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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1D MODELING REPORT

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Abbreviations

Abbr.	Meaning
1D	One dimensional
2D	Two dimensional
cm	Centimeter
CS	Critical sector
DEM	Digital Elevation Model
DHMZ	State Hydro-meteorological Service of Croatia
DTM	Digital Terrain Model
FABDEM	Forest And Buildings removed Copernicus DEM
GIS	Geographic Information System
GS	Gauging Station
H	Stage (water level)
HEC-RAS	Hydrologic Engineering Center's River Analysis System
HNWL	High Navigation Water Levels
HRV	Croatia
km	Kilometer
LIDAR	Light Detection and Ranging
LNWL	Low Navigation Water Level
m	Meter
maAs	meters above Adriatic Sea
m^3/s	Cubic meters per second
Max	Maximum
Min	Minimum
Q	Discharge
RHMZ	Republic Hydro-meteorological Service of Serbia
SRB	Serbia
TIN	Triangulated Irregular Network
ToR	Terms of Reference

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 SRB-HRV stretch of the Danube River.

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 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 Report on hydrological analysis and update of ENRs will not be part of this report which is focused on hydraulic modelling, but is given as a separate document.

1. Study and Model Area

The project focal point is the quest for alternatives which may enhance the navigational conditions on the stretch of the Danube which flows between Serbia and Croatia.

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 Backa 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 Backa 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.

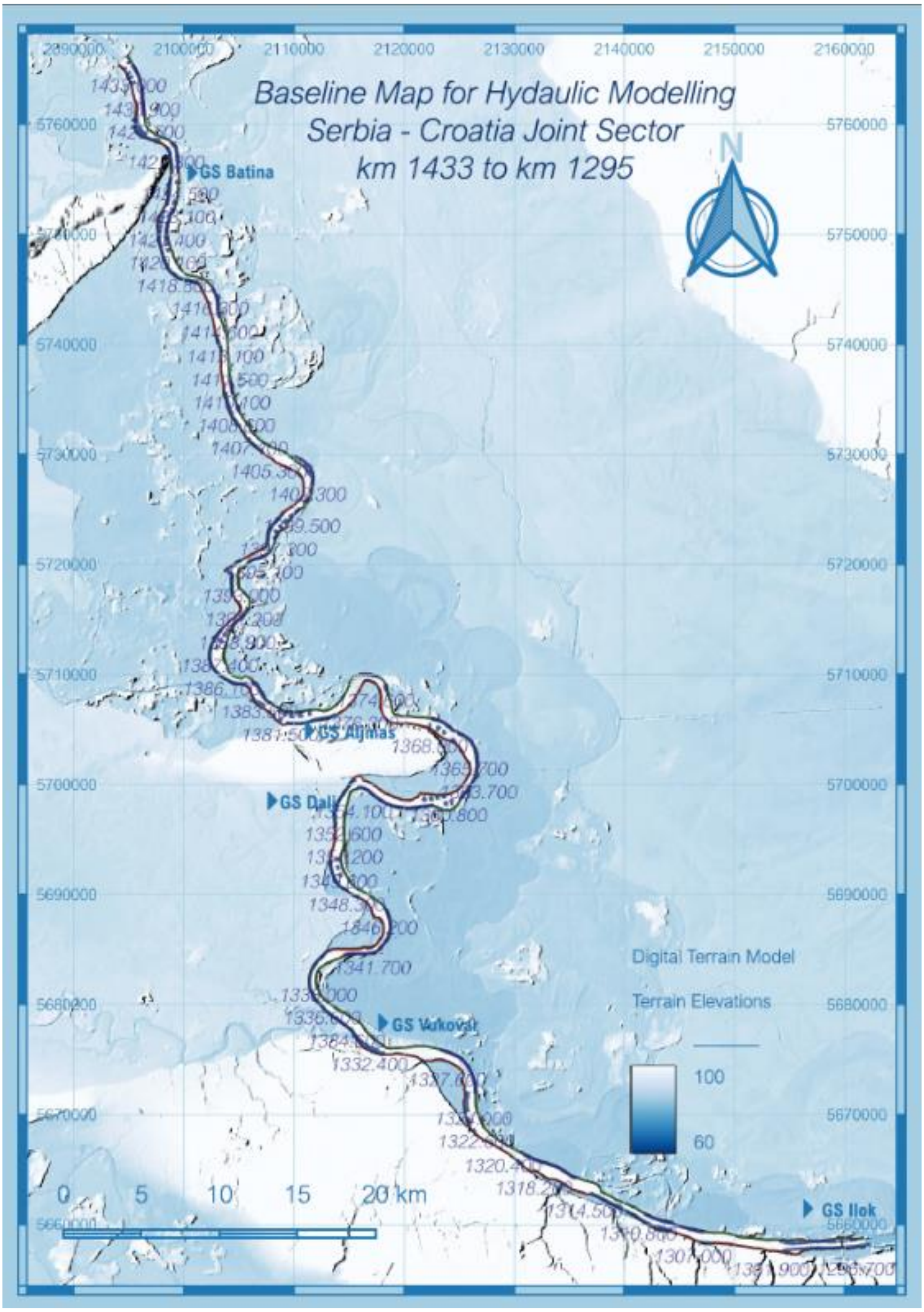

Figure 1: A detailed map of the analyzed stretch with topographic representations, location of the cross-sections, training works and location of relevant Hydrologic Stations

2. Model Setup

2.1. 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.

2.1.1. 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.

2.1.1.1. 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).

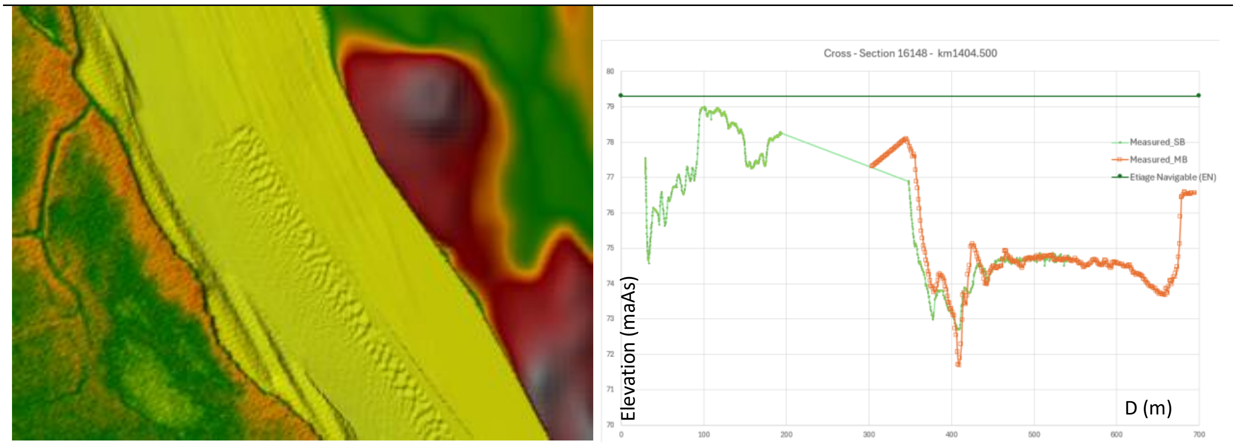

Figure 2**:** (A) segment of the riverbed composed of data collected by both single-beam and multi-beam methods. (B) Overlapped cross-sections generated from the single-beam and multi-beam data.

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
Zidovski Rukavac	km 1,398 to 1,389
Usce	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 some cases, the matching between the classic bathymetry and the LIDAR data was remarkably accurate, while in other cases, the agreement was less satisfactory.

