Developing High-Definition Flood Inundation Maps Using Raster Adjustment with Scenario Profiles

to Support Property-Specific Flood Risk Management

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Abstract

Flood inundation maps (FIMs) are essential to understanding, communicating, and managing flood threat scenarios. The state-of-the-practice (SOP) is rapidly advancing to address demand for online, raster, High-Definition FIMs (**HD-FIMs**) meeting dual requirements for high resolution and rigorous *local* accuracy. Raster Adjustment with Scenario Profiles (**RASP**) is fundamental to preparing HD-FIMs by correcting errors in SOP model-generated raster FIMs.

RASP consists of four straightforward steps utilizing advanced geographic information system vector and raster tools:

1. Extract stream-network profiles and important contour lines from a starting raster FIM.
2. Establish control points with improved scenario accuracy at key locations along the profiles.
3. Shift the extracted profiles and contours to fit the profile control points.
4. Adjust the starting raster by sub-watershed units to fit the shifted profiles and contours.

Preparation of the first-in-the-nation HD-FIM for the historic Amite River Basin 2016 Flood (the fourth most expensive in the US at the time) illustrates the significant benefits of RASP. Using 300-plus profile control points along more than 6,100 km (3,800 mi) of streams, RASP achieved significant corrections to a SOP model-generated hindcast FIM. RASP reduced the starting raster's basin-wide root mean square error and bias by 38 and 49 percent to 0.20 and 0.03 m (0.66 and 0.09 ft). RASP lowered both error metrics in all eleven watersheds, with bias reductions of 50 percent or better for seven watersheds.

When SOP model-generated raster FIMs cannot be expeditiously obtained, RASP enables meeting demand for *provisional* HD-FIMs by fitting a best-available starting raster FIM to professionally-sourced, profile-informed control. RASP can thus provide crucial rectification of AI-generated FIMs.

Practical Applications

Detailed procedures for RASP's four steps and three preliminary tasks for preparing required datasets are provided in the attached **Supplement Materials**, along with a list of useful GIS tools readily automated with today's GIS software.

Remarkable generative AI image/raster manipulation techniques are increasingly touted for further automation of *provisional* FIMs for a range of flood scenarios. However, the accuracy and utility of AI-generated FIMs depend on reasonable scenario control points. Managing *property-specific flood risk* requires profile-informed HD-FIMs, emphasizing local professional expertise with relevant watershed and sub-watershed characteristics, stream networks, conveyance transitions, and scenario-specific conditions.

Data Availability

The data and other information that support the findings of this study are in the public domain and available from the Amite River Basin Drainage & Water Conservation District. Requests may be made at https://amitebasin.org/contact-us-1.

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1. Introduction

Flood inundation maps (FIMs) are essential for informing the public, especially property-stakeholders, about flood threats in order to facilitate their risk management decisions. FIMs are also crucial to federal, state, and local governance of floodplains. Accelerating flood damage costs due to climate change and decades of questionable floodplain development practices are now intensifying private and public flood risk management efforts and escalating demand for raster High-Definition FIMs (HD-FIMs) providing both high resolution and rigorous *local* accuracy. This paper describes a crucial task for preparing HD-FIMs: Raster Adjustment with Scenario Profiles (**RASP**).

This paper first briefly reviews flood inundation mapping and FIM formats, resolution, and accuracy before turning to the emerging HD-FIM raster requirements, today's supporting technological advances, and the current challenge to developing HD-FIMs posed by limitations in state-of-the-practice (SOP) modeling. It then presents the RASP method to overcome these limitations. The example application of RASP to prepare the first-in-the-nation HD-FIM for the historic Amite River Basin 2016 Flood is then discussed. This paper concludes with a note on future expanding development of *provisional* HD-FIMs, leveraging generative artificial intelligence in raster FIM adjustment together with RASP's professional flood profile control.

2. FIM Background

2.1. Overview

Over recent decades FIMs have been increasingly relied upon to inform the public, especially property-stakeholders, about flood threats and support federal, state, and local governance of floodplains. FIMs depict the maximum water surface elevation (MaxWSE), or in some cases peak height above ground. FIMs are not a snapshot in time as flood peaks do not usually occur simultaneously over an entire area.

Figures 1a-h illustrate FIMs for a range of scenarios, including historic floods, hypothetical meteorological events, probabilistic inundation levels, proposed flood mitigation projects and programs, future sea level rise, future landscape changes, dam and levee failures, and, vitally, forecasts of pending floods.

For over 40 years the National Flood Insurance Program (NFIP) has prepared FIMs depicting the 1 percent Annual Exceedance Probability (AEP) flood that are widely-used in property-stakeholder due diligence and government programs directed at flood insurance participation, flood mitigation investment, relocation assistance, and regulating land development and building. Figure 1c is an example of the NFIP FIMs, termed Flood Insurance Rate Maps or FIRMs.

2.2. Formats

Over their history, FIMs have been prepared using one of three formats:

1. Two-dimensional (2D) vector. This format depicts just the area (lateral extent) of inundation using a simple boundary line (polygon). 2D vector FIMs were prepared by hand prior to the adoption of computer-aided drawing and mapping software and workstations in the 1980s. Older FIMs, including older FIRMs, are in this format, as well as newer FIMs when only the presence of flooding is mapped. See Figure 1a.
2. Three-dimensional (3D) vector. This format labels vectors—which can include points, profile lines, contour lines, or polygon boundary lines—to define the MaxWSE. With the rise of geographic information system (GIS) software and associated computer processor capacity during the 1990s, production of 3D vector FIMs became common. This format has been employed since then for most NFIP FIRMs. See Figure 1c.
3. 3D Raster. This format depicts the inundated area using a very fine-scale grid, with each grid cell having a specified MaxWSE value. When displayed, grid cells are color-filled according to the MaxWSE value. The use of rasters for terrain elevation (referred to as a digital elevation or terrain model, DEM/DTM), expanded in the 2000s with advances in remote-sensing technology, raster-GIS software, computational and graphic processors, and larger digital storage. For example: between 1999 and 2009 the State of Louisiana conducted Light Detection and Ranging (LiDAR) surveys across the state and produced statewide 5-meter DEMs. Raster formats for FIMs have gradually become

more common over the last ten years with progress in powerful computer models capable of simulating 2D inundation. (Appendix Note 1.) See Figures 1b and 1d through h.

In addition to inundation, FIMs include other key geographic information, such as a base map (often an aerial image); key hydrography vectors (e.g., channel flowlines, shorelines, hydrologic unit boundaries); other useful vectors (e.g., road network, jurisdictional boundaries, etc.); a legend; the horizontal coordinate system and projection; the vertical coordinate system; a bar scale; and a north arrow.

A significant limitation of vector formats is that estimating a location-specific MaxWSE requires a professional to interpolate the location-specific MaxWSE from the given vectors, accounting for particular watershed and scenario conditions. The raster format overcomes this limitation by directly supplying location-specific MaxWSE at a fine-scale throughout the inundation area.

Regardless of the generated format, for over two decades FIMs have been converted to digital images—e.g., PDFs, JPEGs, etc.—for convenient public online viewing, screen-grabbing, and downloading. (Appendix Note 2.) During the 2010s, web-serving of FIM images progressed to include tiling to facilitate panning and zooming of large-scale, highly detailed images. Figures 1a through h are all screenshots from websites. Figures 1b, c, f, and h are from tiled images.

With its detailed gridded MaxWSE information and easy access, the online raster is now the preferred FIM format for all flood scenarios.

2.3. Resolution and Accuracy

When FIM vectors are created, their *mapped resolution* is indicated by the smallest distance employed between points and vertices delineating lines and polygons. For FIM rasters, mapped-resolution is indicated by the grid cell side length.

When a FIM is presented on a screen or printed, the displayed image is composed of picture elements or pixels. Image pixels themselves are grid cells, with the number of image pixels fixed for a given screen or print area. As an FIM presentation is zoomed in/out (magnified/demagnified) the displayed size of mapped features increases/decreases and the number of image pixels displaying a given map area increases/decreases. The *displayed resolution* is the map distance represented by a pixel side at any particular level of zooming. A bar scale conveniently illustrates the effect of changes in the display resolution with zooming. Notably, the FIM displayed-resolution is rarely the same as the mapped-resolution of vectors or rasters. Image pixel sizes are often smaller than the mapped-resolution of vector features but larger than raster grid cells.

The accuracy of FIM vectors and rasters is assessed by comparing the mapped location and elevation for representative points—in the defined horizontal and vertical coordinate systems, such as geographic latitude/longitude and the North American Vertical Datum of 1988—versus their true reference location and elevation as established via state-of-the-practice (SOP) ground survey.

Horizontal and vertical accuracy are conventionally described using root mean square error (RMSE), which indicates the spread of discrepancies within a set of comparisons. Assuming a Gaussian distribution for the spread, a 95 percent confidence interval corresponds to ± 1.96 x RMSE. Equally important for FIMs is average error, which indicates a consistent positive or negative bias within the set of discrepancies. For the RMSE to largely reflect random errors, the bias should be small with respect to the RMSE.

Problems often arise with older vectors—such as channel flowlines, watershed boundaries, and flood inundation boundaries—prepared with imagery or DEMs at coarser resolution and accuracy. These older vectors will have significant alignment discrepancies when overlaid on more recent imagery and DEM/DTMs. FIMs should include a note regarding the map resolution and accuracy of key data layers, including hydrology vectors, DEM/DTMs, and flood MaxWSE vectors/raster.

3. HD-FIMs

3.1. Requirements

Intensifying private and public flood risk concerns are now escalating demand for FIMs with both high resolution and high accuracy—i.e., high definition. High-resolution of parcel-level details often requires 1-m (3.3-ft) *mapped resolution* or better for vectors and rasters for more populated watersheds, together with online *display resolution* capable of being zoomed to show the mapped details.

High accuracy requires horizontal RMSE for vectors and rasters consistent with the high resolution (American Society of Photogrammetry and Remote Sensing 2024). Given property-specific flood damage sensitivity to small variations in flood height, with magnified aggregate damages in urbanized floodplains, high accuracy corresponds to a vertical RMSE goal for FIMs, as well as HD-DEM/DTMs, of 0.15 m (0.5 ft), likely to become more exacting over the coming decade.

