Guidance for Flood Risk Analysis and Mapping

Flood Depth and Analysis Rasters

December 2020

FEMA

Requirements for the Federal Emergency Management Agency (FEMA) Risk Mapping, Assessment, and Planning (Risk MAP) Program are specified separately by statute, regulation, or FEMA policy (primarily the Standards for Flood Risk Analysis and Mapping). This document provides guidance to support the requirements and recommends approaches for effective and efficient implementation. Alternate approaches that comply with all requirements are acceptable.

For more information, please visit the FEMA Guidelines and Standards for Flood Risk Analysis and Mapping webpage (www.fema.gov/flood-maps/guidance-partners/guidelines-standards). Copies of the Standards for Flood Risk Analysis and Mapping policy, related guidance, technical references, and other information about the guidelines and standards development process are all available here. You can also search directly by document title at www.fema.gov/multimedia-library.

Table of Revisions

The following summary of changes details revisions to this document subsequent to its most recent version in February 2018.

Affected Section or Subsection	Date	Description
Added Sections 2.6 and 3.4	December 2020	Information added for Floodway Water Surface Elevation and Depth Rasters
Entire Document	December 2020	Updated terminology, aligned with approach for a consistent raster dataset that approximates the Regulatory product but is not identical.

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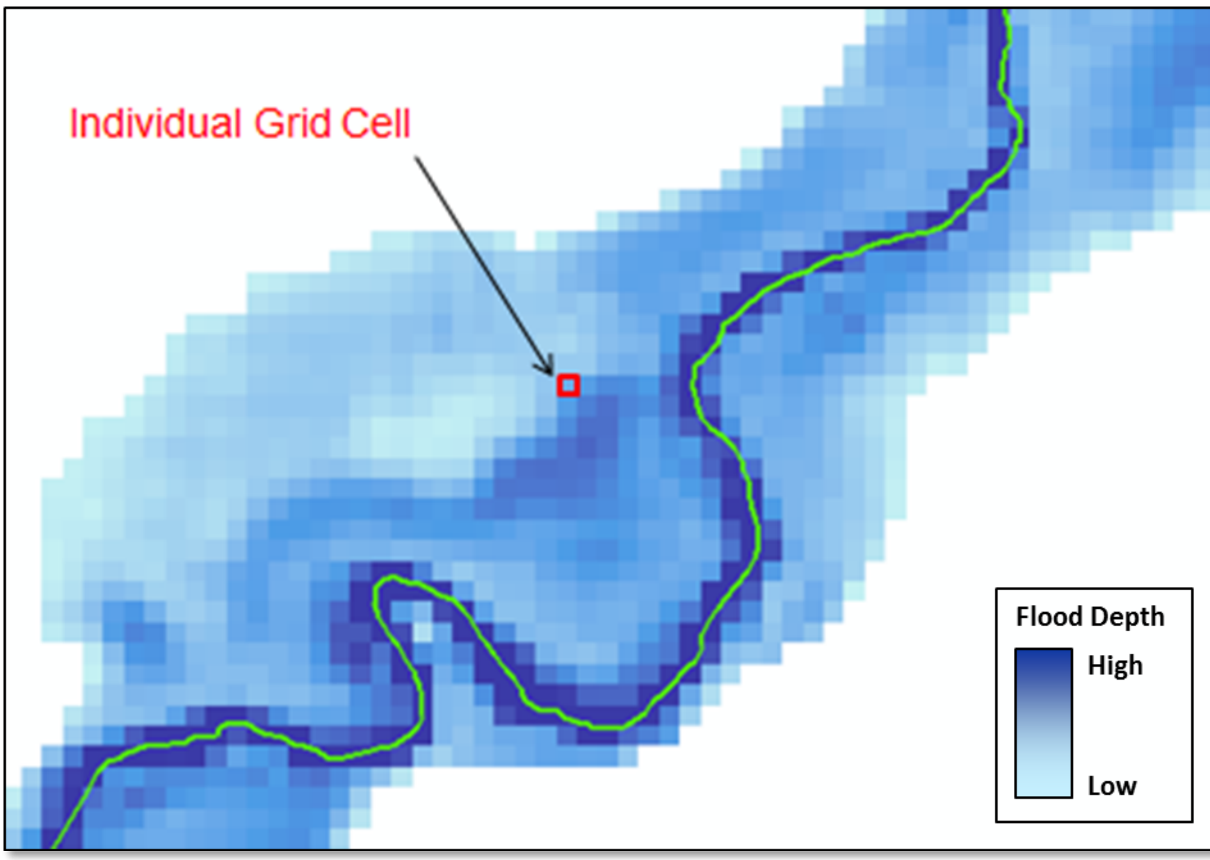
1.0 Definitions

One of the primary ways to communicate more complete flood risk information and to inform actions that can be taken to reduce flood risk is to deliver detailed information on depth of flooding, probability of flooding, and other flooding characteristics in the form of raster datasets (see Figure 1, where the darker blue areas represent greater flood depths). Similar to the pixels of a photo or graphic, a grid is a digital raster dataset that defines geographic space as an array of equally sized square cells arranged in rows and columns. The value in each cell represents the magnitude in that location of the flooding characteristic represented by that particular grid. Within the Flood Risk Database (FRD), raster datasets can be produced to reflect water surface elevations (WSELs), depths, velocities, percent-annual-chances of flooding, and other values. Other raster datasets that are unique to coastal areas and dams are also available within the Coastal-Specific Non-Regulatory Datasets Guidance and Dam-Specific Non-Regulatory Datasets Guidance documents.

Figure 1: Flood Depth Grid Example



1.1 Grid Cell Resolution

Several considerations should be taken into account when selecting the cell size for the rasters to be delivered within the FRD. The depth and analysis rasters in the FRD have an inherent relationship to the underlying topographic data used during the development of the flood hazard delineations depicted on the Flood Insurance Rate Map (FIRM). The raster cell size (resolution) of all raster datasets in the FRD should be based on the density of the ground elevation data used and the appropriate precision that can be supported by the data. Normally, all the raster datasets should use the same raster cell size. However, it is strongly recommended that the cell size for the WSEL grids be no larger than 10 feet x 10 feet. This will allow for a more accurate depiction and retrieval of WSEL values from that raster dataset.

The overall file size of each raster dataset is directly related to the size of the raster cells selected. For example, the decision to use a 1 meter resolution raster as opposed to a 3 meter resolution raster will approximately increase the file size on disk by a factor of 9 (nine 1m x 1m raster cells can fit within one 3m x 3m raster cell). Using very small cell sizes (smaller than 1m resolution), however, may result in a flood risk database that is difficult for most users to be able to access and use.

1.2 Raster Cell Origin

In order to be able to properly orient each raster with one another, and to more accurately compare one flood risk data value (such as depth) to another (such as velocity) at a given location, each raster dataset within the FRD should use the same origin, cell size, rotation, and coordinate system. Since many of the raster datasets are derived from other rasters (for example, the depth rasters are derived from the water surface elevation rasters, and the percent-annual-chance rasters are derived from those), setting a common origin for all raster datasets within the study area provides for proper alignment of raster cells when comparing one raster dataset to another.

2.0 Water Surface Elevation (WSEL) Rasters

The Water Surface Elevation (WSEL) raster is generally the first raster dataset that will be produced as part of a Flood Risk Project. A separate WSEL raster is produced for each flood event (e.g. 1-percent-annual-chance, 0.2-percent-annual-chance, 1-percent-annual-chance future conditions, 1-percent+, etc.) or flood scenario (e.g. dam or levee overtopping) for which modeled elevations are available. Therefore, the 10-percent-annual-chance WSEL raster is one dataset, the 4-percent-annual-chance WSEL raster is another dataset, and so on. Each WSEL raster provides the modeled WSEL values within the inundation extent of that particular flood event or scenario. In locations outside the corresponding mapped floodplain, a value of “NODATA” is assigned (see Figure 2).

The WSEL raster is the source from which many of the other raster datasets (such as the depth and percent-annual-chance rasters) are generated. As such, these derivative datasets inherit their quality and accuracy from the corresponding WSEL rasters. Therefore, it is critical that the WSEL rasters be produced with a level of quality that will meet program standards (especially Standard ID (SID) #415), so they can be used to retrieve one’s flood elevation at any given location within the mapped floodplain.

For example, in the case of flood events that will be mapped on regulatory products (1-percent and 0.2-percent-annual-chance), or for any other flood event that is mapped, the WSEL rasters should be created to align to those corresponding flood boundaries. This will build agreement between the various products and datasets produced as part of a Flood Risk Project. and build user’s trust in the datasets. In other words, for a given flood event (such as the 1-percent-annual-chance flood), the 1-percent-annual-chance WSEL raster should have values of

“NODATA” for cells outside of the mapped regulatory 1-percent-annual-chance floodplain. Similarly, the WSEL cells within the mapped floodplain should report a WSEL value. At confluences, WSEL rasters created for a network of multiple flooding sources should be combined to reflect one overall, seamless WSEL raster for each flood event or scenario. Backwater elevations and extents at confluences should be correctly accounted for as part of the WSEL raster creation process (see Figure 3). Section 2.6 provides additional detail regarding the checks that should be performed, and common challenges that must be overcome, in order to produce a high-quality WSEL raster that adheres to FEMA standards.

Figure 2: Example Showing Values Returned When Pointing and Clicking Different Locations on the WSEL Raster