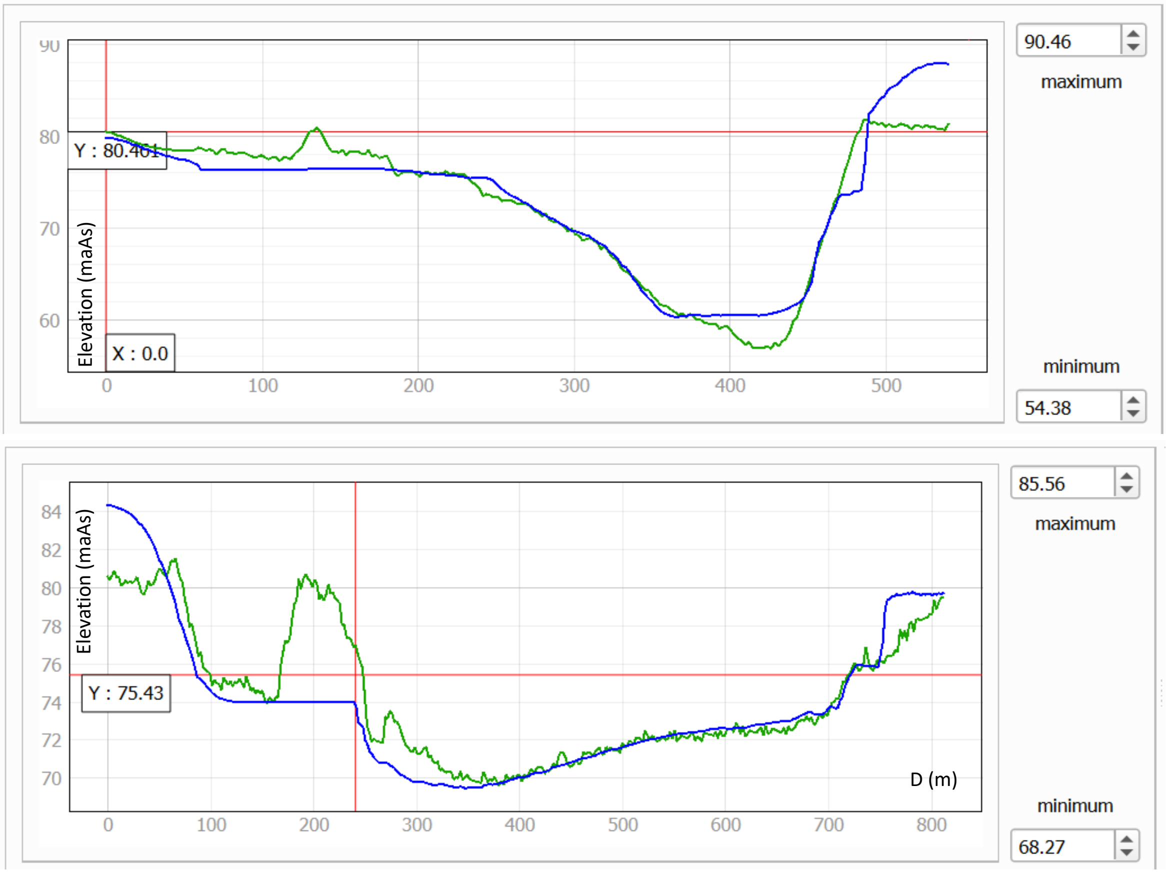

Figure 5: A comparison between two cross-sections is shown, where the green line represents the surface surveyed by LIDAR, and the blue line represents the cross-section through the hybrid model composed of the data described above

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, 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.

2.1.1.2. 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.

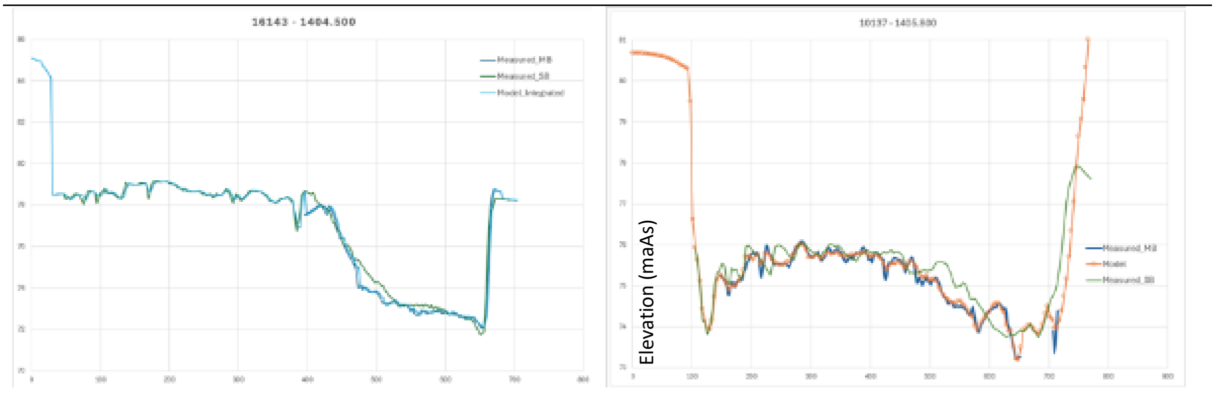

Figure 6: Cross-Section 16143 – 1404.5 and 10137 - 1405.8 Verification of the Hybrid DEM by the comparison between cross-sections: measured by the single-beam, measured by the multibeam and Hybrid DTM model

2.1.2. 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 results of the hydrological study (Annex 1) revealed inconsistencies between data obtained from Serbian and Croatian hydrological stations, leading to conclusion the calibration and verification data sets should be sourced from either the Serbian or Croatian side, as combining data from both may introduce uncontrolled biases that are difficult to address. The model results (water surface elevations) will be compared with elevations obtained from the Rating Curves for each hydrological station recurrently to the satisfying calibration results. This approach will utilize time-averaged values from Croatian hydrological stations for which Rating Curves are available, ensuring consistency in the calibration process.

2.2. 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.

2.2.1. 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. The section of the Hybrid DTM is enclosed on a Figure 7.

