Collaborative hydraulics - next generation tools for highway design in complex interactions with river

Marina Babić-Mladenović, Vanja Damjanović, Boris Krunić, Nevena Cvijanović, Luka Stojadinović

Jaroslav Černi Water Institute, Jaroslava Černog 80, 11226 Pinosava, Belgrade, Serbia
(corresponding author: marina.babic-mladenovic@jcerni.rs)

Article history:
Received: September 9, 2022
Revision: September 15, 2022
Accepted: September 19, 2022

Abstract: The impact of the highway on the environment is inevitable, particularly when the highway interacts with watercourses and existing water facilities. Hydraulic engineers are responsible for demonstrating that impacts of the highway will be avoided or minimized to the extent possible. The crucial and indispensable step in this process is the hydraulic analysis of the watercourse and its interaction with various structures located or planned in the river valley. Since traditional hydraulic tools do not effectively support the required levels of inquiry and analysis, "collaborative hydraulics" with next-generation tools had to be introduced to enable better design, enhanced communication, and more efficient design delivery. Next-generation tools include two-dimensional (2D) hydraulic modelling software, graphical interfaces, and supporting resources. 2D modelling is presently very efficient, intuitive, and accessible to engineers and designers, due to the advances in computer hardware, modelling software, Geographic Information Systems (GIS), and survey practices. The visualization capabilities are high and assist in communicating design results and implications to various stakeholders through visually rich graphical output. Crucial for "collaborative hydraulics" implementation is a computational platform, which connects different software packages, and enables the effective exchange of data and communication between various specialists included in a design team. This paper presents the main features of the "collaborative hydraulics" approach, and some results of its application on the Morava Corridor Project. The work on the Morava Corridor Project is in progress, and hydraulic models are upgraded accordingly to be further used during the implementation of the project (design, construction, and maintenance).

INTRODUCTION

Highway construction can have significant general and local effects on the geomorphology and hydraulics of river systems. Hence, it is necessary to consider induced short-term and long-term responses of the river, the impact on environmental factors, the aesthetics of the river environment, and the effects of erosion and sedimentation on the surrounding landscape and the river. These analyses present challenges to hydraulic modelling, design, and regulatory compliance [1].

Practicing engineers and designers have routinely used one-dimensional (1D) hydraulic modelling tools in transportation hydraulics for nearly 60 years. A 1D model is an adequate tool to analyse hydraulic problems that are generally simple but becomes less reliable if the real-world hydraulics deviates from the 1D assumptions (only downstream flow direction, constant water level in cross-section, etc.). If used in a project with high hydraulic complexity, the 1D model can give extremely erroneous results.

The assessment of environmental impacts associated with river crossings became very important in recent years [2]. Consequently, hydraulic engineers become responsible for demonstrating that impacts of the new development will be avoided or minimized to the extent possible. The crucial and indispensable step in this process is the hydraulic analysis of the watercourse and its interaction with various structures located or planned in the river valley. When the appropriate hydraulic model is developed and justified, it will be used to determine the hydraulic and morphological characteristics of the natural regime and investigate the hydraulic consequences of the designed interventions and infrastructure. It can be used in the design of complex bridge crossings, analysis of bridge options, evaluation of complex floodplain geometry, flood risk assessment, flood mapping, channel restoration, fish habitat analysis, sediment transport analysis, bridge scour analysis, channel stability analysis and scour countermeasure design.

Since traditional hydraulic tools do not effectively support the required levels of inquiry and analysis, "collaborative hydraulics" with next-generation tools had to be introduced. Next-generation tools include two-dimensional (2D) hydraulic modelling software, graphical interfaces, and supporting resources that can be applied in infrastructure design to improve understanding of the complex interactions between the river and the highway. Since 2D models avoid many of the limiting assumptions required by 1D models, their results can significantly improve the ability to design safer, more cost-effective, and resilient structures [3].

The advances in computer hardware, modelling software, Geographic Information Systems (GIS), and survey practices made 2D modelling very efficient, intuitive, and accessible to engineers and designers. The visualization capabilities are high and assist in communicating design results and implications to various stakeholders through visually rich graphical output.

In addition, the advances in parallelization methods accelerate computation making 2D models competitive. In particular, new technologies offer important speed-ups and allow fast simulations of large-scale scenarios [4].

This paper aims to present the methodology and results of hydrological and hydraulic modelling provided by Jaroslav Černi Water Institute (JCWI) to contribute to the development of safe and rational technical solutions on the Morava Corridor Project [5].

COLLABORATIVE HYDRAULICS – WHAT DOES IT MEAN?

Successful solutions of river engineering problems can be found only if an adequate and multidisciplinary team of engineers (experienced in hydrology, hydraulics, erosion and sedimentation, river mechanics, soil mechanics, structures design, economics, the environment, etc.) is engaged. A good collaboration of team members is needed to streamline project development, including environmental, regulatory, and engineering activities [8].

These requirements led to the development of "collaborative hydraulics" meaning the collaboration between different models (hydrology, 1D hydraulics, 2D hydraulics, hydraulics of objects, etc.), where all models are synchronous and allow different users to work simultaneously on the preparation of specific analyses and designs.

There are several key steps important for successful hydraulic analysis. The preceding step is hydrological modelling of the complete river network, providing boundary conditions for hydraulic modelling in a full range of possible hydrological conditions (including the impact of climate change). The next step is setting up of 2D hydraulic model based on GIS and other data, its calibration, and simulation of different scenarios. The final step includes postprocessing, analysis of results, and derivation of conclusions on environmental and engineering issues. The details of these 3 steps are presented below.

Crucial for "collaborative hydraulics" implementation is a computational platform, which connects different software packages, and enables the effective exchange of data and communication between various specialists included in a design team.

Step 1: Hydrological modelling

The main task of hydrological modelling is to compute inputs for 2D hydraulic model. Since the design criteria for different structures (as highway, bridges, levees and other structures) are usually hydraulic parameters (water level or flow velocity) having a certain probability of occurrence, hydrological modelling should define the relevant flood scenarios [9]. Hydrological modelling usually considers the complex process of converting precipitation into a runoff, and the propagation and transformation of flood waves along the river course.

Step 2: 2D hydraulic modelling

2D hydraulic models are used for the analysis of flood risk, the design of structures crossing the river, the bridge scour analyses, and river rehabilitation and aquatic habitat assessment.

Understanding the purpose of the analysis and potential uses of the results, assessing the availability of data, and selecting appropriate software are the essential steps when planning 2D model development.

Typical data needed for 2D hydraulic modelling include: Terrain data (digital elevations from LiDAR, photogrammetry, or field surveys); River bathymetry; Upstream boundary conditions (river discharges); Downstream boundary conditions (usually rating curve); Land use data (to assess hydraulic roughness parameter); Geometry of hydraulic structures (bridges, culverts, and other inline or diversion structures); Other data and application-specific information.

The amount, quality, and type of data required to create a 2D model can vary depending on the model application's goal and the data acquisition's feasibility.

The terrain data will be used to create the model geometry. The terrain data quality significantly impacts the 2D model quality, and thus modelers should use the most accurate data considering economic or accessibility limitations.

The results of 2D hydraulic model are specific hydraulic variables, which can be used for different design purposes: Velocity magnitude, direction, and distribution; Water depth and water level; Discharge (flow distribution, through structures, overtopping); Unit discharge; Shear stress; Stream power. The results also provide the basis for computation of other variables as Froude number, bed shear stress, etc.

Step 3: Post-processing and graphical visualization

Understanding the simulated scenario's hydraulic impacts is better if based on the good presentation of 2D model results. The presentation usually includes plots of water surface contours and flow patterns over the model domain, but other computed variables can be presented as well.

Most 2D models have the capability to perform algebraic, geometric, and temporal operations on the computed variable data sets to create new data sets. If data post-processing is unavailable, the software should be able to export the model results in formats needed for visualization tools and further analyses. Only in that case, modelers will be able to review and present 2D model results effectively.

Computational platform

All the previously explained steps require specific hardware and software. In many cases, a substantial amount of time is spent for preparing the input data for different software and exchanging the data between engineers. The cost of hardware and software for each team member is not insignificant. When the project workflow requires a lot of input data and many design iterations, it is a challenge to ensure that numerous engineers involved in the processing, analysis and presentation of the results are using the latest and appropriate data.

Most of the above-mentioned problems can be avoided when the project team uses a computational platform (an organized set of databases, mathematical models, server components and tools that rely on appropriate dedicated hardware). In that case all computations are performed on a central computational server, and the automatic exchange of input/output data between different models is enabled [10].

Basic elements of computational platform are central database, computational server, and user applications. Central database contains all input data (GIS data, time series, etc.), different versions of 2D model and their results, as well as metadata. The computational server is a host of hydrological and 2D hydraulic models, as well as postprocessing algorithms. The models are connected by specific components that enable adequate selection of data from the central database, transformation of data to formats needed for the model application and modelling in dedicated hardware. User applications are web-based applications enabling the users (modelers, designers, and selected stakeholders) to access the functionalities of the computational platform.

