Combined geodetic surveying methods for 2D flood modeling

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Key words: bathymetry, LiDAR, digital elevation model, 2D hydraulic modeling

SUMMARY

Application of 2D hydraulic modeling (2D modeling) is rapidly becoming the preferred analytical approach across a broad spectrum of study types, including transportation hydraulic studies, bridge scour, flood control design, river restoration, habitat evaluation, floodplain mapping, and many others. The amount, the quality, and the type of data necessary to create 2D models vary depending on the model application and the feasibility of obtaining the data. Compared to other data types, terrain data is the most important data set for 2D modeling, because the terrain has the most influence on the movement of water for open channel flow. Terrain data typically takes the most resources to obtain a sufficient representation of a project area. Therefore, it is crucial to choose a geodetic method to collect spatial data in order to ensure, at the same time, a high accuracy, the required substrate details, and an efficiency of the procedure. Due to the development of geodetic technologies in the last few decades, nowadays are available various and mutually compatible geodetic instruments and methods of obtaining high-precision spatial data. Having in mind the specific needs of hydrographic and hydraulic research and analysis, for the generating of adequate geodetic substrate, the integration of topographic and bathymetric methods of land surveying is most often necessary. In this paper a combined method of terrain data collecting with LiDAR (Light Detection and Ranging) and Echo Sounder System will be presented, along with the final results of 2D hydraulic modeling on the example of "Moravian Corridor Highway Project". The aim of the proposed method is to provide a complete picture of the river catchment, its facilities and river structures for modeling process, in order to contribute to the development of safe and rational technical solutions and high-quality construction of motorway structures and river regulation.

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1. INTRODUCTION

Hydraulic models are simplified representations of complex systems including flowing water, the channel bed and overbanks, vegetation, sediment and other transported materials. Models are developed to gain insight into these processes, either to understand the nature of these interactions (in which case we are performing analysis) or to guide modifications of these systems in beneficial ways (performing design). Numerical hydraulic models are simplified mathematical representations of this reality. Numerical models come in a variety of types, including 1D, 2D, and 3D, that provide a range of approximations of basic hydraulic principals (Figure 1). In this context, 1D means that the variability of hydraulic components such as flow depth and velocities are considered only in the streamwise direction (upstream or downstream) in the governing equations. Any components of hydraulic forces that do not act in the streamwise direction are neglected.

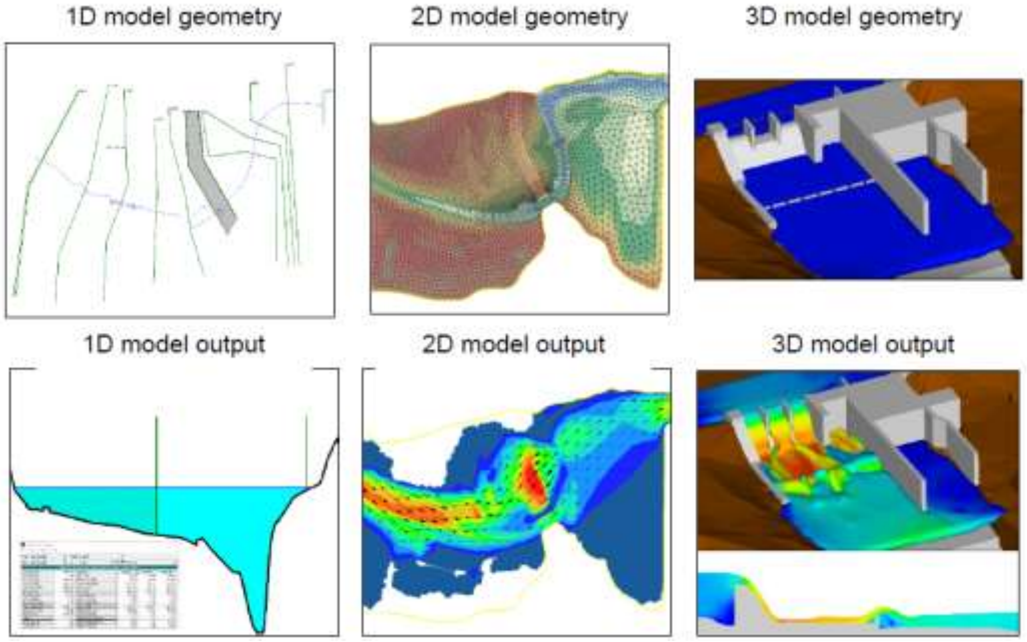


Figure 1. Example 1D, 2D, and 3D model geometry and output (Source: Robinson et al. 2019)

Since 2D models require fewer assumptions than 1D models, the planning and development of a 2D model is often more straightforward than a comparable 1D model. This is especially true when complex hydraulics exist at a project location. As modelers become proficient in working with geospatial data, GIS, and modeling software, developing a 2D model can often be completed more efficiently than a 1D model. Two-dimensional models are useful tools for many transportation hydraulic engineering applications, including, but not limited to, the design of waterway crossing structures such as bridges and culverts; bridge scour analyses; bank stabilization and scour countermeasure design; floodplain analyses; and river rehabilitation and aquatic habitat assessment.