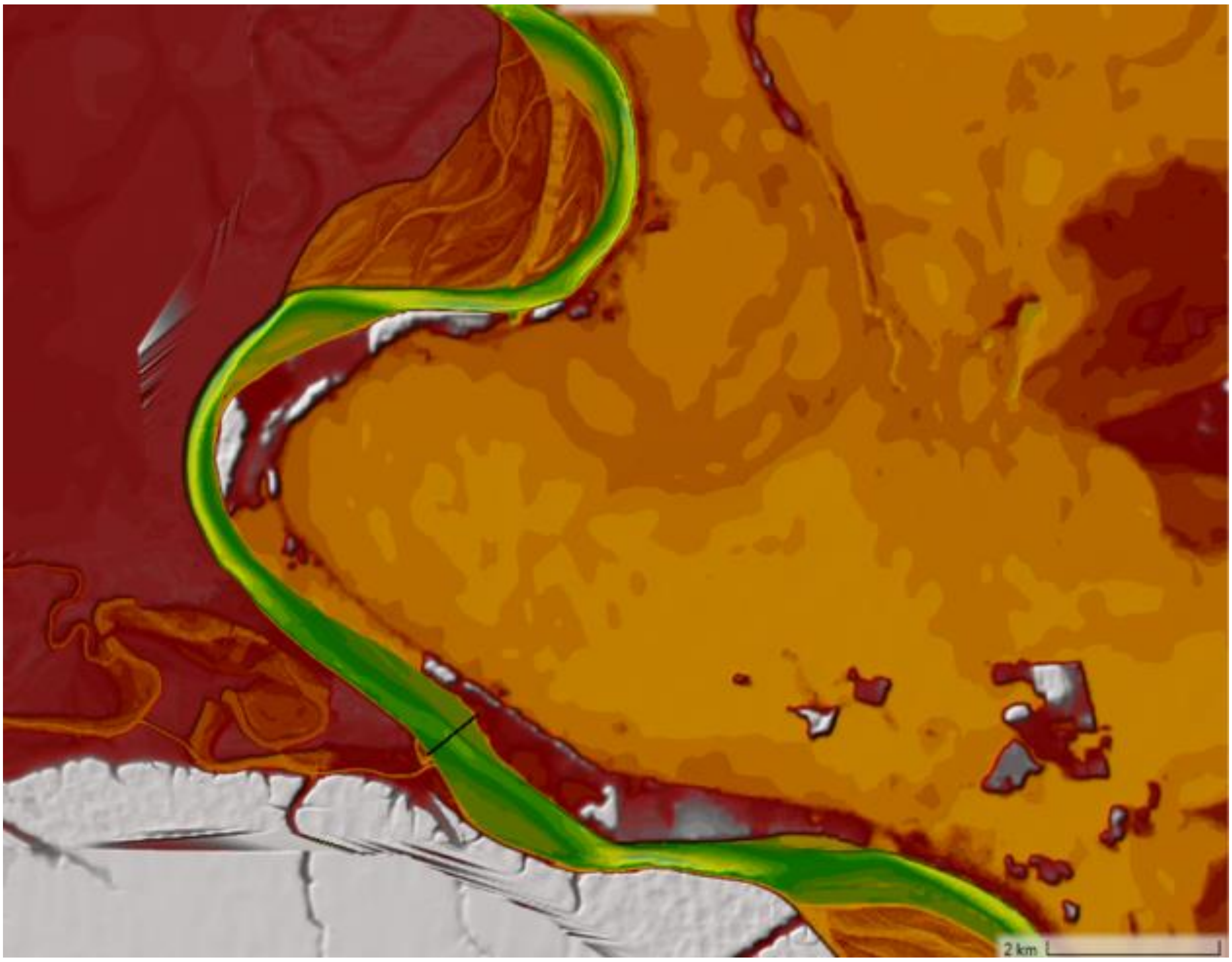

Figure 7: The segment of the Hybrid DEM with riverbed 3D model and terrain of the surrounding floodplain areas

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).

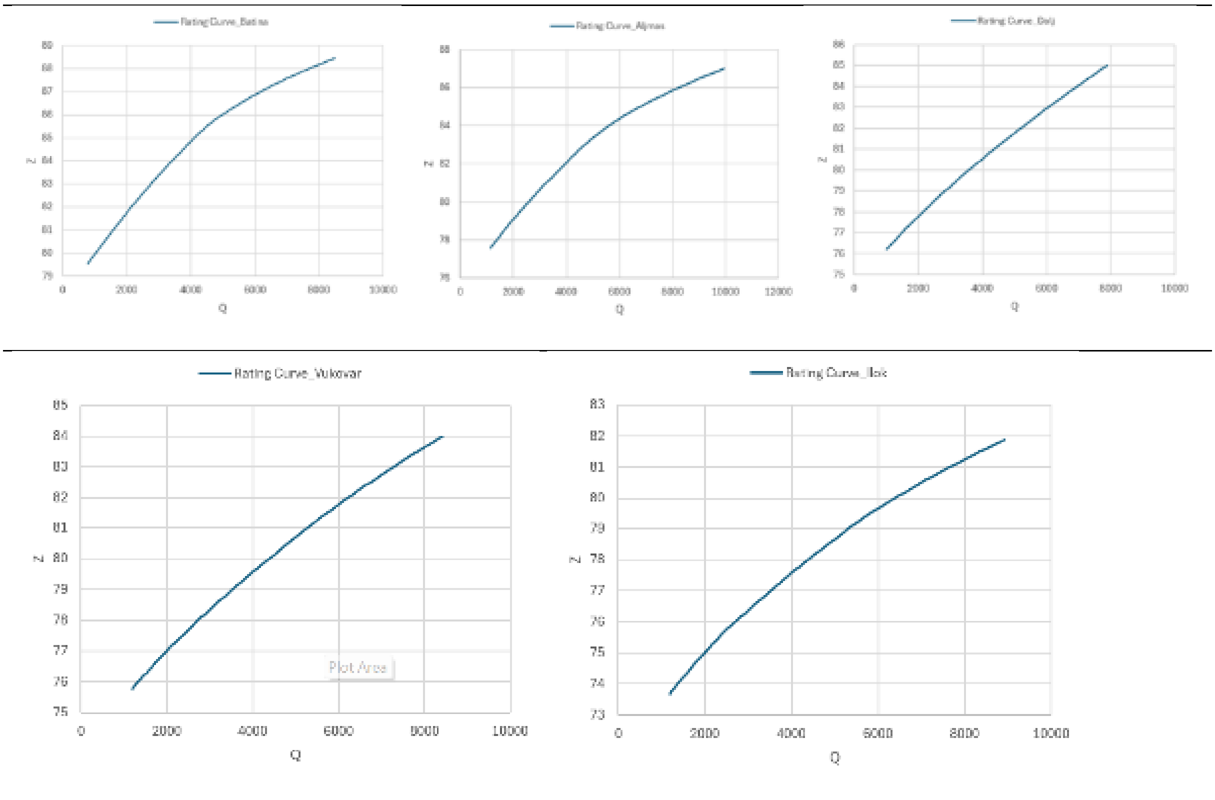

Figure 8: The Rating Curves for the Hydrographic Stations operated by the Croatian Metheorological Institute. Rating Curves respectfully: 1. Batina; 2. Aljmas; 3. Dalj; 4. Vukovar and 5. Ilok (this rating curve is the boundary condition at the same time)

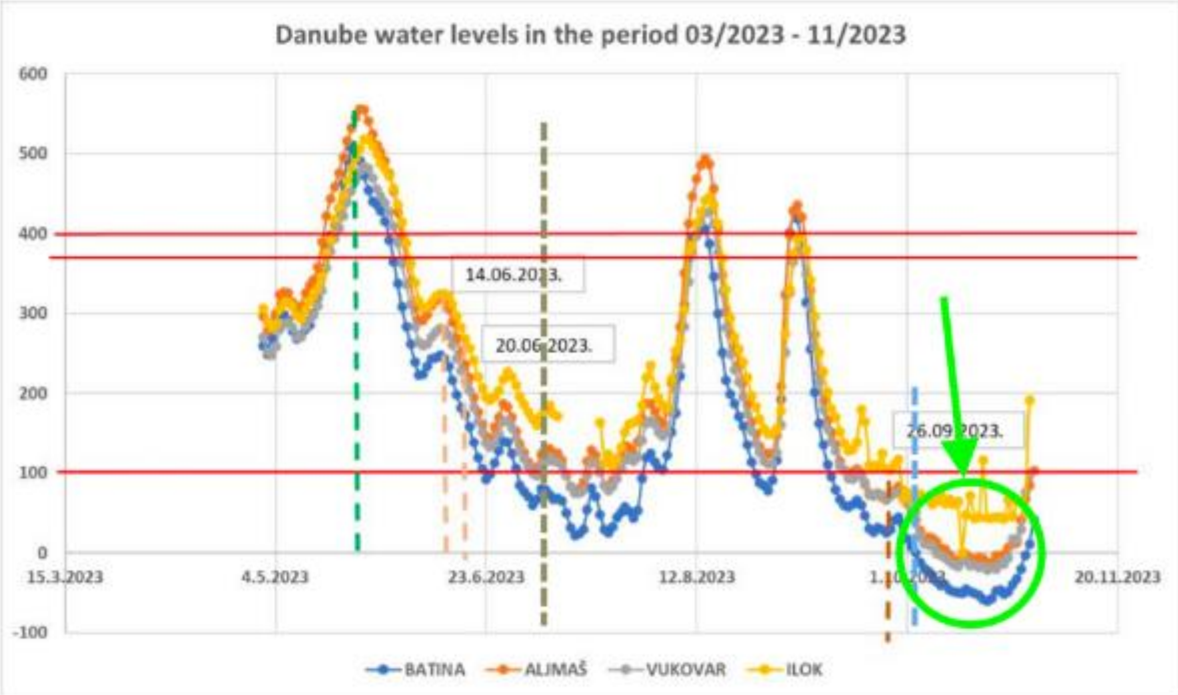

Figure 9: Recorded water elevations on the Danube in the period 03/2023-11/2023 with indicated measurement dates (a portion of time series encircled with green color were used for calibration)

2.2.2. 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).

