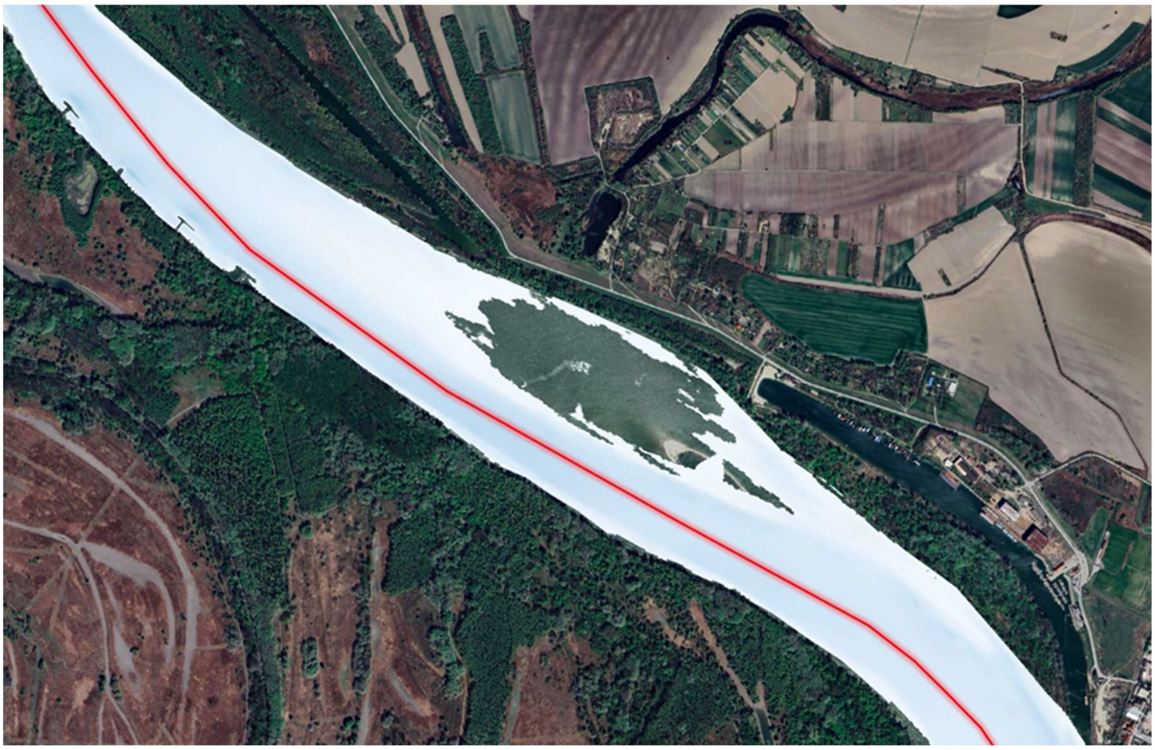


Figure 173: Area under water at low flow $Q_{95\%}$ – Scenario 1

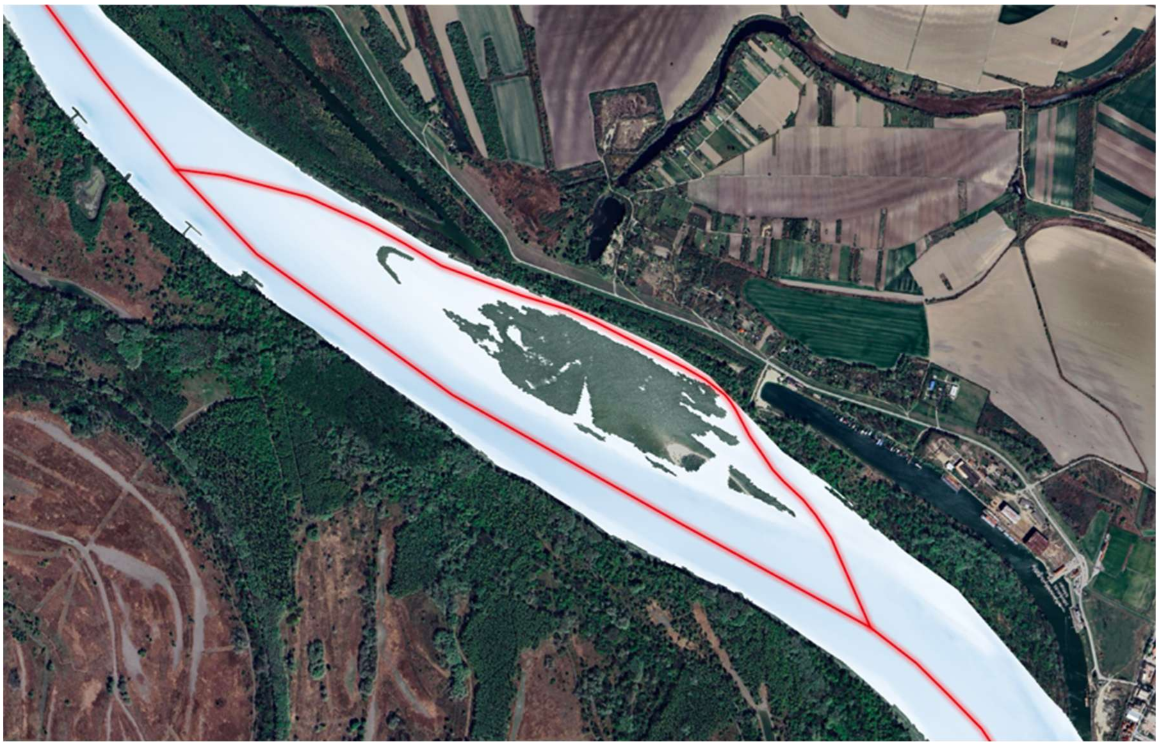


Figure 174: Area under water at low flow $Q_{95\%}$ – Scenario 4 (Similar to Scenario 2)

