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Hydraulic analysis of unsteady flow in case of the Tribistovo dam break

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Abstract: This paper presents a hydraulic analysis of unsteady flow due to a possible dam break of the Tribistovo reservoir located in the Municipality of Posušje, Bosnia and Herzegovina. Flood wave propagation is calculated and flood maps are derived for different dam break scenarios. The methodology adopted for the development of the flood wave propagation model is based on the use of available tools for collection, processing and graphical display of geospatial data and tools for hydrodynamic modeling of transient flow. The selected approach is conservative and results are, as a rule, the worst case scenarios. Flood areas are obtained on the basis of hydraulic calculations with the most unfavorable assumptions: maximum water level in the reservoir, maximum inflow in the reservoir (with the return period of T = 10 000 years), instantaneous/gradual and total dam break, all of which result in extreme flooding.

Key words: flood wave propagation, dam break, Tribistovo reservoir

Hidraulička analiza nestacionarnog strujanja u slučaju rušenja brane Tribistovo

Sažetak: U radu je prikazana hidraulička analiza nestacionarnog strujanja uslijed mogućeg rušenja brane akumulacije Tribistovo smještene u općini Posušje, Bosna i Hercegovina. Propagacije poplavnih valova proračunate su za različite scenarije otkazivanja brana. Metodologija usvojena za razvoj modela širenja poplavnog vala temelji se na korištenju raspoloživih alata za prikupljanje, obradu i grafički prikaz geoprostornih podataka i alata za hidrodinamičko modeliranje nestacionarnog strujanja. Odabrani pristup je konzervativan i rezultati su u pravilu najgori scenariji. Poplavne površine su određene na temelju hidrauličkih proračuna s najnepovoljnijim pretpostavkama: maksimalni vodostaj u akumulaciji, maksimalni dotok u akumulaciju (s povratnim razdobljem T = 10 000 godina), trenutno/postupno i potpuno rušenje brane, što rezultira ekstremnim poplavama.

Ključne riječi: propagacija poplavnog vala, rušenje brane, akumulacija Tribistovo

1. INTRODUCTION

Dam break is a low probability event that does not happen very often, but is very dangerous and with catastrophic consequences if it does happen. In recent years, the number of dam failure cases reported in the world has been decreasing, and it is mainly cases of failures of small dams that have been reported. Earth and rock fill dams usually fail if water flows over the dam body or due to insufficient discharge capacity of the dam outlet structures. A dam break poses a serious hazard to residents and properties downstream of the dam. A comprehensive approach to disaster management, which includes disaster prevention, mitigation, alerting, rehabilitation and reconstruction, is important to eliminate or mitigate potential adverse impacts due to dam failure.

Experiences gained through recorded cases of dam breaks show the importance of flood wave propagation analysis as a basic research work required for spatial planning of downstream areas, which also includes the development of population evacuation plans and measures and activities needed to protect settlements, economic and other assets as well as natural resources.

This paper presents a hydraulic analysis of water flow due to possible failure of the Tribistovo reservoir dam located in the municipality of Posušje, Bosnia and Herzegovina (OKON, 2018). Hydraulic analysis of flood wave propagation was performed for different dam failure scenarios. The methodology adopted for the development of the flood wave propagation model is based on the use of available tools for collection, processing and graphical presentation of geospatial data and tools for hydrodynamic modeling of unsteady flow caused by dam failure. The selected approach is conservative and results are, as a rule, the worst case scenarios. This means that the most unfavorable boundary conditions were selected in the calculations: maximum water level in the reservoir, maximum inflow into the reservoir (return period T = 10,000 years), immediate/ gradual and total dam failure, resulting in extreme floods.

2. MATERIALS AND METHODS

2.1 The study area

The Tribistovo reservoir was formed on the Ričina watercourse. The area of the municipality of Posušje is 461.1 km², and according to the results of the 2013 census, 20 settlements of the municipality are inhabited by a population of 20,477 (ENOVA, 2016).

The subject area is located on the border of the Mediterranean and temperate continental climate, while in the mountainous area, the area of the Blidinje Nature Park, there is an influence of the mountainous climate. Temperatures range from -15 °C to +35 °C. Summers are long, warm and dry, and winters are short and mild with heavy precipitation, usually rain, but also some snow. The average annual precipitation is about 1500 mm, but with pronounced irregularity over time (ENOVA, 2016). The relief is hilly and mountainous and encompasses four terraced karst plateaus: Posuško and Virsko Polje, Tribistovo, the pearl of Rakitno, and the mountainous area around Blidinje Lake.

