UNIVERSITA' POLITECNICA DELLE MARCHE
ENVIRONMENTAL ENGINEERING
Hydraulic engineering and renewable energy

1D HEC-RAS MODEL DEVELOPMENT

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Submitted to:
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ABSTRACT

In this collaborative project, we undertook the development of a 1D hydraulic model using the HEC-RAS software package for the Wabash River in Indiana, USA. Our objective was to create an accurate representation of the river's hydraulic behavior to support various engineering analyses and flood management efforts. Beginning with the acquisition of terrain data from the United States Geological Survey (USGS) and the projection from the Spatial Reference website, we imported this information into RASMapper, a component of HEC-RAS, to facilitate the visualization and manipulation of key hydraulic features. Through meticulous delineation and definition within RASMapper, we identified and characterized critical geometrical elements such as the river's channel, floodplain boundaries, bridges, and other hydraulic structures.

With the geometrical framework established, we proceeded to conduct a comprehensive study flow simulation using HEC-RAS. Employing various flow scenarios and boundary conditions, we analyzed the river's hydraulic response under different flow regimes, including normal flow, flood events, and channel modifications. Our simulations enabled us to assess factors such as water surface profiles, flow velocities, and floodplain inundation extents, providing valuable insights into the river's hydraulic behavior and potential flood hazards.

The outcomes of our project contribute to the broader understanding of river hydraulics and support informed decision-making in river management and flood risk mitigation. By leveraging the capabilities of HEC-RAS and RASMapper, we demonstrated the effectiveness of 1D hydraulic modeling techniques in capturing the complex dynamics of river systems and informing engineering practices for sustainable water resource management.

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INTRODUCTION

The management of water resources and mitigation of flood risks are critical challenges faced by engineers and hydrologists worldwide. In addressing these challenges, hydraulic modeling plays a pivotal role in understanding river behavior, assessing flood hazards, and designing effective flood management strategies. One widely used tool in hydraulic modeling is the Hydrologic Engineering Center's River Analysis System (HEC-RAS), a versatile software package developed by the United States Army Corps of Engineers.

HEC-RAS is a robust and user-friendly software tool designed for hydraulic modeling of river systems. It offers a suite of powerful features for conducting detailed analyses of flow hydraulics, sediment transport, and geomorphic changes in rivers and streams. HEC-RAS utilizes a variety of computational methods, including the one-dimensional (1D) hydraulic modeling approach, to simulate flow conditions and predict hydraulic behavior accurately.

1D modeling, as implemented in HEC-RAS, is a widely used method for simulating flow in rivers and channels. Unlike more complex 2D or 3D models, which require extensive computational resources and data inputs, 1D modeling simplifies the representation of river flow by considering flow characteristics in one dimension (typically the longitudinal direction of the channel). This approach divides the river cross-section into discrete reaches, allowing for efficient calculation of flow variables such as water surface elevation, velocity, and discharge.

A fundamental component of hydraulic modeling using HEC-RAS is the study flow analysis, which involves the simulation of flow conditions under various scenarios and boundary conditions. By inputting data such as river geometry, channel roughness, and upstream flow rates, engineers can assess the hydraulic behavior of rivers under different flow regimes, including normal flow, flood events, and channel modifications. Study flow analysis enables the evaluation of factors such as water surface profiles, flow velocities, and floodplain inundation extents, providing valuable insights into river hydraulics and flood risk assessment.

STATE OF THE ART

In contemporary hydraulic engineering, the utilization of advanced computational tools has revolutionized the understanding and management of water flow dynamics, particularly in river systems and flood-prone areas. Two prominent software packages, MIKE 11 and HEC-RAS, stand out as essential tools for hydraulic modeling and flood prediction.

MIKE 11, developed by DHI Water · Environment · Health in Denmark, offers a comprehensive platform for simulating one-dimensional flows in diverse water bodies, including rivers, estuaries, and irrigation systems [1]. Its robust computational procedures, based on the one-dimensional energy equation, enable accurate evaluations of energy losses caused by friction and contraction/expansion phenomena. Moreover, MIKE 11 provides solutions for complex flow situations, such as hydraulic jumps and river confluences, through the incorporation of the momentum equation [1].

In contrast, the Hydrologic Engineering Center River Analysis System (HEC-RAS), developed by the U.S. Army Corps of Engineers, offers a versatile platform for hydraulic modeling, particularly in river systems and floodplain management. HEC-RAS employs a combination of one-dimensional and two-dimensional modeling techniques to simulate river flows and inundation scenarios [2]. The software's computational framework, including the solution of the one-dimensional Saint Venant Equation for steady flow and an implicit finite difference method for unsteady flow, ensures accurate representations of hydraulic processes [2].

Recent advancements in flood modeling have focused on addressing the challenges posed by changing climatic conditions and increasing weather extremes. Studies have underscored the importance of developing effective flood models capable of accurately predicting inundation scenarios resulting from extreme rainfall events [2]. One notable development in flood modeling research is the emergence of combined 1D–2D flood modeling, which integrates one-dimensional channel flow representations with two-dimensional overbank flow simulations [2]. This approach enhances the accuracy and efficiency of flood modeling, particularly in simulating river overflow inundation scenarios.

To assess the effectiveness of combined 1D–2D flood modeling, researchers have conducted simulations using the HEC-RAS model, focusing on events such as the Baeksan river levee breach in South Korea in 2011 [3]. Simulation results have demonstrated the applicability and accuracy of the HEC-RAS 1D–2D coupling method in accurately predicting inundation extents during flood events, thereby highlighting the potential of advanced hydraulic modeling tools in flood disaster control and mitigation efforts [2].

Overall, the integration of advanced computational tools like MIKE 11 and HEC-RAS, along with innovative modeling approaches such as combined 1D–2D flood modeling, represents a significant advancement in hydraulic engineering. These tools and methodologies play a crucial role in enhancing our understanding of water flow dynamics and in effectively managing flood risks in vulnerable areas.

MATERIAL AND METHOD

1. CASE STUDY

The Wabash River /ˈwɔːbæʃ/ (French: Ouabache) is a 503-mile-long (810 km)[2] river that drains most of the state of Indiana in the United States. It flows from the headwaters in Ohio, near the Indiana border, then southwest across northern Indiana turning south near the Illinois border, where the southern portion forms the Indiana-Illinois border before flowing into the Ohio River.

It is the largest northern tributary of the Ohio River and third largest overall, behind the Cumberland and Tennessee rivers. From the dam near Huntington, Indiana, to its terminus at the Ohio River, the Wabash flows freely for 411 miles (661 km). Its watershed drains most of Indiana. The Tippecanoe River, White River, Embarras River and Little Wabash River are major tributaries. The river's name comes from a Miami word meaning "water over white stones", as its bottom is white limestone, now obscured by mud.

The Wabash is the state river of Indiana, and subject of the state song "On the Banks of the Wabash, Far Away" by Paul Dresser. Two counties (in Indiana and Illinois); eight townships in Illinois, Indiana, and Ohio; one Illinois precinct, one city, one town, two colleges, one high school, one canal, one former class I railroad, several bridges and avenues are all named for the river itself while four US Navy warships are either named for the river or the numerous battles that took place on or near it.

For this project we choose the area in which Tippecanoe river will become tribute to Wabash river and create a junction and also there was a bridge on lower part of the river which is considered on the project.