Hydraulic modeling, as well as analysis of the river flow, sediment transport, planning the sludge removal, design of hydraulic structures is impossible without knowledge of bathymetry of the water body. Terrain data is the most important data set for 2D modeling because the terrain has the most influence on the movement of water for open channel flow, compared to other data types. The portions of terrain having an impact on hydraulics are referred to as hydraulic controls. Typical hydraulic controls include (Robinson et al. 2019):

- River channel geometry
- Grade control within the channel (riffle, weir, dam, diversion)
- Grade transition from channel to floodplain
- Flow paths within the floodplain
- High ground within the floodplain
- Natural constrictions within the channel or floodplain
- Roadway embankments
- Bridges, culverts, and other hydraulic structures (not always represented by mesh geometry)
- Surface roughness.

Land topography survey methods are unsuitable for underwater applications, and various methods of subaqueous geodetic measurements have been developed for this purpose. The survey of the riverbed can be one-time or periodic, and the method itself is chosen depending on the size of the watercourse and hydrological-hydraulic conditions at the time of surveying, as well as the purpose itself. Over the years, one of the most common was the method of measuring transverse profiles at predefined intervals on the basis of which a terrain model necessary for calculations or design is later formed. The development of advanced geodetic technologies has not only enabled considerably greater detail of the survey, but also simplified the measuring of the complete riverbed with significant time savings. One of the most popular modern techniques is certainly LiDAR, which is a modern system of laser imaging of large areas in order to collect spatial information. Although these methods alone give satisfactory results, it is common practice to use terrain data from multiple sources with varying levels of accuracy to create a terrain data set for 2D modeling.

2. CONCEPTS OF LASER SCANNING TECHNOLOGY

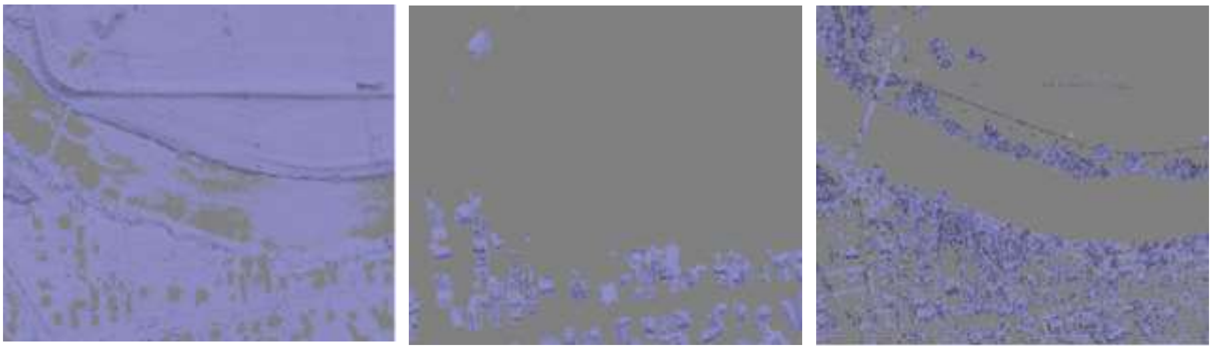
LiDAR, also known as laser detection and ranging (LaDAR) or optical radar, is an active remote sensing technique which uses electromagnetic energy in the optical range to detect an object (target), determine the distance between the target and the instrument (range), and deduce physical properties of the object based on the interaction of the radiation with the target through phenomena such as scattering, absorption, reflection, and fluorescence (Diaz et al., 2017). This system includes four basic components for data collection and orientation of laser beams: laser, a unit of the Inertial Navigation System (INS) that includes an Inertial Measurement Unit (IMU) for correcting the orientation of the mobile platform, Global Navigation Satellite System (GNSS) and a computer storage unit. The integration of these components into a single unit provides an integrated surveying system, which allows rapid collection of a large number of accurate data in a relatively short period of time (Vasić et al., 2014).

Laser, as the foundation of all scanners and profilers used today for measurement purposes, is a part that performs precise measurement of distances to objects. Its basic components are: optics, photodetectors and electronics. There are two different procedures of laser measurements. The first is the Time-of-Flight (TOF) method, where distance is determined the based on the elapsed time between the moment of emission of a short but extremely intense laser pulse, and its return to the emitter after reflection from the targeted object (Bellisai et al, 2013). TOF LiDAR is widely used in engineering fields such as robot navigation, automatic guided vehicle, and three-dimensional measurement applications in several industries because they have the advantages of non- contact, wide range, and high precision measurement (Amann, et al., 2001). In the second method, Multiple-Frequency Phase Comparison (MFPC), the laser emits a continuous beam of laser radiation instead of a short pulse, so the length value is derived by comparing the emitted and received versions of the sine wave of the emitted beam and by measuring the phase difference between them (Vasić, 2018).