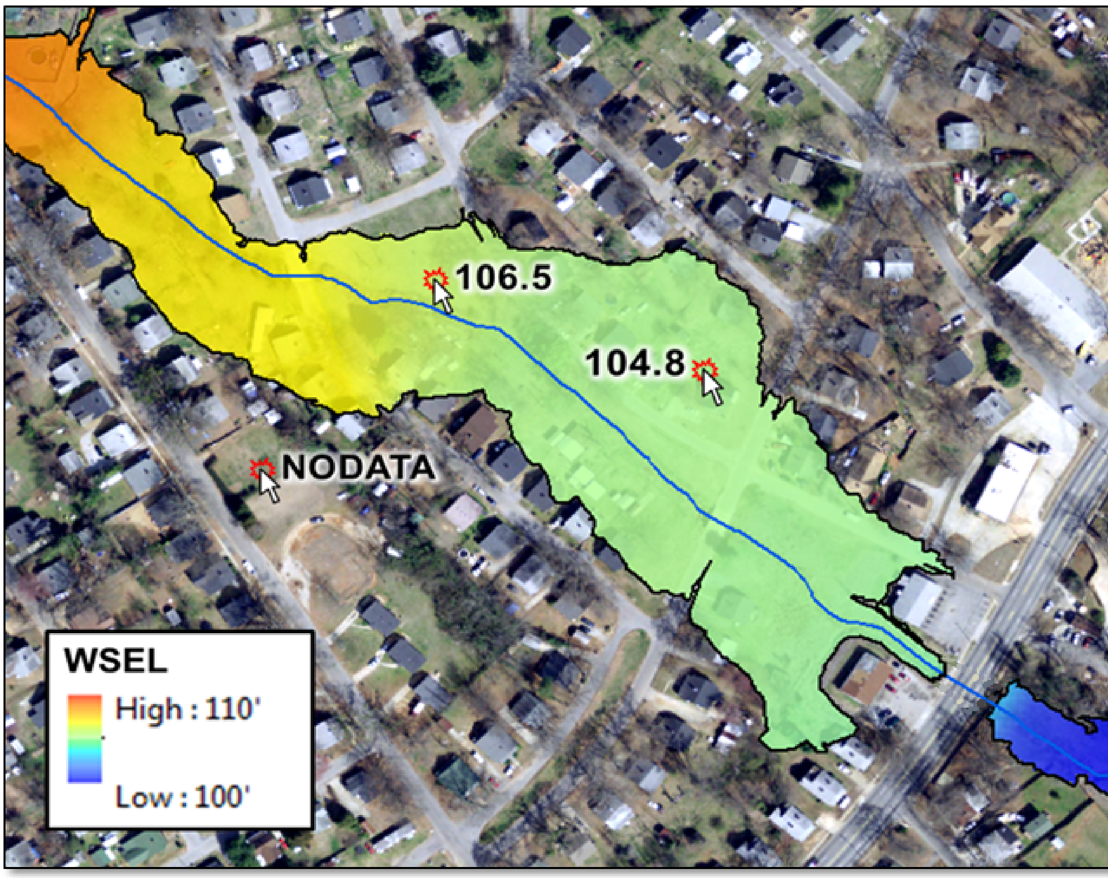
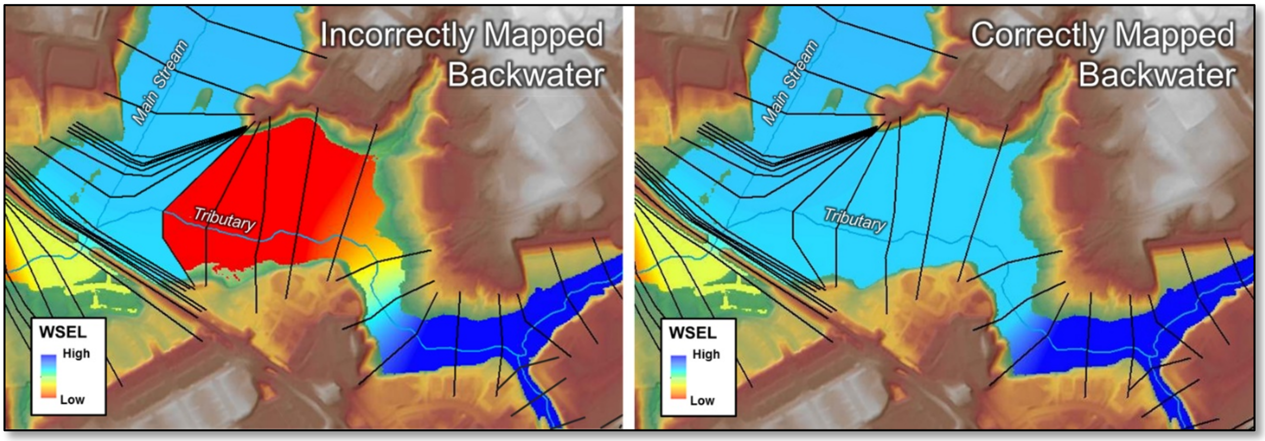


Figure 3: Proper Accounting for Backwater Mapping in the WSEL Raster



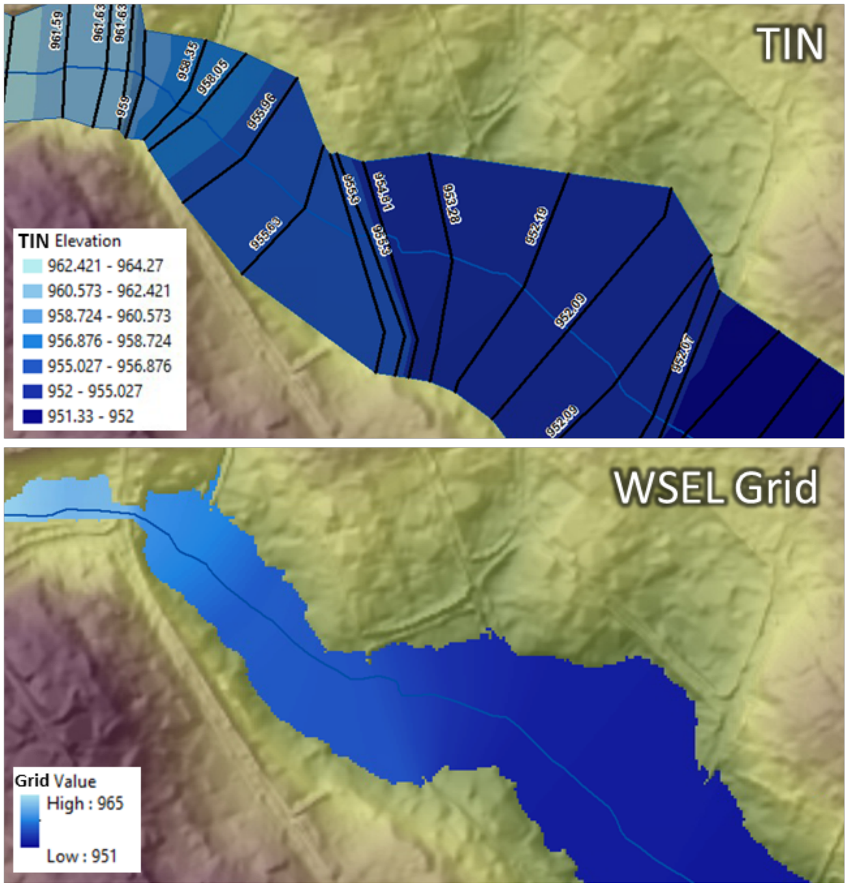
2.1 Riverine WSEL Rasters

Water surface elevation rasters form the basis from which the depth rasters, percent-annual-chance rasters, and many of the other raster datasets are generated. For new or revised flooding sources, they should reflect the proposed regulatory elevations (i.e. reflect backwater conditions even if the new model does not). Water surface elevation rasters created from effective data should reflect the effective regulatory elevations as shown on the FIRM and are expected to align to the mapped boundaries. For effective streams where all the effective modeled cross sections may not be available, it may be necessary to add “mapping” cross sections prior to generating the WSEL rasters to recreate the effective flood profile properly and accurately.

For 2-D modeling, the WSEL raster is typically one of the standard datasets that is output from the model, and may only require minor editing to be suitable, depending on the hydraulic model used. For 1-D models, however, while Mapping Partners may utilize differing hydraulic models, Geographic Information System (GIS) software and platforms, creation of the WSEL rasters typically involve the following common elements:

- Use the water surface elevations from the hydraulic model to create a 3D water surface. This can be accomplished by generating a Triangulated Irregular Network (TIN) from the vector water surface features and attributes and converting that TIN into a raster format (see Figure 4). In the case of 1-D step backwater analysis, the water surface elevations will be extracted from modeled cross-sections. Completing this process on a stream by stream basis and then merging the individual rasters together using the MAXIMUM value approach in GIS can help to address some of the common problems experienced in confluence areas.

Figure 4: RASTER Creation from a TIN



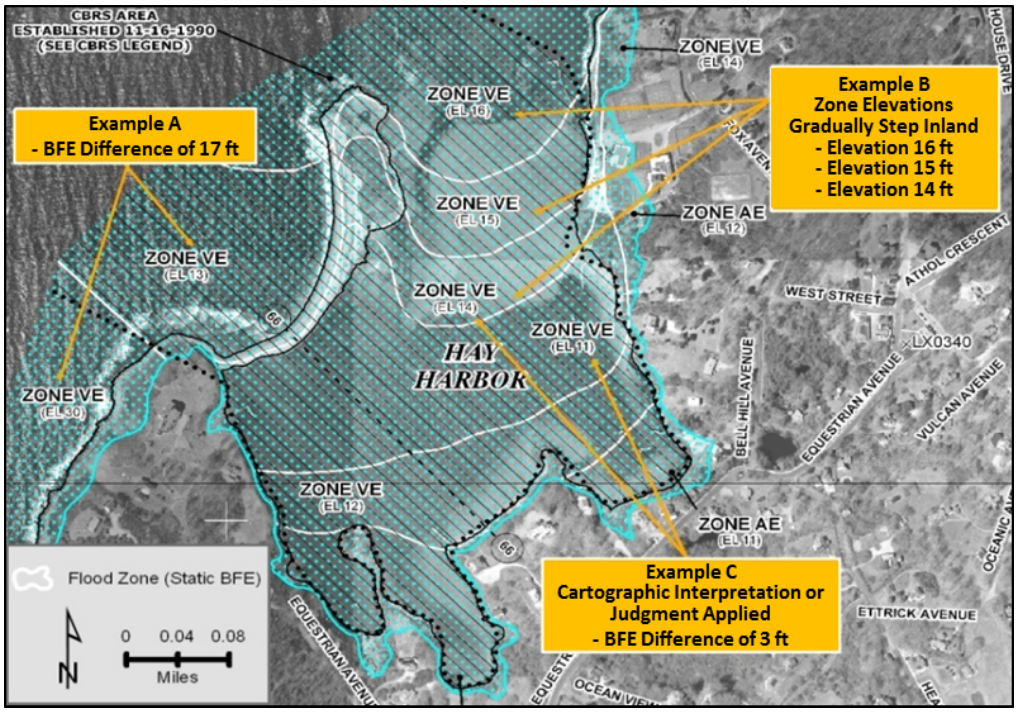
- Remove the cells from the raster (assigning a value of "NODATA") where the water surface elevation is below the ground elevation.
- Make sure backwater is appropriately accounted for and that other accuracy and reasonability checks are performed.
- If creating a WSEL raster for a flood frequency that is included on the FIRM (1-percent and 0.2-percent-annual-chance), "mask" the raster to the floodplain boundary. If islands exist in the WSEL raster, that were removed from the regulatory boundaries on the FIRM, Mapping Partners should fill those in so as to preserve agreement between the WSEL raster and the corresponding delineations on the FIRM.

2.2 Coastal WSEL Rasters

WSEL rasters for coastal flooding sources should reflect the total water level (combination of wave setup, stillwater, and wave height elevations), as opposed to just the stillwater elevation. As such, they are generally only created for the recurrence intervals for which the wave crest elevations have been calculated/estimated, such as the 1-percent-annual-chance flood. Coastal WSEL rasters are most often created by using the regulatory-mapped coastal floodplain zones and their associated base flood elevations directly. It may not be appropriate to create them in areas controlled by wave runup (see Section 3.1 for more information).

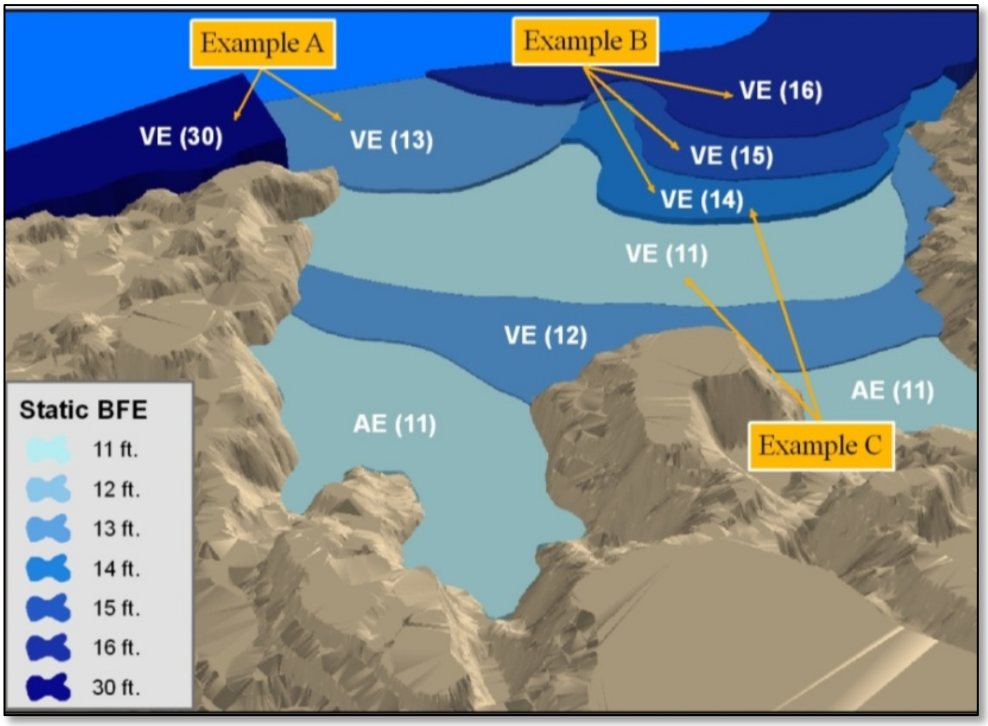
Coastal modeling culminates in static water surface elevations assigned to the mapped coastal floodplain zones. It is important to note that final mapped flood hazard areas often represent engineering judgment and/or intentional generalization of the specific coastal model outputs. Therefore, while users may be tempted to use coastal modeling GIS layers, such as coastal transects, use of the final mapped floodplains to generate coastal water surface rasters is considered the best guidance to apply, as it is intended to yield results that most closely match the FIRM. Therefore, coastal floodplain mapping with associated static Base Flood Elevations (BFEs) (as shown on Figure 5) will normally be used to generate coastal 1-percent-annual-chance WSEL rasters. This is accomplished by simply converting the FIRM-based polygons to a raster and using the static elevations of each as the source from which to assign the water surface raster elevations.