Fig. 1 Study area location [wabash river and Tippecanoe junction]

2. DATA ACQUISITION

For this project the terrain and projection files were required to deal with formation of geometrical data. So, we downloaded the terrain file (DEM) of the study area from USGS explorer (https://earthexplorer.usgs.gov/) and the projection data was downloaded from (https://spatialreference.org/ref/epsg/4735/#) the spatial reference website by searching the study area and choosing the projection which suits our study area.

3. HEC-RAS PROJECT

A. RAS Mapper

The first thing to do was creating a new project and assigning the location on our pc. And we imported the projection file and then we imported our terrain file to the RAS Mapper as we can see on the figure below.

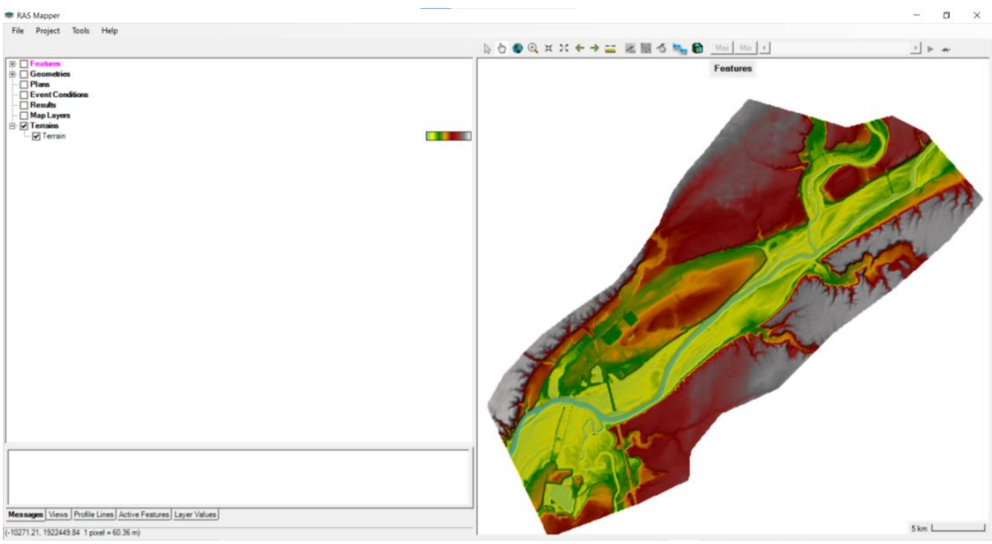


Fig. 2 imported terrain and projection on RAS Mapper

Then after importing the terrain and projection files we then we drew the geometrical features using the terrain feature as a reference these features were, river center lines, river bank lines, Flow path and cross-section. These features are explained as follows:

1. River Center Line:

First, we created a centerline to define the overall extent of the model. River centerline is also used to establish the river reach network for HEC-RAS. The example dataset has Wabash River flowing from northeast to southwest (upper right to lower left) and Tippecanoe River meeting it as a tributary. So there are three reaches as shown in the figure below: upper Wabash River, lower Wabash River and Tippecanoe River (tributary).

We created/digitized one feature for each reach approximately following the center of the river, and aligned in the direction of flow. Zoom-in to the most upstream part of the upper Wabash Riverto see the main channel (blue outline shown in figure 3).

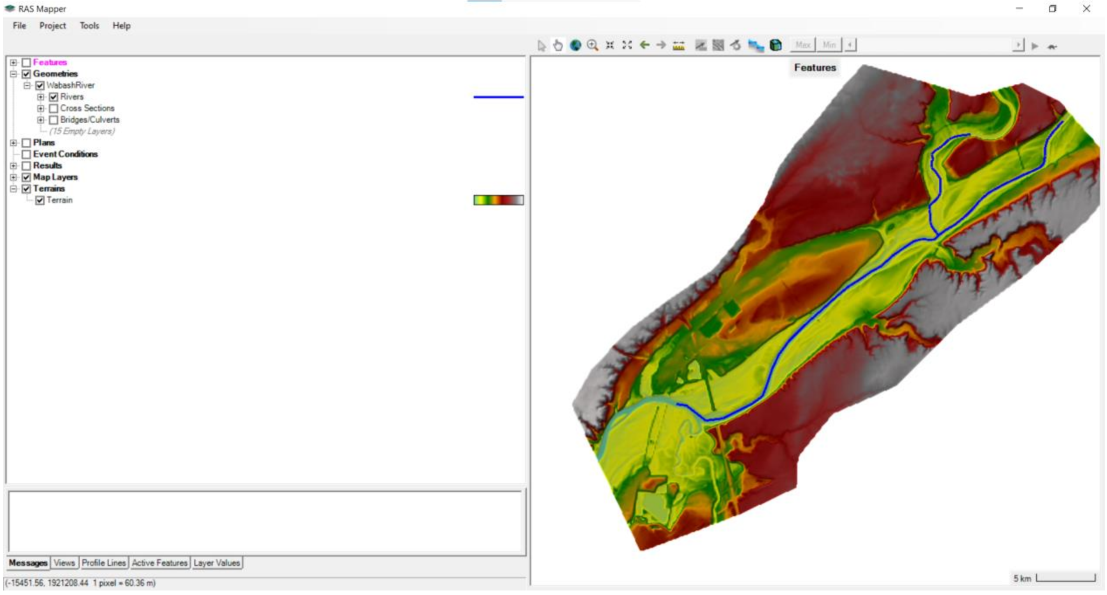


Fig. 3 River center line

2. River Bank Lines:

Bank lines are used to distinguish the main channel from the overbank floodplain areas. Information related to bank locations is used to assign different properties for cross-sections. For example, compared to the main channel, overbank areas are assigned higher values of Manning's n to account for more roughness caused by vegetation. Creating bank lines is similar to creating the channel centerline, but there are no specific guideless with regard to line orientation and connectivity - they can be digitized either along the flow direction or against the flow direction, or may be continuous or broken. In our case we drew the lines along the flow direction.

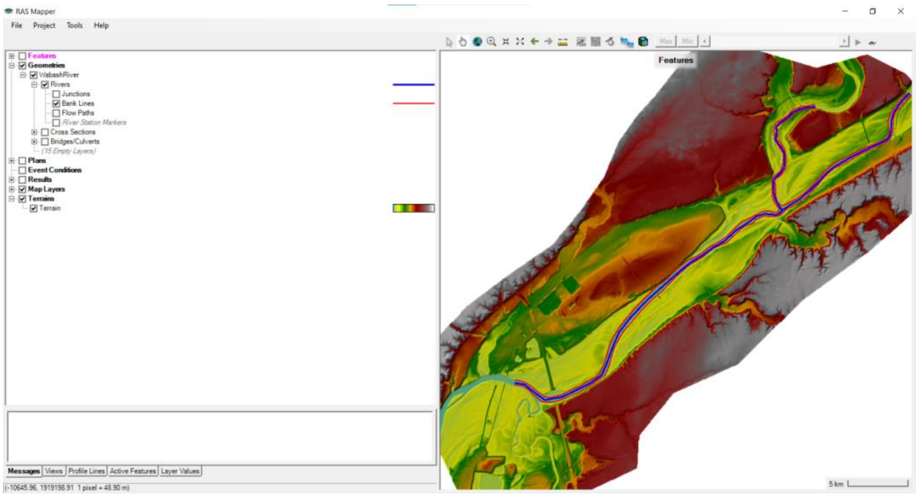


Fig. 4 Bank Lines

3. <u>Flow paths:</u>

The flow paths are used to determine the downstream reach lengths along the left over bank, the main channel and the right over bank. The reach length along the main channel can be extracted using the centerline since it lies approximately at the center of the main channel and run parallel to the main channel. For the left and right over bank, we need to digitize the left and right flow paths respectively.