7.4.2.1.4. Water surface elevation differences for high flow conditions

In order to assess the impact of the proposed structures on flow patterns under high water levels, flow simulations were carried out for three scenarios (Scenarios 1, 2, and 4) under discharges close to the bankfull flow and under $Q_{1\%}$ flow conditions (the discharge at which HNWLs are realized). For the first discharge, the geometry was limited to the main channel, while for $Q_{1\%}$, a portion of the overbank area was also included in the model, using less reliable data sources due to the lack of more accurate information on the geometry of the floodplain areas. In the case of the first discharge, differences between scenarios were slightly larger, although still minor. The evaluation table shows the water level differences at the upstream end, where the largest difference between Scenarios 4 and 1 was 3 cm. As explained in the methodology, such increases in water level are positively evaluated from an ecological perspective, considering they may result in more frequent floodplain inundation, assuming no contamination of adjacent areas occurs.

7.4.2.1.5. Near bank velocities

The second indicator that considers hydraulic conditions near overbank flow is the ratio of flow velocities along the banks between Scenario 1 and the scenarios with measures. All proposed interventions in Scenarios 2 and 4 have only a local hydraulic effect, meaning that the most significant differences in flow velocity occur only in the immediate vicinity of the proposed structures. For each structure, the maximum and minimum velocity ratios between Scenario 2 and Scenario 1, as well as between Scenario 4 and Scenario 1, are provided (Table *44*).

Expert assessment indicates that the observed local differences in flow velocities are unlikely to have a significant (either negative or positive) impact on sediment transport between the main channel and the floodplains. Specifically, the project proposes at most two structures in the system of structures (sills and chevrons). In the case of the T-groyne, which although located between two existing structures is not embedded, a high-velocity zone appears along the bank beside the upstream area of flow deceleration (Scenario 4 compared to Scenario 2). Similarly, in the case of the proposed sidearm channel, part of the main flow is redirected toward the left bank, which balances the area of increased velocity between the two floodplain zones.

Table 44. Minimum and Maximum differences in calculated velocities (near bankfull discharge conditions)

		V [m/s]	V [m/s]	ratio [-]	V [m/s]	ratio [-]	
		S1	S2	S2/S1	S4	S4/S1	
Apatin	Chevrons	1.00	1.07	1.07	1.07	1.07	
	Sills	0.94	0.92	0.98	0.90	0.96	min
		1.08	1.17	1.08	1.17	1.08	max
Čivutski	T-groyne	0.24	na		0.05	0.21	min
		0.33	na		0.64	1.94	max
Drava Confluence	Channel	0.70	0.79	1.13	na		
Drava Confluence	Sills	1.20	na		1.02	0.85	min
		1.35	na		1.40	1.04	max
Aljmaš	Channel	0.35	0.70	2.00	na		
Staklar	Sills	1.21	na		1.14	0.94	min
		1.30	na		1.37	1.05	max

7.4.2.1.6. Bank erosion

In the numerical simulations conducted, no significant differences in flow velocities were observed along the longer sections near the riverbanks, neither under dominant flow conditions nor during high water levels. Furthermore, the project does not consider measures that would alter the bank configuration over longer stretches, meaning that none of the scenarios lead to an improvement in this indicator.

7.4.2.2. Naturalness of solution

In Scenarios 2 and 4, new river training structures are proposed with the primary goal of improving navigational conditions. However, the introduction of new structures reduces the so-called naturalness of the area (including more specific problem of reducing lateral connectivity if structures are near the banks and change its shape), meaning that the structures themselves have a negative impact in an "ecological" sense. The introduction of this indicator is in line with the establishment of a biosphere reserve, which include the considered section of the Danube. Therefore, in this project, the increase in the number of structures compared to the current state, although desirable from the navigation standpoint, is assessed with a score lower than 1 but higher than zero, given that there are no formal restrictions on this number.

In Scenario 2, aside from four proposed structures in the Apatin sector, a sidearm channel is introduced that would effectively eliminate three existing groynes, resulting in a net addition of only one structure. In contrast, Scenario 4 involves the construction of nine entirely new structures. Accordingly, Scenario 2 receives a score of 0.5 under this criterion, while Scenario 4 is assigned a score of 0.25.

7.4.2.3. Sediment and water quality

The potential negative environmental impact of dredging is quantified through the relative dredging needs presented in Table 42. Accordingly, in this context, all three additional scenarios are rated more positively than the "Do Nothing" scenario, with Scenario 4 receiving the highest score under this criterion.

In this project, water quality assessment can only be indirectly addressed based on the results of hydraulic calculations. Since, across different flow conditions, only localized changes in hydraulic parameters were observed in the scenarios with interventions—changes that could negatively influence water quality parameters (e.g., localized backwater zones)—Scenarios 2 and 4 are not assigned a score lower than 1. This is also due to the fact that potentially positive effects were observed, both under extremely low-flow conditions (activation of flow along the left bank near the chevrons in both Scenarios 2 and 4) and under higher discharges (activation of additional flow paths in Scenario 2). Additionally, more frequent flooding, which may positively influence matter exchange between the main channel and floodplain, can also be mentioned here, although this effect is already considered within the morphological criterion that evaluates general transverse flow mixing.