When using the computational platform, there is no need for manual exchange of data between engineers and preparation of data in formats that differ between models. Errors are impossible since the computational platform ensures that all the team members are using the same dataset, updated after every design iteration. Secondly, there is no need for additional training in using high-performance parallel computing hardware, which is often required for large-scale flood simulations [11]. Engineers use relatively simple user applications, while server components communicate with dedicated hardware.

CASE STUDY OF THE MORAVA CORRIDOR PROJECT

Basic facts on the Project

The corridor of the future highway E-761 (the Morava Corridor) is located in central Serbia, mostly in the Zapadna Morava River valley. The highway E-761 route is 111 km long and follows an approximately 138 km long river stretch.

The Morava Corridor passes through predominantly agricultural areas, located across four municipalities and three cities (Ćićevac, Varvarin, Kruševac, Trstenik, Vrnjačka Banja, Kraljevo and Čačak). The Morava Corridor is divided into 3 sectors and 9 sections as presented on Figure 1.

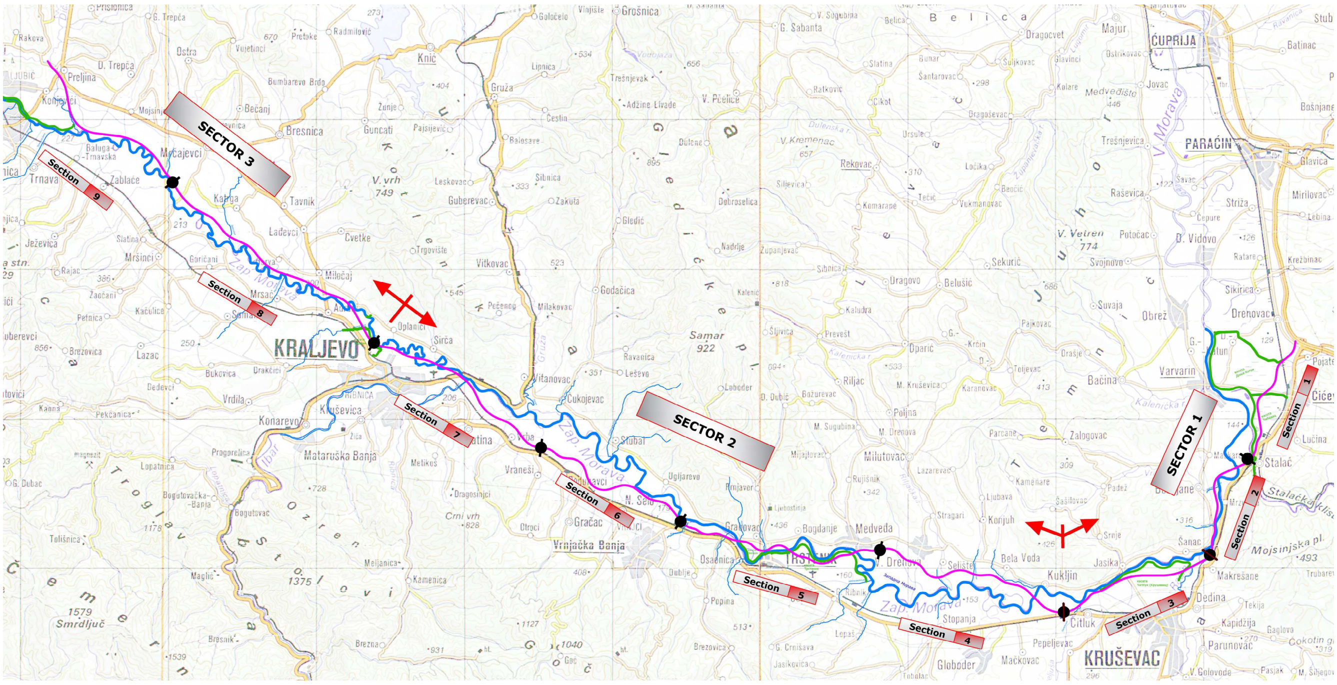

***Figure 1**. The route of E-761 highway along the Zapadna Morava river*

The Zapadna Morava is a typical alluvial river. Its alluvial riverbed is very unstable and deformable, with the occurrence of bed wandering, meandering and pronounced fluvial erosion. The flood protection system is not continuous (there are long stretches without embankments or with the embankment along one of the riverbanks); city areas are protected, while the agricultural areas are left to be flooded. Most of the existing embankments would be overtopped by a 100-year flood because they were designed to provide a lower protection level.

The route of the Morava Corridor is located almost in its entirety in the zone exposed to flooding by the Zapadna Morava, and a very long part is in direct contact with the river flow (at intersections and in zones where the motorway route is near the riverbed). That is why the particularly important part of the Morava Corridor Project are hydro-technical works with the main objective of protecting the motorway from flooding and fluvial erosion.

The analysis of needed hydro-technical interventions started in 2016 when the Hydrotechnical Study of E-761 Motorway Corridor was prepared. It comprised hydrological analysis of flood flows (based on data observed in the period 1955-2015) and 1D hydraulic modelling. Also, potentially critical sections, where fluvial erosion processes could endanger the highway, were identified based on available maps.

1D model for steady-state flow conditions was used for hydraulic calculations of low, medium and high flows of the different return periods. The hydrodynamic model of the river valley was based on the 2007 bathymetric survey of the main river channel and available maps in scale 1:25000.

The same 1D model was used in Preliminary Designs of the Zapadna Morava River regulation along the E-761 Highway, prepared between 2017 and 2019. River regulation works and flood protection measures were designed in several phases, in accordance with the development of the highway design. The general goal was to define the optimal river training solution that will minimize the negative impacts of the highway construction on the water regime and, at the same time, provide quantities of materials needed for the highway construction. Final preliminary designs included bank protection, meander cut-offs and reconstruction of the existing flood embankments, scattered along the 138 km long river route.

The next phase of the Morava Corridor project started in 2020, after the signing of the contract for its construction. The recommendation of consultants of the financing institutions was to apply state-of-the-art hydrological and 2D hydraulic models during the implementation of the project (design, construction, and maintenance) and asses the impacts of Morava Corridor development both in the present and the climate change conditions [6].

Between 2020 and today, JCWI provided new and detailed hydrological and hydraulic modelling, with the global goal to contribute to the development of safe and rational technical solutions, to the good quality of highway structures and of river regulation, i.e., to the successful realization of the entire Morava Corridor Project.

The timely preparation of relevant hydro-technical information resulting from hydrological-hydraulic modelling supports full coordination in the design and construction of the highway and hydro-technical works.

Together with the new hydrological and hydraulic models, new tools had to be created and applied to assist JCWI modelers in the preparation of models, numerous recurring simulations, post-processing and analyses of the massive modelling results. These new tools and applications were gathered within the computational platform.

Hydrological model

Hydrological model provides relevant inputs for the hydraulic models of the Zapadna Morava river along the Morava Corridor and tributaries that intersect with highway route (as the Južna Morava, Rasina and Ibar).

HEC-HMS software package is used for hydrological modelling of river floods in current climate conditions and the conditions expected due to climate change. Precipitation-runoff processes on all tributaries were modelled for both climate scenarios.

Details of the hydrological model are presented in the paper River Network Modeling to Improve Understanding of Complex Interactions Between River Environment and Highway Design.

2D hydraulic models

When choosing an adequate hydraulic model, JCWI team considered two options: 1D/2D model, which may be a problem in terms of its stability and reliability of the results, and the integral 2D model, which is a better option but very complex and demanding.

When choosing software for 2D modelling, JCWI team was aware that the software must be appropriate for comprehensive analyses of the Morava Corridor impact on the environment. The software package had to: be flexible when modelling of hydraulic structures (low/high level of input data); use a very complex model geometry of a long river reach (at least 3 million elements); have an acceptable processing time when modelling long-lasting flood waves; allow the access to the input/output files, as they need to be incorporated into the calculation platform.

RiverFlow2D solver (Hydronia LLC - Florida) was chosen in view of the previous considerations, and especially the significant requirements for processor time as it gives a possibility of parallelization/hardware acceleration.

Two types of hydraulic models were prepared and used for 2D hydraulic analyses needed for the Morava Corridor Project development.

The first category are integral models of the whole domain of the Morava Corridor, used to assess overall impacts of this development.

The integral hydraulic model of the existing conditions includes more than 150 km of rivers in the Project range (part of the Velika Morava, part of the Juzna Morava, 138 km of the Zapadna Morava), existing bridges, embankments, roads, and railroads. The spatial extent of the model is presented on Figure 2.

The model uses a digital terrain model (grid 1x1m) based on Lidar scanning of the terrain in 2018 and 2020. Data on underwater parts of riverbeds is obtained by 2020 bathymetry and incorporated in DTM.

The outputs from the hydrological model (107 hydrographs) are inputs for integral hydraulic model. The downstream boundary condition is a rating curve at km 176 of the Velika Morava River.

The preliminary Manning's roughness coefficients were assigned based on the literature, using Corine Land Cover data for floodplains, and granulometric composition of the riverbed sediment [7]. The final values of Manning's coefficients were defined through the calibration and verification process, which was based on the data observed at 4 hydrological stations (3 on the Zapadna Morava and 1 on Velika Morava) during 2014 flood event.