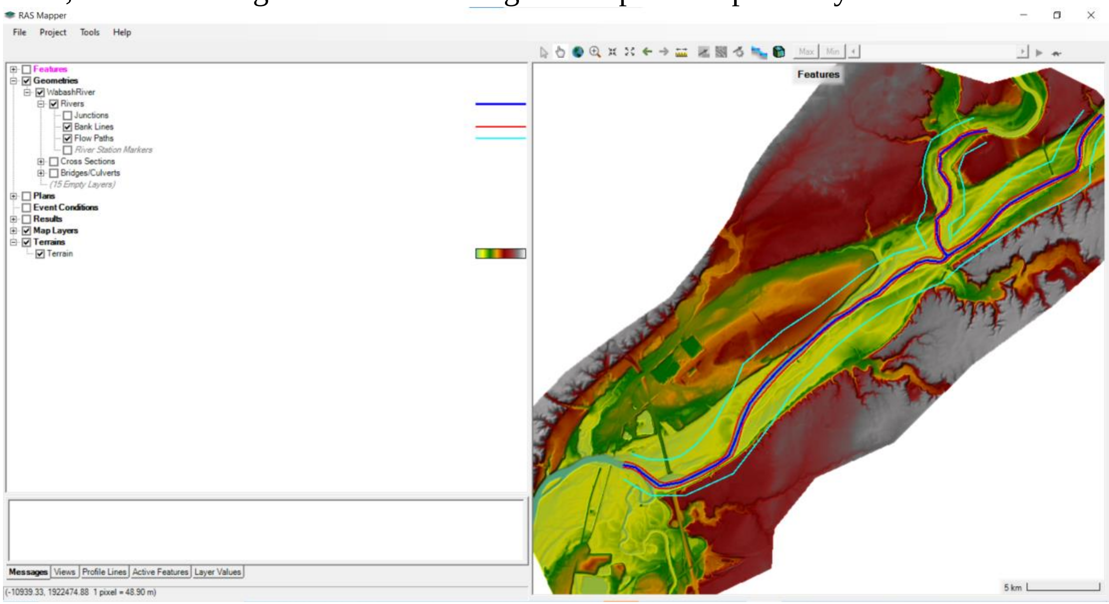


Fig. 5 Flow Paths

4. <u>Cross-Sections:</u>

Cross-sections are one of the key inputs to HEC-RAS. Cross-sections are used to extract the elevation data from the terrain to create a ground profile across channel flow. The intersection of cross-sections with other RAS layers such as centerline and flow path lines are used to compute HEC-RAS attributes such as bank stations (locations that separate main channel from the floodplain), downstream reach lengths (distance between cross-sections) and Manning's n. Therefore, creating adequate number of cross-sections to produce a good representation of channel bed and floodplain is critical. Certain guidelines must be followed in creating cross-sections:

- They are digitized perpendicular to the direction of flow.
- They must span over the entire flood extent to be modeled.
- They are always digitized from left to right (looking downstream).
- Each Cross-Section should intersect the centerline, both bank lines and both flow paths once [3].

Even though it is not required, but it is a good practice to maintain a consistent spacing between cross-sections. In this exercise, let us use an approximate spacing of 300 meters (1000 feet) for all cross-sections. In addition, if you come across a structure (eg. bridge/culvert) along the channel, make sure you define one cross-section each on the upstream and downstream of this structure. The upstream and downstream cross-sections must be no farther than 100 – 200 feet from the structure. Structures can be identified by using the aerial photograph or by looking at the DEM. For example, we will use one bridge location in this exercise at the downstream end of the lower Wabash River reach as shown below (bridge location is shown in circle; there is one downstream too):

All of these features were done on RAS Mapper so as we can have our geometrical data which we are going to use for the simulation of the 1D steady flow and analysis.