7.4.2.4. Birds, fish and flora

The following section of the report provides the text serving as a justification for the scores assigned to criteria E4 (bird populations), E5 (fish populations), and E6 (flora). As in the case of navigation, due to their particular importance, these criteria will be described and evaluated by sector, with specific impacts of the proposed structures identified and discussed.

Considerable environmental indicators ensure that the interventions included in Scenarios 2 and 4 are functional and environmentally responsible.

7.4.2.4.1. Sector Apatin

Two chevrons

Species such as the white-tailed eagle (Haliaeetus albicilla), the black kite (Milvus migrans), the kingfisher (Alcedo atthis) and the sand martin (Riparia riparia) depend on the natural structure of riverbanks and riparian habitats for nesting and foraging. Careful planning of construction work and outside sensitive breeding periods with the preservation of important vegetation zones can help to reduce disturbance and maintain the ecological balance.

New sediment deposits behind the planned chevrons are new and good habitats for foraging and nesting for some bird species.

In the long term, the construction of chevrons can lead to the formation of new river islands and shelters, creating diverse habitats that are particularly suitable for herons, cormorants and other waterfowl.

For fish fauna, the formation of new habitats and the altered flow could provide new habitat niches for spawning and feeding (Aspius aspius, Barbus barbus, Chondrostoma nasus, Squalius cephalus).

The restriction of activities during the spawning season of the protected and strictly protected fish species Aspius aspius, Gymnocephalus balonii, Leuciscus idus and Squalius cephalus must also be taken into account.

Two sills

Improved flow conditions and changes in sediment morphology can increase the complexity of the habitat and create microhabitats that support different life stages of fish.

This hydro-engineering measure is not expected to significantly affect birds of prey inhabiting the riparian zone, provided that construction works are carried out outside the breeding season and disturbance is minimized.

7.4.2.4.2. Sector Čivutski rukavac

Detached T-groyne

With regard to bird species associated with the river and riparian area, planning construction works outside the breeding season and peak winter months and maintaining undisturbed zones nearby can help to mitigate these impacts. The creation of quiet zones behind the groyne pro-vides a favorable habitat for feeding for some bird species such as kingfisher, heron etc.

From an ichthyological point of view, the new hydro-morphological features favor both rheophilic (current-loving) and limnophilic (still water-preferring) fish species. The installation of a groyne could change the local hydraulic conditions by increasing the current velocity in the vicinity of the structure and creating areas with lower currents in the groyne field. This hydrodynamic variability can improve habitat diversity and support different life stages of fish — from spawning to juvenile fish development. For rheophilic species, a higher flow velocity can improve oxygen supply and the availability of spawning substrate. Meanwhile, limnophilic species can utilize the calm, shallow waters within the groyne field as a refuge or nursery habitat.

7.4.2.4.3. Sector Drava Confluence

Sidearm channel

The reopening of the side channel has the potential to have a positive impact on the biota by restoring the lateral connection between the main river and its tributaries. This reconnection can improve habitat diversity, benefiting in particular fish species— that rely on the side channels for spawning, feeding or as a refuge at high water levels (Rutilus virgo, Chondrostoma nasus, Squalius cephalus, Cobitis elongatoides). Restoring the natural flow in the side channels can also reduce stagnation and improve water quality, creating favorable conditions for aquatic invertebrates and macrophytes that form the basis of the food web.

The opening of the side arm will improve the hydrological connection between the main channel and the adjacent riparian waters, leading to the restoration of more natural flow patterns and water level dynamics. This improved hydrological regime can have numerous positive ecological effects, particularly for bird biodiversity. By restoring the flow exchange between the main river and its tributaries, the measure supports the reactivation of floodplain processes, which are crucial for the creation and maintenance of diverse wetland habitats. These dynamic conditions create a mosaic of shallow water areas, vegetated edges and sediment banks — important features for foraging, resting and breeding for a variety of bird species. In particular, the reconnection of the side arm is expected to benefit waterfowl, waders and migratory birds as they will find new or improved habitats during critical periods such as spring and autumn migration. The presence of quiet, nutrient-rich and structurally diverse microhabitats helps to improve feeding opportunities and overall habitat quality. In addition, this measure can contribute to improved fish availability, which can support predatory bird species such as the white-tailed eagle (Haliaeetus albicilla) and the black kite (Milvus migrans), and improve feeding conditions, particularly for the kingfisher (Alcedo atthis), due to the presence of clear, slow-flowing water zones.

Two sills

This intervention could change the local hydraulic conditions, sediment transport and flow regime. This redistribution of a volume of water in a selected area of the river could have long-term ecological benefits, including the creation of new microhabitats and improved conditions for rheophilic and limnophilic fish species, contributing to the maintenance of a dynamic and resilient river ecosystem.

This hydro-engineering measure is not expected to significantly affect birds of prey inhabiting the riparian zone, provided that construction works are carried out outside the breeding season and disturbance is minimized. The creation of slow-flowing zones behind the sills can improve habitat conditions by providing suitable resting places for waterfowl and feeding areas for various bird species. Based on currently available data, no colonies of sand martins (Riparia riparia) have been detected in the area proposed for the construction of the sills. Therefore, bank stabilization and reduced erosion are not expected to have a negative impact on this species.