The inertial navigation system is intended for determining the navigation parameters of an object in space and consists of at least three accelerometers, three gyroscopes and a computer unit. The principles of INS are based on the measurement of acceleration in translational motion along axes and angular velocities of rotation around axes. Its advantage is that, once the device is initialized, it does not require external resources to determine position, orientation, or speed (Ninkov et al., 2010). This makes it resistant to interference and therefore has a great application in the military industry, navigation, surveying and many other areas (Maksimović et al., 2018).

GNSS enable autonomous geospatial positioning with global coverage. Calculating the position of points on the Earth by GNSS is achieved by measuring the distance (pseudolength) to the satellite and applying trilateration. There are two basic types of pseudolength measurements, code ones and phase ones. Determining the coordinates of points by GNSS can be performed in three modes: static, kinematic and differential (Delčev, 2016).

LiDAR technology uses the working principle of the emission of laser infrared rays towards the desired surface and the measurement of the reflection time to the sensor. By knowing this time interval, as well as the position and orientation of the sensor, it is possible to obtain three-dimensional coordinates of points on the land surface. The mirror inside the laser transmitter moves during surveying, rotating perpendicular to the direction of flight, which provides measurement in a wider band (Ninkov et al., 2010). The absolute position of the sensor is determined by GNSS, using phase measurements in the mode of relative kinematics, and the positions in between are obtained by prediction, using INS. The emitted laser beam can have multiple signal reflection (multi-beam LiDAR), which causes a particular point to have the same 2D coordinates but different heights (Vasić, 2018). It is usual for the first reflection to come from vegetation, water or similar, while the last refers to the very surface of the terrain or artificial objects (Figure 2). Thanks to the fact that each measurement is separately georeferenced, the LiDAR methodology overcomes the problems of aerotriangulation and orthorectification.



a) ground b) objects c) vegetation

Figure 2. Presentation of the point cloud classification layers obtained with LiDAR (Source: IJČ)

Laser data collection can be terrestrial and aerial. However, when it comes to surveying terrain on longer sections, such as riverbeds, traffic infrastructure, etc., the most widely used are Mobile Laser Scanning (MLS) systems that are installed on land transport vehicles (road, rail, or watercraft) and Airborne Laser Scanning (ALS) systems integrated on the air platform. For hydrographic application, it is possible to use Bathymetric lidar, which is similar to traditional aerial lidar, except it enforces a green laser that can penetrate water. The bathymetric lidar is limited to clear water with minimal turbulence. Because of this limitation, it is often used along coasts but has narrow application along many of the nation's rivers due to high turbidity levels (Robinson et al. 2019).

3. ECHO SOUNDER SYSTEMS

An Echo Sounder (ultrasonic depth sounder) is a device that determines the vertical distance between the current level of the water mirror and the bottom. They work on the principle of measuring the speed of the sound wave which traveled through water, ie. from the probe to the bottom and back. As the speed of sound waves propagating through the water at a certain temperature is constant, the depth is proportional to the travel time of the wave (Babić, 2018). Depending on the characteristics, echo sounders may differ as single-frequency and multi-frequency, as single-channel and double-channel, and according to the number of beams as single-beam and multi-beam (IHO, 2015). Hydrographic echo sounders for shallow waters are usually built with two channels that operate at two frequencies, one low and the other higher. The simultaneous recording of two frequencies allows the separation of the riverbed return from the soft surface sediments and the underlying rock due to their different acoustic impedances (IHO, 2015).

Single-beam systems collect a single point, typically every second, as the boat moves across the water. They typically collect data along cross-sections at specified locations or with a specific spacing and may also provide a profile survey along the channel centerline. (Robinson et al, 2019). Unlike the Single-beam, the Multibeam echo sounder has hundreds of very narrow beams that send sound pulses. This series of pulses provides a very high angular resolution, which allows the riverbed area to be measured from several different angles (IJČ, 2018). Thanks to this, the use of multibeam gives a complete 3D representation of the underwater surface. Also, multibeam echo sounders make corrections for the ship's movements on the water, which increases the accuracy of measurements and provides the possibility of obtaining maps of a larger area of the river in less time. The most common method of collecting bathymetric data is with sonar, attached to a boat (Figure 3), and combined with a GNSS or robotic total station to provide the location of the sonar device (IHO, 2015).

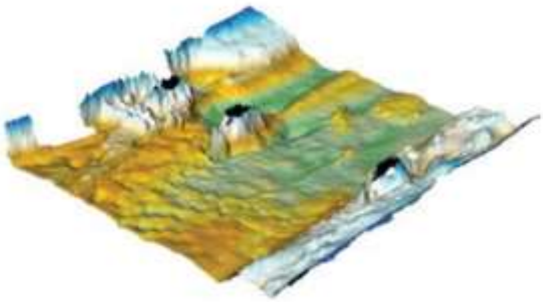


Figure 3. Boat equipped with echo sounder and GPS device (left) and 3D view of the river bottom measured with multi beam echo sounder (right) (Source: IJČ, 2018)

The GNSS receiver combined with the ultrasonic depth gauge provides a functional system for the direct calculation of three-dimensional bottom coordinates. These two systems are connected in such a way that the discrete point with measured depth is assigned a position obtained by GNSS positioning. The offset between the phase center of the GNSS antenna and the echo sounder probe is determined during system installation, so that all the values are corrected for the vertical offset value. The density of the points can be defined in advance by the time interval or the traveled distance. Depending on the density of the colleced points and the future purpose, the data can be displayed in the form:

- transverse and longitudinal profiles (if the survey was performed in predefined directions at a greater distance from each other),
- digital terrain model (DTM) (data collected with higher density).