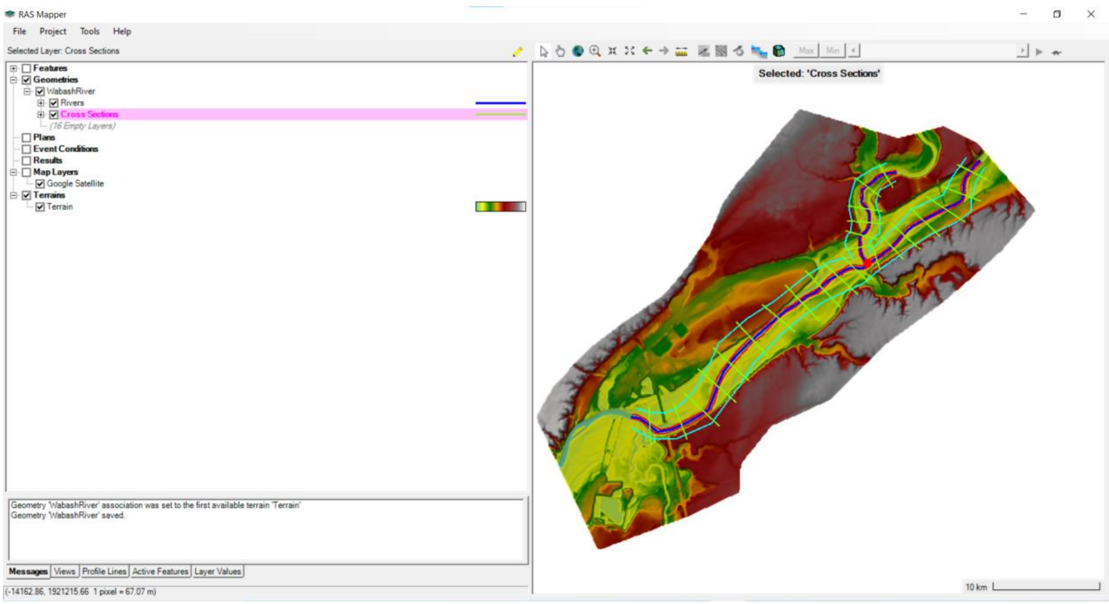


Fig. 6 Geometry done on RAS Mapper with cross-sections

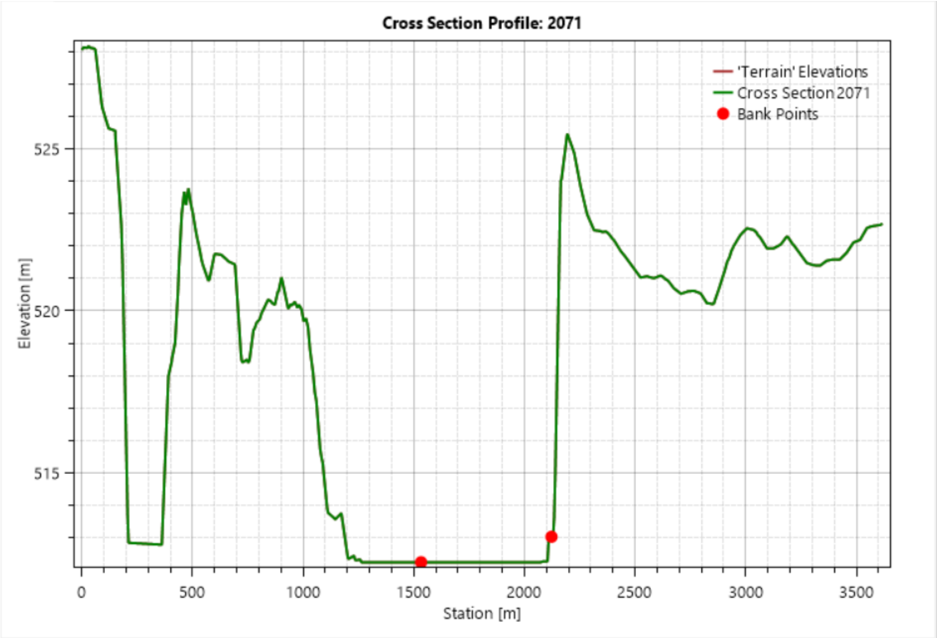


Fig. 7 cross-section profile example

B. 1D HEC-RAS simulation

After saving the mapper and closing it the river centerline and cross-sections have been imported automatically from the RAS Mapper. In geometry editor we checked every cross-section and all were good. So, we headed to assigning manning coefficient for ROB, LOB and main channel as follows:

- ➢ Left Over Bank (LOB) - 0.06
- ➢ Right Over Bank (ROB) - 0.06
- ➢ Main Channel - 0.035

The next step was doing 2x interpolation between cross-section. And we chose to do the cross-section interpolation between some of the cross-sections.

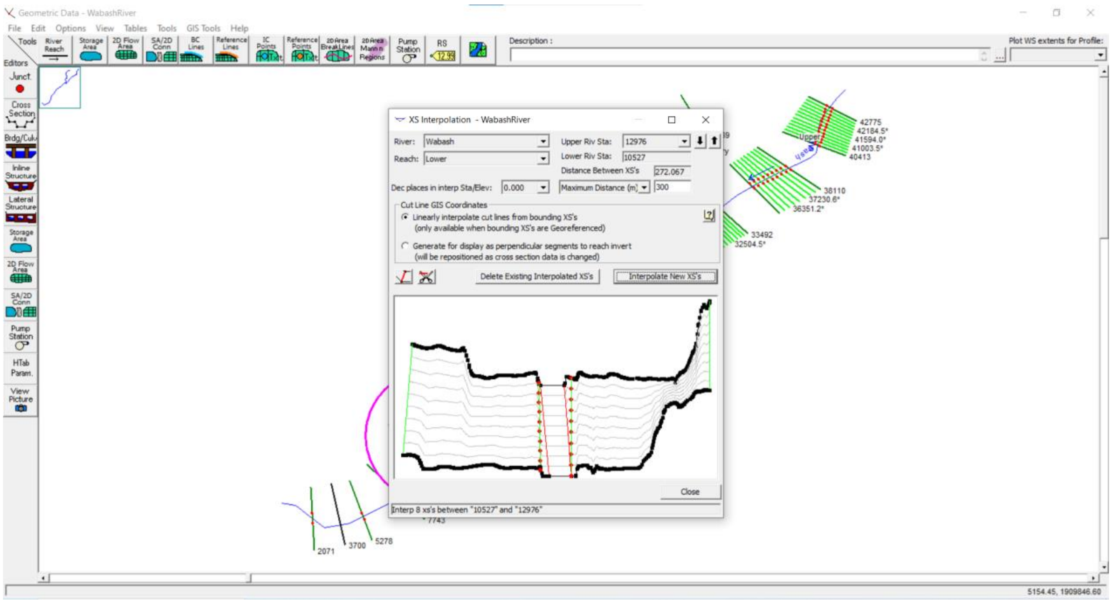


Fig. 8 2X's Interpolation

1. <u>Bridge:</u>

Our bridge was located between station 5278 and 2071 in lower Wabash and we specified a number which relies between these two stations (3700).

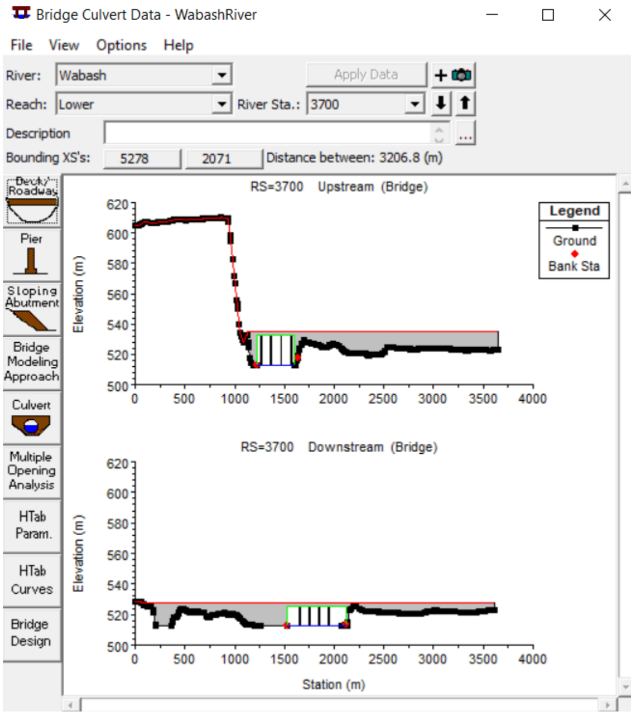
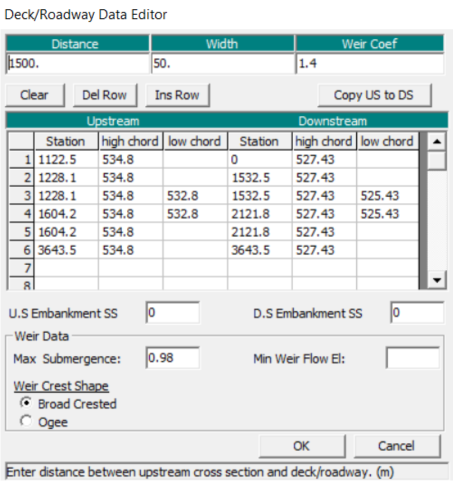


Fig. 9 Bridge

Generally, bridges are not captured in a DEM, which is a 2D representation of topography. What we needed to do here was defining the elevation of the road and the opening through which the water will flow. First we found out what is the top elevation of the bridge. From the figure above, we are going to assume it to be around 534.8 ft. Next, we need to know the opening for the bridge. In this case, we are going to assume that the opening is between 1250 ft and 1750 ft along the station (x-axis) axis. We will also assume that the road is around 6 ft thick, which means the elevation of the lower chord of the bridge is 524ft where the bridge is open. Then having this information we filled the Deck/roadway editor.


