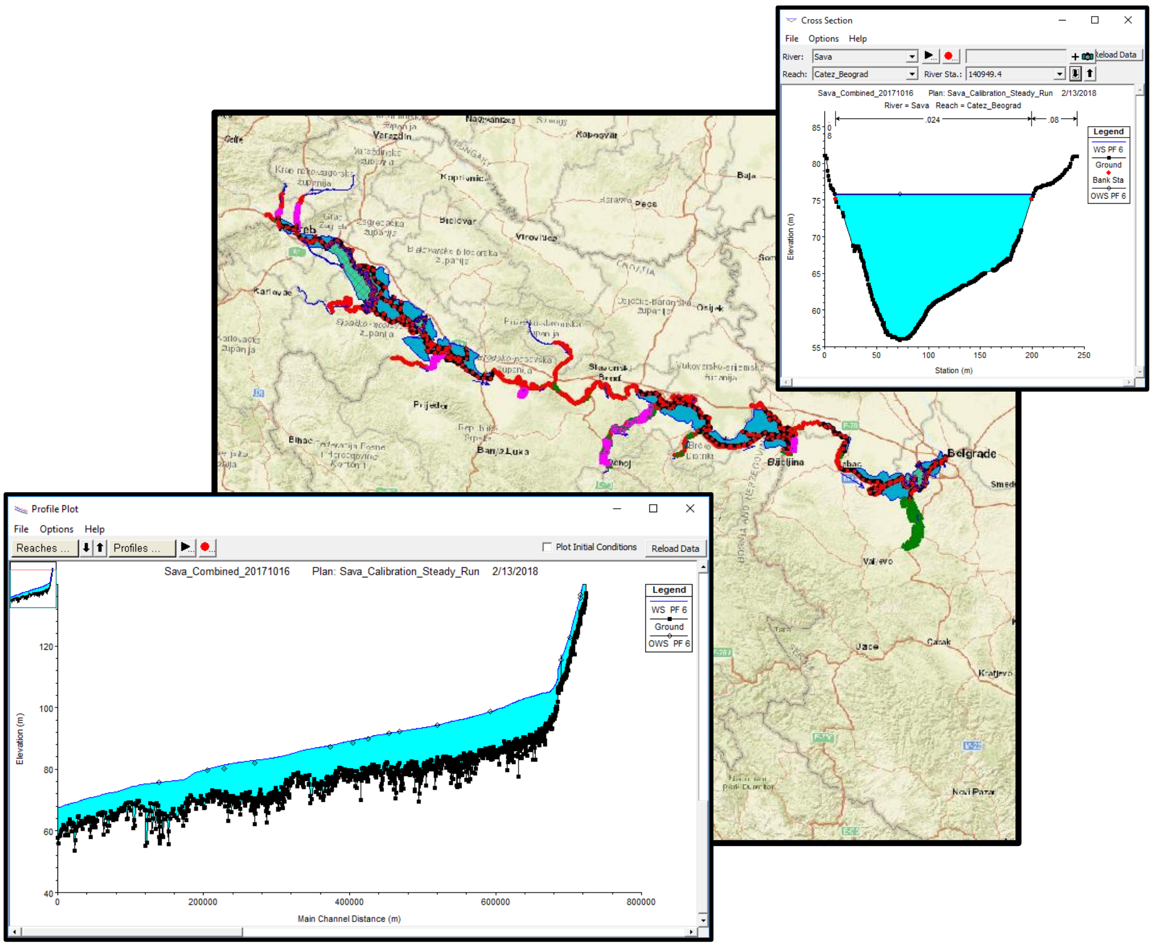
Sava River Basin Flood Study: HEC-RAS Technical Documentation Report

September 2018



INTERNATIONAL SAVA RIVER BASIN COMMISSION

US Army Corps of Engineers

US EUROPEAN COMMAND EUCOM

Table of Contents

List of Figures

List of Tables

1. INTRODUCTION

The International Sava River Basin Commission (ISRBC) is composed of the four Sava River Riparian countries, Bosnia and Herzegovina, Croatia, Serbia, and Slovenia, as the parties ratifying the Framework Agreement on the Sava River Basin (FASRB) in 2002. In addition, a Memorandum of Understanding on cooperation between the ISRBC and Montenegro was signed in December of 2013. The FASRB forms the basis for transboundary cooperation of governments, institutions, and individuals for sustainable development of the Sava River Basin (ISRBC 2016). The ISRBC, as a joint institution comprised of members from the ratifying countries, is charged with coordinating the implementation of the FASRB under a permanent Secretariat as its executive body (ISRBC 2016). The ISRBC provides political and economic stability within the area through its support of international navigation, sustainable water resources management, and hazard risk reduction within the river basin, which are the three main goals of the FASRB. The U.S. Government has an abiding interest in peaceful multilateral cooperation by the Sava River Basin nations to develop their water resources for mutual benefit, which is the underpinning goal of the relationship between the US and the ISRBC and member countries.

The ISRBC's Permanent Expert Group for Flood Prevention (PEG FP) is charged with developing a flood risk assessment methodology leading to joint identification of potential significant flood risk areas, preparation of joint flood risk and flood hazard maps, developing and implementing a flood risk management plan, and design and implementation of a joint flood forecasting and flood warning system. The overall goal of this project is to develop hydrologic and hydraulic (H&H) modeling to support these endeavors of the PEG FP.

Currently, the H&H modeling in the Sava region consists of a discontinuous collection of models developed using various software applications across multiple jurisdictional boundaries. The PEG FP desires to apply a systems-based approach to floodplain management and to develop H&H models of the Sava River Watershed that will be shared between the member nations. To aid the ISRBC and its member countries to achieve the goal of a system-wide H&H model, the U.S. Government is providing technical support through the US Army Corps of Engineers (USACE) by developing a comprehensive hydrologic model of the Sava River Basin and a hydraulic model of the Sava River. The models will be used to prepare flood inundation mapping and to support the flood forecasting system. Successful development of the joint Sava River Watershed H&H models will have a direct impact on international efforts to develop integrated flood hazard and risk maps, integrated data collection, and flood forecasting and warning systems, which will reduce vulnerability to natural, technological, and willful hazards.

The purpose of this document is to provide a general description of the hydraulic model development. The hydrologic model and associated data and documentation was provided to the ISRBC and its member countries in December 2016. The outputs from the hydrologic modeling serve as inputs in the hydraulic model discussed in this document. To attain the full H&H models, both the hydrologic and hydraulic model and associated documentation can be provided by the ISRBC. The hydraulic model product includes reaches of the Sava River Mainstem from the border of Slovenia and Croatia downstream to the mouth in Belgrade, Serbia. In addition, downstream reaches of several of the major Sava River tributaries are included in the hydraulic model. USACE has developed the hydraulic model for this project using the Hydrologic Engineering Center's River Analysis System (HEC-RAS) software. All HEC-RAS models are provided to the ISRBC and member countries in HEC-RAS version 5.0.3. Much of the hydraulic model geometry is built from light detection and ranging (LiDAR) collected in 2017, which was a separate project funded by the US Government's European Command (EUCOM).

1.1 AUTHORITY

The Humanitarian Assistance (HA) program is authorized by title 10 U.S.C., section 2561, and its projects are funded by the Overseas Humanitarian, Disaster and Civic Aid (OHDACA) Appropriation. Projects include the refurbishment of medical facilities, construction of school buildings, digging of wells, improvement of sanitary facilities, and training of host country personnel in internally displaced person and refugee repatriation operations, as well as in disaster relief and emergency response planning.

Cooperating agencies and nations participating in the Sava River modeling effort include: the ISRBC; Slovenia; Croatia; Bosnia & Herzegovina; Serbia; EUCOM; the U.S. Army; the U.S. Department of State; and USACE.

1.2 RIVER AND BASIN INFORMATION

The Sava River Basin (Figure 1) is a major drainage basin of the Danube River watershed, located in southeastern Europe with a total area of approximately 97,700 km^2, which comprises about 12% of the total Danube River drainage area. The Sava River also represents the third longest tributary and the largest discharge to the Danube River at approximately 945 km long and an average discharge of 1,700 m^3/s at Belgrade, respectively. The Sava River Basin is shared among six countries: Slovenia (12% by area), Bosnia & Herzegovina (39.2% by area), Croatia (26% by area), Serbia (15.5% by area), Montenegro (7% by area), and Albania (0.2% by area). The Sava River headwaters begin in the Slovenian Alps, draining through Croatia and Bosnia and Herzegovina to the confluence with the Danube River in Serbia. The Sava River Basin represents not only an important water resource for the region as a potential flood hazard, but also hosts outstanding biological and landscape diversity and provides a substantial contribution to the local economy through its navigation capability.

The Sava River Basin has endured several major floods in its history, most recently in May 2014 when several casualties and wide spread economic damages were experienced. To reduce flooding risk for the inhabitants of the basin, several structures and systems have been implemented including an extensive levee system and complex diversion and offline flood storage area system for attenuating damaging flood waves. These flood protection features are extremely important to the livelihood of the inhabitants in the region as most of the population resides within the historical Sava floodplains, which are flat and low-lying areas highly susceptible to flooding. Without the extensive flood protection system, widespread flooding would be endured much more frequently.

Figure 2 illustrates a conceptual schematic of the hydraulic modeling effort. The river reaches in blue indicate the reaches that were modeled using cross sectional geometry in HEC-RAS. The areas in green represent the various retention areas that make up the central Sava Flood Protection System. These areas were included in the schematic because they represent some of the complexities of the Sava River system. In addition to the features outline in Figure 2, the hydraulic model also includes other features such as lateral structures representing levees and stretches of high ground and additional storage areas representing the lower lying areas behind levees.

Figure 1: Overview Map of the Sava River Basin

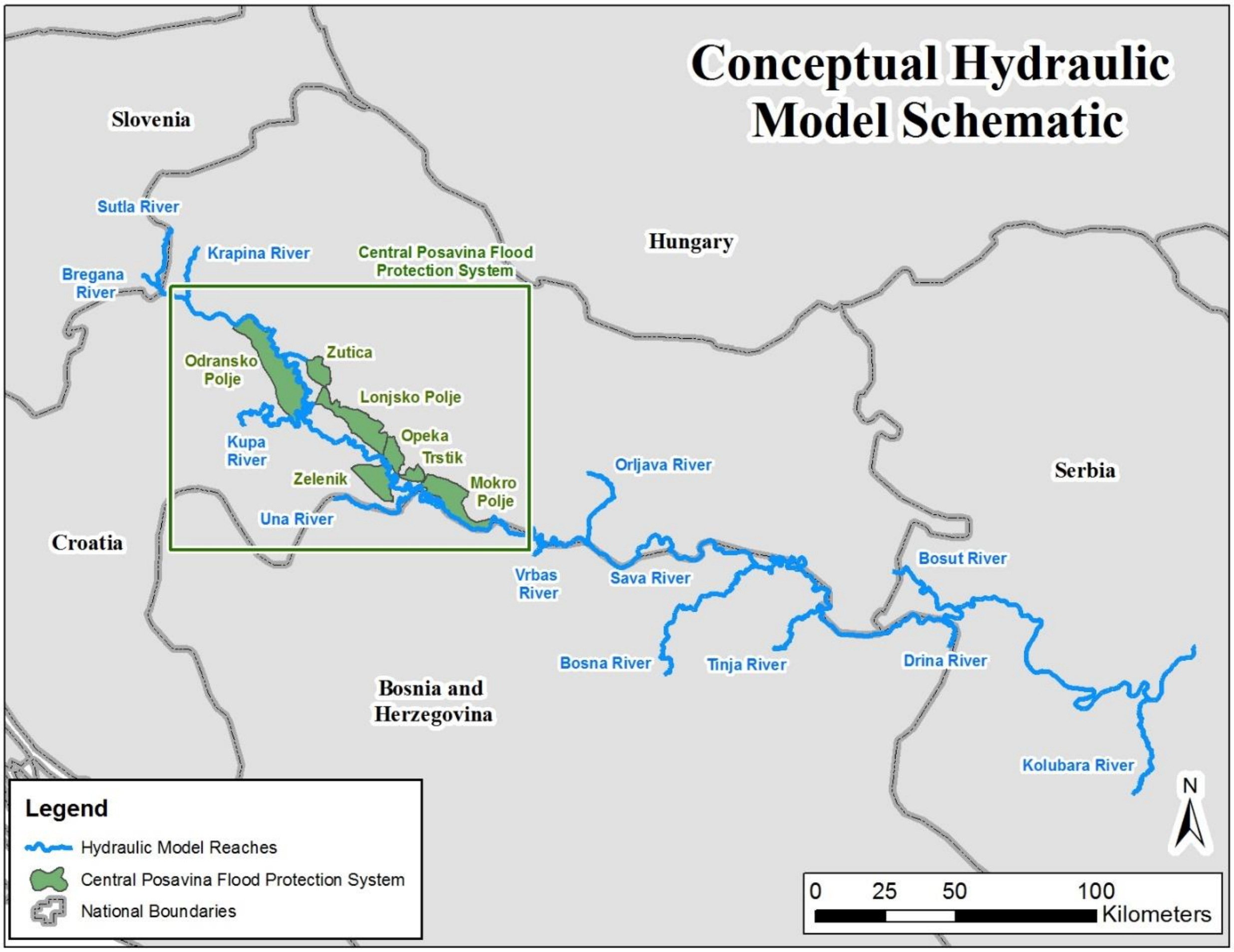


Figure 2. Conceptual Schematic of the Hydraulic Model

2. PRELIMINARY CONSIDERATIONS FOR MODEL DEVELOPMENT

The purpose of this section is to describe initial efforts performed as part of the hydraulic model development for the Sava River and tributaries. These initial tasks included: acquisition of existing modeling; extensive data acquisition; the conceptual design of the hydraulic model; the determination of possible storm event model calibration periods; and the establishment of calibration to evaluate model performance.

2.1 EXISTING MODELING

For many modeling efforts, the first step is to acquire any existing models that could be used to better understand the hydraulic characteristics of the system and to aid in the development of the model geometry. This hydraulic study relies on the collection of high-resolution LiDAR data, which is very valuable in defining model geometry in the overbank areas of the river system. However, LiDAR is unable to define the bathymetric or underwater portions of the model geometry, which is why existing modeling that includes bathymetrically surveyed cross sections is so important. This study is based on existing modeling from two sources: existing hydraulic modeling from Sava River riparian countries and modeling developed by USACE and ISRBC in the first phase of this study.

Over many years, the riparian countries of the Sava River have engaged in the development of various hydraulic models for various reaches of the Sava River and its tributaries using various computer modeling software. The ISRBC compiled any available modeling from the various riparian country sources and compiled the modeling for the Sava River and tributaries over the past several years. Once compiled, this existing modeling was reformatted and georeferenced to be imported into HEC-RAS.

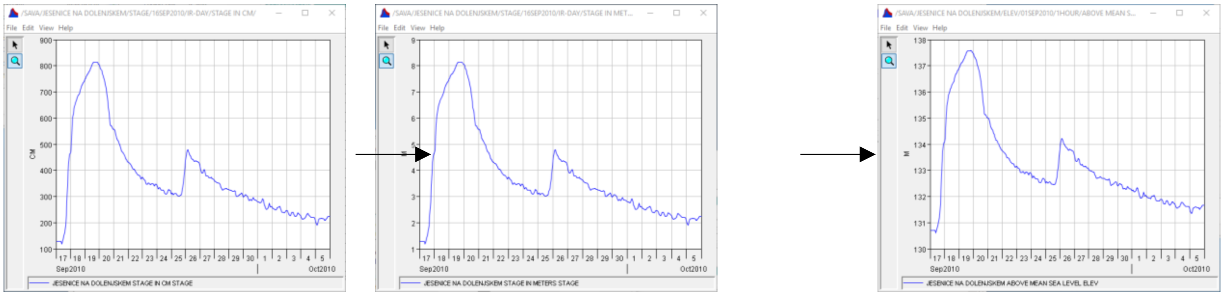
In addition to modeling provided by the Riparian countries, USACE developed an unsteady hydraulic model of the Sava River mainstem. The model submitted by USACE has since been further refined by the ISRBC. At the time of the development of the Phase 1 hydraulic model, very limited and low accuracy digital terrain information existed. A lack of reliable terrain information made it difficult to produce an accurate hydraulic model.

USACE developed a final system-based hydraulic model covering the extents shown in Figure 2 using the compile models from previous phases, the ISRBC, and the Sava River riparian countries. As mentioned in Section 1 of this document, EUCOM funded the collection of LiDAR in coordination with the ISRBC and its member countries with an extent that covered the main corridor of the Sava River and low lying areas behind the network of levees along the Sava River. The LiDAR information was used to update the overbank areas of the cross sections from the existing modeling, while the cross sections of the existing modeling were used to define the bathymetric regions of the cross section geometry. Ultimately, this approach results in the best possible cross sectional geometry with the available data.

2.2 DATA ACQUISITION

Data required for the Sava River System HEC-RAS model includes: gauge data such as elevation time series; rating curve information at gauges; physical characteristics of the flood protection retention areas such as gated structures and retention area extents; and LiDAR which can be used to define cross sectional geometry (as described in Section 2.1), elevation-storage curves for retention areas, and top of levee/high ground elevation profiles.

Unlike hydrologic modeling, gauge data is not generally used as an input because flow inputs at hydraulic boundaries is provided from outputs from the hydrologic model, which was the case for this study. For this study gauge, data was used for model calibration. The gauge data used for model calibration was provided by the ISRBC during the development of the hydrologic model. A substantial amount of data was collected as part of previous modeling efforts. The data received from the ISRBC was provided as stage data referenced in centimeters above each gauge datum. USACE converted the stages to meters and added the datum for each gauge to the stage in meters to produce an elevation time series record for all available gauges along the mainstem Sava River. HEC's Data System Storage Viewer (HEC-DSSVue) was used to store the original stage data and math functions within HEC-DSSVue were used to convert all stages to elevation. A more thorough review of HEC-DSS and HEC-DSSVue is provided in the accompanying *Sava River Basin Flood Study: HEC-HMS Technical Documentation* Report conducted by USACE during this phase or by accessing technical documentation manuals on HEC's website (http://www.hec.usace.army.mil/software/hec-dssvue/). An example of the process is provided in Figure 3.



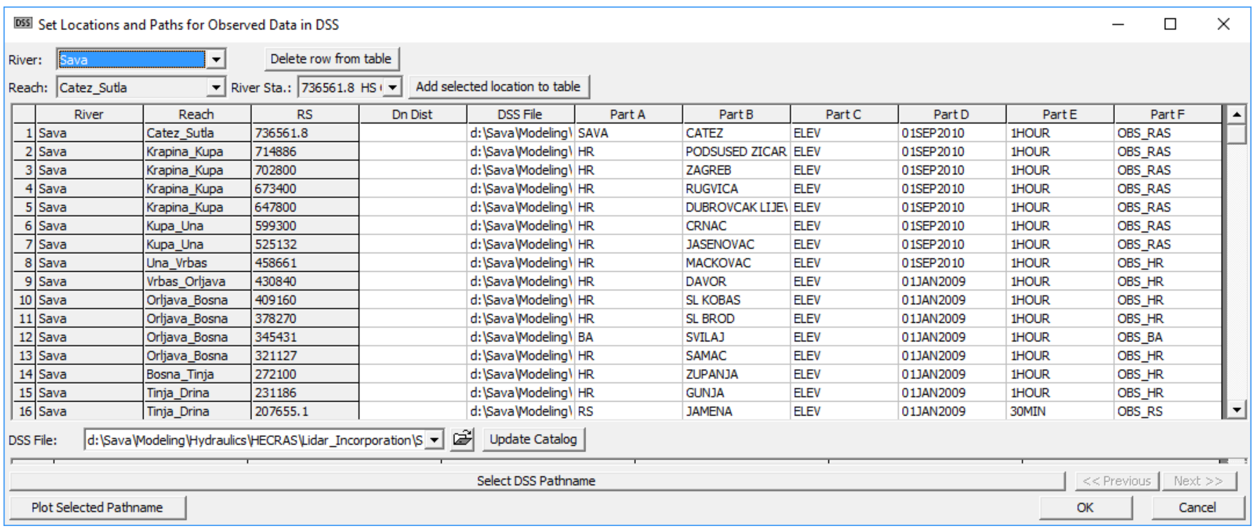
Original stage data in centimeters

Stage data converted from centimeters to meters

Elevation data derived from adding the gauge datum to the stage datum in meters

Figure 3. Process of converting original stage data to elevation data

Once the stage data was converted to elevation data, the data was input into the HEC-RAS model as observed data in the options of the unsteady flow data editor. Because the data is required to be stored in DSS format for HEC-RAS to read it, Figure 4 shows how the data is linked to an external DSS file and parsed by various pathname parts (Part A through Part F).



	River	Reach	RS	Dn Dist	DSS File	Part A	Part B	Part C	Part D	Part E	Part F
1	Sava	Catez_Sutla	736561.8		d:\Sava\Modeling\	SAVA	CATEZ	ELEV	01SEP2010	1HOUR	OBS_RAS
2	Sava	Krapina_Kupa	714886		d:\Sava\Modeling\	HR	PODSUSED ZICAR	ELEV	01SEP2010	1HOUR	OBS_RAS
3	Sava	Krapina_Kupa	702800		d:\Sava\Modeling\	HR	ZAGREB	ELEV	01SEP2010	1HOUR	OBS_RAS
4	Sava	Krapina_Kupa	673400		d:\Sava\Modeling\	HR	RUGVICA	ELEV	01SEP2010	1HOUR	OBS_RAS
5	Sava	Krapina_Kupa	647800		d:\Sava\Modeling\	HR	DUBROVCAK LIJE\	ELEV	01SEP2010	1HOUR	OBS_RAS
6	Sava	Kupa_Una	599300		d:\Sava\Modeling\	HR	CRNAC	ELEV	01SEP2010	1HOUR	OBS_RAS
7	Sava	Kupa_Una	525132		d:\Sava\Modeling\	HR	JASENOVAC	ELEV	01SEP2010	1HOUR	OBS_RAS
8	Sava	Una_Vrbas	458661		d:\Sava\Modeling\	HR	MACKOVAC	ELEV	01SEP2010	1HOUR	OBS_HR
9	Sava	Vrbas_Orljava	430840		d:\Sava\Modeling\	HR	DAVOR	ELEV	01JAN2009	1HOUR	OBS_HR
10	Sava	Orljava_Bosna	409160		d:\Sava\Modeling\	HR	SL KOBAS	ELEV	01JAN2009	1HOUR	OBS_HR
11	Sava	Orljava_Bosna	378270		d:\Sava\Modeling\	HR	SL BROD	ELEV	01JAN2009	1HOUR	OBS_HR
12	Sava	Orljava_Bosna	345431		d:\Sava\Modeling\	BA	SVILAJ	ELEV	01JAN2009	1HOUR	OBS_BA
13	Sava	Orljava_Bosna	321127		d:\Sava\Modeling\	HR	SAMAC	ELEV	01JAN2009	1HOUR	OBS_HR
14	Sava	Bosna_Tinja	272100		d:\Sava\Modeling\	HR	ZUPANJA	ELEV	01JAN2009	1HOUR	OBS_HR
15	Sava	Tinja_Drina	231186		d:\Sava\Modeling\	HR	GUNJA	ELEV	01JAN2009	1HOUR	OBS_HR
16	Sava	Tinja_Drina	207655.1		d:\Sava\Modeling\	RS	JAMENA	ELEV	01JAN2009	30MIN	OBS_RS

Figure 4. Example of Observed Flow Input into HEC-RAS

One approach to calibrating an unsteady flow HEC-RAS model is to first use steady flows to calibrate known rating curves. For gauges under the management of Croatia's Meteorological and Hydrological Service (DHMZ), rating curves at those gauges were provided. For other gauges outside of DHMZ's purview, USACE used observed elevation and discharge data to determine a rating curve. The process to back calculate a rating curve from observed data includes plotting flow versus time in Microsoft Excel and fitting a trendline curve to the data. Excel provides the ability to derive a formula for the trendline curve. This formula was then used to derive a rating curve from the lowest to the highest elevation in the observed dataset. Figure 5 illustrates and example of the curve derived in Excel.

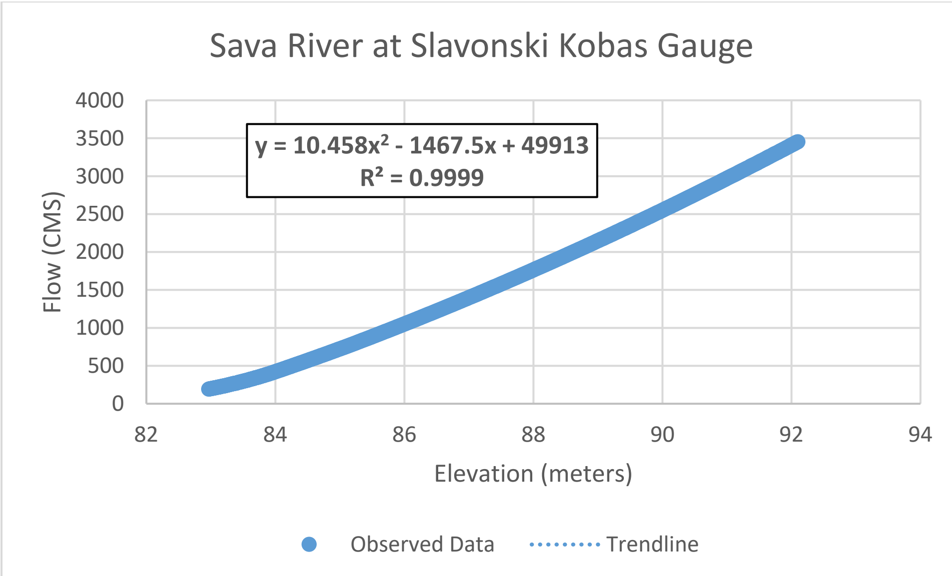


Figure 5. Example of Rating Curve Development using Microsoft Excel

One of the more complex components of the Sava River is Central Sava Flood Protection System, which includes elaborate gated/weir diversions into retention areas and overflow areas that allow the historical floodplain of the Sava River to be used during high flow events. In order to capture the hydraulic characteristics of this system, the ISRBC provided documentation on the system, which included drawings and specifications of the various features in the system. For the gated structures, the ISRBC provided gate opening information for the specific events evaluated during this study. This information provided USACE with enough information to develop a conceptual approach on how the system could be modeled in HEC-RAS. In addition, this information provided key inputs into the development of model geometry. Figure 6 illustrates an overview of the flood protection system.

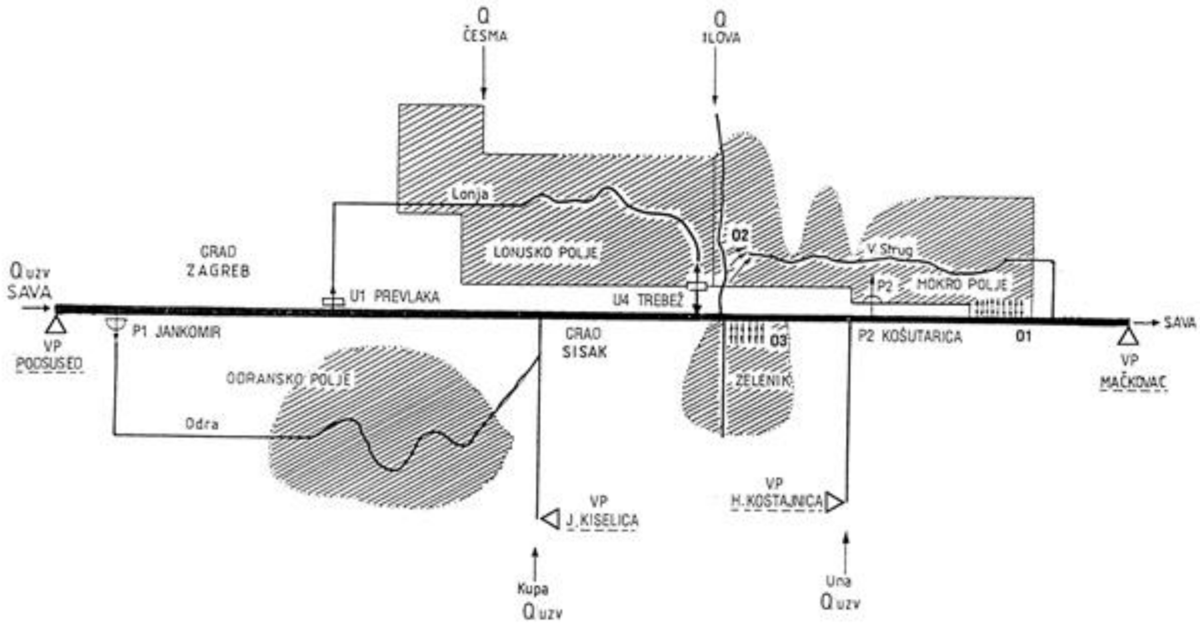


Figure 6. Sava River Flood Protection System Schematic

Historically, hydraulic models relied almost completely on surveyed data to define cross section geometry; however, with the advancement of LiDAR collection over the past 25-30 years, LiDAR has become the industry standard for developing cross sectional geometry in hydraulic models. Previous phases of this study have been hindered due to a lack of LiDAR data, which can be used to define the terrain digitally at a high level of accuracy and resolution.

Fortunately, EUCOM entered into a contract to provide this information with geospatial surveying company FlyCom, which is located in Slovenia. FlyCom collected elevation points via aerial survey at 10 points per square meter along the mainstem Sava River (generally the area between levees) and in urban areas such as Zagreb, Croatia and Belgrade, Serbia. In retention and low lying overbank areas, points were collected at 5 points per square meter. The raw bare earth-classified points were used to develop a digital elevation model (DEM) with a resolution of 0.5 square meters grid cell size. The required vertical accuracy of the LiDAR collection was 10 cm and all data was collected during a non-vegetation and snow state with the rivers remaining in their channels at near average heights.

Figure 7 shows the areas where LiDAR was collected and is separated into areas where 10 points were collected per square meter (red) and 5 points were collected per square meter (blue). The LiDAR collection was very specific to the proposed modeling area and was coordinated with Sava River riparian countries to ensure that this collection was not redundant with any future LiDAR collection plans throughout the region. The LiDAR data and products can be accessed through the ISRBC.

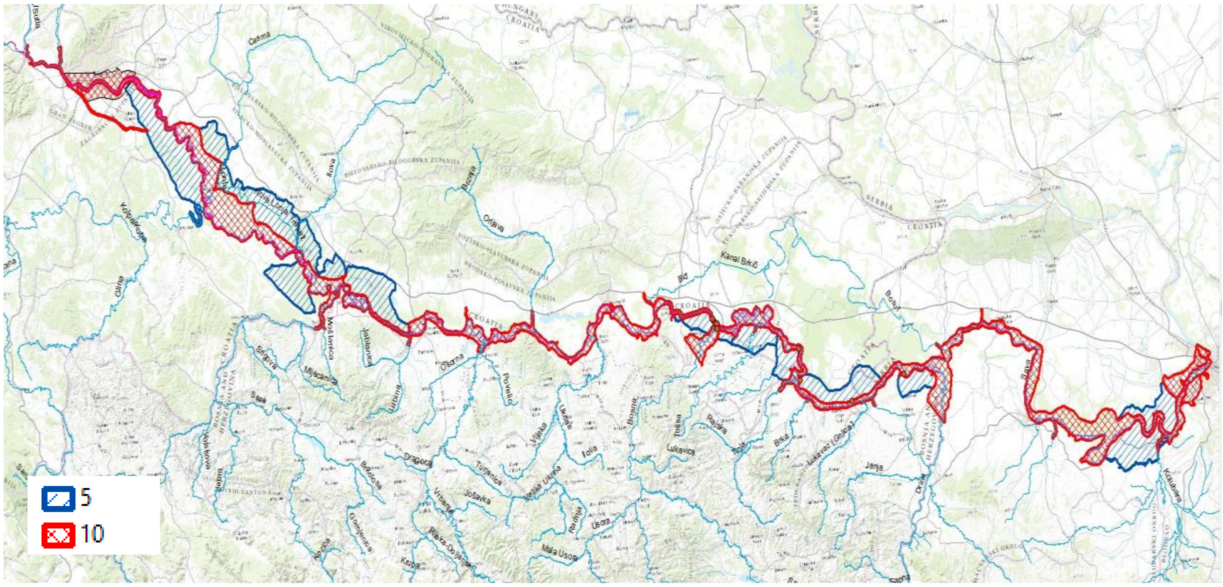


Figure 7. LiDAR Collection Areas

2.3 CONCEPTUAL MODEL DESIGN

The Sava River mainstem is relatively simple when flood elevations remain in the channels and within the levee system; however, as larger events occur and the system of diversions, diversion channels, and retention areas are activated, the system becomes much more complex hydraulically. The goal of this study is to provide a model, which represents the Sava River system for all levels of events.

USACE's first step was to evaluate the available data and modeling and become familiar with the hydraulic characteristics of the system. Once the system was understood, USACE developed a conceptual model of the design to determine what components of HEC-RAS would be needed to represent the system.

Figure 2, provide above in this document, illustrates the stream reaches to be included in the HEC-RAS model and the retention areas of the Central Sava Flood Protection System. The mainstem Sava River course and tributaries can easily be represented by cross sections, which provide station and elevation at various intervals along the river.

Levees and high ground can be represented with lateral structures, which represent the top of levee/high ground elevation profiles with station and elevations. As the name indicates, these lateral structures run laterally to the mainstem Sava River. Points along the lateral structures are tied to cross section locations. The water surface elevation computed at each cross section can be projected onto the lateral structures to determine when overtopping occurs. Lateral structures are also used to represent side channel weirs such as the Jankomir, Palanjek, and Košutarica Weirs, and an example of the September 2010 event flood profile projected onto Jankomir Weir is shown in Figure 8.

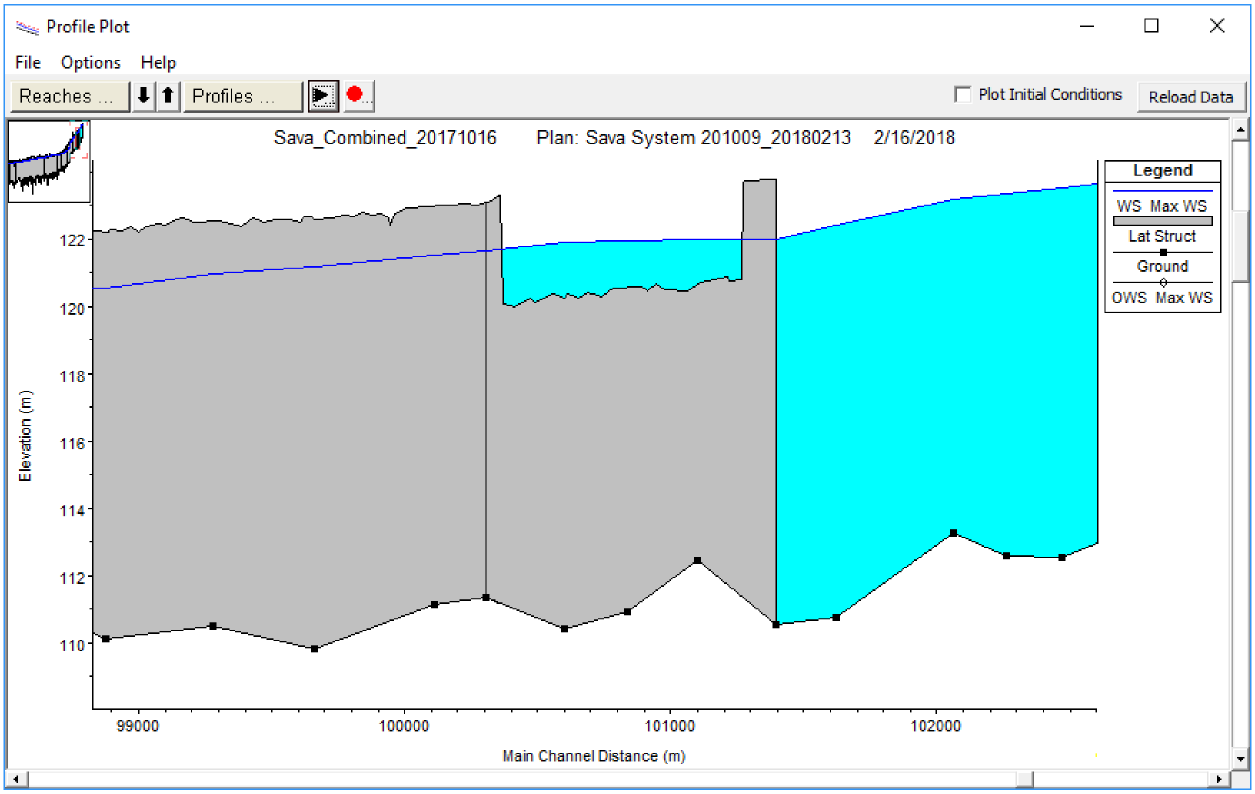


Figure 8. Jankomir Weir Overtopping During September 2010 Event

For gated structures like the Prevlaka Gates, which allow flood waters to leave the Sava River and flow into the Lonja Canal, lateral structures were used to represent the top of the gated structure and gates were added to the structure as shown in Figure 9. The operations of the gates are controlled in HEC-RAS through unsteady flow data editor.

The design of the system is to allow flood waters to leave the Sava River over weirs and high ground overflows and through gated structures to route these flood waters to retention areas directly or through canals. In HEC-RAS, these retention areas can be represented using storage areas, which simulates the retention area as a level pool routing using an elevation versus storage rating curve. In situations where it is necessary, retention areas can also be represented as 2-dimensional areas using a finite volume method of routing flow through the retention area.

From a conceptual level, a system of cross sections, lateral structures, and storage/2D areas are used to represent the hydraulic characteristics of the entire system for all levels of flooding. Section 3 will provide more detail related to the development of the HEC-RAS components described conceptually in this section.

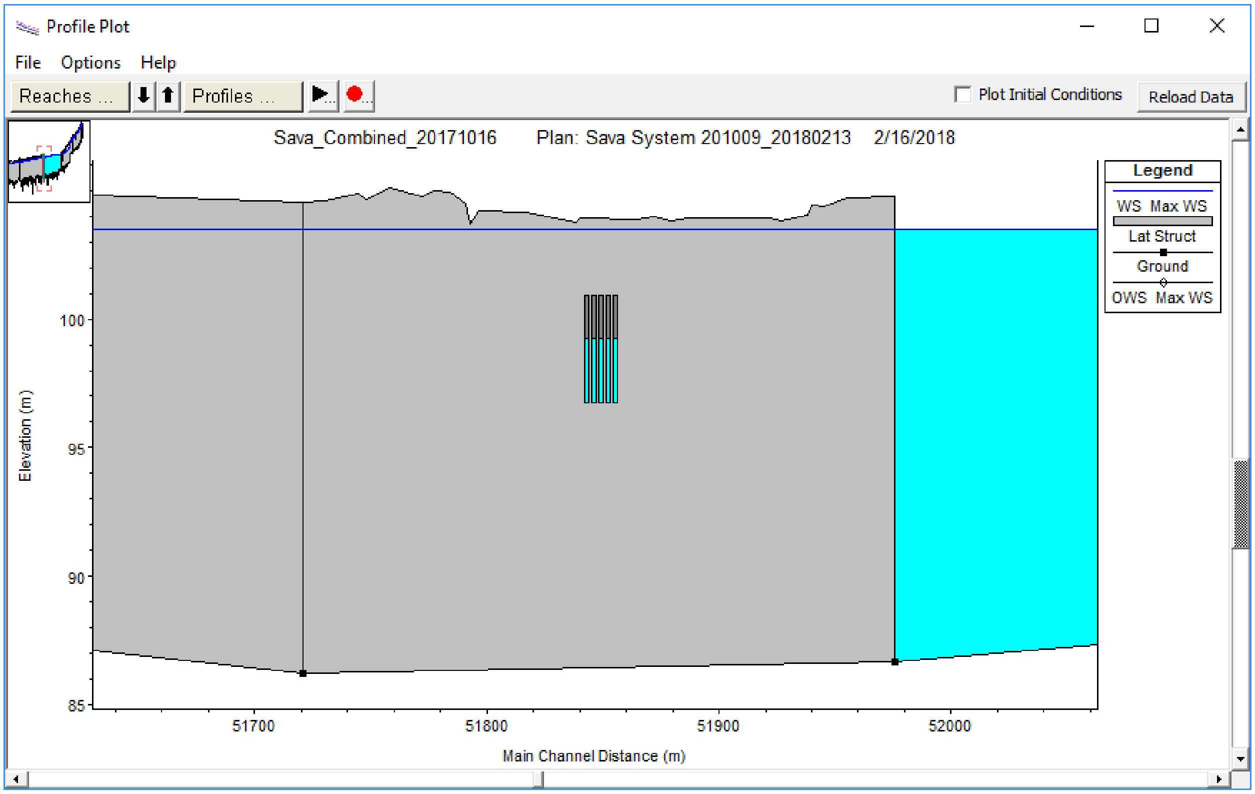


Figure 9. Prevlaka Gates During the September 2010 Event

2.4 MODEL CALIBRATION PERIOD DEVELOPMENT

The purpose of this project was to produce an event-based calibrated hydrologic and hydraulic model to support future endeavors of the ISRBC and its member countries. The hydrologic models were produced previously during this project, and the results (outflows) from the hydrologic models serve as inputs into the hydraulic model. During the development of the hydrologic models, the ISRBC hydro yearbooks were used to identify significant storm events over the past 5-7 years. For the hydraulic model development, three calibration event periods were chosen due to their significant size, widespread effect on the Sava River, and the availability of reliable data for the entire Sava River. The sheer size of the Sava River Basin allows for flood events to occur in certain areas of the basin while not occurring in others. Therefore, the three events chosen represent an event that affected the entire Sava River, the middle Sava River reach, and the lower Sava River reach. The three events chosen are provided in Table 1.

Table 1: HEC-RAS Model Calibration Periods

Event Name	Start Date	End Date	Most Affected Area
December 2009 Event	12/19/2009	2/3/2010	Entire Sava River
September 2010 Event	9/15/2010	10/16/2010	Middle Sava River Region
May 2014 Event	4/12/2014	6/13/2014	Lower Sava River Region

3. HYDRAULIC MODEL ANALYSIS

The main goal of the hydraulic model developed for this project is to accurately represent the hydraulic characteristics of the Sava River and associated offline storage/retention areas using the best available data. The primary outputs of the hydraulic model include water surface profiles and inundation mapping for specific flood events. The purpose of this section is to describe in detail how the hydraulic model was developed using existing models, data, and information. In a previous phase of this Sava River project, an HEC-RAS hydraulic model was developed. This phase represents a continuation of this work with the primary difference being the availability of high resolution LIDAR data and a fully calibrated HEC-HMS model providing flow inputs into the HEC-RAS model.