The geological structure is dominated by stratified limestone and dolomite, and massive to thickly stratified limestone, dolomite, limestone breccia and chert. This area belongs to the geotectonic unit of the Outer Dinarides, or the high karst zone with specific surface and underground hydrogeological relationships as a result of joint action of tectonics and geochemistry. The hydrogeological uniqueness of this karst basin is the result of the deep and exceptionally strong regional karstification, which causes the development of extreme karst forms, as well as the development of a complex system of underground channels (Bonacci et al., 2013).

The most significant registered earthquakes near the Tribistovo reservoir are the earthquake in Počitelj from 1 August 1907. with magnitude M = 5.7 and intensity in the epicenter I = 7 MCS, and the earthquake in Imotski of 15 March 1923, with magnitude M = 6.2 and intensity between 8 and 9 on the MCS scale (Trkulja, nn). In this zone, earthquake hypocenters are at depths between 2 and 22 km. According to the prognostic map of seismic intensities in BiH for a period of 100 years based on the MCS scale (Brlek, 2016), the subject area is in the vicinity of a focal zone in which earthquakes of very high intensity are expected. According to the seismological map of the wider region for a return period of 500 years (INTEGRA, 2017) this area is on the transition between zones 8 and 9 according to the MCS scale.

In hydrological terms, the primary characteristics of the Posušje Municipality area is that the surface hydrographic network is poorly developed. These are mainly intermittent surface flows, while the majority of runoff from the basin occurs underground. The Ričina River, on which the Tribistovo reservoir is formed, is part of the Trebižat River basin.

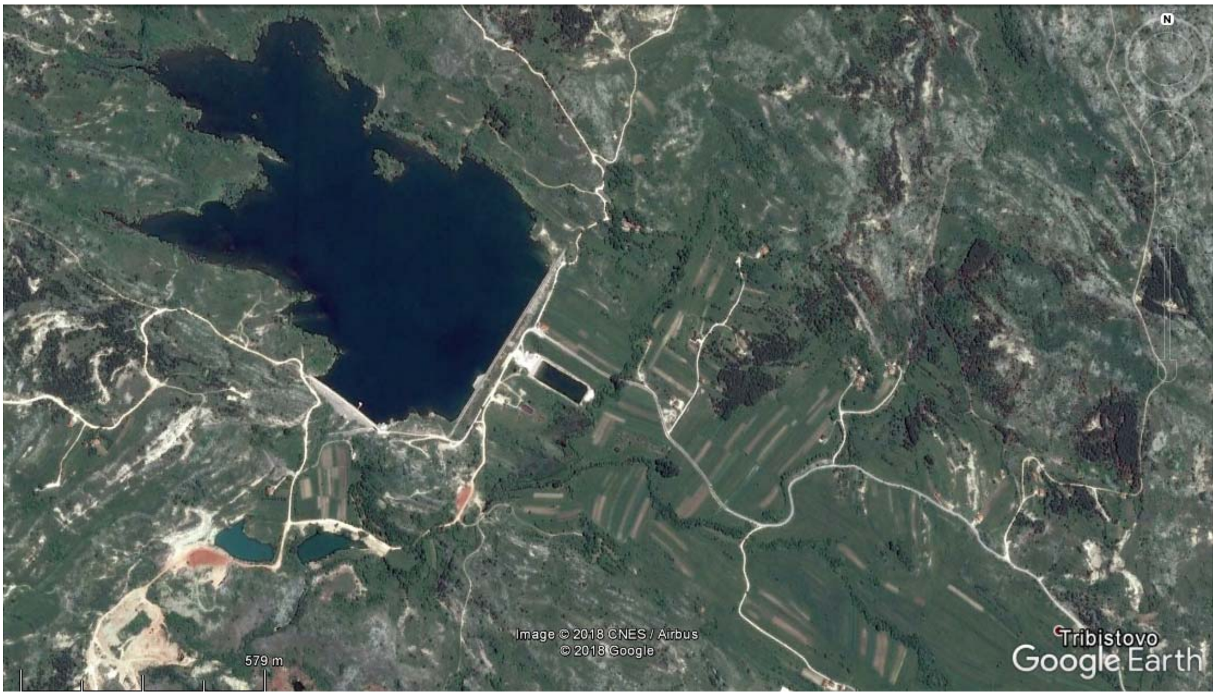

Figure 1. The Tribistovo reservoir (source: GoogleEarth)