Deck/Roadway Data Editor

Distance	Width	Weir Coef
1500.	50.	1.4

Clear Del Row Ins Row Copy US to DS

	Upstream			Downstream		
	Station	high chord	low chord	Station	high chord	low chord
1	1122.5	534.8		0	527.43	
2	1228.1	534.8		1532.5	527.43	
3	1228.1	534.8	532.8	1532.5	527.43	525.43
4	1604.2	534.8	532.8	2121.8	527.43	525.43
5	1604.2	534.8		2121.8	527.43	
6	3643.5	534.8		3643.5	527.43	
7						
8						

U.S Embankment SS 0 D.S Embankment SS 0

Weir Data

Max Submergence: 0.98 Min Weir Flow El:

Weir Crest Shape
- Broad Crested
- Ogee

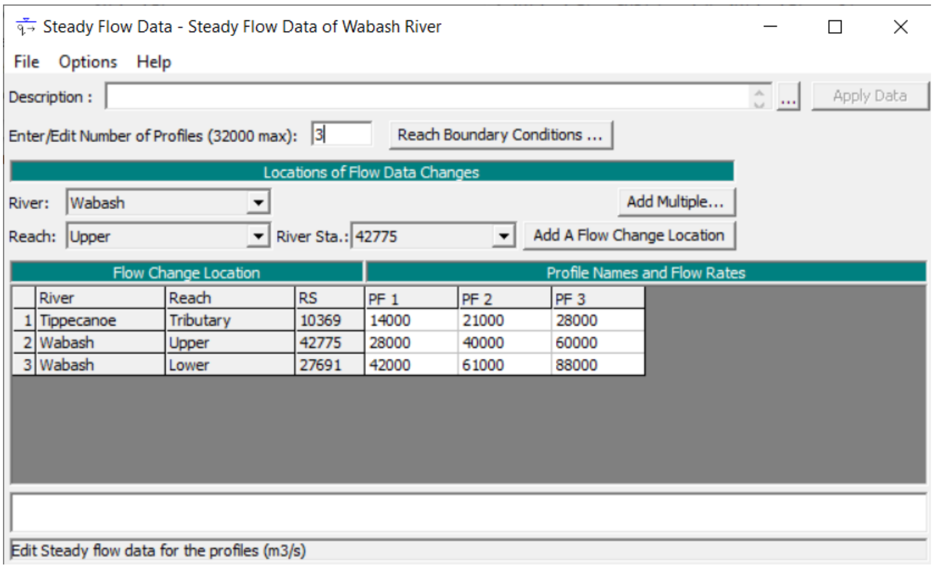
OK Cancel

Enter distance between upstream cross section and deck/roadway. (m)

Fig, 10 Deck/Roadway Data

2. Inserting Flow Data And Boundary Conditions:

Each flow that needs to be simulated is called a profile in HEC-RAS. In this project we created three hypothetical profiles.



Fig, 11 Flow Data

The flow conditions defined in the above window are upstream conditions. To define downstream boundary, we clicked on Reach Boundary Conditions. Then selected Downstream for Wabash Lower Reach, clicked on Normal Depth, and inserted 0.002 as shown below.

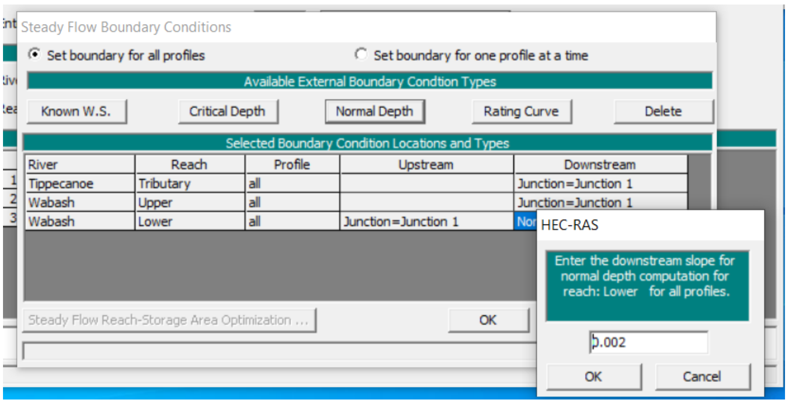
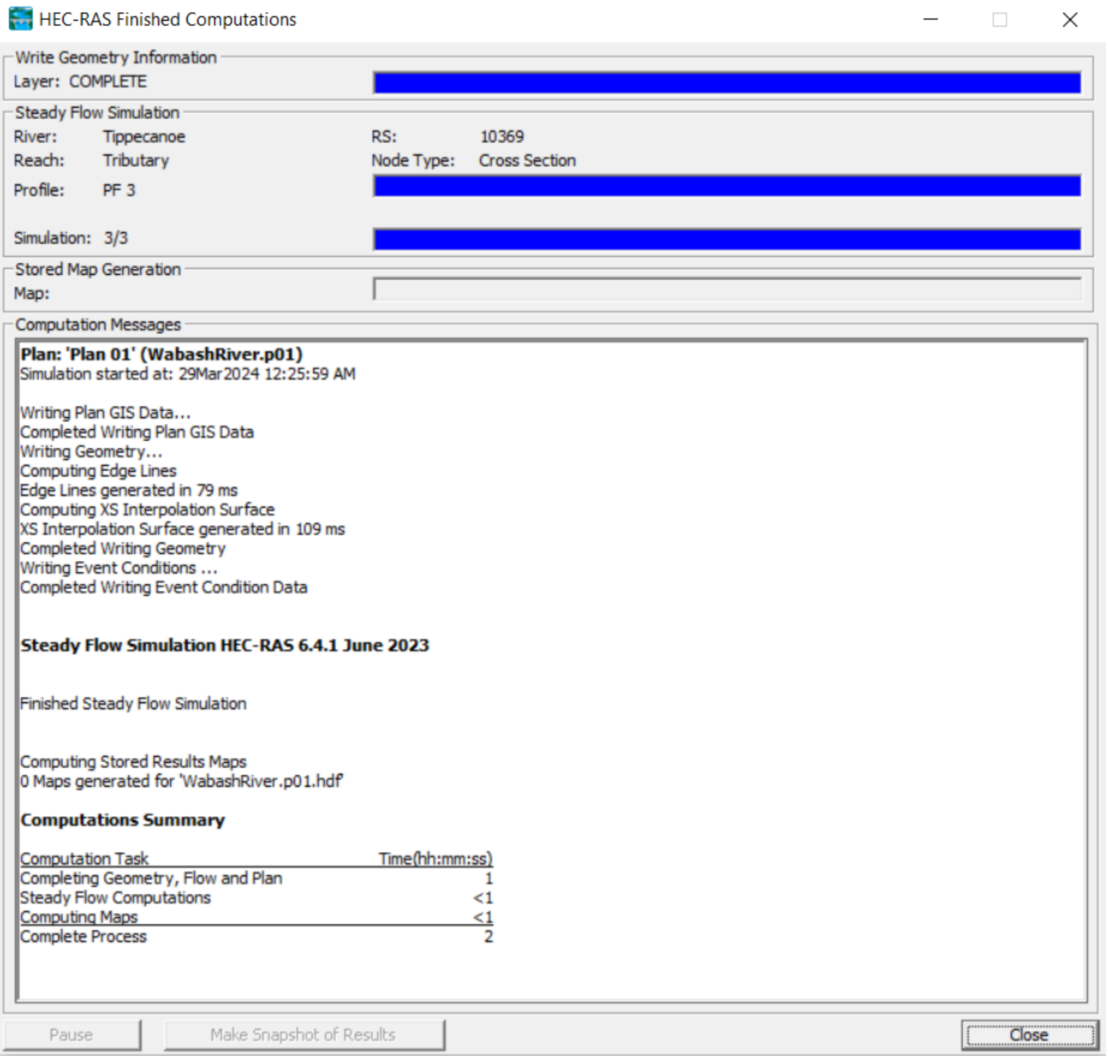


Fig. 12 boundary condition for downstream

After this it was ready to run the simulation. And on the steady flow analysis window we chose sub critical flow regime.