Figure 5: Coastal Floodplain Mapping Examples



While coastal water surface mapping may produce outputs that appear unnatural, (noted in Example A - Figure 5 and Figure 6) the stair-step effect between coastal zones is considered normal and acceptable. The same applies even if the stair-stepping effect is like Example B (where the transition is gradual) or Example C, which may also appear unnatural but is a function of the mapping process where cartographic interpretation and/or engineering judgment has been applied.

Figure 6: Stair-Stepped Coastal Elevations



2.3 Shallow Flooding and Ponding WSEL Rasters

Zone AH areas are used to depict shallow flooding areas, and most commonly report a static BFE on the FIRMs. Similarly, ponding areas can also be shown as a Zone AE on the FIRMs with a static BFE. The static BFEs in these cases are stored in the FIRM Database as an attribute of the S_FLD_HAZ_AR feature class.

To create the WSEL raster for areas with static BFEs, the following process generally applies. Variations that produce the same outcome may be followed.

1. The WSEL raster results should support the elevations shown on the FIRM. For the 1-percent-annual-chance WSEL raster, the Mapping Partner should convert the associated polygon area on the FIRM to a raster and attribute all the raster cells in that area with the static elevation shown on the FIRM and reflected in the FIRM Database. If the static elevation value in the FIRM Database has been rounded to the nearest whole foot, the WSEL raster should reflect the value rounded to the whole foot. If the value in the FIRM Database is shown to the tenth of a foot, the WSEL raster should similarly report the static elevation to the tenth of a foot.
2. If the 0.2-percent-annual-chance area has been calculated and mapped on the FIRM (shaded Zone X), its WSEL raster should also match the extents shown on the FIRM.
3. All WSEL rasters (10-percent, 4-percent, etc.) in shallow flooding or ponding areas should be rounded using the same precision as the 1-percent-annual-chance WSEL raster.

Zone AO is also used to depict shallow flooding areas, but since Zone AO reports flood depths on the FIRM, and not flood elevations, WSEL rasters should not be created for Zone AO floodplains. If the new or effective model from which the Zone AO depths were derived is available, and there is a desire to produce a WSEL raster, consideration should be given to depicting the flood zone on the regulatory FIRM as something other than a Zone AO. Information is provided in Section 3.3 for producing depth rasters in Zone AO areas.

2.4 Dam WSEL Rasters

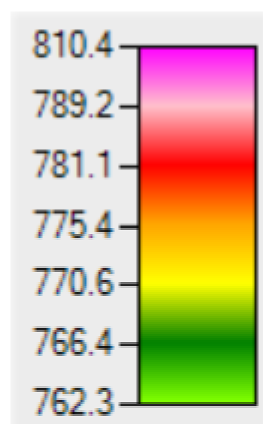
WSEL rasters created for dam-related flooding are produced in much the same way as they are for a typical study. The only difference is that the WSEL raster may be based on a specific flood scenario rather than frequency-based results (such as the 1-percent or 0.2-percent-annual-chance floods). Unique combinations of flooding event, dam release type (piping, failure, or overtopping), and the hydrologic condition of the reservoir at the time of the release are used to differentiate the WSEL rasters for dams. The L_Dam_Scenario table in the Flood Risk Database provides the naming conventions that can be used for each dam WSEL raster, depending on the type of dam release scenario depicted. For example, rather than produce the typical 1-percent-annual-chance WSEL raster, a dam-related WSEL raster could be created to reflect the flood elevations from a sunny day piping failure of the dam where the reservoir was full to capacity.

2.5 Levee WSEL Rasters

Similar to dams, WSEL rasters for levees can be developed to correspond to a percent-annual-chance of flooding, but also can be based on the flood elevations resulting from a historical flood event, or overtopping scenario, among others. The L_Levee_Scenario table in the Flood Risk Database provides the naming conventions that can be used for each levee WSEL raster, depending on the type of scenario depicted. The process to create levee WSEL rasters is the same as for a typical study. The difference is simply in the flood scenario depicted.

2.6 Quality Considerations when Creating/Checking WSEL Rasters

As previously mentioned, because many of the flood risk datasets are derived, in one way or another, from the WSEL rasters, it is imperative that the WSEL rasters be produced with a level of quality that would meet SID #415. A quality control (QC) process should be utilized to check that the WSEL rasters are of such a quality that they match regulatory data (elevation and extent), as required by FEMA standards. One qualitative way to test this would be to investigate different areas within the floodplain, and assess whether the 1-percent-annual-chance WSEL raster at those locations would be what a floodplain administrator or other user would reasonably estimate to be the BFE, using the available regulatory products.



When reviewing the WSEL rasters, it may be helpful to adjust the display settings and symbology of the rasters such that errors are more easily identifiable. For example, some GIS software has the ability to change a raster's display settings such that its color ramp is rendered based on the current display extent rather than its entire extent. This effectively means that when zoomed in, anomalies in the raster show up more clearly because the color ramp of the raster is being symbolized over a smaller range of WSEL values – abrupt changes in color may be an indication of errors, or at least areas that may warrant further investigation.

The following considerations and examples provide greater insight into what a quality WSEL raster consists of and help to highlight some of the aspects of the WSEL raster that should be checked when evaluating its quality. It should be noted that WSEL rasters created from 2-D models will not exhibit many of the following problems, as 2-D models are not dependent on cross-section placement and alignment.

2.6.1 Appropriate Input Data

For 1-D models based on cross-sections, the cross-sections play a critical role in creating or checking for an accurate WSEL raster. All modeled cross-sections should be used, as each is necessary to make sure that the WSEL raster is an accurate depiction of the model. Failing to include all modeled cross-sections in the creation or QC process will result in an incorrect WSEL raster. The only exception to this is for cross-sections in backwater. Depending on the methodology used by Mapping Partners to create the WSEL rasters, it may be advantageous to remove certain tributary cross-sections that are within backwater to create a better product. Cross-sections for an individual stream that intersect one another should also be cleaned up prior to creating the rasters.

For WSEL rasters created from effective studies, especially those that are much older, some modeled cross-sections may not have been mapped and may not be available digitally. In these cases, it is necessary to manually add “mapping” cross-sections to be able to accurately capture the inflections in the effective flood profile. Figure 7 provides an example of an effective study where two manual cross-sections (indicated by the green “+” sign on the profile) should be added upstream and downstream of the road to properly match the model. Otherwise, the resulting WSEL raster would incorrectly reflect the elevations shown by the red dashed line on the profile, and as Figure 8 highlights, the WSEL values in the raster would be underestimated upstream of the road and overestimated downstream of the road.

Figure 7: Adding Modeled Cross-Sections to Provide More Accurate Raster Representation (Profile View)

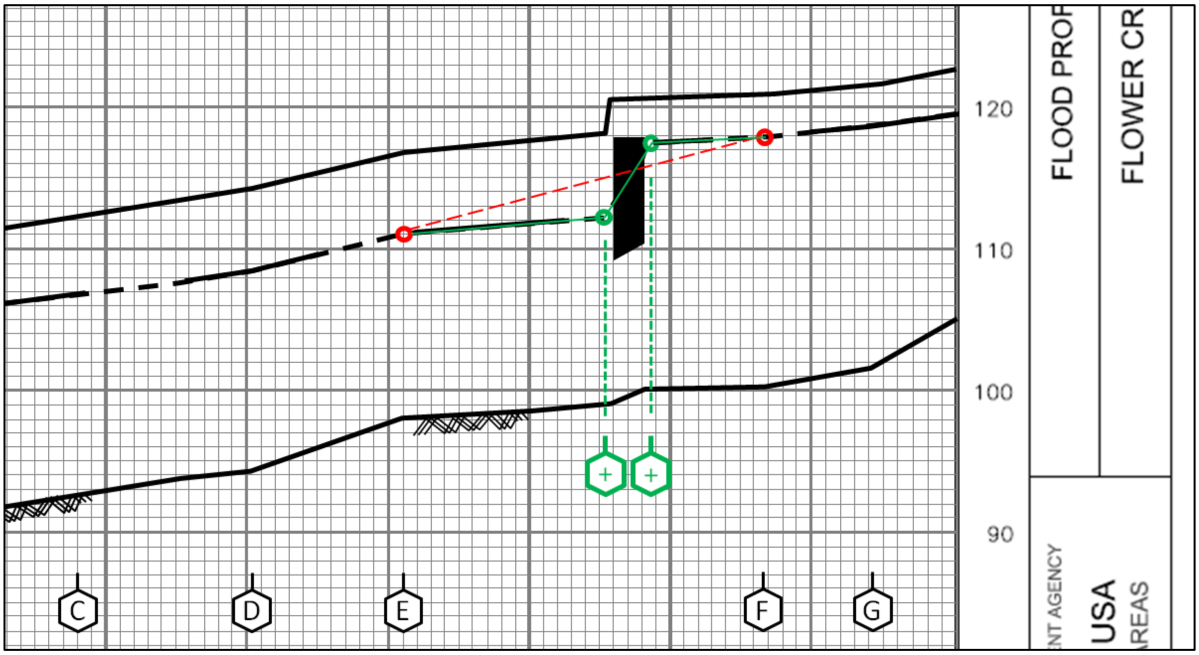
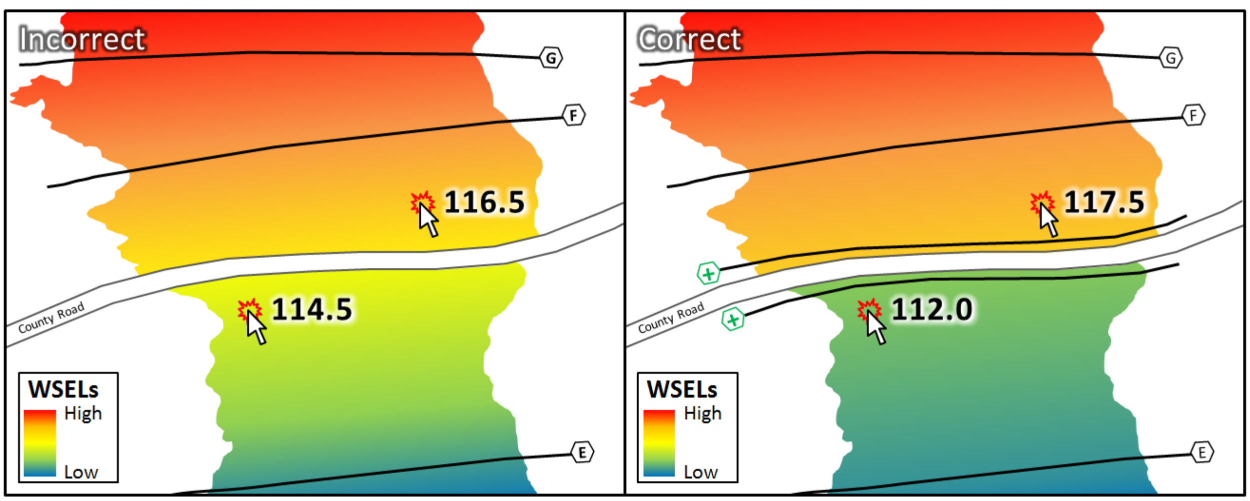