The Tribistovo reservoir was formed in 1989 to solve the problems of water supply to the town of Posušje and other surrounding settlements. The planning documents also specify its use for the purposes of irrigation, energy and flood wave control. The reservoir was formed by constructing an earthfill dam with a construction height of 21 meters on the Ružički stream in the Ričina River basin and a barrier embankment with a construction height of 13 meters on part of the divide between the Močila stream and the Ružički stream (Figure 1). The reservoir is located northeast of Posušje at a distance of about 7 km. The artificial storage lake Tribistovo has a water table area of 700,000 m^2. The total lake volume at a normal backwater elevation of 913.50 m a.s.l. is $5x10^6$ m^3, of which the usable volume is 4.5 million m^3, and the rest is planned for sediment deposition.

The dam is built of rock fill with an upstream reinforced concrete screen. The dam crest is at an elevation of 915.50 m a.s.l., its length is 234.10 m, while the total width is 4.00 meters. On the left side of the dam, there is a spillway and a chute for evacuation of high water. The barrier embankment is on the left side of the reservoir and separates it from the lateral depression. The embankment is formed of rock fill with clay core and does not have a grout curtain. The elevation of the embankment crest is at 915.50 m a.s.l., while the length of the embankment crest is 548.50 m.

Lake levels range from 906 m a.s.l. to the designed water level in the reservoir of 913.50 m a.s.l. + depth of water flowing over spillway (up to approx. 0.5 m). The absolute highest water level so far was recorded in 2005 and was 913.99 m a.s.l. The reservoir has never been completely emptied. In winter, water from the reservoir regularly overflows.

On the dam and barrier embankment of the Tribistovo reservoir, the following measurements are specified by the technical monitoring project and are performed: water level in the reservoir, displacements of control points in horizontal and vertical direction, seepage water, groundwater levels, visual observations of buildings structures and soil, observation of banks and the catchments area of the reservoir. Air temperature and precipitation are monitored at the town's HM station in Posušje. Icing of the reservoir is not recorded.

2.2 Adopted methodology

The methodology for determining flood hazard maps due to possible dam failure can be shown schematically:

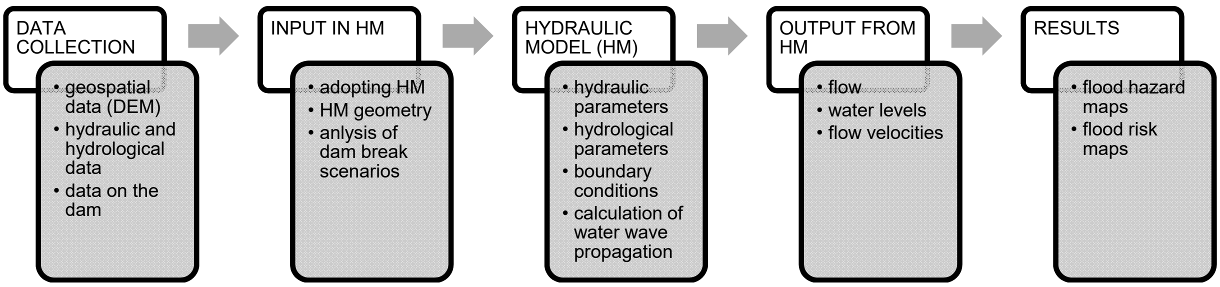

Figure 2. Schematic view of the adopted methodology

The adopted methodology is based on the use of available tools for collecting and working with geospatial databases and their graphical representation, and tools for hydrodynamic modeling of flow under unsteady conditions prevailing in flow caused by a dam break. Data on topography, hydrology and hydraulic data, data on dam materials and geometry are collected and processed in order to establish a hydraulic flood wave propagation model in case of dam failure.