Crucially, flood risk management today demands more than overall FIM-wide high accuracy suited to managing *aggregate risk* (in which many property-specific risk errors largely cancel-out). *Managing property-specific risk* needs rigorous *local* accuracy, with both low vertical RMSE and bias at least for the neighborhood scale.

3.2. Supporting Technologies

The escalating demand for online HD-FIMs is converging with several rapid technological advances supporting their development:

HD terrain and hydrography data acquisition. The latest LiDAR and bathymetric survey technologies capture data capable of producing HD-DEM/DTMs. Expanded stream gauge networks and post-flood high water mark (HWM) surveying provide extensive high-quality data for flood model calibration. Terrain elevation and bathymetric data usually exceed 0.05-m horizontal and 0.1-m vertical (2- and 4-in) RMSE (USGS 2025). HWM data has similar horizontal RMSE and is approaching 0.15-m (0.5-ft) vertical RMSE (see Section 5.2).

GIS vector and raster processing. The latest GIS technology facilitates organizing and editing the gigabyte (and larger) files of HD-terrain and other data and automates production of HD-DEM/DTMs, together with HD-hydrography (channel flowlines, shorelines, and hydrologic unit boundaries). HD-DEM/DTMs are routinely prepared at 1-m (3-ft) horizontal resolution, with vertical RMSE goals of better than 0.3-m (1-ft) (Aziz et al 2024). With additional manual editing, hydrography 2D vectors can achieve 1-m horizontal RMSE (Terziotti and Archuleta 2020).

High-resolution 2D flood modeling. With exponential increases in computational power—including cloud resources—flood modeling codes can ingest the latest HD-data, HD-DTMs, and HD-hydrography, and then simulate complex 2D floodplain inundation scenarios. Today's 2D flood models readily generate results in the form of 1-m (3.3-ft) MaxWSE raster FIMs (Appendix Note 1.) SOP 2-D flood models capture distinctive characteristics in flood flow and MaxWSEs. Figure 2 demonstrates the capability of SOP models to depict subtle floodplain patterns in a high-resolution raster FIM, along with key details in MaxWSE profiles along channel flowlines associated with major conveyance transition features, such as channel junctions, bridges, and weirs.

These advances are quickly increasing the availability of model-generated, scenario-specific, high-resolution raster FIMs. At the same time another recent advance makes these SOP model-generated raster FIMs more user-friendly.

Web-GIS/Smart Maps. Progress in web hosting for large, dense image files, along with fiber optic and wireless data transmission, enables enhanced interfaces for high-resolution raster FIMs. Web interfaces allow users to simply click on a screen point and quickly obtain the raster grid cell value. Some interfaces also provide dynamic raster color-coding to maintain full color range contrast when displaying low-gradient areas. Web-sites can provide multiple high-resolution FIM, DTM, base-map, and vector layers for users to choose from (Appendix Note 3.). Figures1c and h depicts a screenshot from a SOP interface.

3.3. The Challenge: SOP Flood Model Limitations

Flood modelers have long observed the dictum that “all models are wrong, but some are useful.” While SOP models (utilizing SOP HD-DTMs and HD-hydrography) can generate rasters like the one shown in Figure 2a, they are subject to accuracy limitations associated with:

- Lower-than-HD quality DTM, hydrography, HWM data, and other data.
- Poor representation of key conveyance transition features (e.g., bridges, culverts, weirs).
- The resolution and accuracy of upstream and downstream hydrologic boundary conditions and spatially-temporally distributed rainfall.
- Simplification of overland runoff and related hydrologic processes.
- Simplification of 2D floodplain circulation dynamics (e.g., physics of frictional resistance).
- Coarse spatial resolution for model computation cells.
- Computational issues creating false MaxWSE mounds/depressions.
- Combining results from separate models—such as separate 1D model for channels and 2D model for floodplains.
- Calibration priorities for flood events and locations.

SOP model-generated rasters usually have acceptable FIM-wide RMSE and bias to support assessing aggregate damages and comparing regional mitigation scenarios. However, the above limitations often result in significant local accuracy issues. The NFIP has long recognized the need to carefully review flood model results for local inaccuracies and provide appropriate revisions as part of preparing FIRMs (FEMA 2024). Future improvements in model codes and practices may one day overcome current limitations and routinely produce HD-FIMs.

4. RASP

Reducing local RMSE and bias errors is crucial for preparing HD-FIMs suitable for property-specific applications. RASP utilizes advanced GIS vector and raster processing capabilities to adjust a starting raster FIM—preferably generated with a SOP 2D model simulation for the scenario-of-interest—to match refined scenario profiles, which have been modified based on improved scenario-specific, profile control points. RASP consists of four straightforward steps:

1. Extract MaxWSE profiles along the channel flowline network from the starting raster, together with important contour lines.
2. Establish control points with improved scenario MaxWSE accuracy at key locations along the profiles.
3. Shift the starting profiles and contours to fit the control points. Using the MaxWSE difference value between the control and the starting raster value at the control points, employ linear interpolation and extrapolation to define MaxWSE difference values at all vertices along the profile and contour lines; add the difference values to starting vertice values to produce revised profiles and contours.
4. Adjust the starting raster by sub-watershed unit to fit the revised profiles and contours. Using the cloud of MaxWSE difference values at profile and contour vertices, employ spatial interpolation and extrapolation to define MaxWSE difference values at all raster cells and then add the differences to the starting raster cell values to produce the adjusted raster.

Unlike a simple rectification (“rubber sheeting”) of a starting raster to fit a set of points with improved MaxWSE values, RASP emphasizes profile-informed adjustments. And unlike a simple lateral extrapolation of MaxWSEs from channel profiles, RASP incorporates floodplain inundation patterns from a starting FIM raster (Appendix Note 4).

The four RASP steps can be readily implemented and largely automated using today's advanced GIS vector and raster processing capabilities. A detailed procedure for the four RASP steps, along with three preliminary tasks for preparing required datasets and a list of useful GIS tools can be found in the attached **Supplement Materials**. The following example illustrates the application of RASP to prepare an HD-FIM using a SOP model-generated starting raster.

5. RASP Application for the Amite River Basin 2016 Flood HD-FIM

5.1. Amite River Basin 2016 Flood

Figure 3 depicts the 5,700 square-kilometer (2,200 square mile) Amite River Basin (ARB) and its eleven subbasins (watersheds), which encompasses much of Baton Rouge, Louisiana and its suburbs. In August 2016 the ARB experienced an unprecedented regional multi-day rainfall-driven flood, with two-thirds of the basin receiving three-day totals exceeding the 1percent AEP and over one-fifth exceeding the 0.1 percent AEP (Keim 2020). This extraordinarily rare, widespread rainfall resulted in shattering previous record crests on most ARB streams. The USGS post-flood analysis estimated that the discharge at the basin's primary, 78-year-old, Amite River gauge near Denham Springs exceeded a 0.2 percent AEP, far eclipsing the previous devastating 1983 Flood (Watson et al. 2017).

The flood impacted 30 percent of housing units in six affected counties (parishes), with most flooded homes uninsured. Total economic losses in the ARB approached $2 billion, making it *the fourth most expensive flood disaster in US history at the time* (Insurance Information Institute 2025).

Given the catastrophic impacts of the 2016 Flood, in 2019 the Amite River Basin Drainage & Water Conservation District (ARBD) chose to take advantage of extensive peak flood data and analysis, a post-flood SOP regional DTM and hydrologic/hydraulic numerical model, and progress in web-enabling FIMs to document the flood scope and magnitude with an online HD-FIM suitable for property-stakeholder use. The following is a summary of the RASP implementation (Bob Jacobsen PE, LLC 2022).

5.2. Preliminary Task 1: Collect Relevant Flood Information

Development of an HD-FIM for the 2016 Flood benefited from substantial peak flood data acquisition and detailed post-flood analyses by both the USGS (Watson et al. 2017) and the ARBD (Bob Jacobsen PE, LLC 2017).

The 2016 Flood in the ARB was extremely well-documented with 467 MaxWSE data points (see Table 1). Of these, 32 MaxWSE values were from USGS stream gauging stations referenced to high-quality benchmark elevations, with RMSE typically well below 0.03 m (0.1 ft). The other 435 MaxWSE values were from floodplain HWM surveys conducted by the USGS and the ARBD. Figure 2a illustrates the location of 53 MaxWSE data points in the Bayou Manchac Watershed.

HWM surveys consist of first identifying and marking high water—where accuracy is affected by the type of high-water evidence (e.g., exterior "rack lines" or interior "scum lines") and the clarity and possible disturbance of the high-water evidence. The MaxWSE for the HWM is then determined using standard real-time global positioning system (GPS) methods—where accuracy is affected by any transfer of elevation from the mark to a temporary benchmark (leveling); the number of GPS satellites accessible; and the duration over which a point is occupied.

HWM dataset error was evaluated using 52 pairs of data points, with pairs having the two points located in close proximity along the same channel reach. These included four types of pairs:

- Seven pairs with both points USGS HWMs—root mean square difference (RMSD) of 0.5 m(1.64 ft).
- Seventeen pairs with both points ARBD HWMs—RMSD, of 0.22m (0.73 ft). The better repeatability of the ARBD HWMs may reflect greater use of interior evidence.
- Two pairs with one point a USGS HWM and the other a nearby gauge data point—differences of 0.06 and 0.11 m (0.21 and 0.37 ft).

- Twenty-six pairs with one point a USGS HWM and the other an ARBD HWMs—RMSD of 0.1 m (0.32 ft) and average difference of 0.015 m (0.05 ft), indicating no major bias between the two programs.

For the combined 52 pairs the overall RMSD was 0.14 m (0.47 ft).

The USGS and ARBD HWMs included seven replications for the real-time survey, with an RMSD of 0.05 m (0.15 ft). This is consistent with the expected repeatability of real-time surveying and indicated most of the overall RMSD is associated with identifying the MaxWSE line.

