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**Original Scientific Paper**

# A PHASED CREATION OF DIGITAL ELEVATION MODEL FOR HYDRODYNAMIC MODELING IN FLAT ZONES

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**Abstract**. *Hydrodynamic modeling of rivers with flood simulation requires an accurate description of the riverbed and inundation morphology. Depending on a geodetic survey method and data collected, the digital elevation models with different accuracy can be created. This paper describes the methodology for creating a hybrid digital elevation model intended for hydraulic calculations, analysis, and results systematization and interpretation. The case study selected for illustration of the methodology is the flat ground area surrounding the Tamiš River in the Panonian Plain in Serbia. The production steps, advantages and disadvantages of the created digital elevation models with different surveying methods are explained, as well as the application of the hybrid digital elevation model for the 1D- and 2D- hydrodynamic modeling.*

**Key words**: *Digital Elevation Model (DEM), Flood Simulation, LIDAR, Hydrodynamic Modeling*

## 1. INTRODUCTION

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

In hydraulic engineering applications, flood-related hydrodynamic modeling requires precise geometry data on both floodplains and the riverbed morphology. The geometry of

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a surface, described in DEM, in hydrodynamic modeling can significantly affect the accuracy of the results, which can lead to erroneous conclusions in both research and engineering applications [2, 3, 4]. The same is reported by the group of experts from Europe [5]: the altitude data on DEM describing the potential floodplain of the river have a significant impact on the reliability and accuracy of the final results of conducted analysis. The vertical accuracy of DEM should be better than 0.5 m [5].

Previous studies have shown that DEM generated from geodetic surveys data can be used for various purposes [6], depending on its accuracy. The EU DEM [7] and other models with similar resolution do not provide high accuracy for hydrodynamic modeling in mountainous and hilly areas due to the large distance between two neighboring surveyed points and large terrain slope (10-30%) [8, 3]. Therefore they can be used for hydraulic calculations in lowland (flat) areas with a gradual or mild elevation changes. However, DEM accuracy has to be verified by field measurements [2], because in flat areas the aspect (direction of slope) is important and it can direct the flow to wrong directions.

Detailed and accurate digital maps and digital elevation models (DEM) are required to ensure the accuracy of inundation modeling as well as the identification of properties at hazard of flooding.

Nowadays, there is a variety of sources, tools and methods to generate DEMs. Ortho-maps are commonly used source to derive DEM from digital airborn and satellite images (horizontal resolution 0.5-2.0 m; vertical resolution 0.3-0.5 m). DEMs are also derived from the vectorised contour lines of 1:10,000 scaled digital map segments (terrain pixel size: 0.85-2.0 m; contour lines available in 1.0 m resolution). SAR (Synthetic Aperture Radar) acquisitions by InSAR (Interferometric Synthetic Aperture Radar) technique can generate high accuracy DEM and topographic maps. The radar can operate during the day and night and can penetrate clouds and rain. SAR technology is cost-effective and can generate DEMs with a vertical error of around 0.3 m, but also has the limitation and can not penetrate the water surface [9, 10, 11]. LiDAR (Laser imaging, Detection and Ranging) is the most accurate remote sensing method of 3D data acquisition for terrain and its coverage. The data obtained by terrain laser scanning from the air have the highest vertical accuracy up to 1 cm horizontal and 2 cm vertical, but have severe limitations under cloudy and rainy conditions and also can not penetrate the water. Laser beam reflects from the water surface and instead of riverbed under water, the elevation of the water surface is registered [9, 12, 2, 3]. For the precise hydraulic modeling, it is necessary to perform additional geodetic survey of the morphology under the water surface using classical geodetic survey methods or echo sounders, i.e. survey of the minor riverbed bathymetry. In this way, high precision of the complete riverbed morphology is obtained [2]. In addition, control geodetic surveys at characteristic points (e.g. base and crest of leveess, high roads, etc.) are desirable, in order to verify existing models and increase the accuracy of the boundary conditions for hydraulic calculations.

This paper presents the methodology for preparation of digital geodetic data sufficiently precise for the needs of hydrodynamic modeling in flat zones. The steps of development, advantages and disadvantages of the generated DEMs with different geodetic survey methods are explained.

The software packages ArcMap [7] and HEC-RAS [13] are used in the research, the latter due to its capabilities in the GIS (RAS-Mapper) module [12], where DEM can be processed and created, model geometry edited, and results displayed.

Based on the hydraulic analysis results and the final flood simulation, flooded areas are shown on the DEM, enabling flood hazard maps creation. A variety of flooding scenarios may be further studied in the prepared model including a dam break, and closing the gates, because the created DEM enables visualisation of simulated flow.

## 2. METHODOLOGY

### 2.1. Materials and Methods

The research is conducted in two phases. In the first phase, the hybrid DEM is created from multiple sources. The second phase is dedicated to modifications of the hybrid DEM according to the requirements of hydrodynamic modeling. The procedure applied in the research is roughly illustrated in Figure 1 and in more detail in Figure 2. The input data comprise a publicly available DEM over Europe (EU-DEM), DEM of major channel above the water surface obtained from LiDAR scanning data, and DEM of minor channel created from the boatborne echo sounder and conventional land survey methods.