The model of flood wave propagation caused by the dam break must take into account:

- Flood wave modeling upstream of the dam
- Dam break modeling
- Modeling of flood wave propagation downstream of the dam

Flood wave modeling upstream of the dam can be performed by 1D or 2D analysis of unsteady flow or by some other calculation method of flood wave propagation. Estimation of dam break location, dimensions, and development time are the key parameters for any risk assessment because they directly affect the assessment of peak outflow and alert time. Unfortunately, these are often the parameters with the most uncertainty. They can be estimated using comparative analysis, regression equations (Froehlich, MacDonald and Langridge-Monopolis, Von Thun and Gillette, Xu and Zhang, etc.), velocity (or shear stress) in relation to the development of erosion or physically based computer models (BREACH). Modeling a flood wave propagation downstream of a dam is the most important part of the analysis of dam break risk assessment.

2.3 Available data

The following were used as input data for the calculations: i) geodetic data, ii) hydraulic and hydrological data and iii) dam data.

In the first step, geodetic data are used to form the geometric boundaries of the hydraulic model. Geospatial data were manipulated using Q-GIS software, in which preparations were made for import of the necessary geospatial data into the hydraulic model HEC-RAS. The Digital Elevation Model (DEM) with a resolution of 5m x 5m was used for calculations for the analyzed area. The data on the dam were used when choosing the mode of dam break, setting restrictions, or, the boundary conditions of the model, as well as transformation of hydrological data (hydrographs). The Institute of Water Management from Sarajevo developed hydrological databases that were used for preparation of project documentation for the Tribistovo reservoir, and the subject hydrological databases were used in this paper as inputs into the hydraulic model. Hydraulic and hydrological data are related to reservoir volume, water wave hydrographs, Manning's coefficients and other parameters required in the hydraulic model.

2.4 Dam break scenarios

Failure of a large dam can be caused by a wide range of reasons, of which the following can be singled out: design errors (undersizing parts of the dam structure related to stability due to the characteristics of foundation soil and input hydrological parameters), dam construction flaws (non-compliance with standards and quality of materials prescribed by the design), inadequate technical maintenance and implementation of supervision of the main parts of the dam and accidental extreme events such as earthquakes, landslides, war effects, etc.

Failure mode of a large dam is primarily a function of its technical characteristics, and especially the type of material (earth fill, concrete, etc.) and structural solution (gravity, arch, etc.). Possible failure scenarios are defined in this respect, primarily because of the method of determining the form and time of dam break. These conditions determine the input parameters that form the basis for the development of a dam failure model and monitoring the propagation of the flood wave resulting from the dam break. (Sopta et al., 2011)

Earthfill dams are often built due to the low construction costs and for preservation of the natural appearance of the site. The main reason of failure of earthfill dams is overflow over the dam body, which most often results from extreme flows in combination with failure of spillway bays due to insufficient dimensions or failure of gates (Bjerke, 2011). The following table shows the possible failure modes of different dam types.

Table 1. Possible failure modes of different dam types (Brunner, 2014)

Failure mode	Earth fill	Concrete gravity	Concrete arch	Concrete buttress	Concrete multiarch
Overflow	X	X	X	X	X
Leakage	X	X	X	X	X
Defects in foundations	X	X	X	X	X
Sliding	X	X		X	
Overturning		X	X		
Bursting	X	X	X	X	X
Equipment failure	X	X	X	X	X

The practice in developing a model of flood wave propagation caused by the failure of large dams so far has usually been by using extreme initial conditions (fully filled reservoir, instantaneous disappearance of a part of the dam body, with simultaneous occurrence of maximum flows) in conducted model simulations for input data, which results in large flooded areas and major damage.

The considered dam failure scenarios for which simulations will be conducted are the following:

- Instantaneous failure of the dam
- Instantaneous failure of the barrier embankment
- Gradual failure of the dam
- Gradual failure of the barrier embankment
- Instantaneous simultaneous failure of the dam and the barrier embankment

3. HYDRAULIC CALCULATION

3.1 Hydraulic model

Flow models can be classified according to the number of dimensions they simulate, according to the equations on which they are based, and according to the numerical schemes applied to solve these equations during the simulation. The selection of model depends on the user's needs, the topographic characteristics of the subject area and the flow conditions to be modeled.