7.4.2.4.4. Sector Aljmaš

Sidearm channel

This intervention is a good measure to restore the natural hydro-morphological dynamics by improving the flow distribution and restoring the lateral connection between the main channel and its floodplain.

From an ecological point of view, these measures can have a particularly positive impact on local wildlife. The opening of the side arm channel can improve the diversity of aquatic habitats and provide valuable spawning, feeding and refuge areas for various fish species, including both rheophilic (Alburnus sava, Aspius aspius) and limnophilic species (Esox lucius, Cobitis elongata). Increased water exchange and greater current variability can improve water quality and oxygen levels, promoting a richer benthic community and healthier fish populations.

The reconnected side channel can also attract bird species, particularly waterfowl and waders, by providing undisturbed shallow water areas ideal for foraging and resting.

The planned construction work must be well planned and timed to avoid sensitive periods such as the fish spawning season and the bird breeding season.

7.4.2.4.5. Sector Staklar

Two sills

Sills can create flow variations, promote the formation of shallow water zones and pools and improve the heterogeneity of the habitat, which can be beneficial for fish— - especially for species that require certain flow and substrate conditions for spawning or feeding. The quieter zones between the structures can also serve as resting or nursery areas for juvenile fish.

In addition, the new shallow water zones and sediment deposits can attract wading birds and provide foraging opportunities for species such as herons, sandpipers and other shorebirds.

7.4.2.5. Scores for Ecology

Based on previous considerations, the scores E1, E2, and E3 are presented for the entire considered section of the Danube (Table 45), as well as the sector-specific scores E4, E5, and E6 (Table 46, Table 47, Table 48 and Table 49).

The overall environmental score is derived (Table 16) by taking scores for E1, E2 and E3 (the scores for whole Danube reach) and averaged scores for E4, E5 and E6 derived in the same way as for the navigation category.

Table 45. Scores E1, E2 and E3 for the entire considered section of the Danube

Subcriteria \ Scenario	S1	S2	S3	S4
River bed volume	ref. value ($\bar{Z}$ = 74.601 *masl*)	*diff.* = +82814 m^3 ($\bar{Z}$ = 74.605 *masl*)	*no changes*	*diff.* = +23835 m^3 ($\bar{Z}$ = 74.602 *masl*)
SHDi	ref. value: $SHDi$ = 0.85	*ratio* = 0.96 ($SHDi$ = 0.82) Bed forms variety slightly reduced but depth variety increased	*no changes*	*ratio* = 0.99 ($SHDi$ = 0.84) Bed forms variety slightly reduced but depth variety increased
Length of LF channels	ref. value: L_{lf} = 44001 m	*ratio* = 1.23 (L_{lf} = 54131 m)	*no changes*	*ratio* = 1.08 (L_{lf} = 47421 m)
Z(Q$_{bankfull}$)	ref. value: *Z* = 84.56 m.a.s.l.	*diff.* = 0 cm (*Z* = 84.56 m.a.s.l.)	*no changes*	diff. = +3 cm (Z = 84.59 m.a.s.l.)
Near bank velocity ratio	ref. value	*Local velocity disturbance (up to 100%)*	*no changes*	*Local velocity disturbance*
Bank erosion length ratio	ref. value	*ratio* = 1.00	*no changes*	*ratio* = 1.00
E$_1$ - Hydro-morphology	**1.0**	**2.0**	**1.0**	**1.5**
Number of structures difference	ref. value	difference = +1 (+4-3)	*no changes*	difference = +8
Level of protection	5-Country biosphere reserve	5-Country biosphere reserve	5-Country biosphere reserve	5-Country biosphere reserve
E$_2$ - Naturalness of solution	**1.0**	**0.5**	**1.0**	**0.25**
Dredging volume	ref. value 133,465 m^3	121,149 m^3	123,403 m^3	113,627 m^3
Water quality parameters	ref. state	*Without significant impact*	*no changes*	*Without significant impact*
E$_3$ - Sediment and Water quality	**1.0**	**1.5**	**1.5**	**1.5**

Table 46. Scores for E4, E5 and E6 - Sector Apatin

Scenario / Subcriteria	S1	S2	S3	S4
Nesting	ref. state	slightly improved condition (chevrons) *Without significant impact* (sills)	*no changes*	slightly improved condition (chevrons) *Without significant impact* (sills)
Wintering	ref. state	slightly improved condition (chevrons) *Without significant impact* (sills)	*no changes*	slightly improved condition (chevrons) *Without significant impact* (sills)
Foraging	ref. state	slightly improved condition (chevrons) slightly improved condition (sills)	*no changes*	slightly improved condition (chevrons) slightly improved condition (sills)
E_4 - Birds	**1.0**	**1.5**	**1.0**	**1.5**
Spawning	ref. state	slightly improved condition (chevrons)	*no changes*	slightly improved condition (chevrons)
Migration	ref. state	slightly improved condition (chevrons)	*no changes*	slightly improved condition (chevrons)
Growing	ref. state	slightly improved condition (sills)	*no changes*	slightly improved condition (sills)
Living	ref. state	slightly improved condition (chevrons)	*no changes*	slightly improved condition (chevrons)
Wintering habitats	ref. state	slightly improved condition (sills)	*no changes*	slightly improved condition (sills)
E_5 - Fish	**1.0**	**1.5**	**1.0**	**1.5**
Creation of new areas for distribution	ref. state	improved condition for 91E0* Alluvial forests (chevrons) Not applicable (sills)	*no changes*	improved condition for 91E0* Alluvial forests (chevrons) Not applicable (sills)
E_6 - Flora	**1.0**	**1.5**	**1.0**	**2.0**