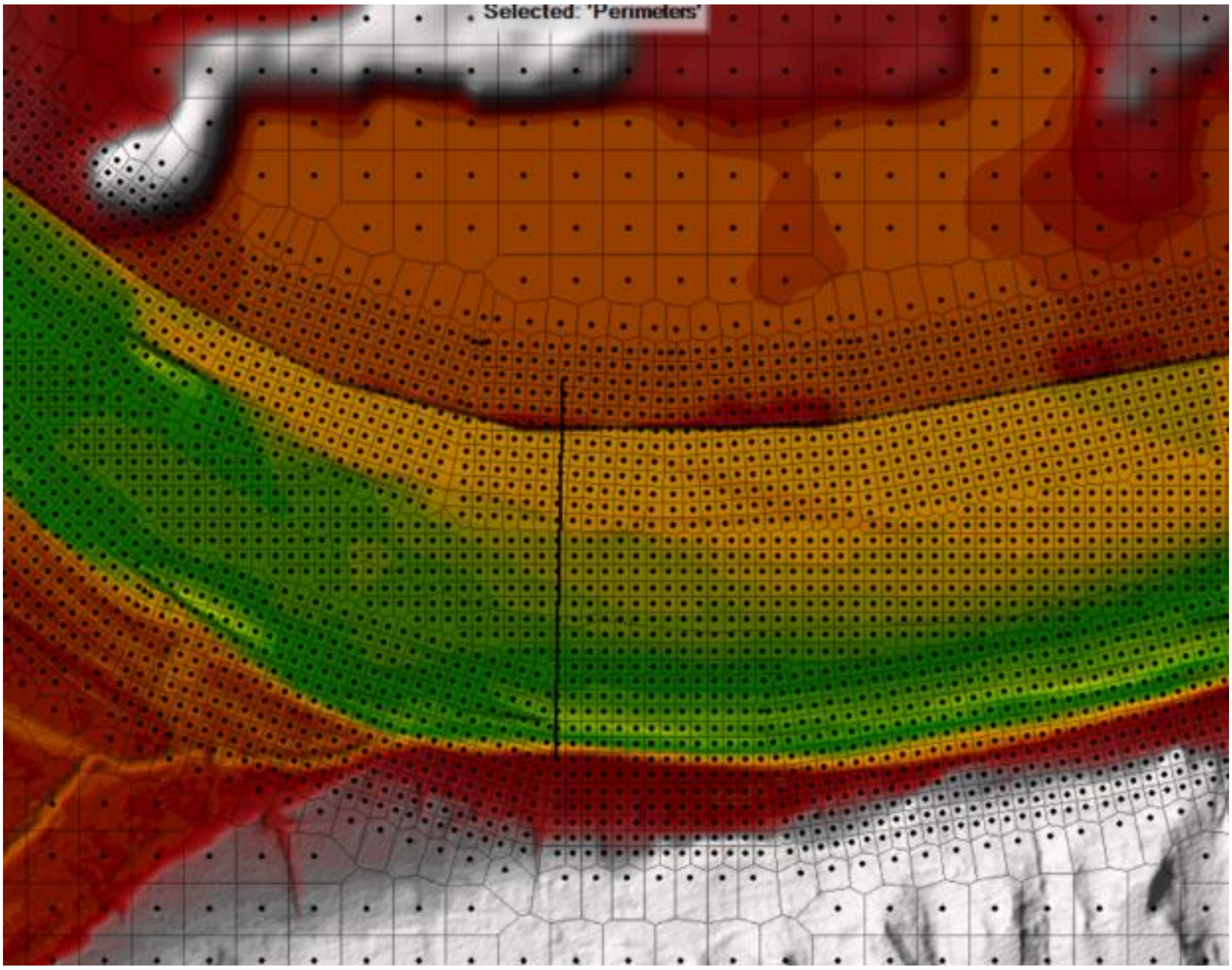

Figure 10: Digital Terrain Model underlined under the numerical grid with calculation points and perimeter border

The numerical grid for the 140 km stretch of the Danube consisted of approximately 300,000 computational points. 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).

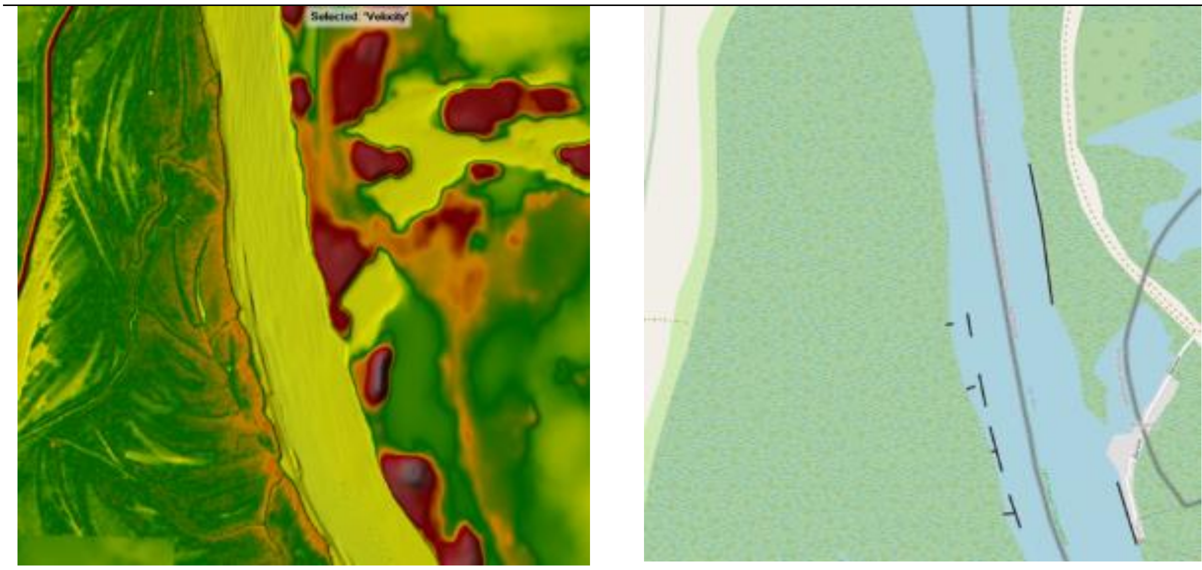

Figure 11: The array of four groins arranged along the right riverbank

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).