3.1 HYDRAULIC MODEL GEOMETRY DEVELOPMENT

Model geometry development for this HEC-RAS model relies on a combination of existing models, available information for gated structures and retention areas, and LiDAR data for overbank areas. This section provides detailed descriptions of how all geometric components of the HEC-RAS model was developed. These components form the building blocks of a hydraulic model and when combined result in the Sava River system model. Each component of the Sava River HEC-RAS system model plays a vital role in properly representing the hydraulic characteristics and processes of the Sava River system.

In addition, this information should provide insight into how the hydraulic model can be improved or how additional modeling could be developed in other areas of the Sava River watershed where local institutions possess more accurate data. For this project, the main focus is the mainstem Sava River and associated retention areas because the newly collected LiDAR data provides the basis for an accurate model.

3.1.1 GEOMETRY PRE-PROCESSING USING HEC-GEORAS

The initial HEC-RAS model development relies on the historical models compiled and combined by the ISRBC. The historical model geometries were generally developed by individual institutions across the Sava River riparian countries using survey data. However, with the recent collection of LiDAR, the historical model geometries were improved using the high resolution terrain data provided by LiDAR.

For the Sava River HEC-RAS model, model geometry data was initially developed using HEC-GeoRAS. HEC-GeoRAS is a tool within ArcGIS Desktop that allows the user to lay out cross sections and other features like lateral structures, 2D/storage area connections, and storage areas at specific locations within the Sava River hydraulic model extent. Figure 10 illustrates an example near the Palanjek weir of how these features are laid out within ArcGIS Desktop using the HEC-GeoRAS tool. Once these features are laid out, HEC-GeoRAS was used to extract the high resolution terrain data from LiDAR. For cross sections, lateral structures, and 2D/storage area connections, the LiDAR data is used to define station-elevation points along the polylines drawn for these features. For storage areas, HEC-GeoRAS can be used to develop a relationship between elevation and storage although this is now much easily completed directly in HEC-RAS.

It is important to note that most if not all of the pre-processing capabilities within HEC-GeoRAS are now available directly within HEC-RAS with a tool known as RASMapper. RASMapper has replaced HEC-GeoRAS for the past several years for the post-processing capabilities such as inundation and depth grid mapping of HEC-RAS results; however, with the release of a new beta-version of HEC-RAS, the capabilities in

RASMapper to pre-process model geometry has been expanded. Due to the timing of this project, most of the pre-processing was handled in HEC-GeoRAS.

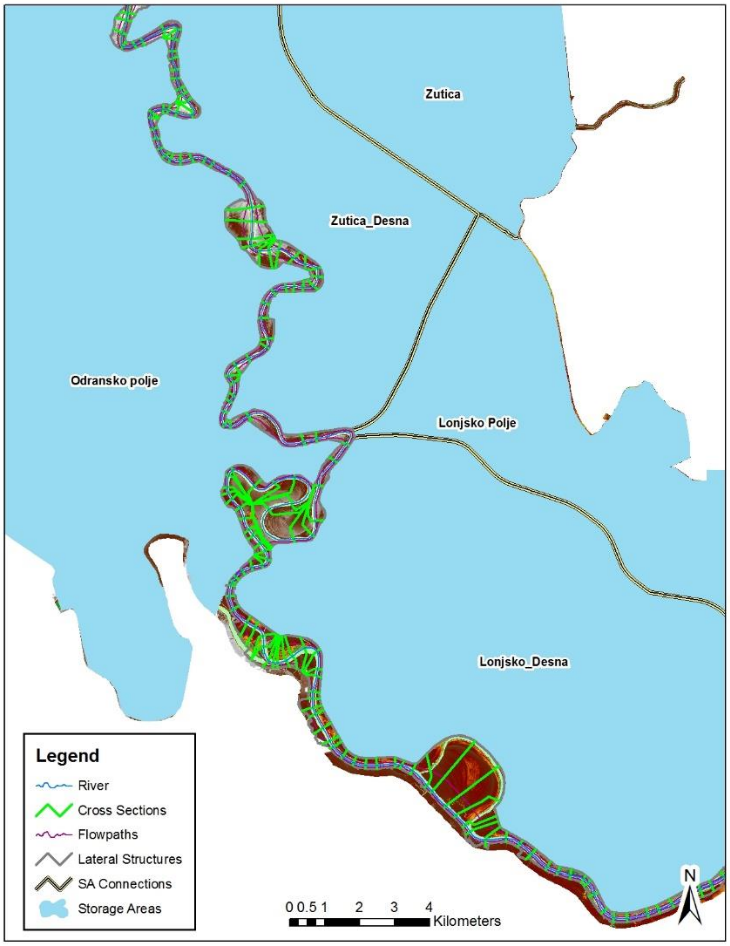
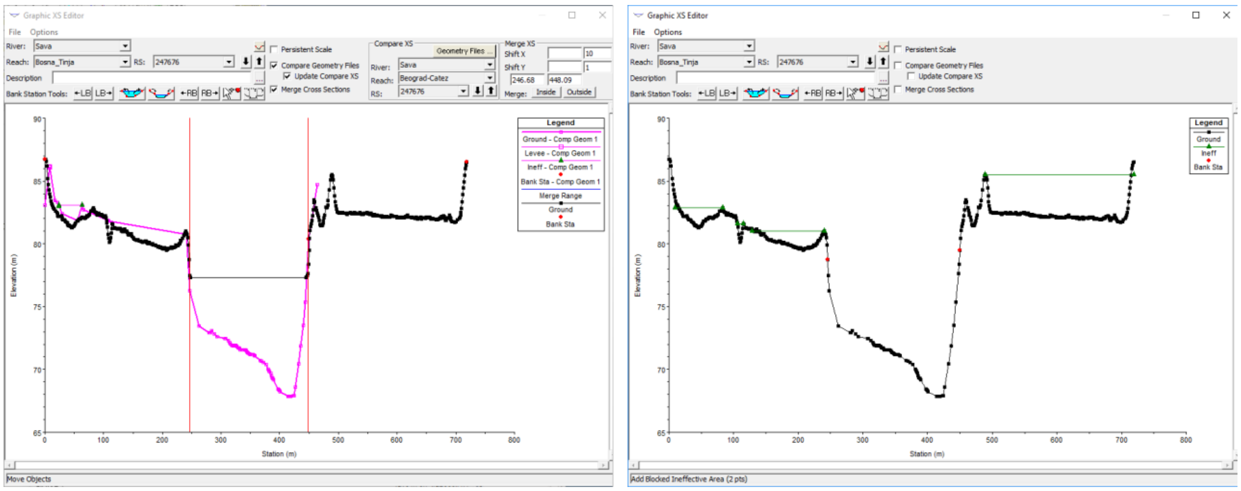


Figure 10. Example of HEC-GeoRAS

Once the model geometry has been pre-processed, an import geometry file can be exported from HEC-GeoRAS and imported directly into HEC-RAS. One limitation of LiDAR is its inability to capture underwater or bathymetric data within a cross section; therefore, the HEC-GeoRAS process followed for this project does not complete the pre-processing step. In order to complete the cross section geometry development, the channel data from the historical hydraulic models provided by the ISRBC was merged into the raw cross sections cut from the LiDAR. Figure 11 illustrates how USACE merged the channel data from the historical hydraulic models into the new cross section data derived from the LiDAR collection using the *Graphical XS Editor* within the geometry editor of HEC-RAS. Once the cross section data was processed with HEC-GeoRAS and imported into a HEC-RAS geometry, the two cross section data sources, historical channel data and raw LiDAR data, can be compared in *Graphical XS Editor*. In addition, the data related to just the channel portion of the historical cross section data can be selected and merged into the LiDAR-based cross section data. The left side of Figure 11 shows two sets of cross sections with the black data being the LiDAR-based data and the magenta data being the historical model data. Notice the flat bottom of the LiDAR-based data, which represents the top of the water surface when the LiDAR was collected. The vertical red lines represent the portion from the historical model data (magenta) that will be merged into the LiDAR-based data. The right side of Figure 11 shows the resulting cross section after the channel data has been merged.



(a) Merging Process (b) Final Cross Section Data

Figure 11. Example of Merging Channel Data into RAW LiDAR-Based Cross Section

This process was followed for all cross sections within the Sava River System model where LiDAR-based data was available. Once completed, the next steps in development of model geometry began and is discussed in more detail in this section of the report.

3.1.2 CROSS SECTION GEOMETRY

The primary product of this project is a 1-D unsteady flow hydraulic model, which relies on cross sections to represent the hydraulic characteristics of the Sava River system. Cross sections are placed along the Sava River and tributary reaches in a manner that captures the prismatic changes in geometry and storage of the system. Placement of cross sections is one of the most important aspects of hydraulic model development.

In HEC-RAS, Cross section data can be viewed and edited through multiple tools/viewers including: the Cross Section Data editor, the Graphical Cross Section Editor, the Plot Cross Section viewer, and the 3D Perspective Plot viewer. In addition to station-elevation data describing the physical geometry of a cross section, other attributes must be provided for each cross section including:

- Bank stations – defines the breakpoints between the channel portion and the left and right overbank portions of each cross section. Bank stations are also generally the points where manning's n-value roughness changes are input.
- Downstream reach lengths – defines the distance from each cross section to the next downstream cross section in the reach for the three major regions of a cross section, channel, left overbank, and right overbank. These distances are primarily used to compute the friction losses between two cross sections.
- Manning's n-values – at a minimum, n-values must be defined for the channel, left overbank, and right overbank with bank station locations defining the breakpoints between these regions. However, Manning's n-values can be further defined horizontally and vertically throughout the cross section geometry.

- Contraction/Expansion Coefficients – used to compute energy losses due to contraction or expansion of flow at cross sections. Coefficients of contraction and expansion are typically assumed to be 0.1 and 0.3, respectively; however, in areas where abrupt changes occur such as at bridges and culverts, these values may be higher.

To illustrate these attributes, the cross section (as viewed in Cross Section Data Editor) nearest the hydro station at Zagreb, Croatia is shown in Figure 12. The figure illustrates the station-elevation data along with the other attributes in the middle portion of the editor.

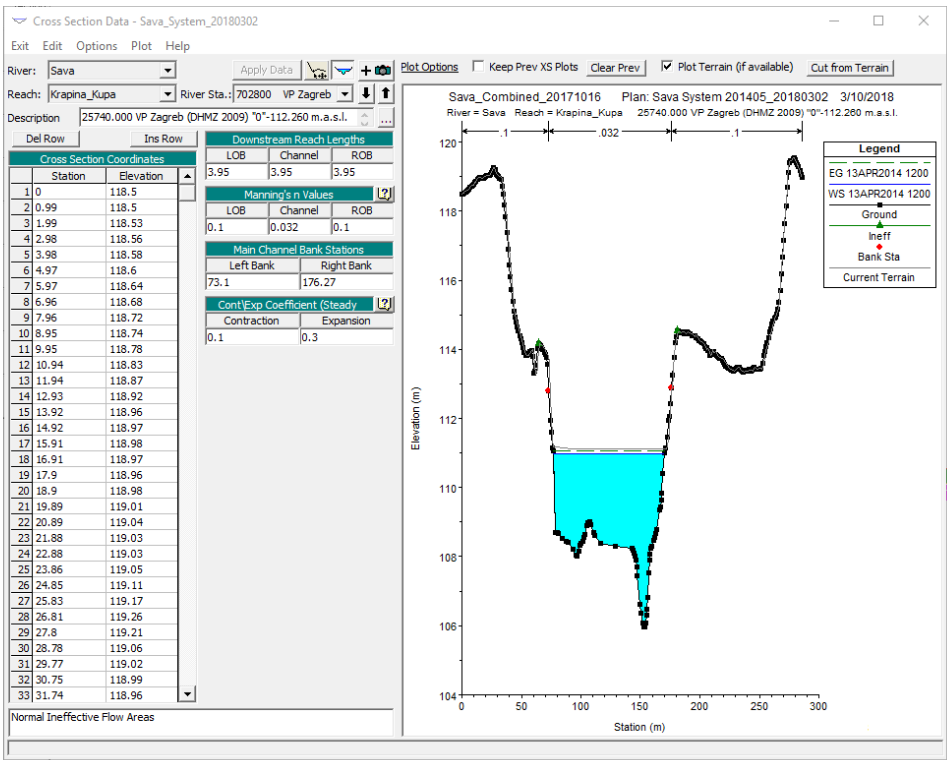


Figure 12. Cross Section Data Editor Example

In addition to the ability to edit these attributes within the Cross Section Data Editor, HEC-RAS also provides the ability to edit these parameters more globally in tables through the geometry editor window. For the Sava River HEC-RAS model, cross section parameters were defined using various methods and are described below for each parameter in more detail.

Bank stations are generally defined at the top of each bank (left and right) but in many cases the water surface produced from bank full discharge, which through research in the US has been estimated at approximately the 1.5-year or 0.67 annual exceedance probability event, can be used to estimate the location of the top of bank. For the Sava River model bank stations were set at a reasonable elevation relatively close to the top of each bank.

Downstream reach lengths, which represents the distance to the next downstream cross section in the three regions (channel, left overbank, and right overbank) of the cross section, were originally derived from existing models but was further refined using flowpaths within HEC-GeoRAS. Figure 13 illustrates how these distances were initially calculated from the flowpaths layer (magenta) within HEC-GeoRAS.

Because these distances directly affect the computation of frictional losses with HEC-RAS, these distances could potentially need to be updated after simulating various levels of events and evaluating if the original layout of flowpaths was correct. However, because the Sava River is so contained between bounding levees for most of its length, the original estimation of downstream reach lengths was accepted.

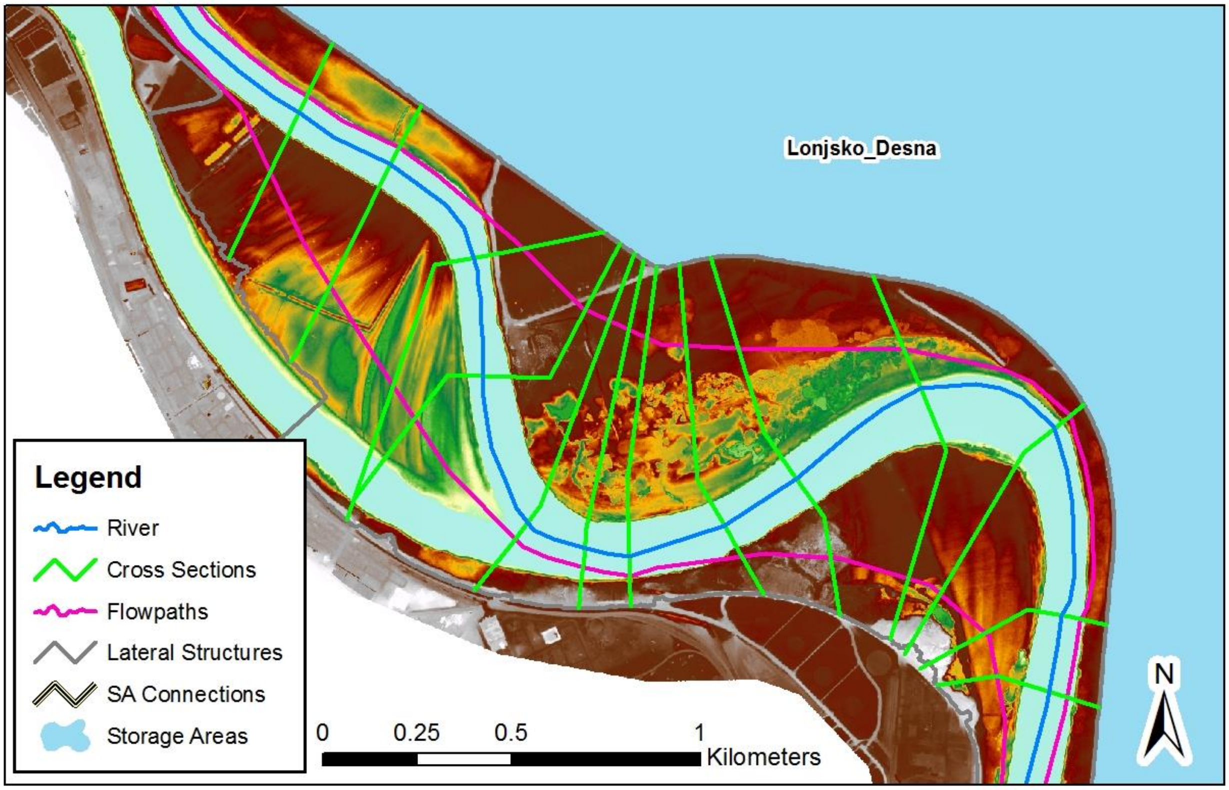


Figure 13. Example of Downstream Reach Lengths Computations

Manning's n-values were originally estimated from aerial imagery, and on average, the Manning's n-values for the channel and overbanks for each cross section averaged about 0.03 and 0.08, respectively. Manning's n-values are typically used as a calibration parameter so these initial estimates were further refined through calibration as described in the *Hydraulic Model Calibration* section of this document.

In addition to the parameters discussed above, setting areas of ineffective flow within a cross section is also important to properly capture the hydraulic characteristics of a reach. In many cases, there are areas within a reach where water can exist but the flow in that area is not effective, which for a 1D flow model is where water is not moving in the longitudinal direction of the river. An example of this situation could be upstream and downstream of a bridge abutment where flow can not fully contract or expand. A common example of this for the Sava River hydraulic model is where a feature in the overbank with much higher elevations than surrounding areas such as a road feature. Water can flood behind the road through culverts and bridges but does not become fully effective behind the road until the water surface elevation overtops the road. See Figure 14 below for an illustration of this example.

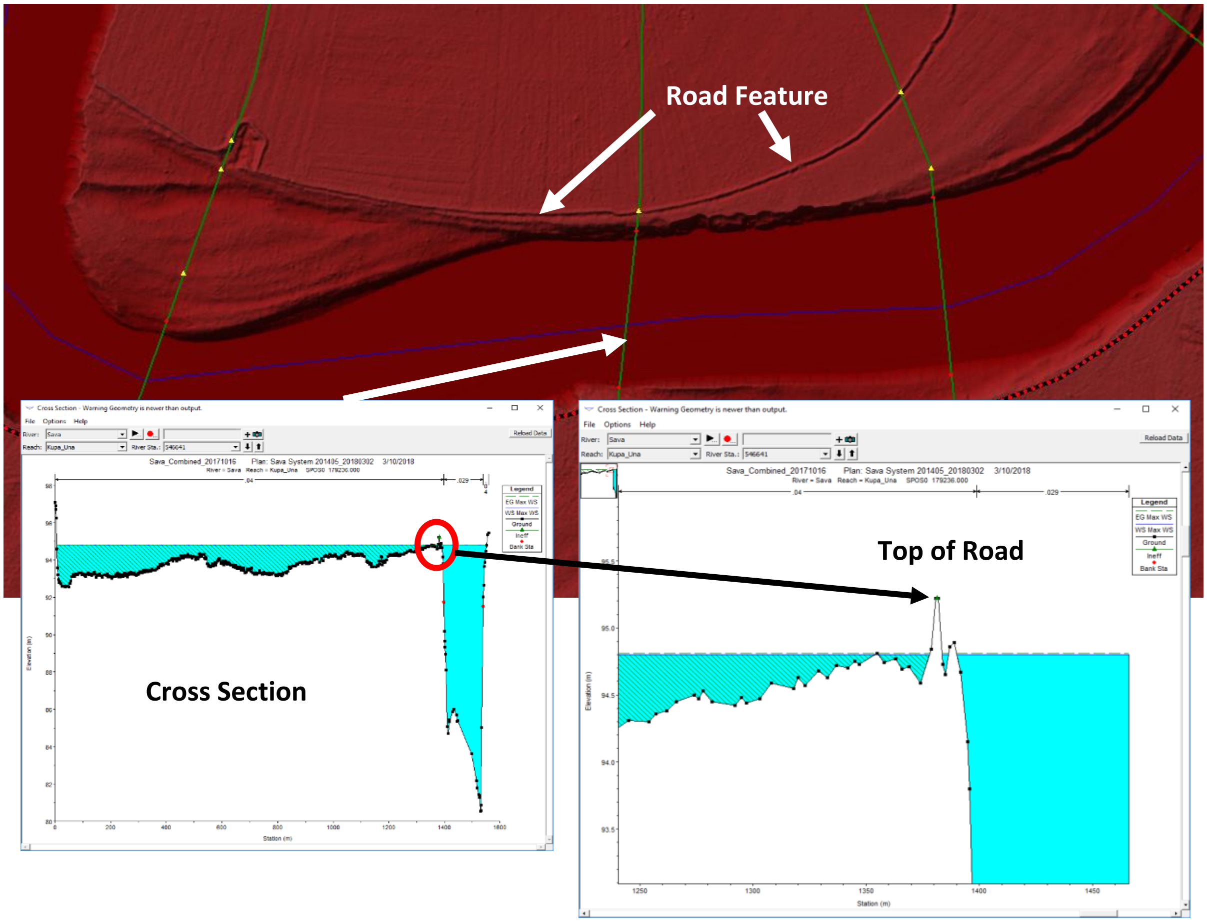


Figure 14. Example of Ineffective Area in a Cross Section

The top image in Figure 14 shows a plan view of an example from the Sava River HEC-RAS model where there is a roadway or high feature in the overbank. The bottom left image shows the cross section identified while the bottom right image shows a zoomed in image where an ineffective station was added to this cross section at the top of the road. Hydraulically, the area behind the high feature will not be computed as flow conveyance until the top of the road is overtopped.

Defining accurate cross section geometry is critical to produce an accurate hydraulic model with the most important information being the station-elevation data derived from LIDAR and a reliable bathymetric data source.

3.1.3 LATERAL STRUCTURES

Lateral structures are used within HEC-RAS to transfer flow from the mainstem model of the Sava River reach to lateral areas adjacent to the Sava River. These lateral areas are represented by storage areas (discussed in the *Storage/2D Areas* section) and usually represent areas behind the major levees of the Sava River, retention areas, or tributary backwater areas.

Functionally, lateral structures are similar to cross sections but they typically run perpendicular to cross section. The station-elevation data of the lateral structure is derived from LiDAR terrain data and is filtered to simplify computations within HEC-RAS. The Sava River HEC-RAS model uses an extensive amount of lateral structures to represent the levees along the Sava River. Once the channel capacity of the Sava River is exceeded and a levee (represented as a lateral structure) overtops, the weir equation is used to computed the overtopping flow over the lateral structure. In this way, a direct connection exists between the cross section geometry used to compute water surface elevations along the mainstem Sava River and the lateral structures used to compute/transfer flow to lateral areas once the water surface elevations exceed the limits of the Sava River.

Figure 15 provides an example of the lateral structure editor for a levied section protecting an area between the Sava River and Lonjsko Polje retention area. The editor is where the user can enter the station-elevation data for the weir and set parameters for the weir such as the weir coefficient. Table 2 provides a general range of potential weir coefficient values for various applications of a lateral structure, but ultimately should calibrated when possible as is further described in the *Hydraulic Model Calibration* section.

In addition to modeling the overtopping characteristics, other features such as gates and culverts can be input into the lateral structure. For the Sava River, this function was utilized to represent the Prevlaka and Trebež gates.

For many levied systems such as the Sava River system, breaches within levees is a major concern during large flood events. HEC-RAS provides the ability to simulate breaches of levees (when using a lateral structure to define the levee) through the lateral structure editor.

Table 2. Ranges of Weir Coefficients for Various Lateral Structure Applications

What is being modeled with the Lateral Structure	Description	Range of Weir Coefficients
Levee/Roadway – 1m or higher above natural ground	Broad crested weir shape, flow over levee/roadway acts like weir flow	0.83 to 1.43
Levee/Roadway – 0.25 to 1m elevated above ground	Broad crested weir shape, flow over levee/roadway acts like weir flow, but becomes submerged easily	0.55 to 1.1
Natural high ground barrier – 0.25 to 1m high	Does not really act like a weir, but water flow over high ground to get into 2D/Storage Area	0.28 to 0.55
Non-elevated overbank terrain. Lateral structure not elevated above ground	Overland flow escaping the main river	0.11 to 0.28

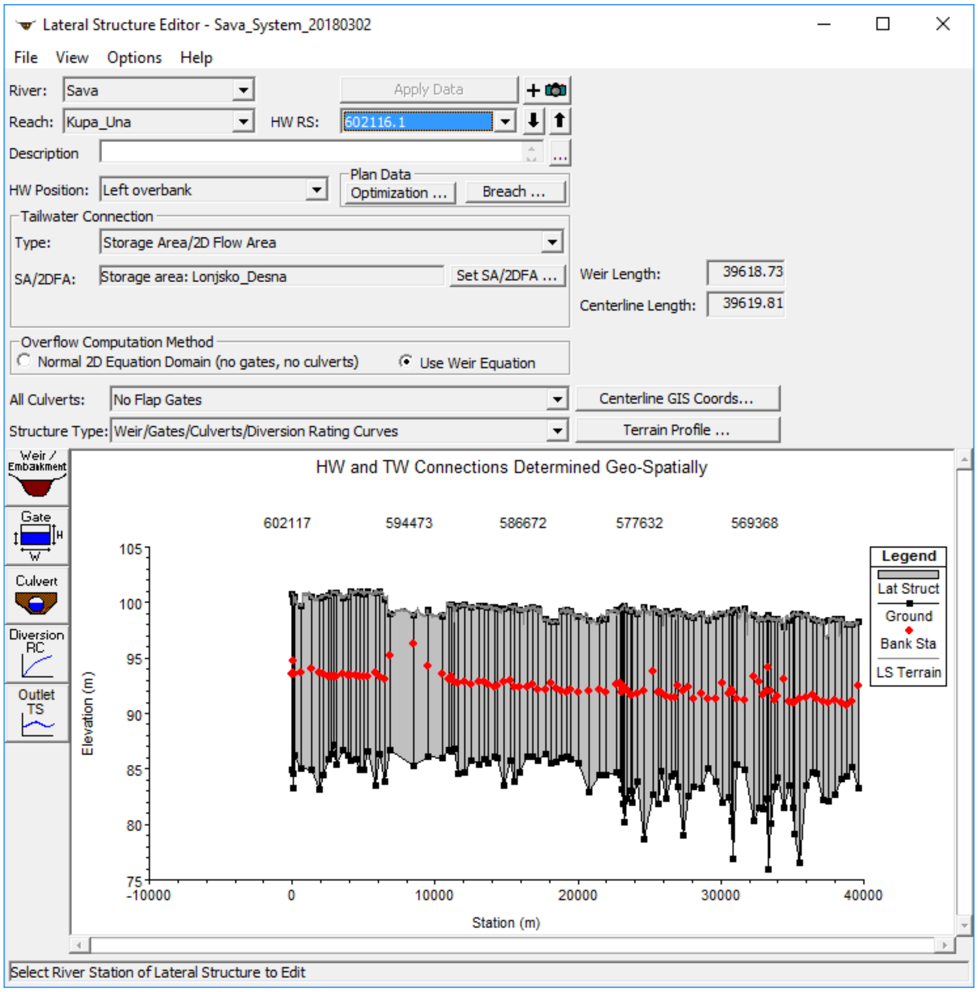


Figure 15. Example of the Lateral Structure Editor

3.1.4 STORAGE AND 2D AREAS

Storage areas are HEC-RAS components that represent areas that can be defined using an elevation vs storage relationship. Flow from another HEC-RAS component, such as a lateral structure or cross section, is passed into a storage area. This transferred flow is converted to a volume of storage for each time step during the unsteady flow simulation, and the elevation-storage relationship is used to compute a flood elevation for each time step. Storage areas use a level pool routing technique; therefore, the flood elevation computed is represented as a flat pool for the entire area.

For the Sava River HEC-RAS model, storage areas are most commonly used to define lateral retention areas such as Žutica, Lonjsko, and Mokro Polje. The flow to these storage areas is passed through or over a lateral structure depending on whether the lateral structure represents a designed high flow diversion weir, a gated structure, or a levee top.

The Storage Area Editor shown in Figure 16 illustrates the simplicity of the input needed for this type of component. At the top of Figure 16, the editor displays the other HEC-RAS components connected to the storage area, and the table in the bottom portion of Figure 16 list the elevation-storage relationship. This relationship can be computed during the HEC-GeoRAS process or, more simply, directly within the Storage

Area Editor using the "Computer E-V table from Terrain" tool. The "Computer E-V table from Terrain" tool utilizes the terrain developed using RASMapper.

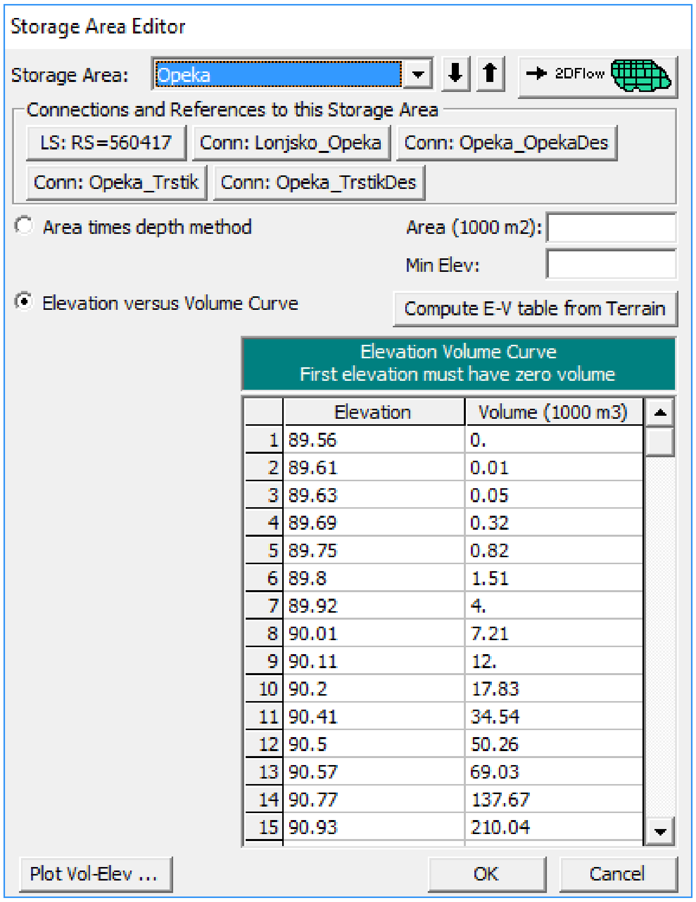


Figure 16. Example of the Storage Area Editor

For most cases, using a storage area to represent lateral areas such as designed retention areas or overflow areas behind levees is a reasonable approach to capture the general flow characteristics into and out of the area. However, if a more detailed understanding of the hydraulic characteristics locally within the lateral area is required, the 2D area component within HEC-RAS may be required. The 2D area component in HEC-RAS allows the user to define a more detailed mesh cell size providing much better resolution of the flow characteristics through the lateral area. HEC-RAS 2D areas use the finite volume method to compute flow from one mesh cell to surrounding cells. This method is much more efficient and reliable than other methods and allows for the total "drying out" of a mesh cell during an unsteady simulation, which makes the simulation much more stable. This approach also allows the user to define the resolution necessary for the specific hydraulic problem by varying the mesh cell size.

Another application of 2D areas was required for the Sava River HEC-RAS model. During model development, several storage areas throughout the Sava River model extent posed stability issues due to the "drying out" of the model. A specific example was the connections between the Sava (upstream) and Kupa (downstream) Rivers to the Odransko Polje. Originally, the concept was conceived that the Odransko Canal would be connected to the Sava River through the Jankomir weir. The Odransko Canal would be modeled using cross sections and then connected to Odransko Polje as a storage area. Figure 17 illustrates the original concept of how this interaction would be modeled.

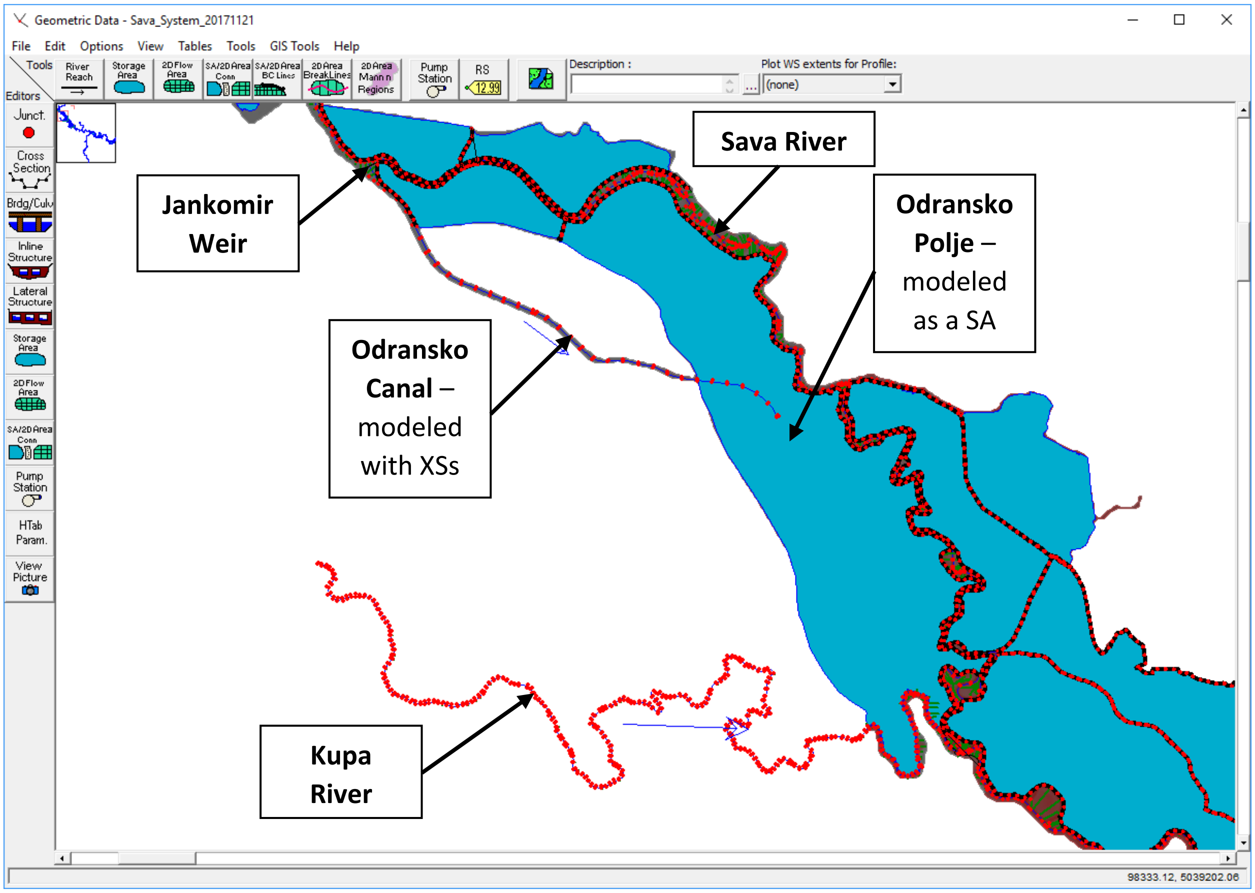


Figure 17. Original Concept of Modeling Sava River-Odransko Polje-Kupa River Interaction

The Odransko Polje retention area is very large and spans a significant area laterally to the Sava River. Because the storage area component uses level pool routing, the flow leaving the cross sections representing the Odransko Canal fills the Odransko Polje from the lowest elevation first, which is significantly downstream within the storage area near the outlet of the retention area into the Kupa River. This creates a large portion of the Odransko Polje that remains dry until enough flow fills the retention area. In addition, this also causes the cross sections representing the Odransko Canal to go dry, which causes a major instability in the model. For these reasons, the decision was made to represent the Odransko Canal and Polje as a 2D area with a very coarse mesh cell size resolution, which drastically improved the stability of the model while maintaining a higher quality model product. Figure 18 illustrates the final design of how the Sava River to Odransko Polje to Kupa River interaction was modeled using a 2D area in HEC-RAS.

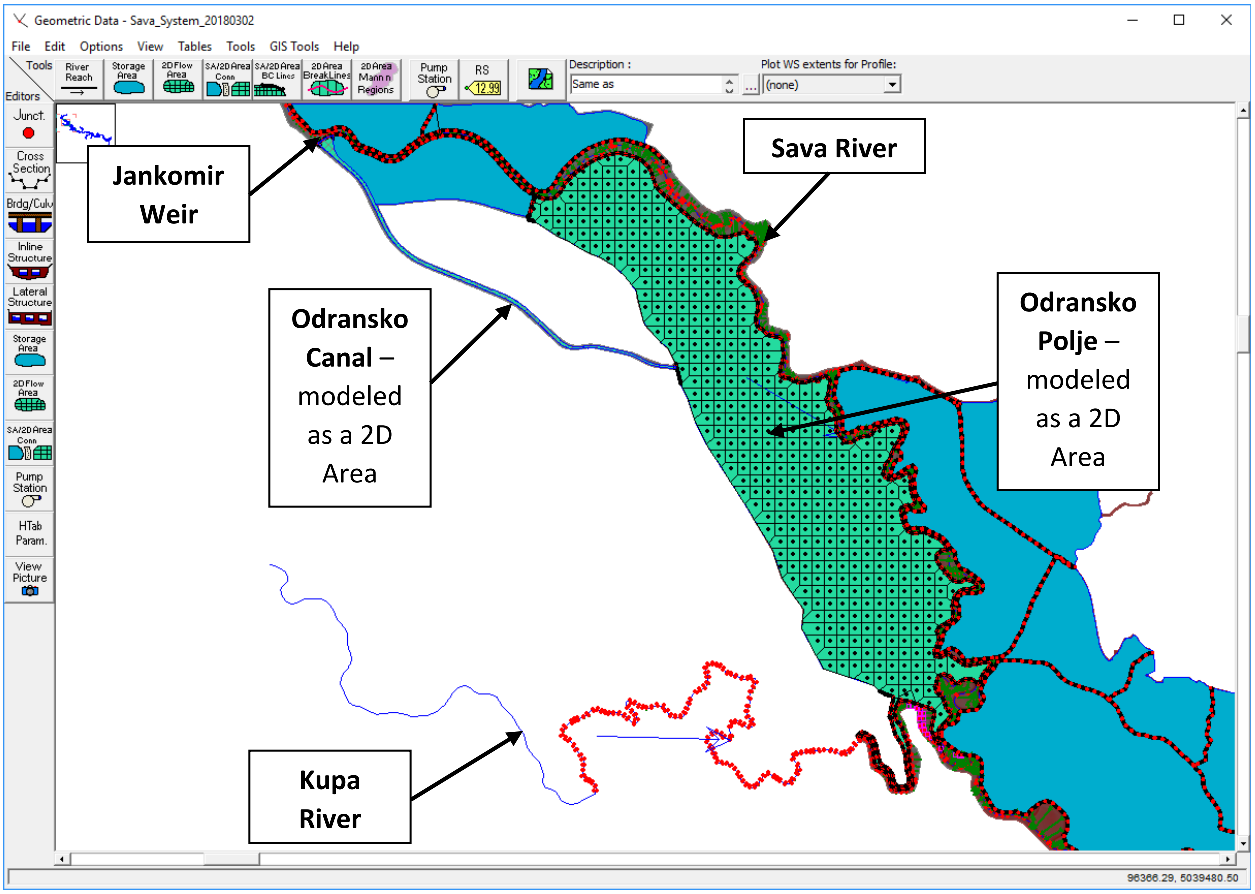


Figure 18. Final Design of Modeling Sava River-Odransko Polje-Kupa River Interaction

Overall, storage areas were used as an efficient and appropriate approach to route flow leaving the Sava River model over and/or through lateral structures to lateral areas throughout the Sava River model extent. In areas where more detailed approaches were necessary, 2D areas were used to represent these lateral areas.

3.1.5 STORAGE AREA AND 2D CONNECTIONS

Throughout the Sava River system, flood waters leave the system to utilize historical floodplains now represented with a system of retention areas, which is the entire basis of the Central Sava Flood Protection System. In some cases, these retention areas, which are primarily represented as storage areas in HEC-RAS (as described in the *Storage and 2D Areas* section), are required to be represented as multiple storage areas with routing of flow between these multiple storage and/or 2D areas.

HEC-RAS provides the ability to perform this type of hydraulic computation using storage/2D area connections. Storage/2D area connections function much like lateral structures in that they represent hydraulic structures computing flows from one storage area to another. Storage/2D area connections are generally overflow sections and use the weir equation to compute flow; however, HEC-RAS also provides the ability to include gates, culverts and breaches through the connections. Figure 19 shows the Connection Data Editor, which requires the user to choose the two storage/2D areas being connected and the station-elevation data used to define the overtopping weir equation.

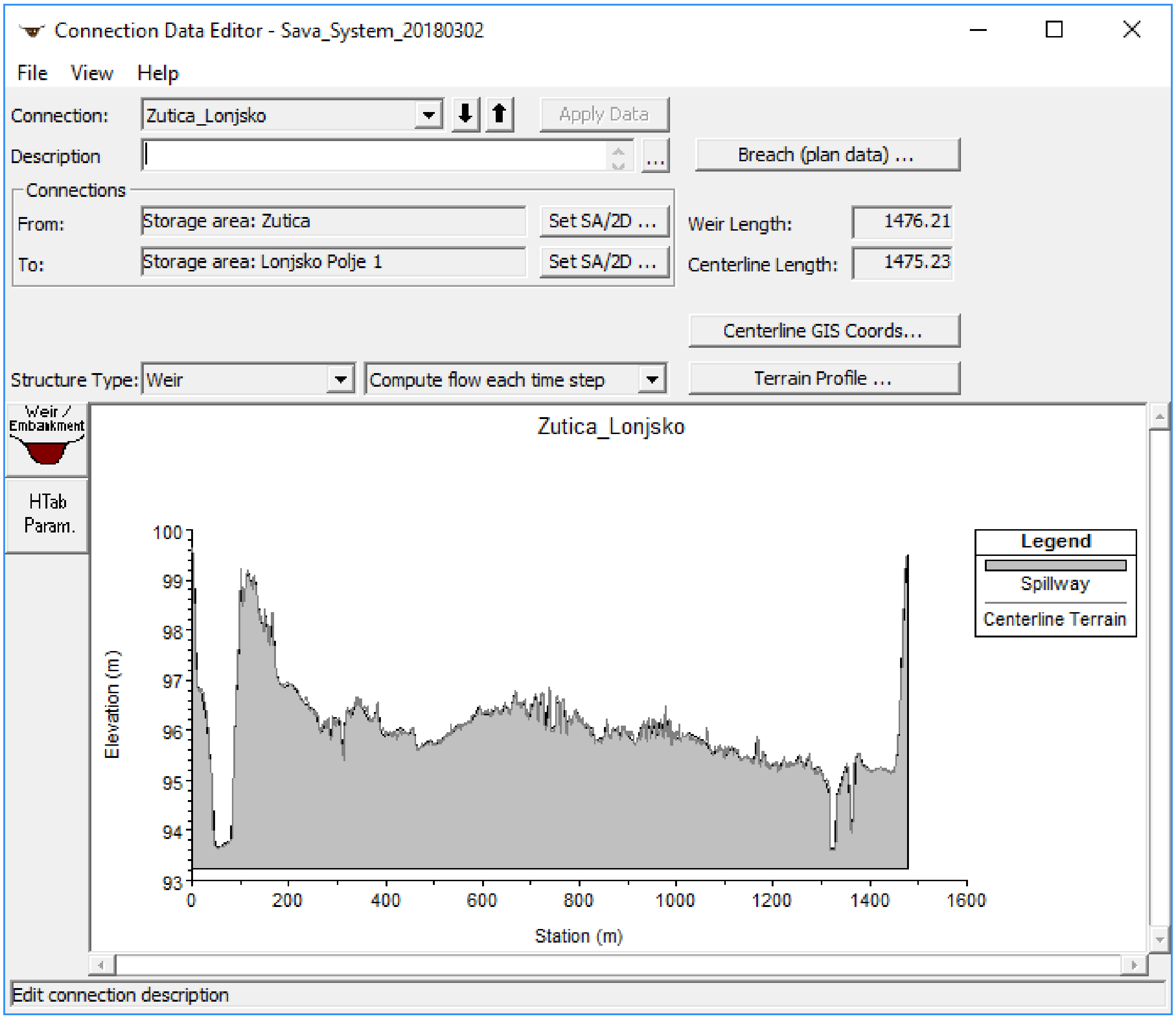


Figure 19. Example of a Storage Area Connection between Žutica and Lonjsko Retention Areas

The most extreme example of complex connections between river reaches to storage areas through lateral structures and connections between multiple storage and 2D areas is the Central Sava Flood Protection System in the middle region of the Sava River. This area includes extensive levees along the Sava River with multiple diversion weirs and gated structures passing flow into vast retention areas. Figure 20 illustrates the flood protection system and provides insight into how this system was modeled within HEC-RAS.