Integral hydraulic models for future conditions are prepared by adding designed structures of the Morava Corridor to the model of the existing conditions. The first version of the integral model included highway embankment, bridges at the intersections of the future highway and main rivers or tributaries (53 bridges), culverts along the highway route (78 culverts), new and reconstructed flood embankments, river meander cut-offs (21 cut-offs), and river regulation structures, as preliminary designed.

Following the advancement in the designs of the highway and river regulation structures, new versions of the integral model were prepared and used to check their impacts. Up to present, 18 integral models were developed and used to find the best solutions for highway and hydro-technical structures in full coordination between hydraulic modelers, designers and the Investor. The integral model which is currently in preparation will include also gravel pits and deposition sites along the highway route.

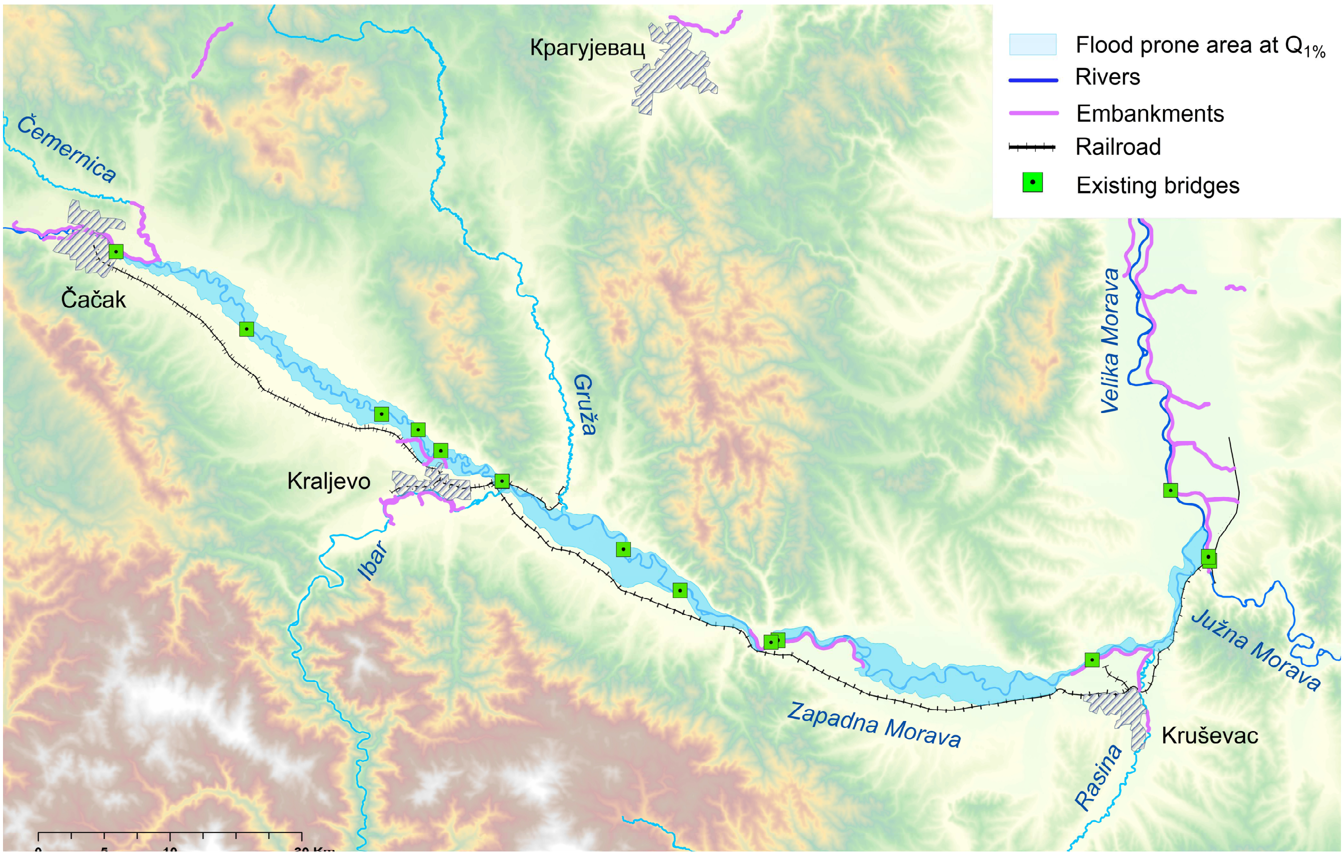

***Figure 2**. Spatial extent of the integral hydraulic model for existing conditions*

Following the request of financing institutions, the recurrent modelling will end when all structures are in place. The 2D hydrological and hydraulic model will among others provide information on: (i) the final river regulation design, including climate change allowance and (ii) the chemical and ecological status of waterbodies affected by the Project in line with the European Union (EU) Water Framework Directive (WFD).

Once the designs are updated, the residual risks identified by the 2D hydrological and hydraulic model will be incorporated into an updated aspects and impacts register and relevant managements plans and procedures, including liaison with local authorities regarding development of a river basin and flood risk management plans. The primary residual risk is likely to be flooding of some residential, industrial, and agricultural land during low frequency, extreme rainfall events.

Partial hydraulic models are prepared for identified critical sections, where a selection of the best-fitted option for bridge or other structure should be found through reiterated flow simulations. The computational network in partial models is more detailed and denser in the zones of interest, thereby providing more detailed results of hydraulic analyses.

Computational platform

The computational platform developed for the Morava corridor supports hydrological, hydraulic and hydrotechnical analyses and calculations explained in the previous chapters. Involved users as modelers, designers, and others communicate with the computational platform via web-based applications.

The computational platform (Figure 3) consists of central database (containing GIS data, time series, models, and results), computational server which enables the preparation of input data for hydrological and hydraulic models and running the models in specific software and on dedicated hardware (HEC HMS and RiverFlow2D), development and user tools.

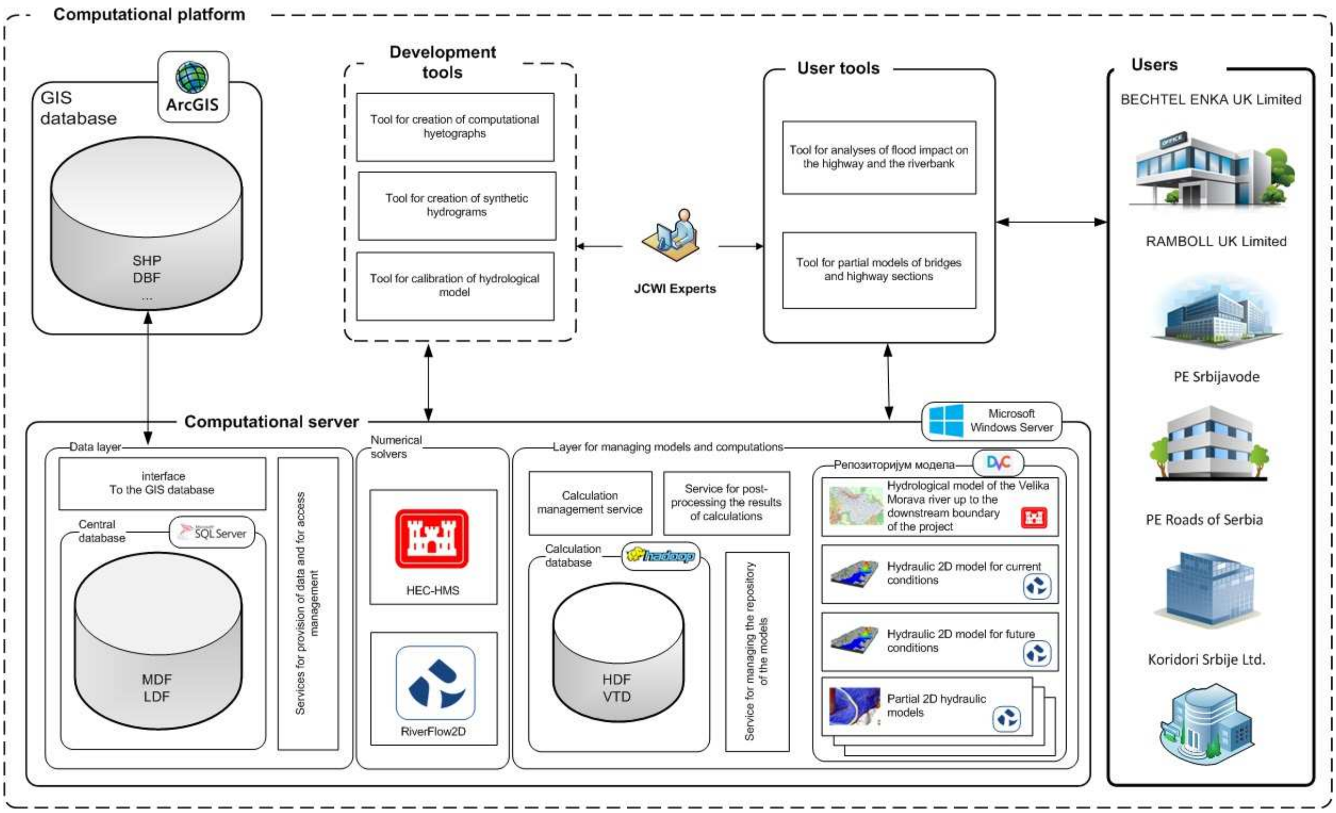

Figure 3. *Scheme of the computational platform*

Computational server presents the core of the computational platform as it is responsible for large-scale computations which were needed in this project. To obtain relevant inputs for hydraulic models, more than 3.000.000 hydrological computations were performed, and about 4.000 processor hours were used. These calculations needed to be performed on high-performance computing clusters (HPC) thru specialized components of the computational server. These servers were able to perform 100 parallel computations at a time. Algorithms for efficient storage and sorting of calculation results were developed, while the results were stored on dedicated storage units.