4. 2D MODELING METHODOLOGY

Hydraulic models are digital representations of the real world. It is important to understand the physical principles represented in a typical model. Most models include aspects of both fluids at rest and in motion. Key physical properties and parameters used to describe and quantify fluid motion include acceleration, velocity, mass, momentum, and energy. The Navier-Stokes equations, named for Claude-Louis Navier and George Gabriel Stokes, apply simplifying assumptions to represent motion of fluids. Most 2D models use a variation of the depth-averaged shallow water equations (SWE) derived from the Navier-Stokes equation. The SWE consider the continuity and momentum principles (Figure 4).

Continuity:

$$\frac{\partial H}{\partial t}+\frac{\partial HU}{\partial x}+\frac{\partial HV}{\partial y}=e$$

How water level changes over time | Net amount of water out of the 2D element

x-component of Momentum:

$$\frac{\partial HU}{\partial t}+\frac{\partial HUU}{\partial x}+\frac{\partial HUV}{\partial y}=\frac{\partial HT_{xx}}{\partial x}+\frac{\partial HT_{xy}}{\partial y}-gH\frac{\partial z}{\partial x}-\frac{\tau_{bx}+\tau_{wx}}{\rho}+D_{xx}+D_{xy}+\Omega HV$$

How velocity changes over time | Inertia terms | Turbulence | Gravity | Bed and Wind Shear Resistance | Dispersion | Coriolis force

Figure 4. Example 2D continuity and momentum equations, and their contributing terms (Source: Robinson et al. 2019)

Many approaches have been developed to represent a systematic numerical method for solving SWE. The approaches discretize the model domain into small geometrically simple shapes. These shapes are referred to as elements (or cells). The collection of elements constitutes a computational mesh that represents the model domain (Figure 5).

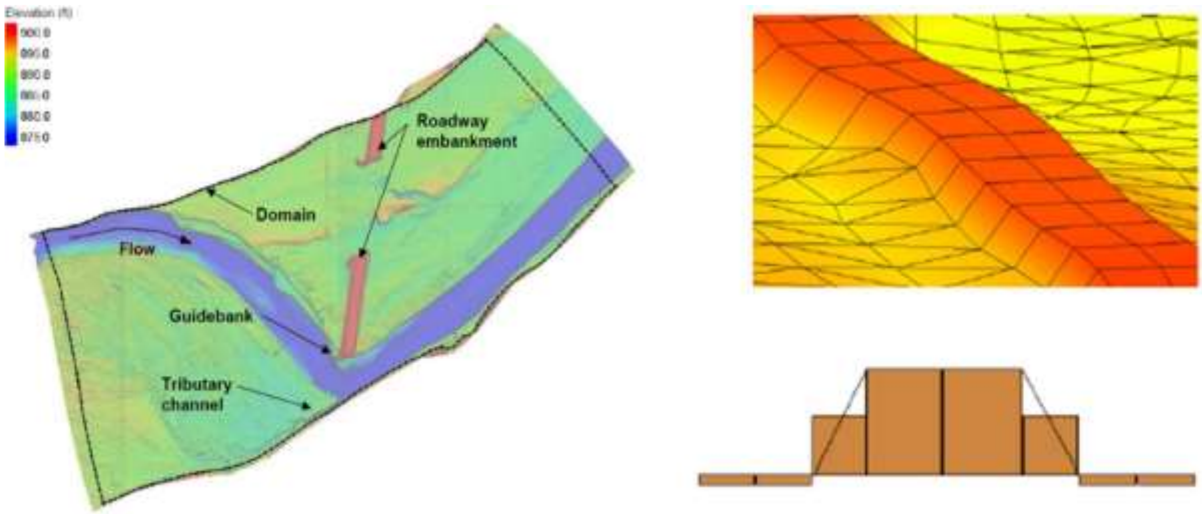


Figure 5. Representation of embankment at nodes and elements
(Source: Robinson et al. 2019)

Typical data needed for 2D modeling include:

- Terrain data (digital elevations from lidar, photogrammetry, or field surveys)
- Upstream boundary conditions (hydrologic data - discharges)
- Downstream boundary conditions (fixed surface water elevation, rating curve, or tidal condition)
- Land use for model domain (hydraulic roughness parameters, Manning's n)
- Hydraulic structure geometry (bridges, culverts, and other inline or diversion structures)
- Aerial imagery, CAD data, and GIS (not required but it is helpful)
- Application-specific information (for example, soil characteristics for sediment transport studies)

Although all data used for a model is important, the mesh geometry, developed from terrain data, has the most significant impact on model results and is the greatest source of uncertainty and error (Figure 6). Recognizing the relative importance of each data type assists modelers in directing how resources, such as time and budget, are spent developing each type of data, and related model components.