Table 47. Scores for E4, E5 and E6 - Sector Čivutski rukavac

Scenario / Subcriteria	S1	S2	S3	S4
Nesting	ref. state	*no changes*	*no changes*	*without significant impact*
Wintering	ref. state	*no changes*	*no changes*	*without significant impact*
Foraging	ref. state	*no changes*	*no changes*	slightly improved condition
E_4 - Birds	**1.0**	**1.0**	**1.0**	**1.0**
Spawning	ref. state	*no changes*	*no changes*	*without significant impact*
Migration	ref. state	*no changes*	*no changes*	slightly improved condition
Growing	ref. state	*no changes*	*no changes*	slightly improved condition
Living	ref. state	*no changes*	*no changes*	slightly improved condition
Wintering habitats	ref. state	*no changes*	*no changes*	*without significant impact*
E_5 - Fish	**1.0**	**1.0**	**1.0**	**1.5**
Creation of new areas for distribution	ref. state	*no changes*	*no changes*	not applicable
E_6 - Flora	**1.0**	**1.0**	**1.0**	**1.0**

Table 48. Scores for E4, E5 and E6 - Sector Drava confluence

Scenario / Subcriteria	S1	S2	S3	S4
Nesting	ref. state	slightly improved condition	*no changes*	*without significant impact*
Wintering	ref. state	slightly improved condition	*no changes*	*without significant impact*
Foraging	ref. state	slightly improved condition	*no changes*	*without significant impact*
E_4 - Birds	**1.0**	**1 .5**	**1.0**	**1.0**
Spawning	ref. state	significantly improved condition	*no changes*	*without significant impact*
Migration	ref. state	significantly improved condition	*no changes*	slightly improved condition
Growing	ref. state	significantly improved condition	*no changes*	*without significant impact*
Living	ref. state	significantly improved condition	*no changes*	*without significant impact*
Wintering habitats	ref. state	significantly improved condition	*no changes*	slightly improved condition
E_5 - Fish	**1.0**	**2.0**	**1.0**	**1.0**
Creation of new areas for distribution	ref. state	improved condition for 91E0*, 3130, 3150	*no changes*	Not applicable
E_6 - Flora	**1.0**	**1.5**	**1.0**	**1.0**

Table 49. Scores for E4, E5 and E6 - Sector Aljmaš

Subcriteria \ Scenario	S1	S2	S3	S4
Nesting	ref. state	slightly improved condition	*no changes*	*no changes*
Wintering	ref. state	slightly improved condition	*no changes*	*no changes*
Foraging	ref. state	slightly improved condition	*no changes*	*no changes*
E_4 - Birds	**1.0**	**1.5**	**1.0**	**1.0**
Spawning	ref. state	significantly improved condition	*no changes*	*no changes*
Migration	ref. state	significantly improved condition	*no changes*	*no changes*
Growing	ref. state	significantly improved condition	*no changes*	*no changes*
Living	ref. state	significantly improved condition	*no changes*	*no changes*
Wintering habitats	ref. state	significantly improved condition	*no changes*	*no changes*
E_5 - Fish	**1.0**	**2.0**	**1.0**	**1.0**
Creation of new areas for distribution	ref. state	significantly improved for 91E0*, 3130, 3150	*no changes*	*no changes*
E_6 - Flora	**1.0**	**2.0**	**1.0**	**1.0**

Table 50. Scores for E4, E5 and E6 - Sector Staklar

Scenario / Subcriteria	S1	S2	S3	S4
Nesting	ref. state	*no changes*	*no changes*	*without significant impact*
Wintering	ref. state	*no changes*	*no changes*	*without significant impact*
Foraging	ref. state	*no changes*	*no changes*	slightly improved condition
E_4 - Birds	**1.0**	**1.0**	**1.0**	**1.0**
Spawning	ref. state	*no changes*	*no changes*	*without significant impact*
Migration	ref. state	*no changes*	*no changes*	*without significant impact*
Growing	ref. state	*no changes*	*no changes*	slightly improved condition
Living	ref. state	*no changes*	*no changes*	*without significant impact*
Wintering habitats	ref. state	*no changes*	*no changes*	slightly improved condition
E_5 - Fish	**1.0**	**1.0**	**1.0**	**1.5**
Creation of new areas for distribution	ref. state	*no changes*	*no changes*	Not applicable
E_6 - Flora	**1.0**	**1.0**	**1.0**	**1.0**

Table 51: Overall score for ecology

Criteria \ Scenario	S1	S2	S3	S4
E_1 - Hydro-morphology	1.000	2.000	1.000	1.500
E_2 - Naturalness of solution	1.000	0.500	1.000	0.250
E_3 - Sediment and Water quality	1.000	1.500	1.500	1.500
E_4 - Birds	1.000	1.275	1.000	1.084
E_5 - Fish	1.000	1.431	1.000	1.275
E_6 - Flora	1.000	1.351	1.000	1.149
Total score $(E1^{0.15} \cdot E2^{0.05} \cdot E3^{0.05} \cdot E4^{0.05} \cdot E5^{0.05} \cdot E6^{0.05})$	**1.000**	**1.144**	**1.020**	**1.036**

7.4.3. Feasibility

7.4.3.1. Technical aspects

The technical feasibility criterion encompasses the complexity of construction works and the time required for a measure to be implemented and produce effects. As described in the MCA methodology, the highest score in this category is 1.0 and is assigned to Scenarios 1 and 3. Scenarios 2 and 4 include measures that differ in terms of implementation duration and construction complexity, while the time frame in which the measures produce effects is approximately the same, as indicated by the sediment transport simulation results. Nevertheless, none of the proposed measures require a significantly longer implementation period compared to the time needed for the effects to manifest, so the scores under this criterion are not significantly reduced.