Performing the hydraulic modelling computations was done using GPU computational servers which enabled significant speedup compared to computations performed on standard CPU processors. Each integral 2D hydraulic model has more than 2.000.000 cells which means that running the model for 5 simulation days generates more than 300 GB of results data. Analysis of one version of integral model requires more than 50 calculations with different boundary conditions to be performed. Computational server ensures that these boundary conditions are transferred from the hydrological calculations to the 2D hydraulic calculations.

Thru model repository, computational server keeps track of all the different versions of 2D hydraulic models developed. Each model is referenced to its own set of input data and calculation results, which enables complete backtracking to any version of the integral model.

Postprocessing of 2D hydraulic model results is also done using the computational server. The results are presented on maps, but also at river cross sections or longitudinal profiles. The spatial distribution of calculated hydraulic variables is projected onto maps and displayed in a wide range of colours and geometric schemes. These maps are used to present flood hazard in riverine areas under various conditions or the flow pattern in the vicinity of different structures. Maps proved to be very useful for communicating hydraulic nuances to different audiences. Presentation of water surface in cross sections and longitudinal profiles also provided designers with a means of assessing design parameters or risks associated with the existing or new structures.

Development tools are made for hydrological modelling (preparation of precipitation data, calibration of a hydrological model, and creating synthetic hydrographs for different conditions – Figure 4). These tools assist in performing mass-scale hydrological computations as input to the 2D hydraulic model.

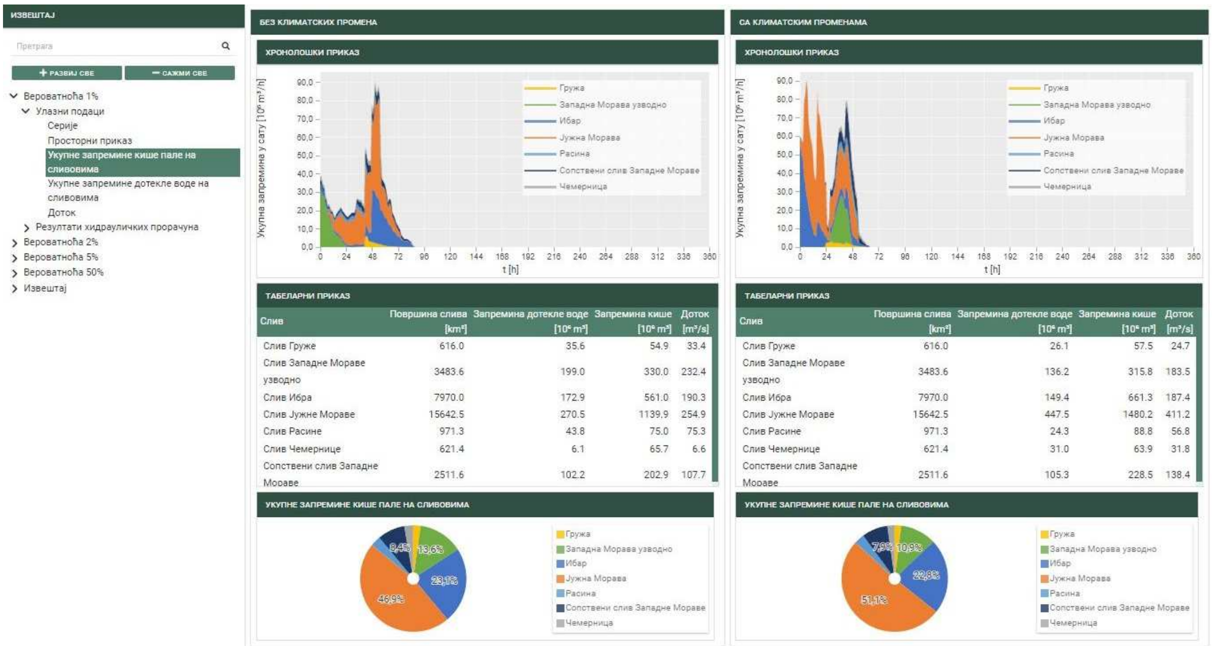

***Figure 4**. Window of the tool for creating synthetic hydrographs*

User tools are made for hydraulic applications and design purposes.

The first user tool is applied in the analyses of flood impact on the highway and the riverbank, based on integral hydraulic model. The user must select a version of the integral hydraulic model from the central database and a probability of the event that will be examined. The computational server then runs the hydrological model, automatically transfers its results to the input to the 2D hydraulics model and runs it. By using this tool, designers can easily evaluate the proposed hydro-technical solutions by examining the predefined areal and cross-sectional views. The areas where certain design criteria are not met (e.g., flooding of protected areas, insufficient freeboard) will be highlighted (Figure 5). In addition, the tool provides export of the results in different formats (eg. csv, landXML, tiff etc.) for more detailed analyses.

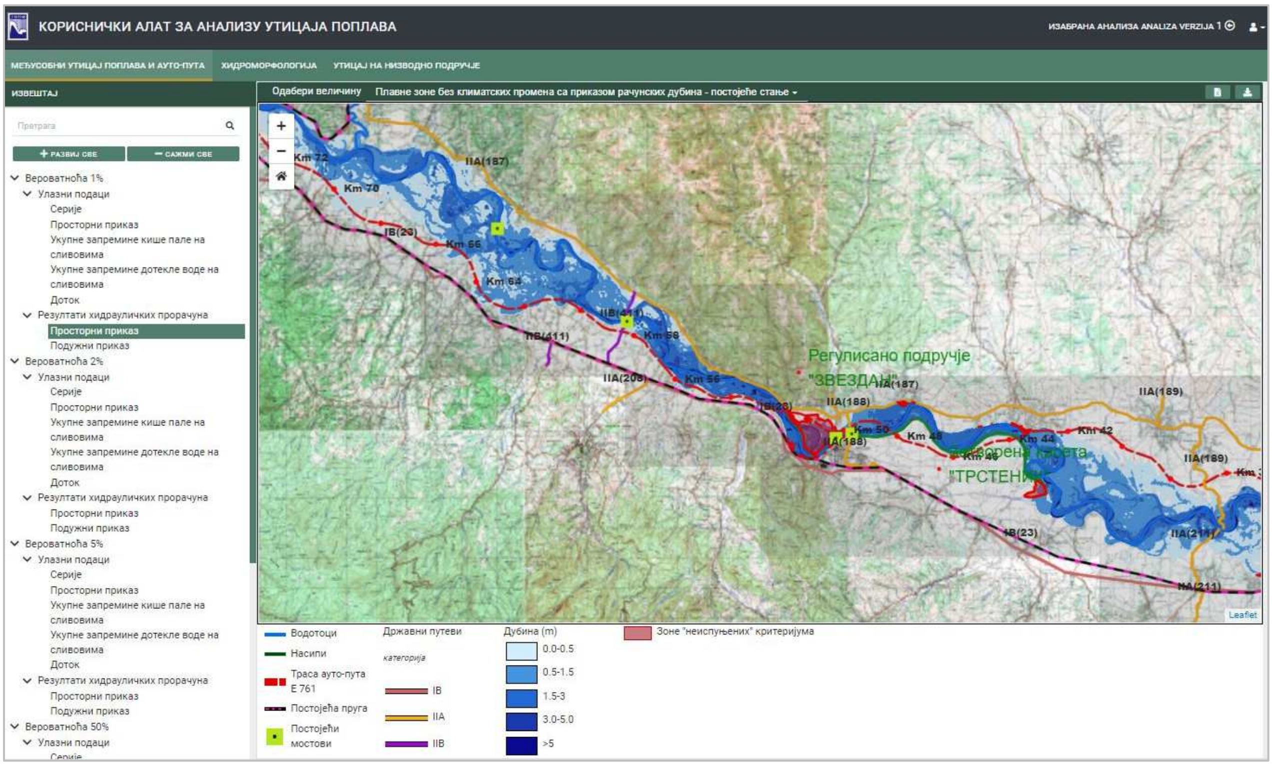

***Figure 5**. Window of the tool for analyzing the impact of floods on the highway and the riverbank*

The second user tool manages partial models for bridges and highway sections. It has two parts, aimed for: (1) model creating and archiving and (2) the analyses of model results. The first section gives the user access to all the partial models and their versions, along with detailed and explanatory metadata. It also enables the modeler to obtain boundary conditions for a partial model from the selected version of the integral hydraulic model. In the end, the modeler can upload a newly created partial model into the archive. The second section of this tool is intended for the visualization of model results (Figure 6). Designers can use this tool to examine the hydraulic nuances of investigated design solutions for highway structures or hydro-technical interventions.