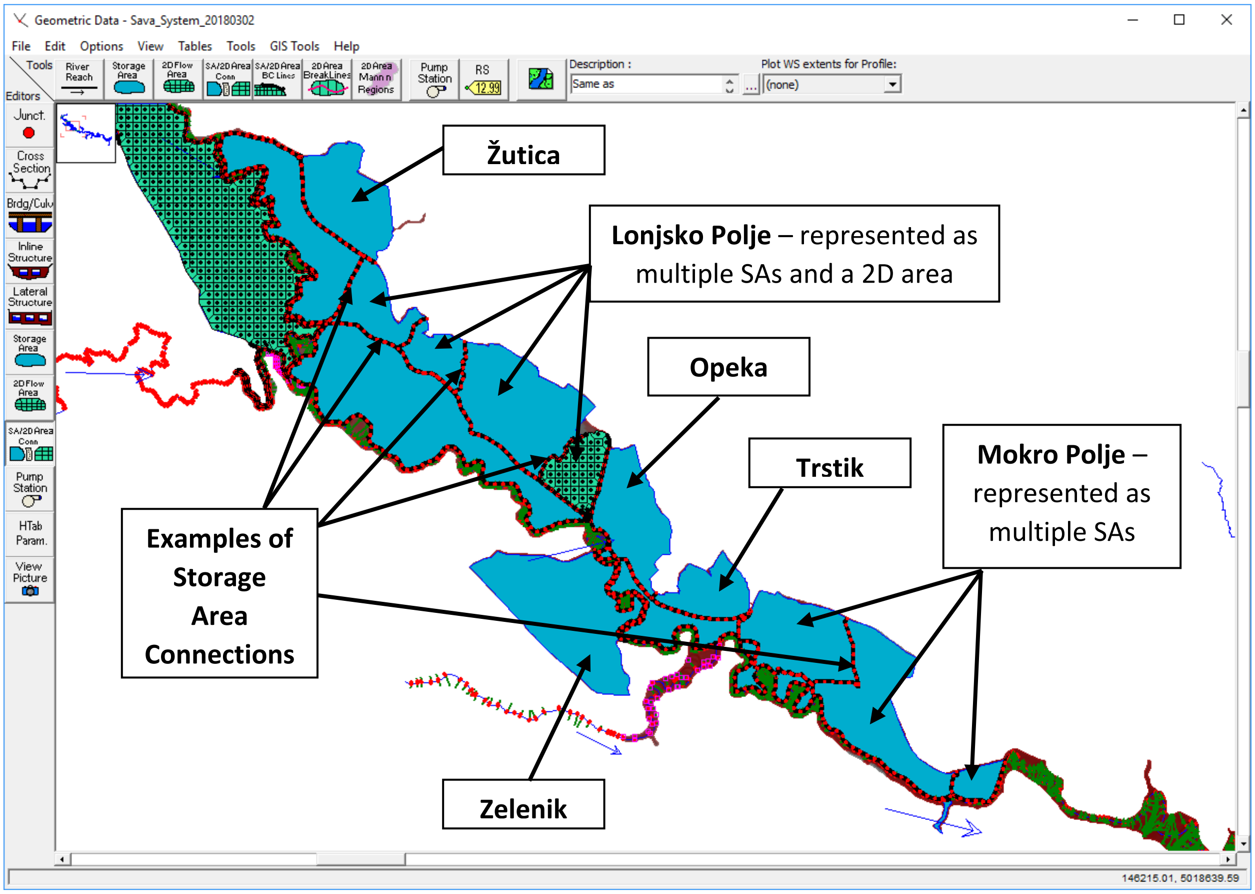


Figure 20. Examples of Storage Areas and Storage Area Connections

3.1.6 TRIBUTARY MODELS

Another unique component of the Sava River HEC-RAS model is the incorporation of major tributaries where existing models were provided by the member countries through the ISRBC. The major tributaries included in the Sava River HEC-RAS system model are:

- Bosna River
- Bosut River
- Bregana River
- Drina River
- Kolubara River
- Krapina River
- Kupa River
- Orljava River
- Sutla River
- Tinja River
- Una River
- Vrbas River

These tributary rivers were modeled using cross section data provided by the member countries and were incorporated into the mainstem Sava River system model. For most of these reaches, the model geometry lies outside of the extent of the LiDAR collected as part of this study; therefore no modifications were made to the model geometry with the exception of where the geometry posed instability issues. In most cases, these instabilities occurred at the most downstream extents of the reach where the tributaries were merged with the Sava River.

In areas where LiDAR information was available, the model geometry provided were merged with the LiDAR in the same manner as was done for the Sava River cross sections. Also, where LiDAR was available in the downstream reaches of these tributaries, the tributary model geometry was connected to storage areas using lateral structures as has been described in previous sections of this report.

In addition, the model geometry for the tributaries was truncated at the upstream end, in some cases, to account for the subbasin breakpoints in the hydrology model as the discharge results from the HEC-HMS model serve as the upstream boundary condition for these tributary models. Figure 21 shows the tributary models included in the HEC-RAS system model and the extents of the models.

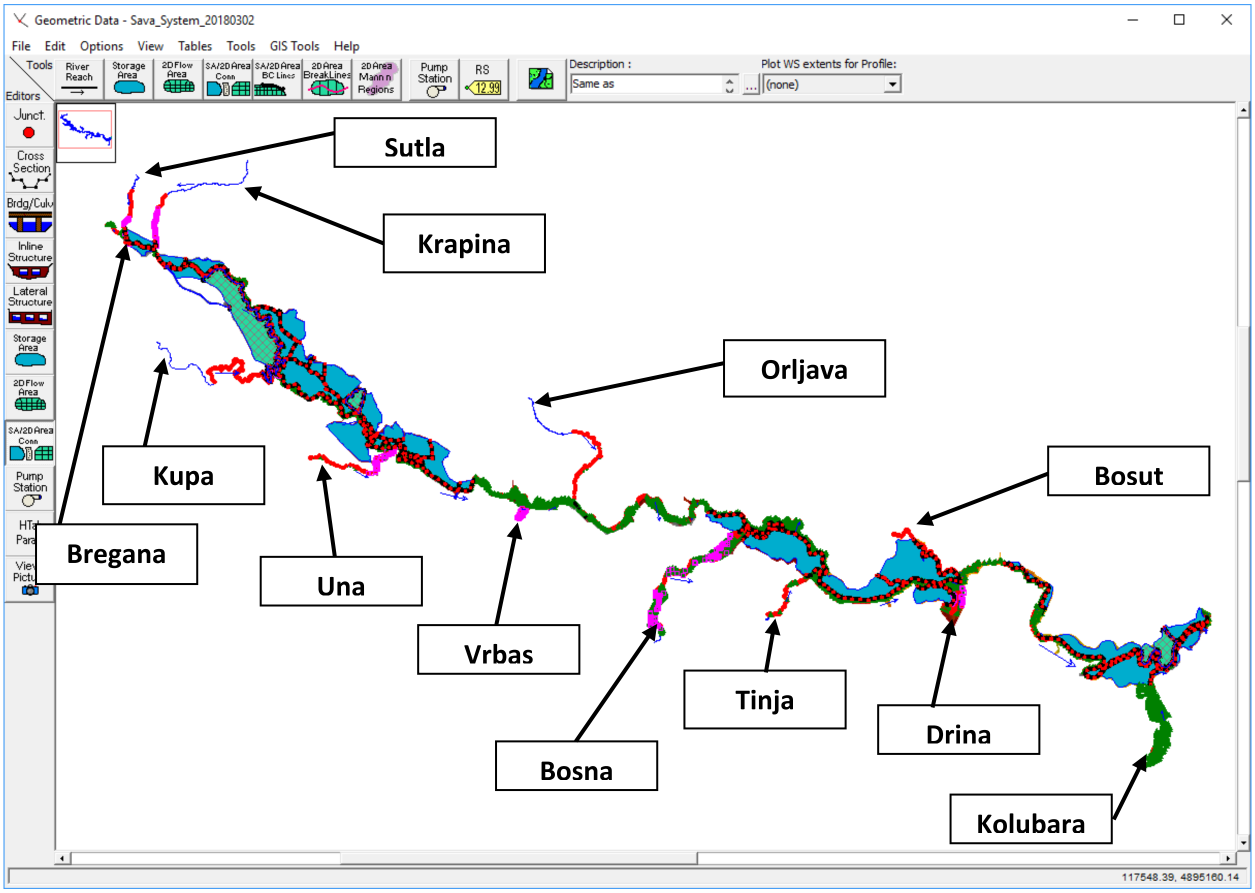


Figure 21. Map of Tributary Models Incorporated in the Sava River HEC-RAS System Model

3.2 HYDRAULIC MODEL BOUNDARY CONDITIONS

In addition to accurate model geometry, boundary conditions are critical to the performance and quality for any hydraulic model. Any hydraulic model requires the user to provide known and/or assumed information at the boundaries of the model such that the computer model can properly compute the complex hydraulic calculations across the rest of the model. The Sava River HEC-RAS model includes three different types of boundary conditions including:

- Initial Conditions – These boundary conditions serve as the initial estimation of certain characteristics such as flow in a reach or water surface elevation in a storage area. These boundary conditions are usually required to ensure the model simulation can begin in a steady, stable state.

- Upstream/Downstream Boundary Conditions – These boundary conditions serve as the most upstream or downstream input, typically flow or stage time series, into each model reach.
- Internal Boundary Conditions – These boundary conditions serve as inputs internal to the model geometry such as flow from a tributary or gate settings on a gated structure.

As is common with many hydraulic model applications, the Sava River HEC-RAS model primarily utilizes flow time series data as boundary conditions throughout the hydraulic model. The flow time series data could be derived from observed gauges; however, for the Sava River model, the origin of flow time series data comes from the Sava River watershed HEC-HMS model completed earlier in this phase of the project. In addition to flow time series data, observed elevation time series data was used as the downstream boundary condition at the Belgrade, Serbia hydro station to account for backwater from the Danube River.

Figure 22 provides better understanding of the link between HEC-HMS and HEC-RAS by showing the HEC-RAS geometry overlaying the HEC-HMS basin delineation and river network. Flow outputs at the nodes in the HEC-HMS model that correspond with the boundaries of the HEC-RAS reaches serve as inputs into the HEC-RAS model.

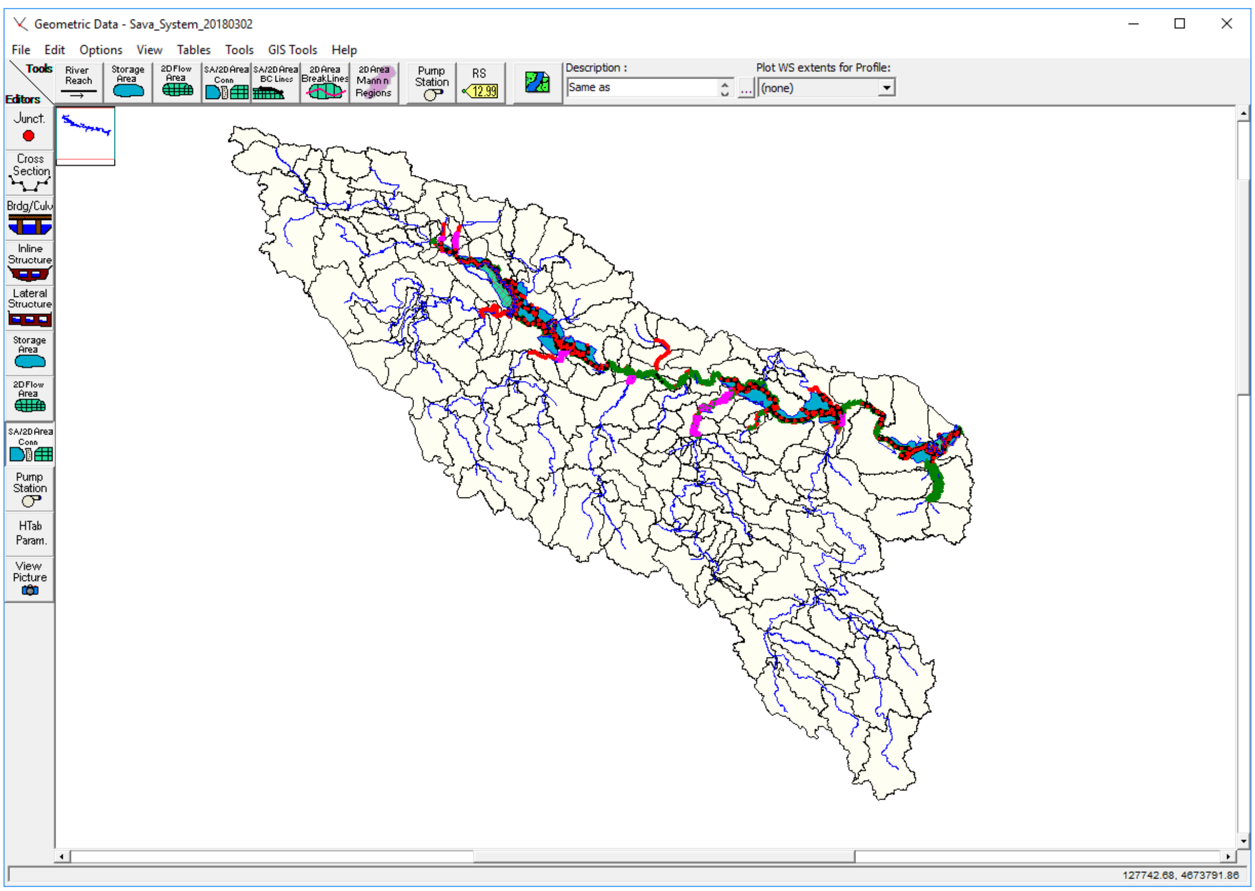


Figure 22. HEC-RAS Geometry and HEC-HMS Basin Model Schematic

In addition to the types of boundary conditions described in this section, the Unsteady Flow Data Editor is also the location where observed data such as stage hydrographs at various hydro stations along the

Sava River are input. These observed datasets are used to calibrate the results of the unsteady flow simulation. The hydro stations used for calibration from upstream to downstream include:

- Čatež
- Jesenice
- Jesenice na Dolenjskem
- Medave
- Podsused Žičara
- Zagreb
- Rugvica
- Dubrovčak Lijevi
- Crnac
- Gušće
- Jasenovac
- Stara Gradiška
- Mačkovac
- Davor
- Slavonski Kobaš
- Slavonski Brod
- Svilaj
- Šamac
- Županja
- Gunja
- Jamena
- Sremska Mitrovica
- Beograd

The remainder of this section will discuss more specifically the different types of boundary conditions used in the Sava River HEC-RAS model.

3.2.1 INITIAL CONDITIONS

Initial conditions in a HEC-RAS unsteady flow hydraulic model serve as the initialization of the model (as the name suggests). For unsteady flow simulations in HEC-RAS, initial conditions, as well as all boundary condition information, is entered through the Unsteady Flow Data editor. HEC-RAS uses the user-provided initial condition input to first compute a steady flow backwater run to compute water surface elevations at every cross section prior to beginning the unsteady simulation. The water surface elevation at any cross section can be overwritten by the user using the "Internal RS Initial Stages..." tool under the "Options" menu in the Unsteady Flow Data Editor. For the Lonja Canal connecting the Prevlaka gates with the Žutica retention area required this option to create a more stable starting condition for the model.

Historically, setting initial conditions within HEC-RAS was time consuming and difficult; however, in recent releases of the software, initial conditions can be more automatically determined. For an unsteady flow simulation, initial conditions typically need to be set for the most upstream cross section in each reach and for all storage areas (if the model geometry includes storage areas). Figure 23 shows the initial conditions tab in the Unsteady Flow Data Editor. The top portion of the figure show where initial flows can be set for the most upstream cross section in each reach while the bottom portion of the figure shows where initial water surface elevations can be input for storage areas.

For the Sava River model, the initial conditions are left blank for most elements as shown in Figure 23. HEC-RAS allows these values to be left blank because the software has been designed to pull this information from other sources automatically. For the most upstream cross section in each reach, HEC-RAS uses the first value in all of the boundary condition hydrographs (discussed further in this section). Values are set from upstream to downstream by adding flows together at junctions as appropriate. For storage areas, the initial water surface elevation can now be left blank. If left blank, the storage area will be assumed to start dry unless the storage area is connected to a lateral structure and the water surface on the lateral structure is higher than the minimum weir elevation. In this case, HEC-RAS will use the average water surface elevation going over the weir, which would mean water would be flowing into the storage area at the beginning of the simulation.

For almost all simulations, the initial conditions are left blank, and HEC-RAS computes the initial condition. In rare cases where instabilities occurred at the beginning of a simulation, initial water surface elevations were required to be input for specific storage areas. The results of the simulation showed where these instabilities occur through the messaging in the run window making it simple to determine if a storage area needed user-defined initial conditions.

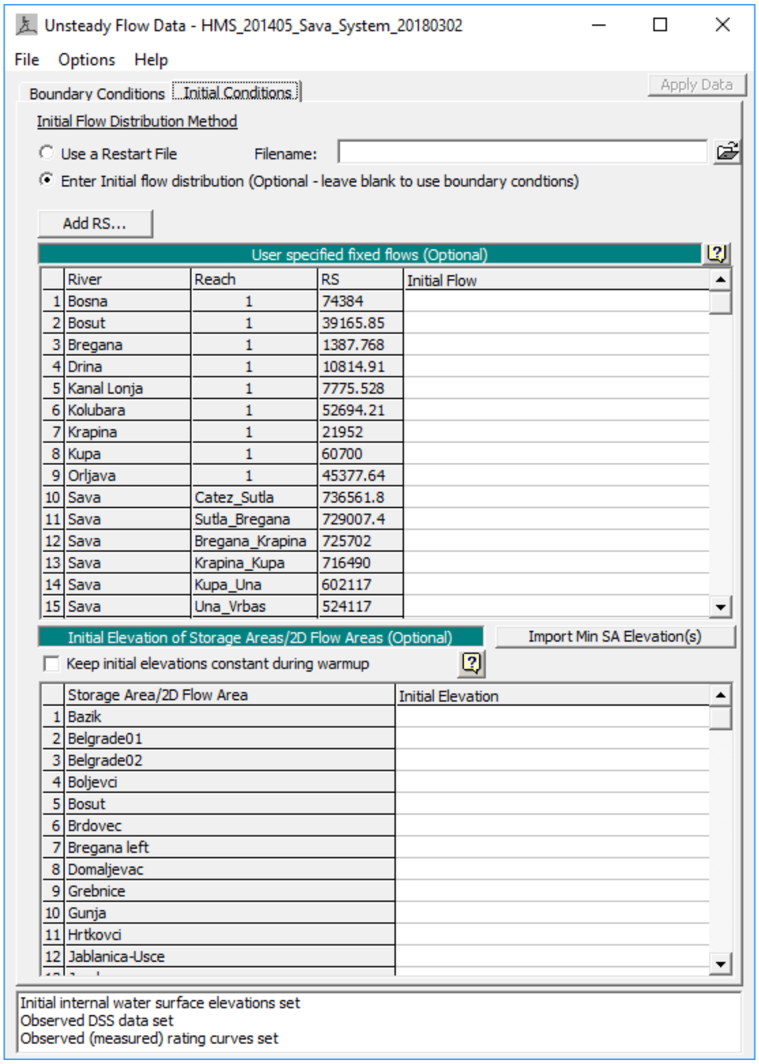


Figure 23. Initial Conditions in the Unsteady Flow Data Editor

3.2.2 UPSTREAM/DOWNSTREAM BOUNDARY CONDITIONS

Every hydraulic model requires assumptions at the extreme boundaries of the geometry. For unsteady flow simulation in HEC-RAS, upstream and downstream boundary conditions are required and are entered through the boundary conditions tab in the Unsteady Flow Data Editor (Figure 24). The information used for these boundary conditions can be assumptions like an energy grade slope or model output from a hydrological model. In addition, observed information like flow or stage hydrographs can be used for these boundary conditions.

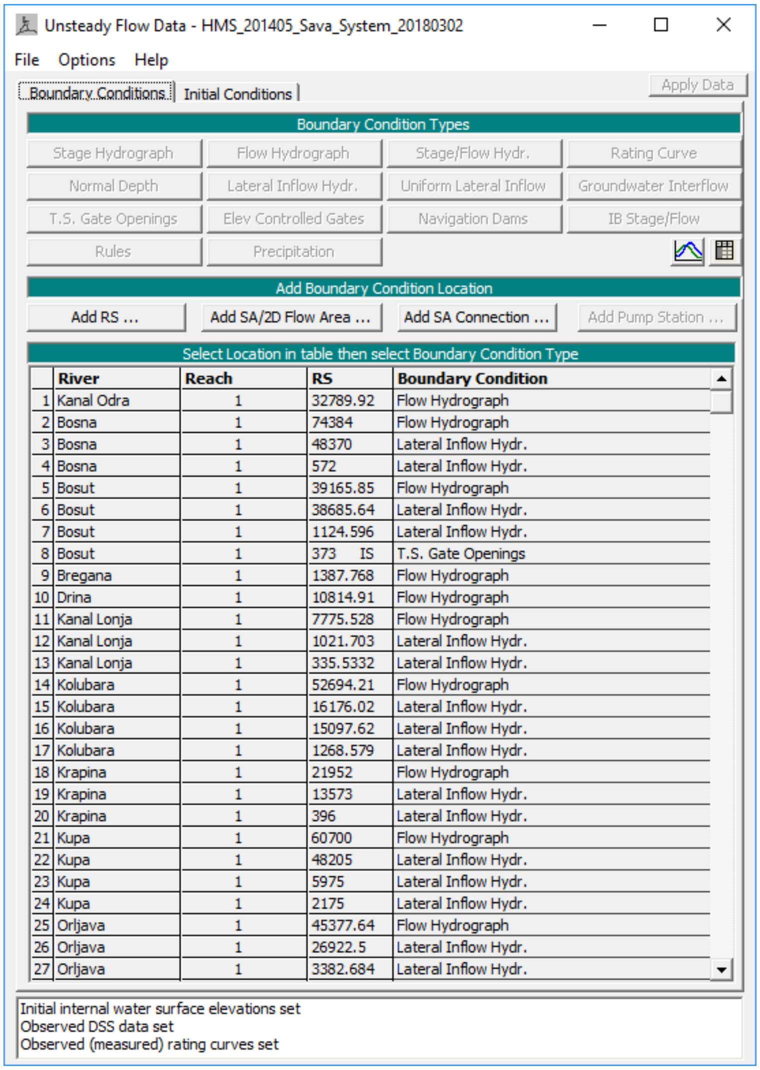


Figure 24. Boundary Conditions Tab of the Unsteady Flow Data Editor

For the Sava River HEC-RAS model, flow hydrograph output from the Sava River watershed HEC-HMS model are used for all upstream boundary conditions. In order to produce the most accurate model possible, the observed stage hydrograph at the hydro station on the Sava River in Belgrade, Serbia is used as the downstream boundary condition. Using the observed stage hydrograph this close to the mouth of the Sava River allows the model to incorporate backwater flooding from the Danube River during the entire simulation.

Upstream boundary conditions are only required for the most upstream cross section of each reach including the Sava River and any major tributary incorporated into the model. For internal reaches within the Sava River where a junction is used to transfer flow from an upstream Sava River reach and major tributary reach downstream to another Sava River reach, upstream boundary conditions are not required. HEC-RAS utilizes the flows from the two upstream reaches to determine the flow on the next reach downstream on the Sava River.

Table 3 lists all of the upstream boundary conditions for each reach in the Sava River HEC-RAS model. In addition, the most upstream cross section in each reach where the flow hydrograph input is applied is also listed along with the HEC-HMS node that serves as the origin for the flow hydrograph.

Table 3. Upstream Boundary Conditions for the Sava River HEC-RAS Model

River	Most Upstream XS River Station (m)	Flow Hydrograph Source from HEC-HMS Node
Bosna River	74384	J_20_19_27
Bosut River	39165.85	J_26_01_09_Nijemci
Bregana River	1387.768	W_03_01_03 (multiplier of 0.5)
Drina River	10814.91	24_DRINA_OUT
Kolubara River	52694.21	J_28_03_01
Krapina River	21952	J_04_02_02
Kupa River	60700	J_06_10_03
Orljava River	45377.64	J_16_02_02
Sava River	736561.8	J_01_13_08_Catez
Sutla River	20080	J_02_01_02_Zelenjak
Tinja River	40981.19	J_22_01_07
Una River	41355.08	J_12_05_03_Kostajnic
Vrbas River	11515.4	14_VRBAS_OUT

3.2.3 INTERNAL BOUNDARY CONDITIONS

Internal boundary conditions are similar to upstream in that the input type is typically a flow hydrograph. Like upstream and downstream boundary conditions, internal boundary conditions are entered into HEC-RAS through the boundary conditions tab of the Unsteady Flow Data Editor as shown in Figure 24. All internal boundary conditions are derived from flow hydrograph outputs from HEC-HMS. The only exception to this are the gate opening information for the gated structures within the Sava River system, which will be discussed later in this section.

The internal boundary conditions are input as lateral inflow hydrographs at various points along the Sava River and major tributary reaches. These boundary conditions are incorporated where there is a junction within HEC-HMS along each reach where local subbasin flows are routed into the reach. Using internal boundary conditions allows for not only runoff from drainage areas above the most upstream cross section of each reach (upstream boundary conditions) but also local drainage areas along the studied reach. The number of internal boundary conditions is too numerous to mention here; however, all boundary condition input locations at HEC-RAS cross sections and the source node of the flow hydrograph from HEC-HMS are provided in Appendix A.

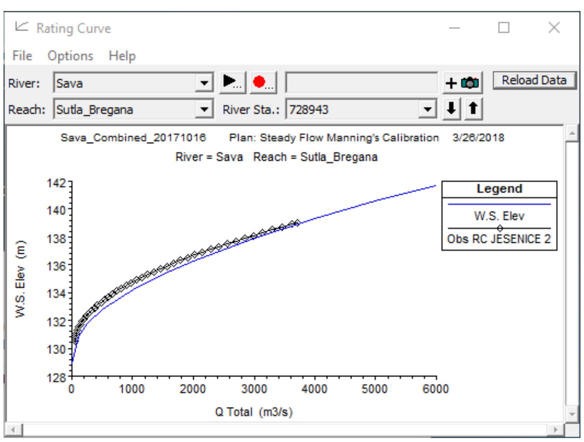
In addition to flow hydrograph inputs, HEC-RAS requires a boundary condition to be set for any structure with gates such that the software knows how to operate the gated structure during a simulation. For the calibration simulations, observed gate opening information was provided by the Sava River riparian countries through the ISRBC and used as an input into the Unsteady Flow Data Editor.

3.3 HYDRAULIC MODEL CALIBRATION

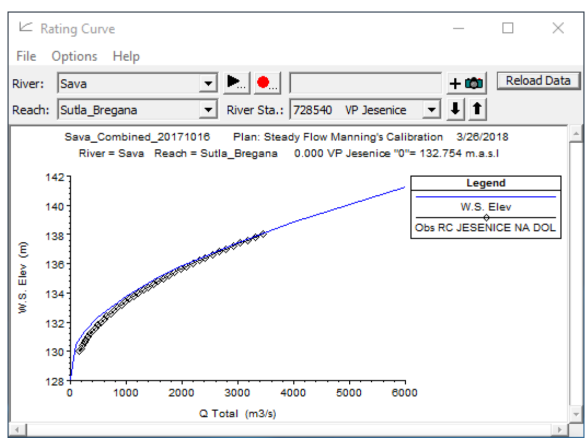
Prior to any efforts to calibrate the unsteady flow model, USACE first developed the model geometry and boundary conditions using the best available data as discussed in previous sections of this report. Detailed calibration was not attempted prior to developing a stable unsteady flow model based on accurate geometry to avoid the requirement to significantly iterate between geometry and boundary condition development and model calibration. However, portions of the geometry were refined throughout the model calibration process as areas for improvement were identified while evaluating the results of the calibration.

The first step in the calibration process included the conversion of the unsteady flow model to a steady flow model and calibration to known and derived rating curves at hydrologic gauging stations along the Sava River. The institutions of the Sava River riparian countries provided rating curves at several stations along the Sava River. In addition, USACE used observed elevation and flow time series data to derive rating curves at other stations along the Sava River. The purpose of this step in the calibration process is to initially calibrate Manning's roughness values throughout the Sava River. This step provides a reasonable initial estimate of Manning's roughness values throughout the Sava River reach.

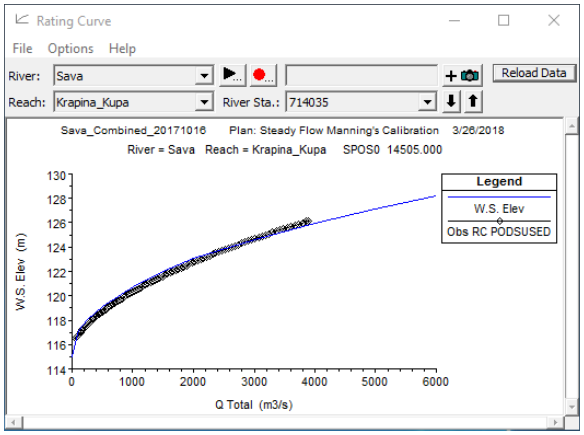
In order to perform this calibration step, USACE input the rating curves into the HEC-RAS model and set up steady flow data for a reasonable range of flows along the Sava River reaches within the HEC-RAS model. HEC-RAS provides the ability to input rating curves at known locations throughout a reach through the *Options* menu of the Unsteady Flow Data editor. In addition, HEC-RAS also reports the results of the steady flow runs using the range of potential flows and plots the resulting computed rating curve against the observed rating curve. Using rating curves at fifteen stations throughout the Sava River, USACE iteratively adjust Manning's roughness values to calibrate to the observed rating curves. Because HEC-RAS steady flow computations use a backwater step calculation, USACE calibrated Manning's roughness values to rating curves from downstream to upstream. Figure 25 displays the results of this steady flow calibration process that provided initial estimates of Manning's roughness values for the entire Sava River reach being studied.



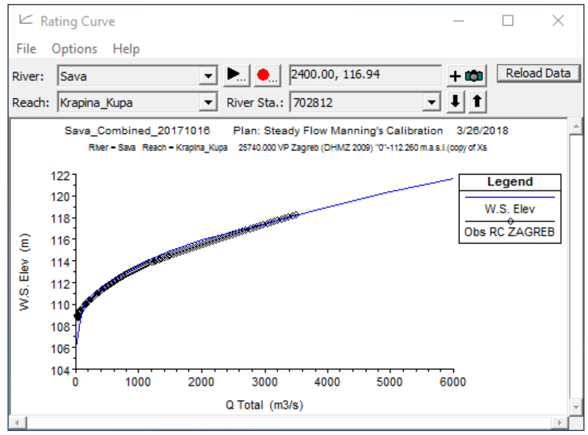
(a) Jesenice 2



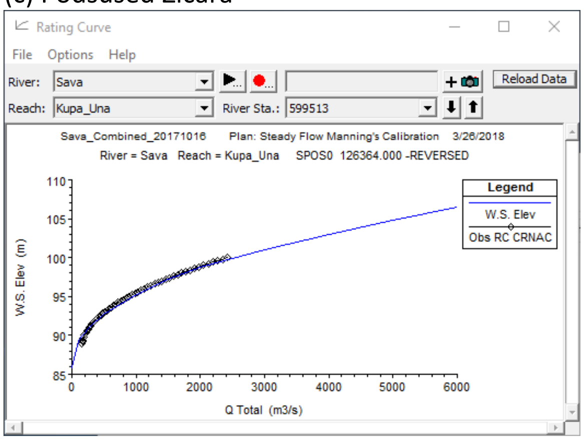
(b) Jesenice Na Dolenjskem



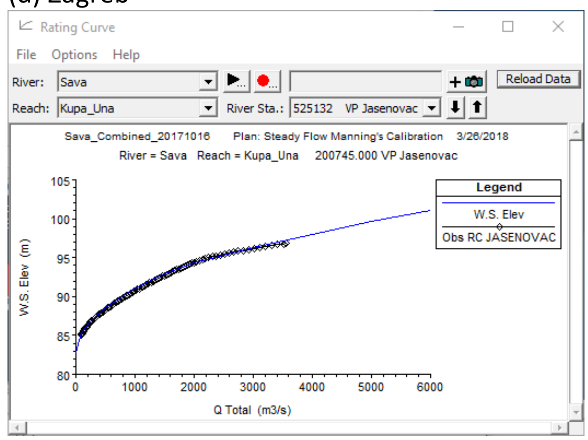
(c) Podsused Žičara



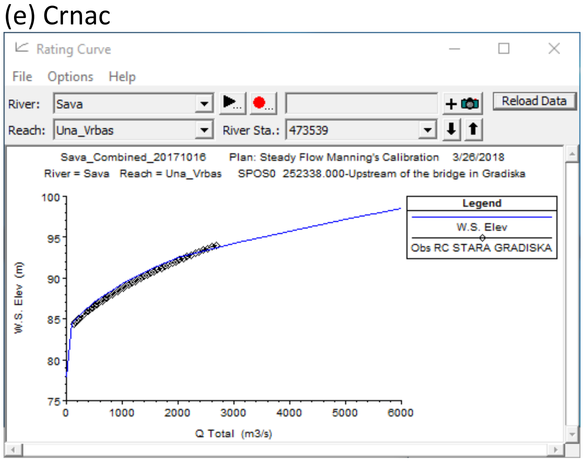
(d) Zagreb



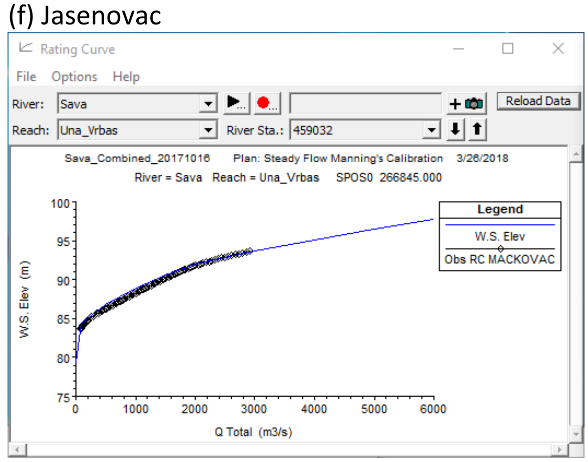
(e) Crnac



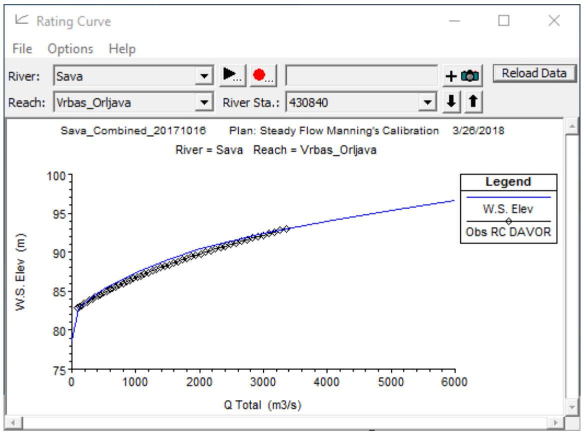
(f) Jasenovac



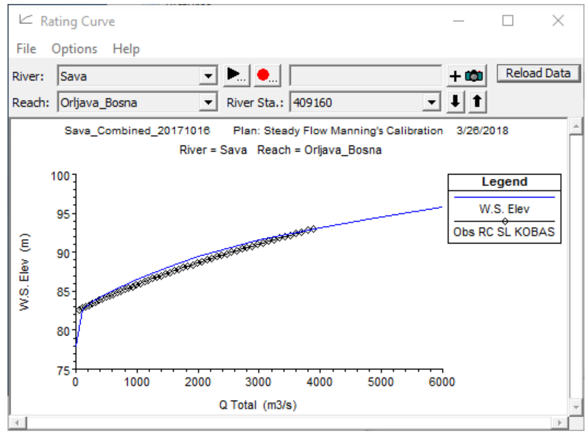
(g) Stara Gradiška



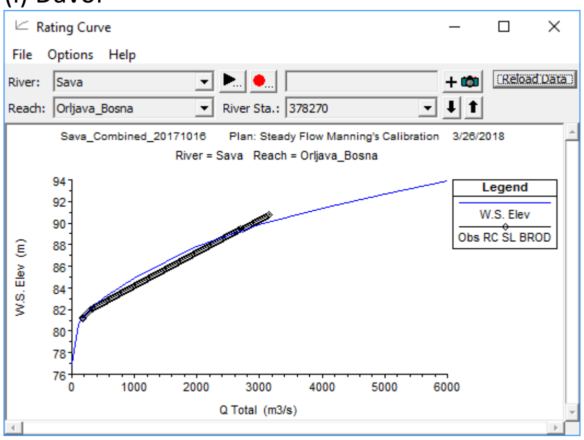
(h) Mačkovac



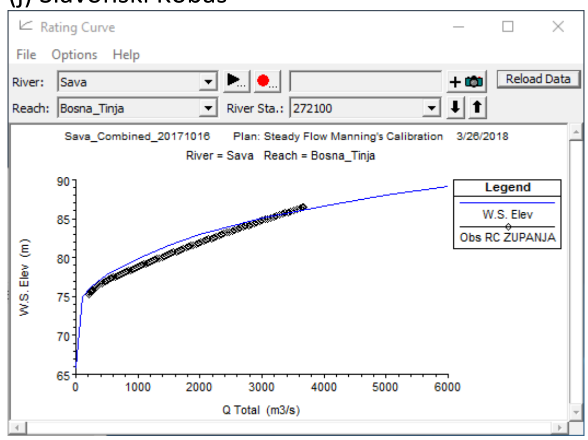
(i) Davor



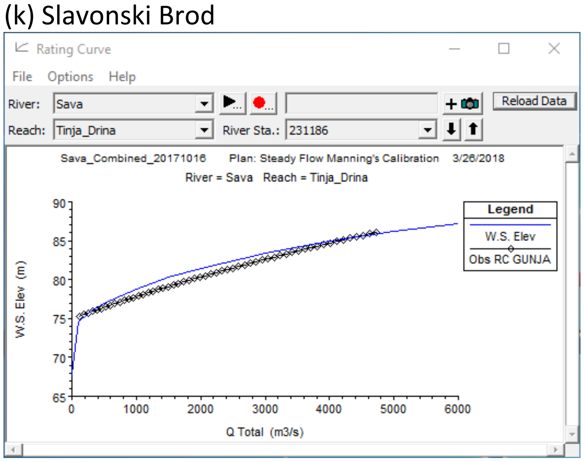
(j) Slavonski Kobaš



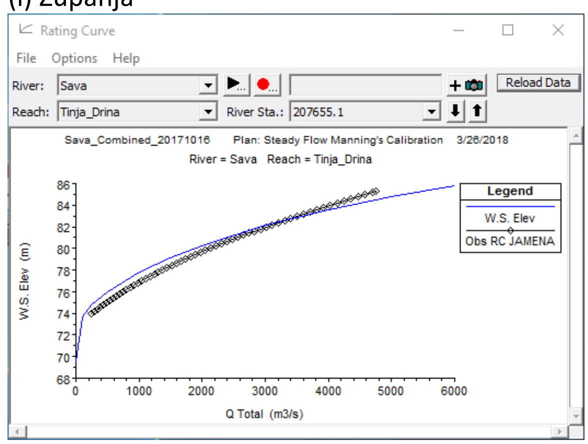
(k) Slavonski Brod



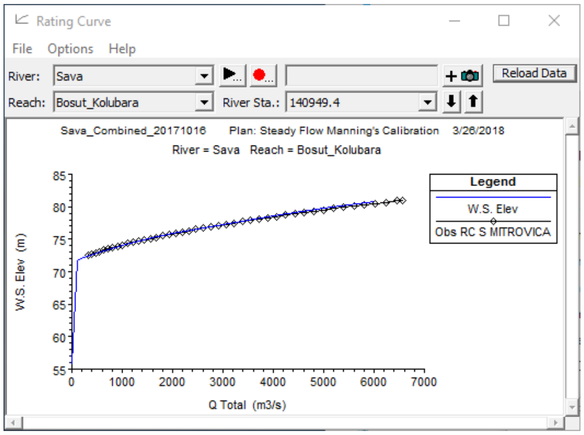
(l) Županja



(m) Gunja



(n) Jamena



(o) Sremska Mitrovica

Figure 25. Results of the Steady Flow Manning's Roughness Calibration

As Figure 25 shows, the results of the steady calibration to rating curves is good throughout the full range of flows; however, this calibration only provides an initial estimation of Manning's roughness based on steady state conditions. In reality, hydraulic characteristics especially Manning's roughness of a natural system actually perform differently between higher and lower flows. Therefore, the next step in the calibration process was to use *Flow Roughness Factors* from the Tools menu in the Geometric Data editor within HEC-RAS.

The *Flow Roughness Factors* tool allows the user to vary the Manning's roughness across the full range of expected flows for the Sava River reach. USACE used this tool to calibrate to the observed elevation hydrographs at each hydrologic stations along the Sava River. In order to conduct this part of the calibration process, calibration zones including a set of HEC-RAS cross-sections were established through the Sava River reach. These calibration zones are a collection of the representative cross sections around each hydrologic station. This calibration was conducted for all three calibration events and the best possible factors were used for each calibration zone.