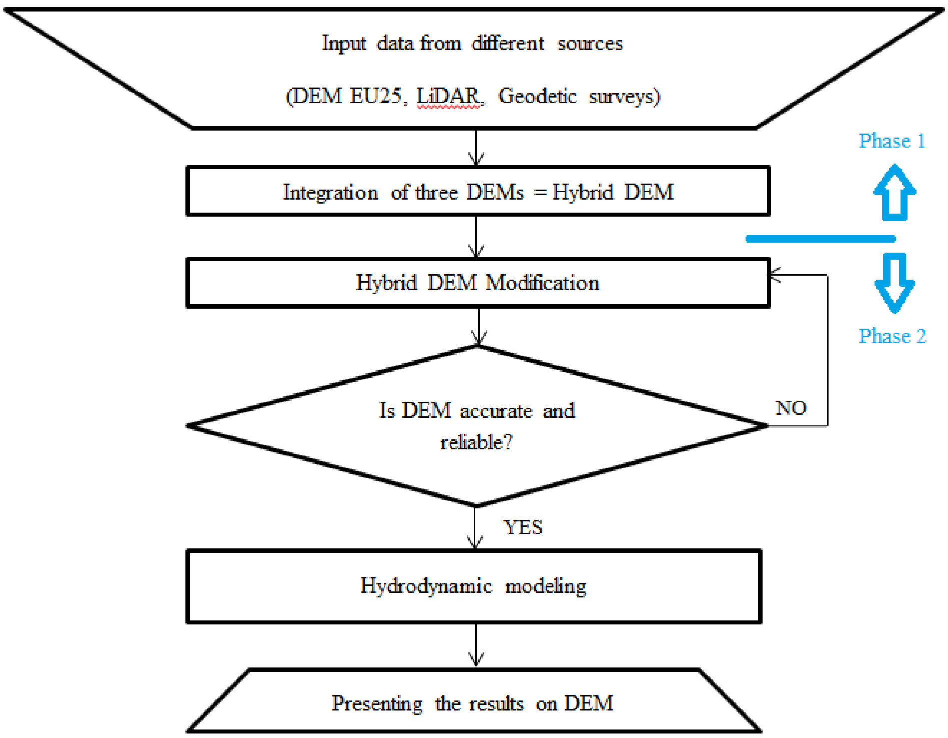


**Fig. 1** Flow chart of hybrid DEM creation and use

The form of hybrid DEM requires a precision, accuracy, and reliability check in order to be applied to a case study of the study area. These criteria are quantified in section 3. The applied method and process of generation of the hybrid DEM form, which can be used to generate geometry on 1D and 2D models and hydraulic calculations, is shown in Figure 2.

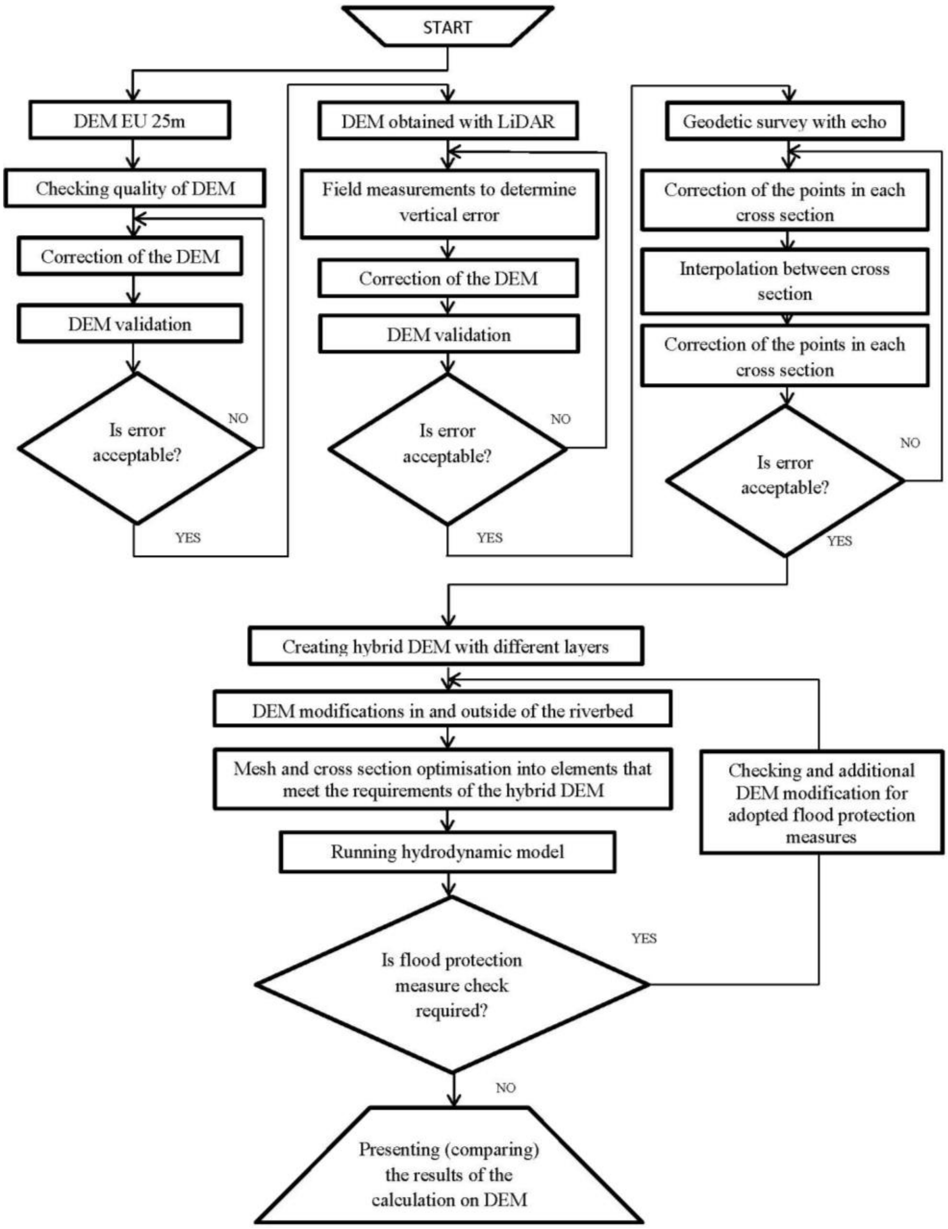


**Fig 2.** Methodology for hybrid DEM data preparation for interactive hydrodynamic modeling

### 2.2. Study area

The domain of the DEM and hydraulic analysis is the Tamiš River from the Danube River mouth (chainage: km 0+000.00), near the Town of Pančevo, upstream to the cross-section upstream of Baranda town (chainage: km 45+325.95), and the Karašac channel from the junction with the Tamiš River near Baranda to its inflow into the Danube River (Figure 3). On the analysed section the right-bank levee along the Tamiš River belongs to the Pančevački Rit flood defense system. On the left-bank, there are intermittent levees built from The City of Pančevo to Uzdin village.