The USGS post-flood analysis included a 2D vector (area) FIM for portions of the flood based only on their gauges and HWMs (see Figure 1a) and the estimated peak stream flow return frequency for the Amite River at the centrally-located, long-term (78-year) Denham Springs gauge.

In addition to the above review of MaxWSE data, the ARBD sponsored post-flood report provided preliminary peak flood profiles along 70 major channels and associated important findings for flood characteristics. The report recommended development of a SOP hindcast simulation and ARB-wide FIM for the 2016 Flood.

5.3. Preliminary Task 2: Compile DTM and Hydrography Datasets

As part of post-flood efforts, the State of Louisiana leveraged federal assistance to prepare a SOP 0.61-m (2-ft) resolution ARB DTM with bathymetry on the five regional rivers and several major named streams (Dewberry Engineers, Inc. 2019). The majority of the DTM topography was based on a 2018 LiDAR survey with project-wide vertical RMSE and bias of 0.037 and 0.004 m (0.12 and 0.01 ft) when compared to 71 ground points, exceeding USGS Quality Level 1 requirements. A vertical accuracy assessment of the 2019 DTM itself was not available. However, a separate review found some indications of local vertical bias exceeding 0.3 m (1 ft) (See Appendix I, Comparison of LDOTD Pavement Survey versus Dewberry DTM in Bob Jacobsen PE, LLC 2022).

The ARBD sponsored updates to ARB hydrography, including:

- Editing the USGS National Hydrography Dataset flowlines consistent with the 2019 DTM and current aerial imagery for 3,700 km (2,300 mi) of 319 named streams—five regional rivers (Amite, Comite, Bayou Manchac, Blind River, and Amite River Diversion Canal), 150 major named streams, 164 minor named streams—plus 2,400 km (1,500 mi) of numerous unnamed tributaries. The network was simplified for RASP purposes by removing parallel lines, braids, and short floodplain tributaries.
- Revising the USGS polygons for the ARB, eleven watersheds, and 182 sub- watershed polygons consistent with the DTM and flowline network.
- Mapping 1,130 conveyance transition points (1,074 bridges, 39 weirs, 4 gates, and 13 tunnels) obtained from state and parish datasets.
- Segmenting flowlines with junctions and conveyance points; the final network included 3,840 reaches.
- Compiling 1,783 provisional bathymetry points from NFIP and parish drainage studies.

The updated hydrography was employed to revise the 2019 DTM with additional hydro-enforcement of channel bathymetry at conveyance transition locations, and "burning" additional channel bathymetry using provisional bathymetry points.

5.4. Preliminary Task 3: Obtain a Starting Raster

As a further post-flood effort, the State of Louisiana also sponsored a SOP ARB flood model to support regional flood mitigation planning (Dewberry Engineers, Inc. 2019). The SOP ARB model utilized the USACE HEC-RAS and Hydrologic Modeling System (HMS) codes and the 2019 DTM . The SOP ARB model calibration included a hindcast simulation of the 2016 Flood. The SOP hindcast produced a 0.61-m (2-ft) resolution MaxWSE raster FIM consistent with the 2019 DTM. Figure 2a depicts the Bayou Manchac Watershed portion of the SOP model-generated hindcast raster.

The SOP model-generated hindcast raster was consistent with the model's intended use for regional mitigation planning, but reflected current SOP limitations noted above in Section 3.3:

- The model utilized a 1-D model for the Amite and Comite River channels and overbank to better depict conveyance effects of bridges, channel geometry, and bottom friction along these two regional rivers, together with a separate 2D model for the remaining ARB areas. However, this approach produced notable breaks in the hindcast raster at the boundary where the two rasters were combined.
- The 2D model lacked the subsequently updated hydrography and DTM, which affected depiction of flood profile transitions along many channels.
- The hindcast employed the post-flood NOAA Stage IV gridded spatial/temporal rainfall estimate without any further correction. An improved rainfall estimate was subsequently sponsored by the ARBD (Keim 2020).
- The rainfall runoff modeling approach limited representation of flood levels in the many upland ARB tributaries, as well as in areas of the central and lower ARB which experienced high flash flooding during the initial days of the event.
- The model was calibrated to optimize simulation of a wide range of flow events, and not to provide the best simulation of the 2016 Flood.
- The calibration prioritized fitting at the center of the ARB near Denham Springs Louisiana.
- For the 2016 Flood hindcast calibration, the downstream MaxWSE elevation boundary at Lake Maurepas was modified upward by 0.2 m (0.7 ft).
- The hindcast results included some isolated WSE mounds/depressions, typically produced by numerical instabilities associated with the computational mesh limitations.

An accuracy assessment of the SOP hindcast raster FIM versus 419 MaxWSE data points (see Table 2) showed a FIM-wide RMSE of 0.23 m (1.06 ft), with bias of 0.05 m (0.18 ft). For just the 32 USGS stream gauge station points these two error metrics were 0.41 and 0.06 m (1.33 and 0.2 ft).

The FIM-wide RMSE of the hindcast raster is compatible with SOP mitigation planning purposes. However, the bias was notably inconsistent—and much higher for several watersheds, particularly four populated watersheds. For the Amite River-from Comite River to Bayou Manchac, Bayou Manchac, Grays and Colyell Creeks, and New River watersheds the bias errors were 0.28, 0.12, -0.10, and 0.18 m (0.91, 0.40, -0.33, and 0.60 ft).

RASP was therefore employed to reduce these errors and provide an HD-FIM more suitable for property-stakeholder use.

5.5. RASP Step 1: Extract Flowline Profiles and Key Contours from the Starting Raster

MaxWSE profiles were extracted from the SOP hindcast raster along the 6,100-km (3,800-mi) ARB stream network, along with several contour lines immediately upstream and downstream of abrupt profile transitions at major bridges, gates, and weirs. Due to the density of the channel network and relatively flat flood surface, more contour lines were not critical to representing gradient patterns in the hindcast raster. Figure 2b illustrates the MaxWSE profile extracted for Bayou Manchac.

5.6. RASP Step 2: Establish Control Points Along the Profiles with Improved MaxWSE Values

A total of 318 control points were defined along the ARB channel network (see Table 3):

- The 32 USGS gauge station records were used as primary control points. The assigned values for these 32 control points equaled the reported MaxWSE.
- 26 points were included at major conveyance transitions with values assigned to improve obvious deficiencies in the representation of head-loss.

- 111 points were projected from nearby floodplain HWMs which supported consistent profile shifts (direction and magnitude), especially consistency with the USGS gauge station and head-loss values.
- 149 points were added to maintain a consistent profile shift from the control points throughout the branched channel network, and consistent MaxWSEs across hydrologic units where there was inundation at the boundary.

5.7. RASP Step 3: Shift the Starting Profiles and Contours to Fit the Control Points

The difference between the MaxWSE control value and the SOP hindcast raster value at the 318 profile control points was linearly interpolated/extrapolated along the vertices of the stream network and contour lines. The difference profiles were then used to shift the hindcast raster profiles and contour lines. Figure 4a illustrates the shift for the Bayou Manchac profile previously given in Figure 2b. Figure 4b includes the location of Bayou Manchac Watershed control points. Importantly, Figure 4a shows how the shift raised a portion of the Bayou Manchac profile and lowered another, while at the same time retaining much of the characteristic information in the starting raster profile.

5.8. RASP Step 4: Adjust the Starting Raster to Fit the Refined Profiles and Contours

The cloud of MaxWSE shift (difference) values for all vertices along the profiles and contours were then used to create difference rasters by watershed. Figure 4b illustrates the difference raster for the Bayou Manchac Watershed.

Watershed difference rasters were then added to the hindcast rasters to create the adjusted MaxWSE rasters. Figures 5a and b depict the MaxWSE and Height (above ground) rasters for the Bayou Manchac Watershed. The resulting adjusted, 0.61-m (2-ft) high-resolution raster for the ARB 2016 Flood was designated HD-FIM Version 1 (HD-FIMv1).

5.9. HD-FIM Accuracy Assessment

The HD-FIMv1 ARB-wide RMSE and bias with respect to the 419 MaxWSE data points were 0.20 and 0.03 m (0.66 and 0.09 ft) (see Table 4), an improvement in these two metrics by nearly 40 and 50 percent over the SOP hindcast raster (see Table 5). Notably, for the 32 validated stream gauge values serving as primary control, RASP reduced both the RMSE and bias to *zero*.

RASP improved both accuracy metrics in each of the eleven watersheds. The RMSE was reduced by 23 percent or more in ten of the eleven watersheds, with a reduction of 44 percent or more in four watersheds. The improved RMSE in each of those ten watersheds was below 0.3 m (1.0 ft), and at 0.22 m (0.71 ft) or better in eight watersheds.

The bias magnitude was reduced in seven watersheds to 0.07 m (0.23 ft) or less. Of the remaining four watersheds, bias magnitude was reduced to 0.19, 0.12, 0.13, and 0.10 m (0.61, 0.40, 0.41 and 0.33 ft). The 0.19-m (0.61-ft) bias magnitude in the Upper Amite River Watershed was negative while the bias errors of the other three were positive.

The remaining discrepancies between the HD-FIMv1 versus MaxWSE data were identified for each watershed (see Figure 6).

5.10. Online Publication and Future Improvement

Following successful development of the HD-FIMv1, the ARBD met with state and local officials and stakeholder groups to solicit comments and suggestions. The ARBD proceeded with online publication of the HD-FIMv1—with 0.61-m (2-ft) mapped resolution raster for MaxWSE, Height above ground, and the DTM (see Figure 7)—subject to future refinement according to seven additional steps:

1. Obtain input from property-stakeholders on potential remaining neighborhood catchment-scale bias; to facilitate this step the online HD-FIMv1 included a User Feedback layer for anyone to add a point location along with a comment regarding local accuracy.
2. Investigate the remaining discrepancies identified in the HD-FIMv1 accuracy assessment together with User Feedback comments; obtain additional HWMs and better estimates of head-loss at key conveyance transitions as feasible; update the MaxWSE dataset.