The calibration process included iteratively adjusting the flow roughness factors for each of the three calibration events until the best calibration at each hydrologic station was achieved for each event. When completed, a collection of the best flow roughness factors was selected that best represented the flow hydraulics of the system.

In addition to adjusting flow roughness factors, other components of the geometry were evaluated during this calibration process such as inflows from HEC-HMS, routing of tributary reaches, and elevations of lateral structures representing levees and high ground. Every model input contains some level of error whether it is random or observational and the modeler must consider the existence of this error. In addition, a modeler must also make assumptions about specific hydraulic characteristics such as weir coefficients for levees and simplifications for top of levee profiles. Therefore, USACE systematically evaluated whether the discrepancies between observed and computed results were a product of the potential errors and assumptions or the need to calibrate Manning's roughness during the calibration process. As the calibration was conducted, USACE evaluated components of the geometry such as levees overtopping to determine if the assumptions for weir coefficients were correct. In addition, USACE relied on pieces of information received from Sava River riparian institutions through the ISRBC to verify some of these assumptions and ultimately arrive at the best possible calibration. For instance, information related to the overtopping of the Jankomir Weir indicated that the peak flow overtopping the weir during the September/October event from 2010 was about 700 CMS. USACE used this information and other information like this to ensure that the weir coefficient assumption was accurate for the Jankomir weir.

Ultimately, at the completion of the calibration process, USACE achieved a final geometry representing the Sava River system with the best possible representative hydraulic characteristics. The results of the calibration process are discussed further in Section 3.4.

3.4 RESULTS AND POST-PROCESSING

The overall objective of this study is to produce an unsteady hydraulic model capable of representing the hydraulic characteristics of the very complex Sava River system for a range of events. This section presents the results of this analysis. Overall, the results indicate that the unsteady hydraulic model produces reasonable and reliable water surface profile results for the calibration events used during this study.

As mentioned in previous sections, the calibration events include the December 2009 event, which was a widespread event affecting the entire Sava River, the September 2010 event, which stressed the Middle Sava Region’s flood protection system of diversions and retention areas, and the May 2014 event, which was a very significant event for the lower region of the Sava River. These events were chosen because they represent events that affect a wide range of conditions for the entire Sava River.

Various results of the unsteady flow hydraulic model were evaluated by USACE to include water surface profiles, stage hydrographs, and inundation areas. The most valuable information related to visualizing the accuracy of the results of the analysis were the observed elevation time series data at the various hydrologic stations along the Sava River. This observed information was used to compare the results of the hydraulic model using the profile and output hydrograph plots within HEC-RAS. Figure 26 through Figure 28 below shows the resulting maximum profile for the 3 calibration events. The results shown in the figures illustrate that the peak water surface elevation results from the hydraulic model match very well to the observed data.

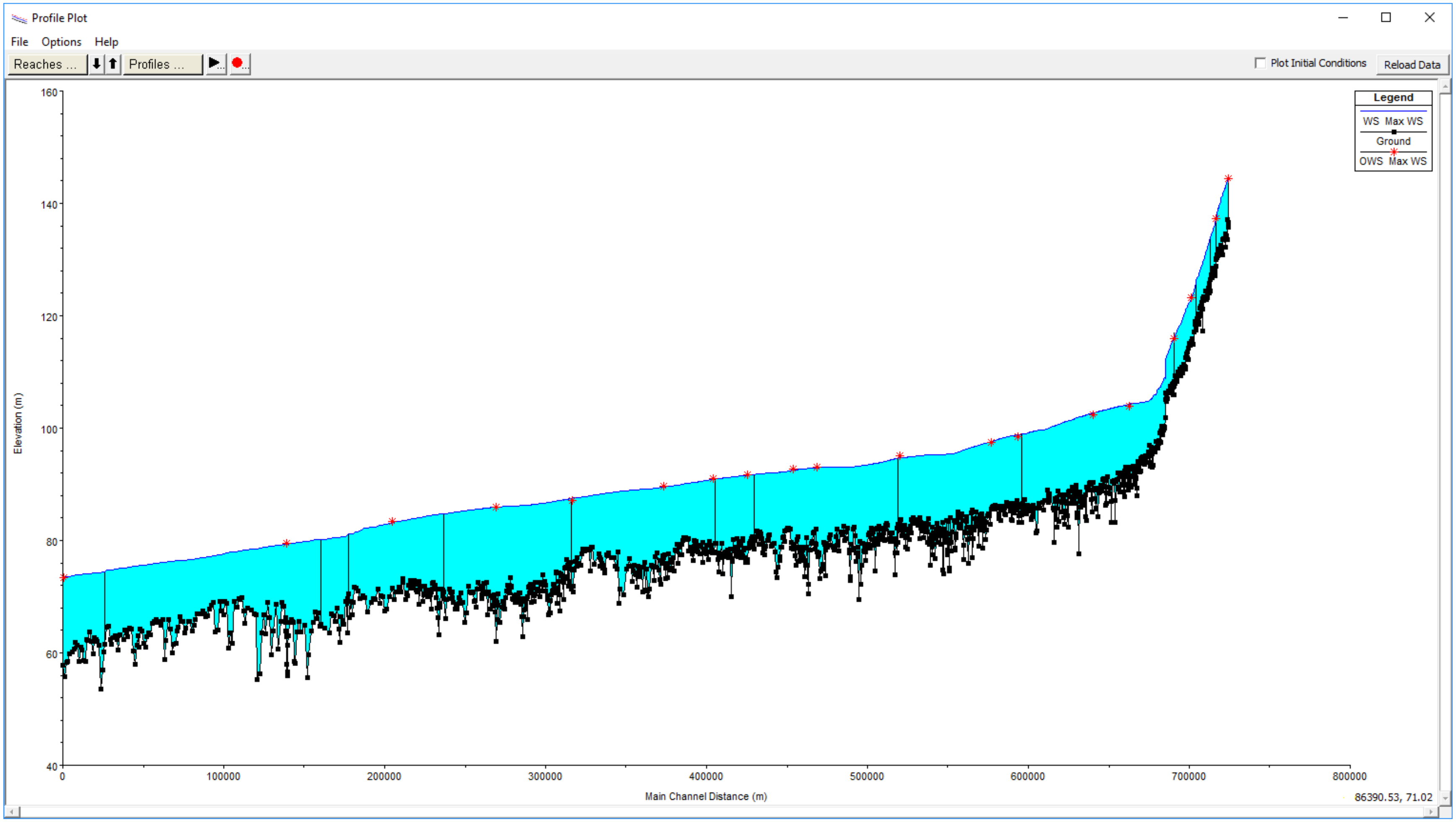


Figure 26. Maximum Water Surface Profile Calibration Plot for the December 2009 Event

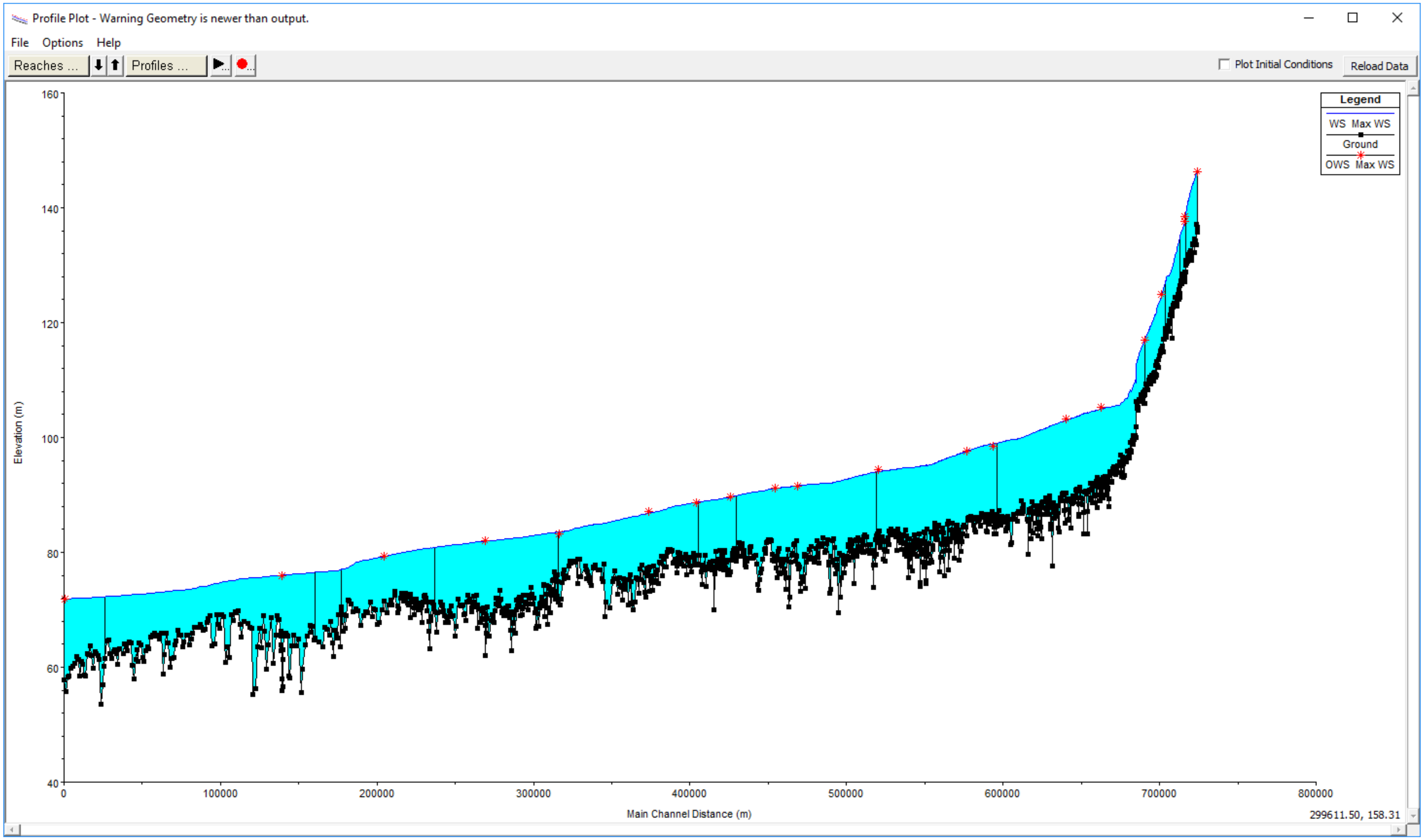


Figure 27. Maximum Water Surface Profile Calibration Plot for the September 2010 Event

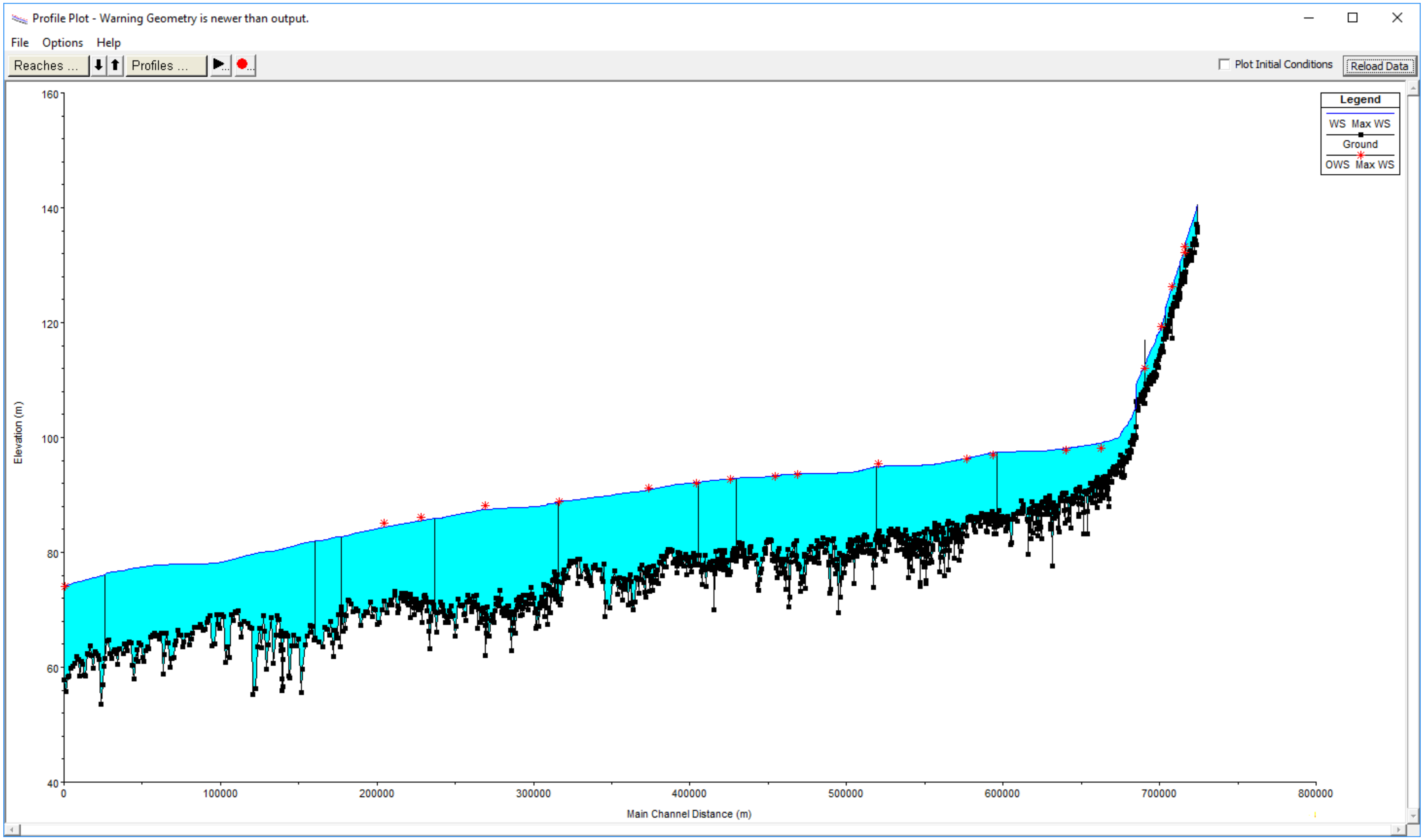
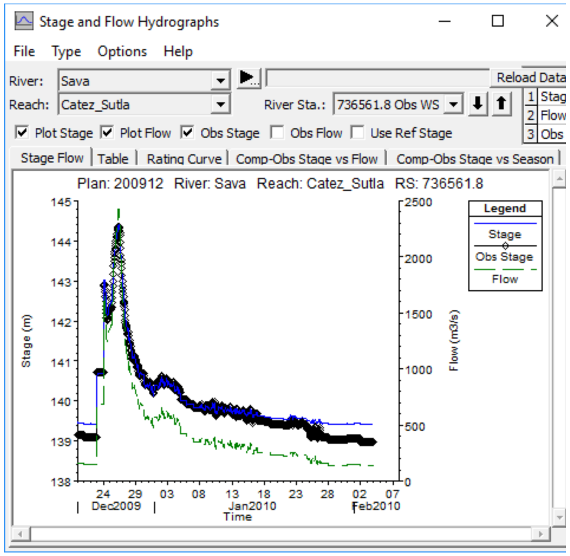


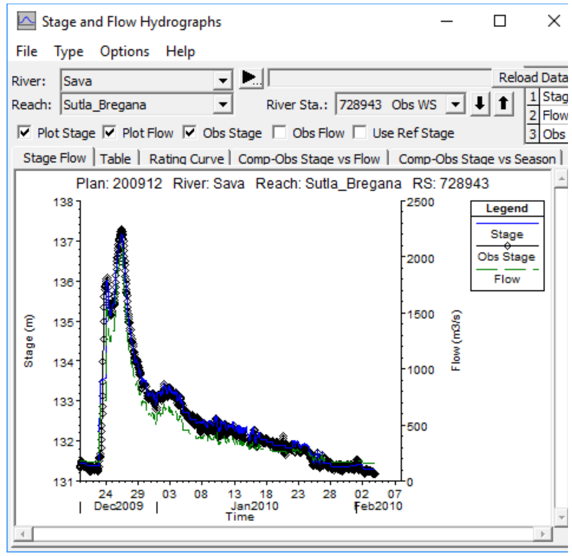
Figure 28. Maximum Water Surface Profile Calibration Plot for the May 2014 Event

The next output option in HEC-RAS used to compare the results of the hydraulic model with observed data was the output hydrograph plot. In HEC-RAS, observed elevation time series data from hydrologic stations can be read directly into the model at specific river stations. USACE imported the observed data into the model and compared the results at each hydrologic station with observed data.

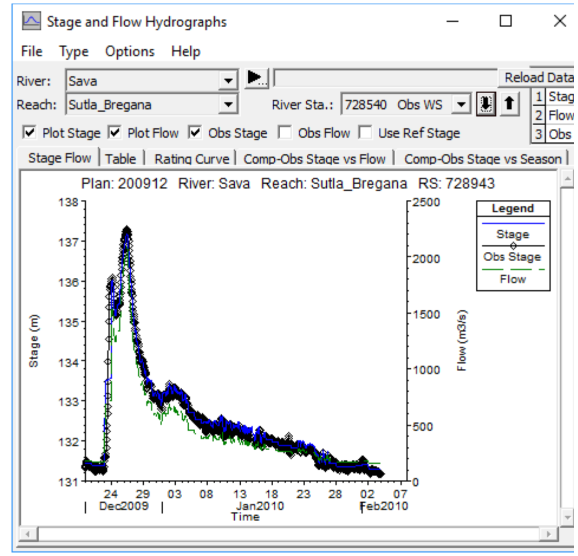
Figure 29 through Figure 31 shows the output hydrograph results at various hydrologic stations for each calibration event. In general, the calibration was very good for the full range of events. As expected, the model has certain areas of weakness, but overall the model produces representative water surface profile and hydrograph results for the Sava River system. Some of the possible weaknesses of the model will be further discussed in *Section 5.1* below in the *Conclusions* section.



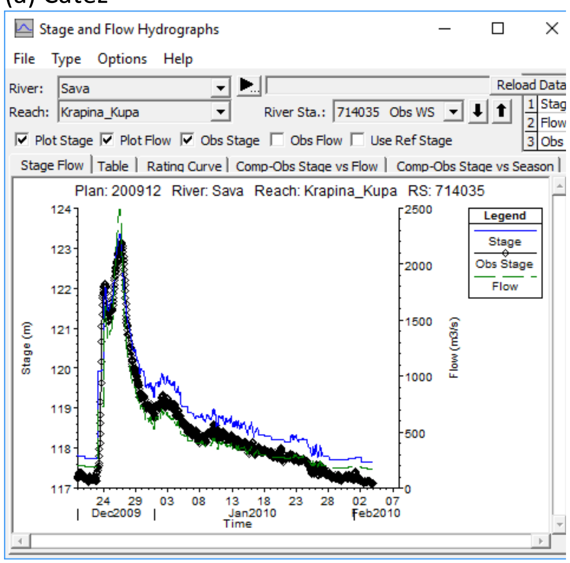
(a) Čatež



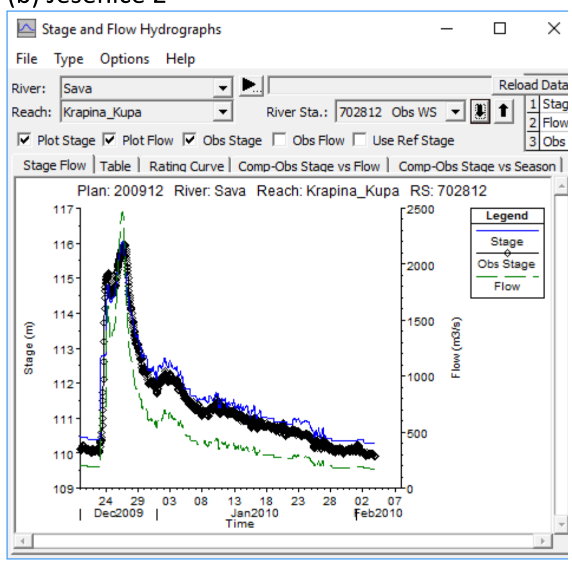
(b) Jesenice 2



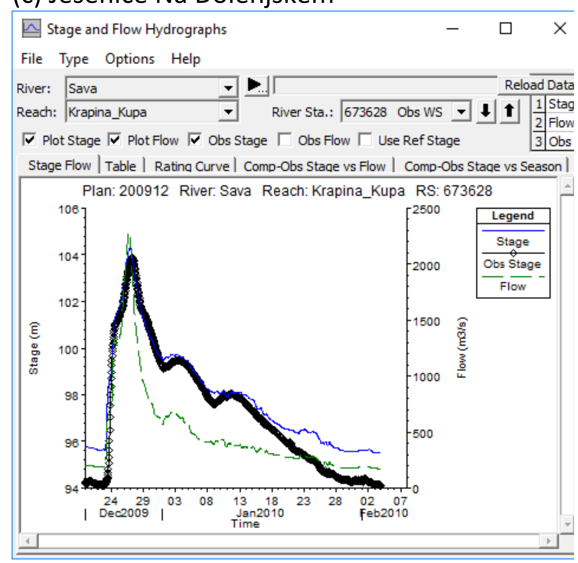
(c) Jesenice Na Dolenjskem



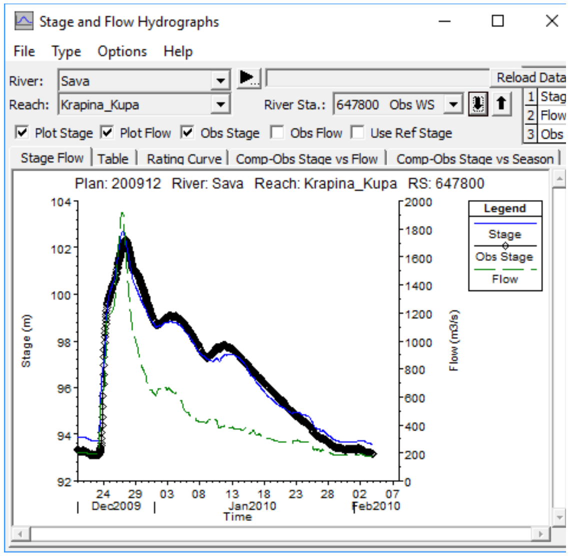
(d) Podsused Žičara



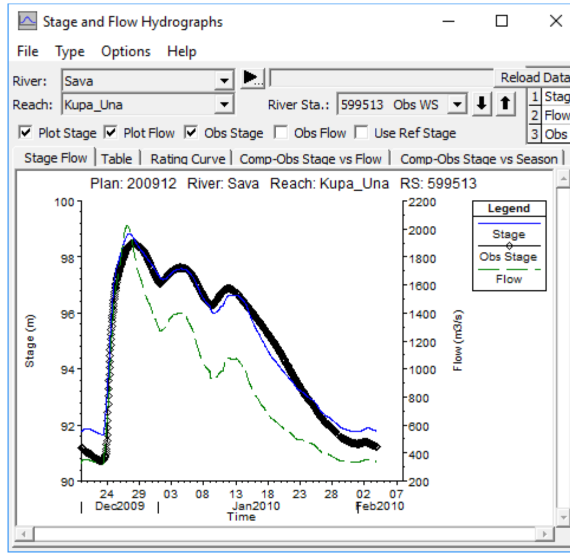
(e) Zagreb



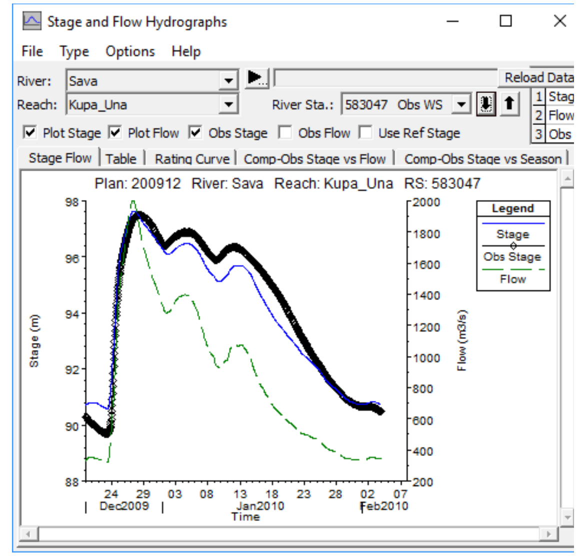
(f) Rugvica



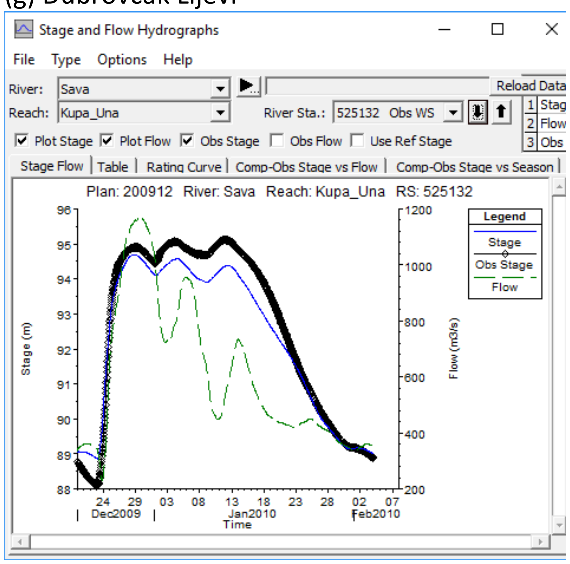
(g) Dubrovčak Lijevi



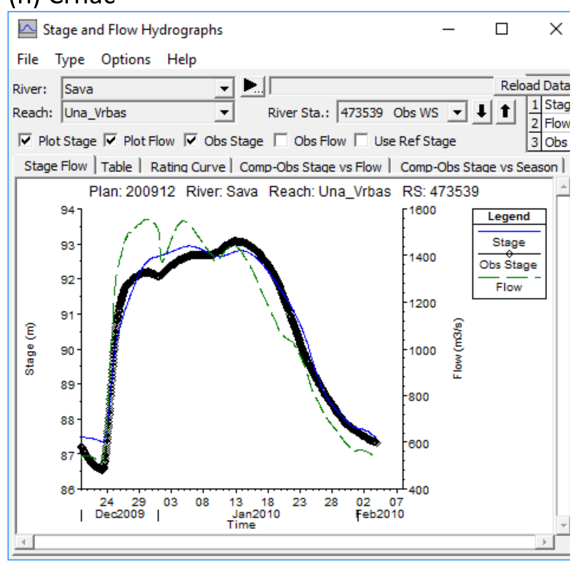
(h) Crnac



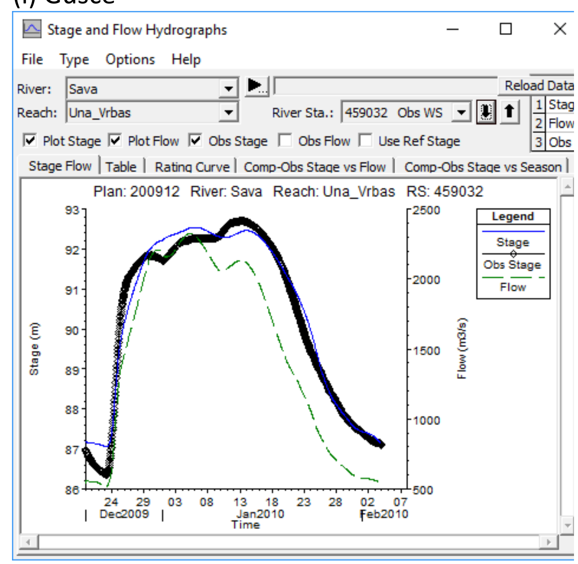
(i) Gušće



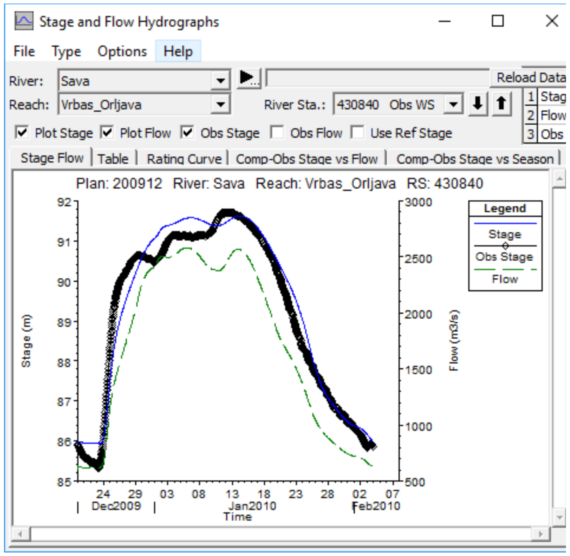
(j) Jasenovac



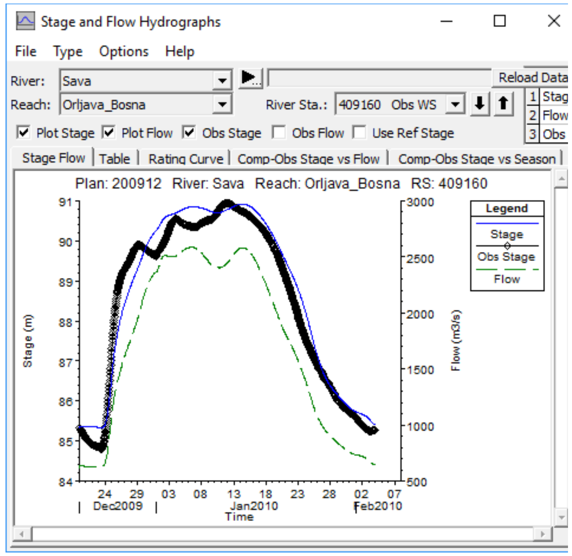
(k) Stara Gradiška



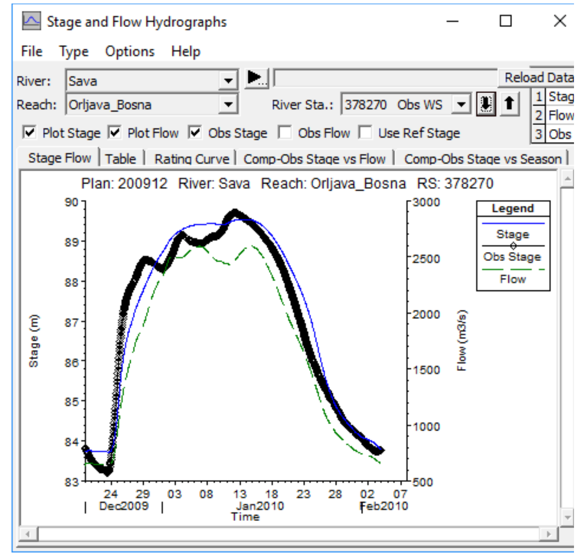
(l) Mačkovac



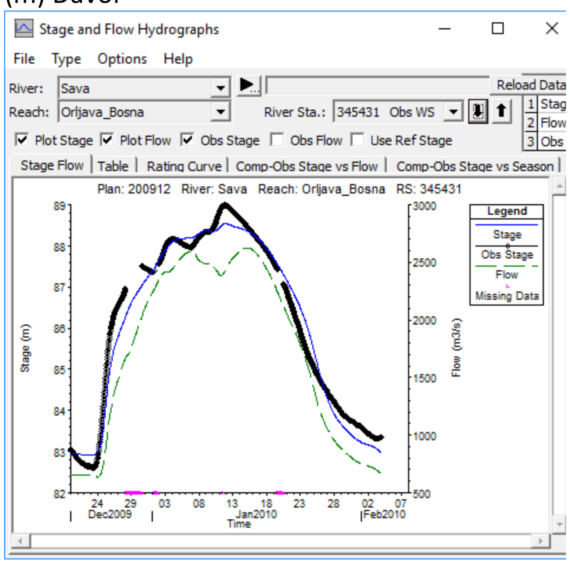
(m) Davor



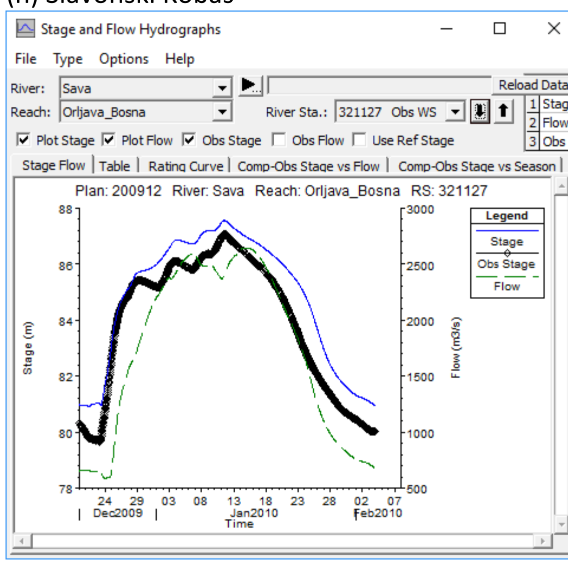
(n) Slavonski Kobaš



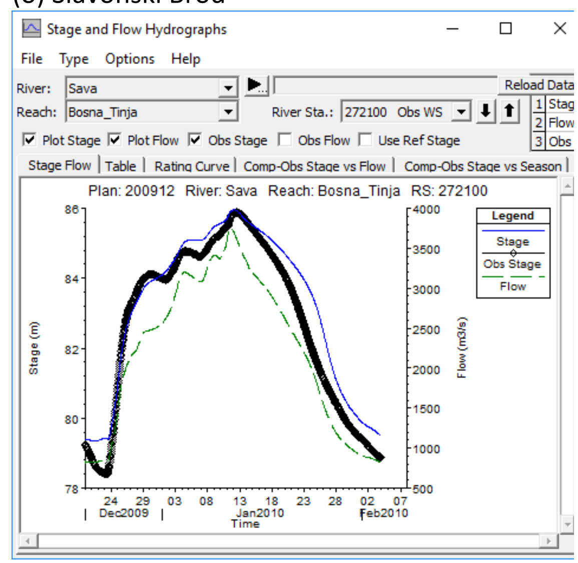
(o) Slavonski Brod



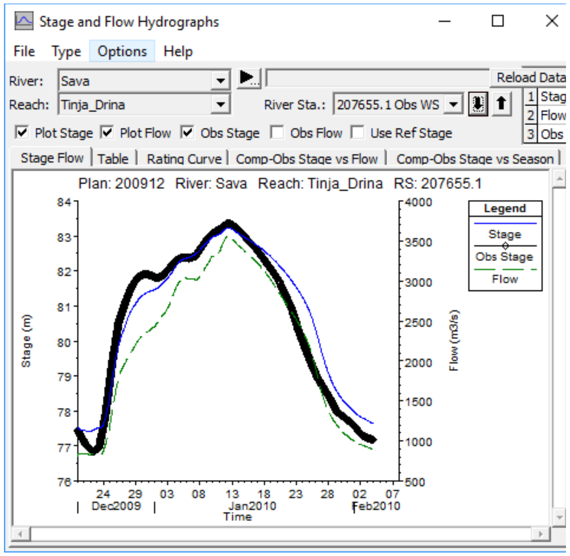
(p) Svilaj



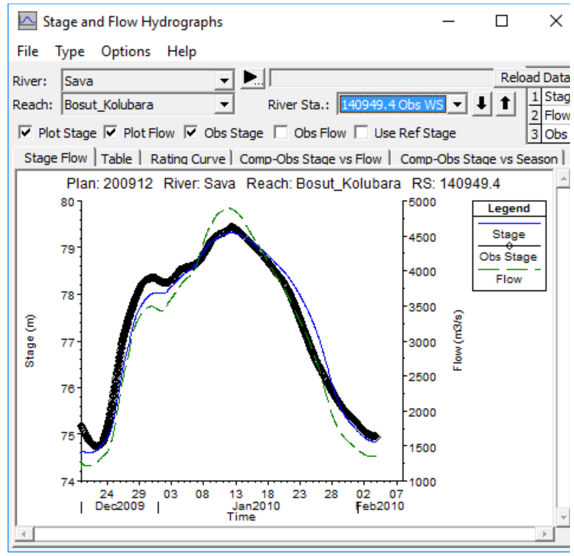
(q) Šamac



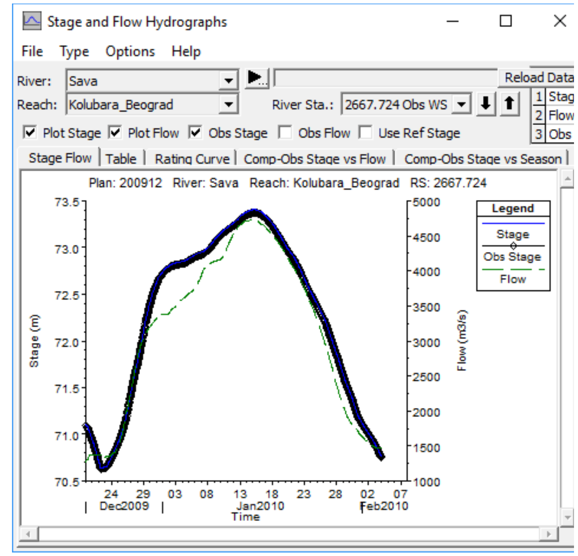
(r) Županja



(s) Jamena

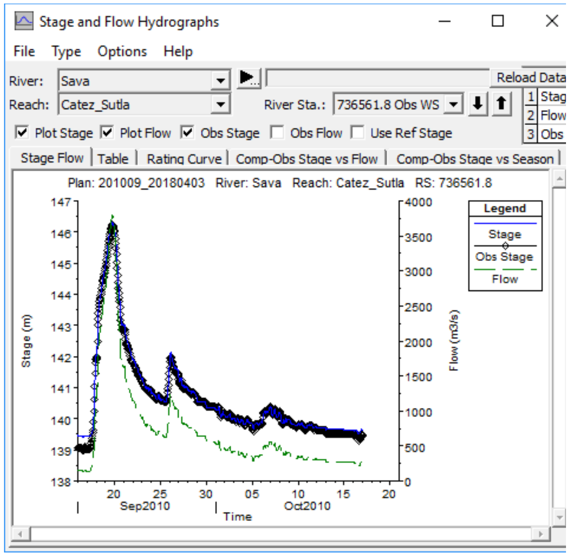


(t) Sremska Mitrovica

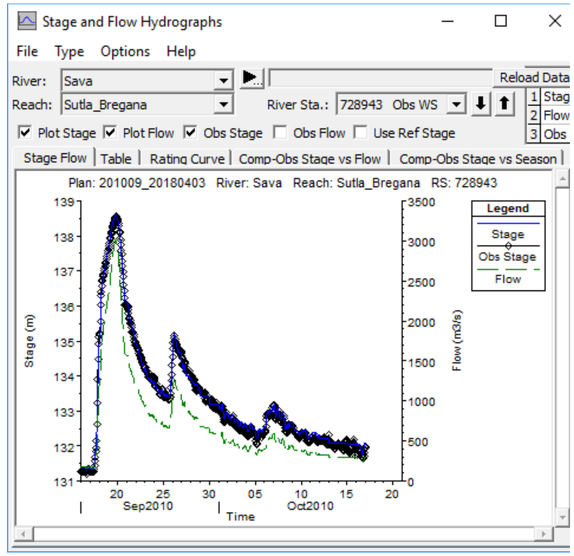


(u) Beograd

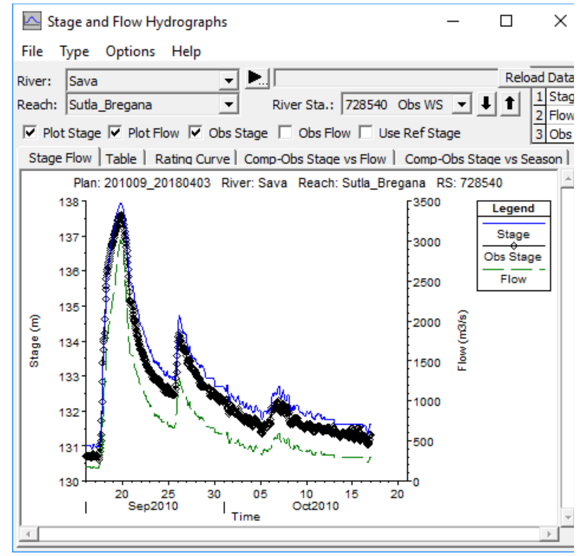
Figure 29. Output Hydrograph Plots for the December 2009 Flood Event