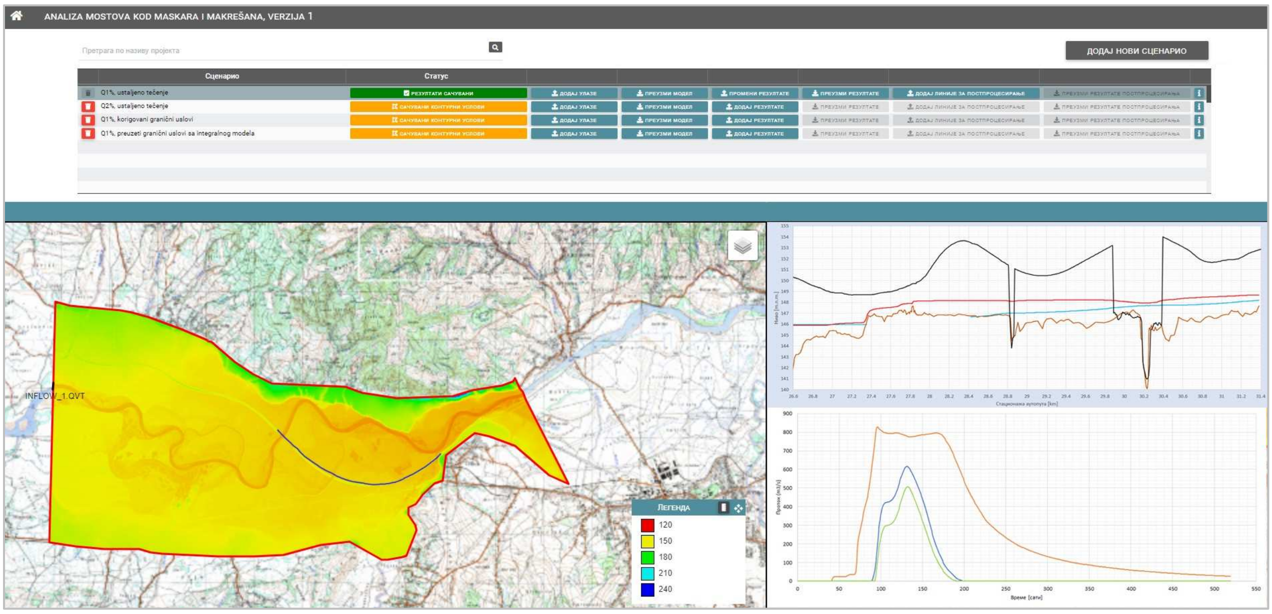

Figure 6. Window of the tool for partial models

Visualization of 2D model results

2D hydraulic model results needed for the design of the Morava Corridor are presented on maps, but also at river cross sections or longitudinal profiles.

The spatial distribution of calculated hydraulic variables is projected onto maps and displayed in a wide range of colours and geometric schemes. These maps are used to present flood hazard in riverine areas under various conditions or the flow pattern in the vicinity of different structures. Maps proved to be very useful for communicating hydraulic nuances to different audiences.

Presentation of water surface in cross sections and longitudinal profiles also provided designers with a means of assessing design parameters or risks associated with the existing or new structures.

Application No 1 - Assessment of flood risk along the Morava Corridor

The first hydrological and 2D hydraulic modelling was undertaken by JCWI in early 2021 to evaluate present-day and future potential flood risks at a catchment level.

The assessment of flood risk induced by the Morava Corridor construction was based on 2D hydraulic modelling results - water levels and flow velocities in the case of 100, 50 and 20-year floods, in present climate conditions and climate change conditions.

The hydrological modelling of climate change conditions used rainfall scenarios derived from an ensemble of climate models. These models have shown to provide reliable projections of potential changes in rainfall characteristics for the region over near, mid and long-term time horizons under multiple climate warming scenarios.

Results of the 2D hydraulic modelling show that, under present climate conditions, the construction of Morava Corridor, as preliminary designed, is likely to increase flood risk in Sectors 1 and 2 and reduce flooding in Sector 3. These conclusions were derived from a comparison of the present conditions with the conditions after the highway construction, both for present climate environment (Figure 7). After modelling of the climate change scenario, it was concluded that the conditions along the highway may worsen in the future (Figure 8).

This exercise ended with general conclusions on flood levels and flow velocities along the Morava Corridor, indicating where the design of the highway and/or river regulation structures should be improved to alleviate flood risks.

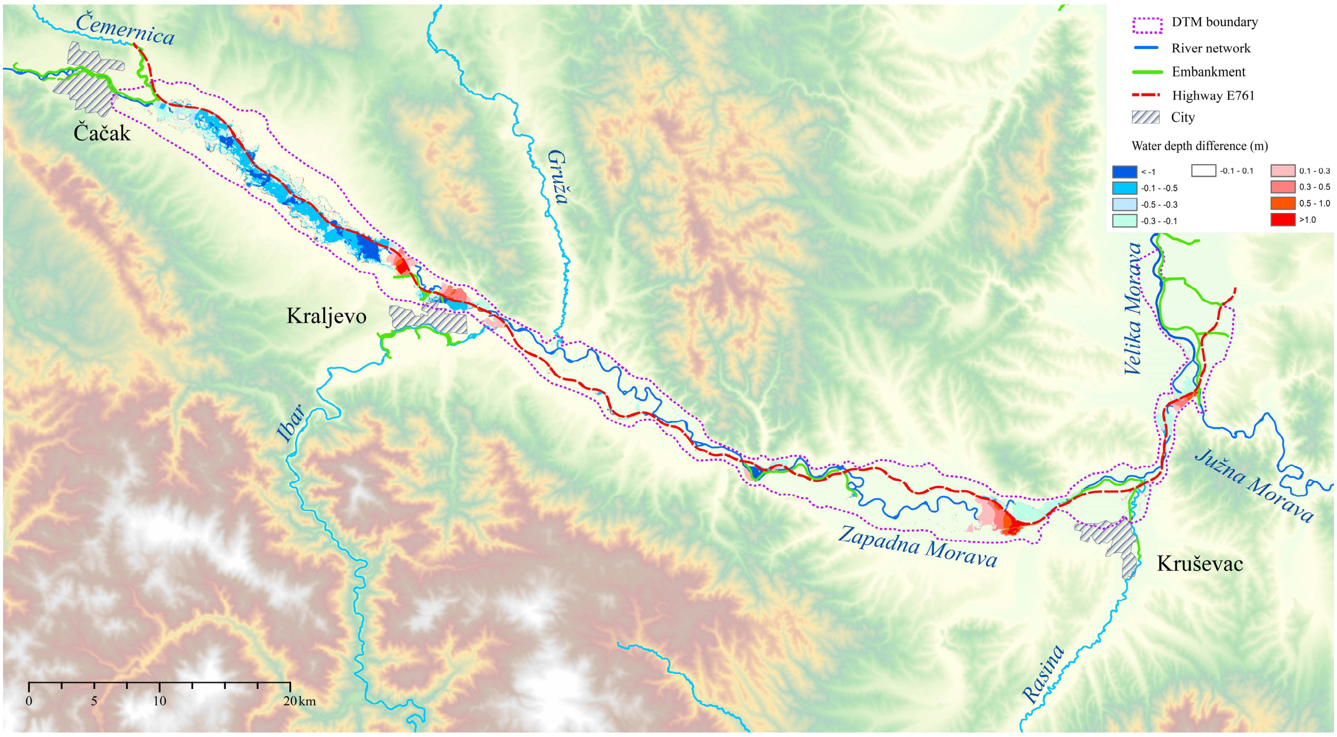

Figure 7. *Indicative map flood risk in case of 100-year flood - present climate conditions*