3. Further refine hydrography datasets in conjunction with other federal, state, and parish agencies.
4. Incorporate any further updates to the DTM by state or local agencies; investigate and address local bias errors in the DTM. (RASP procedures can also be used in conjunction with high quality pavement survey data to shift road profiles extracted from a DEM/DTM raster, and then the shifted road profiles can be used to refine the DEM/DTM.)
5. Obtain a new SOP hindcast raster incorporating: a) the latest improvements in the ARB HEC-RAS model; b) DTM refinements; c) hydrography updates; d) improved spatially-temporally distributed rainfall estimates for the event (Keim 2020); e) an appropriate Lake Maurepas boundary condition; f) parameter calibration optimizing the hindcast accuracy in all eleven watersheds; and g) elimination of the hindcast raster break associated with the separate 1D and 2D models as well as MaxWSE anomalies associated with computation instability.
6. Employ RASP with the updated MaxWSE data, DTM, hydrography, and SOP hindcast raster; apply at more localized hydrologic units as appropriate.
7. Publish the improved HD-FIM version online together with a revised accuracy assessment.

6. Conclusion and Future Applications (including AI)

The confluence of worsening flood hazard, escalating demand for better location-specific information from property-stakeholders and government agencies, together with advancing simulation, GIS, and internet technology, is driving a revolution in flood mapping. The above example illustrates the crucial role of RASP in refining a SOP model-generated, scenario-specific, starting raster to prepare an HD-FIM.

In addition, RASP can facilitate preparing *provisional* HD-FIMs given appropriate starting raster FIMs and control points. Development of a watershed SOP model often requires many months—sometimes years if terrain and hydrography data must be acquired and processed. Even when a SOP model is available, simulation of a scenario-of-interest may require many weeks. Provisional FIMs can be a pragmatic alternative when there are resource constraints, and especially when “time is of the essence”—such as for forecasts and for hazard scenarios to support property-stakeholders in risk valuation and insurance due diligence.

In such circumstances, a readily available SOP raster generated for another scenario may serve as a convenient starting raster for producing a provisional HD-FIM. Generally, a model scenario close to the scenario-of-interest is preferred to better represent inundation patterns. When there is no available SOP starting raster for any scenario, a raster produced by a dated watershed model—or even one derived from an older vector FIM—can be employed, though with significant additional limitations. The RASP Preliminary Task 3 includes an option for using RASP tools to convert an older vector FIM into a starting raster.

Generative artificial intelligence (AI) image manipulation techniques are being adopted to further automate the modification of starting raster FIMs to create scenario FIMs (see Bao et al 2025 and Fathom Global 2025). However, absent sufficient well-located, reasonably accurate, scenario control points, pure AI machine-generated scenario FIMs are limited to managing large-scale aggregate risk. As shown by the ARB 2016 Flood HD-FIM example, addressing property-specific flood risk greatly benefits from the RASP profile-informed approach incorporating professional expertise with relevant watershed and sub-watershed characteristics, stream networks, conveyance transitions, and scenario-specific conditions.

In the coming years, applications of RASP—combining best available starting rasters, professionally-sourced profile control, and the latest automated raster FIM processing—can hasten the widespread development of a one-stop online Smart Flood Map featuring an HD-DTM and HD-FIMs for a wide range of current and future scenarios in elevation and height above ground. A Smart Flood Map can support property-specific queries for full-spectrum hazard curves plus calculations of current and future probability-weighted average annual damage costs and damage risk Present Value—thereby enhancing the full range of public and private efforts to assess and manage flood risk.

Table 1. MaxWSE Data Points by Watershed

Watershed	USGS Gauge	HWMs	Total
Upper Amite River	0	7	7
Amite River-Beaver Ck to Comite R	3	45	48
Sandy Creek	0	16	16
Upper Comite River	2	11	13
Lower Comite River	4	82	86
Amite River-Comite R to B Manchac	2	57	59
Bayou Manchac	7	46	53
Grays & Colyell Creeks	0	92	92
New River	4	28	32
Upper Blind River	2	8	10
Lower Amite & Blind Rivers	8	43	51
Total Amite River Basin	**32**	**435**	**467**
Wet in both the SOP Hindcast and HD-FIMv1 rasters	32	387	419

Table 2. Accuracy of SOP Hindcast Raster versus MaxWSE Data Points, m (ft)

Watershed	Error Range				RMSE		Average Error	
Upper Amite River	-0.73	to	-0.23	(-2.41 to -0.76)	0.51	(1.67)	-0.48	(-1.56)
Amite River-Beaver Ck to Comite River	-0.74	to	0.48	(-2.43 to 1.57)	0.41	(1.35)	-0.32	(-1.04)
Sandy Creek	-0.75	to	0.58	(-2.47 to 1.90)	0.56	(1.83)	-0.18	(-0.6)
Upper Comite River	-0.58	to	0.49	(-1.90 to 1.61)	0.30	(0.99)	0.03	(0.10)
Lower Comite River	-0.99	to	0.67	(-3.25 to 2.21)	0.33	(1.08)	0.15	(0.50)
Amite River-Comite R. to B Manchac	-0.16	to	0.98	(-0.54 to 3.20)	0.39	(1.27)	0.28	(0.91)
Bayou Manchac	-0.55	to	1.41	(-1.81 to 4.61)	0.37	(1.20)	0.12	(0.40)
Grays & Colyell Creeks	-0.50	to	0.24	(-1.65 to 0.80)	0.20	(0.65)	-0.10	(-0.33)
New River	-0.83	to	0.67	(-2.73 to 2.20)	0.34	(1.11)	0.18	(0.60)
Upper Blind River	-0.29	to	0.39	(-0.96 to 1.27)	0.23	(0.76)	0.15	(0.48)
Lower Amite & Blind Rivers	-0.84	to	0.57	(-2.74 to 1.88)	0.25	(0.81)	0.10	(0.33)
Total Amite River Basin	**-0.99**	**to**	**1.41**	**(-3.25 to 4.61)**	**0.32**	**(1.06)**	**0.05**	**(0.18)**

Table 3. RASP Profile Control Points by Watershed

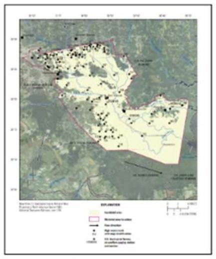
Watershed	USGS Gauge	Conveyance Transitions	From HWMs	For Algorithm	Total
Upper Amite River	0	0	0	2	2
Amite River-Beaver Ck to Comite R	3	1	10	2	16
Sandy Creek	0	0	2	4	6
Upper Comite River	2	2	4	6	14
Lower Comite River	4	2	6	9	21
Amite River-Comite R to B Manchac	2	5	18	10	36
Bayou Manchac	7	8	16	30	61
Grays & Colyell Creeks	0	4	28	16	48
New River	4	0	11	25	40
Upper Blind River	2	0	3	22	27
Lower Amite & Blind Rivers	8	4	13	23	48
Total Amite River Basin	**32**	**26**	**111**	**149**	**318**

Table 4. Accuracy of HD-FIMv1 versus MaxWSE Data Points, m (ft)

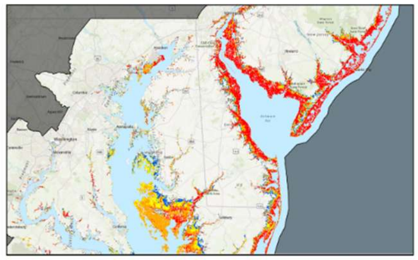
Watershed	Error Range				RMSE		Average Error	
Upper Amite River	-0.45	to	0.061	(-1.46 to 0.20)	0.26	(0.85)	-0.19	(-0.61)
Amite River-Beaver Ck to Comite R	-0.55	to	0.77	(-1.80 to 2.54)	0.28	(0.92)	-0.05	(-0.15)
Sandy Creek	-0.45	to	0.89	(-1.48 to 2.91)	0.54	(1.78)	0.12	(0.40)
Upper Comite River	-0.41	to	0.41	(-1.34 to 1.36)	0.19	(0.62)	0.02	(0.08)
Lower Comite River	-0.77	to	0.58	(-2.53 to 1.89)	0.21	(0.68)	0.01	(0.03)
Amite River-Comite R to B Manchac	-0.17	to	0.60	(-0.56 to 1.98)	0.22	(0.71)	0.13	(0.41)
Bayou Manchac	-0.25	to	0.59	(-0.82 to 1.92)	0.16	(0.53)	0.07	(0.23)
Grays & Colyell Creeks	-0.45	to	0.39	(-1.47 to 1.29)	0.15	(0.50)	-0.01	(-0.02)
New River	-0.09	to	0.52	(-0.30 to 1.69)	0.14	(0.45)	0.05	(0.18)
Upper Blind River	-0.02	to	0.39	(-0.08 to 1.28)	0.17	(0.55)	0.10	(0.33)
Lower Amite & Blind Rivers	-0.91	to	0.46	(-2.99 to 1.51)	0.18	(0.59)	-0.01	(-0.03)
Total Amite River Basin	**-0.91**	**to**	**0.89**	**(-2.99 to 2.91)**	**0.20**	**(0.66)**	**0.03**	**(0.09)**

Table 5. Accuracy Improvement for HD-FIMv1 versus SOP Hindcast Raster

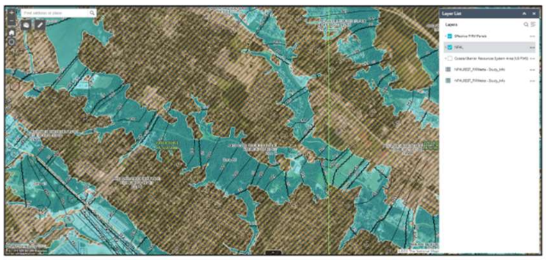
Watershed	RMSE Reduction			Average Error Reduction		
	Magnitude, m (ft)		Percent	Magnitude, m (ft)		Percent
Upper Amite River	0.25	(0.82)	49	0.29	(0.95)	61
Amite River-Beaver Ck to Comite R	0.13	(0.43)	32	0.27	(0.89)	86
Sandy Creek	0.02	(0.05)	3	0.06	(0.20)	33
Upper Comite River	0.11	(0.36)	37	0.00	(0.01)	15
Lower Comite River	0.12	(0.40)	37	0.14	(0.46)	93
Amite River-Comite R to B Manchac	0.17	(0.57)	44	0.15	(0.50)	55
Bayou Manchac	0.20	(0.67)	56	0.05	(0.18)	44
Grays & Colyell Creeks	0.05	(0.15)	23	0.09	(0.31)	94
New River	0.20	(0.65)	59	0.13	(0.42)	70
Upper Blind River	0.06	(0.21)	28	0.05	(0.15)	31
Lower Amite & Blind Rivers	0.07	(0.22)	28	0.09	(0.31)	92
Total Amite River Basin	**0.12**	**(0.40)**	**38**	**0.03**	**(0.09)**	**49**