The flow of a fluid with a free surface is described by Navier-Stokes equations:

$$\underbrace{\rho\left(\frac{\partial u}{\partial t}+u\cdot\nabla u\right)}_{1}=\underbrace{-\nabla p}_{2}+\underbrace{\nabla\cdot\left\{\mu\left[\nabla u+\left(\nabla u\right)^{T}\right]-\frac{2}{3}\mu\left(\nabla\cdot u\right)I\right\}}_{3}+\underbrace{F}_{4} \qquad (1)$$

where u is the fluid velocity, p is the pressure, ρ is the density and μ is the dynamic viscosity. The first term of the equation corresponds to inertial forces, pressure forces are represented by the second term, viscous forces by the third term, and external forces acting on the fluid by the fourth term.

Navier-Stokes equations represent the conservation of momentum, and they are solved together with the continuity equation, which represents the law of conservation of mass:

$$\frac{\partial p}{\partial t}+\nabla\cdot\left(\rho u\right)=0 \qquad (2)$$

These equations are the foundation of fluid flow modeling. The values of velocities and pressures within a given problem geometry are determined by solving them with particular boundary conditions. Since Navier-Stokes equations, because of their complexity, can only be analytically solved for a limited number of simple problems, they are solved numerically instead, and some assumptions are often introduced for their further simplification. Thus, by introducing free surface conditions and averaging the velocity over depth, the Navier-Stokes equations are reduced to a 2D shallow water model determined by Saint Venant's equations. Saint Venant's equations consist of the equation of the law of conservation of mass and the equation of the law of conservation of momentum for an unsteady 2D flow which, in the absence of fluid sinkholes and springs, are (Sopta et al., 2011):

$$\begin{aligned} &\frac{\partial(v_x h)}{\partial t}+\frac{\partial}{\partial x}\left(v_x^2 h+\frac{1}{2}gh^2\right)+\frac{\partial(v_x v_y h)}{\partial y}=gh\left(S_{bx}-S_{fx}\right)\\ &\frac{\partial(v_y h)}{\partial t}+\frac{\partial(v_x v_y h)}{\partial x}+\frac{\partial}{\partial y}\left(v_y^2 h+\frac{1}{2}gh^2\right)=gh\left(S_{by}-S_{fy}\right)\end{aligned} \tag{3}$$

$$\frac{\partial h}{\partial t}+\frac{\partial(v_x h)}{\partial x}+\frac{\partial(v_y h)}{\partial y}=0 \tag{4}$$

where h is the water depth, t is time, x and y spatial coordinates, v_x and v_y are velocity vector components averaged over depth, S_{bx} and S_{by} are bottom slopes in the x and y directions, and S_{fx} and S_{fy} friction slopes in the x and y directions calculated according to the expressions in which n is the Manning coefficient:

$$S_{fx}=v_x\sqrt{v_x^2+v_y^2}\left(\frac{n^{3/2}}{h}\right)^{4/3} \quad ; \quad S_{fy}=v_y\sqrt{v_x^2+v_y^2}\left(\frac{n^{3/2}}{h}\right)^{4/3} \tag{5}$$

Most models used for calculations of dam post-failure flow use 1D or 2D hydrodynamic models based on the numerical solving of Saint Venant’s partial differential equations that describe unsteady water flow in open streams.

The advantages of flow modeling with 1D models are reflected in simpler model formation, faster calculation and less data required. They can be used for river flows that do not have pronounced 2D effects or they are not relevant. They are most commonly used to model long sections of watercourses or watercourses with slightly variable cross-sections. In these cases, it can be assumed that the results of the 1D model will be comparable with the results of the 2D model. 1D models may also be used to describe some 2D flow conditions, however, this requires considerable skill and experience if a reasonable level of accuracy is to be achieved (Morris, 2000). Wherever flow cannot be described well enough with a 1D model, 2D models should be used.

The hydrodynamic model HEC-RAS (Hydrologic Engineering Center), which is used for calculating the unsteady flow and propagation of the flood wave caused by dam break, was selected for modeling the failure of the Tribistovo dam and barrier embankment. A more detailed overview of the selected hydraulic model is given below.

3.2 Model forming

Since a two-dimensional flow calculation model has been adopted in the work methodology, it is necessary to use a three-dimensional model of the terrain, with the highest possible resolution. The model geometry was formed using the available geodetic data, or a digital terrain model, with the resolution of 5mx5m. The model geometry also includes the input and description of the characteristics of structures, dams and reservoirs. A 2D calculation area was marked in the model and a mesh with 51,529 elements with an average size of 630 m² was generated within it. A graphical representation of the generated calculation mesh is given in the following figures.