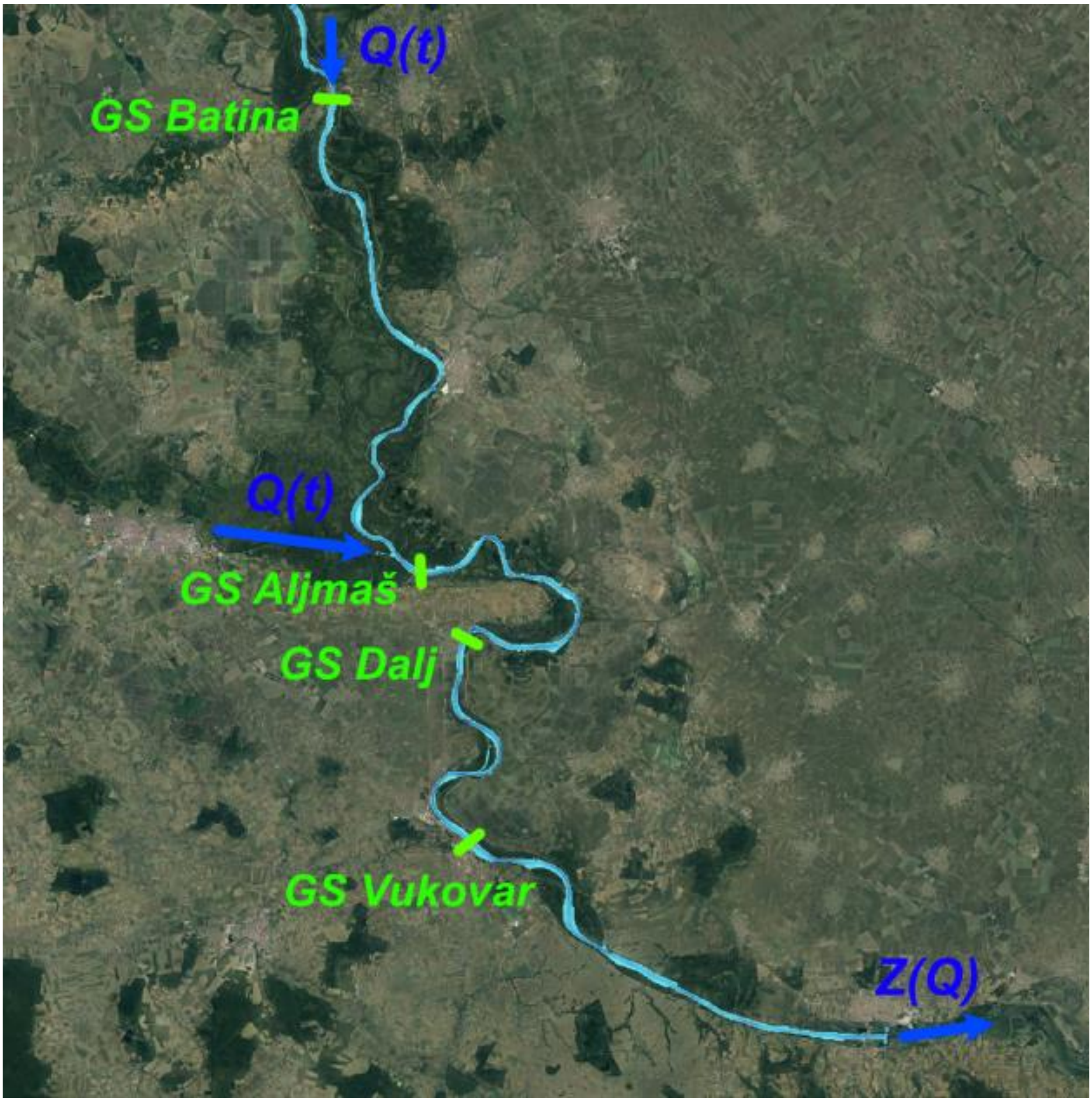

Figure 12: Locations of the boundary cross sections (the end of blue arrows) and Croatian gauging stations whose data were used for model calibration and verification (green lines)

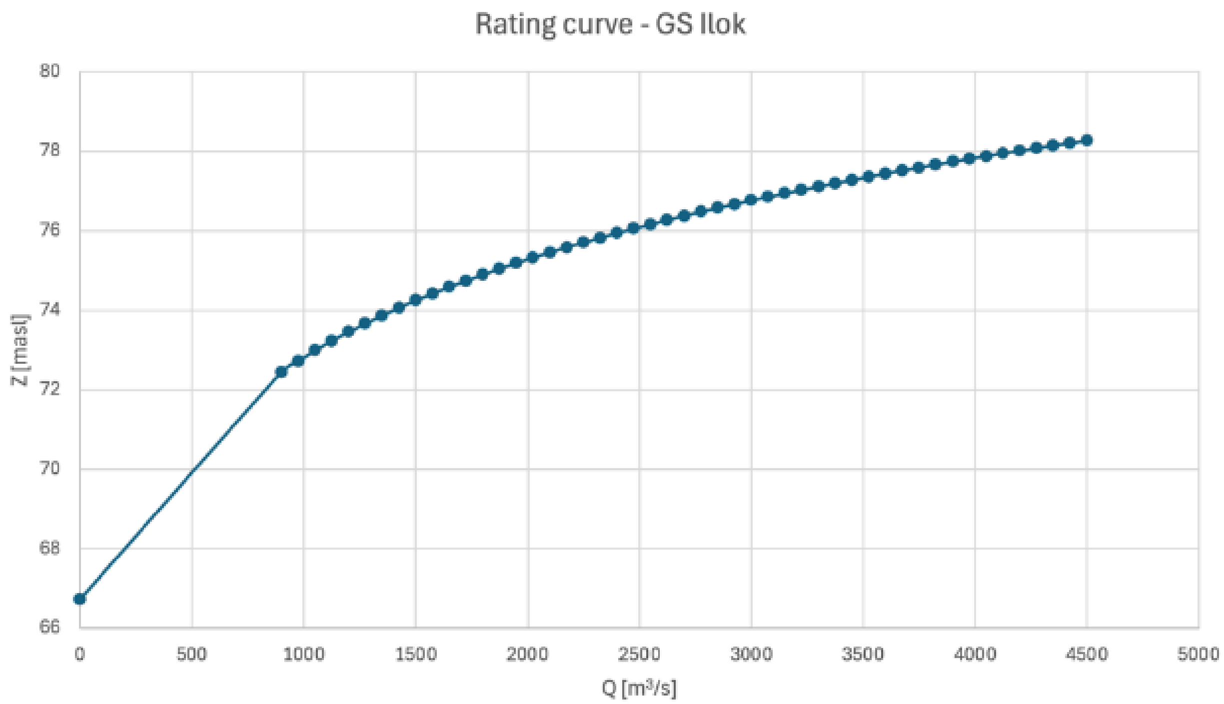

Figure 13: GS Ilok, Rating curve – Downstream boundary condition

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.

3. 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 Mannings'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-1/3s (initial value is 0.0300 m-1/3s), 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.

3.1. 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 rates of 950 m^3/s was selected at the GS Batina cross section and 350 m^3/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	Aljmas	Batina
Z_{DHMZ} [masl]	75.96	76.70	77.88	79.86
Z_{HECRAS} [masl]	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.

3.2. 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 Belisce from the same period was selected and applied to the model (Figure 15). The measurement results from the Belisce 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.

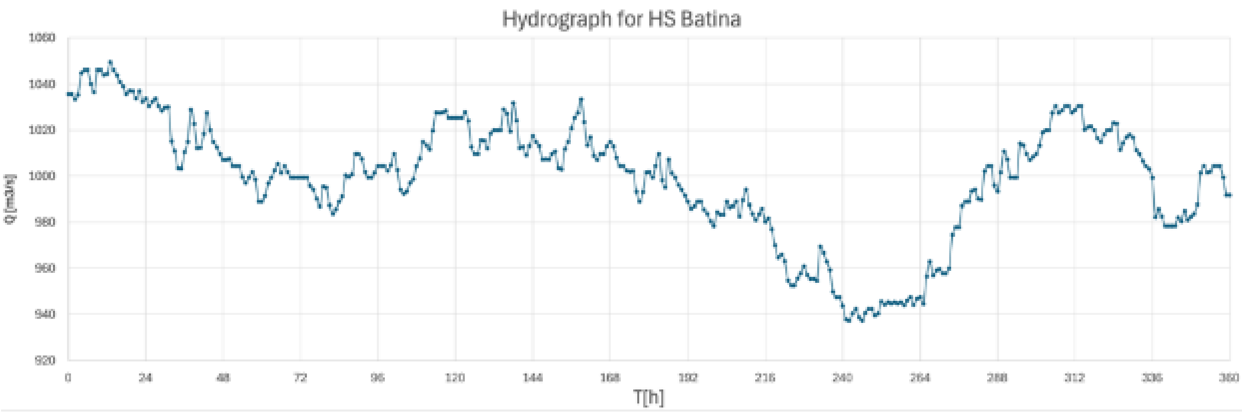

Figure 14: HS Batina (Danube), Time series for verification (discharges derived from recorded water surface elevations using the rating curve)

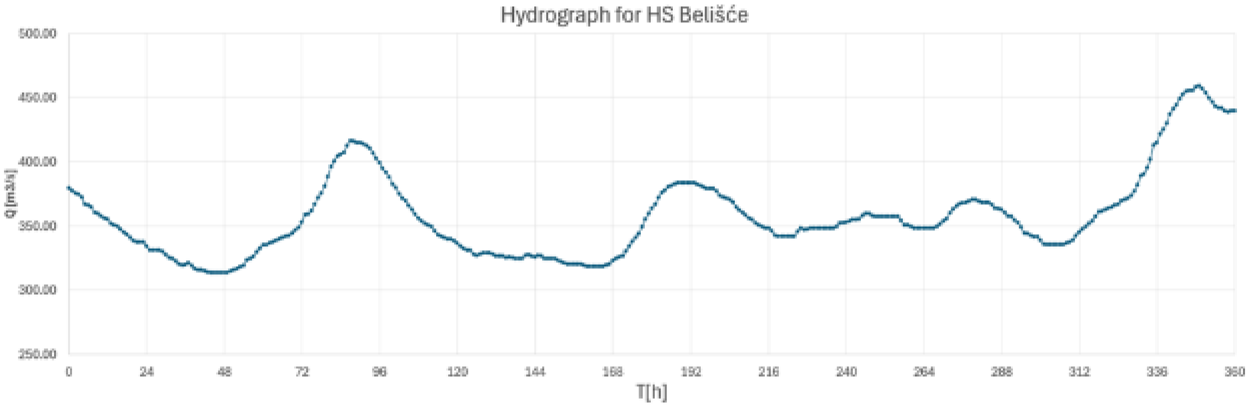

Figure 15: HS Belisce (Drava), Time series for verification (discharges derived from recorded water surface elevations using the rating curve)

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 10 cm. 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.