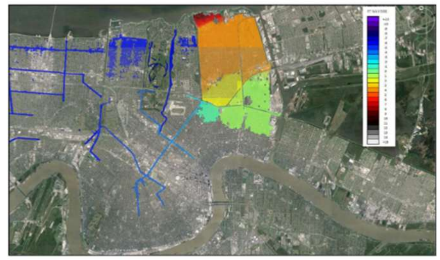
a. Amite River Basin August 2016 Flood
2D vector, PDF



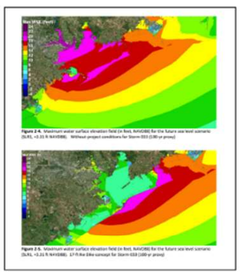
b. Category 3 Hurricane Storm Surge Scenario
Raster, tiled image



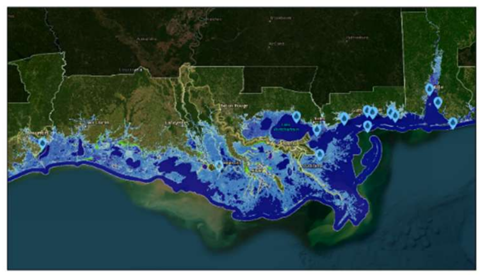
c. NFIP 1 percent AEP
3D vector, tiled image



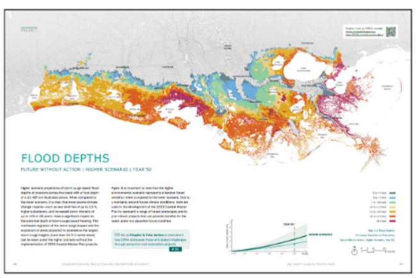
d. Metro New Orleans Polder Levee Breach Scenario
Raster, PDF



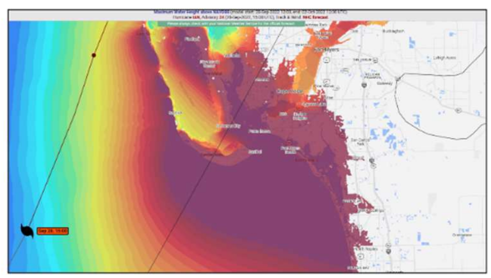
e. Hurricane Storm Surge Scenario Without
versus With Ike Dike Project—Raster PDF



f. Future Sea Level Rise Coastal Louisiana
Raster, tiled image



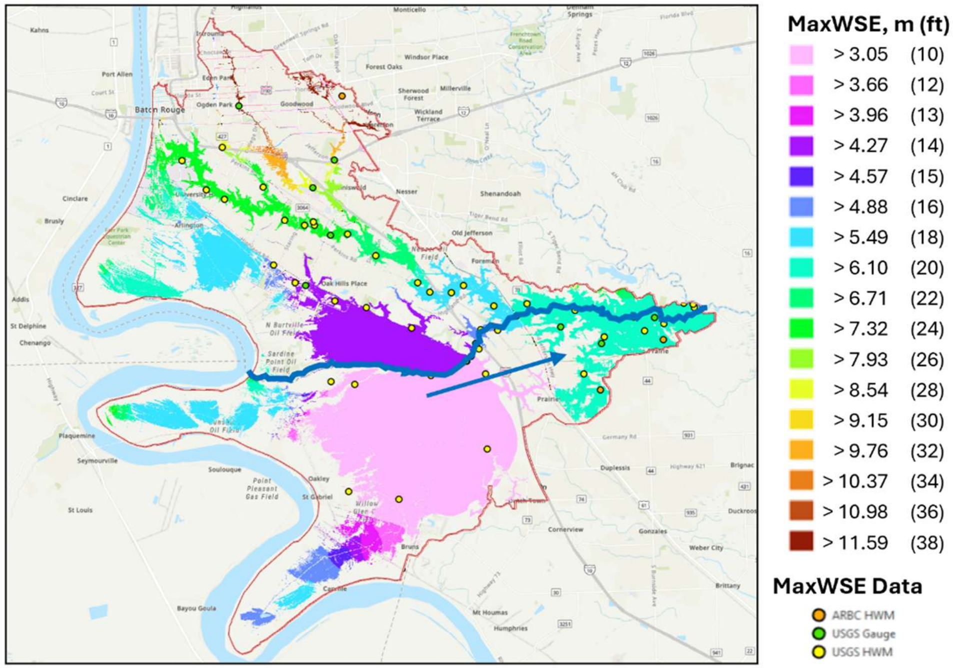
g. 1 percent AEP Flooding in 50 Years without Action
Raster PDF



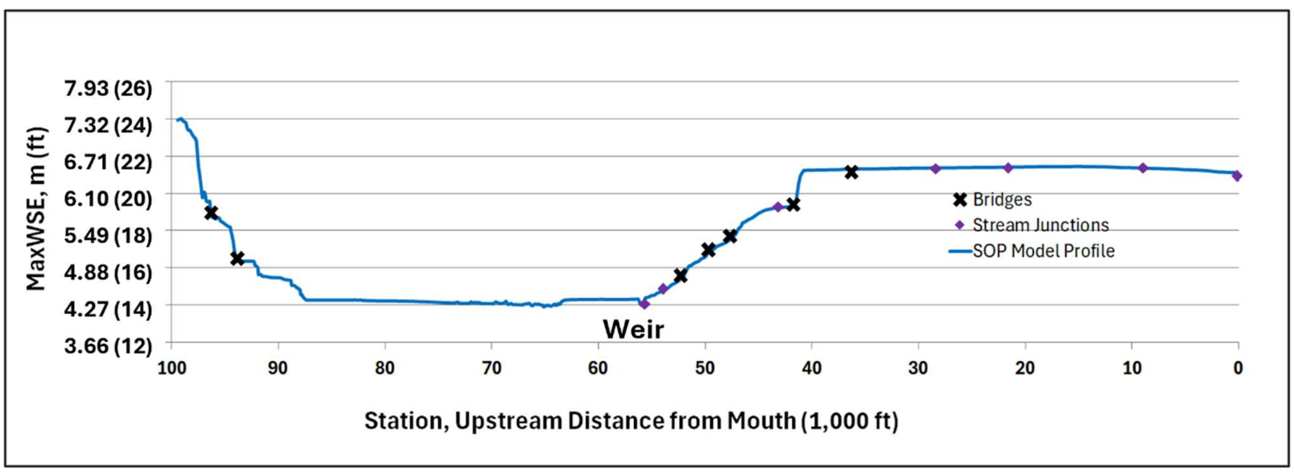
h. Hurricane Ian Storm Suge Forecast
Raster, tiled image

Figure 1 Example FIMs

a. Watson et al. 2017 (USGS); b. NOAA 2025a; c. FEMA 2025; d. Bob Jacobsen PE, LLC 2016; e. Texas A&M University—Galveston 2025; f. NOAA 2025b; g.; Coastal Protection and Restoration Authority of Louisiana 2023. h. Coastal Emergency Risk Assessment 2022



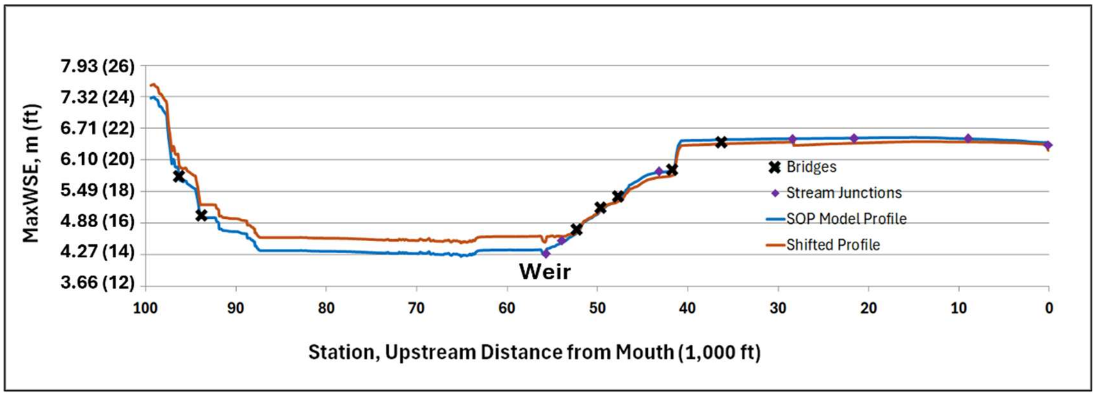
a. Model-Generated Raster FIM



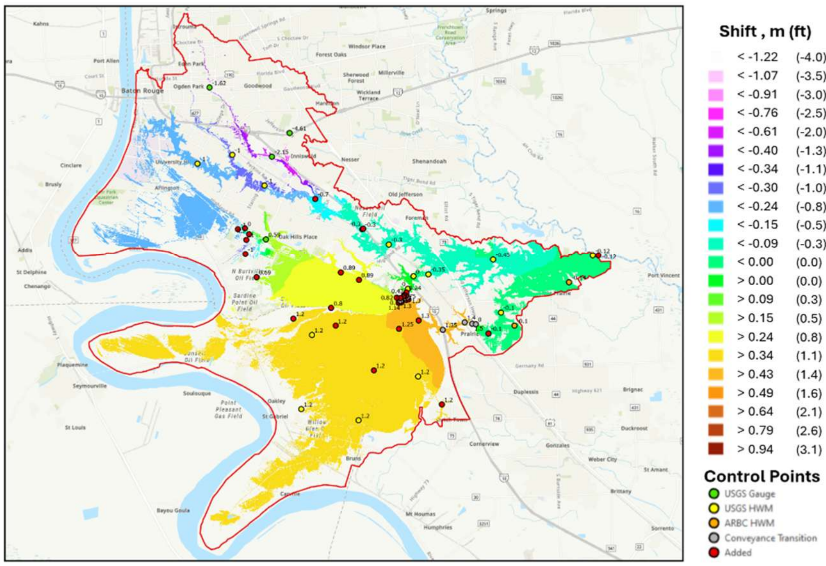
b. Model-Generated Profile

Figure 2. SOP Hindcast for ARB 2016 Flood, Bayou Manchac Watershed
Dewberry Engineers, Inc. 2019