In assigning the scores for the criterion Technical Aspects, the characteristics of individual river training structures in terms of required resources for construction and complexity of works (affect implementation duration) are shown in Table 52 and Table 53. In the first column of the first table, rank 1 indicates the shortest implementation time, with longer durations represented by higher ranks. Similarly, in Table 53, Rank 1 corresponds to the least complex works, with complexity increasing with higher ranks. In any case, the complexity of these works, similar to the implementation time, cannot significantly impact the selection of any measure in a negative way.

Table 52: Technical Aspects of River Training Structures – Resources Required for Construction

ranking	river training work	activities	amount of equipment	quantity of material
1	sill	construction below water	pontoon, excavator, barge	limited quantities
2	groyne	construction above and below water, option for various layers	pontoon, excavator, barge	average quantities
3	chevron	construction above and below water, option for various layers	pontoon, excavator, barge	large quantities
4	excavation	construction below water	pontoon, excavator, barge	very large quantities

Table 53: Technical Aspects of River Training Structures - Complexity of the construction process

ranking	river training work	activities	level of precision required	materials
1	groyne	supply and install of armor layer above water and at various depth	precision required	grading 150/450 mm grading 63/150 mm
2	chevron	supply and install of armor layer above water and at various depth	more precision required	grading 150/450 mm grading 63/150 mm
3	excavation	underwater excavation	some precision required	sand, stone
4	sill	supply and precisely install at deep water	high precision required	grading 150/450 mm grading 63/150 mm

7.4.3.2. Financial aspects

The financial aspect takes into account the monetary costs and benefits of the applied measures in the scenarios. Costs and benefits are annualized by adopting a lifespan of 30 years for the measures.

The cost calculation considers the implementation of measures and, in the case of structures, includes:

- Costs of the works:

- Geodetic surveys
- Earthworks
- Rockworks
- Designing

- Costs of the equipment:

- Smart Aton Buoys (Equipping existing Aton buoys with echo sounders)
- Designing

In, the cost values per sectors and the total costs for all analyzed scenarios are presented.

Table 54. Investment costs for the analyzed scenarios

Investment cost of the works (eur/year)						
Scenario	Sektor					Total Costs
	Apatin	Čivutski rukavac	Drave confluence	Aljmaš	Staklar	
Scenario 1 (S1) Doing nothing	0.00	0.00	0.00	0.00	0.00	0.00
Scenario 2 (S2) Structural and revitalization measures	41,596.84	0.00	92,650.20	170,109.72	0.00	304,356.75
Scenario 3 (S3) Fairway realignement	1,282.05	0.00	2,849.00	0.00	1,709.40	5,840.46
Scenario 4 (S4) Structural measures	41,596.84	16,090.03	16,597.96	0.00	18,144.02	92,428.85

The benefits of the measures are related to savings in dredging costs. These savings were estimated based on data on the quantities of dredged material in this section of the Danube during the period for which data were available (from 2011 to 2016). These quantities were converted into annual values and multiplied by the percentage of savings for each scenario (according to Table *42*) in order to express the savings (using the unit cost of dredging) in monetary terms. The annual dredging volume values were obtained by converting the total volume dredged over a 6-year period into an annual value and distributing it by sectors according to Table *55*. The distribution of volumes by sectors was carried out by averaging the dredging needs for different widths (levels of service) based on the results of the hydraulic analysis.

Table 55. Required dredging according to level of service approach

No.	Sector	Quantity of sediment within the fairway of 2.5m depth (m^3)									CRO	SRB		Sscenario 2	Sscenario 3	Scenario 4
		Width 100m	Width 120m	Width 150m	Width 200m	p1	p2	p3	p4	p	V(m^3/year)	V(m^3/year)	C(eur/year)	B(eur/year)		B(eur/year)
1	Bezdan	0	0	0	4745	0.0%	0.0%	0.0%	2.2%	0.5%	287	-	-	-		-
2	Siga Kazuk	0	0	0	1106	0.0%	0.0%	0.0%	0.5%	0.1%	67	-	-	-		-
3	Apatin	7,035	14,635	26,821	54,311	85.8%	76.7%	48.2%	24.9%	58.9%	31,149	31,149	532,457	127,057	8,914	113,704
4	Civutski Rukavac	343	1,494	8,164	52,977	4.2%	7.8%	14.7%	24.3%	12.7%	6,737	6,737	115,155	-	-	1,411
5	Drava Confluence	0	441	4,221	22,013	0.0%	2.3%	7.6%	10.1%	5.0%	2,642	0	22,578	205	56	4,592
6	Aljmas	0	0	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	-	0	-	-	-	-
7	Staklar	733	1,571	3,823	14,781	8.9%	8.2%	6.9%	6.8%	7.7%	4,074	12,223	139,291	4,694	-	44,264
8	Erdut	0	0	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	-	-	-	-		-
9	Bogojevo	0	0	0	330	0.0%	0.0%	0.0%	0.2%	0.0%	20	-	-	-		-
10	Dalj	0	0	0	344	0.0%	0.0%	0.0%	0.2%	0.0%	21	-	-	-		-
11	Borovo 1	0	415	5,431	26,555	0.0%	2.2%	9.8%	12.2%	6.0%	3,186	-	-	-		-
12	Borovo 2	0	346	6,863	40,353	0.0%	1.8%	12.3%	18.5%	8.2%	4,314	-	-	-		-
13	Vukovar	0	0	0	2	0.0%	0.0%	0.0%	0.0%	0.0%	0	-	-	-		-
14	Sotin	0	0	0	85	0.0%	0.0%	0.0%	0.0%	0.0%	5	-	-	-		-
15	Opatovac	0	0	0	37	0.0%	0.0%	0.0%	0.0%	0.0%	2	-	-	-		-
16	Mohovo	93	177	368	748	1.1%	0.9%	0.7%	0.3%	0.8%	405	-	-	-		-
17	Ilok	0	0	0	0	0.0%	0.0%	0.0%	0.0%	0.0%	-	-	-	-		-
							c,dredging=		8.55	eur/m^3	Total "Benefit" (eur/year) =			131,956	8,970	163,972