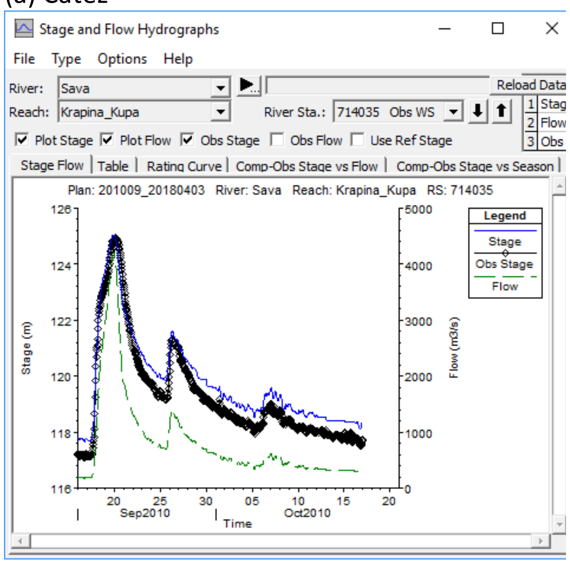
(a) Čatež



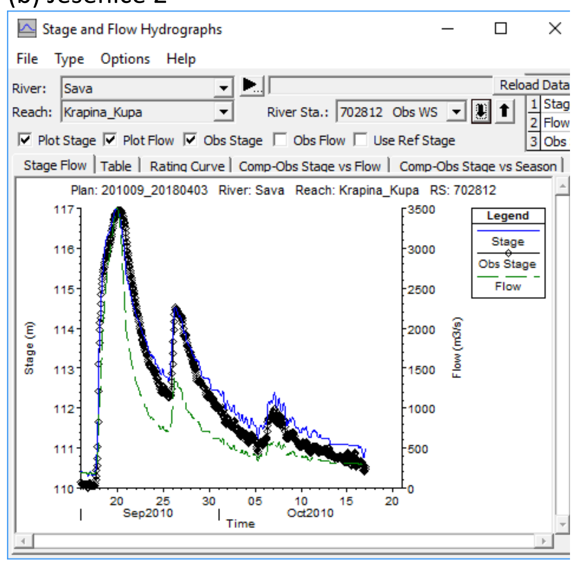
(b) Jesenice 2



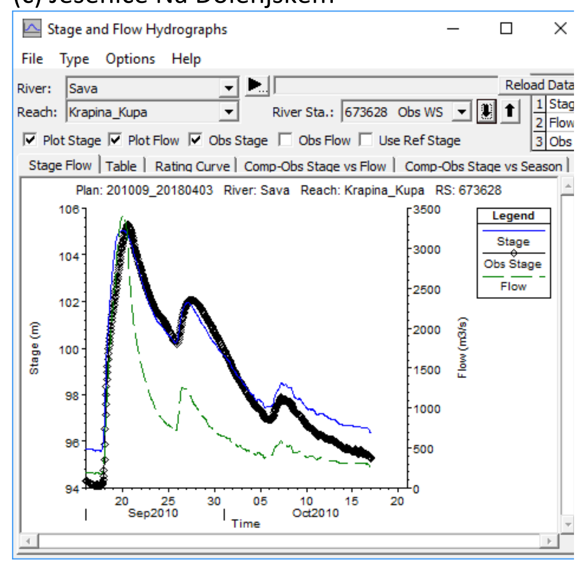
(c) Jesenice Na Dolenjskem



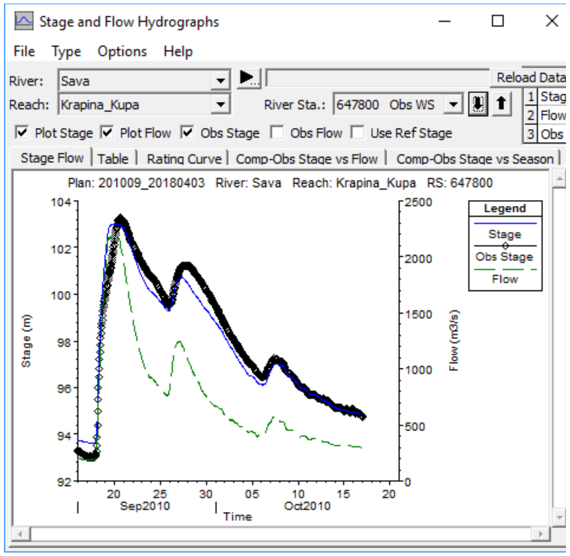
(d) Podsused Žičara



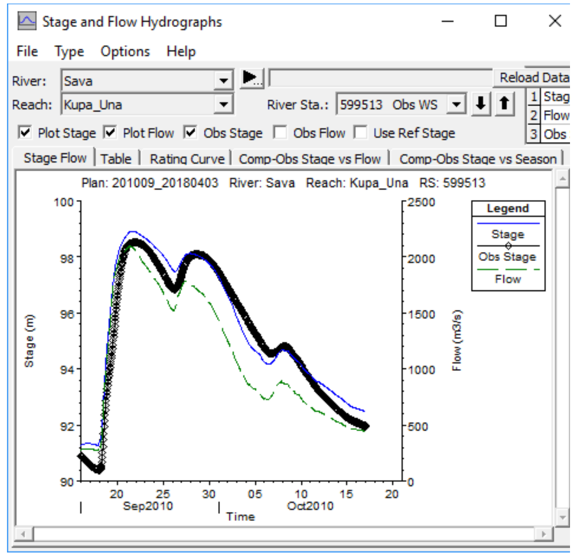
(e) Zagreb



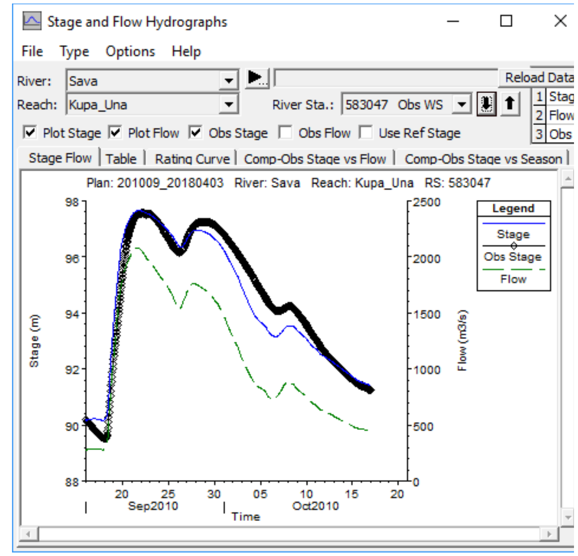
(f) Rugvica



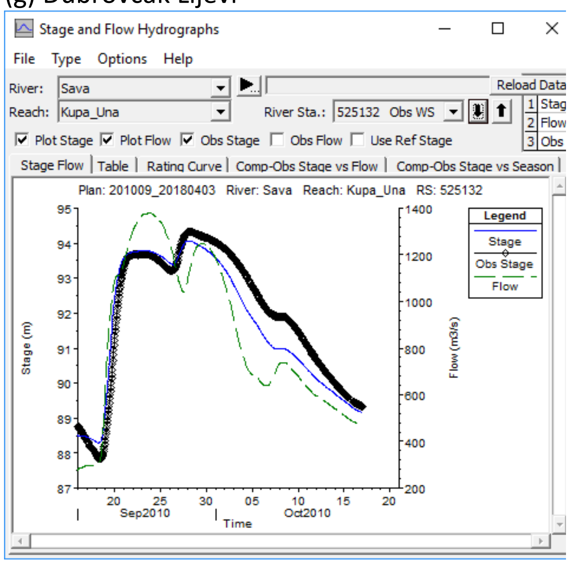
(g) Dubrovčak Lijevi



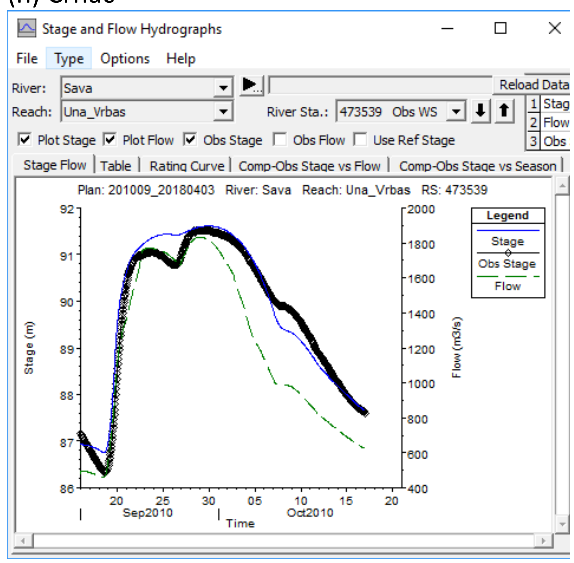
(h) Crnac



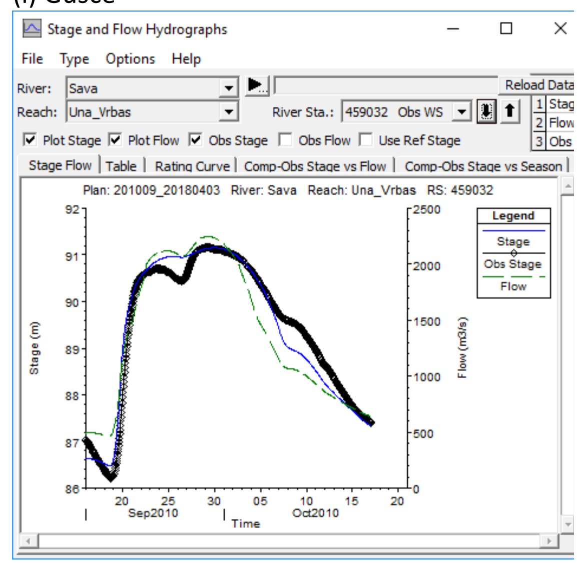
(i) Gušće



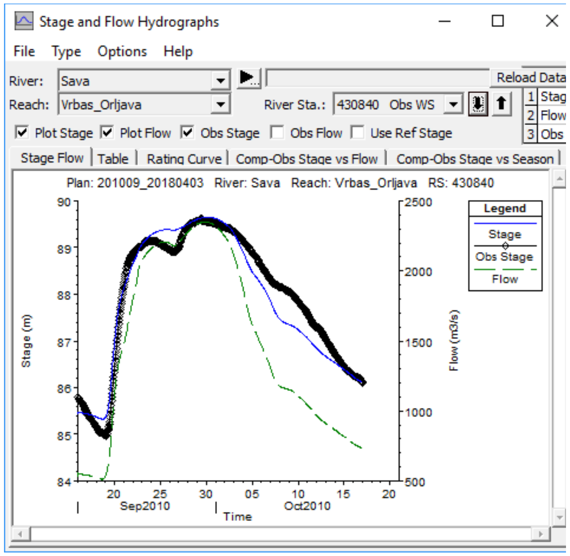
(j) Jasenovac



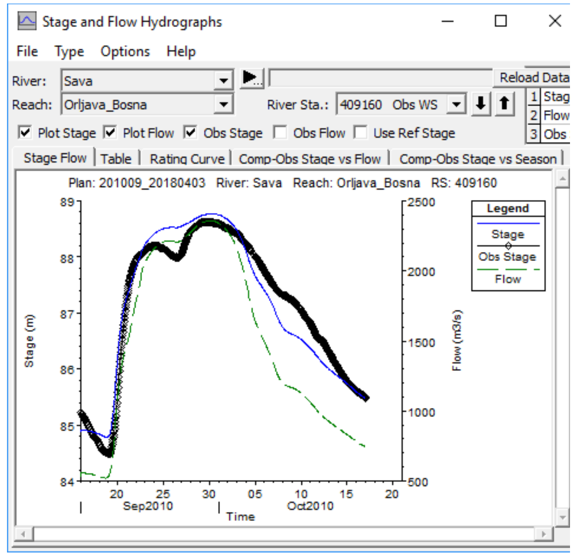
(k) Stara Gradiška



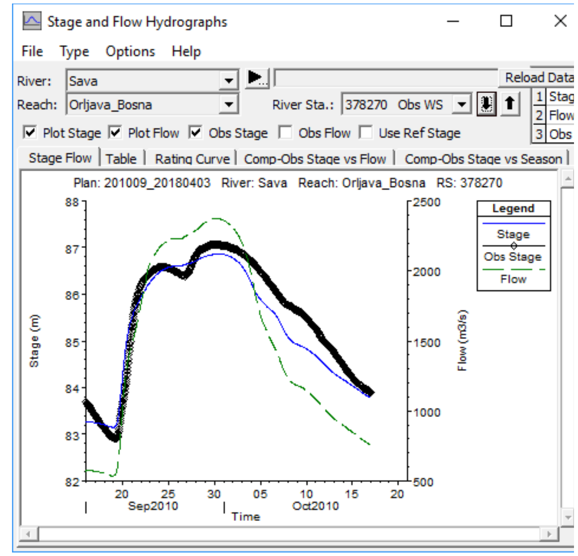
(l) Mačkovac



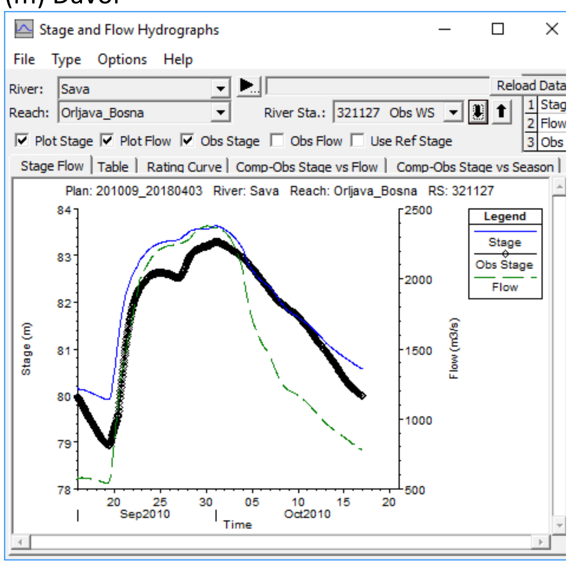
(m) Davor



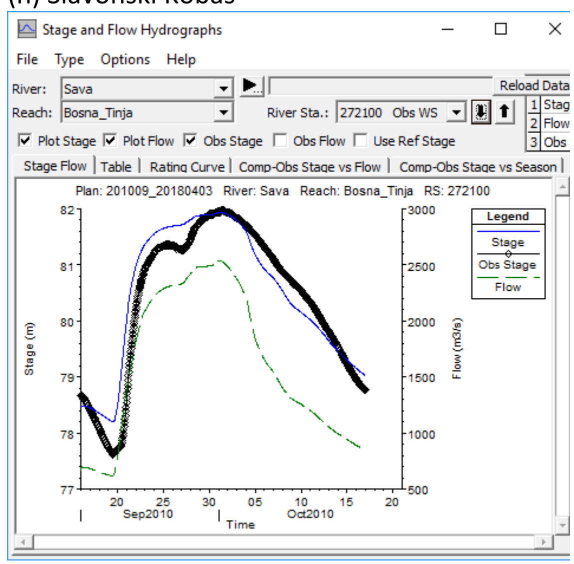
(n) Slavonski Kobaš



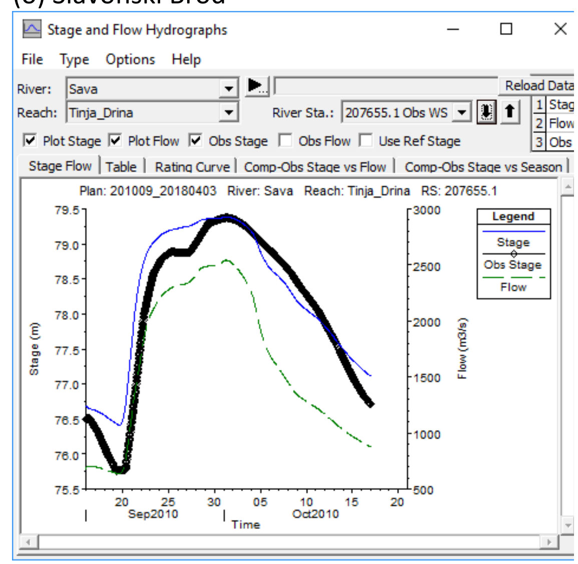
(o) Slavonski Brod



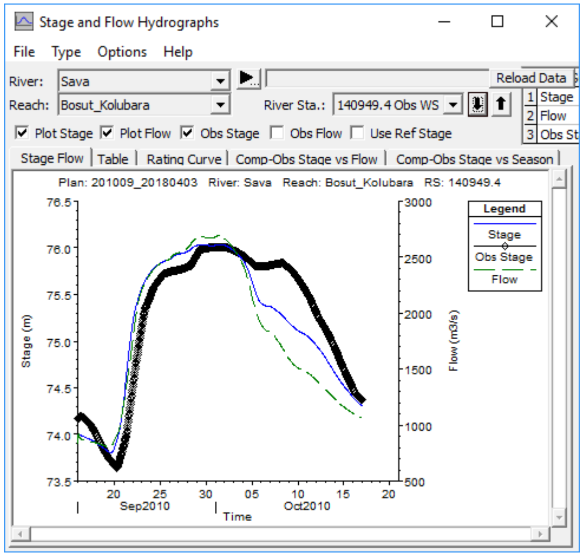
(p) Šamac



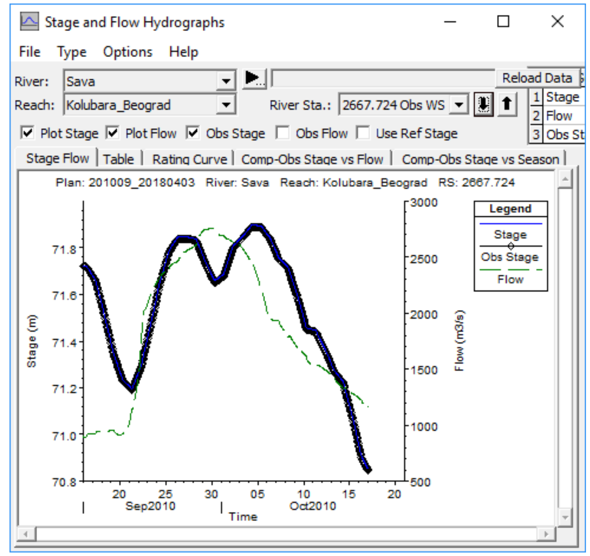
(q) Županja



(r) Jamena

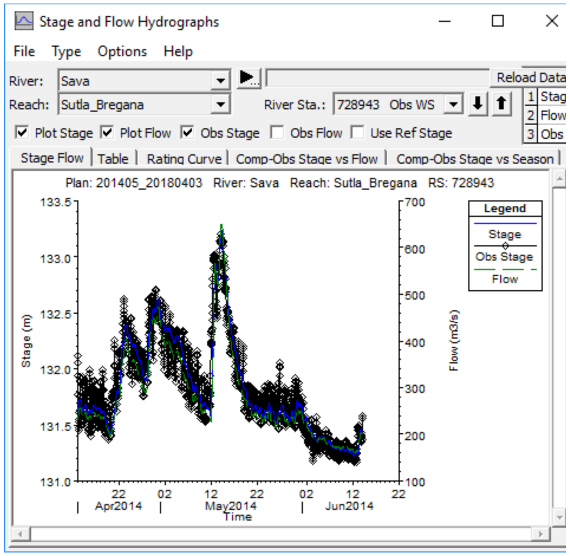


(s) Sremska Mitrovica

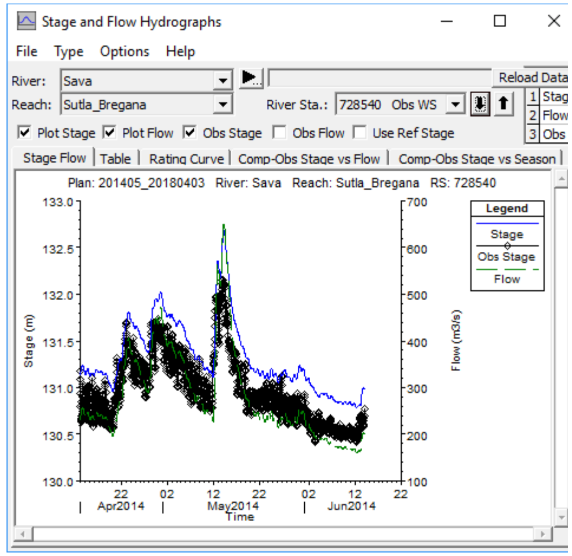


(t) Beograd

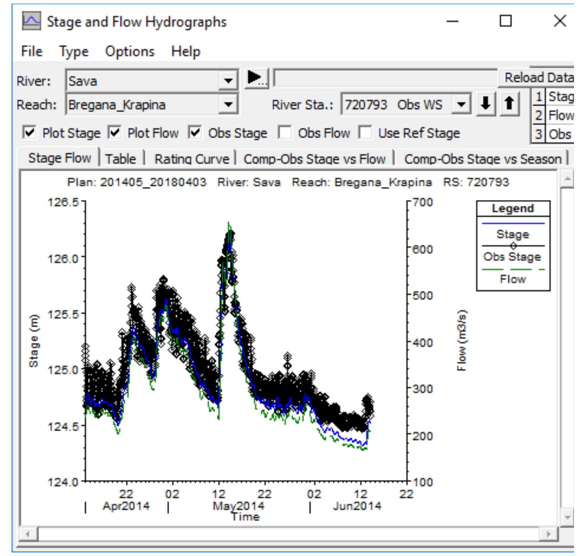
Figure 30. Output Hydrograph Plots for the September 2010 Flood Event



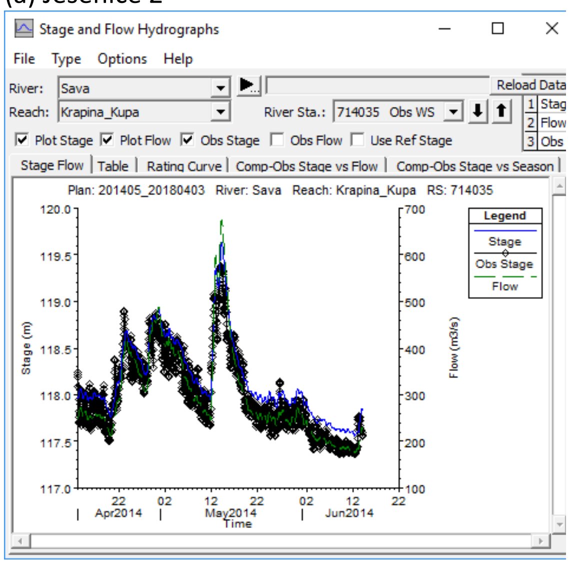
(a) Jesenice 2



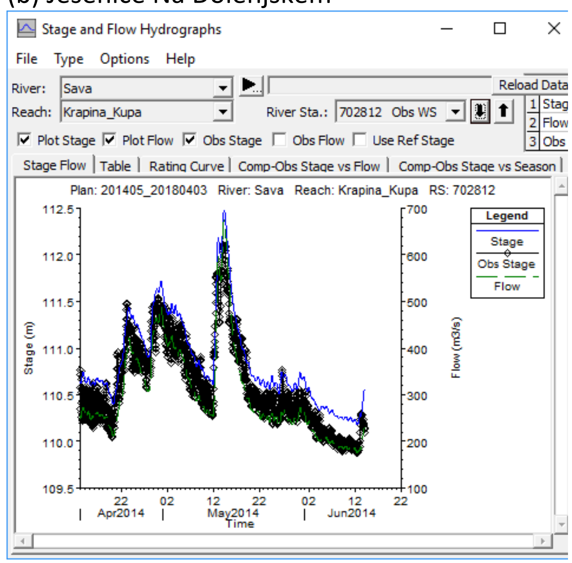
(b) Jesenice Na Dolenjskem



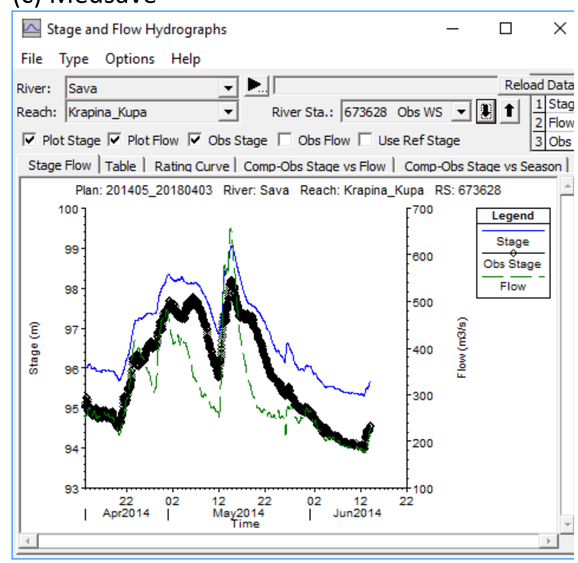
(c) Medsave



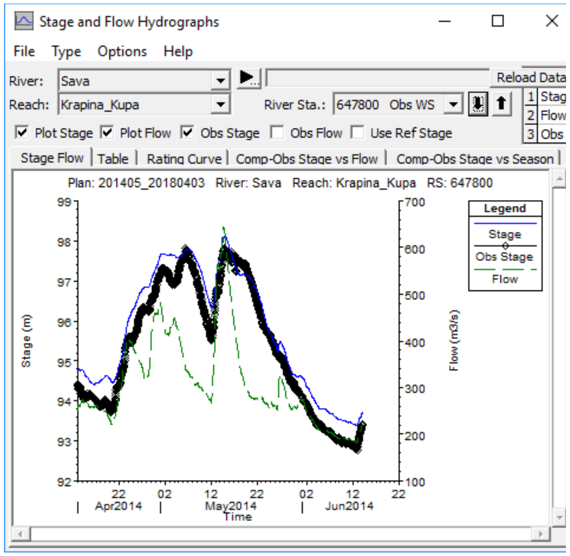
(d) Podsused Žičara



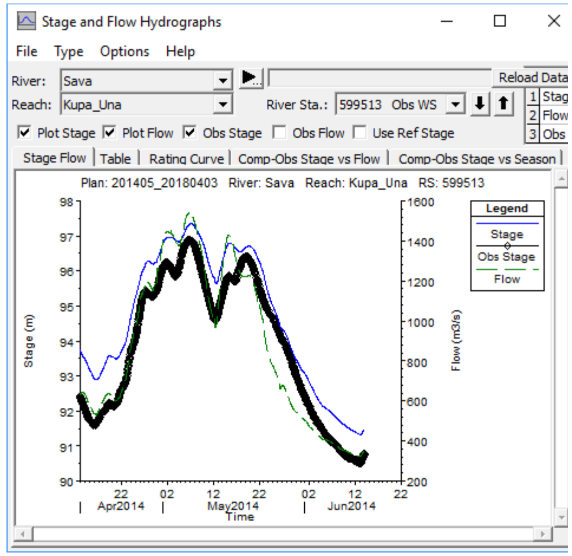
(e) Zagreb



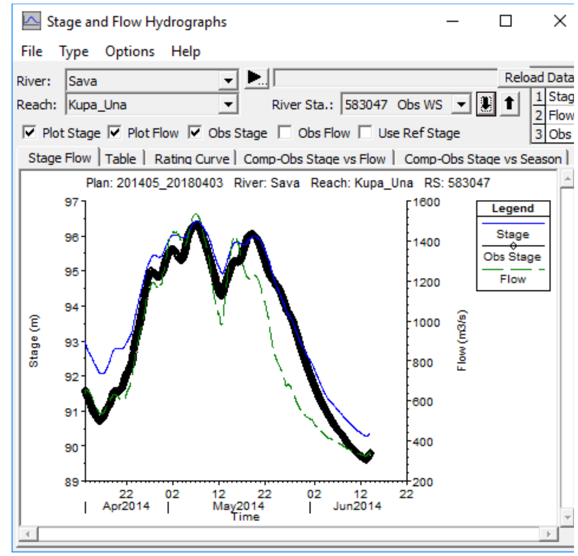
(f) Rugvica



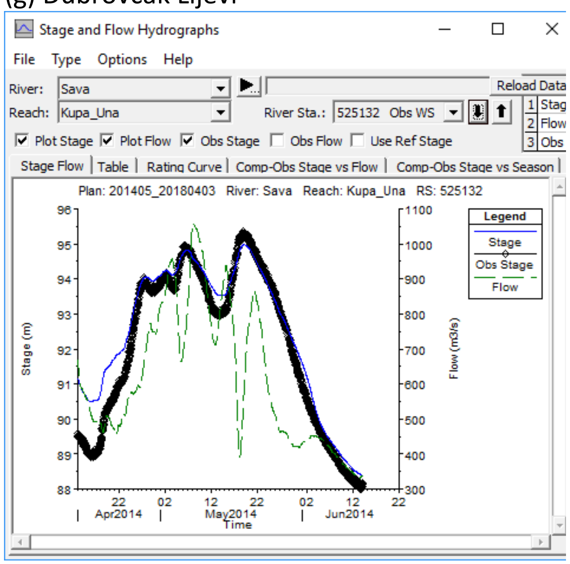
(g) Dubrovčak Lijevi



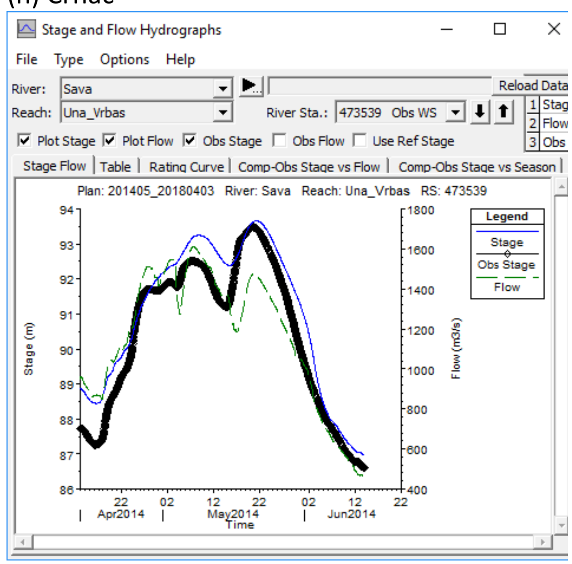
(h) Crnac



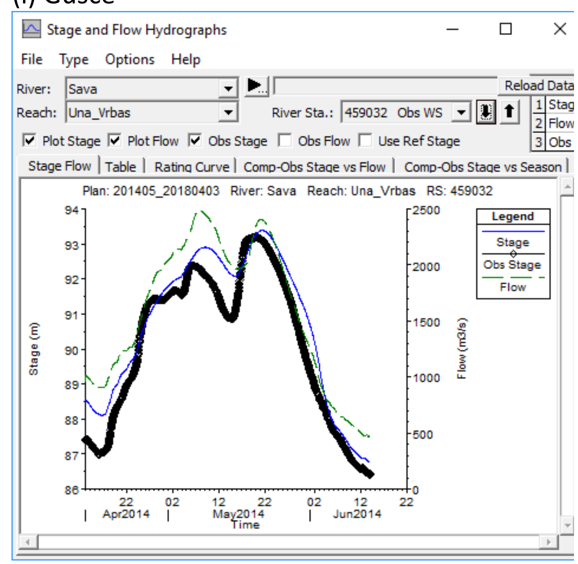
(i) Gušće



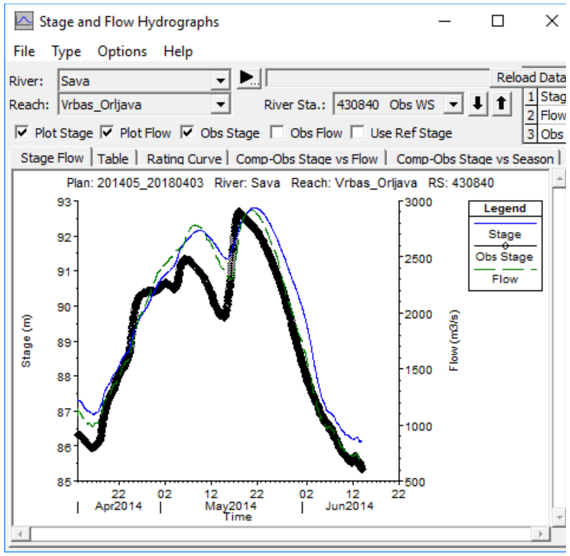
(j) Jasenovac



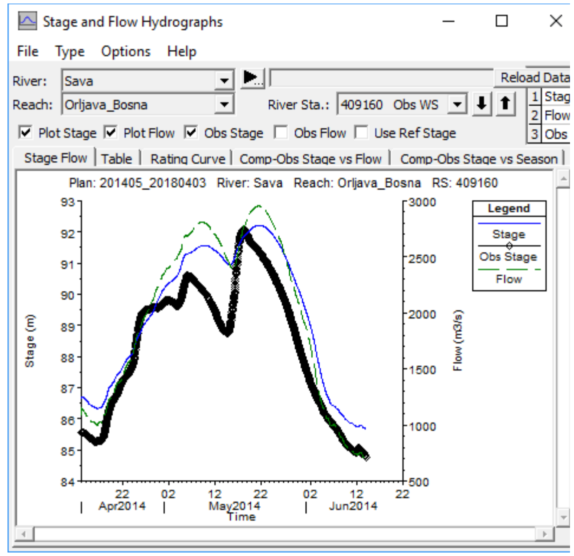
(k) Stara Gradiška



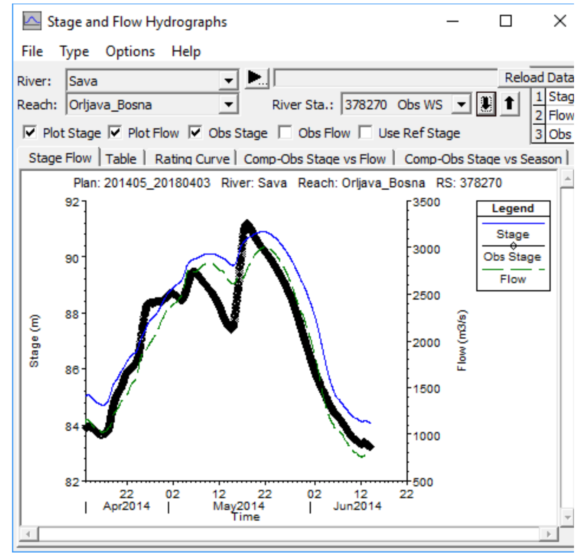
(l) Mačkovac



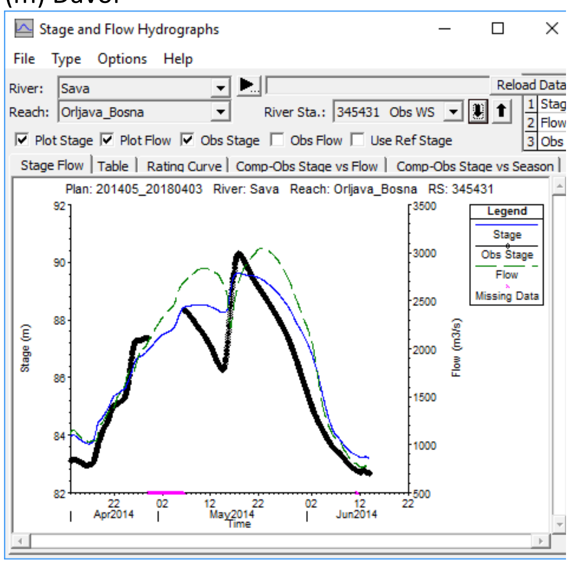
(m) Davor



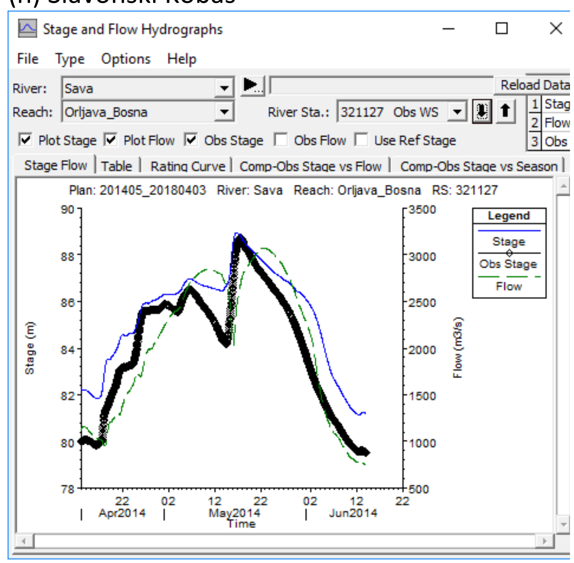
(n) Slavonski Kobaš



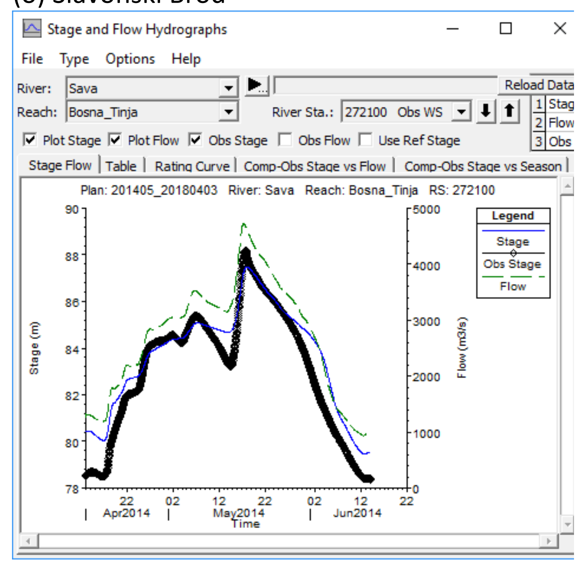
(o) Slavonski Brod



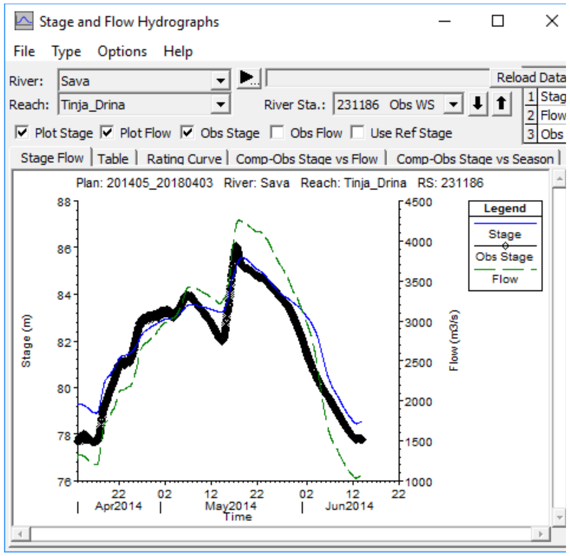
(p) Svilaj



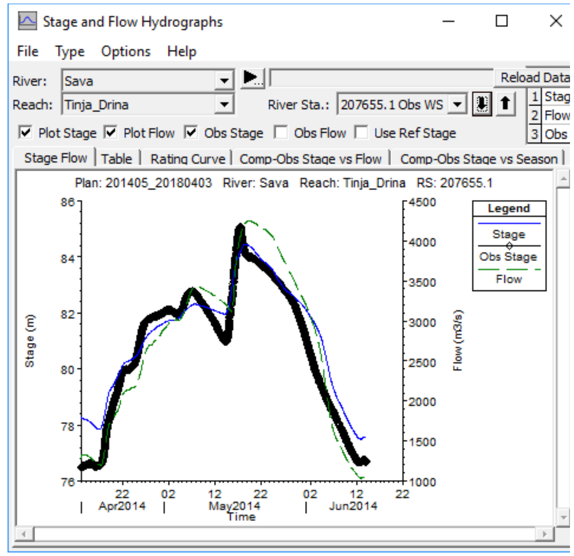
(q) Šamac



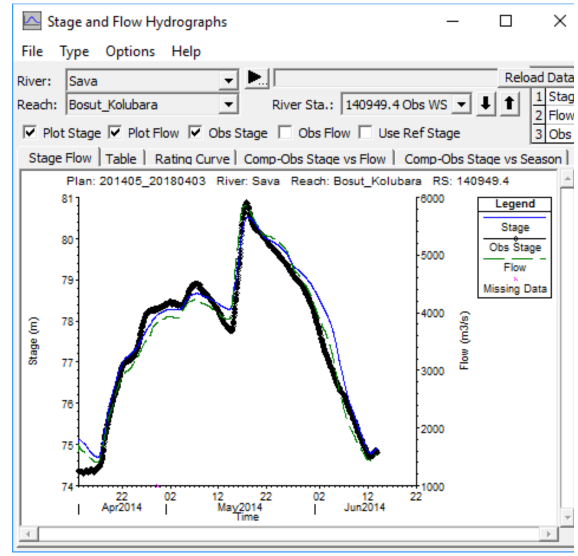
(r) Županja



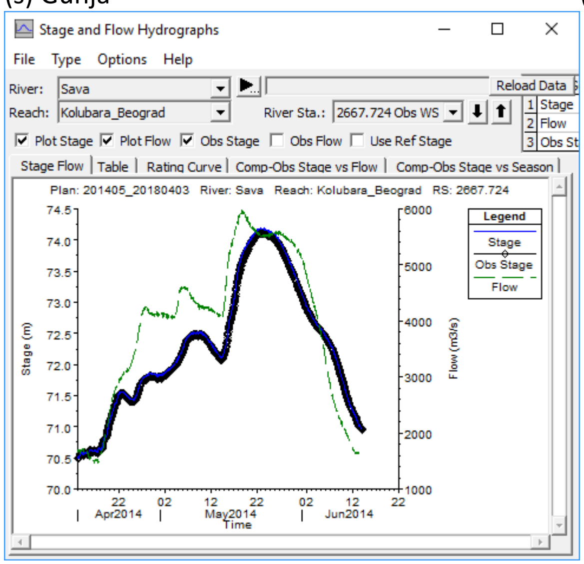
(s) Gunja



(t) Jamena



(u) Sremska Mitrovica



(v) Beograd

Figure 31. Output Hydrograph Plots for the May 2014 Flood Event

HEC-RAS also provides the ability to post-process water surface profiles into geospatial representations of the flood event in the form of inundation areas, depth grids, water surface grids, and various other output formats for the maximum water surface elevation or the water surface profile at any time step during a simulation. The tool in HEC-RAS that provides this capability is call RASMapper and can be accessed from the main menu by clicking on the RASMapper button as shown in the red box below in Figure 32.

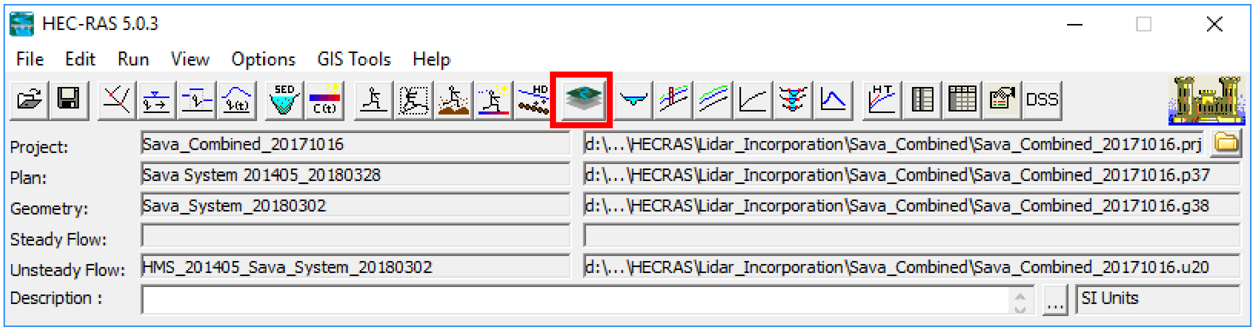


Figure 32. HEC-RAS Main Menu with the RASMapper Option Highlighted

For more information related to RASMapper, the HEC-RAS User's Manual provides a detailed description of the capabilities and instructions for RASMapper. The user's manual can be accessed from the help menu found in many of the windows in HEC-RAS and RASMapper. RASMapper computes the depth, velocity, and water surface automatically in memory, which provides the user with almost instantaneous geospatial results with the ability to overlay the results over a terrain or a GIS map service that includes base maps with streets or aerial imagery. For illustrative purposes, several examples of output from RASMapper are provided in the Figures below. Figure 33 shows an example of the depth grid mapping produced for the September 2010 event in the vicinity of Zagreb. This figure also illustrates some of the flooding that occurred in the Odransko Polje retention area. Figure 34 illustrates the depth grid mapping from the May 2014 event over laying the area near the mouth of the Kolubara River.

RASMapper provides many different ways to visualize data. In addition, RASMapper allows the use to visualize different parameters depending on the type of analysis (steady or unsteady) and the complexity of the geometry (1D or 2D). Tools within RASMapper also make it very easy to export results to formats that can be used in other software like ArcGIS Desktop or Google Earth.