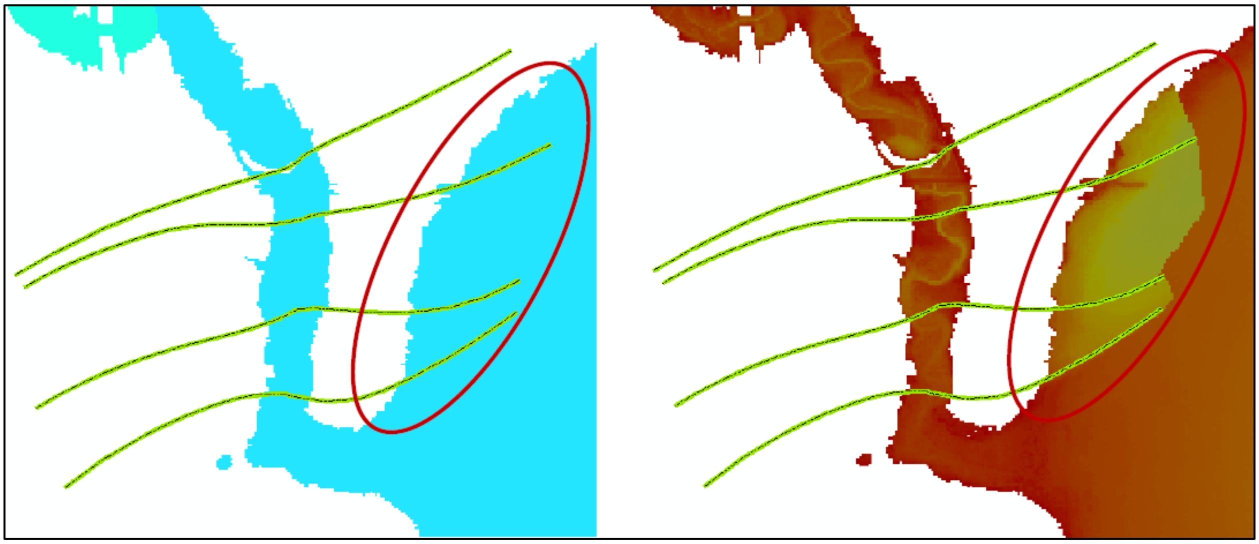
Figure 8: All Modeled Cross-Sections are Necessary for Accurate Raster Representation (WSEL Raster View)



For new studies, the cross-sections used to create or QC the WSEL raster should be available digitally and will be attributed with the modeled elevations. For effective studies, the water surface elevations attributed to the cross-sections should match the effective flood profile and floodway data tables. Drawdowns should be eliminated prior to creating or checking the WSEL raster.

1-D model cross-sections should also be reviewed for cases where cross-section extents terminate within the floodplain of another flooding source. This most often can occur around stream confluences. If these are not trimmed prior to creating or checking the WSEL raster, then errors in the raster will be present, as shown in Figure 9. As the example shows, depending on the display settings used in GIS, the error may not be discernable from a visual inspection of just the WSEL raster alone (left image), but is clearly seen when looking at the same area's associated depth raster (right image).

Figure 9: WSEL Raster Errors Resulting from Untrimmed Cross-Sections

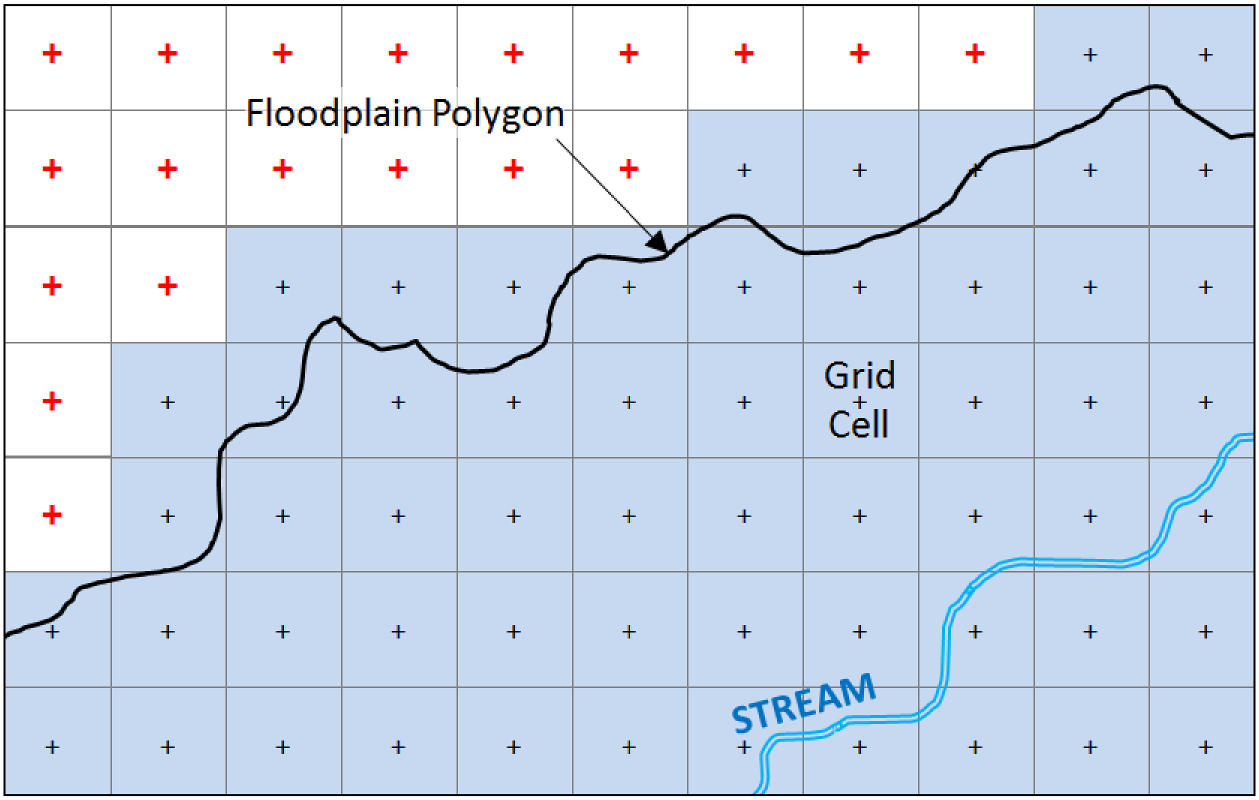


2.6.2 WSEL Raster Agreement with Applicable Flood Hazard Area Polygon

If a mapped flood hazard polygon exists and is being provided to a community or other stakeholders (such as is the case with the 1-percent-annual-chance floodplain shown on a regulatory FIRM), then that polygon feature and its corresponding WSEL raster should agree with one another. In other words, aside from natural differences that will occur at the floodplain boundary when comparing a raster product (WSEL raster) with a vector product (floodplain polygon), the two corresponding products (e.g. 1-percent WSEL raster and 1-percent floodplain, 0.2-percent WSEL raster and 0.2-percent floodplain, etc.) should match in terms of spatial coverage and extents.

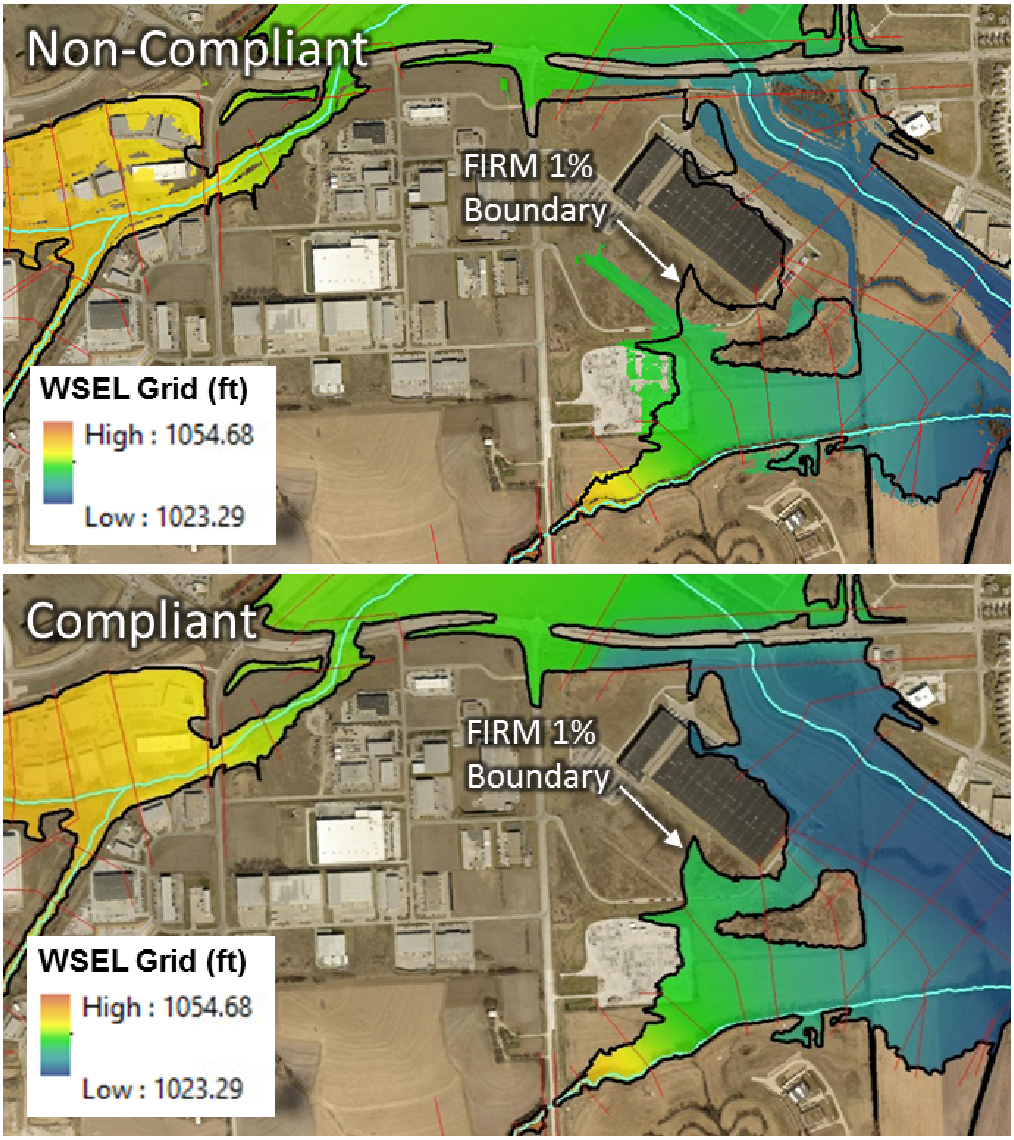
Because different options exist within GIS when converting a polygon to a raster (or vice versa), at a minimum, all cells whose entirety fall outside the mapped floodplain should be coded as "NODATA" (cells with a bold red centroid symbol in Figure 10). All cells whose entirety falls within the mapped floodplain should contain a value, and it is strongly recommended that any cell that touches the mapped floodplain, regardless of the percentage of the cell that is within the flood polygon, store a WSEL value (i.e. cells shaded blue in Figure 10). Doing so will help ensure that an elevation is returned if a user were to try to retrieve a WSEL at all locations within the mapped floodplain.