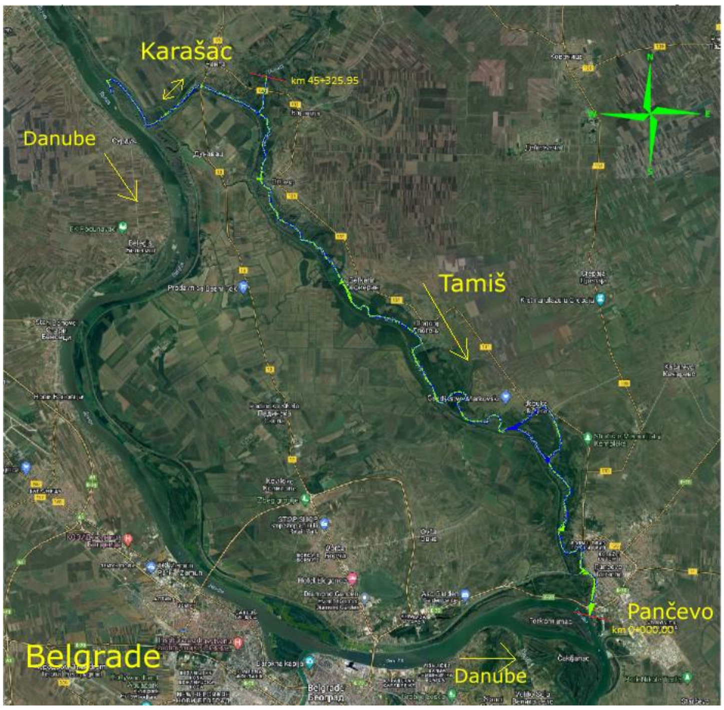


**Fig. 3** Spatial domain of the hydraulic model and the DEM [3]

## 3. Creation of Hybrid DEM

### 3.1. Phase 1: Acquisition of source data

*3.1.1. Digital elevation model EU 25 m*

The first source for the development of the hybrid DEM for hydrodynamic modeling is a publicly available European DEM with a horizontal resolution of 25 m obtained from the 2013 Copernicus project managed by the European Commission. The statistical validation of EU-DEM v1.0 documents a relatively unbiased (0.56 m) overall vertical accuracy of 2.9 meters RMSE, which is fully within the contractual specification of 7 m RMSE. For the teritory of Serbia achieved RMSE is 3.18 m and mean error (ME) is -2.65 m. [8, 14].

Using the ArcMap software, the territory of the Republic of Serbia was cropped out and used for further generation of the hybrid DEM.

The EU DEM of 25 m resolution does not provide sufficient details [2]. The distance between two neighboring points of 25 m is too large for the intended purpose, and thin linear shapes and structures cannot be clearly recognized on the model. Levees, local roads, railway infrastructure, streams and similar features less than 25 m wide, do not appear on DEM (Figure 4).

Due to the low resolution of the EU DMT 25 m in most cases, especially in the flat zones, it is difficult to properly set the axis of the watercourse. Larger rivers with a width more than 25 m, such as the Danube River can be identified on this DEM, while the streams or smaller watercourses are often not even identifiable. In wide valleys or in domains with a slight change in terrain elevation, EU DEM 25 m is a useful source for the preparation of hybrid DEM for river basin studies.