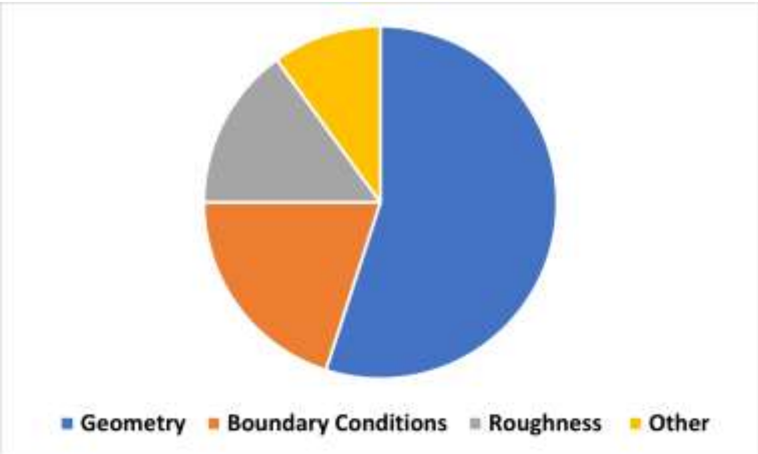


Figure 6. Approximate importance of data type to model results

5. 2D HYDRAULIC MODELING OF WEST MORAVA

West Morava is the left tributary of Great Morava. It is formed by merging Moravica and Đetinja near the village of Leposavić. The length of the river to the composition with South Morava is about 210 km, with a basin area of 15,755 km^2. Due to the crossing of the highway over the West Morava, at km 9 + 933 of the highway, two parallel bridges will be built in the left and right lanes of the highway. The width of each of the bridge structures is 14.75 m. The highway crossing is located on the lowest part of the West Morava, about 3.7 km upstream from its composition with the South Morava, ie the upstream end of the Great Morava (Figure 7).

In the previous phases of bridge design at km 9 + 933, the results of the linear (1D) model of hydraulic steady flow calculation for conditions of 100-year high water of the West Morava were used. However, it should be noted that the 1D model does not provide enough information if:

1. has no privileged flow direction (wide inundations, variable flow directions in the riverbed or on inundations), or is
2. necessary to more precisely define the flow pattern in the zone of an object or on a shorter river section with specific flow conditions (sharp rising limb of hydrograph, turbulent flow, etc.).

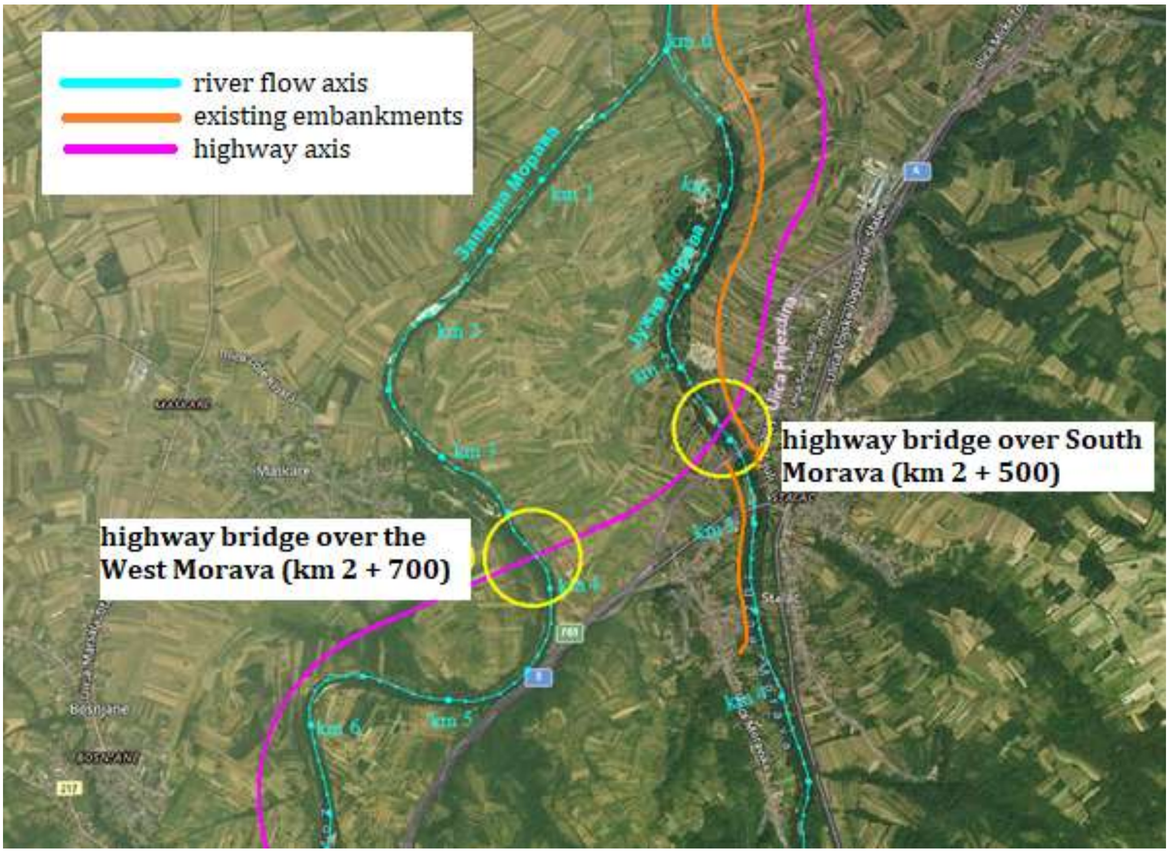


Figure 7. Section of the highway crossing over the West Morava (Source: IJČ, 2020)