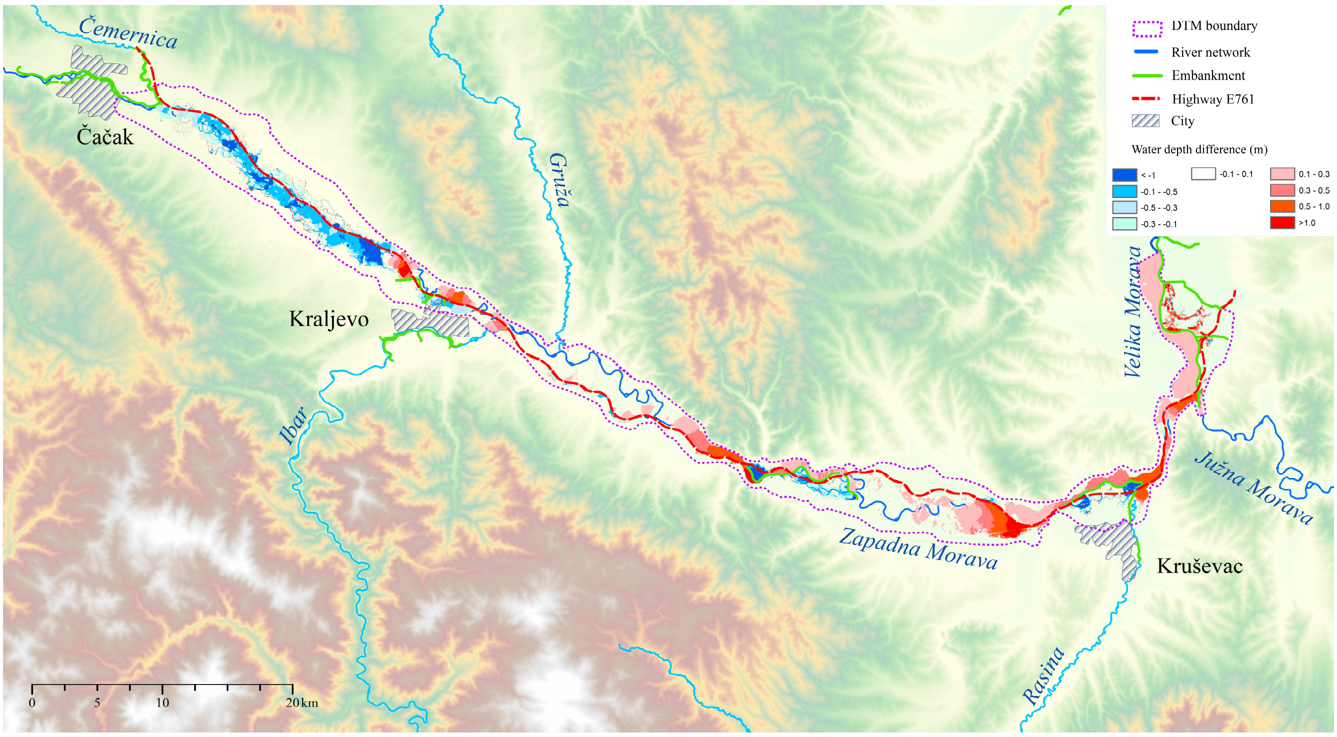

Figure 8. *Indicative map flood risk in case of 100-year flood – future climate conditions*

The 2D modelling also demonstrated that the highway is climate resilient and should not flood under more frequent and intensified future extreme rainfall events. The problems were encountered on some flood protection levees, and sections of the existing roads and railroads since these don't have required freeboard or may even be overtopped by flood waters. The graphical basis for the risk analysis of one flood embankment in the Zapadna Morava valley is presented on Figure 9. The graph indicates if the criterium for flood protection (100-year flood WSE plus 1 m freeboard) is met or not.

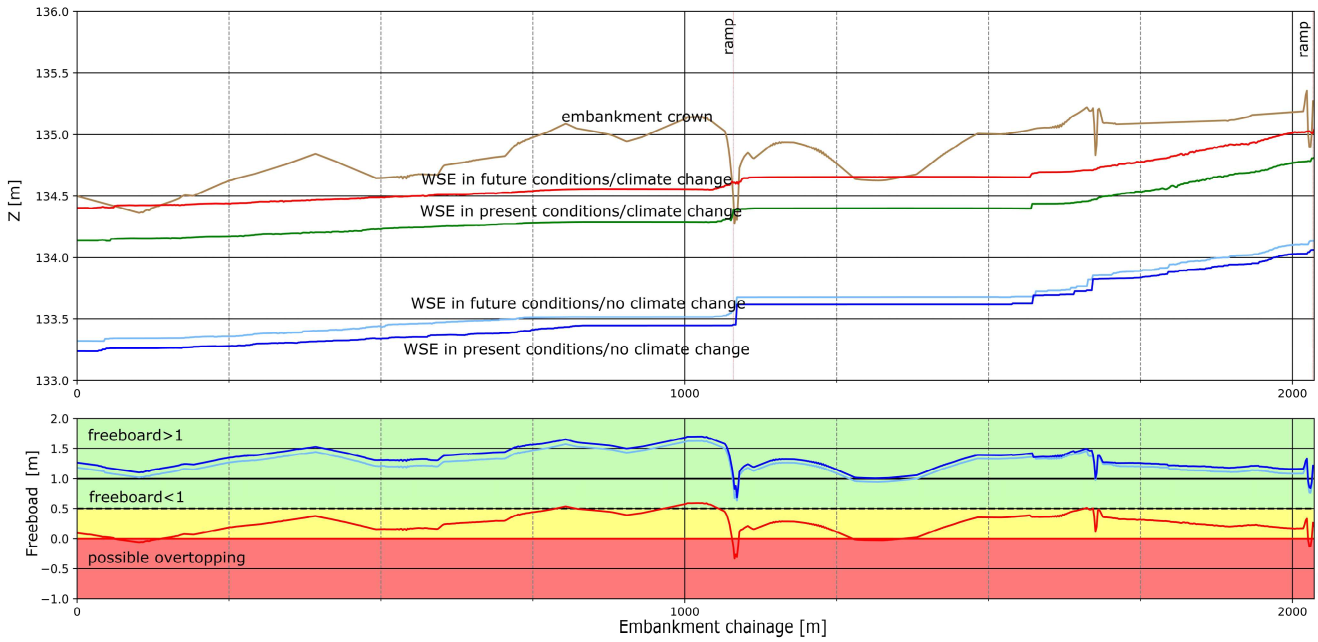

Figure 9*. The analysis of the flood embankment resilience to floods*

Application No 2 - River crossing analysis

Detailed design of both the river regulation and motorway features (e.g., bridges and culverts) is ongoing, and JCWI and highway designers are working together to reduce flood risk to acceptable levels. Special attention is devoted to several critical river crossings, where 2D hydraulic analysis indicated high flood risk.

The detailed analysis of the crossing at km 29.9 of the highway Section 4 is presented as an example of 2D hydraulic modelling, made in a few phases in search for the best design. This exercise lasted from October 2021 to February 2022 and followed a top-to-bottom approach.

The route of the highway on Section 4 is located in the valley of the Zapadna Morava River, from r. km 22.5 to r. km 41.8. The river valley is very wide (2 to 5 km) and the riverbed meanders through it. Several old riverbeds are visible. The riverbed has variable dimensions, with a width ranging from 30 to 250 m and a depth of 3 to 20 m. On the right side of the valley are the railway and state road.

The preliminary design of the river crossing at km 29.9 of the Zapadna Morava River had foreseen the construction of highway embankments on the right and left side (3-8 m high; protected with concrete lining from km 27.6 to km 32.6; lining up to a height of 0.5 m above the 100-year flood level) and two parallel bridges for highway lines (each 14.75 m wide; 506 m long with 13 spans). Two openings are foreseen in the embankment on the left side of the valley, for the local road at km 27.9 (10 m wide) and the Neskov creek at km 28.5 (48 wide with 3 spans).

The assessment of flood risk, based on a comparison of the results of the 2D integral hydraulic models for the existing conditions and the conditions after highway construction, had shown that the crossing, if built as preliminary designed, will have adverse effects even it the present climate situation (Figure 10). Upstream of the highway crossing the level of 100-year flood would increase by 0.5 to 1 m. In the right corner of the crossing, the water level will rise more than 1 m and overflow of the railroad and state road by flood waters can be expected. Downstream from the crossing, the water depths will be lower, which indicates that the area upstream of the crossing will act as flood retention. The increase of flow velocities can be expected also, in the areas of the highway bridge and openings, as well as along the railroad.

The understanding of present and future hydraulic conditions on this critical location is crucial for initiation of the problems induced by construction of the highway crossing on the Zapadna Morava river.

The flow pattern in the existing state of the river valley (Figure 11-left) is governed by geomorphological elements as pronounced meandering of the present riverbed, old riverbeds and topography of the terrain. At the area of the crossing, the right side of the river valley with a few deeper parts (abandoned riverbeds) has a significant role in flood conveyance.