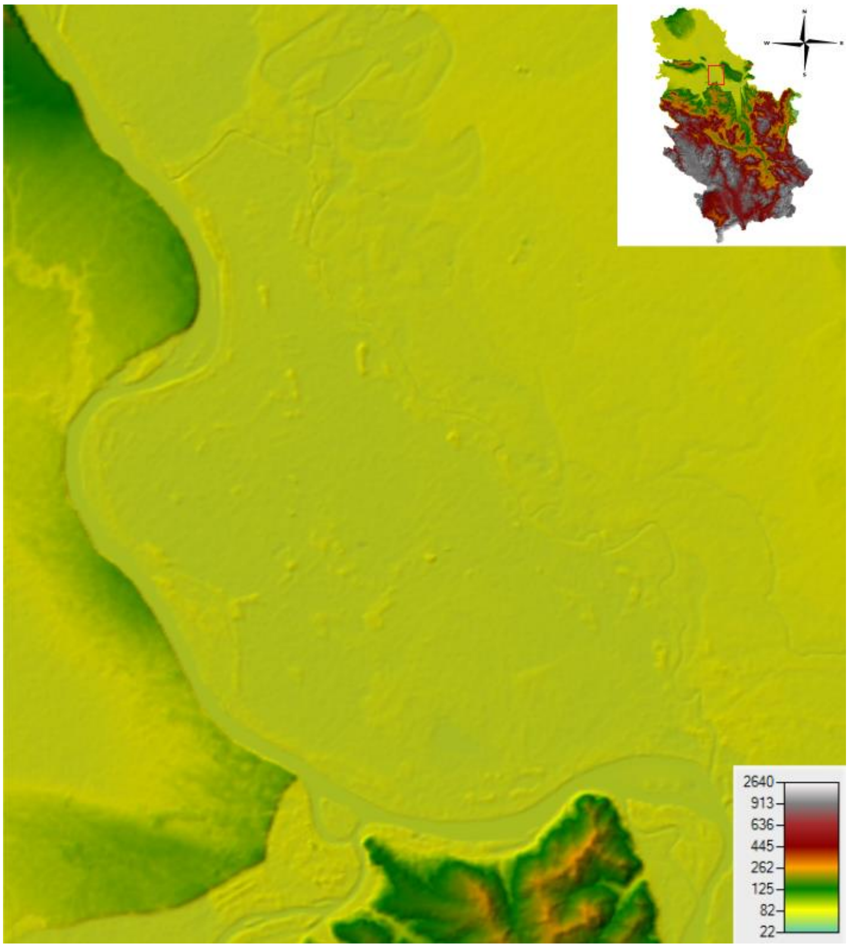


**Fig. 4** The case study area DEM with a horizontal resolution of 25 m

*3.1.2. Digital Elevation model obtained with LiDAR technology*

A targeted laser scanning campaign of the subject Tamiš River area was conducted. The LiDAR technology belongs to the field of remote sensing, it measures the distance to an object or the surface of the Earth via laser pulses. Technology itself is based on measuring the time of sending and returning the reflected signal. Consequently, the three-dimensional (x, y, z) coordinates of each point are obtained. As a result of this kind of survey, a large number of points are obtained, representing digital surface model (DSM). The DSM is then filtered – the features not relevant for hydraulic modeling in flat areas are removed, and a high accuracy DEM of the analyzed area is generated in raster format with vertical accuracy of 2 cm, confirmed by conventional land survey. That confirms that the DEM obtained from laser scanning is the source of high accuracy for the implementation of precise hydraulic calculations, flood simulation, and for visualisation of the obtained results.

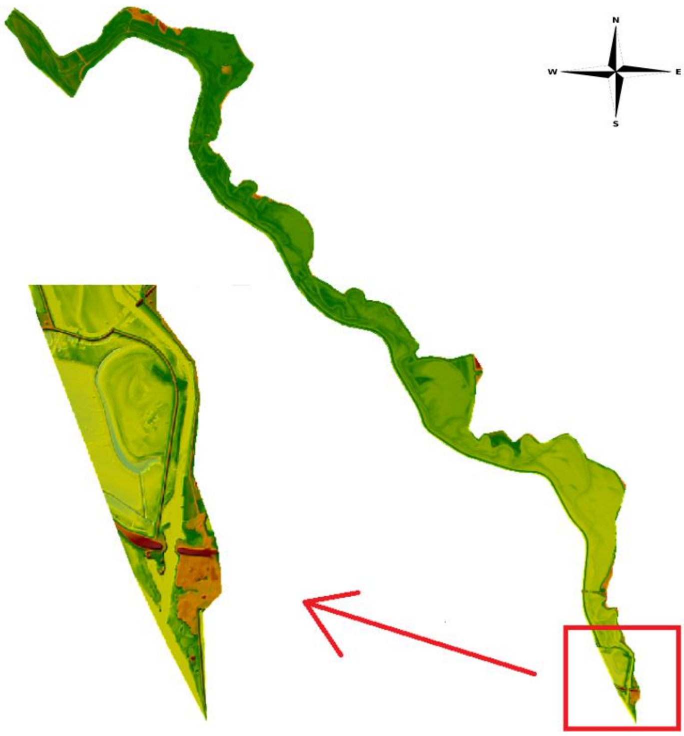


**Fig. 5** DEM obtained with LiDAR technology

Although the LiDAR technology provides high accuracy, there are known limitations to its application related to the surface type and moisture content – it cannot penetrate water surface or water saturated media.

The shape of the watercourse is clearly visible on the analyzed section (Figure 5), and the model shows the water surface elevation at the time of survey (Figure 5 and Figure 6 – red line) instead of the riverbed configuration.

### *3.1.3. Digital Elevation model obtained from Geodetic survey*

A field geodetic survey is performed for obtaining bathymetry data. A DEM that represents topography of seafloor or riverbed is also called Digital bathymetry model (DBM) [15].

Geodetic surveys of cross-sections were made from the natural Tamiš River estuary to the Danube River near the Pančevo Town, to the absolute stationing at km 45+325.95 and the entire watercourse of the Karašac from the junction with the Tamiš River to the junction with the Danube River (Figure 3). Parts of the cross-section were surveyed under water with echo sounder from the boat (Figure 6).

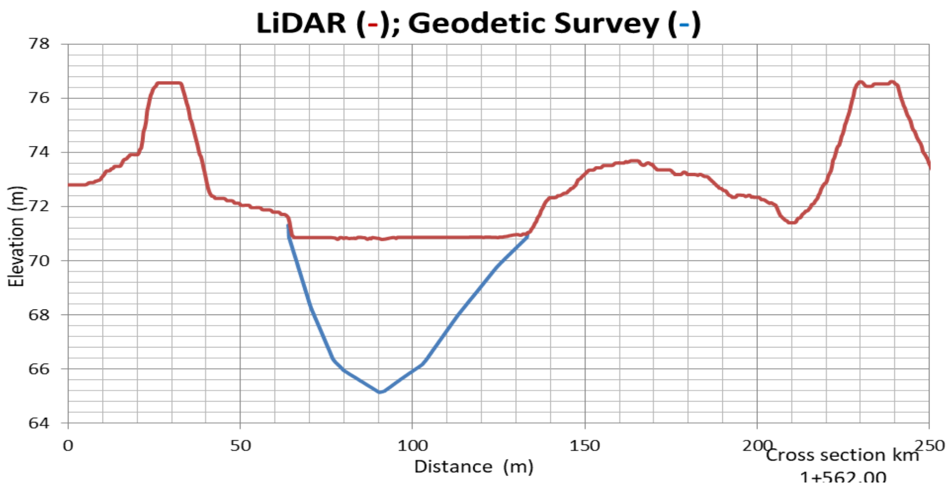


**Fig. 6** Cross-section surveyed with LiDAR technology and the boatborne echo sounder

The detailed conventional geodetic survey of the features representing internal boundary conditions for hydrodynamic modeling (bridges, gates, junction) is also conducted on both watercourses.

Because the scanning with LiDAR technology and echo sounder were not performed at the same time, the water surface level from these two sources differed. When scanning with an echo sounder during the water elevation lower compared to the one during LIDAR scanning, certain parts of the riverbed were not surveyed at all. This problem was overcome by linear interpolation between two neighbouring vertical points in a cross-section [16].

The number and location of surveyed cross-sections is time&cost optimized and it was not adequate for hydrodynamic modeling. Therefore, a longitudinal interpolation of the riverbed is performed in HEC-RAS with approximate distance of 100 m along the river axis between the interpolated cross-sections. In order for the interpolation to represent the real riverbed shape as accurately as possible, the bank points for interpolation were set for adjacent cross sections [12]. Figure 7 shows the position of the cross sections along the studied river reach used to create the raster bathymetry DEM.