The results of this analysis demonstrated the financial justification of Scenarios 3 and 4, which were positively evaluated according to the benefit-to-cost ratio (Table *56*). Scenario 2 was negatively evaluated due to a significantly worse ratio.

Table 56. Benefit-Cost ratio for analysed scenarios

Scenario	Total Benefit (eur/year)	Total Cost (eur/year)	B/C
Scenario 1 (S1) Doing nothing	Ref	Ref	Ref
Scenario 2 (S2) Structural and revitalization measures	131,956	304,357	0.43
Scenario 3 (S3) Fairway realignement	8,970	5,840	1.54
Scenario 4 (S4) Structural measures	163,972	92,429	1.77

7.4.3.3. Scores for feasibility

Taking into account the previously explained two aspects of the feasibility of the considered measures, the scores shown in **Error! Reference source not found.** are derived.

Table 57. Overall scores for feasibility

Scenario / Indicators - Subcriteria	S1	S2	S3	S4
Response time	no response time	*mid-term*	*short period*	*mid-term*
Execution of works	without execution works	Moderate difficulty	improving marking system (simple implementation)	Moderate difficulty
F_1 - Technical aspects	**1.0**	**0.5**	**1.0**	**0.5**
B-C	ref. state (B-C<0)	significantly lower B-C	*significantly higher B-C*	*significantly higher B-C*
F_2 - Financial aspects	**1.0**	**0.25**	**2.0**	**2.0**
Total score ($F1^{0.05} \cdot F2^{0.15}$)	**1.000**	**0.812**	**1.072**	**0.972**

7.4.4. Climate change vulnerability

Proposed alternative solutions may be affected by climate change in the future. Few studies on climate change impacts on hydrological extremes in the Danube River basin suggest contradictory projections of future low flows and generally consistent projections for floods in the middle Danube basin. The main findings from these studies are shown in Table 58.

Table 58: Overview of findings from previous studies on climate change impacts in the Danube River basin

Source	Assessment method and scenarios	Periods and location	Low flows	Floods
Stagl and Hattermann (2015)	Climate + hydrological modelling; A1B (SRES), RCP 2.6, RCP 6.0, RCP 8.5	2031-2060 vs. 1971-2000 Bratislava, Bazias	Reduced summer and autumn runoff	Increased spring runoff

Source	Assessment method and scenarios	Periods and location	Low flows	Floods
ICPDR (2018)	Review of previous studies; different scenarios	Different periods; Middle Danube	Worsened low flow conditions in terms of duration and frequency	Increased flood intensity and duration; earlier onset of flood peaks
Bisselink et al. (2018)	Climate + hydrological modelling; RCP 8.5	2026-2055* vs. 1981-2010 Common SRB-CRO Danube stretch	Increased 5th percentile of discharge in autumn, winter and spring; no change in summer	Increased 99.5th percentile of discharge in winter, spring and summer; uncertain signal in autumn
Probst and Mauser (2023)	Climate + hydrological modelling; RCP 2.6, RCP 8.5	2031-2060 vs. 1971-2000 Bezdan	Increased summer runoff; no change in autumn runoff; increase of about 5% in mean annual low flow	Increased winter and spring runoff; increase of about 10% in mean annual flood

*Average 30-year period from 11 climate simulations centered around the year of exceeding +2°C in global warming level

Regarding **low flows**, Stagl and Hattermann (2015) projected a general decrease in summer and autumn runoff under various considered climate change scenarios, with ensemble median change ranging from –5% to –19%. Based on an overview of multiple studies and projects, ICPDR (2018) concludes that the low flow conditions would deteriorate in terms of duration and intensity. On the other hand, the maps provided by Bisselink et al. (2018) show for the Serbian-Croatian joint stretch of the Danube an increase in 5th percentile of river discharge (i.e., low flow that is exceeded with probability of 95%) in autumn, winter and spring, and no change in summer. More specifically, Probst and Mauser (2023) provide projections of the change in hydrological regime at Bezdan showing an increase in low flows in both near and far future under two climate change scenarios, with an increase of about 5% in mean annual low flow.

In terms of **floods**, spring runoff is expected to increase (Stagl and Hattermann, 2015) as well as winter runoff (Probst and Mauser, 2023), flood intensity and duration would increase (ICPDR, 2018), and 99.5th percentile of discharge is expected to increase in winter, spring and summer (Bisselink et al., 2018). Probst and Mauser also project an increase of about 10% in mean annual flood.