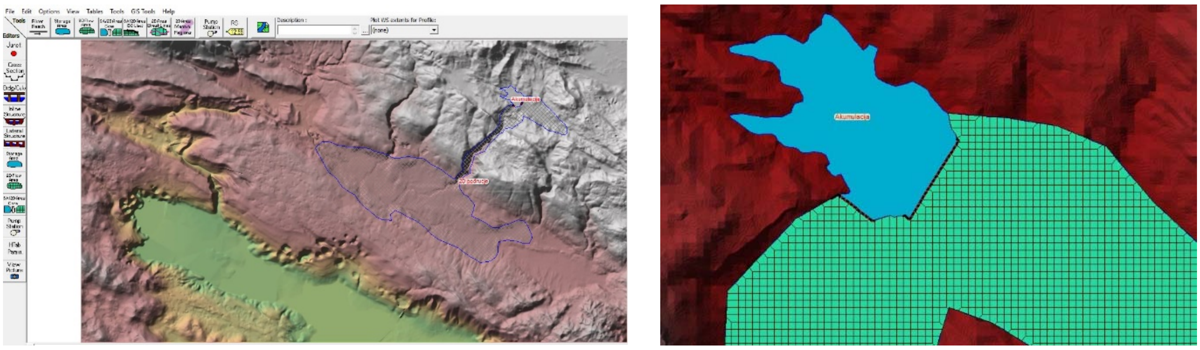

Figure 3. Left: map of the area with generated calculation mesh of the 2D model area; right: detail of the reservoir with the generated calculation mesh

After entering the geometric and hydraulic elements, and generating the calculation mesh, input of initial and boundary conditions was performed for the selected flow model, non-stationary flow; calculations were performed.

As already pointed out, the hydrodynamic model HEC-RAS was used in the paper, and the adopted approach of solving full 2D Saint Venant equations requires more computational power and thereby results in longer operation times. Avoiding numerical instability requires a finer mesh in the areas of 2D mesh where the profile or direction of flow rapidly changes. The model solver uses an implicit solving algorithm using the finite volume method that allows a larger computational time step. The calculation procedure is as follows: initial depth - water movement between elements calculated on the basis of initial depth and flow curve - new volume in the element determined on the basis of flow during the calculation time step - depth in each element determined from the curve volume-depth - new initial depth. This calculation algorithm is very robust and makes it possible for 2D elements to be filled with water or empty, so that it can describe a sudden appearance of water in the elements. Parts of the 2D mesh take into account the terrain levels within the elements by creating geometric and hydraulic property tables that represent the levels in relation to the volume of the elements and the levels in relation to the flow surface of the profile for each element. The mesh elements in the HEC-RAS 2D model therefore do not have a flat bottom or a single depth. Each cell surface is treated as a cross section for which detailed tables of hydraulic properties are determined. This allows the use of larger 2D mesh elements, without losing information about the actual characteristics of the terrain. HEC-RAS can only generate uniform 2D meshes (Brunner, 2016).

The course of calculations in the model is previously described, and the following figure shows the model results on the selected background, in this case on a digital terrain model of the considered area, in RAS Mapper, a tool for presenting calculation results.