**Fig. 7** Cross-sections in a part of the river reach used for creation of raster bathymetry DEM (RAS Mapper)

After the set of representative cross-sections was created in this way, a river bathymetry DEM (DBM) was generated in raster format with adjusted resolution of 10 cm, corresponding to the accuracy of the surveyed points with an echo sounder.

The RAS-Mapper automaticaly creates a DEM by taking altitude data from cross-sections using averaged elevation areas between them [12].

*3.1.4. Creating hybrid DEM with prioritization of layers*

The reference state coordinate system WGS 84/UTM zone 34N is used for all the three DEMs.

The hybrid raster DEM is composed in RAS-Mapper as a new terrain layer where all three DEMs are listed as input terrain files, prioritized, and the target vertical resolution is set to 10 cm [12]. Here, the lowest layer of the hybrid DEM is the 25 m resolution EU DEM, the next is the one obtained with LiDAR, and the final layer is river bathymetry DBM, the one constructed from a geodetic land survey. All DEMs are in the raster format. Stiching on the boundaries of different terrain layers is also performed within new terrain layer creation in RAS-Mapper, by triangulating surfaces between imported terrain models. The result is a continuous surface without peaks and sinks.

The quality of DEM was measured by comparing coordinates (x, y, z) of known points and corresponding points in DEM. Because of the terrain configuration in the study area, and built flood protection structures, the flow-accumulation image was not created and converted to main flow lines. The measures of the DEM quality are different in such cases and include number of broken flowlines, and average flow path displacement [17]. When fitting geodetic surveys of cross-section of the riverbed and levee points to LiDAR surveys, a hight consistency of 1-2 cm is found.

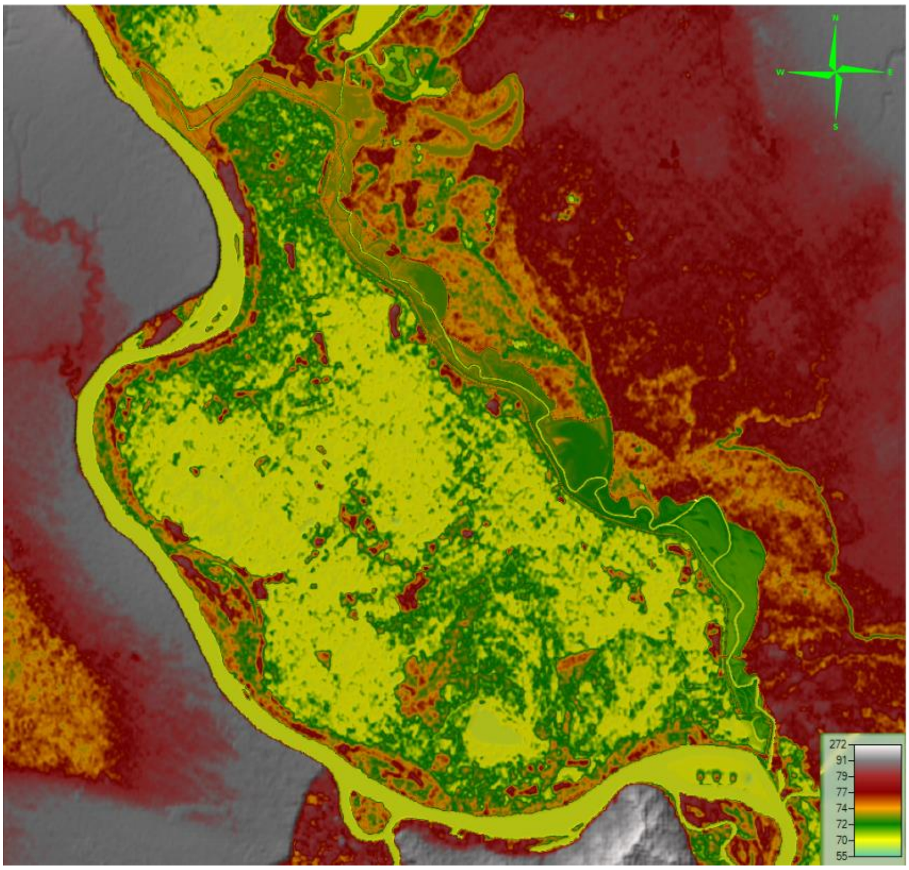


**Fig. 8** Hybrid multilayer DEM of the study area

### 3.2. Phase 2: Finalizing the hybrid DEM

In the final DEM creation phase, corrections and modifications are made to provide a complete study area presentation of the appropriate accuracy for hydrodynamic modeling in flat area: minimum requirements are 10 m x 10 m horizontal and minimum 0.5 m vertical resolution [5].

#### *3.2.1. DEM corrections and modifications to improve appearance of significant features*

RAS-Mapper in HEC-RAS enables the terrain modification. Parts of DEM which have not been well captured by the LiDAR were filled in using land surveyed data on high terrain elevations i.e. patched in the GIS module.

Based on the surveyed elevations of the infrastructure objects, a modification of hybrid DEM was performed on the clone terrain layer, as suggested in RAS Mapper

Users Manual and levees and main roads were included in it [18]. After the modification of the DEM on the part of the DEM that covers the EU DEM 25 m, the roads are clearly visible but discontinuous, while riverbed is continuous (Figure 9a). This is due to terrain modification by “high ground option” selected as terrain modification method in RAS Mapper [18]. Also, upon the geodetic survey data, piers and a lock (Figure 9b) were inserted near the Pančevo gate.