Fig, 13 Finished computation

RESULT AND DISCUSSION

After computing the study flow analysis the firs thing we did was visualizing the result on RAS Mapper by marking result and depth we can visualize the profiles as follows.

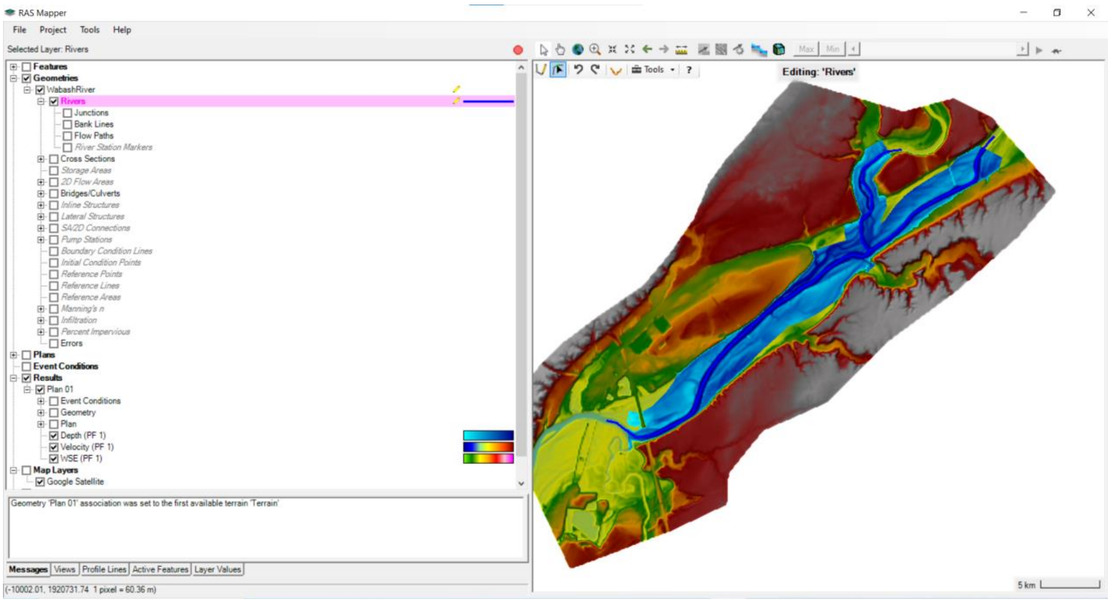


Fig. 14 Result on RAS Mapper [Depth]

1. Maximum Average Velocity computation:

In our project, we sought to gain insights into the hydraulic characteristics of the Wabash River and its tributary, Tippecanoe, by analyzing the maximum average velocity at specific cross-sections. By focusing on cross-sections with high velocity values across different reaches, we aimed to understand variations in flow dynamics and channel behavior.

Cross Section Output

File Type Options Help

River: Wabash Profile: PF 1

Reach Upper RS: 40885.4* Plan: Plan 01

Plan: Plan 01 Wabash Upper RS: 40885.4* Profile: PF 1

		Element	Left OB	Channel	Right OB
E.G. Elev (m)	536.93	Wt. n-Val.	0.060	0.035	0.060
Vel Head (m)	0.20	Reach Len. (m)	438.78	472.32	491.06
W.S. Elev (m)	536.73	Flow Area (m2)	9440.10	6031.21	4896.76
Crit W.S. (m)		Area (m2)	9440.10	6031.21	4896.76
E.G. Slope (m/m)	0.000154	Flow (m3/s)	9184.79	15354.23	3460.98
Q Total (m3/s)	28000.00	Top Width (m)	919.10	313.12	808.11
Top Width (m)	2040.33	Avg. Vel. (m/s)	0.97	2.55	0.71
Vel Total (m/s)	1.37	Hydr. Depth (m)	10.27	19.26	6.06
Max Chl Dpth (m)	19.31	Conv. (m3/s)	739794.8	1236717.0	278766.9
Conv. Total (m3/s)	2255278.0	Wetted Per. (m)	925.87	313.69	811.19
Length Wtd. (m)	466.38	Shear (N/m2)	15.41	29.06	9.12
Min Ch El (m)	517.42	Stream Power (N/m s)	15.00	73.99	6.45
Alpha	2.08	Cum Volume (1000 m3)	65737.35	96677.51	161060.00
Frctn Loss (m)	0.05	Cum SA (1000 m2)	5762.36	3729.60	14964.93
C & E Loss (m)	0.03				

Fig. 15 Resulting parameters of Upper Wabash [cross-section with max. Average Velocity]

Cross Section Output

File Type Options Help

River: Tippecanoe Profile: PF 1

Reach Tributary RS: 8870.43* Plan: Plan 01

Plan: Plan 01 Tippecanoe Tributary RS: 8870.43* Profile: PF 1

		Element	Left OB	Channel	Right OB
E.G. Elev (m)	536.06	Element	Left OB	Channel	Right OB
Vel Head (m)	0.21	Wt. n-Val.	0.060	0.035	0.060
W.S. Elev (m)	535.85	Reach Len. (m)	243.21	299.74	354.29
Crit W.S. (m)		Flow Area (m2)	2018.65	4157.47	4279.66
E.G. Slope (m/m)	0.000188	Area (m2)	2018.65	4157.47	4279.66
Q Total (m3/s)	14000.00	Flow (m3/s)	1281.86	9852.52	2865.62
Top Width (m)	1574.12	Top Width (m)	434.56	279.12	860.44
Vel Total (m/s)	1.34	Avg. Vel. (m/s)	0.64	2.37	0.67
Max Chl Dpth (m)	16.25	Hydr. Depth (m)	4.65	14.90	4.97
Conv. Total (m3/s)	1021031.0	Conv. (m3/s)	93487.2	718551.8	208991.7
Length Wtd. (m)	305.54	Wetted Per. (m)	435.81	279.44	860.76
Min Ch El (m)	519.60	Shear (N/m2)	8.54	27.43	9.17
Alpha	2.28	Stream Power (N/m s)	5.42	65.01	6.14
Frctn Loss (m)	0.06	Cum Volume (1000 m3)	85826.30	61852.95	104488.20
C & E Loss (m)	0.00	Cum SA (1000 m2)	5331.47	2165.15	6758.84

Fig. 15 Resulting parameters of Tippercanoe Tributary [cross-section with max. Average Velocity]