All the mentioned data are calculated in the 2D model. The 2D hydraulic model was formed to check the impact of the construction of the bridge on the river flow of the West Morava and includes the river valley 3700 m downstream and 2300 m upstream from the future bridge.
The basic inputs for the estimation are:

- geometric characteristics of the riverbed,
- discharges,
- roughness coefficients of the main channel and inundation areas,

- downstream boundary condition - water surface elevations on the most downstream part for the corresponding discharges.

A hydraulic analysis was developed using the Hydrologic Engineering Center's River Analysis System (HEC-RAS solver).
For the purposes of 2D modeling of the immediate zone of the bridge, cross-sections of the main channel of West Morava were used. Part of them is surveyed in 2007 at a distance of approximately 50 m (marked yellow in Figure 8) and the rest of them is was collected in 2020 (marked blue in Figure 8). The geometry of the main riverbed outside the bridge zone was formed of transverse profiles measured in 2016 at an average distance of 500 m (marked green in Figure 8).

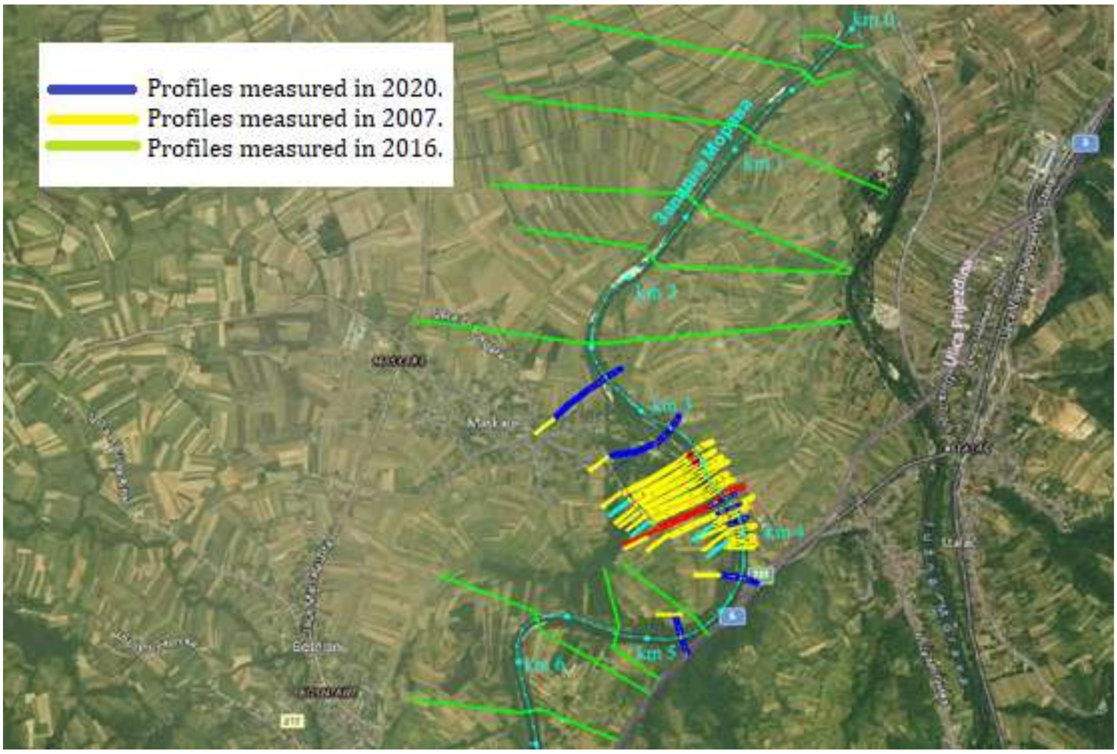


Figure 8. Profiles used to create 2D models (Source: IJČ, 2020)

The riverbed made of data from 2007 and 2020 was integrated into a previously prepared 3D substrate obtained by the LiDAR method. The integration resulted in a digital terrain model (Figure 9), which is the basis for the development of a flat model of the existing condition of the West Morava.
Two flow simulations were performed:
- 100-year flood for existing conditions,
- 100-year flood for designed conditions.

Simulation results are presented in figures 10 and 11.