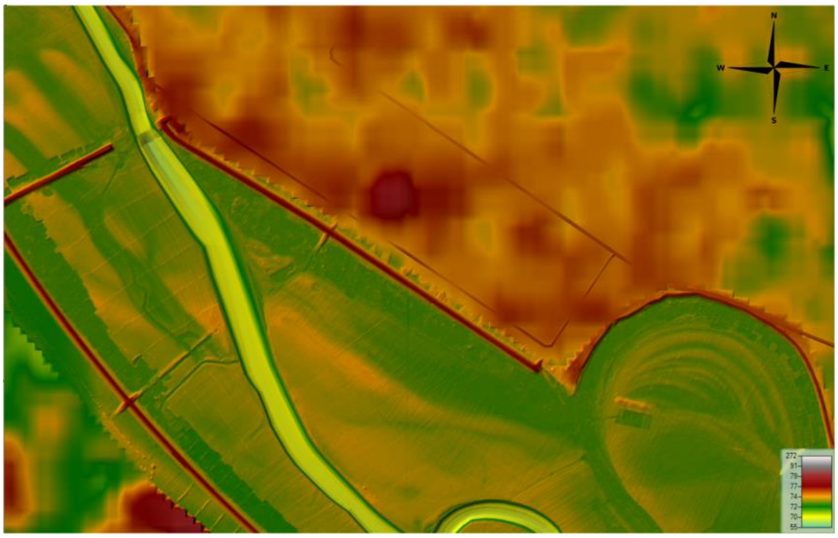

**Fig. 9a** Corrections of the DEM – the main roads added into the model

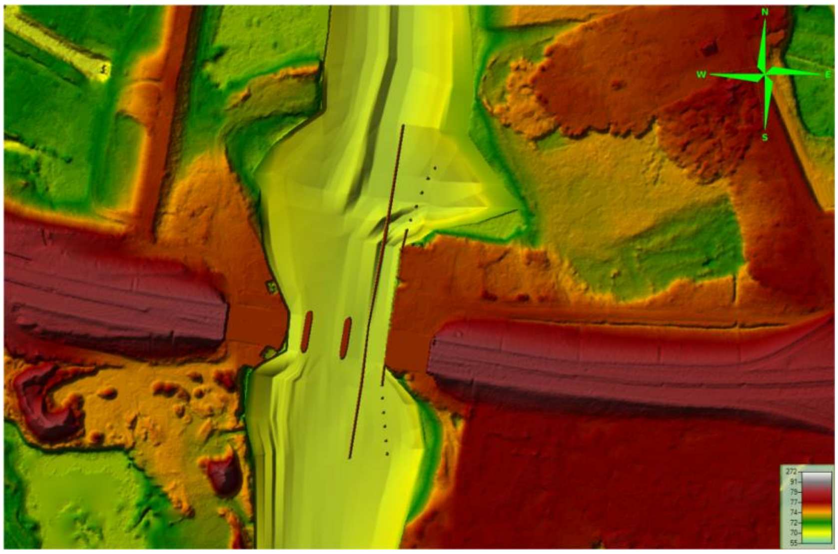

**Fig. 9b** Modifications on the DEM – lock and piers added

*3.2.2. DEM use in 1D hydraulic model*

The 1D hydraulic model requires geometric elements, i.e. computational cross sections, for establishing morphology functions and performing calculations between cross sections [19].

To have a stable numerical simulation, a larger number of cross sections than surveyed are required. Therefore, additional cross-sections are needed to provide the shorter distance (about 100 m) between them. The created hybrid DEM in its final form is used to generate cross-sections from the high elevation on the left bank to the right bank (Figure10). Due to the high resolution of DEM, there is a large number of points on the cross-sections. In flat inundations, such large number of points does not contribute to the accuracy of the calculation, but results in longer computational time. It is confirmed in this reasearch that reduction of the number of points in the cross-sections in flat inundation is recommended without any loss of the model accuracy [20].

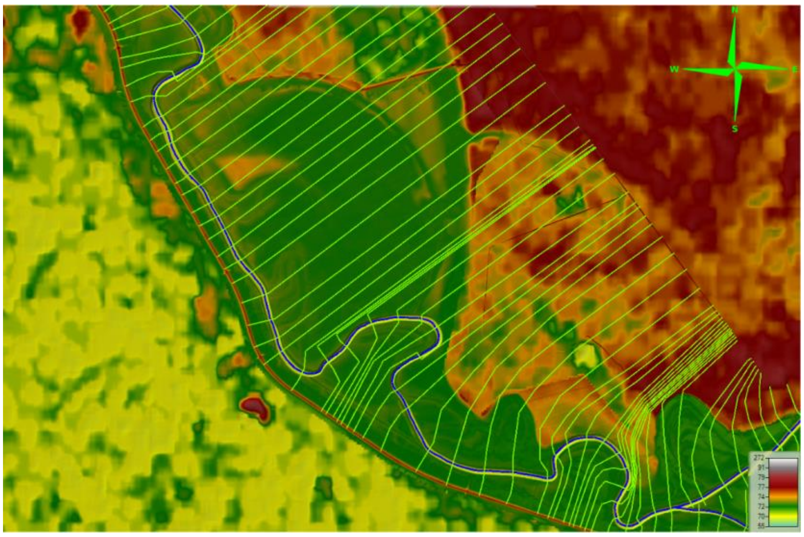

**Fig. 10** 1D model with generated cross-sections prepared for hydraulic calculations

*3.2.3. DEM use in 2D- hydraulic model*

The 2D hydraulic model uses computational mesh directly connected to the created hybrid DEM. The density of computational mesh cells reflects a change in elevation. Each cell size of the mesh can be considered a cross-section with its own detailed hydraulic characteristics.

In innudation, a high degree of calculation accuracy is achieved with 25 m x 25 m cell size. Smaller cell size and denser computational mesh contribute to a more precise calculation of fluid flow from one computational cell to another, which is required to provide at the locations of abrupt changes in the geometry of the riverbed and terrain. Here, in such places (levees, barriers, high terrain, roads), as well as in the main riverbed of the watercourses, the computational mesh is condensed and the size of cells from 2 m x 2 m up to 10 m x10 m is set (Figure 11).

If the cell size is not well set, it could happen that the levees are skipped in the calculation. The consequence is unrealistic flood in the protected and unprotected zone, as can be seen in the Figure 12. Figure 13 shows the difference between inapropriate and apropriate mesh generation at the location shown in Figure 12.