Figure 10: WSEL Raster Alignment with Floodplain Polygon at Edge of Boundary



Within the mapped floodplain, the same guidance applies – where islands have been removed from the mapped flood hazard area polygon, those same areas should be shown with a value in the WSEL raster. Figure 11 shows a comparison between an incorrectly created WSEL raster (top image) that does not agree with the mapped floodplain, versus a correctly created WSEL raster (bottom image) that matches the mapped floodplain.

Figure 11: Comparison of Incorrect vs. Correct WSEL Raster Agreement to Mapping



The WSEL raster extent and elevations for a given flood frequency (e.g. the 1-percent-annual-chance) should also be larger than or equal to the extents and elevations of the raster for lower flood magnitudes (e.g. the 2-percent-annual-chance), and should be smaller than or equal to the extents and elevations of the raster for the higher flood magnitudes (e.g. the 0.2-percent-annual-chance). In other words, in areas where the 1-percent and 0.2-percent-annual-chance floodplains have been mapped, there should be no 1-percent-annual-chance WSEL raster cells with values where there is also not a corresponding 0.2-percent-annual-chance WSEL raster with values. Just as it would not be appropriate to show the mapped 1-percent-annual-chance flood hazard polygon wider than the 0.2-percent-annual-chance flood hazard polygon, it is not appropriate to show something similar with the corresponding WSEL rasters.

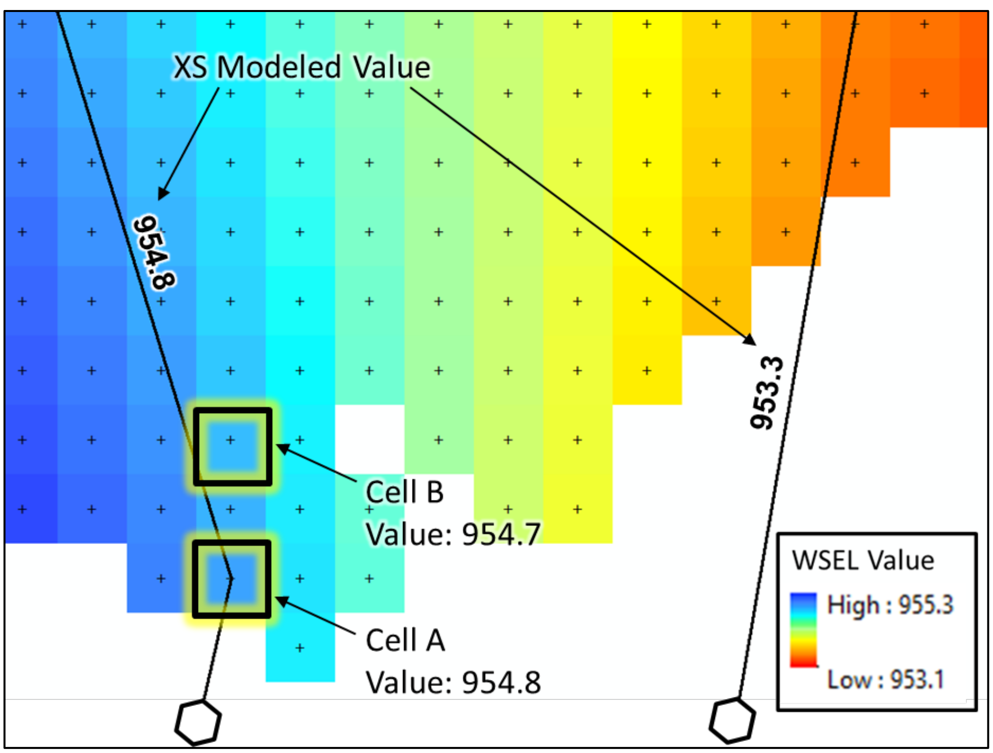
2.6.3 Elevation Accuracy

The WSEL raster should provide an accurate representation of the hydraulic model results and should depict expected flood elevations at all locations within the mapped floodplain. This means that not only do the WSEL raster elevations match at modeled cross-sections, but that raster elevations in between cross-sections are also appropriate – including at confluences. Per the Flood Risk Database Technical Reference, all WSEL raster cell values should be rounded to the nearest tenth of a foot prior to submitting. It is recommended that this rounded, final product be the one tested when performing the following QC checks.

2.6.3.1 Elevation check at modeled cross-sections

For cross-sections not influenced by backwater, the values of WSEL raster cells that intersect the cross-section should match within 0.5 feet of the modeled cross-section elevation for that corresponding flood event. The actual raster values assigned when creating a WSEL raster from cross-sections are generally dependent on where the cross-section intersects the cell, in relation to its centroid. For example, as shown in Figure 12, WSEL raster cells whose centroid is very close to where the cross-section line intersects should have their values nearly identical to the cross-section value (cell A), whereas those that intersect, but whose centroid is farther away will show more of a difference (cell B). This is to be expected. The slope of the water surface profile between cross-sections will influence how rapidly the WSEL transitions from cell to cell the farther you move away from the cross-section.

Figure 12: WSEL Raster Values in Relation to Cross-Section and Cell Centroid Intersection



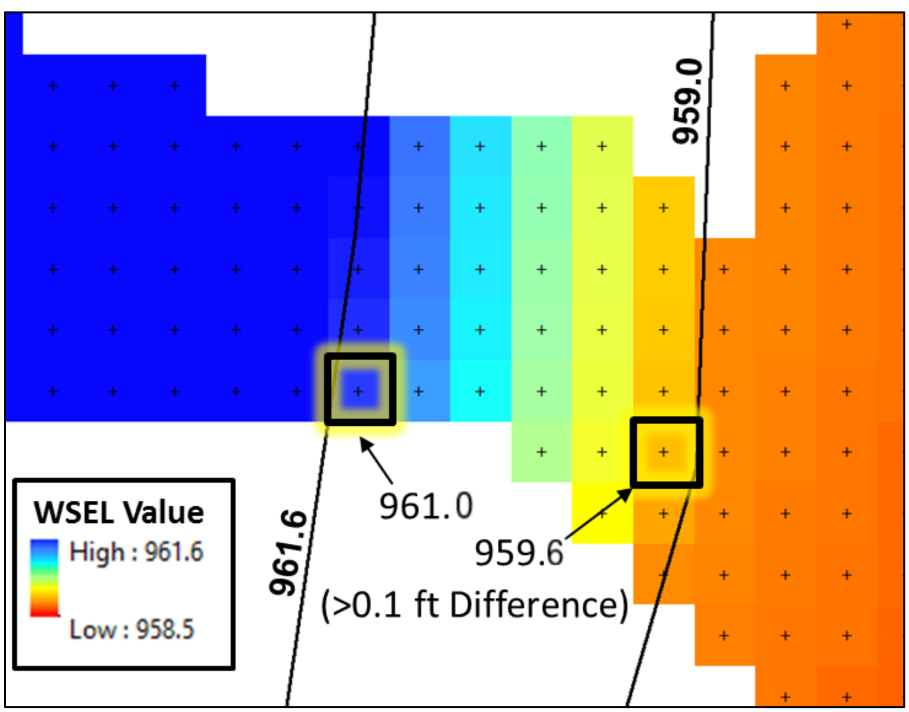
In steeper reaches of stream, the slope of the water surface profile, size of the raster cells, and cross-section alignment may, however, result in differences greater than 0.5 feet when comparing the elevation of the cross-section to the intersecting WSEL raster values. Figure 13, for example, shows a zoomed-in view of a WSEL raster at a road crossing, where the 1-percent-annual-chance flood elevations upstream and downstream of the road are 961.6 and 959.0, respectively – a 2.6 feet change over approximately 65 feet of stream distance (water surface slope of 4-percent). The WSEL raster was created with a cell resolution of 10 feet. All raster cells intersecting the cross-sections, with the exception of the two highlighted cells, have their WSELs within 0.5 feet of the modeled cross-section value. These two raster cells, however, would be an example of an acceptable exception to the 0.5 feet tolerance, given that they are accurate within the limitations of the slope of the water surface and the WSEL raster cell resolution.

The following equation can be used to check for locations between consecutive cross-sections where similar, allowable exceptions to the 0.5 tolerance rule may exist, such as is shown in the example in Figure 13:

- Elevation change / stream distance * cell size ("Slope-Cell Resolution Value" (SCRV))

As a general rule of thumb, an SCRV of 0.3 provides a good initial threshold for testing. The majority of cross-section-intersecting WSEL raster cells should be within the 0.5 feet tolerance if the SCRV is less than 0.3. For areas where the SCRV is greater than 0.3, however, there is the potential (depending on how far the cell centroid is from the cross-section) that more than a 0.5 feet discrepancy could exist and still be acceptable, as highlighted by the two cells in Figure 13. The SCRV between these two cross-sections is 0.4, but the two highlighted cells are the only ones that have greater than a 0.5 feet tolerance, due to where the cross-section intersects in relation to their cell centroid.

Figure 13: Example of Allowable WSEL Raster vs. Cross-Section Elevation Differences

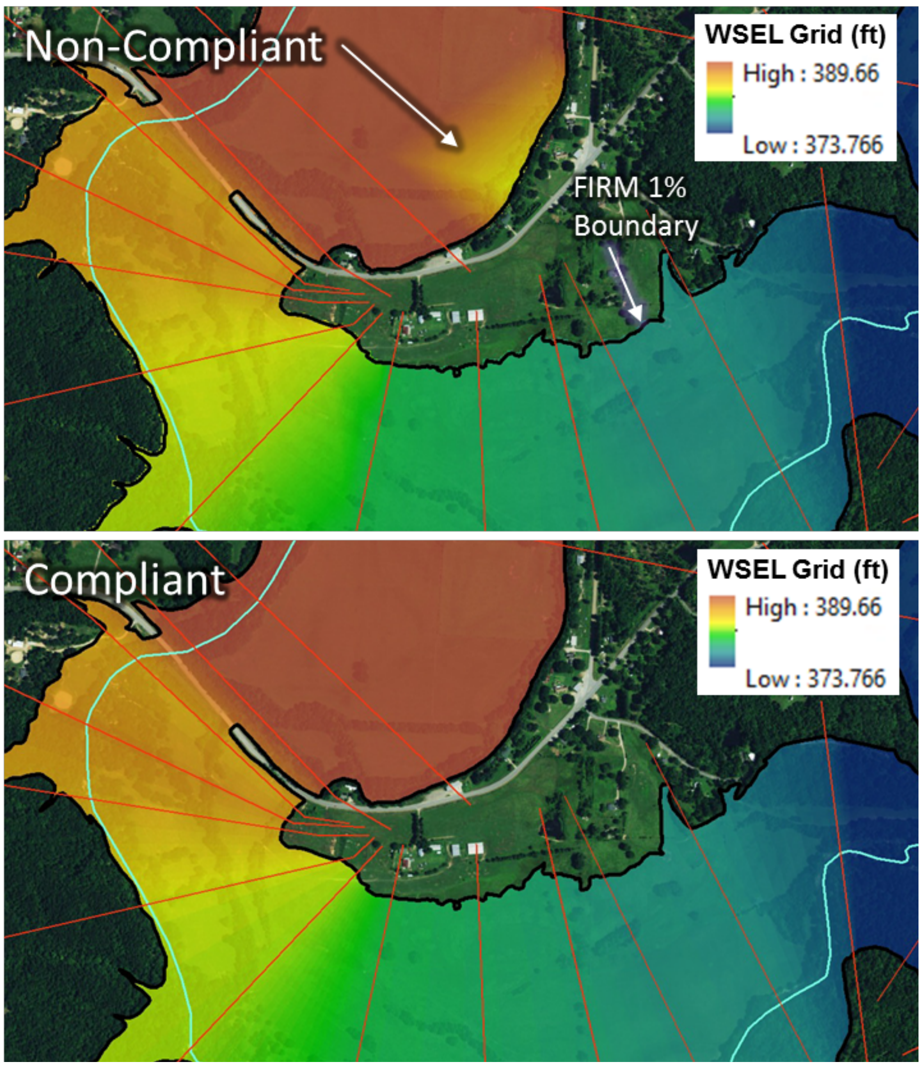


As a best practice, if there are multiple areas along a studied stream or within the project area that are failing the 0.5 feet tolerance check, but are acceptable given the slope of the stream, then decreasing the WSEL raster cell resolution for the entire study area should be considered.