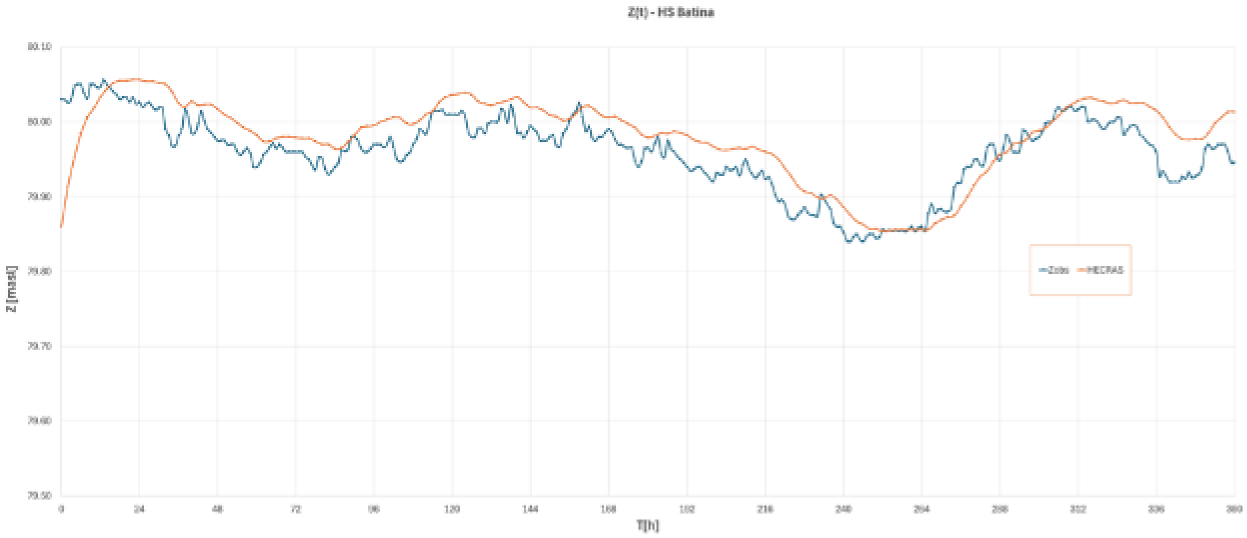

Figure 16: HS Batina (Danube), Comparison between Calculated (red line) and Observed elevations

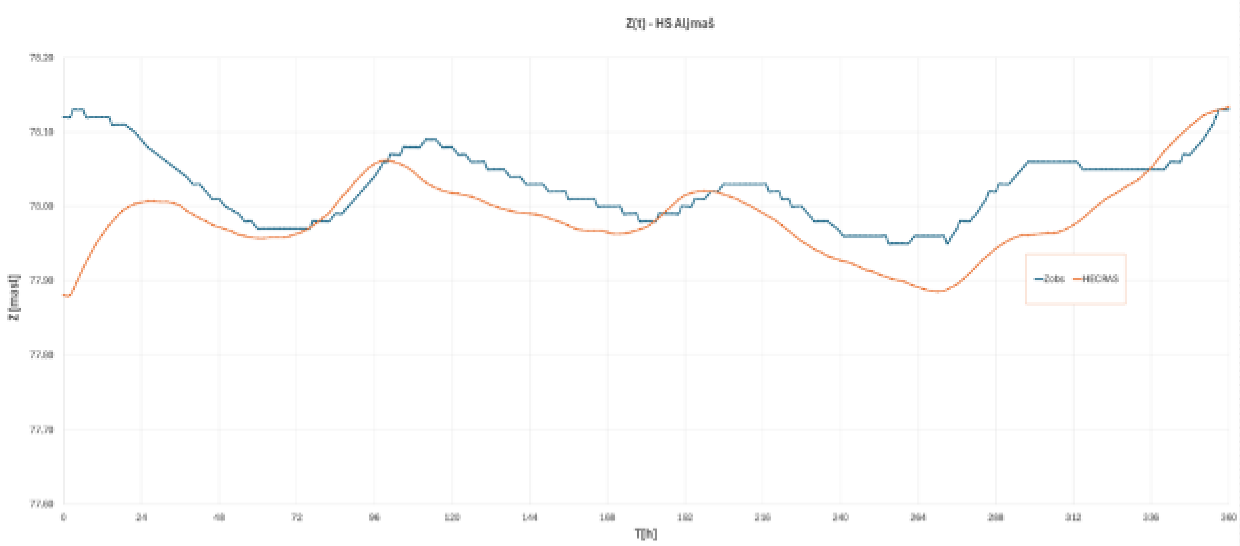

Figure 17: HS Aljmas (Danube), Comparison between Calculated and Observed elevations

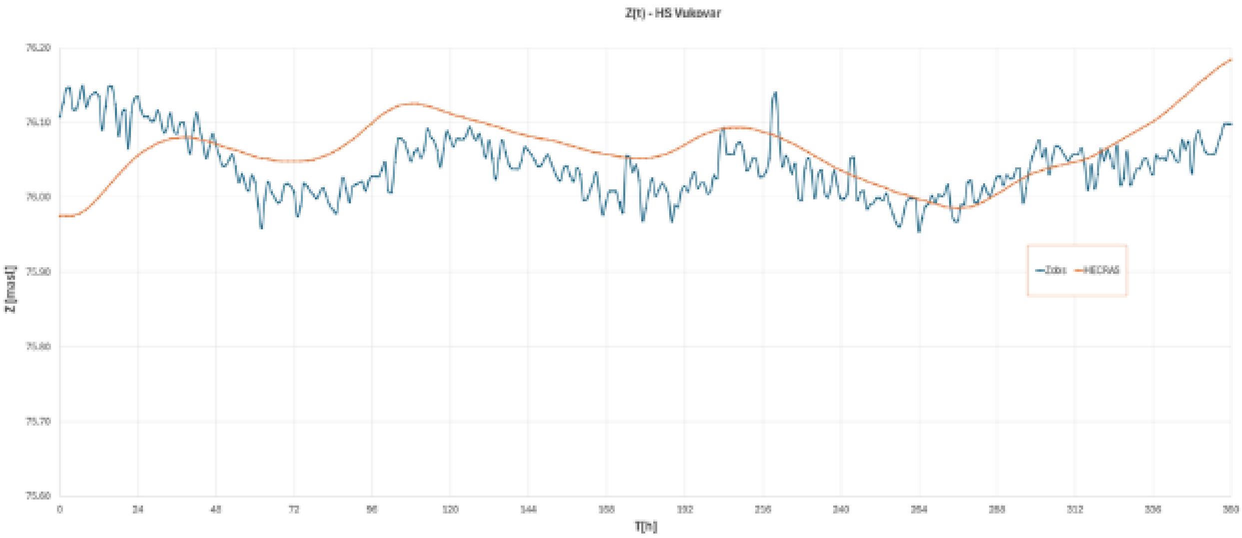

Figure 18: HS Vukovar (Danube), Comparison between Calculated and Observed elevations

4. 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 950 m³/s and downstream from the confluence of 1,300 m³/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 (1,180 m³/s and 1,435 m³/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, 1,450 m³/s (for sector upstream of Drava confluence including HS Batina) and 1,715 m³/s (for sector downstream of Drava confluence including HSs Vukovar, Dalj and Aljmas). 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 Q94%

In the calibration process and later in the calculation of LNWLs (Low Navigational Water Levels), discharges of 1450 m³/ upstream of the Drava confluence and 1715 m³/s downstream were used. For the entire downstream section, the discharge adopted was the one corresponding to the Aljmas station, which represents the lowest $Q_{94\%}$ discharge downstream of the Drava confluence. This ensures water surface elevations that are on the "safety 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 Aljmas and Ilok (Backa 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 (2.5 m) is met. These maps are shown in the Figure 21 and Figure 22, respectively for the sectors Apatin and Staklar as examples.