The total number of cells in the Tamiš computational mesh is 764,277 while the maximum cell area is 1,586.59 $m^2$, and the minimum is 1.61 $m^2$.

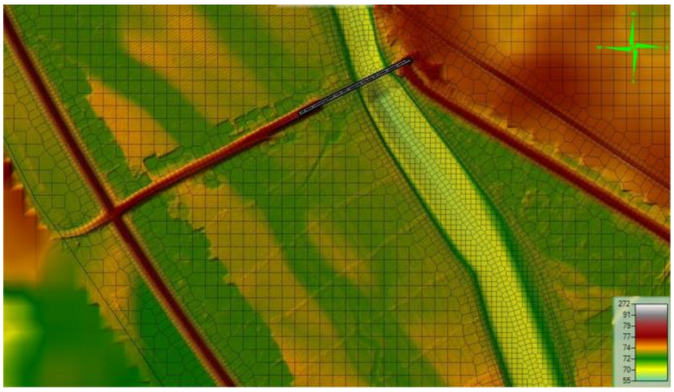

**Fig. 11** 2D model computational mesh - shape and size of cells

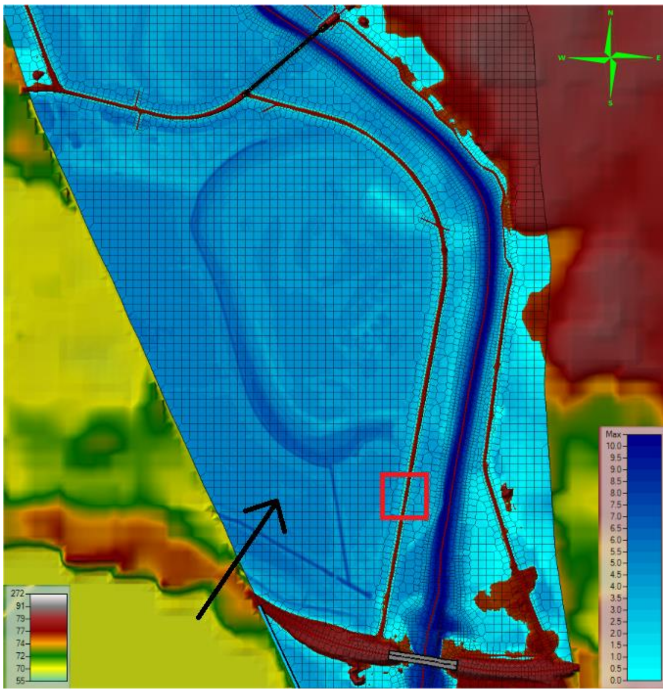

**Fig. 12** Unrealistic flooding (as shown by black arrow) due to an inappropriate cell size in the computational mesh

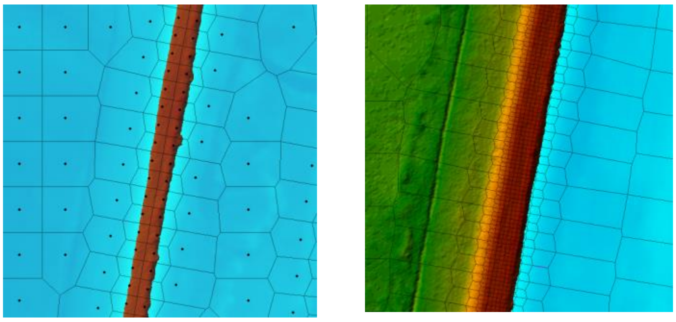

**Fig. 13** Computational mesh of red rectangle in Figure 12**:** Left – inappropriate generation, Right – appropriate generation

## 4. THE HYBRID DIGITAL ELEVATION MODEL AND OPTIMIZED HYDRODYNAMIC MODEL USE FOR FLOOD SIMULATION

Upon the creation of hybrid DEM and optimized model, use of the model for flood simulation and visual presentation of flood wave propagation (usually combined with satellite image), a valuable decision tool is obtained [3].

The flooded area obtained by the 2D hydraulic model simulation for 100-year flood in the study area is presented below (Figure 14). Hydraulic calculations have shown that there is no overflow of the right-bank levee of the Tamiš River when the 100-year flood occurs. On the left-bank, several settlements are endangered during the 100-year flood due to insufficiently high levees, or their absence. The locations where water overflows the levees are shown on the hybrid DEM in Figure 15 and Figure 16.

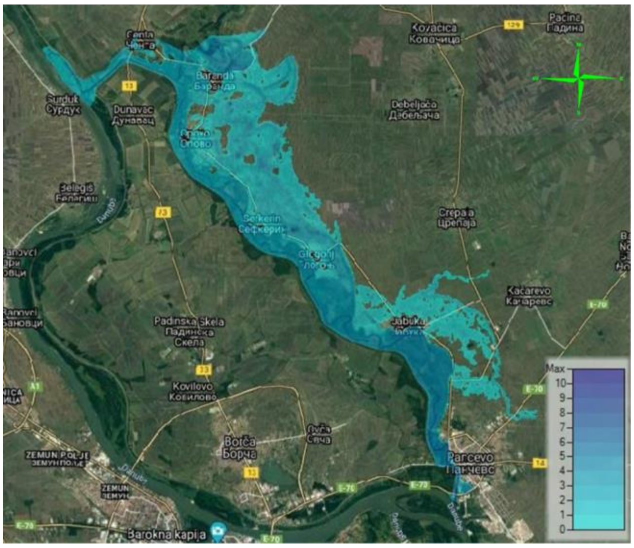


**Fig. 14** Flooded area for 100-year flood in the existing condition

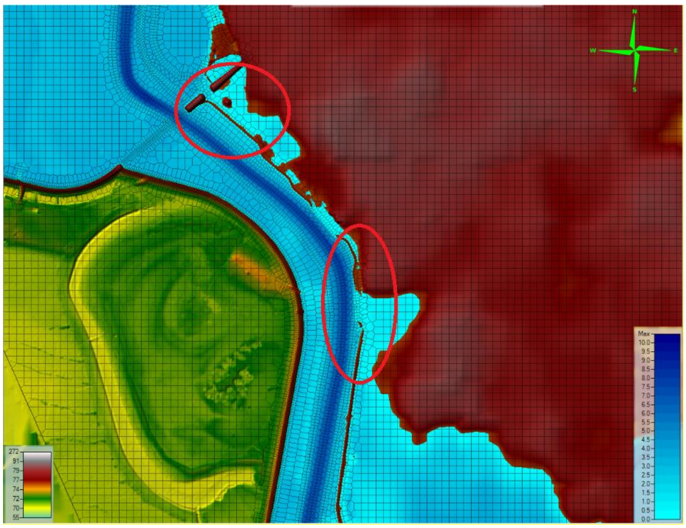

**Fig. 15** The downstream section of the study area - Locations where water overflows the levees during 100-year flood shown on hybrid DEM