Inconsistent findings related to low flows from the literature are not surprising, having in mind that they are based on the projections obtained from climate models based on different climate change scenarios and application of hydrological models, while it is well known that all these elements are subject to uncertainties. For example, Intergovernmental Panel on Climate Change (IPCC) states in its report (IPCC, 2021) that there is *medium confidence* in model projections showing an increase in the frequency of hydrological droughts in Western and Central Europe, but that there are large uncertainties related to hydrological and impact modelling.

The observed discharges at hydrological stations in the common Serbian-Croatian stretch of the Danube are clearly showing increased reference low flows (discharges with duration of 94%) in the last 30 years (as presented in Hydrological study in this project). This supports the most recent findings from Bisselink at al. (2018) and Probst and Mauser (2023), although this increase cannot be attributed to climate change without further research. On the other hand, the observed discharges and calculated reference flood flows (discharges with duration of 1%) show a slight decrease from the previous reference 30-year period, and this observational evidence does not support findings from the climate change impact studies on increased flood flows. However, it should be noted that the discharges of 1% duration represent extreme floods for which the measurement uncertainties can be considerable because the stage-discharge relationships in the high-flow domain are typically extrapolated and not based on the measurements. Due to these uncertainties, together with those related to climate and hydrological modelling in the climate change impact studies, firm conclusions are impossible, and the magnitude of change in flood flows cannot be estimated with any certainty. According to Probst and Mauser (2023), climate change in the Danube region is expected to exceed the global average, with projected warming in the middle Danube by the end of the 21st century ranging from +1.2°C under the optimistic RCP 2.6 scenario to +4.2°C under the pessimistic RCP 8.5 scenario. To better understand the consequences of these warming trends on the Danube's hydrological regime, additional studies employing hydrological models and IPCC greenhouse gas emission scenarios are needed to assess future discharge of the Danube and its tributaries.

Based on all this, we consider here only the impact of the increase of low flows in the common Serbia-Croatian stretch on the proposed scenarios is considered. If climate change projections for increases in low flows in the future would materialize, this could potentially influence the effectiveness and necessity of the proposed solutions in the following way:

- **Scenario 1 ("Do Nothing"):** If low flows continue to increase naturally, the navigation conditions at historically defined LNWL might improve without intervention, as higher discharges would be more frequent. However, in certain unstable sectors natural processes alone may not solve all bottleneck issues even with higher low flows.
- **Scenario 2 and 4 (Structural Measures):** These scenarios involve structures designed to manage flow and sediment specifically to ensure navigability at LNWL. The height of some structures, like groynes, is based on LNWL + 1m. If the LNWL increases due to climate change, these structures might interact with flow conditions differently than anticipated based on the 1994-2023 LNWL definition. While designed to work under varying flow regimes, their optimal performance or the need for them at specific historical LNWL elevations might be altered if low flow conditions shift significantly. Acknowledging that the structural performance may vary under extreme discharge events, and while this primarily refers to high flows, extreme low flows (even if higher than historical minimums) or significant shifts in flow duration curves could also impact performance.
- **Scenario 3 (Fairway Realignment):** If low flows increase and lead to altered sediment dynamics (e.g., less severe deposition), the reliance on dredging might decrease, making this minimal intervention approach potentially more effective or easier to manage.

7.4.4.1. Scores for climate

Taking into account both aspects of climate change (sensitivity and resilience), the final scores for the climate change criterion are derived and shown in Table *59*.

Table 59. Scores for climate change criteria

Scenario / Indicators - Subcriteria	S1	S2	S3	S4
Aspect of sensitivity	ref. state	*moderate sensitivity*	*low sensitivity*	*moderate sensitivity*
Aspect of resilience	ref. state	*moderate adaptivity*	*high adaptability*	*moderate adaptivity*
C - Climate change vulnerability	**1.0**	**0.5**	**1.0**	**0.5**

7.4.5. Total score

The final scores are derived according to the adopted formula and weighting coefficients described in the report. In Table *60*, the overall scores for the groups of criteria are presented again, scaled by the weighting coefficients, which for navigation, environment, feasibility, and climate change are 0.40, 0.35, 0.20, and 0.05, respectively.

Table 60. Total score for analyzed scenarios

	Group score for navigation	Group score for environment	Group score for feasibility	Group score for climate change	**Total Score**
S1	1.000	1.000	1.000	1.000	**1.000**
S2	1.026	1.144	0.901	0.966	**1.022**
S3	1.075	1.020	1.072	1.000	**1.176**
S4	1.137	1.036	1.035	0.966	**1.177**

The solutions ranked by total score:

1. Scenario 4 - Structural measures
2. Scenario 3 - Fairway realignment
3. Scenario 2 - Structural and revitalisation measures
4. Scenario 1 - Do nothing

7.5. Conclusions

According to the adopted criteria and the corresponding scores, the scenario proposing new river training structures is considered optimal. Scenario 2 represents the optimal option key group of criteria within this project (criteria related to navigation), and based on expert evaluations, it also provides better financial (savings due to reduced dredging needs) and ecological outcomes (increased river bed volume, higher water levels, depth variability, etc.) compared to the “do-nothing” approach.

In addition to this optimal scenario, the project also identifies, albeit limited, potential for fairway realignment (Scenario 3), as well as a combined consideration of measures such as sidearm channel construction, which, although not yielding direct financial benefits, may result in ecological co-benefits.

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