Cross Section Output

File Type Options Help

River: Wabash Profile: PF 1

Reach Lower RS: 2071 Plan: Plan 01

Plan: Plan 01 Wabash Lower RS: 2071 Profile: PF 1

E.G. Elev (m)	521.92	Element	Left OB	Channel	Right OB
Vel Head (m)	1.06	Wt. n-Val.	0.060	0.035	0.048
W.S. Elev (m)	520.86	Reach Len. (m)			
Crit W.S. (m)	517.88	Flow Area (m2)	5785.53	5063.01	250.67
E.G. Slope (m/m)	0.002000	Area (m2)	5785.53	5063.01	250.67
Q Total (m3/s)	42000.00	Flow (m3/s)	14327.58	27138.81	533.61
Top Width (m)	1926.88	Top Width (m)	1074.22	589.30	263.36
Vel Total (m/s)	3.78	Avg. Vel. (m/s)	2.48	5.36	2.13
Max Chl Dpth (m)	8.61	Hydr. Depth (m)	5.39	8.59	0.95
Conv. Total (m3/s)	939050.0	Conv. (m3/s)	320340.8	606778.6	11930.7
Length Wtd. (m)		Wetted Per. (m)	1076.49	589.35	264.65
Min Ch El (m)	512.25	Shear (N/m2)	105.43	168.53	18.58
Alpha	1.45	Stream Power (N/m s)	261.09	903.34	39.55
Frctn Loss (m)		Cum Volume (1000 m3)			
C & E Loss (m)		Cum SA (1000 m2)			

Fig. 15 Resulting parameters of Lower Wabash [cross-section with max. Average Velocity]

The analysis of flow characteristics at selected cross-sections along the Wabash River and its tributary, Tippecanoe, provides valuable insights into the hydraulic behavior of the river system. By focusing on cross-sections with high average velocities, we can better understand the flow dynamics and conveyance capacities within each reach.

Upper Wabash Reach (Average Velocity: 0.97 m/s):

- The observed average velocity in the upper Wabash reach indicates moderate flow dynamics.
- This reach likely represents a transitional zone where the river begins to gain momentum and exhibit increased flow velocities.
- The relatively moderate velocity suggests that the upper Wabash reach may have a relatively gentle slope and wider channel geometry, allowing for efficient flow conveyance and reduced flow resistance.

Tributary (Tippecanoe) Reach (Average Velocity: 0.64 m/s):

- The average velocity in the tributary reach of the Tippecanoe River is notably lower compared to the upper Wabash reach.
- This lower velocity may be attributed to several factors, including reduced flow volume, increased channel roughness, or variations in channel morphology.
- The tributary reach likely experiences reduced flow velocities due to interactions with surrounding vegetation, variations in channel width, or localized hydraulic controls.

Lower Wabash Reach (Average Velocity: 2.48 m/s):

- The average velocity in the lower Wabash reach is substantially higher compared to both the upper Wabash and tributary reaches.
- This elevated velocity suggests that the lower Wabash reach experiences more energetic flow conditions, possibly due to steeper channel slopes, narrower channel widths, or hydraulic controls such as bridges or constrictions.
- The higher flow velocity in the lower Wabash reach indicates increased flow conveyance and potentially greater erosion forces, which may influence sediment transport and channel morphology.

The observed variations in flow velocities among the three reaches highlight the complex hydraulic interactions within the Wabash River system. Understanding these variations is essential for effective river management and flood risk assessment, as they influence floodplain inundation patterns, sediment transport dynamics, and habitat conditions. Further investigation into the factors influencing flow velocities, such as channel geometry, hydraulic roughness, and localized hydraulic structures, is warranted to refine hydraulic models and inform sustainable river management practices.

2. Rating Curve

In our analysis of the rating curves for the various cross-sections within each reach, a notable observation emerged. We observed a consistent breakage point in the rating curves across all cross-sections within each reach. This observation piqued our interest and prompted a closer examination of potential factors contributing to this phenomenon.

The observed breakage in the rating curves across all reaches underscores the significant impact of the bridge on flow dynamics within the entire river system. While the bridge's direct influence is most pronounced in the lower Wabash, its hydraulic effects propagate upstream, altering flow velocity and depth profiles in the tributary and upper Wabash. Factors such as flow constrictions and hydraulic interactions with bridge structures contribute to the observed disruptions in the rating curves.

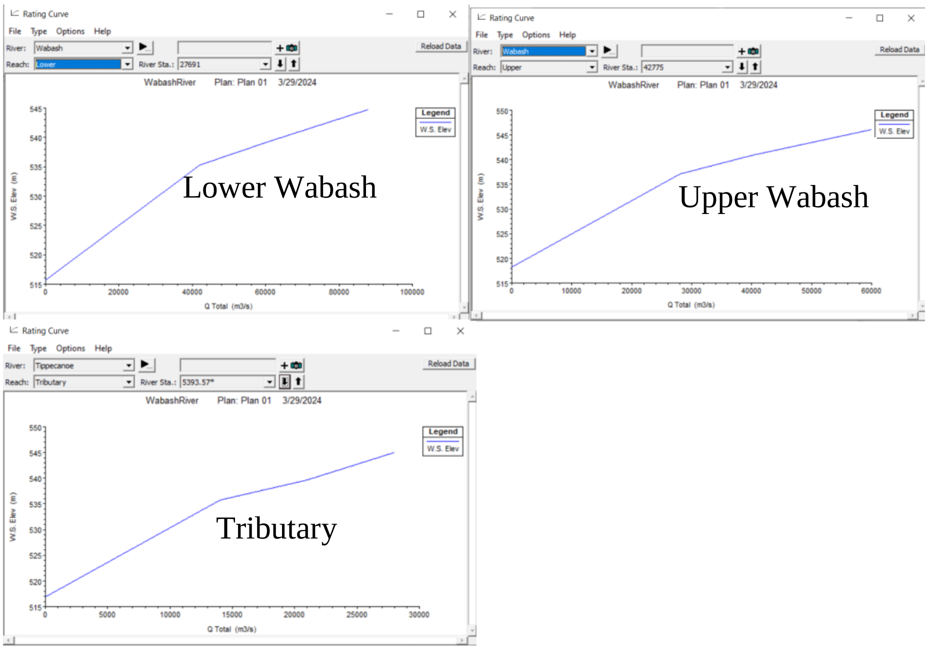


Fig. 16 Rating Curves

Recognizing the far-reaching influence of the bridge on flow dynamics highlights the importance of accurately representing hydraulic controls in the modeling process. Despite being located in the lower Wabash, the bridge's hydraulic effects necessitate consideration throughout the river system to ensure the reliability of hydraulic models and the accuracy of flood predictions. Failure to account for these effects can lead to inaccuracies in flow predictions and water level estimations, compromising the overall effectiveness of flood risk assessments.

3. Flow Profiles and Bridge Overflow Analysis

In the analysis of flow profiles within the river system, particularly concerning the presence of bridges, significant observations were made that shed light on hydraulic behavior under varying conditions.

Profile 1:

The first flow profile indicated a hydraulic condition where water levels remained below the bridge clearance, indicating no overtopping of the bridge structure. This scenario suggests a relatively stable hydraulic regime within this reach, where the flow capacity is well-matched with the hydraulic characteristics of the channel.

Profiles 2 and 3:

In contrast, the subsequent flow profiles (Profiles 2 and 3) depicted a notable deviation from the previous hydraulic state. Here, water levels surpassed the clearance of the bridge, indicating an overflow condition. This occurrence highlights a hydraulic scenario where the flow capacity of the river exceeds the conveyance capacity of the bridge structure, leading to potential inundation and flooding risks.