2.6.3.2 Elevation check in between modeled cross-sections

The WSEL change from cell to cell should be gradual and consistent in between consecutive modeled cross-sections along a reach of stream. Abrupt changes should not be present. WSEL raster cell elevations should be less than or equal to the elevation of the upstream cross-section and greater than or equal to the elevation of the downstream cross-section. Figure 14 highlights an example of a WSEL raster where the elevations at the cross-sections are correct and the extents match the corresponding floodplain area, but errors are present in between cross-sections.

Figure 14: Importance of WSEL Raster Elevation Checks in Between Cross-Sections



One additional way to test for WSEL raster errors and anomalies in between cross-sections is by checking the slopes in GIS (i.e. a “slope raster”). Figure 15 shows what the slope raster looks like for the top and bottom examples shown in Figure 14, respectively. Changes in slope can be expected at modeled cross-sections (inflection points), but otherwise should be gradual and consistent in between the cross-sections. A slope raster can reveal inconsistencies in the WSEL raster that otherwise might have gone unnoticed.

Figure 15: Slope Raster Reveals WSEL Raster Anomalies in Between Cross-Sections

2.6.3.3 Static elevations

In areas where static BFEs or other elevations are shown, such as in ponding or coastal areas, the WSEL raster should match that elevation. Sections 2.2 and 2.3 of this document provide further guidance to understand the types of checks that should be performed on these flooding sources.

2.6.4 Confluences and Backwater

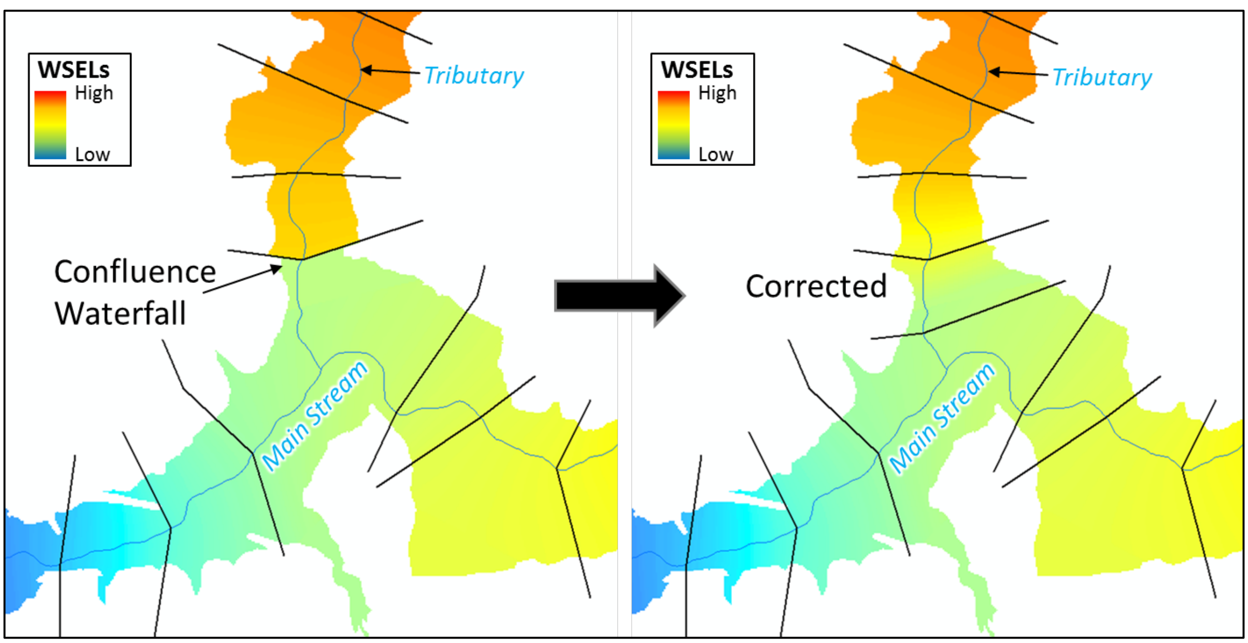
For 1-D models, confluences require special care and checking to make sure the WSEL raster is produced appropriately and compliant with standards. In a 2-D model that comprises multiple flooding sources, WSEL rasters are already generated correctly to reflect backwater effects at confluences, due to the networked nature and hydrodynamics of that type of model. However, many Flood Risk Projects that use 1-D analysis methods do so by modeling individual streams one at a time, and therefore, backwater effects from larger streams are often accounted for as a mapping exercise after the models are run. Although various methodologies exist for accomplishing this, proper backwater must be reflected within the WSEL rasters so as to comply with standard ID #415.

The following scenarios and graphics depict various problems at confluences that must be corrected prior to finalizing the WSEL rasters.

2.6.4.1 Gaps and Waterfalls

Gaps and waterfalls at confluences exist when the first cross-section of a modeled tributary is at a WSEL that is higher than the backwater WSEL of its receiving stream. This is primarily a modeling issue. The slope raster can also help identify these occurrences, as the change in floodplain width at the first tributary cross-section may not be as pronounced as the example below shows. To correct this, modeling changes should be considered for the tributary and/or the main stream, and then remapped as appropriate.

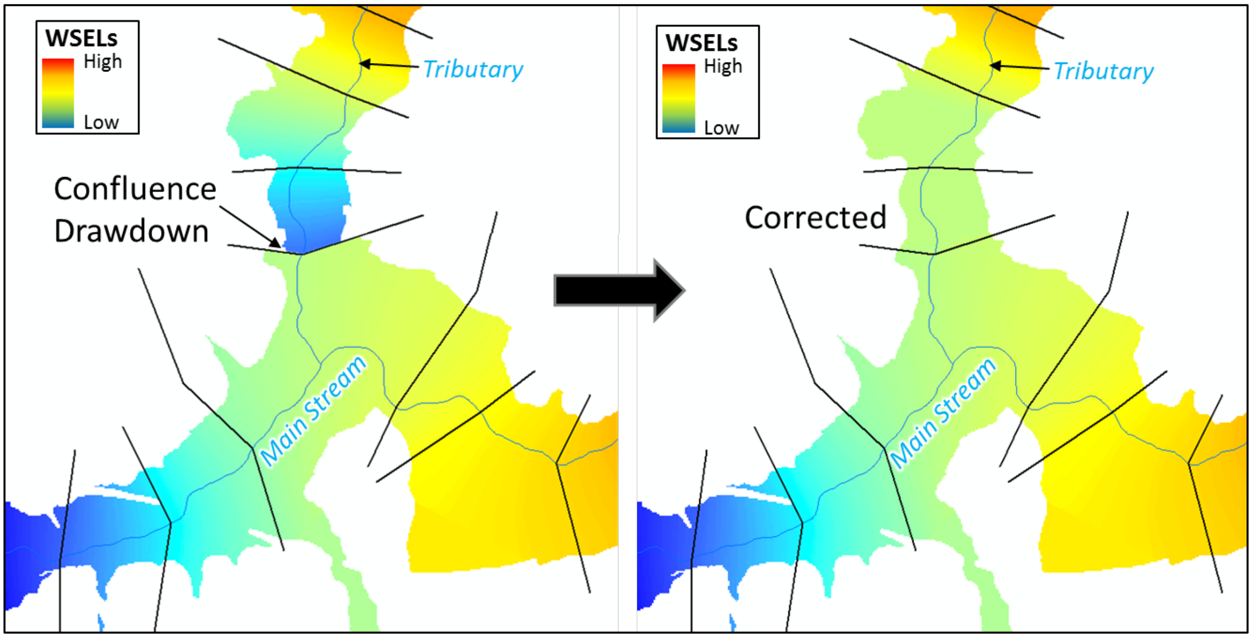
Figure 16: Confluence Mapping Error – Gaps & Waterfalls



2.6.4.2 Drawdowns

Drawdowns at confluences occur when the higher backwater elevation of the main stream is partially carried up the tributary but does not extend to the point where the tributary comes out of backwater. Thus, the WSEL raster in this situation appears as if there is drawdown, where the elevation drops, or draws down, when moving in an upstream direction along the tributary. To correct this, the WSEL raster needs to reflect the backwater elevation from the main stream up the tributary until the tributary's modeled elevation is higher than the backwater. It is important to note that it would not be accurate to simply adjust the elevation of the relevant WSEL raster cells to reflect the backwater elevation – rather, the WSEL raster would need to be recreated using the appropriate elevation to make sure that not only are the elevation values correct (vertical accuracy), but the extents are also correct (horizontal accuracy).

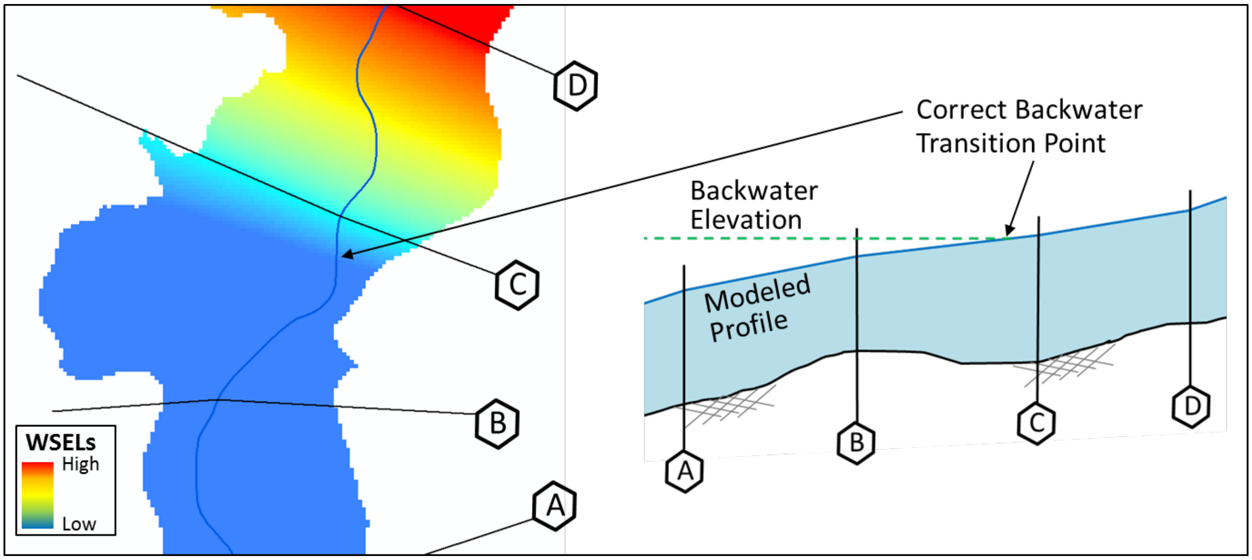
Figure 17: Confluence Mapping Error – Drawdowns



2.6.4.3 Location where Backwater Elevation should Terminate

Visualizing a flood profile helps to understand where the backwater elevation from a main stream should terminate along a tributary. The WSEL raster should be an accurate representation of where the tributary comes out of backwater. A hypothetical profile generated for the tributary using the WSEL raster as a source should be able to replicate the inflection point where the elevation transitions from backwater from the main stream to the modeled elevation from the tributary. This will most often occur in between modeled cross-sections. Simply assigning the backwater elevation to all of the tributary's modeled cross-sections in backwater and then generating the WSEL raster will not accurately reflect this transition point.