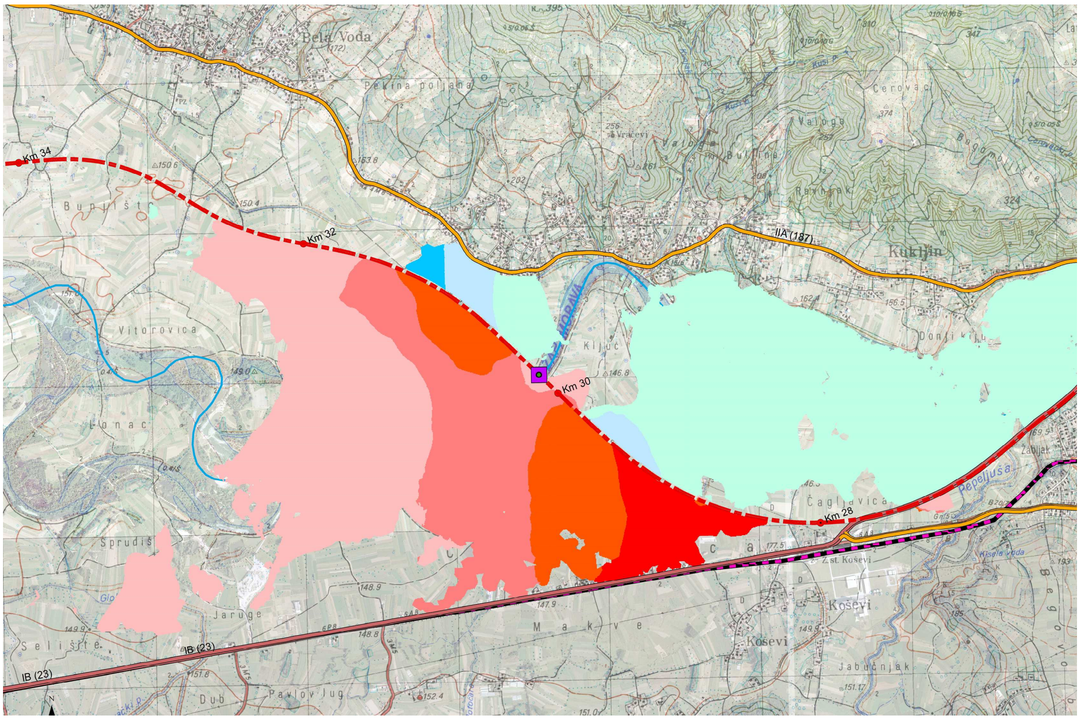

Figure 10. *Indication of critical location – higher level of 100- year flood after construction of the E-761 highway (present climate conditions)*

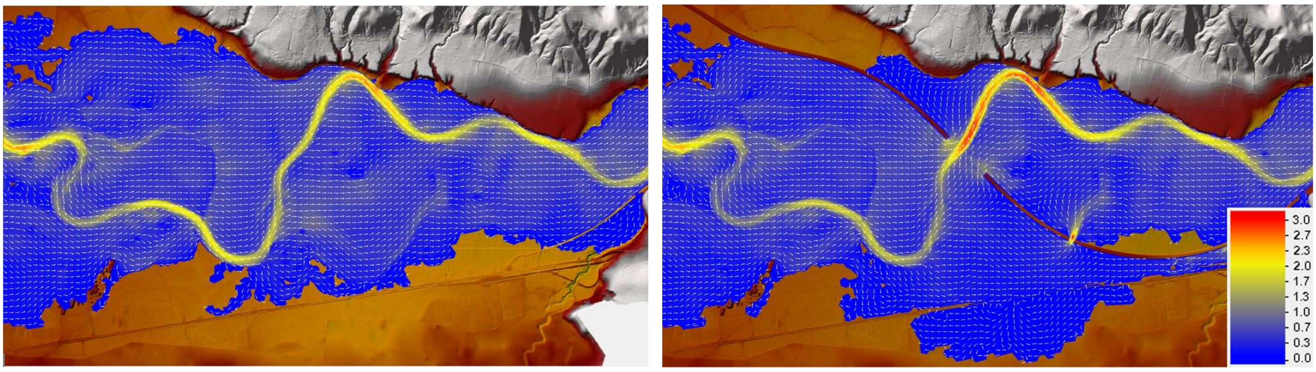

Figure 11. *Flow pattern and velocity distribution in the river valley before and after highway construction (conditions of 100-year flood)*

After the construction of the crossing (Figure 11-right), the entire flow over the left flood plain is directed towards the bridge opening, with a return flow downstream of the highway embankment. Complete change of the flow pattern is expected on the right side of the river valley, where the highway embankment directs a major flow portion towards the right side of the river valley, resulting in flooding of the railroad and state road. Furthermore, significantly increased flow velocities at and downstream of the bridges over Zapadna Morava and the Neskov creek will induce fluvial erosion and endanger bridge structures.

When the impacts of the river crossing as preliminary designed were understood (including the change of water levels presented on Figure 10), JCWI modelers examined numerous possible modifications of the bridge and/or river geometry to find the best solution to prevent flooding of the existing infrastructure.

The investigated options included: extension of the bridge opening on the left bank by 160 m; extension of the bridge opening on the right bank (up to the Neskov creek, app.1000 m); riverbed regulation in the bridge area; an embankment along the railroad on the right bank and their combinations.

New versions of the integral model were made for each option, and their results were used for comparison of the flood prone areas (Figure 12) and water levels along the railroad (Figure 13). The results were presented to the Investor and the highway design team.

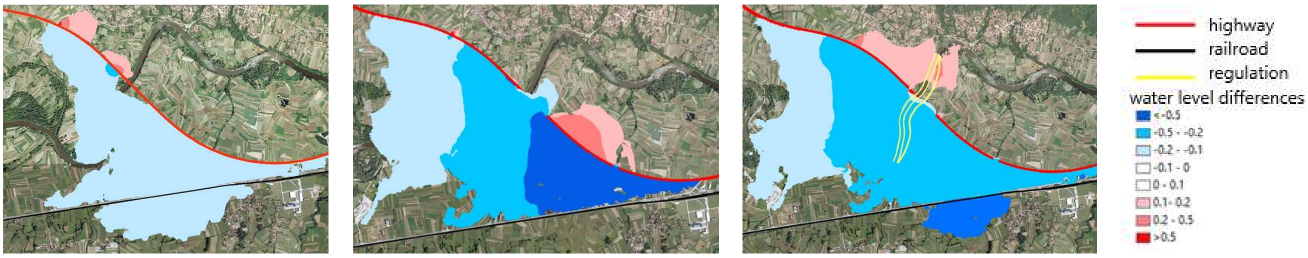

***Figure 12**. Difference of the extent and water depth in 100-year flood areas for the preliminary designed crossing option and its modifications: bridge L=660 m (left), bridge L=1500 m (center); bridge L=740 m and river regulation (right)*

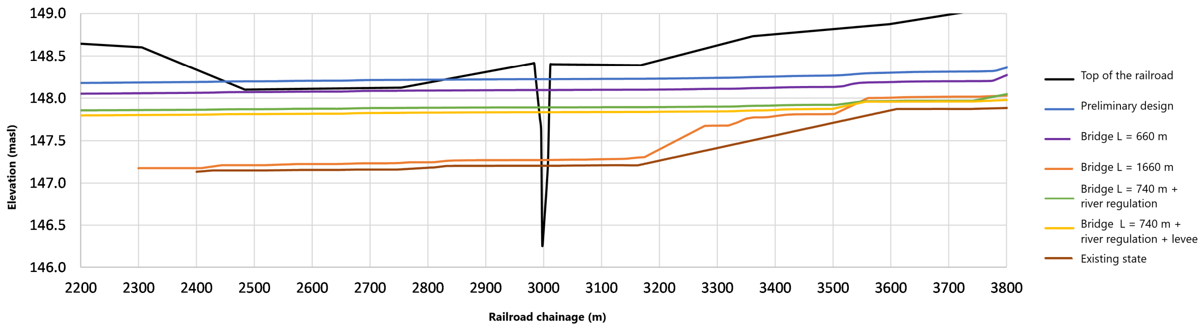

***Figure 13**. Levels of 100-year flood along the endangered section of the railroad for investigated options*

2D hydraulic modelling demonstrated that moderate modifications of the bridge, even in combination with riverbed regulation, cannot solve the problem because the railroad flood protection criterium (1 m above 100-year flood level in the present climate conditions) cannot be achieved (Figure 12). The extension of the bridge span to maximum (app. 1660 m), although providing the best flood regime, was seen as costly and abandoned. Therefore, it was found that the only option to prevent the flooding of the important assets on the right side of the river valley is to build a new flood protection levee, 2750 m long.

In the next step, 2D integral hydraulic model was used to analyse the height of the new levee (the top of the levee is on 100-year flood level with a 1 m freeboard), if bridge across the Zapadna Morava river has length of 500 m, 660 m or 740 m.

Final decision of the highway investor relayed on the results of the 2D hydraulic partial model of the area. The highway designer provided the design of 2 options for the bridge construction (with specified position and dimensions of bridge piers and abutments). These were: (1) Bridge 500 m long (12 bridge piers), and (2) The same bridge with the extension towards left, total length 660 m (16 piers). In both options, the new levee provides the protection of infrastructure and nearby assets on the right side of the river valley, upstream of the crossing.

The conclusion of this hydraulic exercise was that by widening the bridge from 500 m to 660 m flow the flow pattern will be improved, especially around left abutment of the bridge (Figure 14). Also, flow velocities near bridge piers and abutments will be reduced between 6 and 37% if the bridge is longer. Consequently, measures to protect piers and abutments from erosion will be easier to implement and less expensive (smaller diameter of riprap and dimensions of lining). Detail around bridge piers is also presented in Figure 14.