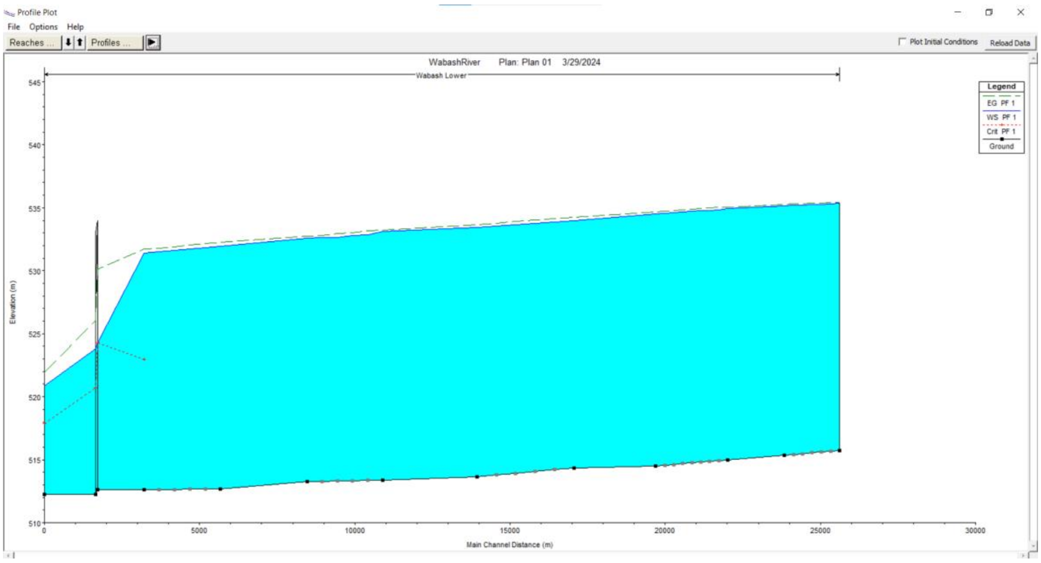


Fig. 17 Wabash Lower [FP 1]

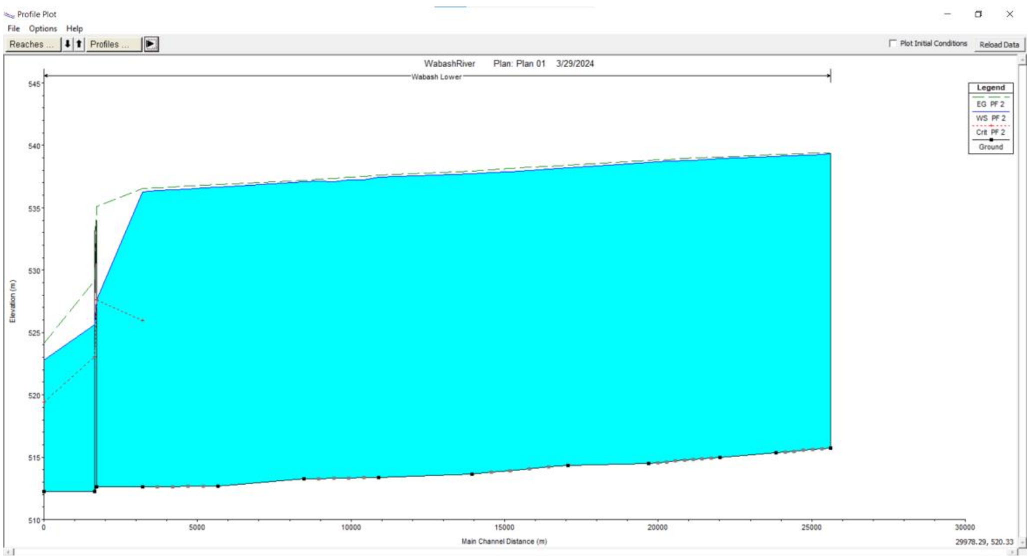


Fig. 18 Wabash Lower [FP 2]

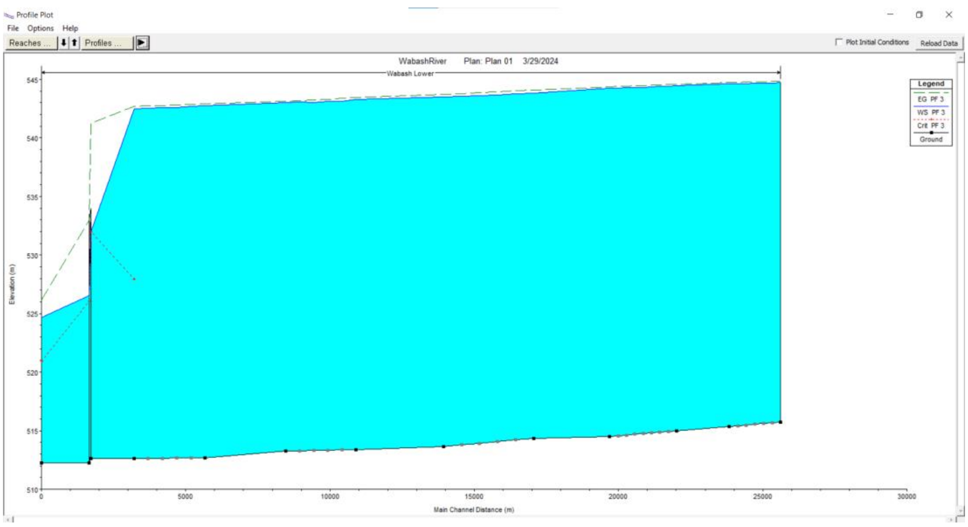


Fig. 18 Wabash Lower [FP 3]

The occurrence of bridge overflow underscores the importance of accurately assessing hydraulic conditions, especially in areas prone to flooding. Understanding the hydraulic behavior under varying flow conditions is crucial for informed decision-making regarding infrastructure design, flood risk management, and disaster preparedness measures.

CONCLUSION

In conclusion, the computational analysis conducted on various hydraulic parameters within the Wabash River system has yielded valuable insights into the intricacies of its hydraulic dynamics and flood risk characteristics. The computation of maximum average velocity across different river reaches unveiled significant variations, with the lower Wabash reach exhibiting the highest velocity. This underscores the critical importance of comprehensively understanding flow dynamics within specific river segments, particularly concerning flood risk assessment and hydraulic infrastructure design.

Moreover, the analysis of rating curves for each cross-section within the river system revealed intriguing patterns, notably breaks occurring at the location of the bridge in the lower Wabash reach. Such anomalies in rating curves suggest potential hydraulic constraints posed by existing infrastructure, emphasizing the need for thorough structural assessments and resilience measures to mitigate flood risk effectively.

Furthermore, examination of flow profiles along the river system highlighted distinct hydraulic behaviors, particularly concerning bridge overtopping. Profiles indicating bridge overtopping underscore the vulnerability of existing infrastructure to hydraulic loading, emphasizing the urgency of implementing robust flood risk management strategies and infrastructure resilience measures.

Overall, these findings underscore the complex interplay between hydraulic dynamics, infrastructure design, and flood risk management within river systems. Understanding and accurately characterizing flow behaviors, such as velocity distributions, rating curve anomalies, and bridge overtopping, are essential for informed decision-making in hydraulic engineering and flood hazard mitigation efforts. As such, stakeholders should prioritize further investigation and address the hydraulic challenges identified, leveraging detailed hydraulic modeling and targeted mitigation measures to enhance the resilience of infrastructure and communities against flood hazards.

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FIGURES INDEX