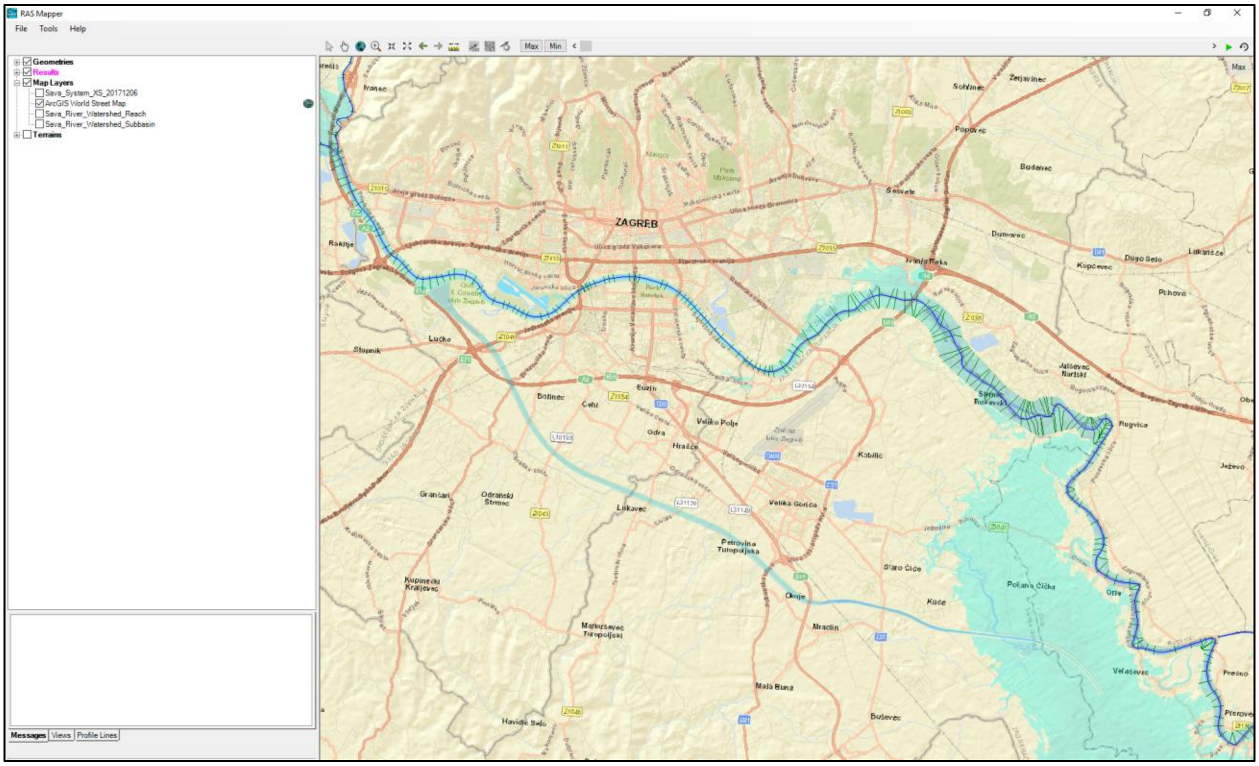


Figure 33. Depth Grid Mapping Overlaying Street Map in Vicinity of Zagreb, Croatia for September 2010 Event

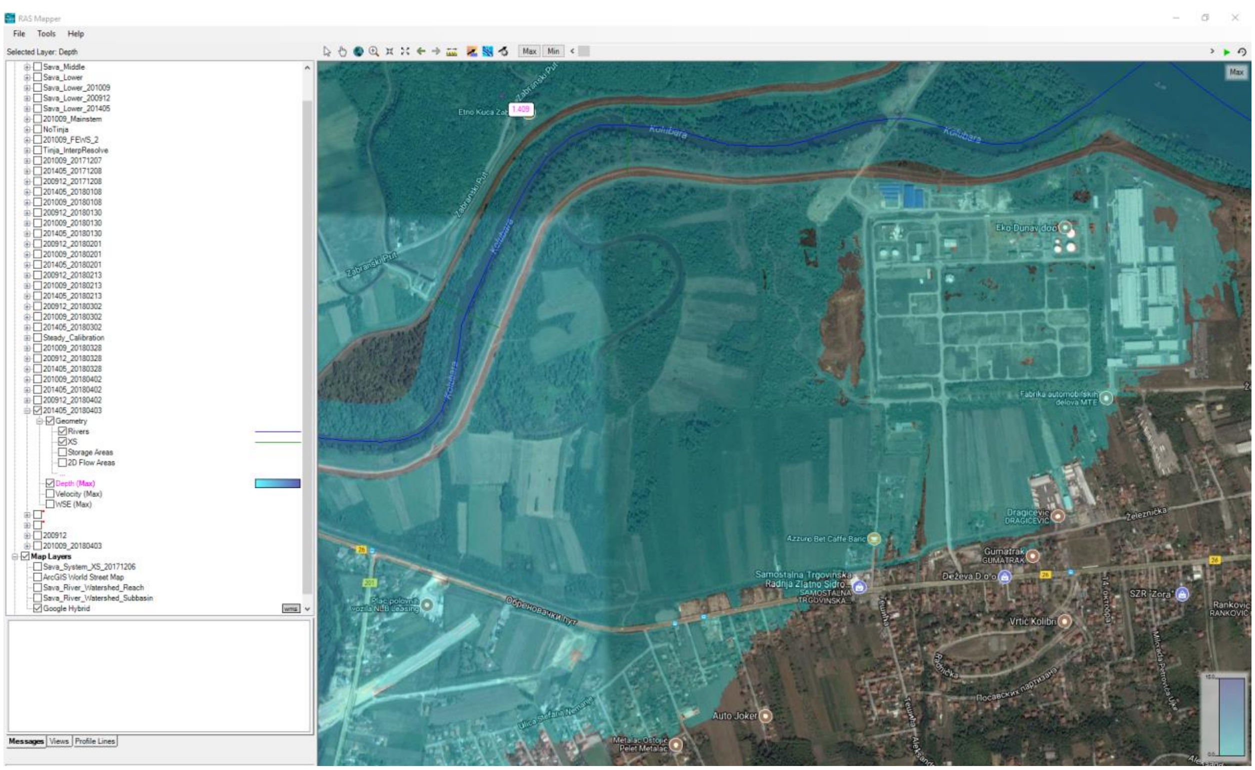


Figure 34. Depth Grid Mapping at Mouth of Kolubara for May 2014 Event

4. SPECIAL ANALYSES

In addition to developing an unsteady flow HEC-RAS model for the Sava River, USACE also conducted several special analyses to demonstrate some of the newer capabilities of HEC-RAS, specifically the new two-dimensional (2D) capabilities. In order to illustrate these capabilities, USACE performed two analyses that rely primarily on the 2D computation capabilities of HEC-RAS. First, USACE conducted a 2D analysis of the Central Sava Flood Protection System including high flow diversion weirs such as Jankomir, Palanjek, and Košutarica; retention areas such as Odransko, Žutica, Lonjsko, Opeka, Trstik, Mokro, and Zelenik; and gated structures such as Prevlaka and Trebež. Second, USACE conducted an example 2D study of a levee breach flowing into a low-lying area behind the levee represented as a 2D area.

4.1 TWO-DIMENSIONAL MODEL INCORPORATION

USACE conducted a 2D analysis of the Central Sava Flood Protection System in the middle region of the Sava River in order to develop better flow characteristics through the flood protection system and to also illustrate some of the newer 2D capabilities available in the HEC-RAS software. In addition, USACE chose to use the September 2010 event for this analysis as it represented the event that placed the greatest stress on the Central Sava Flood Protection System.

HEC-RAS is capable of computing purely 2D analyses; however, using a combination of 1D unsteady with 2D area components is more beneficial in some cases because this option provides the ability to model specific areas using 2D analysis while maintaining relatively shorter computation times due to the use of 1D unsteady flow for portions of the model. For this analysis, USACE utilized the 1D Sava River system unsteady model (discussed in previous sections) as a starting point for this analysis. The main difference is that the storage areas used to represent the retention areas of the Central Sava Flood Protection System were converted to 2D areas; therefore this analysis is actually a combination of 1D and 2D analyses.

Within HEC-RAS, 1D and 2D unsteady analyses are organizationally handled the same, which makes it much simpler to convert portions of a 1D unsteady model to a 1D/2D unsteady model. As will become evident from this report, many of the same screens and tools apply to both types of analyses. As with 1D unsteady flow analysis in HEC-RAS, a simulation plan consists of a geometry and an unsteady flow file. HEC-RAS simply provides some advanced capabilities within the plan, geometry, and flow file options that provide the 2D analysis capability. In addition, additional capabilities have been added to RASMapper to facilitate model development and results visualization. The main objective of this section of the report is to identify and explain the differences between the 1D and 2D analyses.

4.1.1 2D GEOMETRY DEVELOPMENT

The extent of this analysis includes the Sava River from the Čatež station downstream to the Mačkovac station. From upstream to downstream, this analysis includes the following flood protection components:

- The Jankomir Weir high flow diversion connected to the Odra Canal into Odransko Polje ultimately joining the Kupa River near the confluence with the Sava River
- The Prevlaka gated structure connected to the Lonja Canal into the of Žutica and Lonjsko retention areas before ultimately rejoining the Sava River through the Trebež gated structure.
- The Opeka, Trstik, and Mokro retention areas on the left bank of the Sava River
- The Zelenik retention area on the right bank of the Sava River

Figure 35 illustrates the modified geometry extent used as the basis for the 2D analysis. In addition to limiting the scope of the Sava River, many of the tributary reaches were excluded from this analysis.

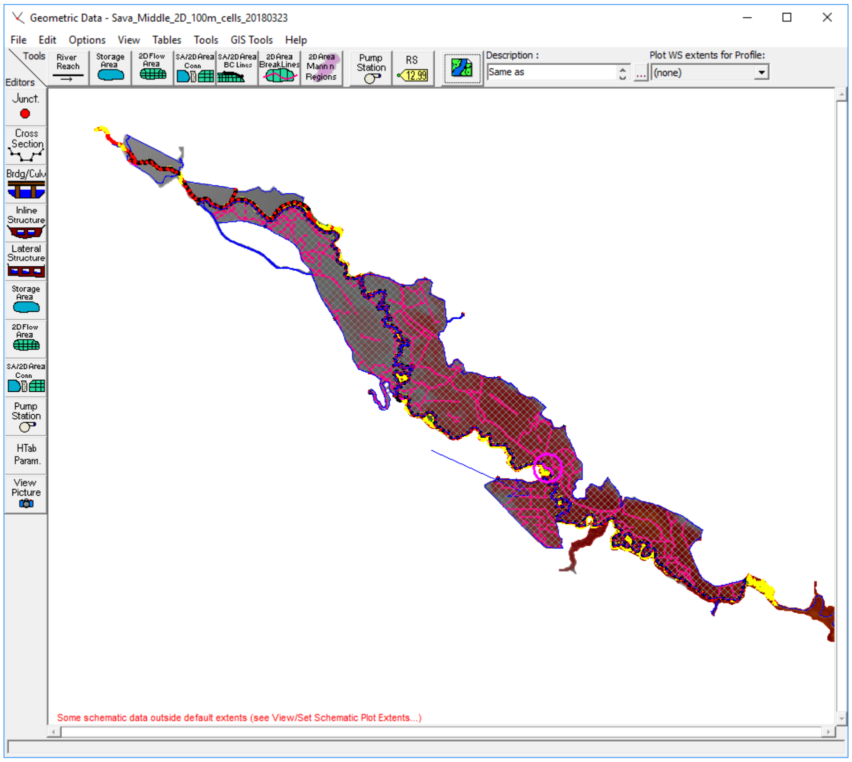
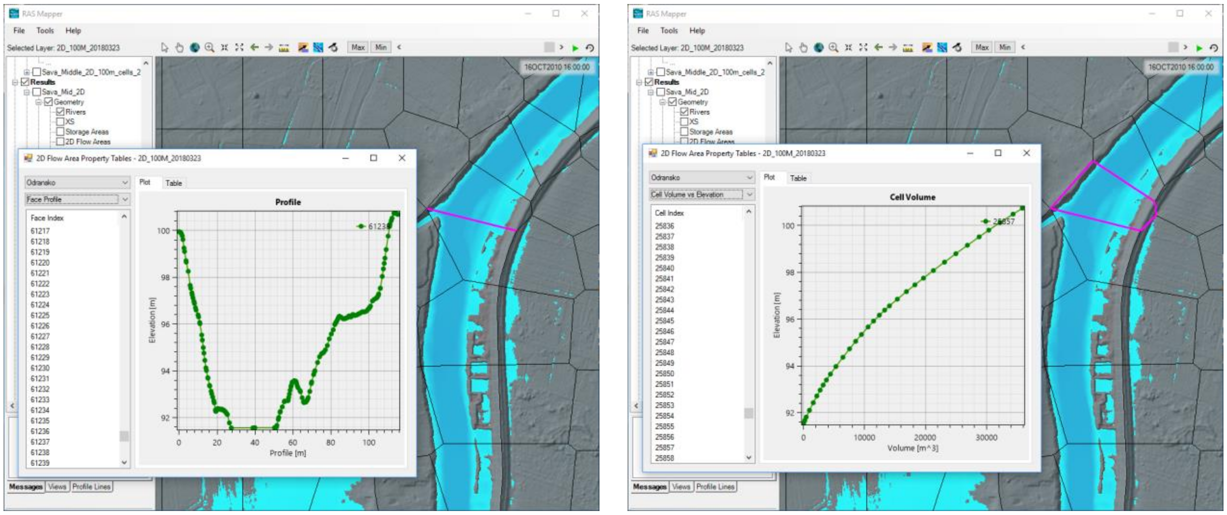


Figure 35. 2D Model Geometry Schematic

One of the major advantages of the 2D modeling components in HEC-RAS is the ability to combine 1D components with 2D components, which aligns well with representing this system. The main stem Sava River can be modeled using 1D cross sections while the retention areas can be represented as 2D areas. Much like with storage areas, the 2D areas are connected to the mainstem using lateral structures representing levees, natural high ground, and diversion structures. Therefore, functionally the 1D/2D model operates similarly to the unsteady model discussed in previous sections.

In order to compute the 2D hydraulic characteristics, HEC-RAS requires the user to develop a 2D mesh within the 2D area. Depending on the level of detail of the topography in the 2D area the user can select a finer or coarser resolution. For this analysis, a mesh cell size of 100m by 100m was used to define the 2D area. The geometry is linked to the terrain derived from the LiDAR data collection.

HEC-RAS uses the finite volume method to compute flow through the 2D area. In order to solve for the finite volume method, HEC-RAS develops property tables for each mesh cell and cell face. These property tables relate specific geometric-based parameters like cell volume, area, and wetted perimeter with elevation for each cell and cell face. These tables can be accessed within RASMapper and plots of these tables are provided in Figure 36 as an example.



(a) Cell Face Elevation Profile (b) Cell Elevation-Volume Relationship

Figure 36. Example of HEC-RAS 2D Property Tables

Once HEC-RAS computes these property tables for each cell within all of the 2D areas within the geometry, flow through any cell face and water surface elevations can be computed for each cell within the mesh. This model includes 4 2D areas: Odransko, Upper Odransko, Left Bank Retention Areas, and Zelenik. Because the flow characteristics within the retention areas are handled using a 2D mesh as opposed to an elevation-storage relationship for an entire storage area, the Žutica, Lonjsko, Opeka, Trstik, and Mokro retention areas were merged into a single 2D area from multiple storage areas and represent the Left Bank Retention Areas 2D area.

Because topography can not be fully define with a uniform mesh cell spacing, linear features such as roads and dikes can be represented with breaklines within HEC-RAS. The advantage to using breaklines is that a breakline forces the cell face to fall on the breakline, which better represents these linear features within a given topography as shown in Figure 37. Without breaklines, water could flow from one side of the dike to other because the topography is only defined where a cell face lies. Figure 38 illustrates the breaklines that were laid out for the Zelenik retention area. In the figure, the breaklines are represented by the red lines in the right overbank of the cross section data representing the mainstem Sava River.

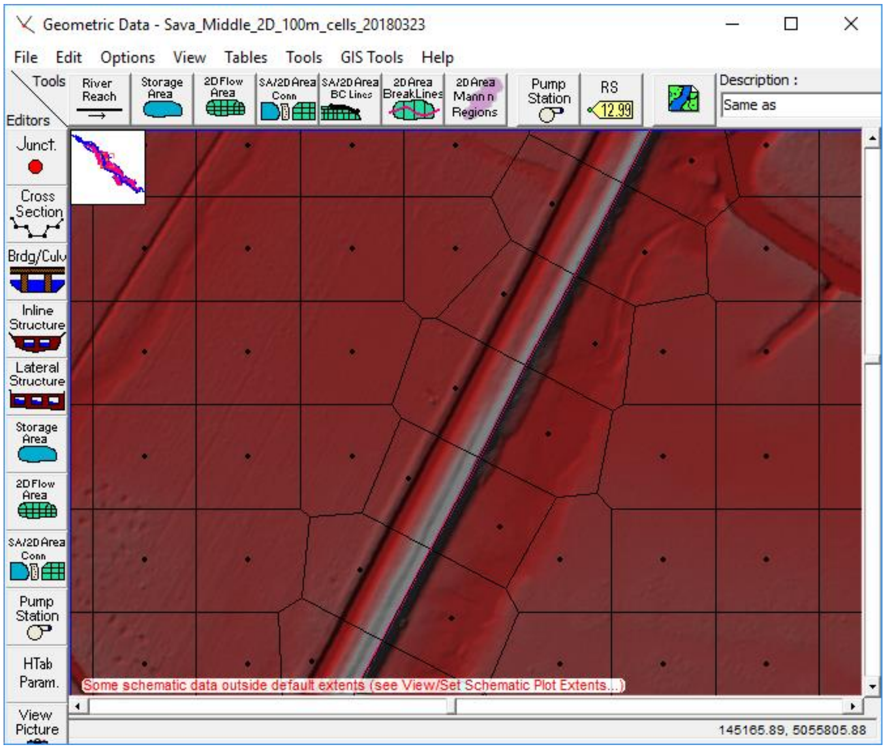


Figure 37. Example of a Breakline Representing a Linear Dike

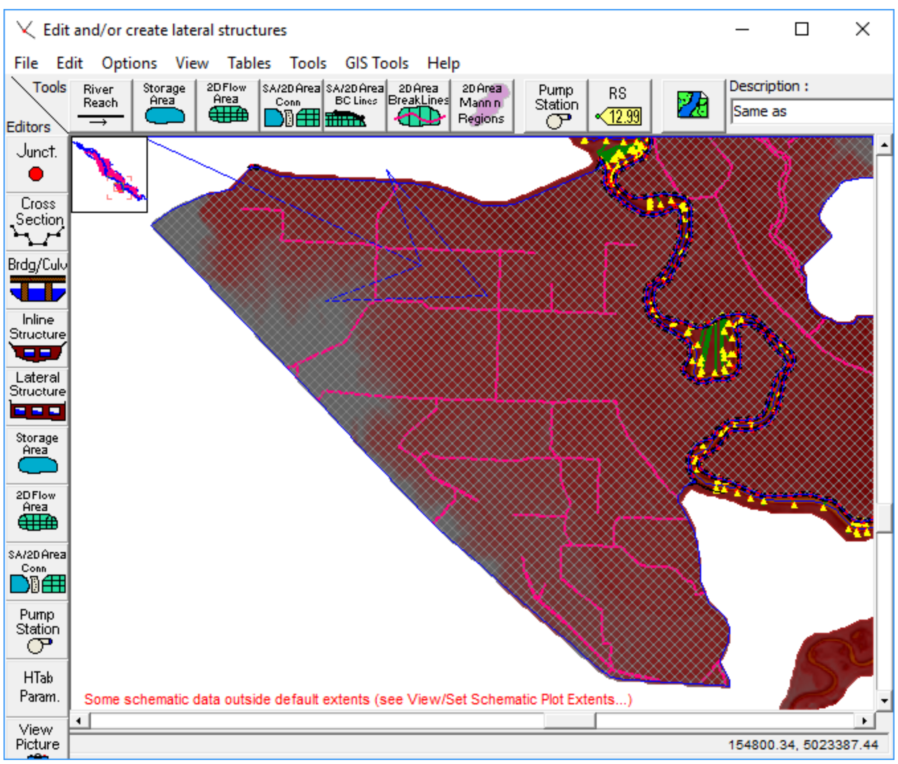


Figure 38. Example of Breaklines for the Zelenik Retention Area

Once the mesh cell spacing of 100m was determined and breaklines were developed for each 2D area, the mesh for each 2D area was generated. These 2D areas represent very large spatial areas requiring a significant number of cells to be generated. Table 4 provides some cell size statistics for each 2D area.

Table 4. Table of Cell Size Statistics for each 2D Area

2D Area	Number of Cells	Average Cell Size (m^2)	Max Cell Size (m^2)	Min Cell Size (m^2)
Odransko	30335	9733.96	27797.81	343.77
Upper Odransko	3519	9554.84	18359.00	2753.50
Left Bank RAs	80711	9778.05	26037.98	8.60
Zelenik	11718	9724.67	19485.05	2665.86
Total	**126283**			

USACE tested various cell spacing dimensions; however, to properly represent the areas being studied, the dimension of 100m was chosen. The disadvantage to this cell size is that the simulations are significantly long; however, the intent of this analysis also provides an example of how the 1D/2D capabilities can be used in the region. Therefore, if an institution is interested in analyzing a specific area, the extent of the 2D area can be reduced significantly to capture the area of interest for the specific analysis.

The final component to the geometry for this analysis is the development of a Manning's roughness grid based on land cover data. Through RASMapper, HEC-RAS has the capability to import land cover as a grid like a tagged image file format (.tif) or vector geometry like a shapefile (.shp). Using land cover data provided by the ISRBC, each land cover type was assigned a Manning's roughness value and the land cover data was imported into HEC-RAS. Once the data was imported, the land cover was associated with the geometry, and HEC-RAS automatically links the land cover to the 2D Area mesh.

Other than the geometry changes discussed above, the 2D geometry is generally the same as the unsteady model.

4.1.2 2D BOUNDARY CONDITIONS

The approach to defining boundary conditions when introducing 2D elements to the geometry is similar to the normal approach of defining boundary conditions with a few differences. This section will highlight those differences.

Just as the Sava system unsteady flow model, this 2D analysis uses inflows from the HEC-HMS model output although the downstream extent of this 2D model is at the Mačkovac station instead of the mouth of the Sava River. Therefore, the number of boundary conditions has changed and the observed elevation time series data at the Mačkovac station is used as the downstream boundary condition. All of the other boundary conditions to the 1D elements are unchanged with a single exception. The Una River reach was removed from the model for this 2D analysis so an additional later inflow hydrograph boundary condition was added at RS 524117 to account for the flow from the Una River basin.

The main difference in terms of boundary conditions for this 2D analysis as compared to the Sava System unsteady flow model is related to how inflows are applied to the newly added 2D areas. For the Sava System unsteady flow model, these 2D areas were represented as storage areas, which act like large level pool reservoirs so the location of where inflows are applied is inconsequential. For 2D areas, the location of where these inflows are applied is much more important and is handled differently.

HEC-RAS version 5.0.3 allows for four types of boundary conditions to be applied to a 2D area including: stage hydrograph; flow hydrograph; rating curve; and normal depth. For this study, only the flow hydrograph 2D boundary condition is used. Inflows to a 2D area are applied using boundary condition lines. In HEC-RAS version 5.0.3, the version used for this study, a boundary condition line can be drawn along the outside of the 2D area representing spatially where the inflow or other boundary condition will be applied to the 2D area. Figure 39 illustrates how the boundary condition line was drawn to represent the cross section where the inflow hydrograph from HEC-HMS will be applied to the 2D area for the Kupa River. In future versions of HEC-RAS boundary conditions can also be applied within a 2D area.

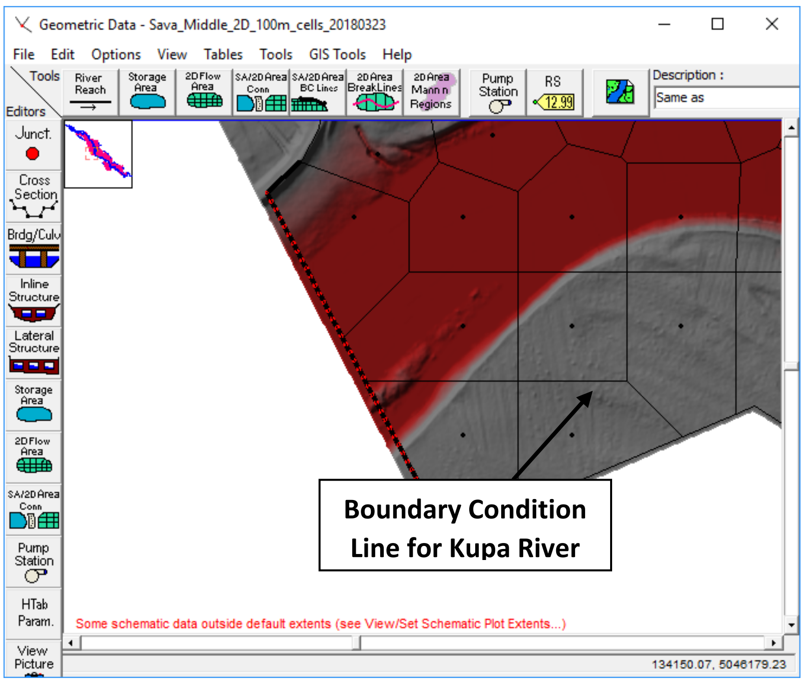


Figure 39. Example of Boundary Condition Line Applied for Kupa River

Once the boundary condition lines are drawn to represent all of the inflows to the 2D areas, the linkage to the data source was defined in the Unsteady Flow Data Editor. This linkage is handled similarly to how data for other boundary conditions are input. Figure 40 shows the unsteady flow data editor and the input screen for the Kupa River boundary condition line. The DSS path and part names are defined for the flow from HEC-HMS model output. Besides this input, HEC-RAS requires an energy grade slope to be defined for the boundary condition line to distribute the flow from the boundary condition line to the exterior faces in the 2D area.

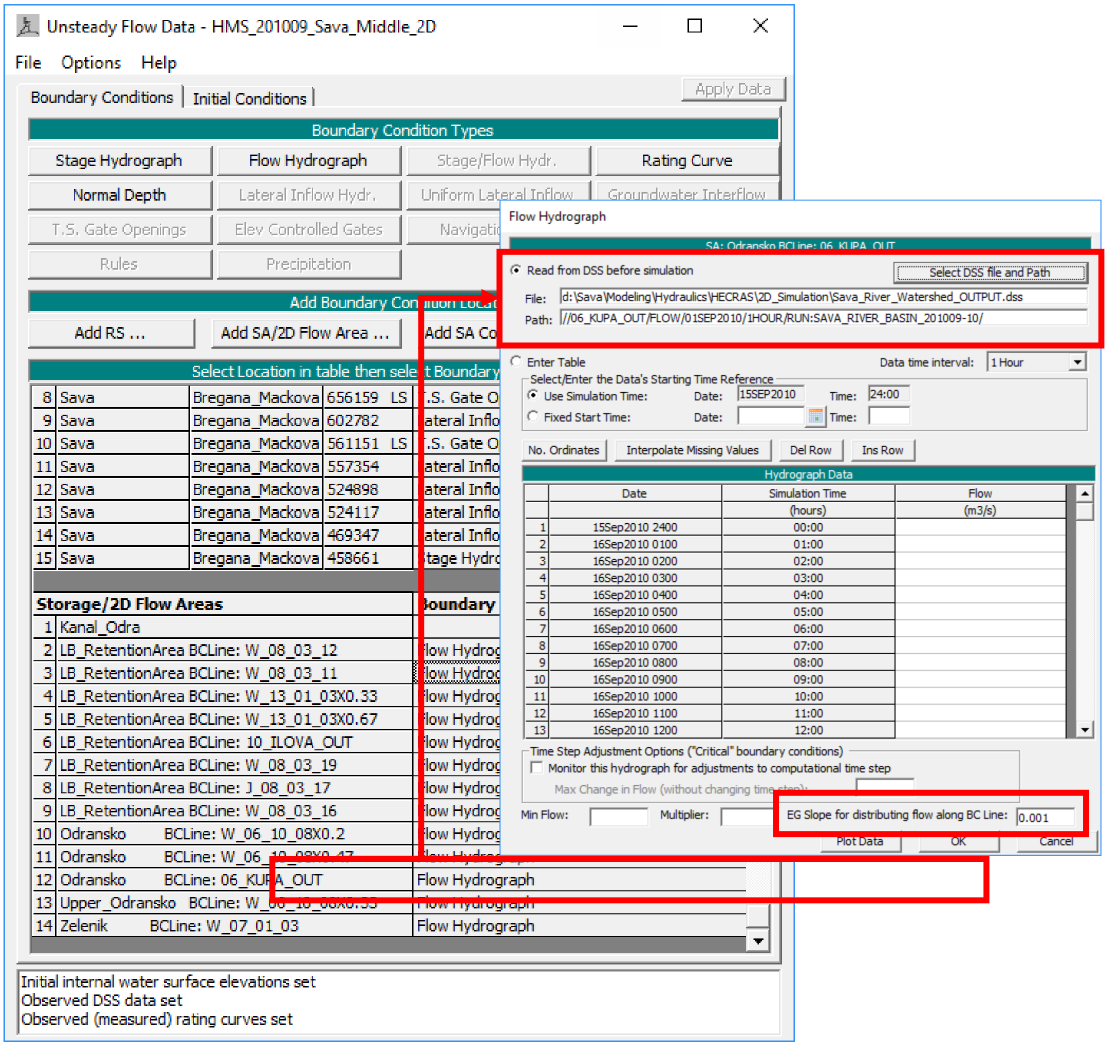


Figure 40. Example of 2D Boundary Condition Input

This process of creating boundary condition lines and defining inputs was followed for all inputs into the four 2D areas throughout the geometry of this analysis. This process is relatively simple and intuitive thanks to the tools provided within the HEC-RAS interface.

4.1.3 2D CALCULATION OPTIONS AND TOLERANCES

As with a 1D unsteady analysis, a simulation that includes purely 2D or a 1D/2D analysis is setup through an unsteady plan. The interface for this analysis is identical to the 1D unsteady analysis as can be seen in Figure 41. The main difference is that this plan relies on a different geometry and flow file (boundary conditions) the development of which are described in the previous subsections of this section of the report.

Another major difference between 1D and 2D analyses is how the calculation options and tolerances are applied. By accessing the *Options* menu shown in Figure 41, the user can select the *Calculations Options and Tolerances…* option.

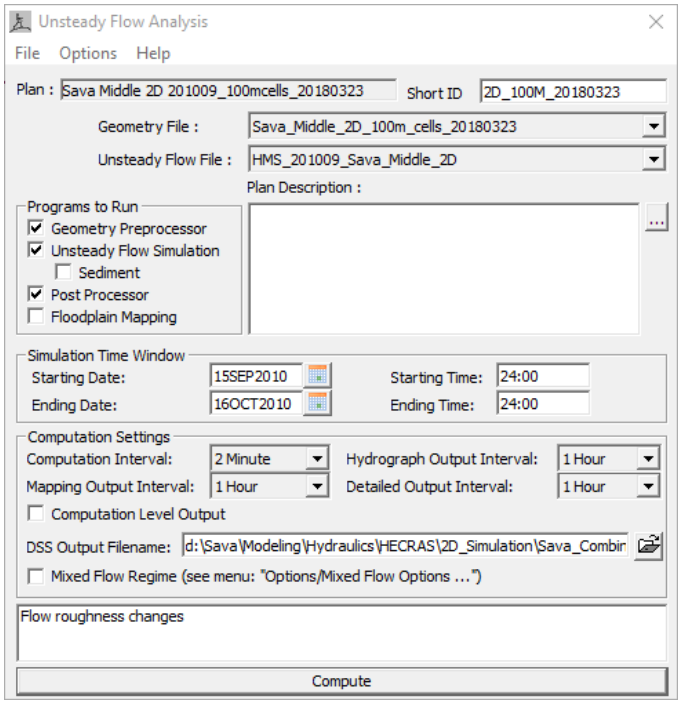


Figure 41. Unsteady Flow Plan Editor

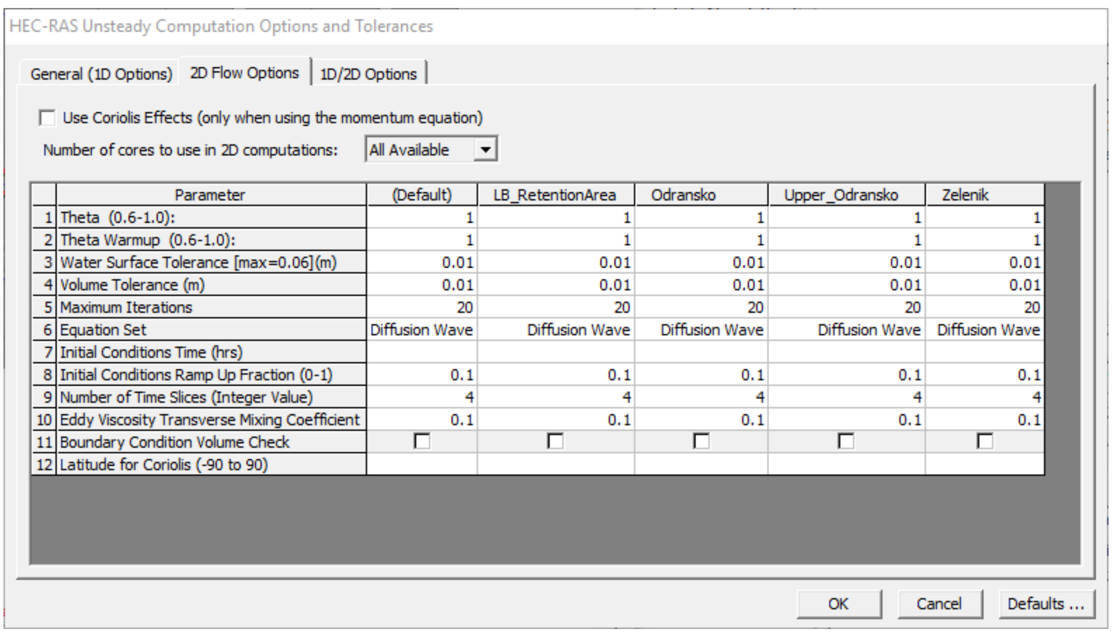
The *Calculations Options and Tolerances* window will display and allow the user to modify specific properties of the simulation. These options and tolerances are typically used to help improve the accuracy and stability of a simulation. Since the addition of the 2D capabilities, two new tabs have been added to this window, *2D Flow Options* and *1D/2D Options*. As with 1D options, it is generally recommended to maintain the program defaults for most parameters; however, it is typically necessary to modify some of the options for 2D areas.

Figure 42 displays some of these options. The first five parameters, theta, theta warmup, water surface tolerance, volume tolerance, and maximum iterations, should typically be left as the program defaults.

The equation set allows the user to use the full momentum equation or the simplified diffusion wave equation to solve the hydraulics of the 2D area. The full momentum equation is derived from the Navier-Stokes equations and includes multiple assumptions like incompressible flow. The main components of the momentum equation are acceleration, Coriolis acceleration, hydrostatic pressure, eddy viscosity, and bottom friction. In some circumstances, the acceleration, Coriolis acceleration, and turbulence terms are small and can be neglected leaving the hydrostatic pressure and bottom friction terms, which forms the diffusion wave approximation. For most large scale 2D modeling efforts, the diffusion wave approximation can be used as it was for this analysis.

In general, the full momentum equations should be used when there are flows with dynamic changes in acceleration, when there is dramatic separation in flows such as around obstacles like bridge piers, or when a very detailed solution is desired. If flow is mainly driven by gravity and friction, the diffusion wave approximation should provide a reasonable solution.

Because HEC-RAS uses the finite volume method to solve flow through the 2D areas, mesh cells within the 2D areas can begin the simulation dry without troublesome stability issues. However, in order to start the simulation with normal flow occurring within the 2D areas, the initial conditions time and ramp up fraction allow the user to simulate an initial wave of flow through the 2D area prior to beginning the formal simulation. The initial flow used during this initial period is based on the boundary conditions connected to the 2D areas within the unsteady flow data editor. The initial time designated here is typically iteratively determined by the time it takes for the 2D area to fill to a normal starting water surface elevation. The initial condition ramp up fraction designates the percentage of time as it relates to the initial conditions time to ramp up to the full initial flow. For example, if the initial flow is 100 CMS, initial conditions time is 10 hours, and the ramp up fraction is 0.1, the flow would increase from 0 CMS to 100 CMS from time zero through the first hour. For the remainder of the 10 hours, the flow would be 100 CMS before the formal simulation would begin. For this analysis, the initial conditions time and ramp up fraction were not used because the 2D areas represent retention areas that are either dry to start the simulation like Odransko or bathymetry was not available to represent the channels within the 2D area. In this case, the terrain elevations represent normal flow as the LiDAR technology is not capable of penetrating the water surface.



	Parameter	(Default)	LB_RetentionArea	Odransko	Upper_Odransko	Zelenik
1	Theta (0.6-1.0):	1	1	1	1	1
2	Theta Warmup (0.6-1.0):	1	1	1	1	1
3	Water Surface Tolerance [max=0.06](m)	0.01	0.01	0.01	0.01	0.01
4	Volume Tolerance (m)	0.01	0.01	0.01	0.01	0.01
5	Maximum Iterations	20	20	20	20	20
6	Equation Set	Diffusion Wave	Diffusion Wave	Diffusion Wave	Diffusion Wave	Diffusion Wave
7	Initial Conditions Time (hrs)					
8	Initial Conditions Ramp Up Fraction (0-1)	0.1	0.1	0.1	0.1	0.1
9	Number of Time Slices (Integer Value)	4	4	4	4	4
10	Eddy Viscosity Transverse Mixing Coefficient	0.1	0.1	0.1	0.1	0.1
11	Boundary Condition Volume Check	☐	☐	☐	☐	☐
12	Latitude for Coriolis (-90 to 90)					

Figure 42. 2D Calculation Options and Tolerances Window

The number of time slices can be a relatively important parameter to develop a stable 1D/2D model. In general, the computation interval for a 1D unsteady model is based on the maximum velocity of the flood wave and the average cross section spacing to satisfy the Courant condition. When incorporating a 2D area into a 1D unsteady model, the cell spacing may be much smaller than the average cross section spacing. In order to maintain the Courant condition for the smaller cell size of the 2D areas, a significantly shorter computation interval may be required, which would result in a much longer simulation time for the same simulation period. Timing slicing provides a way to vary the computation interval between the 1D and 2D computations. For instance, the average cross section spacing for the Sava System unsteady modeling is about 450 m; however, the average cell size of the 2D areas in this analysis are 100 m. A computation interval of 2 minutes is sufficient to satisfy the Courant condition for the 1D computations; however, a 2 minute computation interval would not be sufficient for the 100 m resolution mesh cells. By using 4 time slices as shown in Figure 42, a 30 second computation interval is used for the 2D areas. Overall, this is much more efficient than using a 30 second computation interval for the entire simulation.

The final three parameters are eddy viscosity transverse mixing coefficient, boundary condition volume check, and latitude for Latitude for Coriolis. The eddy viscosity transverse mixing coefficient controls the effects of turbulence in the 2D flow field; however, this is not considered for this analysis since the diffusion wave approximation is used. The boundary condition volume check, when activated, will balance flow over a weir that is connected to a 2D area. Finally, the latitude of Coriolis is required to consider the effects of Coriolis acceleration, which is related to the effects of the earth's rotation on the solution and more significant near the poles of the earth.

Figure 42 also shows that all of these parameters can be varied for each 2D area, which is very useful when different mesh cell sizes are used for different 2D areas. Setting these options are the final consideration prior to computing a 1D/2D hydraulic simulation using the geometry and flow file discussed in previous sections.

4.1.4 2D MODEL RESULTS

Once the geometry was modified and the boundary conditions were defined as discussed in the sections above, USACE began simulating the September 2010 event to evaluate the results. For the 1D components such as cross sections and lateral structures, results can be displayed similarly to those of the full Sava System unsteady flow model. These options include options such as profile and cross section plots in the HEC-RAS interface and inundation areas and depth grids in the RASMapper interface.

For results in the 2D areas, RASMapper must be used to plot simulation results. Results in 2D areas can be plotted for any cell within the 2D mesh by right-clicking on a cell or cell face within the RASMapper interface and choosing a parameter option from the Time Series Plots submenu under the mesh section of the menu. Various parameter results versus time can be plotted including water surface, depth, and velocity. Figure 43 illustrates a water surface plot resulting from the 1D/2D simulation. The data from this plot can also be tabulated and used in another visualization software.

In addition to plotting results for cells and cell faces, many of the visualization tools for 2D areas like plotting inundation mapping, depth grids, water surface grids, and velocity grids is similar to the visualization tools discussed in previous sections. Another tool available for both 1D and 2D is the ability to plot velocity arrows and tracers. The primary advantage for this tool in a 2D area is that the results indicated direction in both the x and y-planes based on the more advanced 2D computations. For 1D solutions, velocities are only conceived in the direction of flow. Figure 44 illustrates the velocity arrows and tracers that can be plotted for simulation results. For a 2D simulation, these arrows inform the modeler when flow is moving from a channel into an overbank area over levee as is shown in Figure 44.

The HEC-RAS User's Manual can be consulted for more information related to visualizing results in RASMapper.