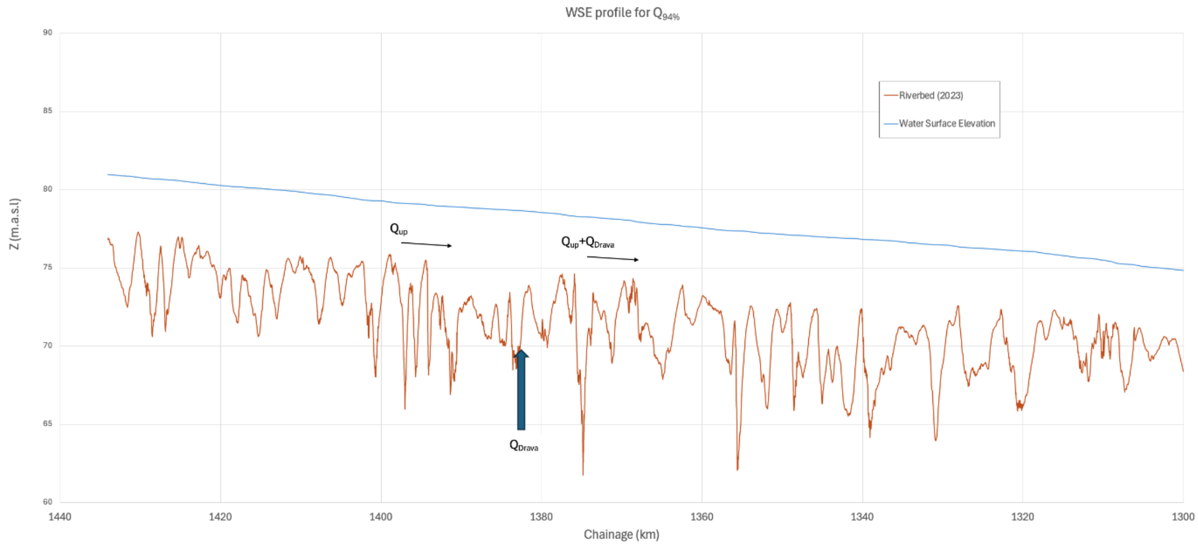

Figure 20: Water surface elevation profile for common stretch of the Danube

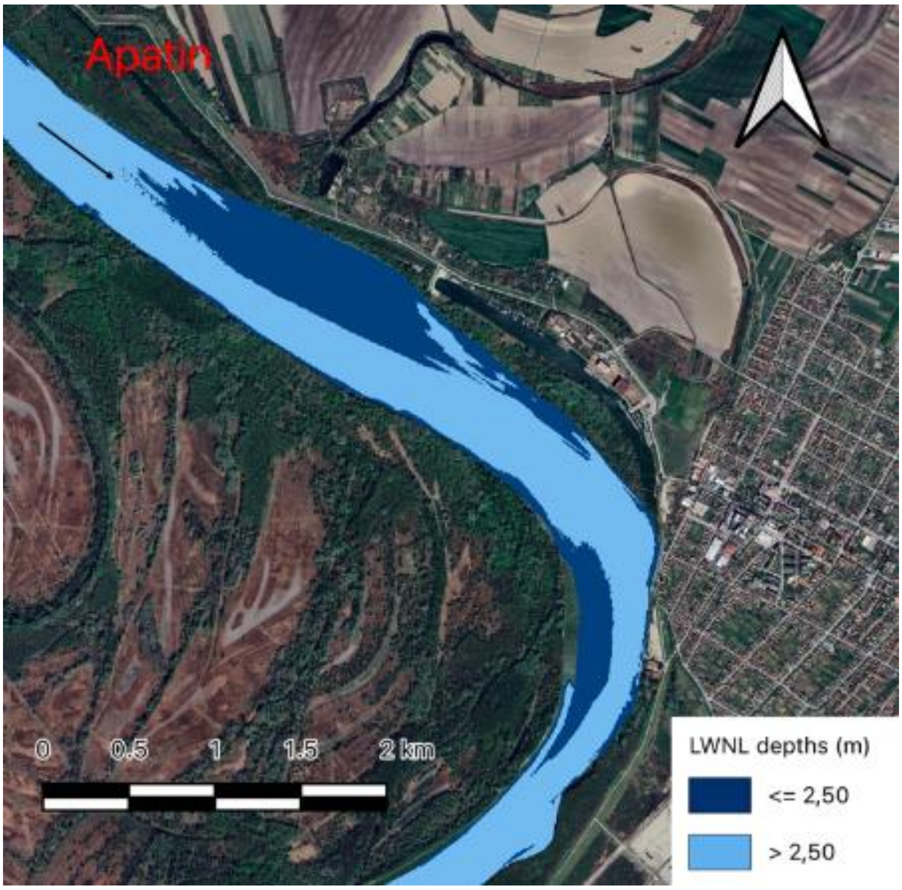

Figure 21: LNWL depth map for CS Apatin

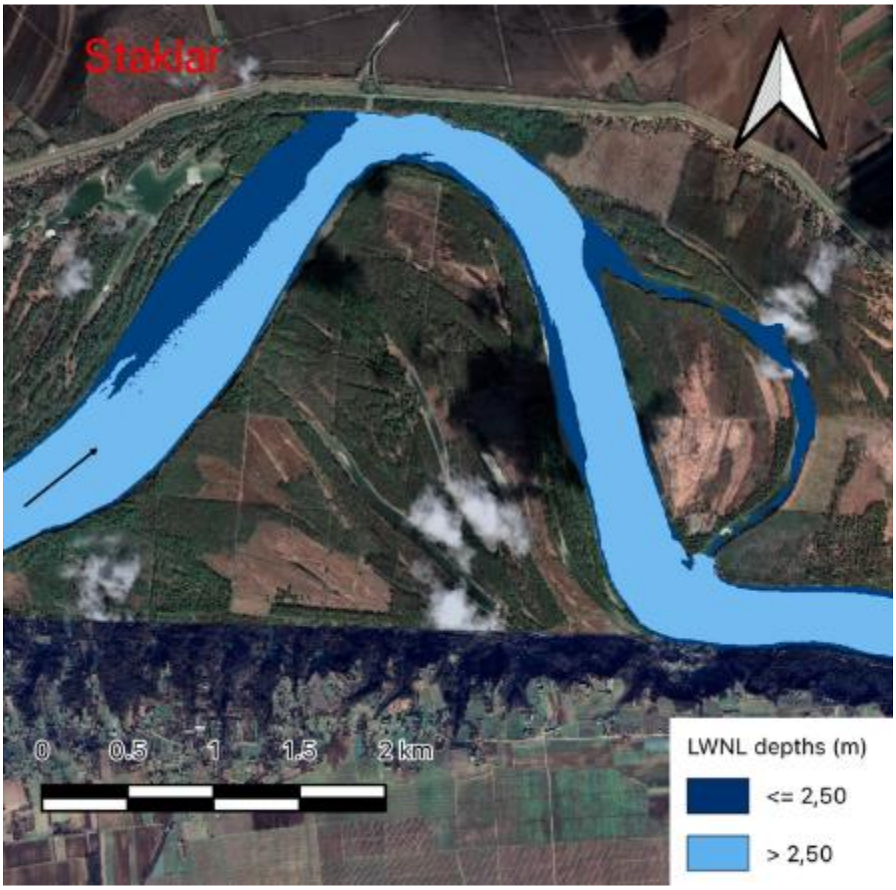

Figure 22: LNWL depth map for CS Staklar

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 200 m 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 200 m 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	Civutski Rukavac	1397.2-1389.0	52,977
5	Drava confluence	1388.8-1382.0	22,013
6	Aljmas	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, 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.