Figure 3. Amite River Basin and Eleven Watersheds

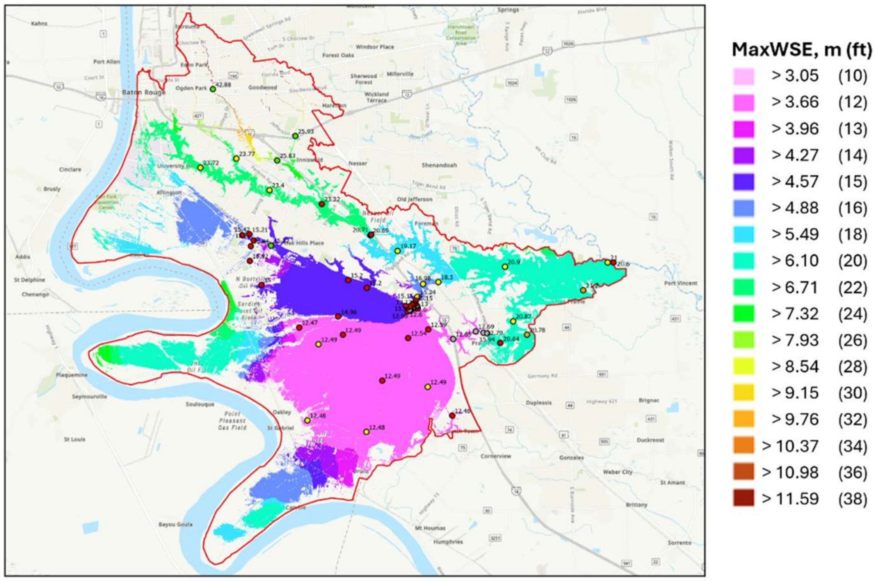


a. Profile Shift

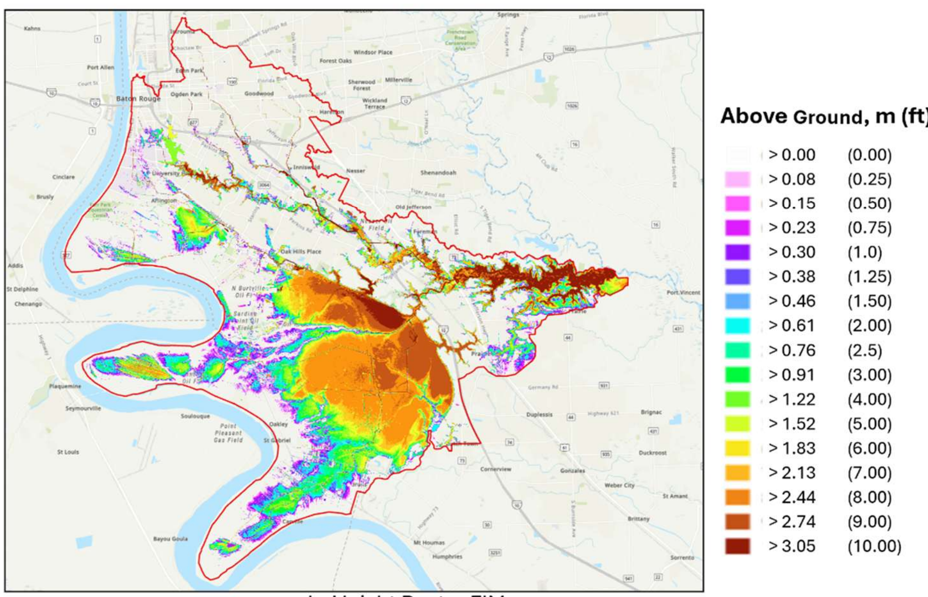


b. Difference Raster

Figure 4. Example Profile and Raster Adjustments, Bayou Manchac Watershed



a. MaxWSE Raster FIM,



b. Height Raster FIM

Figure 5. HD-FIMv1, Bayou Manchac Watershed

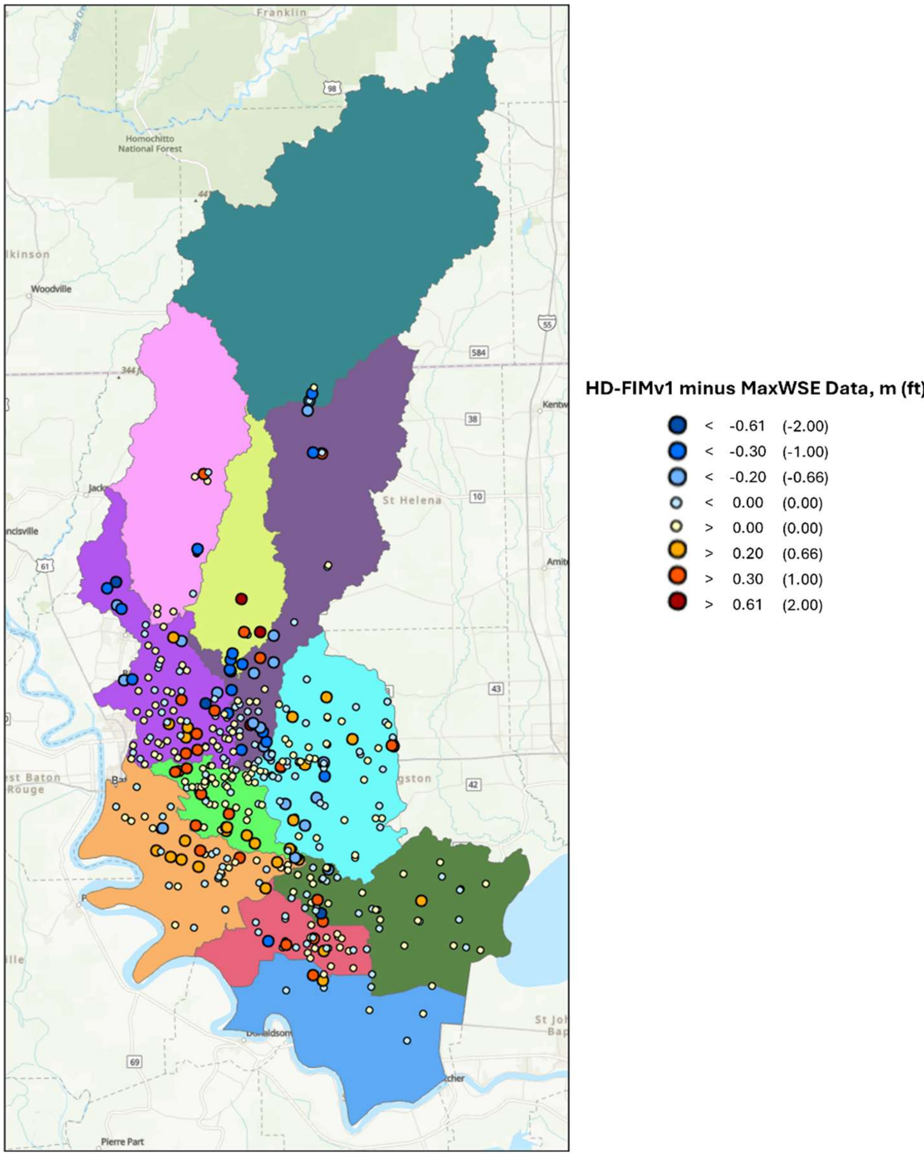
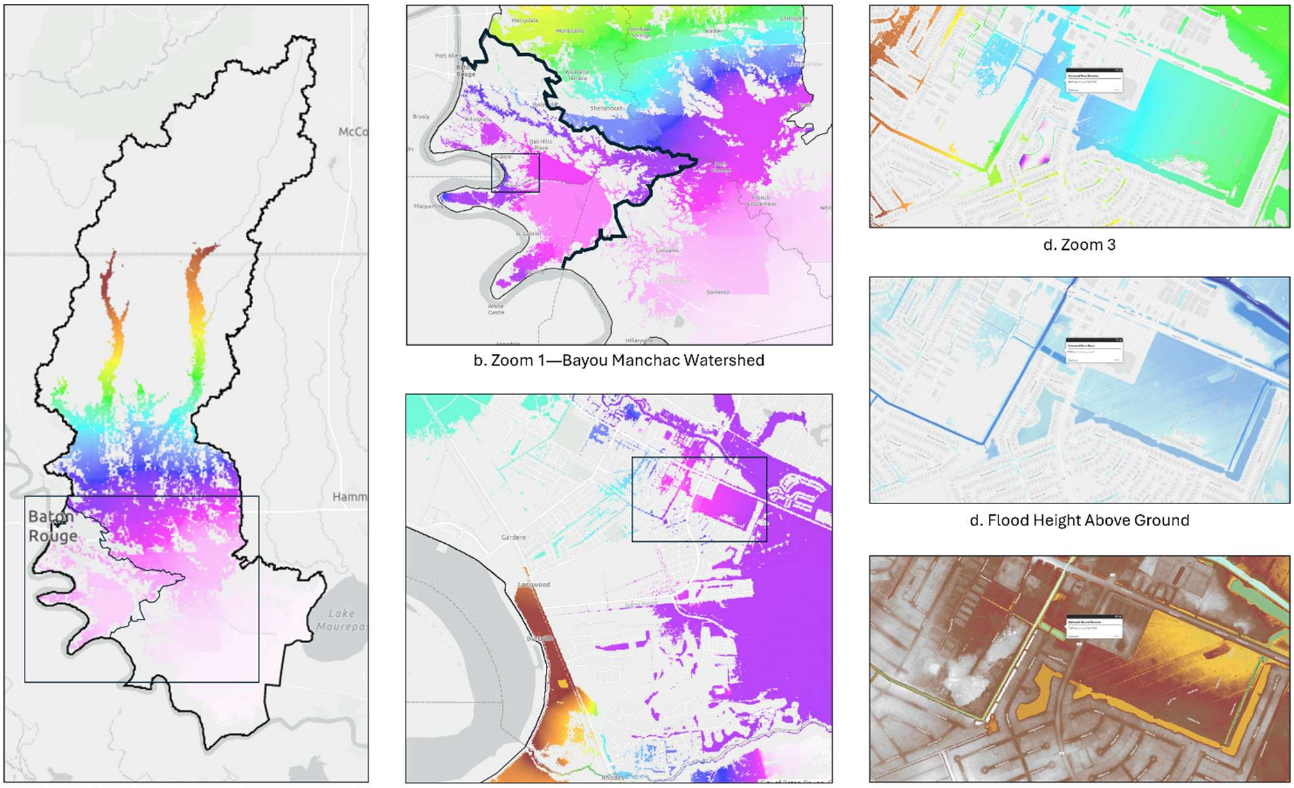