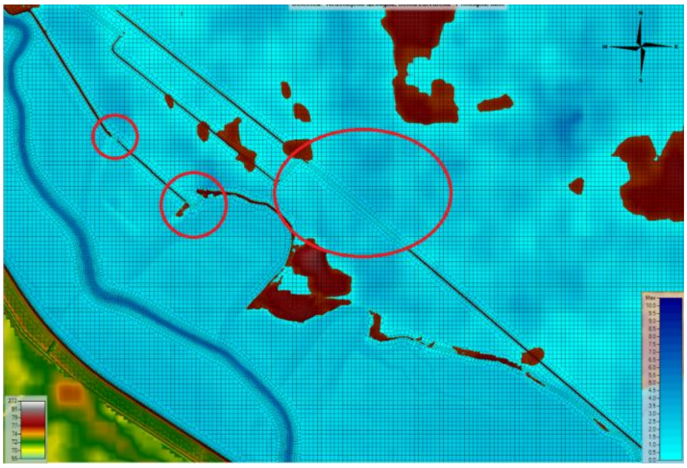

**Fig. 16** The midcourse section of the study area - Locations where water overflows the levees during 100-year flood shown on hybrid DEM

Based on the 100-year flood simulation results in the present conditions, it is proposed to raise the right-bank levee by 1 m from the calculated water level. The rise of the existing levees on both banks was simulated by inserting additional modifications in the hybrid DEM. The results of hydraulic calculations on the altered hybrid DEM with raised levees scenario are shown in Figure 17 on the satellite imagery. In this scenario, the raised levees provide protection from the 100-year flood in the study area.

**Fig. 17** 100-year flood scenario with crest of the levees raised as a proposed flood protection measure

## 5. CONCLUSION

This reasearch systematizes steps in DEM creation for hydrodinamic modeling. The methodology was demonstrted in the case study area of the Danube River bypass consisting of the Karašac channel and the Tamiš River in Serbia. Considering the relevance of terrain configuration in hydrodynamic modeling, the accuracy of DEM is crucial for flood modeling. A hydraulic model based on low accuracy DEM would produce unrealistic results and may lead to wrong conclusions in both research and engineering applications. The methodology shown in the case study, consisting of a series of actions related to the preparation and processing of different elevation data, depicts one of the most difficult scenarios in digital elevation modeling.

A hybrid DEM was created in GIS environment (Arc Map, RAS Mapper) using EU DEM, LiDAR, geodetic land and bathymetry surveys as elevation sources. The 1D and 2D HEC-RAS hydrodynamic models are built by using a hybrid DEM as geometric input data source.

Based on the described methodology for phase development of DEM for hydraulic calculations, the following can be concluded:

1. The EU DEM at 25 m resolution is coarse to recognize thin linear shapes including levees, roads, railway infrastructure, and smaller watercourses;
2. The DEM obtained with LiDAR technology provides high accuracy. The research shows LiDAR levees elevation matches the elevation obtained by the field geodetic surveys at the accuracy of 1-2 cm. A large number of points on LiDAR based DEM on the other hand, sometimes overloads hydrodynamic simulations, and it is necessary to reduce the number of points in cross-sections. The main disadvantage of the LiDAR DEM is the inability to show the riverbed below the water surface,

and provide the inner geometry of the structures over the watercourse, relevant for flow simulation;

3. The geodetic surveys by echo sounder from the boat and land surveys of all structures crossing the riverbed, enables DEM finalization by providing the DBM or Bathymetry DEM (geometry of the riverbed under the water);
4. The hybrid DEM consists of prioritized DEM layers created from three data sources. With its modification for insertion of hydraulic structures and infrastructure (bridge piers, locks, levees, roads) it provides a precise elevation data source for generating a 1D and 2D hydrodyinamic model specific geometry;
5. The hybrid DEM can be further modified for simulating various flow conditions and flood protection measures.

Appart from measuring hybrid DEM quality by comparing coordinates of known points, other measures targeting hydrodynamic modeling should be considered. Future research steps should include flow accumulation image analysis by conversion to main flow lines and selection of adequate hybrid DEM quality measures.

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# FAZNA IZRADA DIGITALNOG MODELA VISINA ZA HIDRAULIČKO MODELIRANJE U RAVNIČARSKIM PODRUČJIMA

*Hidrauličko modeliranje rečnih tokova i simulacije poplavnih događaja zahtevaju dostupnost geometrijskih podataka koji dovoljno precizno opisuju morfologiju rečnog korita i inundacija. U zavisnosti od načina snimanja i prikupljanja podataka na terenu, kreiraju se digitalni modeli terena različite tačnosti. U radu je opisana metodologija izrade geodetskih podloga za potrebe hidrauličkih proračuna, analizu, sistematizaciju i interpretaciju dobijenih rezultata na primeru slivnog područja "Donji Tamiš". Objašnjene su faze izrade, prednosti i nedostaci dobijenih digitalnih modela visina različitim metodama snimanja, kao i primena kreiranih podloga za formiranje 1D i 2D hidrauličkog modela.*

Ključne reči: *Digitalni model visina (DMV), LiDAR, Hidrauličko modeliranje, Simulacije poplavnog događaja*