5. 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 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.

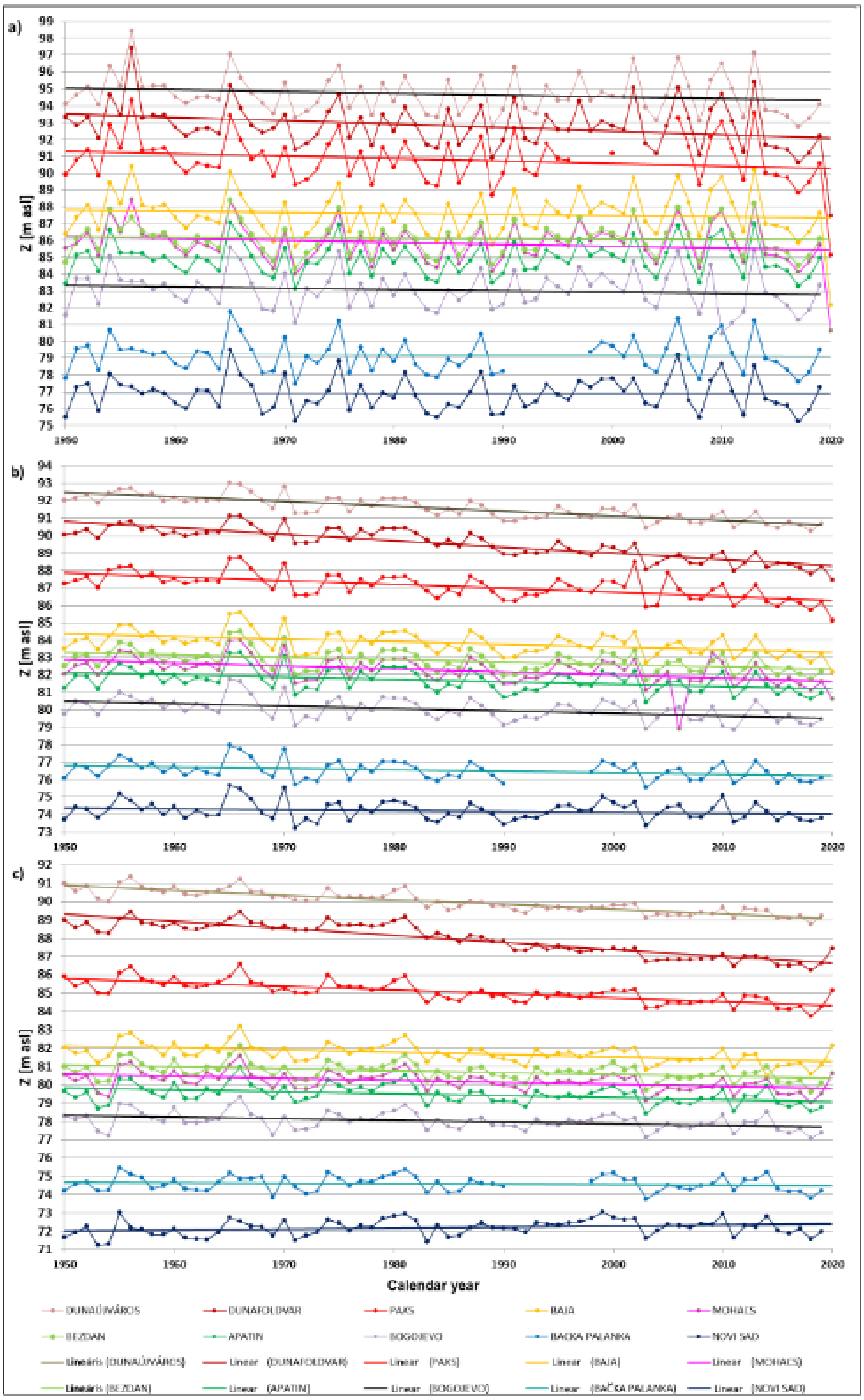

Figure 23: Annual a) maximum, b) mean and c) minimum water levels with linear trends (source "Hydrological indicators of the riverbed incision along the free-flowing Danube River reach from Budapest to Slankamen relevant for the lateral connectivity between the river channel and floodplains")

While the 1D 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 2)—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.

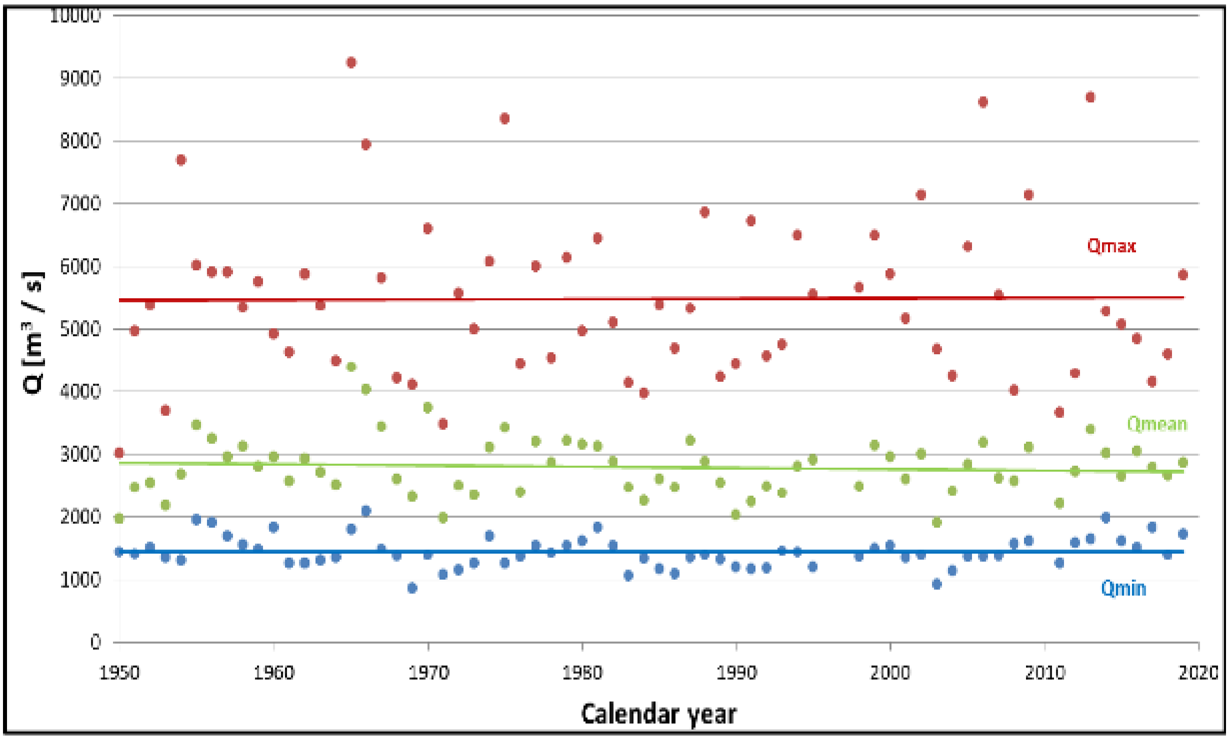

Figure 24: Annual maximum, mean and minimum discharges at Bogojevo gauging station (source "Hydrological indicators of the riverbed incision along the free-flowing Danube River reach from Budapest to Slankamen relevant for the lateral connectivity between the river channel and floodplains")

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.

6. Conclusions

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

- By creating a integral 2D 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.

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