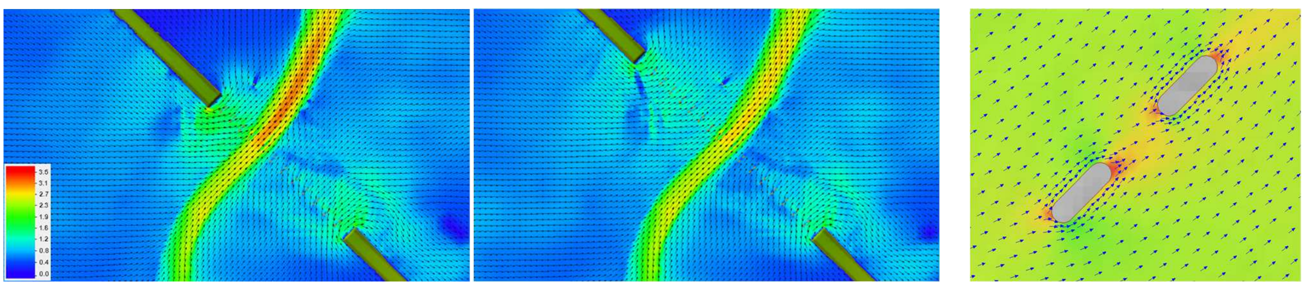

***Figure 14**. Flow pattern and velocities in the bridge opening (left: bridge L=500 m; centre: bridge L=660 m) and around bridge piers (right)*

CONCLUSIONS

Numerical simulation has become an important tool in recent years to help in the wide spectrum of studies, including hydraulic studies of interaction between the man-made structures as highways and rivers.

Development of acceleration technology has turned 2D hydraulic modelling into affordable one and improved the accuracy of the interaction analyses. The major benefits of 2D modelling approach are: (a) Improved project quality and resiliency (better representations provide planning and design teams with better data, leading to improved project quality); (b) Enhanced collaboration (graphical visualizations offer better tools for communicating the often complex interaction between waterways, the infrastructure, and the surrounding environment); (c) Streamlined Delivery (improved collaboration through 2D visualizations offers real potential for reducing environmental, regulatory, engineering and other impediments to project delivery).

Next-generation tools are currently applied in a very demanding process of Morava Corridor design. Following the request of consultants of international financing institutions, the design process is based on state-of-the-art hydrological and hydraulic models that use a huge amount of spatial and other data.

The computational platform with superior computational and data analysis efficiency is used to support high-resolution simulations at a large scale and hence provide next-generation modelling tools for understanding complex hydrological and hydraulic processes.

A contemporary top-to-bottom approach to river hydraulics was applied in the Morava Corridor Project. The first step was the identification of the new development impacts and its complex interactions with the river, on a catchment scale. In the next step, design options intended to minimize the impacts of a critical crossing on the environment were investigated using integral hydraulic models. The results of hydraulic simulations were presented to a large pool of decision makers including Investors of the highway and hydro-technical structures and highway designers. At the end, when only a few options remained, very detailed results of the partial hydraulic model were used to determine a final solution that will be designed according to the Law on planning and construction.

The work on the Morava Corridor Project is in progress, and hydraulic models are upgraded accordingly to be further used during the implementation of the project (design, construction, and maintenance).

REFERENCES

[1] Federal Highway Administration. (December 2001). River Engineering for Highway Encroachments - Highways in the River Environment. Retrieved from the US Department of Transportation website: https://www.fhwa.dot.gov/engineering/hydraulics/pubs/nhi01004.pdf

[2] Federal Highway Administration. (15 July 2019). Overview of Practices for Adopting 2D Hydraulic Modeling; Office of Bridges & Structures. Retrieved from the US Department of Transportation website: https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif19058.pdf

[3] Federal Highway Administration. (October 2019) Two-dimensional Hydraulic Modeling for Highways in the River Environment - Reference Document. Retrieved from the US Department of Transportation website: https://www.fhwa.dot.gov/engineering/hydraulics/pubs/hif19061.pdf

[4] Echeverribar, I. Morales-Hernández, M. Brufau, P. Garcia Navaro, P. (2018). Numerical simulation of 2D real large scale floods on GPU:the Ebro River, E3S Web of Conferences 40, 06007.

[5] Jaroslav Černi Water Institute. (2021). *Pojate – Preljina E-761 Motorway "Morava Corridor"*. Hydrological and hydraulic models and analyses- Inception report

[6] Jaroslav Černi Water Institute. (2021). *Pojate – Preljina E-761 Motorway "Morava Corridor"*. Hydrological and hydraulic models and analyses - Initial Modeling Results.

[7] Babić-Mladenović, M. (2018). River Regulation, *1st edition*, Belgrade: Jaroslav Černi Water Institute.

[8] National Cooperative Highway Research Program. (2020). Highway Hydraulic Engineering State of Practice. Retrieved from the National academies website: https://nap.nationalacademies.org/catalog/25848/highway-hydraulic-engineering-state-of-practice

[9] National Cooperative Highway Research Program. (15 March 2019). Applying Climate Change Information to Hydrologic and Coastal Design of Transportation Infrastructure-Final Report. Retrieved from the NCHRP website: https://onlinepubs.trb.org/Onlinepubs/nchrp/docs/NCHRP1561_DesignProcedures.pdf

[10] Lianga, Q. Xiaa, X. Hou, J. (2016). Catchment-scale high-resolution flash flood simulation using the GPU-based technology. Proceedings of the 12th International Conference on Hydroinformatics, Incheon, 975 – 981.

[11] Liu, Q., Qin, Y., Li, G. (2018), Fast Simulation of Large-Scale Floods Based on GPU Parallel Computing. *Water 2018*, 10, 589.

Editors

Dejan Divac
Nikola Milivojević
Srđan Kostić

CONTEMPORARY WATER MANAGEMENT: CHALLENGES AND RESEARCH DIRECTIONS

Proceedings of the International Scientific Conference
in the Honour of 75 Years of the

Jaroslav Černi Water Institute

October 19-20, 2022, Belgrade, Serbia

EDITORS
Dejan Divac
Nikola Milivojević
Srđan Kostić

CONTEMPORARY WATER MANAGEMENT: CHALLENGES AND RESEARCH DIRECTIONS

Proceedings of the International Scientific Conference
in the Honour of 75 Years of the

Jaroslav Černi Water Institute

October 19-20 2022, Belgrade, Serbia

Publisher

Jaroslav Černi Water Institute
Jaroslava Černog 80, 11226 Belgrade, Serbia
www. jcerni.rs, office@jcerni.rs

For the Publisher

Prof. dr Dejan Divac, Director General

Editors

Prof. dr Dejan Divac
dr Nikola Milivojević
Prof. dr Srđan Kostić

Cover page design

Tanja Jeremić

Printing

M&G Marketing, Belgrade

Circulation

1000 copies

PREFACE

Institute of Hydrology was established in 1947 within the Serbian Academy of Sciences. The Hydraulics Laboratory was established that same year within the Federal Ministry of Electricity, a predecessor of the later Hydropower Institute created in 1950. These two institutions were soon merged under the auspices of the Serbian Academy of Sciences into the Hydrotechnical Institute Eng. Jaroslav Černi. This Institute merged with the Serbian Water Management Institute in 1959 to create today's Jaroslav Černi Water Institute.

Over the past decades, the Institute has been the backbone of scientific research in the field of water in Serbia and the former Yugoslavia. The international scientific conference Contemporary Water Management: Challenges and Research Directions is organized to celebrate 75 years of the Institute's long and successful history. The Scientific Board selected 26 papers to provide readers with the best view of the current research results, as well as the further scientific research directions and potential challenges in the future. Selected papers are classified into six conference topics according to the corresponding research field, although one should note that most of the presented works is multidisciplinary, which is after all a characteristic of a modern problem-solving approach in the field of water. Hence, the chosen conference topics and corresponding papers represent only one possible way of classification of the presented works.

We wish to express our gratitude to the International Scientific Board and the Organizing Committee of this international conference for their efforts in selecting the papers, reviewing, and organizing the conference. We also wish to express our gratitude to all the authors of selected papers for the time they spent presenting the results of their research in a way suitable for this conference, and for contributing to the celebration of 75 years since the establishment of the Jaroslav Černi Water Institute. Respecting the importance of jubilee and wishing to express gratitude to previous generations of scientific workers, the Honorary Committee was also formed.

Following the path of previous generations, the Institute's present and future staff remain privileged, and under duty and obligation to continue and improve the scientific and research work of the Institute in the years and decades to come.

Belgrade, October 2022

Editors

CONTENTS

LARGE HYDROTECHNICAL STRUCTURES – HISTORICAL HERITAGE AND CULTURAL LANDSCAPES

DAM SAFETY

COMPLEX FLOOD PROTECTION AND DRAINAGE SYSTEMS

CIP - Каталогизација у публикацији - Народна библиотека Србије, Београд

556(082)
626/628(082)

INTERNATIONAL Scientific Conference in the honour of 75 years of the Jaroslav Černi Water Institute (2022 ; Belgrade)
Contemporary Water Management : challenges and research directions :
proceedings of the International Scientific Conference in the honour of 75 years of the Jaroslav Černi Water Institute, October, 19-20, 2022, Belgrade, Serbia / editors Dejan Divac, Nikola Milivojević, Srđan Kostić. - Belgrade : Jaroslav Černi Water Institute, 2022 (Belgrade : M&G Marketing). - 430 str. : ilustr. ; 30 cm

Tiraž 1.000. - Bibliografija uz svaki rad.

ISBN 978-86-82565-55-0

a) Хидрологија - Зборници b) Хидротехника - Зборници

COBISS.SR-ID 76403977

9 788682 565550