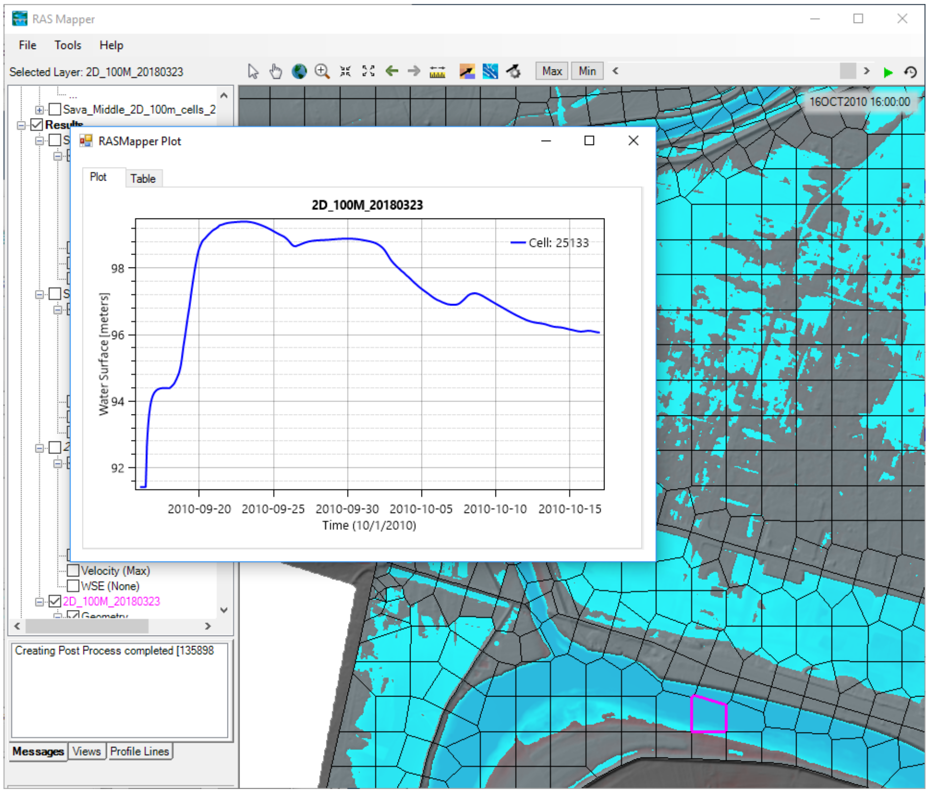


Figure 43. Example of Water Surface Plot in 2D Area

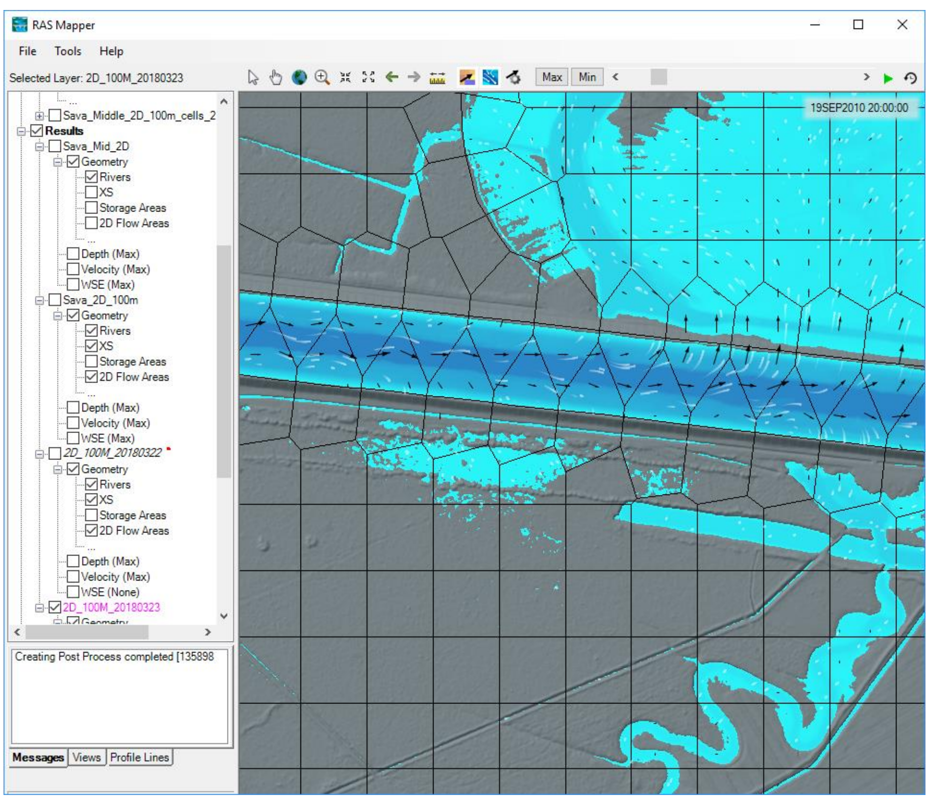


Figure 44. Example of Velocity Arrows and Tracers in a 2D Area

4.2 LEVEE BREACH ANALYSIS

USACE also conducted a levee breach analysis to provide an example of the new 2D capabilities within HEC-RAS as these tools levee breaching and 2D output. For this analysis, USACE evaluated several possible levee breaches that occurred during the May 2014 flood event along the middle and lower Sava River regions during which multiple breaches occurred in the region upstream and downstream of the confluence between the Bosna and Sava Rivers. The purpose of this analysis is to provide the ISRBC and its member countries with a model that demonstrates the HEC-RAS levee breaching capabilities as an example; therefore, only a single off channel storage area was analyzed as part of this analysis.

Many of the 2D modeling standard functions within HEC-RAS are discussed in Section 4.1; therefore, this section only discusses functions specifically related to the levee breach analysis.

4.2.1 LEVEE BREACH GEOMETRY DEVELOPMENT

The extent of this analysis includes the Sava River from the Županja station downstream to the Sremska Mitrovica station. In addition, this model geometry includes the downstream reaches of the Tinja, Bosut, and Drina Rivers. In general, this model is identical to the 1D unsteady model discussed in Section 3 for the extent of this levee breach analysis.

Figure 45 illustrates the modified geometry extent used as the basis for the 2D levee breach analysis. In addition to limiting the scope of the Sava River, many of the tributary reaches were excluded from this analysis.

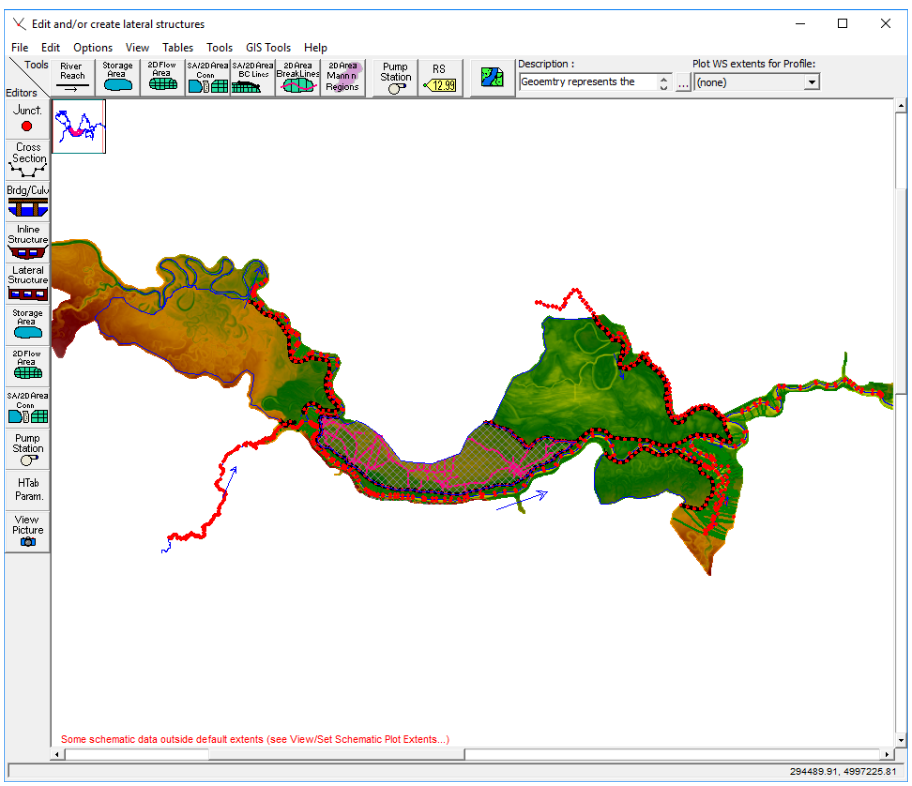


Figure 45. 2D Levee Breach Model Geometry Schematic

The primary change from the 1D unsteady model is that the Gunja storage area was converted to a 2D area as the breaches being studied for this analysis occurred at 2 levee locations along this reach of the Sava River. As discussed in Section 4.1, the Gunja 2D area is connected to the Sava River mainstem 1D model using a lateral structure. The breaches being analyzed as part of this analysis are applied to this lateral structure to allow the flow to pass from the Sava River through the lateral structure and into the Gunja 2D area.

Figure 46 provides a more detailed view of the Gunja 2D area with the 2 levee breaches for the May 2014 event also highlighted. Based on the information provided by the ISRBC, the two levee breaches are noted as the Rajevo Selo and Račinovci levee breaches. In addition, Figure 46 also illustrates the various breaklines distributed throughout the 2D area in bright pink.

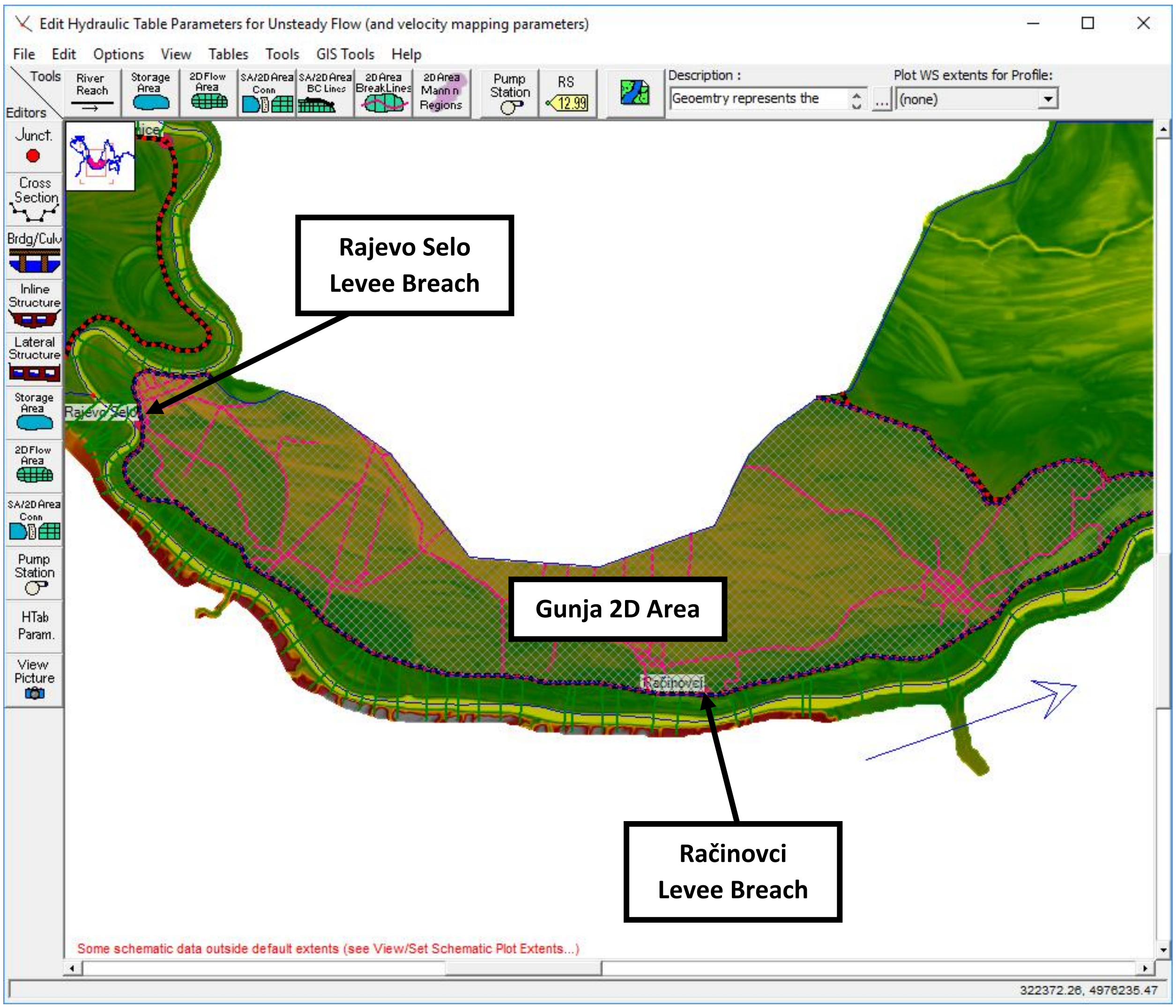


Figure 46. Detailed Levee Breach Analysis Area

In order to compute the 2D hydraulic characteristics, HEC-RAS requires the user to develop a 2D mesh within the 2D area. Similarly to other 2D analysis, a mesh cell size of 100m by 100m was used to define the 2D area. The geometry is linked to the terrain derived from the LiDAR data collection.

Because topography can not be fully define with a uniform mesh cell spacing, linear features such as roads and dikes can be represented with breaklines within HEC-RAS. An extensive amount of breaklines was used for this 2D area due to detailed analysis being conducted and the presence of several urban areas with a high concentration of roadways. Figure 47 provides a detailed example of how breaklines were defined for this 2D area. In addition, the figure also illustrates the 2D mesh cells created based on the extensive breaklines in this urban area.

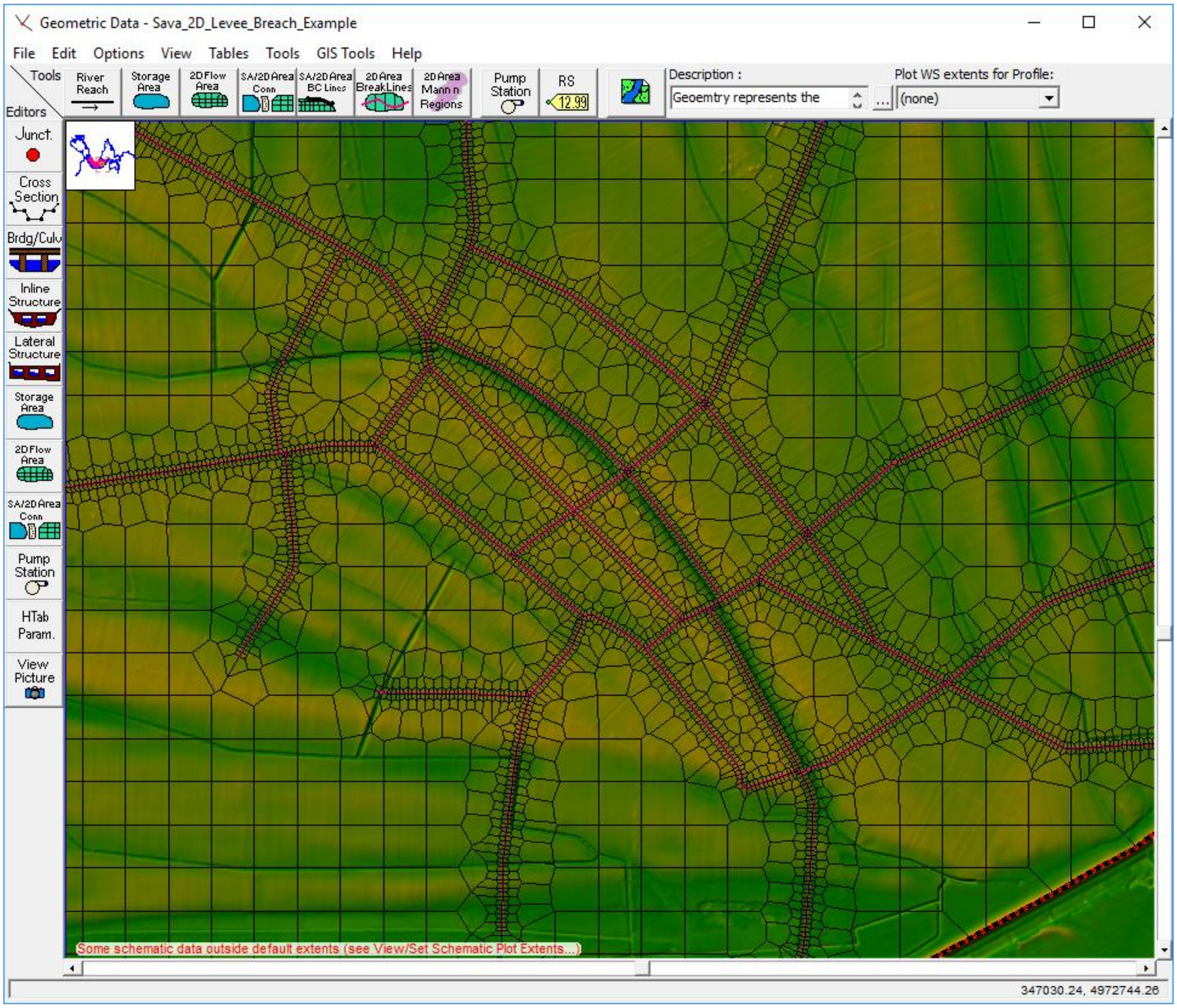


Figure 47. Example of Breaklines for Levee Breach Analysis

Once the mesh cell spacing of 100m was determined and breaklines were developed for the Gunja 2D area, the mesh for each 2D area was generated. The general statistics for the Gunja 2D area are:

- Number of Cells – 49699
- Maximum Cell Size – 19837.22 m^2
- Minimum Cell Size – 37.46 m^2
- Average Cell Size – 2632.63 m^2

Due to the level of detail of the breaklines, the average cell size indicates that the detail of the 2D mesh is much more refined around the linear structures represent by the breaklines.

In general, the geometry development processes discussed thus far are similar those discussed in Section 4.1; however, the level of detail is much greater for this analysis.

The goal of this analysis is to represent observed levee breaches during the May 2014 flood, which were numerous throughout a specific reach of the Sava River. For the purposes of providing a demonstration of the levee breaching capabilities of HEC-RAS, USACE chose these two levee breach locations based on the availability of observed high water marks and through consultation with the ISRBC. The ISRBC provided general information related to these breaches, although some assumptions were required to develop the levee breach input data into HEC-RAS.

HEC-RAS requires the following information for inputting breaches:

- Breach center station
- Breach final bottom width
- Breach final bottom elevation
- Left and Right breach side slopes
- Breach weir coefficient
- Breach formation time
- Failure mode – piping or overtopping
- Trigger – set time, water surface elevation, or water surface elevation and duration
- Breach progression curve

Much of the information required was derived from a shapefile of the breaches provided by the ISRBC including location, top width, final bottom elevation, and approximate time of failure. The breach formation time, side slopes, breach weir coefficient, and breach progression curves were assumed based on USACE's experience with levee breaches. In addition to the breach shapefile provided by the ISRBC, a summary of the levee breaches was provided by the ISRBC. From this document, the failure mode was determined. *However, official information from the competent Croatian bodies was not available at the time of preparation of this model. For this reason, the results obtained are not official and as such could not be taken for any official purposes.*

Based on the information available, the breach at Rajevo Selo was not a result of overtopping flows but rather seepage and piping failure caused the levee to breach in this location as shown in Figure 48. Based on the information provided, Figure 49 shows the information input for the Rajevo Selo levee breach. For both levee breaches, the breach progression curve is based on a sine wave, which has been seen as an adequate representation of breach progression on other levee breach studies.

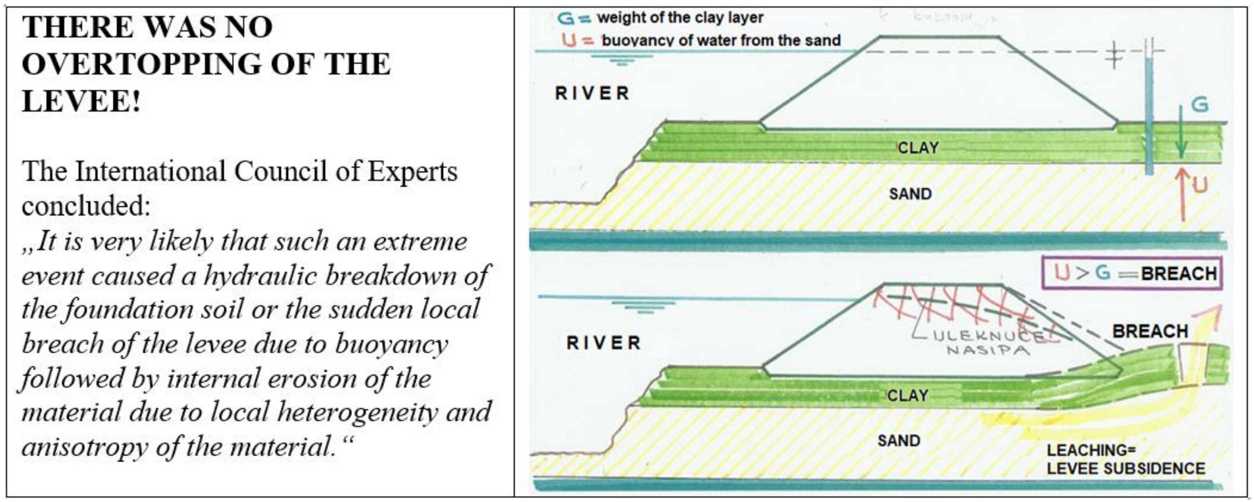


Figure 48. Piping Failure Diagram at Rajevo Selo

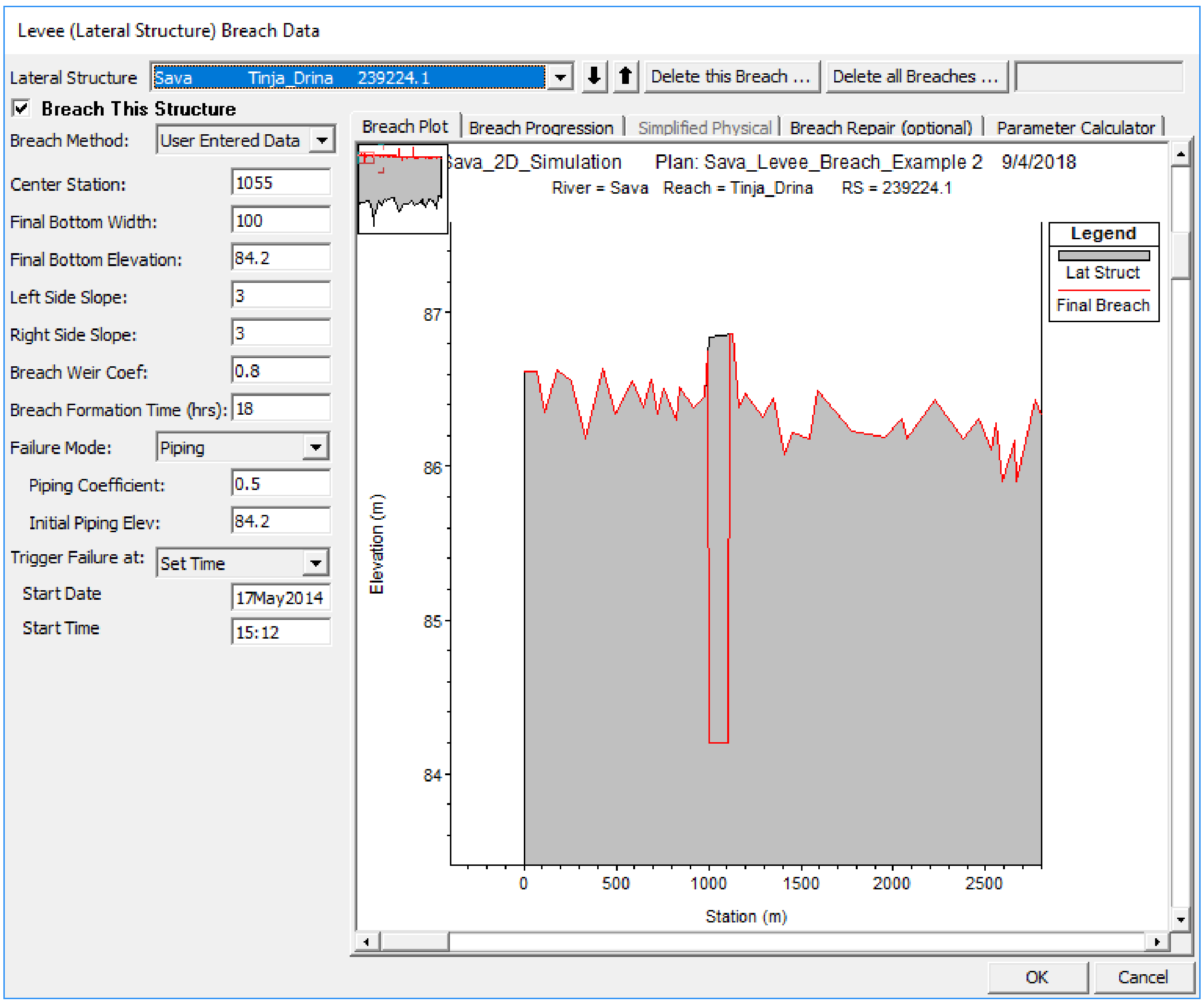


Figure 49. Breach Input Data for Rajevo Selo

For the Račinovci levee breach, less information was available in the summary report; however, the levee breach shapefile provided by the ISRBC was sufficient to define the levee breach parameters. Again, this breach was the result of piping as opposed to overtopping. One critical piece of information that was not provided was the final breach bottom elevation; therefore, USACE assumed the final bottom elevation based on the surrounding terrain at the base of the levee. Figure 50 shows the information input for the Račinovci levee breach.

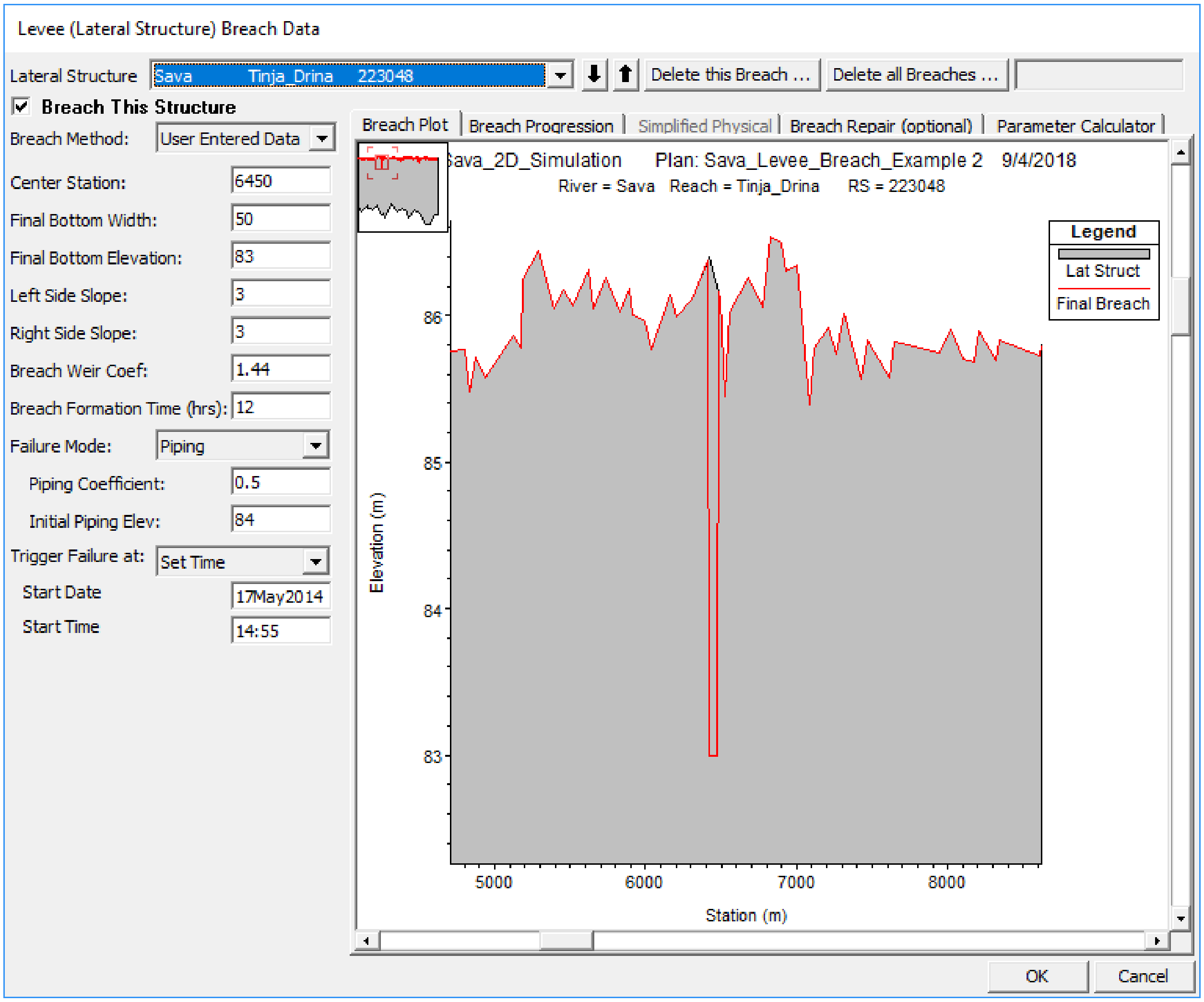


Figure 50. Breach Input Data for Račinovci

Within HEC-RAS, levee breaches are input through either the plan editor or the lateral structure editor. The user can activate the breach depending on the type of analysis being conducted. When the levee breach is activated, the breach will occur based on the trigger, which for these breaches was set based on a time of breach provided by the ISRBC. The flow through the breach is computed using the weir equation, which can rely on a different weir coefficient than the lateral structure to which the breach is assigned. For this analysis, the water surface on the outside of the levee is computed through the 1D unsteady analysis of the Sava River, which is used to compute flow through the breach based on the weir equation. This flow is then transferred to the Gunja 2D area, where 2D flow hydraulics are computed to determine the flow characteristics behind the levee.

4.2.2 LEVEE BREACH BOUNDARY CONDITIONS

As discussed in Section 4.1, the approach to defining boundary conditions when introducing 2D elements to the geometry is similar to the normal approach of defining boundary conditions and for this analysis was very simple due to the limited extent of the model.

The extent of the hydraulic model for this analysis includes the Sava River from the Županja station downstream to the Sremska Mitrovica station along with the downstream reaches of the Tinja, Bosut, and Drina Rivers. For the Sava River tributaries, the boundary conditions from the 1D analysis, which are based on outputs from the HEC-HMS model, were used. Similarly, the local flow contributions along the Sava River are also based on the HEC-HMS results. To produce as accurate a water surface as possible on the Sava River, the observed stage hydrographs at the two bounding stations (Županja and Sremska Mitrovica) were used. This approach provides high confidence in the water surface profiles computed along the Sava River and is acceptable because the main purpose of this analysis is to evaluate the flow characteristics for the two levee breaches.

In terms of boundary conditions, the levee breach analysis does not have an effect on how the boundary conditions are applied because the primary introduction of flood waters to the 2D area is computed internally through the breaches in the model.

4.2.3 LEVEE BREACH CALCULATION OPTIONS AND TOLERANCES

As with a 1D unsteady analysis, a simulation that includes purely 2D or a 1D/2D analysis is setup through an unsteady plan. The interface for this analysis is identical to the 1D unsteady analysis as can be seen in Figure 51. The primary difference that can be noticed is at the bottom of the editor where the display shows the presence of two levee breaches and the indication that these breaches are activated. In addition, the levee breach input window can be accessed by double-clicking the levee breach message at the bottom of this editor.

As discussed in Section 4.1, the *Calculations Options and Tolerances* window can be access from the options menu on the unsteady flow analysis editor and will allow the user to modify specific properties of the simulation. These options and tolerances are typically used to help improve the accuracy and stability of a simulation. Since the addition of the 2D capabilities, two new tabs have been added to this window, *2D Flow Options* and *1D/2D Options*. As with 1D options, it is generally recommended to maintain the program defaults for most parameters; however, it is typically necessary to modify some of the options for 2D areas.

The *Calculations Options and Tolerances* parameters are discussed in detail in Section 4.1 and the HEC-RAS User’s Manual. For the levee breach analysis, similar parameters are used as compared to the 2D model of the central Sava flood protection system. Figure 52 illustrates the parameters used for the 2D analysis of the levee breach. For this analysis, only a single 2D area, the Gunja 2D area, is represented.

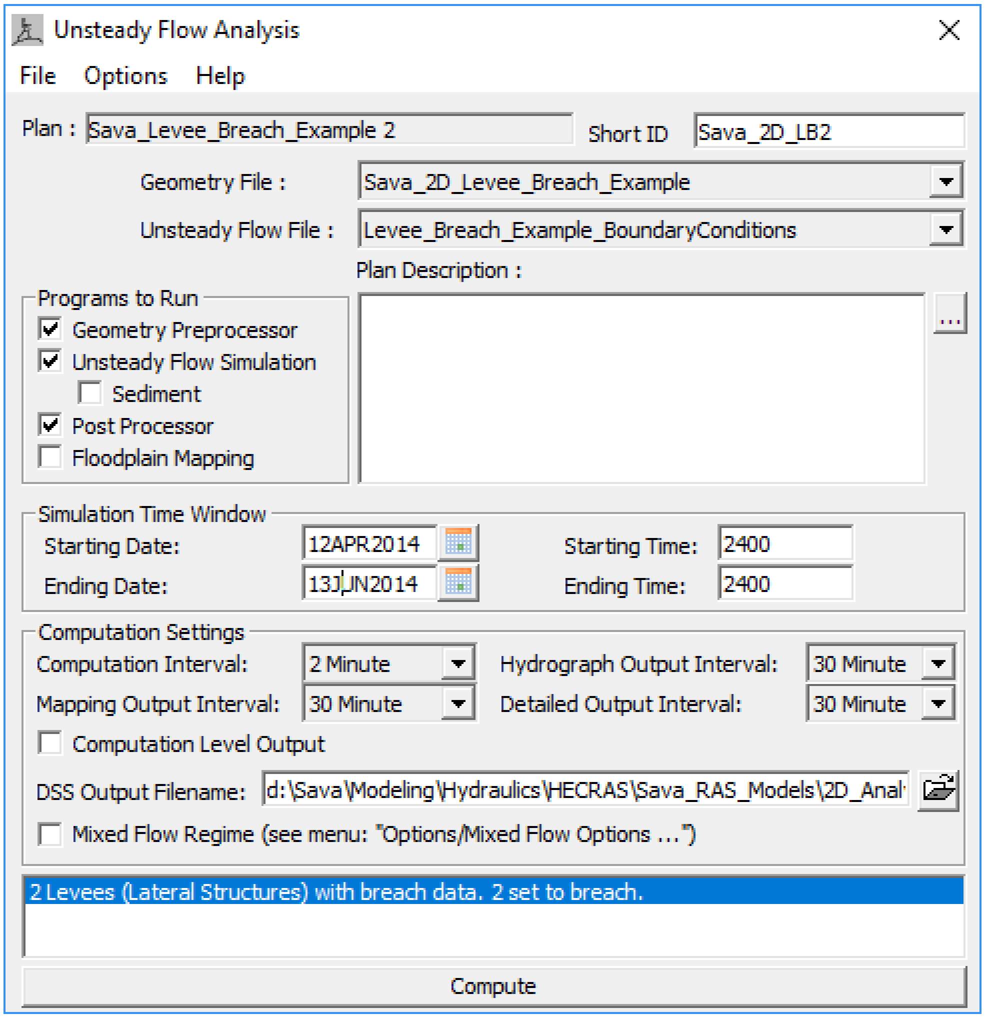
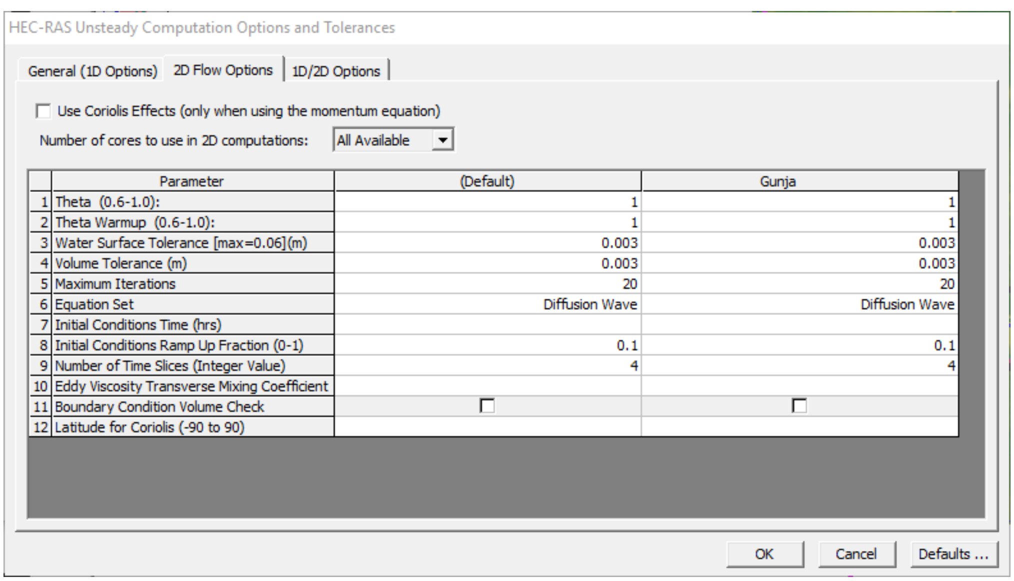


Figure 51. Unsteady Flow Plan Editor for the Levee Breach Analysis



	Parameter	(Default)	Gunja
1	Theta (0.6-1.0):	1	1
2	Theta Warmup (0.6-1.0):	1	1
3	Water Surface Tolerance [max=0.06](m)	0.003	0.003
4	Volume Tolerance (m)	0.003	0.003
5	Maximum Iterations	20	20
6	Equation Set	Diffusion Wave	Diffusion Wave
7	Initial Conditions Time (hrs)		
8	Initial Conditions Ramp Up Fraction (0-1)	0.1	0.1
9	Number of Time Slices (Integer Value)	4	4
10	Eddy Viscosity Transverse Mixing Coefficient		
11	Boundary Condition Volume Check	☐	☐
12	Latitude for Coriolis (-90 to 90)		

Figure 52. Calculation Options and Tolerances Window

4.2.4 LEVEE BREACH MODEL RESULTS

Once the geometry was modified and the boundary conditions were defined as discussed in the sections above, USACE began simulating the May 2014 event to evaluate the results of the levee breach analysis. For the levee breach analysis, most of the results of interest are located in the Gunja 2D area and were evaluated are only available within RASMapper.

Figure 53 shows an overview of the inundation boundary resulting from the levee breach analysis. As this figure illustrates three urban areas experienced a large amount of flooding as a result of the levee breaches including Gunja, Račinovci, and Strošinci.

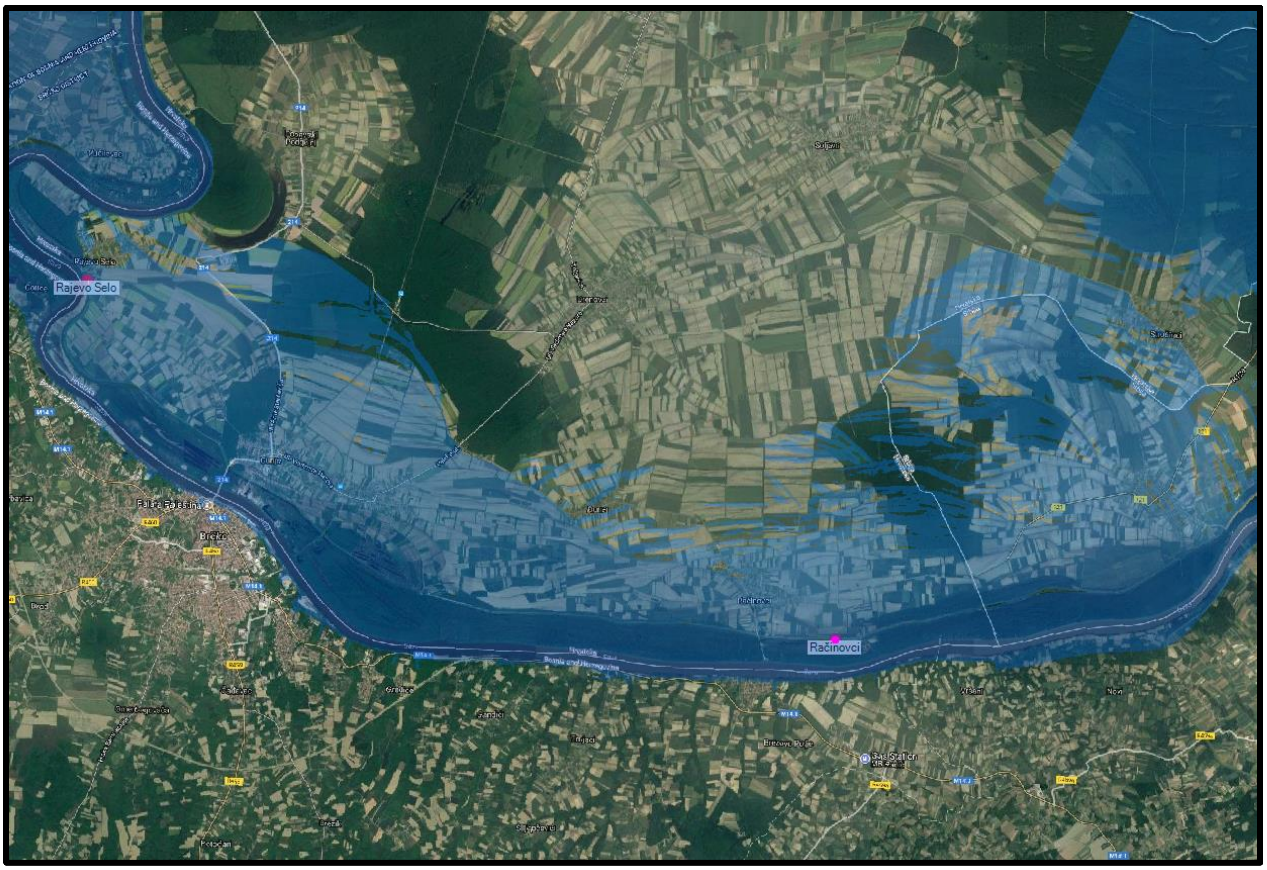


Figure 53. Inundation Boundary of Levee Breach Analysis

In addition to inundation boundaries, depth grids, and water surface grids, other useful mapping information is provided through RASMapper. Figure 54 illustrates static velocity arrows and particle tracing capabilities of RASMapper at the location of the levee breach at Račinovci.