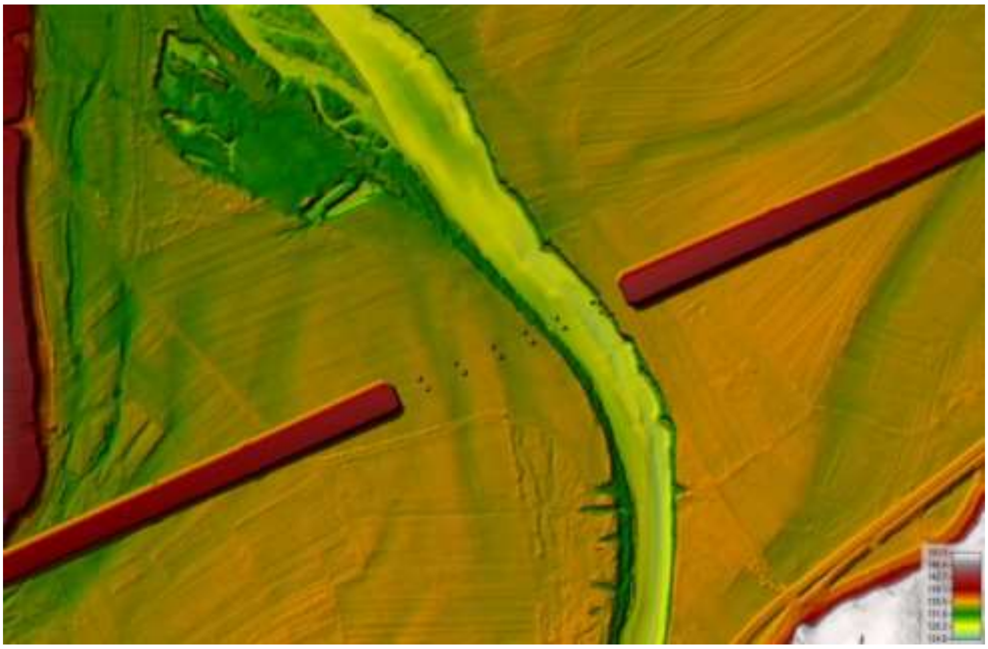


Figure 9. Digital terrain model of West Morava riverbed with integrated facilities of the future highway (Source: IJČ, 2020)

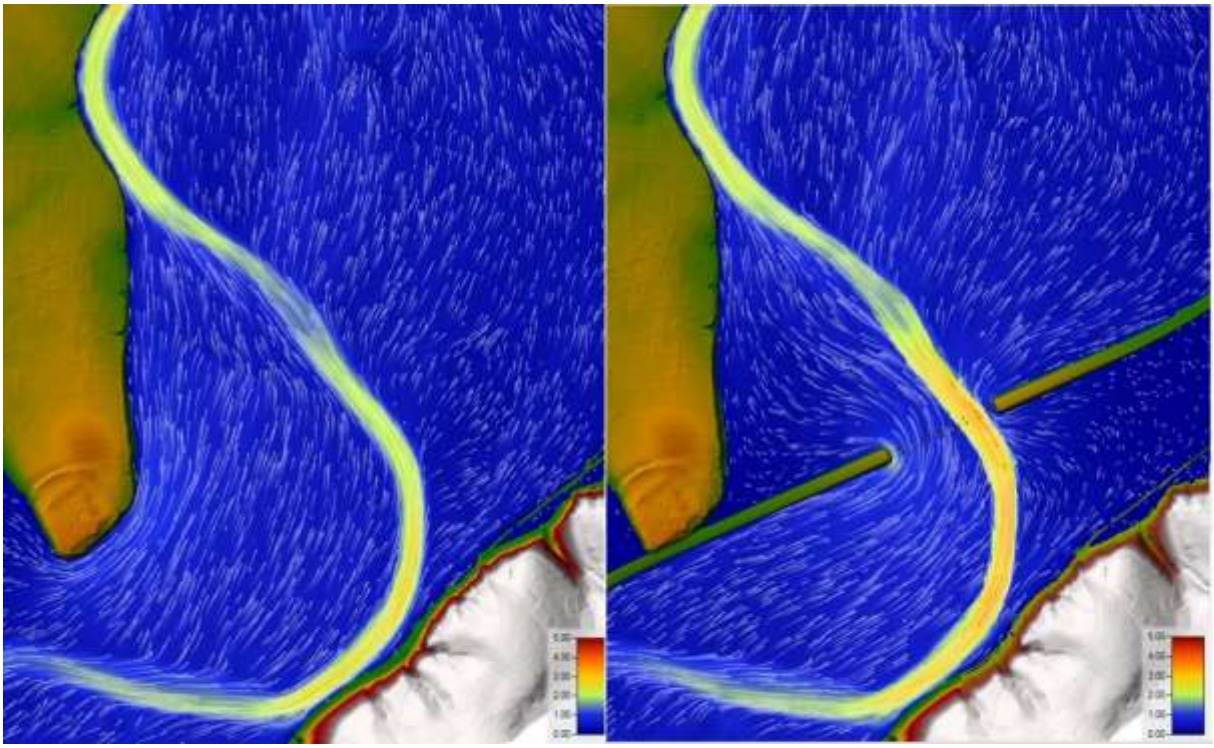


Figure 10. Flow pattern and velocity distribution at future bridge area for existing conditions (left) and for designed conditions (right) (Source: IJČ, 2020)

Based on the hydraulic analysis results a list of conclusions were made:

- Construction of highway will narrow the river inundation and flow area from 2km to 340m and thus significantly modify flow conditions at bridge area,
- The proposed highway disposition will increase flow depths,
- The proposed bridge disposition will increase flow velocities at riverbed,
- The greatest impact is at the left bridge abutment where the flow velocities are increased from 1m/s to 2,5 m/s.
- The bridge construction would need hard scour protection measures.