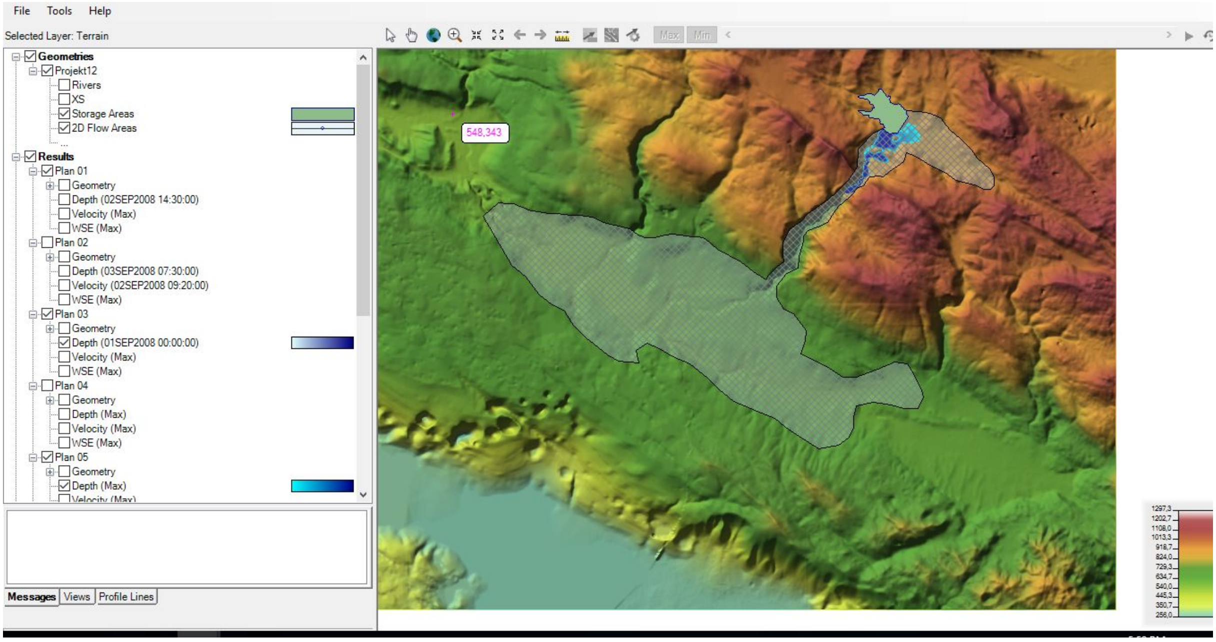

Figure 4. Calculation results with generated 2D calculation mesh of the model area

3.3 Results of the hydraulic model

Water levels, flows and flow velocities were obtained as model results. The hydraulic model results will serve as an input to GIS tools, in which the existing geospatial data (topographic maps, high-resolution satellite photos and digital terrain models) will be used to display the results of hydraulic calculations, thus producing the final results - floodplain maps. These maps should be used to prepare plans for disaster prevention and management of areas that may be affected.

Maps of flood zones are formed on the basis of calculation results and appropriate topographic or other geoinformation databases. Based on the maps, it is possible to determine risk maps and prepare plans for prevention and management of a disaster that may occur in case of dam failure for the areas that may be affected by the resulting disaster. Based on the risk maps, criteria and methods for declaring and implementing notification and alerting measures should be defined. The following is a view of the flood areas, or hazard maps for the considered cases of dam failure: cases of complete break of the dam and/or of the barrier embankment and cases of gradual break of the dam or of the barrier embankment. The results are shown on topographic maps.