Figure 6. Remaining Discrepancies for HD-FIMv1 versus MaxWSE Data Points



a. Amite River Basin August 2016 Flood MaxWSE

b. Zoom 1—Bayou Manchac Watershed

c. Zoom 2

d. Zoom 3

d. Flood Height Above Ground

e. DTM

Figure 7. Online HD-FIMv1 for the ARB 2016 Flood
Amite River Basin Drainage and Water Conservation District 2022

Appendix

Note 1. 2D flood modeling capabilities to address complex circulation domains evolved in the 1990s. Examples include the Federal Emergency Management Agency (FEMA) FEMA/TetraTech Surge model; the National Oceanic and Atmospheric Administration (NOAA) Sea, Lake, and Overland Surges (SLOSH) model; and the US Army Corps of Engineers (USACE) Resource Management Associates (RMA-2) model. 2D models improved rapidly with investments in DTMs along with multi-processor "supercomputers" and parallelized hydrodynamic codes—such as the Advanced Circulation (ADCIRC) code. Demand for better 2D models escalated following the devastating floods of 2005 Hurricanes Katrina and Rita. Subsequent leaps in desktop computer parallel processing have greatly expanded the application of high-resolution 2D floodplain modeling. In 2016 the USACE's published their desktop Hydrologic Engineering Center River Analysis System (HEC-RAS) Version 5.0 code with 2D capabilities, including a RAS Mapper utility to create and edit raster FIMs from model results.

Note 2. FEMA initiated scanning of FIRMS into digital image versions in 1992 under their Quality Level Three (Q3) Program. By the mid-2000s internet server and user bandwidth advances allowed the digital images to be shared with the public via the web. In Louisiana, for example, following the 2005 Hurricanes Katrina and Rita floods, FEMA created a website to make coastal parish FIRMs and related information available via the web.

Note 3. In 2009 Louisiana State University provided a web GIS interface for statewide FIRMs featuring seamless, zoom-able, parish-wide images. In 2018 FEMA made the National Flood Hazard Layer—including FIRM information—available through a web GIS interface.

Note 4. A direct lateral extrapolation method provides MaxWSE contours that are generally perpendicular to channel flowline. An alternative lateral interpolation method provides MaxWSE contours that follow the terrain flowpath (see Nobre, A.D., L.A. Cuartas, M.R. Momo, D.L. Severo, A. Pinheiro, and C.A. Nobre. 2016. "HAND Contour: A New Proxy Predictor of Inundation Extent." *Hydrological Processes* 30, no.2: 320-333).

Bio

Bob Jacobsen PE has 45 years of professional experience in south Louisiana water resource management, specializing in innovative environmental and flood risk management. He served as the lead flood hydrology consultant to Louisiana regional agencies in the aftermath of the 2005 Katrina disaster and the Amite River Basin 2016 Flood. He is the author of the ARB 2016 Flood HD-FIM. Bob is a past-president of the American Society of Civil Engineers Louisiana Section.

is a Past-President of ASCE's Louisiana Section. He

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Supplemental Materials: RASP Detailed Procedure

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Introduction

Raster Adjustment with Scenario Profiles (**RASP**) is crucial to developing High-Definition Flood Inundation Maps (HD-FIMs) by reducing local errors in state-of-the-practice (SOP) model-generated rasters.

RASP utilizes advanced GIS vector and raster processing capabilities to adjust an initial raster FIM to match refined scenario profiles based on improved scenario control point values. Unlike a simple rectification ("rubber sheeting") of a starting raster to fit a set of points, RASP emphasizes informed adjustments to the key details in channel profiles. And unlike a simple lateral extrapolation of MaxWSEs from channel profiles, RASP incorporates floodplain inundation patterns from the initial raster.

The RASP method consists of four straightforward steps:

5. Extract MaxWSE profiles along the channel flowline network from the starting raster, together with important contour lines.
6. Establish control points with improved scenario MaxWSE accuracy at key locations along the profile lines.
7. Shift the starting profile and contour lines to fit the control points using the MaxWSE difference value at the control points (between the control and the starting raster value); employ linear interpolation and extrapolation to define MaxWSE difference values at all vertices along the profile and contour lines; add the difference values to the starting vertice values to produce revised profile and contour lines.
8. Adjust the starting raster by sub-watershed unit to fit the MaxWSE difference values at the cloud of profile and contour vertices; employ spatial interpolation and extrapolation to define MaxWSE difference values at all raster cells and then add the differences to the starting raster cell values to produce the adjusted raster.

Below are a list of useful GIS tools and detailed descriptions for three preliminary tasks and the four-step RASP procedure.

In addition to refining a SOP model-generated, scenario-specific raster, RASP can be employed to prepare *provisional* HD-FIMs by combining an appropriate set of profile control points with a suitable available starting raster. Provisional HD-FIMs can be a pragmatic alternative when there are resource constraints, and especially when "time is of the essence"—such as in forecasting and in supporting property-stakeholders due diligence. When no starting raster is available, the third preliminary task addresses steps for using RASP tools to convert a vector FIM into a starting raster.

RASP procedures can also be employed with other types of three-dimensional (3D) surface rasters, such as reducing errors in digital elevation/terrain models (DEM/DTMs) with the use of high-quality road surveys.

In the future, researchers are likely to explore the ability of machine learning tools to assist in defining scenario control points and in optimizing interpolation/extrapolation algorithms.

GIS Tools

Use of these tools requires working knowledge of GIS software (e.g., ArcGIS Pro from ESRI), 3D spatial referencing, and basic vector, network, and raster dataset setup and editing. The first seven tools are built-in to ArcGIS Pro.

Snap—Using a set of points and a set of 2D lines relocates each point to the closest line location.

Extract Values to Points—Using a set of points and a raster, extracts the raster grid cell value at each point and includes it as a new point attribute.

Feature to 3D by Attribute—Using a set of 2D lines with a numeric attribute, creates a set of 3D contour lines where the Z value for vertices on each line is assigned based on a designated attribute.

Clip Raster—Using a specified polygon and raster, clips the raster to just that portion lying within the polygon.

Mosaic to New Raster—Using two rasters, creates a third combined raster based on cell-by-cell operator (e.g., order of raster listed, maximum value, sum, etc.).

Greater Than—Using two rasters, creates a third raster indicating which of two input raster pixel value is greater.

Con—Using two rasters, creates a third raster based on a condition (IF-THEN).

RASP is aided by developing additional vector and raster processing scripts, such as:

Segment 2D Lines—Using a set of 2D lines and a set of snapped points with attribute for sub-segment length, subdivides any line with a snapped point into three separate segments, as defined by snapped point attribute; used to create separate segments at conveyance transitions.

Fill Raster— Using a raster and a set of contiguous polygons encompassing the raster, creates a single raster that completely fills the respective polygons. The filling of each polygon is based only on those portions of the raster within the respective polygon and uses an appropriate spatial interpolation/extrapolation method.

Extract 3D Lines from Raster—Using a set of 2D lines and an expanded raster, creates 3D lines (profiles) where vertex Z is extracted from the raster.

Convert 2D Lines to 3D Using Points— Using a set of 2D lines and a set of snapped points with a numeric attribute, creates 3D lines where the Z value for each vertex is calculated using the snapped points—with linear interpolation for intermediate vertices and linear extrapolation for any remaining upstream vertices.

Add/Subtract 3D Lines—Using two 3D lines with identical vertex locations, creates a new 3D line with vertex Z equal to the sum of—or difference between—the vertex Z values in the two versions.

Export 3D Lines—Using one or more sets of 3D lines with identical vertex locations, exports a series of CSV files with separate files based on line Name (filterable by other attribute); the CSV file tabulates vertex station (distance along Name from origin) versus respective vertex Z for the full combined length of the 3D line in each set; using point files, the respective CSV file also lists points snapped to the Name line by station and with selected attributes; used for exporting flowline DTM and FIM profiles and location of conveyance transition points and Control Points.

Fill Raster Using 3D Lines —Using a set of 3D lines and a set of contiguous polygons encompassing the 3D lines, creates a single raster that completely fills the respective polygons. The filling of each polygon is based only on those portions of the 3D lines within the respective polygons and uses an appropriate spatial interpolation/extrapolation method. Most methods (e.g., nearest neighbor) provide MaxWSE contours perpendicular to the channel flowline at the intersection. An alternative method that provides MaxWSE contours following the terrain flowpath is described in Nobre, A.D., L.A. Cuartas, M.R. Momo, D.L. Severo, A. Pinheiro, and C.A. Nobre. 2016. “HAND Contour: A New Proxy Predictor of Inundation Extent.” Hydrological Processes 30, no.2: 320-333.

Raster Patch—Using a raster, a set of 2D lines, and a set of snapped points with attributes for patch dimensions and interpolation control, creates a raster patch at each point, with the patch having grid cell values based on patch perimeter values in the raster; used for hydro-enforcement of channels at bridge and culvert locations.