6. CONCLUSION

In this paper the application of 2D hydraulic modeling for the purposes of the "Moravian Corridor Highway Project" is presented. The role of geodesy in this process reflects in providing a sufficiently precise digital terrain model, which presents one of the main inputs of the 2D model. Thanks to the rapid modernization of technologies, today it is possible to obtain the necessary data much faster and more accurately. This paper shows the combined method of bathymetric surveys performed with an integrated system of Echo Sonder and GNSS and LiDAR technology. In order to create an adequate basis for hydraulic modeling, the riverbed formed of transverse profiles made in 3 phases (2007, 2016 and 2020) is integrated with the LiDAR substrate measured in 2018. Based on these input data, as well as other parameters listed in the paper, the results and analysis of 2D modeling were derived. They are presented in the last chapter together with the conclusions reached. As stated in the paper, the accuracy of DMT has the greatest impact on model errors. For this reason, it is necessary to make the optimal choice of data collection method for each project in order to meet the required precision with minimal resource consumption. Although as the leading technology of mass data collection in recent decades, LiDAR meets all these requirements as a stand-alone method, in combination with other measurement techniques it reaches its full potential.

REFERENCES

Amann, M. C., Bosch, T., Lescure, M., Myllylä, R. & Rioux, M. (2001). Laser ranging: a critical review of usual techniques for distance measurement. *Opt. Eng. 40(1),* 10-19.

Babić Mladenović, M. (2018), Uredjenje vodotoka. Beograd, Institut za vodoprivredu Jaroslav Černi (IJČ), ISBN 978-86-82565-51-2

Bellisai, S., Bronzi, D., Villa, F., Tisa, S., Tosi, A., & Zappa, F. (2013). Single-photon pulsed-light indirect time-of-flight 3D ranging. *Optics Express*, *21*, 5086–5098. https://doi.org/10.1364/OE.21.005086

Delčev, S. (2016): Geodetska metrologija, Građevinski fakultet Univerziteta u Beogradu, Beograd, Akademska misao.

Diaz, J.C.F., Carter, W.E., Shrestha, R.L., Glennie, C.L. (2017). LiDAR Remote Sensing. In: Pelton J., Madry S., Camacho-Lara S. (eds) Handbook of Satellite Applications. Springer, Cham. https://doi.org/10.1007/978-3-319-23386-4_44

Institut za vodoprivredu Jaroslav Černi (IJČ) (2018). Izvedeni projekat geodetske podloge posebne namene za akumulaciju LJukovo za potrebe uređenja akvatorije i priobalja, Beograd.

Institut za vodoprivredu Jaroslav Černi (IJČ) (2020). Rezultati 2D hidrauličkog modeliranja Zapadne Morave u zoni mosta na km 9+933 autoputa, Beograd.

International Hydrographic Organization (IHO) (2011). Manual on Hydrography, 1st edn. Publication M-13, Monaco, International Hydrographic Bureau.

Maksimović, J., Sušić, Z., Batilović, M., Đurović, R. & Ninkov, T. (2018). High precision geodetic works in the tunnel breakthrough process. In *Proceedings of the 14th International Scientific Conference INDiS 2018.*, Novi Sad, Serbia, 491-497.

Ninkov, T., Bulatović, V., Sušić, Z. & Vasić, D. (2010). Application of laser scanning technology for civil engineering projects in Serbia. *FIG Congress Sydney*, Australia.

Puente, I., Gonyales-Jorge, H., Arias, P. & Armesto, J. (2011). Land-based mobile laser scanning systems: a review. *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XXXVIII-5/W12.163-168.

Robinson, D., Zundel, A., Kramer, C., Nelson, R., deRosset, W., Hunt, J., Hogan, S., & Lai, Y. (2019). Two-Dimensional Hydraulic Modeling for Highways in the River Environment: Reference Document (dot:51778), FHWA-HIF-19-061, Federal Highway Administration Resource Center. https://rosap.ntl.bts.gov/view/dot/51778

Shan, J.(ed); Toth, C.(ed) (2018). Topographic Laser Ranging and Scanning. CRC Press, Boca Raton, USA. 654 p.

Vasić, D., Ninkov, T., Bulatović, V., Sušić, Z. & Marković, M. (2014). Terrain mapping by applying unmanned aerial vehicle and lidar system for the purpose of Designing in Serbia Ingeo 2014, 6th International Conference on Engineering Surveying, 217–222.

Vasić, D. (2018). Model geodetskog premera savremenim akvizicionim tehnologijama. Doctoral thesis, Faculty of Technical Sciences, University of Novi Sad, Novi Sad Forestry Commission, Serbia.

BIOGRAPHICAL NOTES

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