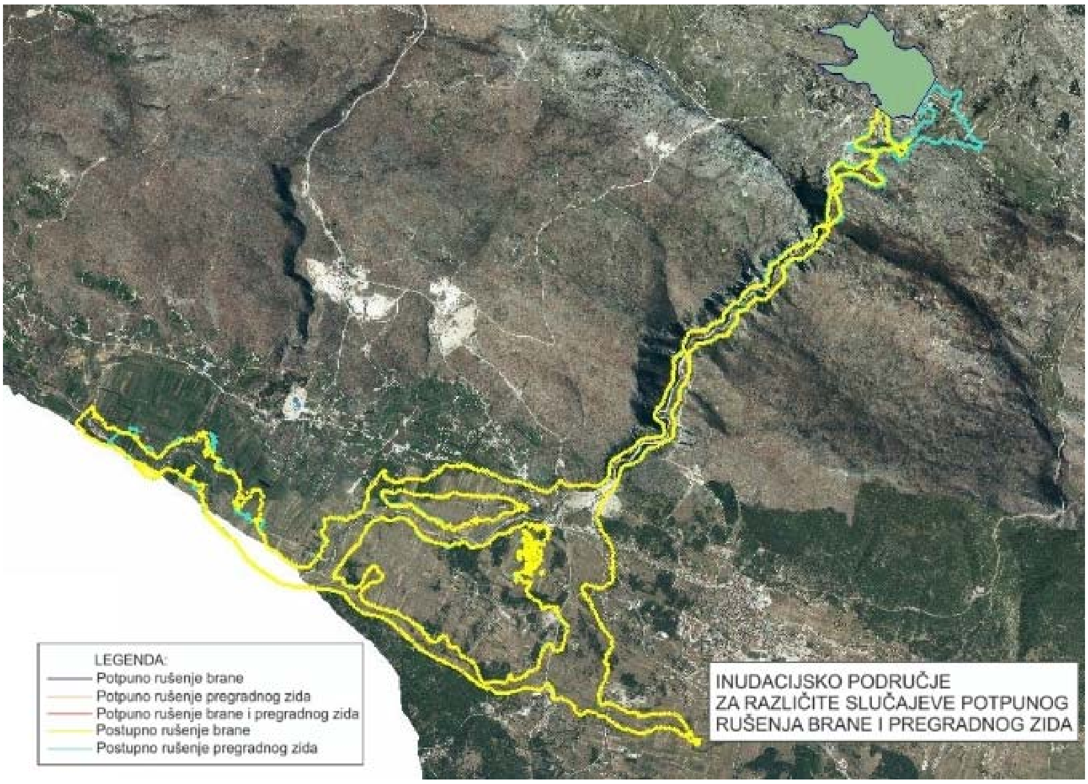

Figure 5. Limits of the flood waves from the hydraulic model for different dam and barrier embankment failure scenarios

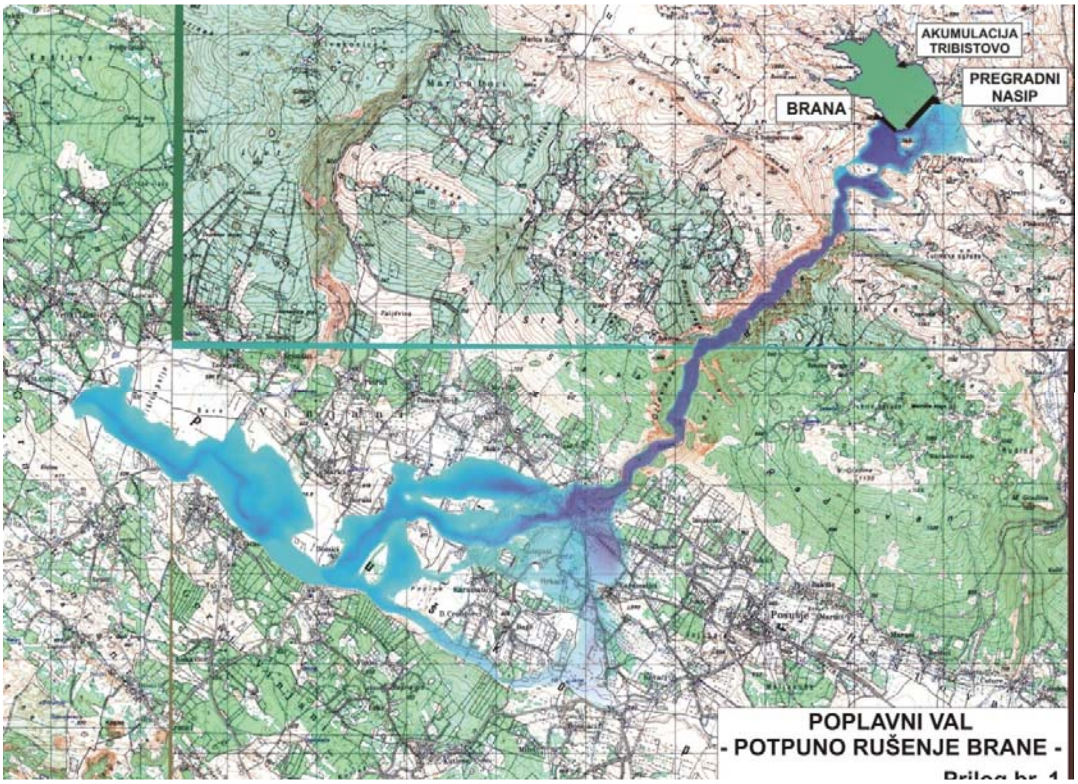

Figure 6. Flood hazard map for instantaneous and complete break of the dam

5. CONCLUDING CONSIDERATIONS

Calculations have shown that the travel time of the flood wave to downstream populated areas is very short, so that the possible time of action after the dam failure is very short. For this reason, it is necessary to focus on preventive measures, which include: constant control of the dam and static characteristics of the embankment and their regular maintenance, as well as establishment of an appropriate alarm system for critical water levels in the reservoir. It is necessary to organize continuous physical, geodetic, seismic, climatological and hydrological observations and measurements, and to perform analyses and interpretations of results and compare them with design parameters in order to determine possible changes and dam failure risks.

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