Raster Strip—Using a raster, a set of 3D lines, a set of snapped points with attributes for inner and outer width and lateral interpolation control, creates raster strips along the 3D lines; used to burn trapezoidal channels into DTM using provisional bathymetry invert profiles.

Preliminary Tasks

1. Collect relevant flood information—including watershed flood history, data, estimates, hydrologic and hydraulic analyses, crucial factors and conditions, previous FIMs and flood profiles, etc.
2. Compile DTM and hydrography datasets (from federal, state, local sources—USGS, FEMA, USACE, NOAA, drainage studies, flood mitigation, bridge designs, etc.); edit as follows. Note that updating hydrography in low-relief floodplains can require extensive manual digitizing.
   - 2.1. Edit Regional flowline network for a) consistency with the DTM; b) high resolution vertices; c) flood profiling, (simplify by removing parallel floodplain channels/braids, cross connections, short tributaries within the inundated floodplain, and unnecessary junctions; d) fixes to network errors (e.g., unconnected lines, junctions of more than three lines, incorrect downstream direction); and e) Stream Name and Type attribute.
   - 2.2. Edit watershed and hydrologic sub-unit boundary polygons to be consistent with the DTM and flowline network and clip the other datasets to the overall basin polygon. **Clip Raster**
   - 2.3. Edit conveyance transition points. These points indicate a natural or man-made channel change that can cause an abrupt shift in the general slope of a flowline's flood profile—such as an obstruction, constriction/expansion, steepening/flattening, and change in channel bottom/bank/overbank cover. Man-made transitions include road/railroad bridges, culverts, weirs, gates, channel modifications, and debris/sediment accumulation. Snap conveyance transition points to the flowline network. Include attributes for applying GIS tools to segment flowlines and creating DTM hydro-enforcement patches. **Snap**
   - 2.4. Edit regional bathymetry invert points. Include attributes for applying GIS tools to create bathymetry DTM strips. Snap bathymetric invert points to flowline network and create 3D bathymetry profile lines.
   - 2.5. Subdivide the flowline network with segments broken out by junctions and channel conveyance transitions. **Segment 2D Lines**
   - 2.6. Add hydro-enforcement of channels to the DTM at bridges and culvert embankments by creating replacement DTM raster patches with interpolation of existing channel bathymetry. **Raster Patch** and **Mosaic to New Raster**
   - 2.7. Add flowline bathymetry to the DTM by creating replacement DTM raster strips based on the bathymetry profiles. **Snap**, **Convert 2D Lines to 3D Using Points**, **Raster Strip**, and **Mosaic to New Raster**
3. Obtain a starting raster FIM, preferably a SOP model-generated raster FIM for the watershed similar to the scenario-of-interest. If a raster FIM is not available prepare one from a watershed vector FIM:
   - 3.1. If the FIM vectors include an inundation area perimeter line that is consistent with the DTM, create a perimeter DTM elevation profile 3D line. Edit as needed to provide high-resolution vertices. The perimeter DTM elevation profile serves as the perimeter MaxWSE profile. **Extract 3D Lines from Raster**
   - 3.2. Develop a "Control Point" dataset with locations along the flowline network reflecting important profile conditions indicated in the vector FIM, including a) the MaxWSE at stream downstream limits (origin vertex); b) the MaxWSEs near stream upper ends—and thus the overall head-loss for stream profiles; and c) reasonable profile slopes; d) important profile slope changes—such as at conveyance transitions; and e) consistent MaxWSEs where floodplains from nearby streams merge. **Snap**
   - 3.3. Assign reasonable control point scenario MaxWSE values based on the vector FIM and professional judgment (e.g., reflecting NFIP studies, bridge designs, flood mitigation plans, and other relevant flood information).
   - 3.4. Create the MaxWSE 3D flowlines along the network. The MaxWSE at all the line vertices is calculated as a function of the Control Point values. **Convert 2D Lines to 3D Using Points**
   - 3.5. Create floodplain MaxWSE contour 2D lines using sufficient vertices. Locate flood surface contour 2D lines as needed to establish important MaxWSE gradient patterns for the scenario. Contour lines can include those provided in the vector FIM, but older vector FIMs based on 1D models often oversimplify flood MaxWSE contour lines. (For example, the USACE HEC-RAS 1D model employs contour lines comprised of three straight line segments, one for the main flowline channel, typically perpendicular to the flowline, plus a lateral extension at each end to represent the left and right floodplain, which are sometimes offset at the outer end in the upstream direction.) Contour lines reflect knowledge of the watershed and hydrologic sub-units, as well as professional experience with similar regional hydrologic conditions. Then convert to MaxWSE contour 3D lines with the Z value for each vertex based on the MaxWSE attribute of the Assign the MaxWSE attribute to each contour line consistent with MaxWSE at the flowline intersection. respective 2D line. **Feature to 3D by Attribute**
   - 3.6. If a perimeter MaxWSE profile has been created, remove portions that are incongruous with the flowline network or contour lines; for example, if the location accuracy for perimeter vertices is suspect and/or terrain elevations estimate for perimeter vertices have changed since the vector FIM's original preparation.
   - 3.7. Create a *filled* starting raster using the complete set of MaxWSE 3D flowlines and contour lines and perimeter line vertices and their MaxWSEs. The raster should be created by hydrological sub-units as appropriate. **Fill Raster Using 3D Lines**
   - 3.8. Create the starting raster with appropriate dry grid cells—change those cell values in the expanded raster with MaxWSE exceeded by DTM elevation to "no values." **Great Than** and **Con.**

RASP Steps

1. Extract flowline profiles and key contours from the starting raster.
   1.1. Create a "Filled Starting" raster extending throughout/encompassing the total basin polygon. Filling should be performed by hydrological sub-unit polygons as appropriate. **Fill Raster**
   1.2. Create a "MaxWSE Contour" 2D line dataset using sufficient vertices. Locate flood surface contour 2D lines as needed to establish important MaxWSE gradient patterns for the scenario. Contour lines reflect knowledge of the watershed and hydrologic sub-units, as well as professional experience with similar hydrologic conditions.
   1.3. Extract "DTM Profile" and filled "Starting MaxWSE Profile" 3D line datasets along the flowline network. **Extract 3D Lines from Raster**
   1.4. Extract a "Starting MaxWSE Contour" 3D line dataset along the "MaxWSE Contour" 2D lines. **Extract 3D Lines from Raster**
   1.5. Plot and inspect the DTM and starting MaxWSE profiles along the flowline network by Stream Name and revise DTM bathymetry if needed. **Export 3D Lines**
2. Establish control points along the profiles with improved accuracy for scenario MaxWSE.
   2.1. Develop a "Control Point" dataset with locations along the flowline network for the scenario-of-interest. Select locations to address important flood profile conditions including a) the MaxWSE at stream downstream limits (origin vertex); b) the MaxWSEs near stream upper ends—and thus the overall head-loss for stream profiles; c) reasonable, consistent Step 3 profile shifts; d) important profile slope changes—such as at conveyance transitions; and e) consistent MaxWSEs where floodplains from nearby streams merge. Include the "Starting MaxWSE" value from the filled starting raster at the Control Point location as an attribute. **Snap** and **Extract Values to Points**
   2.2. Assign "Control MaxWSE" values for Control Points as an additional dataset attribute. Define reasonable values based on data or estimates (from relevant historical floods, NFIP studies, bridge designs, flood mitigation plans, other studies) and professional judgment.
   2.3. Calculate an additional attribute "Difference" for Control Point dataset equal to respective "Control MaxWSE" minus the filled "Starting MaxWSE."
3. Shift the starting profiles and contour lines to fit the control points.
   3.1. Create a "Difference Profile" 3D line dataset along the flowline 2D line network. The Z values for all vertices are calculated as a function of the Control Point Difference values—with linear interpolation/extrapolation. **Convert 2D Lines to 3D Using Points**
   3.2. Create an "Adjusted MaxWSE Profile" 3D line dataset along the flowline 2D line network with the scenario MaxWSE as the Z value at all vertices. The Z values for vertices are calculated as equal to the sum of respective "Starting MaxWSE" and the "Difference" values. The "Adjusted MaxWSE Profile" 3D lines shift the "Starting MaxWSE Profiles" to match the "Control MaxWSEs" while maintaining many of the starting profile characteristics. **Add/Subtract 3D Lines**
   3.3. Plot the "DTM Profiles," "Starting MaxWSE Profiles," and "Adjusted MaxWSE Profiles" together and inspect the "Adjusted MaxWSE Profiles" for reasonableness; revise Control Points and Control MaxWSEs as necessary. **Export Profiles**
   3.4. Assign the Adjusted MaxWSE as an attribute to each "MaxWSE Contour" 2D line consistent with Adjusted MaxWSE value at the flowline intersection. Create an "Adjusted MaxWSE Contour" 3D line dataset. **Feature to 3D by Attribute**
   3.5. Create a "Difference Contour" 3D line dataset with the Z value at all vertices calculated as equal to the Adjusted MaxWSE minus the Starting MaxWSE from the vertices in the respective 3D contour lines. **Add/Subtract 3D Lines**
4. Adjust the starting raster to fit the shifted profiles and contours.
   4.1. Create a "Filled Difference" raster using the "Difference Profile" and "Difference Contour" 3D line datasets. The raster should be created by hydrological sub-units as appropriate. **Fill Raster Using 3D Lines**
   4.2. Create a "Filled Adjusted" raster by summing the "Filled Difference" raster and the "Filled Starting" raster. **Mosaic to New Raster**
   4.3. Create a final "Adjusted MaxWSE" raster with appropriate dry grid cells—change those cell values in the "Filled Adjusted" raster with MaxWSE exceeded by DTM elevation to "no values." **Great Than** and **Con**
   4.4. Create a final "Adjusted Height" raster by subtracting the DTM from the "Adjusted MaxWSE" raster. **Mosaic to New Raster**
   4.5. Inspect the final "Adjusted MaxWSE" and "Height" rasters for reasonableness ; revise Control Points, Scenario-Specific MaxWSEs, and MaxWSE Contours as necessary.