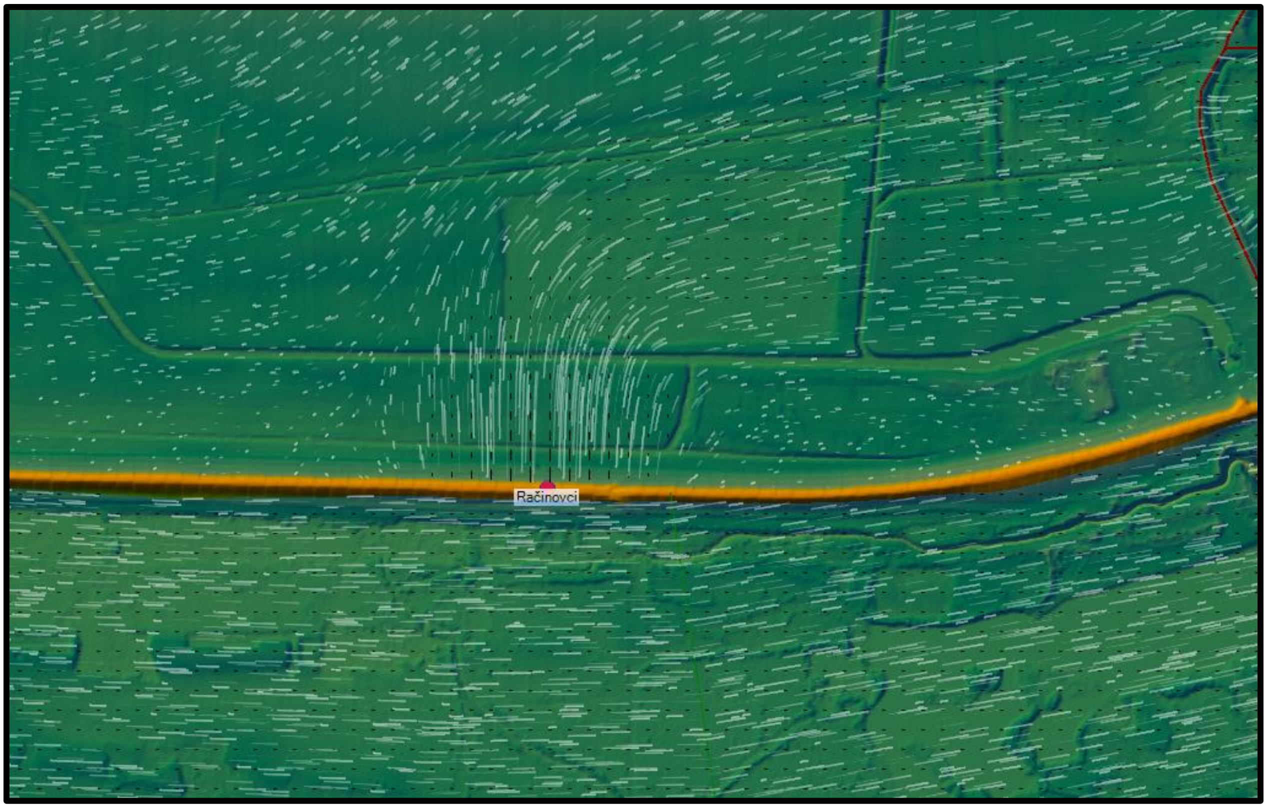


Figure 54. Static Velocity Arrows and Particle Tracing for the Račinovci Levee Breach

For the analysis of these two levee breaches, USACE was fortunate to be provided high water mark information and an approximate inundation boundary based on satellite remote sensing. Figure 55 shows the inundation results of the 2D modeling levee breach analysis in comparison to the approximate satellite-based inundation boundary. The results of this analysis shows that the model generally reproduces this observed data set.

In addition to the comparison of boundary conditions, the ISRBC also provided several high water marks throughout the area behind the levee affected by the levee breaches. The statistical comparison of the observed versus computed water surface elevations (WSELs) are provided in Table 5.

Table 5. Statistical Results of Observed versus Computed WSELs for Levee Breach Analysis

Statistical Parameter	Entire Dataset	Excluding Outliers
Total Number of HWMs	22	18
Average of Differences (m)	-0.03	0.20
Average of Absolute Differences (m)	0.37	0.21
Standard Deviation of Differences	0.58	0.20
Standard Deviation of Absolute Differences	0.44	0.19
Coefficient of Determination	0.58	0.95

The results of this statistical comparison shows that the comparison between observed and computed WSELs is very good. This analysis did, however, point out a weakness in the northwest region of the 2D area just east of Rajevo Selo. The area in Figure 56 is somewhat protected by roadway embankments, with probable bridge openings within these roadway embankments. With lack of detailed information for these bridge openings, USACE configured the 2D mesh to allow flow to pass from one side of the embankments to the other in areas where there are apparent bridge openings as shown in Figure 57. This configuration is probably allowing too much flow to pass through the roadway embankment. To correct this issue, the detailed bridge opening information can be obtained and the breaklines representing the roadway embankments can be converted to an internal SA/2D area connection. Once converted the bridge opening information can be input into the internal SA/2D area connection, which will allow the proper amount of flow through the roadway embankment. Overall, this is not a significant issue and is probably not critical; however, this issue was pointed out to show that the statistical comparison is marginally improved when the HWM points in the area behind these roadway embankments are removed from the statistical calculations.

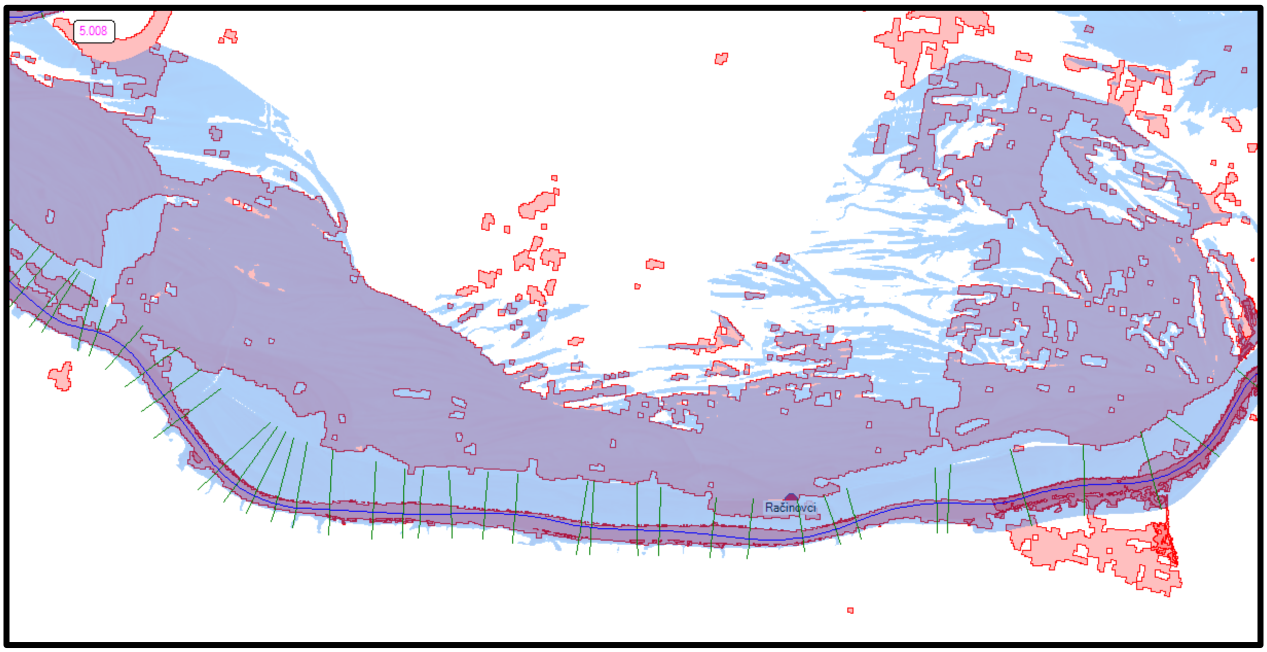


Figure 55. Modeled Inundation Boundary versus Satellite-Based Inundation

Overall, the results of the 2D hydraulic analysis of these two levee breaches indicates that the model is adequately reproducing inundation extents and depths resulting from the May 2014 levee breaches. The results provided in Table 5 shows that average difference in comparative WSELS is around 0.2 m and the coefficient of determination is approximately 0.95 (when removing outliers), which supports the accuracy of the model. In addition, Figure 55 illustrates that the inundation boundary produced by the model closely matches the satellite-based inundation area with the exception of the area east of Rajevo Selo discussed above.

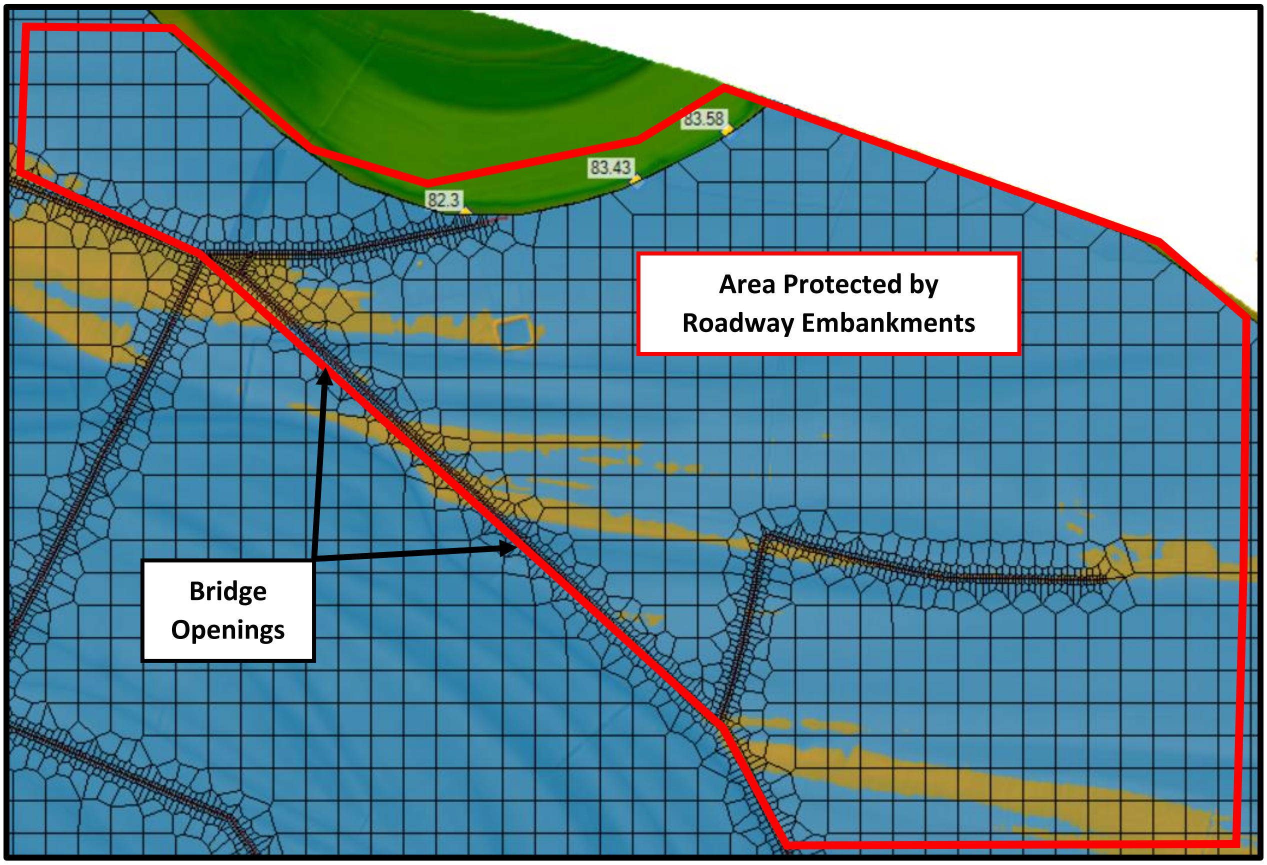


Figure 56. Inundation Area East of Rajevo Selo

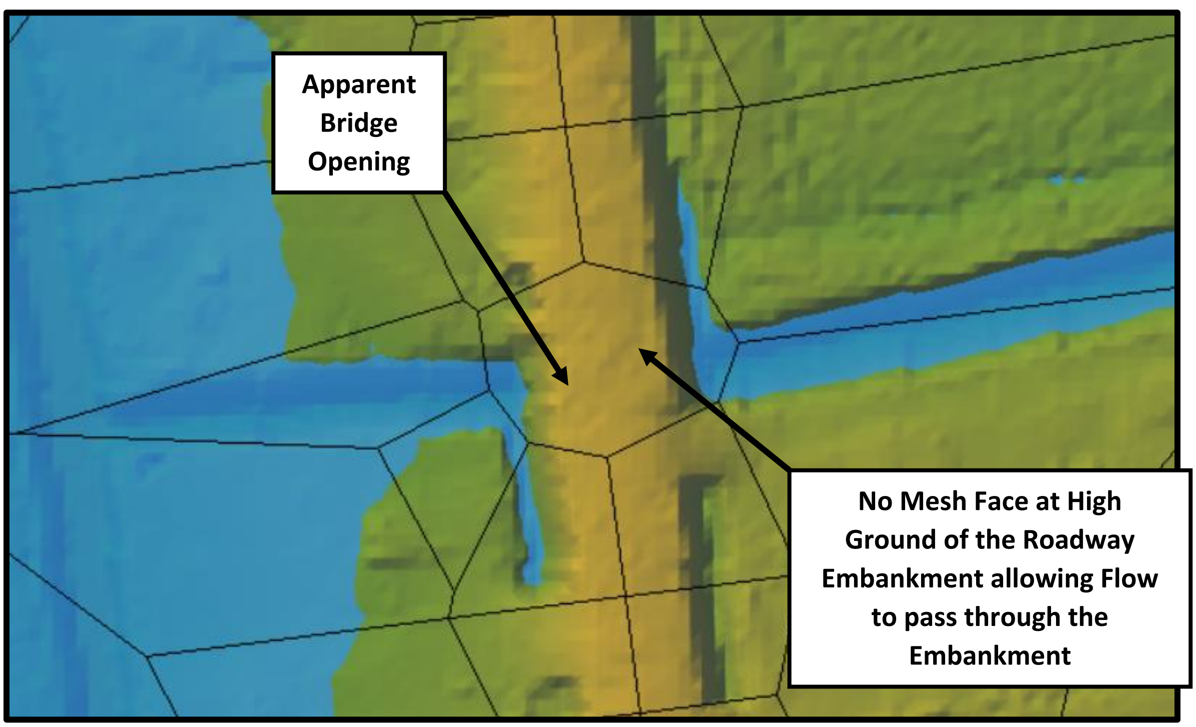


Figure 57. Example of 2D Mesh Configuration to Pass Flow through a Bridge Opening

5. CONCLUSIONS

The purpose of this section is to summarize the effort undertaken by USACE to develop hydraulic modeling for the Sava River System, to identify potential limitations of the modeling products, and to discuss recommendations for future improvements to the modeling products. The overall effort included the development of multiple types of models and products.

5.1 MODEL LIMITATIONS AND RECOMMENDATIONS

Limitations and uncertainty in a hydraulic model can be related to several different sources such as data accuracy and availability, knowledge uncertainty, and model method limitations. Understanding of a particular model's limitations is an important factor to ensure proper application of the model and to improve the model as new data and modeling techniques become available. The major areas of limitations and uncertainty for this hydraulic model include:

1. Hydrologic discharge inputs
2. Sufficient digital terrain information
3. Location of levee breaches and unknown hydraulic connections

5.1.1 HYDROLOGIC DISCHARGE INPUTS

The primary input to HEC-RAS is discharge or flow data. For the modeling in this study, output from the hydrologic model developed using HEC-HMS in an earlier phase of this project serves as the discharge inputs into the HEC-RAS models. The uncertainty in these inputs includes uncertainty and errors related to the hydrologic modeling itself and, more significantly, to the meteorologic inputs into the hydrologic model. In general, meteorologic data is the most difficult to measure and apply spatially over a basin in an accurate manner because this data is typically derive from point measurements or some sort of radar-based device. Both of these methods of measurement have limitations with point data only providing information at a single point while radar-based devices inherently have significant error.

Ultimately, this is not an error or uncertainty that can be controlled by a hydraulic modeler; however, the uncertainty should be understood to help discern when the error may be negatively affecting hydraulic model results.

Detailed recommendations for improving the hydrologic model are provided in the HEC-HMS Technical Documentation Report provided as a separate report to the ISRBC. The most critical recommendation for the improvement of any model is to continually use the model either by calibrating historical events and/or calibrating to new events as they occur. Continual use of a model allows users to identify weaknesses in the model such that determination of the source of these weaknesses can also be identified. Typically weakness in a hydrologic model are related to:

- Data or lack of data
- Estimation of hydrologic parameters
- Subbasin delineation

As new data becomes available, the data should be incorporated, and the model should be tested to determine how this new data affects the performance of the model. For instance, if new meteorologic stations are implemented, these stations should be added to the model to determine if additional calibration of the model is necessary. Similarly, if a hydrologic station is added to the new network, the calibration of the model should be tested at the new location. If a node is not available at this location, the delineation may need to be altered to include the new hydrologic station. Finally, accurate subbasin delineation is one of the most critical improvements that can be made because the rainfall-runoff is directly related to drainage area. During the hydrologic model development, available data was used to develop the most accurate delineation possible especially in the low-lying floodplain areas along the Sava River and in Karst areas where inter-basin transfer is observed. The delineation should be continuously investigated and considered when new digital terrain information becomes available.

Finally, another consideration is HEC-HMS version improvements. The Hydrologic Engineering Center is continuously improving the model capability and adding features that could improve the performance of the model. Users should monitor new releases of software and determine if model software improvement deem necessary an upgrade to a new version.

5.1.2 SUFFICIENT DIGITAL TERRAIN INFORMATION

The hydraulic modeling developed throughout this study has benefitted greatly from the collection of high-resolution and accuracy LiDAR data. In the previous phase, lack of high quality digital terrain made it very difficult to produce an accurate hydraulic model or inundation mapping. The limitation discussed here relates to locations where LiDAR was not collected. Specifically, two areas are identified in this document including areas along the Sava River mainstem where very high flood waters exceeded the capacity of the Sava River and areas in the upstream areas of the tributary reaches.

Although the LiDAR collection was very extensive, areas exist where flooding directly originating from the Sava River extends out into the floodplain where LiDAR data was not collected. The area along the right bank of the Sava River between the village of Orahova and the town of Gradiška represents such an area. In this short reach, the right bank floodplain is not protected by a levee, and during certain flood levels such as the December 2009 event, flood waters can extend out into the overbank. Unfortunately, this overbank area was not included in the extent of the LiDAR collection; therefore, it can not be represented with a hydraulic model element to account for the floodplain storage this area provides. In addition, the results in this area can not be properly mapped. Figure 58 shows an example of a specific cross section within this reach where the terrain does not cover the entire overbank area sufficiently. The area circled in red shows where the right bank of the cross section is overtopped and flood waters can extend out into the flood plain. The map in the background of the figure illustrates where the inundation/depth grid boundary is being cut off at the extents of the cross section.

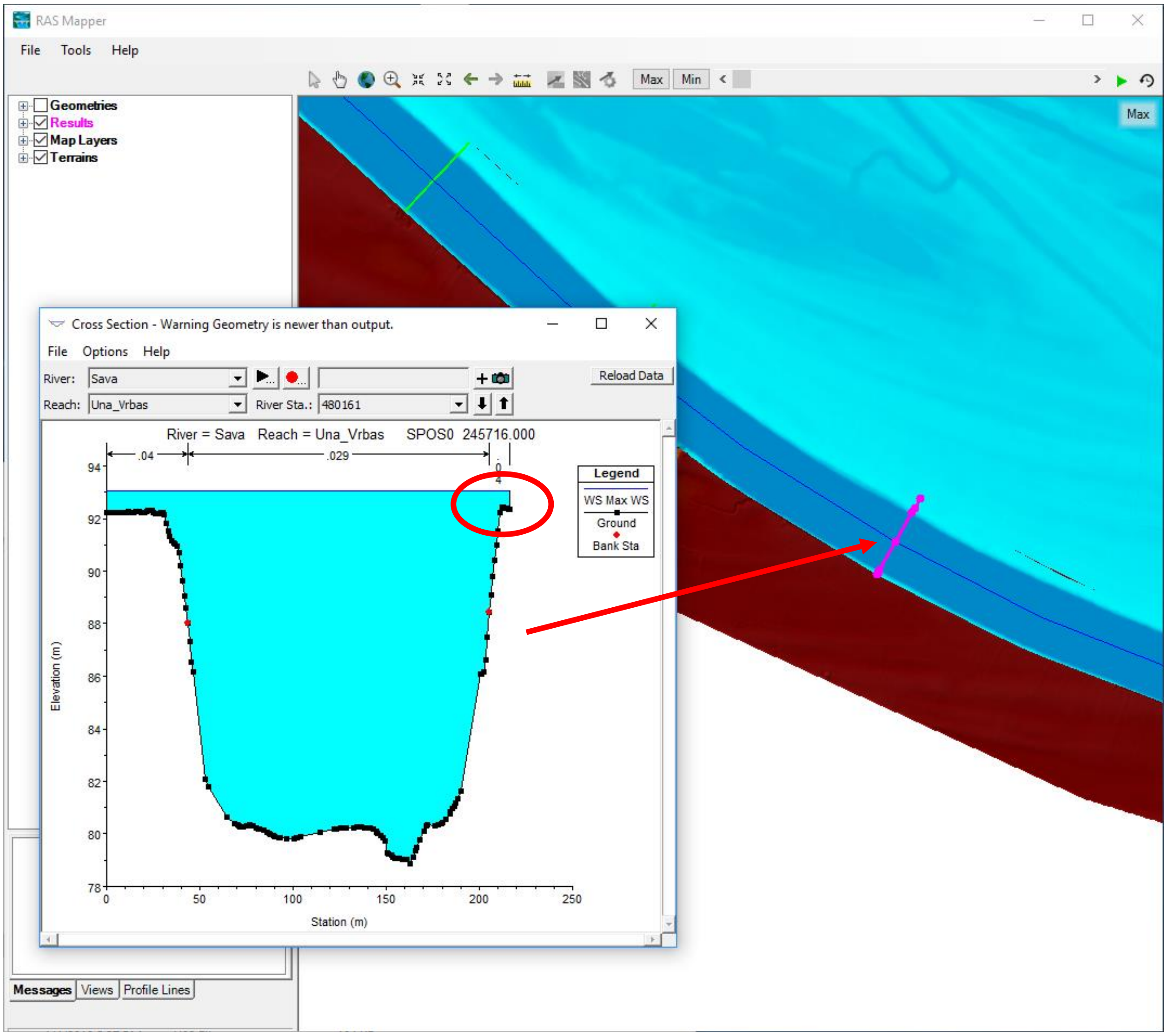


Figure 58. Example with Insufficient Digital Terrain Coverage

Fortunately, the solution to this issue very simple. If there is another source of digital terrain data or if additional data is collected in the future, the additional data can be combined with the existing RAS terrain in RASMapper to achieve a terrain that has full coverage of the area. Once a complete terrain is created, a lateral structure along the extents of the cross sections on the right bank can be combined with a storage area representing the entire area that could be flooded much like has been done in other areas of this hydraulic model. This issue is not a widespread problem in the model; however, it was noticed during model development. This modification to the model would properly represent the floodplain storage that exists in this reach of the Sava River.

In addition to the types of areas described above, areas exist on the tributary reaches where LiDAR data was not collected as shown in Figure 59 for the Vrbas River reach model. As was requested by the ISRBC, many of the major tributaries to the Sava River were included in the system model because the member countries have provided valuable hydraulic modelling throughout this project. As the figure shows, some of the cross sections representing the backwater area of the Vrbas River are covered by the digital terrain;

however, some are not. In general for this situation, USACE utilized as much of the terrain as possible to update the models provided by the member countries. In situations where terrain data did not exist, USACE left the model data as was delivered as no reliable basis for updating the geometry existed.

If additional digital terrain data exists or if new data is collected in the future, the solution to this issue is to merged the new terrain data with the existing terrain as described for the issue above. The cross section geometry can then be updated with this new terrain. In addition, with new digital terrain, additional cross sections can be created to represent a larger extent of the tributary reaches in the same manner that this entire system model was developed.

The Hydrologic Engineering Center has made drastic improvements to the HEC-RAS modeling software in recent years. One of the greatest improvements is the ability to develop model geometry within HEC-RASMapper, which is a new tool within the HEC-RAS software. Some of the HEC-RASMapper improvements relevant to adding and/or updating model geometry, especially for Sava River tributaries, includes:

- Allows the incorporation of channel bathymetry into existing digital terrain
- Allows for the addition and modification of cross section cutlines for existing model geometry
- Allows for the station-elevation data to be pulled directly from the digital terrain into any new or modified cross section cutlines
- Virtually all pre-processing capabilities of HEC-GeoRAS have been incorporated into HEC-RASMapper, which makes creating new model geometries and updating existing model geometries seemless

The scope of this modeling effort did not included detailed model develop for Sava River tributaries; however, tributary models were included to the greatest extent possible. HEC-RASMapper provides a relatively easy method to updating the tributary models as new information, such as more expansive digital terrain, bathymetric channel surveys, and bridge surveys, is collected or becomes available. Channel bathymetry data can be added to an existing or new digital terrain by taking the bathymetry data as cross sections and deriving a bathymetry terrain in HEC-RASMapper. HEC-RASMapper then allows this bathymetry terrain to be merged with overall terrain that covers the area of the model. HEC-RAS documentation provides detailed information for this process and should be consulted when attempting this improvement. Once a terrain with the landscape and bathymetry data is created, existing model cross section geometry can be easily updated in HEC-RASMapper or through the Cross Section Editor. Additionally, cross sections can be moved or added and station-elevation data can be derived from this new terrain.

Existing or new bridge surveys can be used to update or add bridges to the hydraulic models of the mainstem Sava River and/or its tributaries. Although bridges are not specifically included in the new HEC-RASMapper pre-processing tools, road geometry can be derived from the terrain and merged with the bridge survey data in the HEC-RAS Bridge Editor to develop a complete bridge geometry. Any necessary lateral structures can also be added in a similar way as lateral structure development is also not specifically a tool in HEC-RASMapper. The expectation is that these tools will be added to HEC-RASMapper in the near future.

HEC-RASMapper has proven to be a great improvement to both pre- and post-processing of model geometry and results, respectively. The capabilities of HEC-RASMapper are continuously being improved and expanded. Extensive documentation is available through the Hydrologic Engineering Center's website and should be utilized as users expanded the scope and capability of the hydraulic modeling products provided through this project.

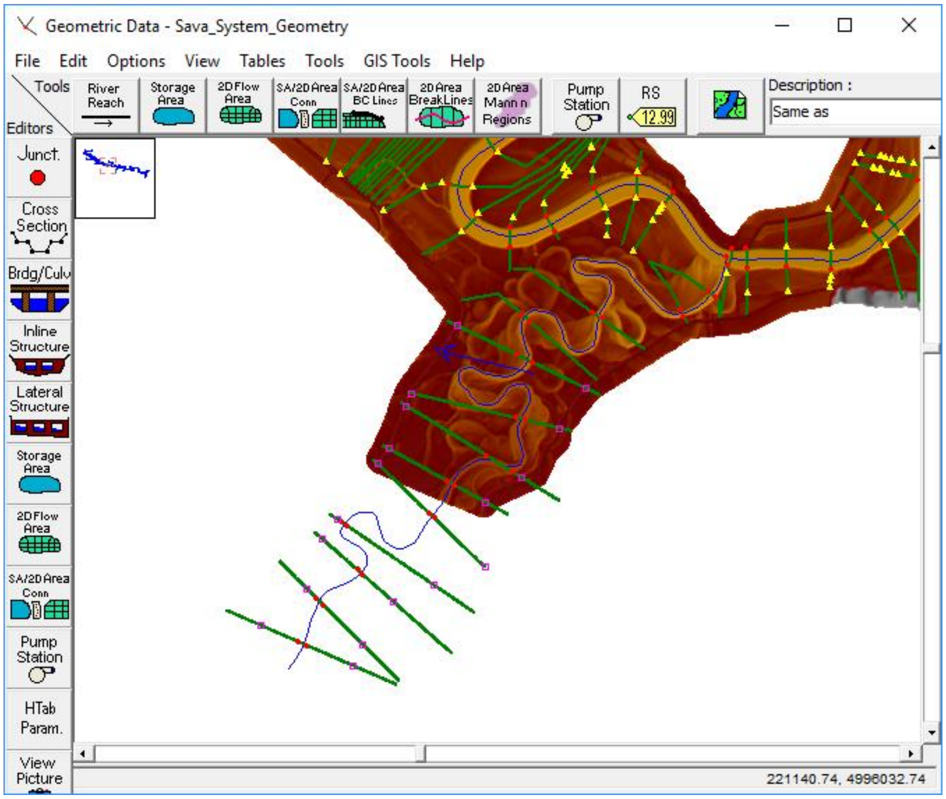


Figure 59. Vrbas River Reach Showing Insufficient Digital Terrain

5.1.3 LEVEE BREACHES AND OTHER HYDRAULIC CONNECTIONS

The Sava River system HEC-RAS model covers a very large extent making it very difficult to account for every hydraulic connection between the mainstem and levee-protected overbank and/or between two areas within the overbank. In addition to standard hydraulic connections through bridges and culverts, levee breaches commonly occur in the Sava River system for large flood events.

Figure 60 shows an example of a location where the mainstem Sava River is connected to the Medsave storage area with a levee. The figure also shows where a small tributary appears to be hydraulically connected to the mainstem through some sort of hydraulic structure like a culvert. Without on-the-ground experience with this area, the method by which to model this connection is difficult. This connection could be an open culvert, a culvert with a flap gate, or a culvert with some sort of sluice gate. In most cases, USACE modeled these areas as hydraulically unconnected unless the levee overtops during the simulation. Modeling these connections as unconnected does not appear to have a negative impact on the overall performance of the model probably due to the fact that these connections are so small in relation to the discharges being simulated.

If these connections appear to be an issue during future simulations, the connection can be modeled using a culvert or gated structure depending on the specific situation within the lateral structure or storage area connection representing the levee.

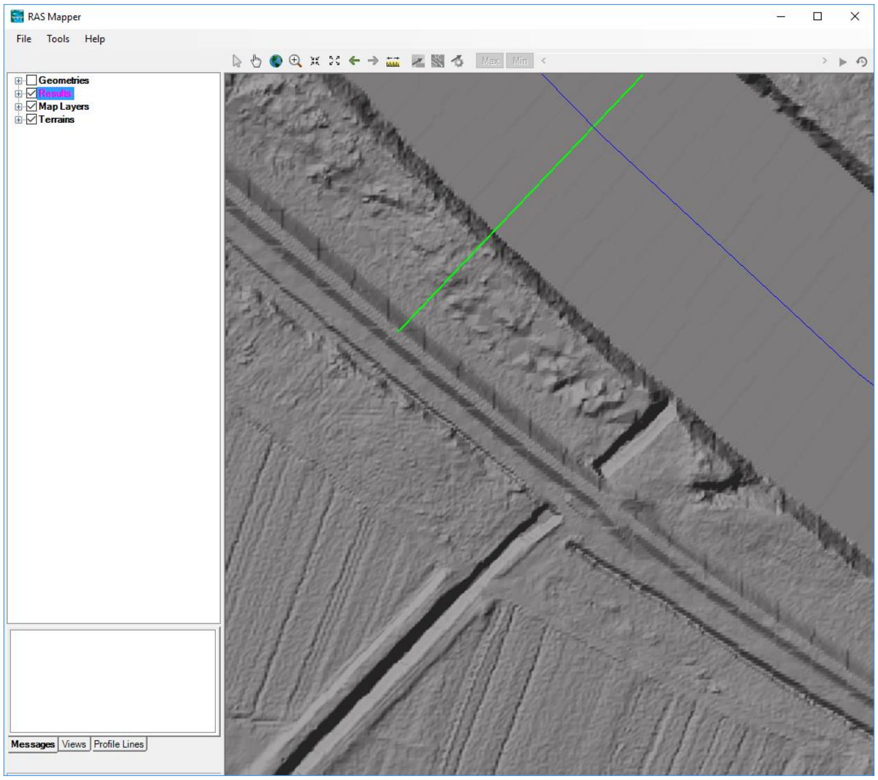


Figure 60. Example of an Apparent Hydraulic Connection through a Levee

In addition to hydraulic connections, connections between hydraulic elements can occur during a flood event due to a levee breach, which is a relatively common occurrence in the Sava River system. During a flood event, levee breaches are difficult to characterize especially in terms of timing and progression. In most cases, the breach characteristics can only be measured after the event has subsided. HEC-RAS provides the capability to include breaches within a simulation although collecting breach information is difficult and many of the breaches that have occurred may not be included in the mode produced during this study.

If it is determined that a breach occurs during the simulation, the modeler can add the breach through the lateral structure and/or storage area connection editor. The primary information needed to conduct this type of analysis is the center station of the breach location, final bottom width, final bottom elevation, side slopes, and breach formation time. In addition, the modeler will need to assume a breach progression function to control the progression of the breach to its final dimensions.

5.2 SUMMARY CONCLUSIONS

The Sava River and its tributaries represent a major flood risk within the Sava River Basin, which touches portions of Slovenia, Croatia, Bosnia and Herzegovina, and Serbia. Recent history and a better understanding of climate change shows that this flood risk has become and will continue to be a significant risk to the welfare of the people within the Sava River Basin. This flood risk emphasizes the need for H&H

modeling capable of simulating medium to large flood events. In previous efforts of this project, USACE produced a Sava River Basin hydrologic model using HEC-HMS. The value of having a basin-wide hydrologic model is invaluable because it allows the technical agencies of the region to simulate the rainfall-runoff response of the basin and incorporate these outputs into a hydraulic model. Additionally, the hydrologic model developed through this project provides the ISRBC and its member countries with a detailed event-based hydrologic model of the entire Sava River Basin that performs well over a wide-range of flood events as shown in the previous report covering the development of the HEC-HMS model

The hydraulic model developed for this project includes the Sava River mainstem from the Čatež station at the border of Slovenia and Croatia downstream to the mouth of the Sava River at its confluence with the Danube River. In addition to the mainstem Sava River reach, the model includes the downstream reaches of most of the major tributaries to the Sava River. The hydraulic model is directly connected to the output from the HEC-HMS model and provides a calibrated event model for a wide range of flow regimes. The hydraulic model in combination with the hydrologic model provides a valuable resource to the region.

In addition to the Sava River unsteady flow system model, USACE also performed some specialized analyses to provide more detailed analyses for specific areas of the Sava River region and to demonstrate some of the newer 2D capabilities within HEC-RAS. The first analysis is a 1D/2D analysis focused on the Middle region of the Sava River where a complex system of diversions and retention areas are in place to reduce flood risk for large flood events. This analysis uses the newer 2D capability in HEC-RAS to simulate the more complex hydraulic characteristics of these retention areas. In addition to this 1D/2D analysis, a levee breach analysis was conducted to demonstrate the capability of HEC-RAS to simulate a levee breach into a detailed 2D area. The main purpose of these analyses is to demonstrate how HEC-RAS could be utilized for more specialized applications.

The goal of this project was to provide a calibrated hydraulic model using HEC-RAS software and the best available data. The HEC-RAS model relies heavily on the output from the HEC-HMS model completed in previous efforts of this project. The general approach to provide the best calibration included the following steps.

1. **Build a Sava River System geometry using LiDAR data and historical hydraulic models**
2. **Calibrate the geometry to known rating curves at hydrologic stations for a wide range of steady flows**
3. **Calibrate the Sava River System model to three flood events that have occurred over the past 10 years.** The three events selected are the December 2009, September 2010, and the May 2014 events. These were selected as the largest events occurring over the past 10 years during a period where observed data was readily available
4. **Develop a 1D/2D model of the Middle Sava River region.** This region was chosen for this more specialized analysis because it contains a complex system of diversions and retention areas intended to reduce flood risk during large floods. This model provides a detailed analysis of the hydraulic characteristics that occur within the retention areas.

5. **Develop a 2D simulation of a levee breach example.** The purpose of this analysis is to demonstrate the 2D capabilities within HEC-RAS specifically in the case of a levee breach, which are relatively common occurrences within the region.

The development of the hydraulic models discussed in this report represents the completion of a multi-year project that has included the development of a hydrologic and hydraulic model (discussed here), the training of technical staff in the use of HEC-HMS and HEC-RAS, the collection of LiDAR information for the main Sava River corridor, and the purchase of computer equipment including personal computers and servers to host and utilize the products produced over the course of this project. The goal of the entire project was to provide advanced modeling products, train the technical staff throughout the institutions in the Sava River riparian countries, and equip the region with the ability to maintain and improve the products provided as well as create new models for the region's purposes.

The modeling products provided over the course of this project are merely tools and don't specifically solve the water resources problems in the region. The intent is that the regional experts use these new tools to better characterize the problems, test potential solutions, and ultimately innovate sustainable solutions to the water resources problems in this extremely diverse region of the world.

The modeling products delivered through this project provide regional experts with the ability to implement valuable initiatives throughout the region such as: region-wide flood risk mapping products, Sava River basin-wide flood forecasting capability, and risk informed alternative analyses to develop solutions to flood risk. Holistically, these products and training provide the region with the ability to improve the water resources within the Sava River Basin.

6. REFERENCES

Bonacci, O. and I. Ljubenkov (2008). Changes in Flow Conveyance and Implication for Flood Protection, Sava River*. Hydrological Processes, Zagreb*, 22(8), 1189-1196.

International Commission for the Protection of the Danube River and International Sava River Basin Commission (2015). *May 2014 Floods in the Sava River Basin*, ICPDR and ISRBC.

International Sava River Basin Commission (2009). *The 2009 Hydrological Yearbook of the Sava River Basin*, Zagreb, Croatia.

International Sava River Basin Commission (2010). *The 2010 Hydrological Yearbook of the Sava River Basin*, Zagreb, Croatia.

International Sava River Basin Commission (2011). *The 2011 Hydrological Yearbook of the Sava River Basin*, Zagreb, Croatia.

United States Army Corps of Engineers (2000). *HEC-HMS Technical Reference Manual*. Hydrologic Engineering Center, Davis, CA.

United States Army Corps of Engineers (2013). *HEC-HMS User's Manual*. Hydrologic Engineering Center, Davis, CA.

United States Army Corps of Engineers (2016). *HEC-RAS User's Manual*. Hydrologic Engineering Center, Davis, CA.

United States Army Corps of Engineers (2016). *HEC-RAS Hydraulic Reference Manual*. Hydrologic Engineering Center, Davis, CA.

APPENDIX A – HEC-RAS BOUNDARY CONDITIONS TABLE

RIVER	REACH	RIVER STATION	HMS INPUT NODE	INPUT TYPE
Sava	Catez_Sutla	736561.8	J_01_13_08_Catez	Flow Hydrograph
Sava	Catez_Sutla	729168.8	W_01_13_10	LIH*
Sava	Bregana_Krapina	716923	W_03_01_03	LIH*
Sava	Krapina_Kupa	702479	W_05_01_03	LIH*
Sava	Krapina_Kupa	673400	W_05_01_06A	LIH*
Sava	Krapina_Kupa	656159 LS	OBSERVERD	TS_GateOpen**
Sava	Krapina_Kupa	602782	W_05_01_06B	LIH*
Sava	Kupa_Una	561152	W_07_01_03	LIH*
Sava	Kupa_Una	561151 LS	OBSERVED	TS_GateOpen**
Sava	Kupa_Una	557354	W_09_01_03	LIH*
Sava	Kupa_Una	524898	W_11_01_03	LIH*
Sava	Una_Vrbas	470103	W_13_01_03	LIH*
Sava	Una_Vrbas	469347	W_13_01_05	LIH*
Sava	Una_Vrbas	458113	W_13_01_08	LIH*
Sava	Una_Vrbas	435553	W_13_01_11	LIH*
Sava	Vrbas_Orljava	411255	W_15_01_03	LIH*
Sava	Orljava_Bosna	388997	W_17_01_03	LIH*
Sava	Orljava_Bosna	388416	18_UKRINA_OUT	LIH*
Sava	Orljava_Bosna	377847	W_19_01_03	LIH*
Sava	Orljava_Bosna	321511	W_19_01_06	LIH*
Sava	Bosna_Tinja	241207	W_21_01_03	LIH*
Sava	Tinja_Drina	206158.6	W_23_01_03	LIH*
Sava	Tinja_Drina	180248.3	W_23_01_06	LIH*
Sava	Drina_Bosut	167019	W_25_01_03	LIH*
Sava	Bosut_Kolubara	139987.6	W_27_01_03	LIH*
Sava	Bosut_Kolubara	51874.75	W_27_01_06	LIH*
Sava	Bosut_Kolubara	50602.45	W_27_01_07	LIH*
Sava	Bosut_Kolubara	29937.46	W_27_01_10	LIH*
Sava	Kolubara_Beograd	9277.477	W_29_01_03	LIH*
Sava	Kolubara_Beograd	1506.963	OBSERVED	Stage Hydrograph
TRIBUTARIES				
RIVER	**REACH**	**RIVER STATION**	**HMS INPUT NODE**	**INPUT TYPE**
Bosna	1	74384	J_20_19_27	Flow Hydrograph
Bosna	1	48370	W_20_19_29	LIH*
Bosna	1	572	W_20_19_32	LIH*
Bosut	1	39165.85	J_26_01_09_Nijemci	Flow Hydrograph
Bosut	1	38685.64	W_26_01_09C X 0.5	LIH*
Bosut	1	1124.596	W_26_01_09C X 0.5	LIH*
Bosut	1	373 IS	OBSERVED	TS_GateOpen**
Bregana	1	1387.768	W_03_01_03	Flow Hydrograph
Drina	1	10814.91	24_DRINA_OUT	Flow Hydrograph
Kanal Lonja	1	7775.528	LOW FLOW***	Flow Hydrograph
Kanal Lonja	1	1021.703	W_08_03_11	LIH*

RIVER	REACH	RIVER STATION	HMS INPUT NODE	INPUT TYPE
Kanal Lonja	1	335.5332	W_08_03_12	LIH*
Kolubara	1	52694.21	J_28_03_01	Flow Hydrograph
Kolubara	1	16176.02	W_28_03_04	LIH*
Kolubara	1	15097.62	W_28_03_03	LIH*
Kolubara	1	1268.579	W_28_03_07	LIH*
Krapina	1	21952	J_04_02_02	Flow Hydrograph
Krapina	1	13573	W_04_02_04	LIH*
Krapina	1	396	W_04_02_07	LIH*
Kupa	1	60700	J_06_10_03	Flow Hydrograph
Kupa	1	48205	W_06_10_05	LIH*
Kupa	1	5975	W_06_10_09	LIH*
Kupa	1	2175	W_06_10_12	LIH*
Orljava	1	45377.64	J_16_02_02	Flow Hydrograph
Orljava	1	26922.5	W_16_02_04	LIH*
Orljava	1	3382.684	W_16_02_07	LIH*
Sutla	1	20080	J_02_01_02_Zelenjak	Flow Hydrograph
Sutla	1	8160	W_02_02_02	LIH*
Sutla	1	415	W_02_03_02	LIH*
Tinja	1	40981.19	J_22_01_07	Flow Hydrograph
Tinja	1	5410.7	W_22_01_10	LIH*
Tinja	1	5089.69	W_22_01_09	LIH*
Tinja	1	1373.77	W_22_01_13	LIH*
Una	1	41355.08	J_12_05_03_Kostajnic	Flow Hydrograph
Una	1	19879.68	W_12_06_02	LIH*
Una	1	1584.358	W_12_06_05	LIH*
Vrbas	1	11515.4	14_VRBAS_OUT	Flow Hydrograph
STORAGE/2D FLOW AREAS				
Lonjsko Polje 1		W_08_03_19 X 0.2		LIH*
Lonjsko Polje 2		W_08_03_19 X 0.15		LIH*
Lonjsko Polje 3		W_08_03_19 X 0.5		LIH*
Lonjsko Polje 4		W_08_03_19 X 0.15		LIH*
Odransko Polje		W_06_10_08		LIH*
Opeka		10_Ilova_OUT		LIH*
Žutica		J_08_03_17		LIH*
Žutica		W_08_03_16		LIH*

* - LIH = Lateral Inflow Hydrograph
** - TS_GateOpen = Time Series Gate Openings
*** - The upstream boundary condition for Kanal Lonja assumes normal flow as a low steady flow