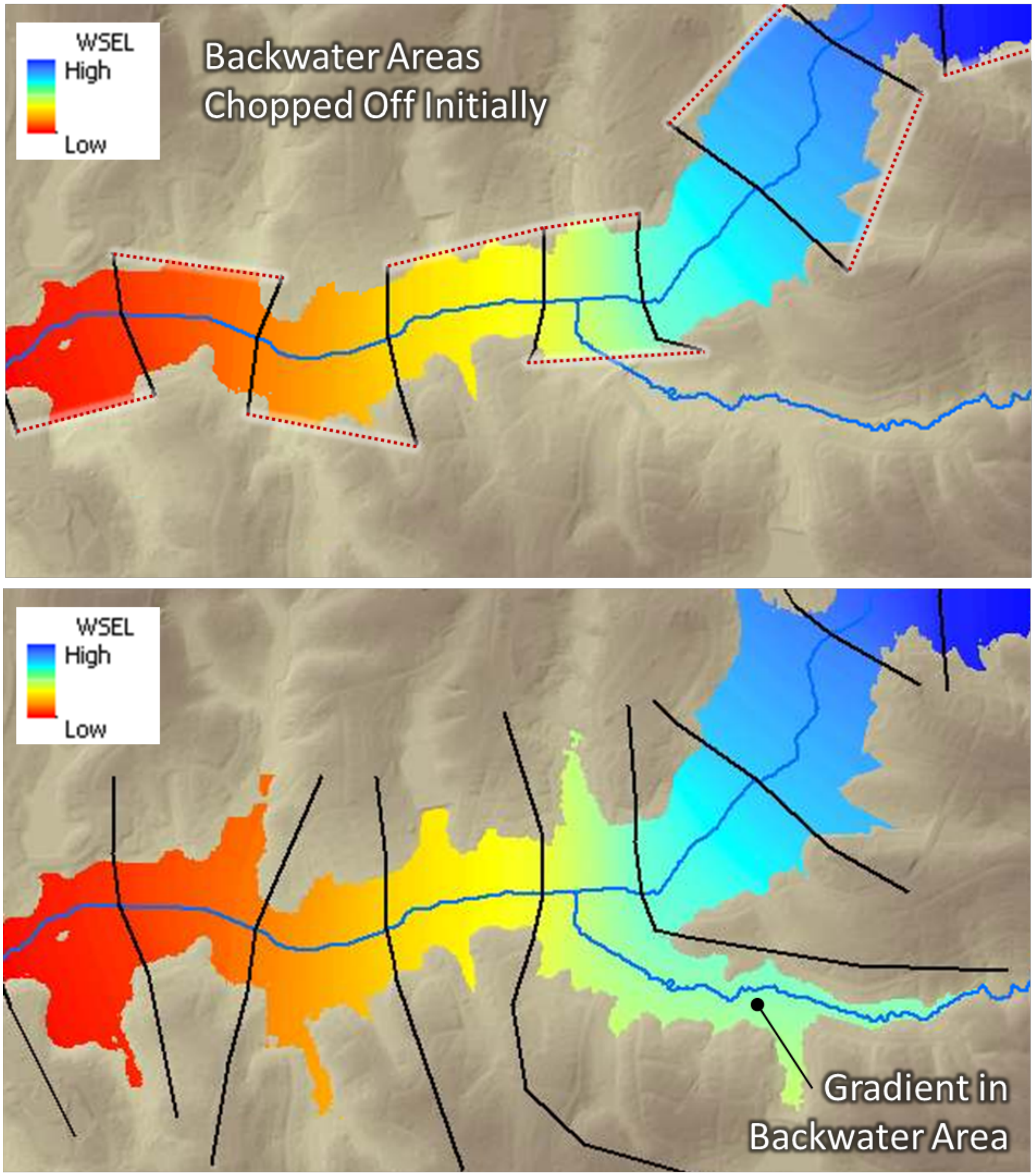
Figure 18: Backwater Elevation Transition Point at Confluences



2.6.4.4 Static Backwater vs. Gradient

Care must be taken to avoid introducing inaccuracies into the WSEL raster on account of the methodology used to map backwater areas. Because many out-of-the-box GIS raster mapping approaches will only map a raster within the bounding area created by the cross-sections (see Figure 19), some backwater fingers would incorrectly be excluded from the WSEL raster without additional effort. It is not recommended to simply extend the cross-sections far enough so that these backwater areas will be mapped. Depending on the size of the backwater finger and the slope of the stream, doing so can result in a gradient from one side of the stream to the other, whereas in reality, a static flooding scenario should be depicted. Although there may be scenarios where this gradient is negligible (less than a 0.1 feet difference), it is recommended to apply a static backwater elevation so as to avoid any gradients introduced in backwater areas, where one side of the floodplain would incorrectly be at a higher elevation than the other side when retrieving one's elevation from the WSEL raster.

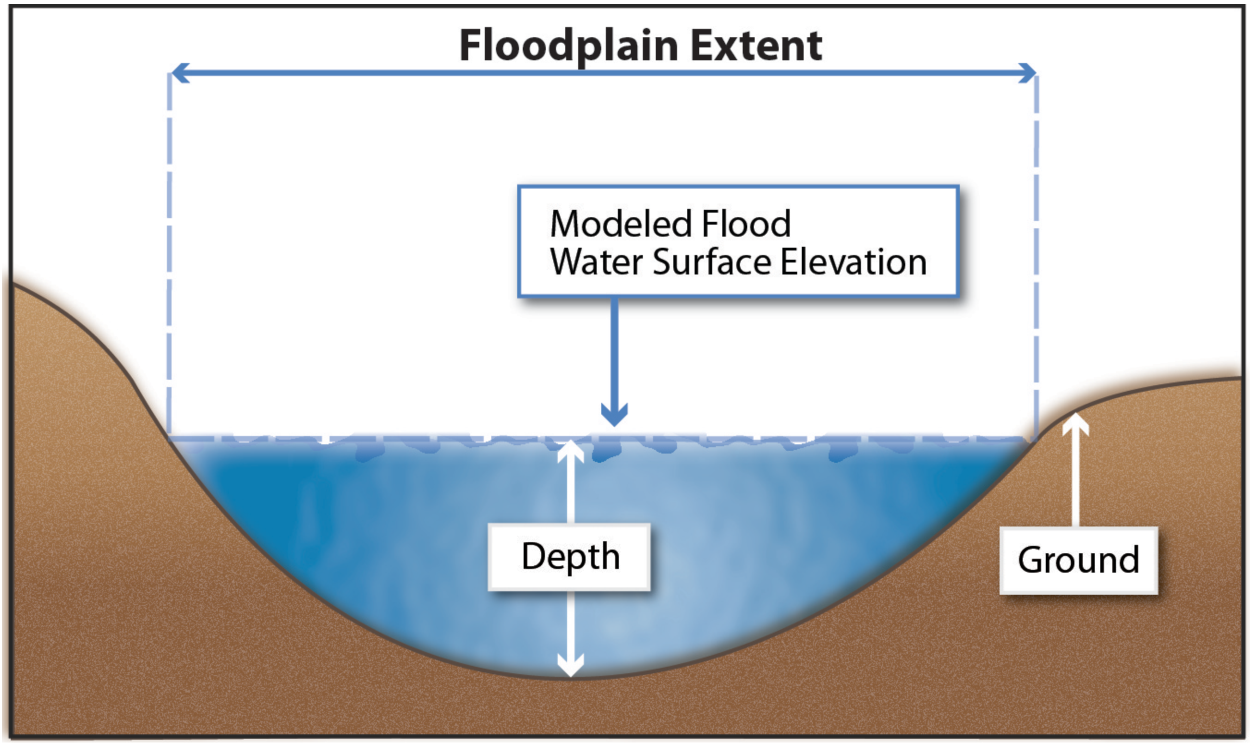
Figure 19: Overextended Cross-Sections can Create False Backwater Gradients



3.0 Flood Depth Rasters

In its simplest form, a flood depth raster is nothing more than the WSEL raster minus the raster representing the ground elevation. Regardless of the variety of methods that may be used to produce the WSEL raster, the process for creation of the depth rasters is the same, with only minor exceptions (see Figure 20).

Figure 20: Depth Raster in Cross Section View



The depth values for each depth raster cell are computed by subtracting the ground elevation value from the water surface elevation value for each return period or flood scenario computed. Ideally, the topographic data used for the development of any depth raster should be the same source as used to generate the effective floodplain boundaries to ensure consistent and accurate results. New or revised studies should use the same source ground data used to generate the new floodplain boundaries.

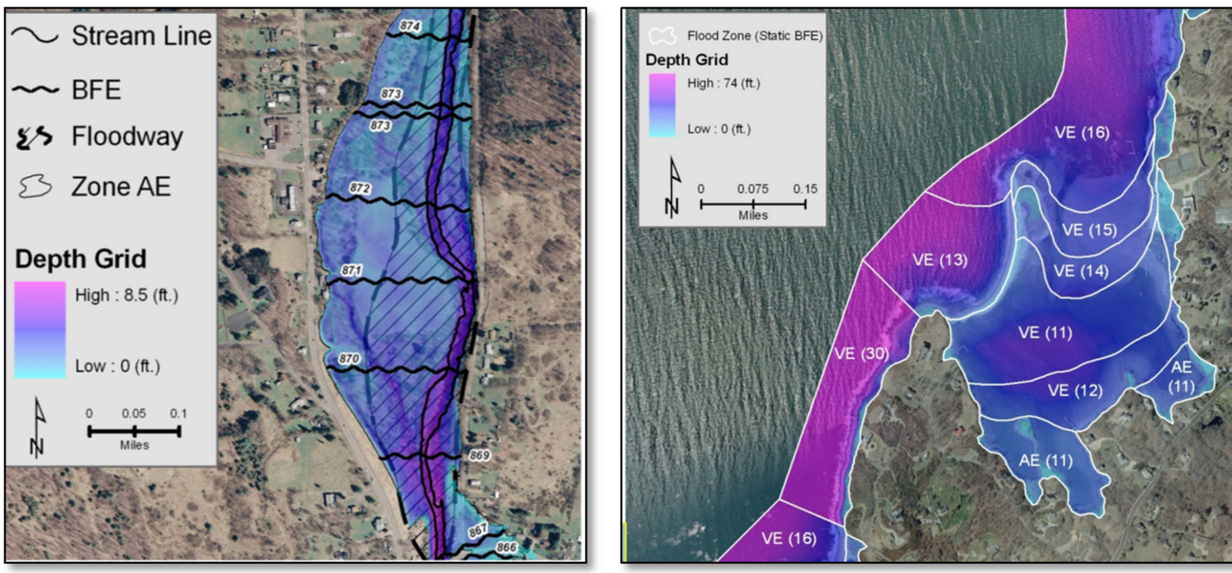
While Mapping Partners may utilize differing engineering models and/or geospatial software or platforms, creation of a depth raster involves the following generic steps that may be performed universally across all GIS platforms:

1. Development of the WSEL raster, per the guidance outlined in Section 2.
2. Development of a ground source raster using the same topographic information that was used in the engineering analysis to produce the flood elevations.
3. Computation of the depth raster by subtracting the ground elevation raster from the WSEL raster for the return period or scenario selected.
4. Removal of any negative values from the resulting depth raster (by either removing the cells or setting them to depths of zero, depending on project preference and/or mapped regulatory floodplain depiction)
5. Rounding of all values to the nearest tenth of a foot

3.1 Depth Raster Considerations for Coastal Areas

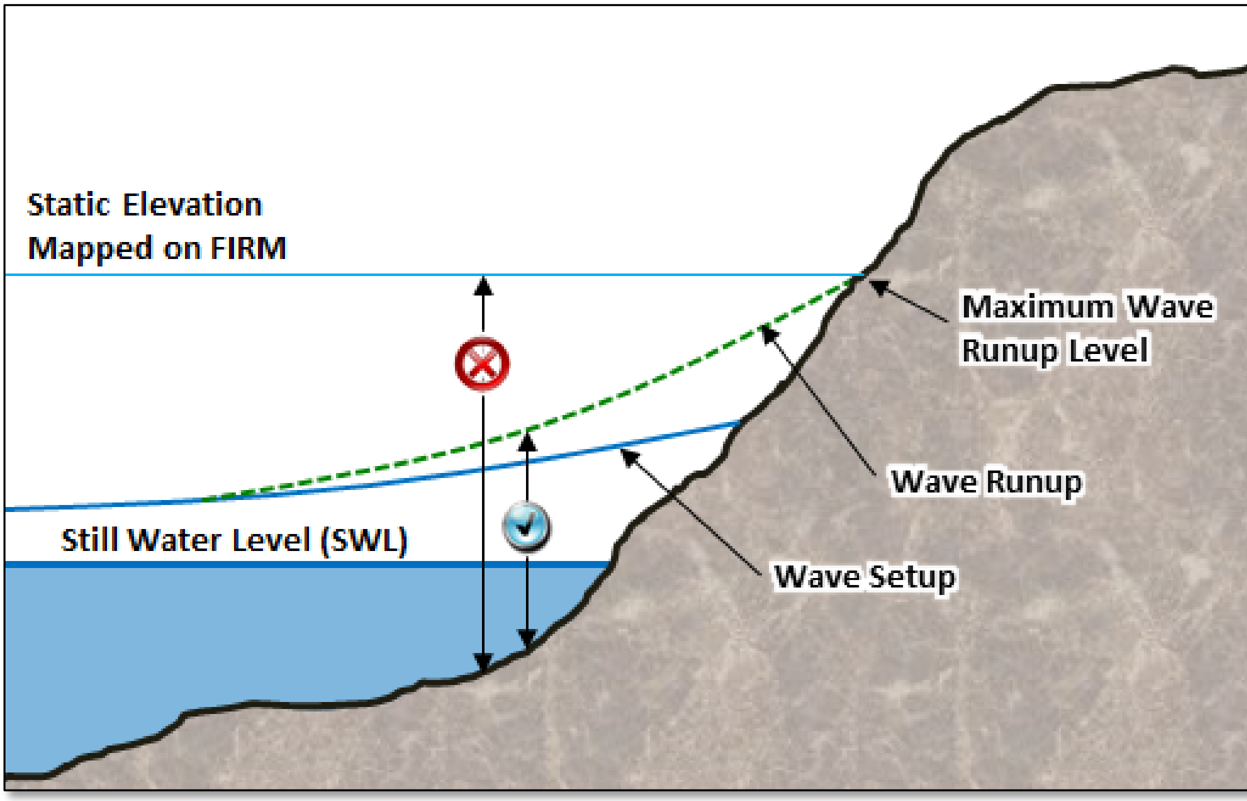
For coastal depth rasters, special awareness is needed in areas dominated by wave runup and/or sheet flow (e.g. bluffs, cliffs, or areas protected by coastal structures). Because wave runup-dominated areas are mapped on the FIRMs as static elevations using the maximum wave runup level (as represented by the VE (30) area in Figure 21 and shown in Figure 22), depth rasters created by subtracting the ground elevation from the WSEL raster would produce artificially-high depths (red “x” in Figure 22), rather than the more natural depths one would expect (checkmark in Figure 22). The coastal modeling results can help identify where wave runup-dominated areas exist. Prior to the creation of coastal depth rasters in areas dominated by wave runup and the publication of that data in the FRD, Mapping Partners should discuss the methodology to ensure that the correct depths are produced in these areas with FEMA, and should receive approval of the methodology. The agreed-upon approach should be explained and included in the project documentation. Otherwise, these areas should be excluded from the final coastal depth raster.

Figure 21: Examples of Riverine and Coastal Depth Rasters



For depth rasters whose extents cover open water at the coast, it is acceptable to use bathymetric data (if available) to produce the associated depth raster(s). However, in the areas over open water, it is preferred to have the coastal depth rasters reflect the depth relative to Mean Sea Level.

Figure 22: Coastal Flood Depth Calculation Methods in Wave Runup-Dominated Areas



Because it is required that Primary Frontal Dunes (PFDs) be included within the mapped coastal high hazard areas on the FIRM, the coastal WSEL raster creation process outlined in Section 2.2 will result in these PFDs being included within the inundated areas of the WSEL raster. Since the creation of the depth rasters should leverage existing data and information from the studies, it is expected that the ground surface used in the creation of the depth rasters along the coast should reflect existing conditions, rather than the eroded dune calculated as part of the analysis process. Thus, because the ground Digital Elevation Model (DEM) used in the creation of the depth rasters does not reflect this erosion, there will likely be locations where the dune elevation reflected in the ground DEM is higher than the elevation reported in the WSEL raster. Similar to riverine areas, rather than reporting negative flood depths, the flood depth raster should reflect depths of zero in these locations.

3.2 Depth Raster Considerations for Inland Open Water Areas

The creation of a seamless depth raster across flooding sources will frequently result in depth raster cells comprised entirely of open water (such as for a lake or pond). For inland open water areas, the ground surface within those cells should not be computed from bathymetric data due to the fact that flood depths are primarily intended to represent an increase in water surface elevation from a non-flooding condition.

To create depth rasters in areas of inland open water, a false terrain surface should be created based on the normal pool water surface elevation as opposed to using bathymetric data (see Figure 23 and Figure 24). This process involves two basic steps as follows:

1. Obtain the normal pool elevation for the open water body. If the normal pool elevation is unavailable, the shoreline elevation may be used to determine a "pseudo" normal pool elevation.

2. Calculate the depth values for each depth raster cell by subtracting the normal pool (or "pseudo" normal pool) value from the calculated water surface elevation values. Figure 23 provides a profile view example showing depths that are based on correct (checkmark) and incorrect (red "x") methods for these types of open water bodies.

Figure 23: Profile View of Correctly (Checkmark) and Incorrectly ("X") Calculated Depths in Water Bodies

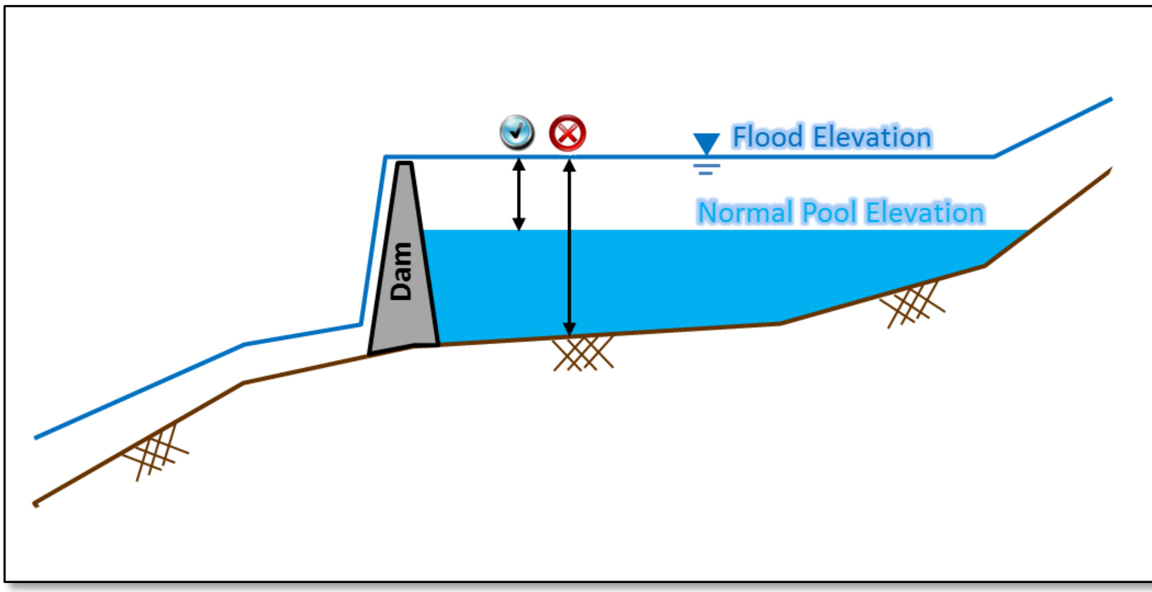
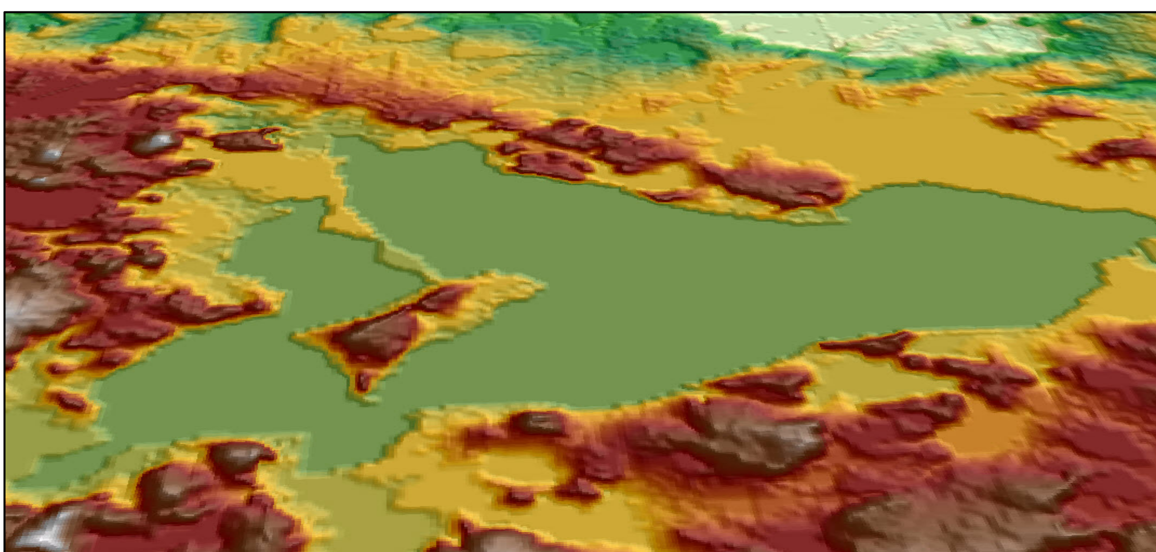


Figure 24: Where Possible, Normal Pool Elevation should be Used to Calculate Flood Depths in Water Bodies



3.3 Depth Raster Considerations for Zone AO Areas

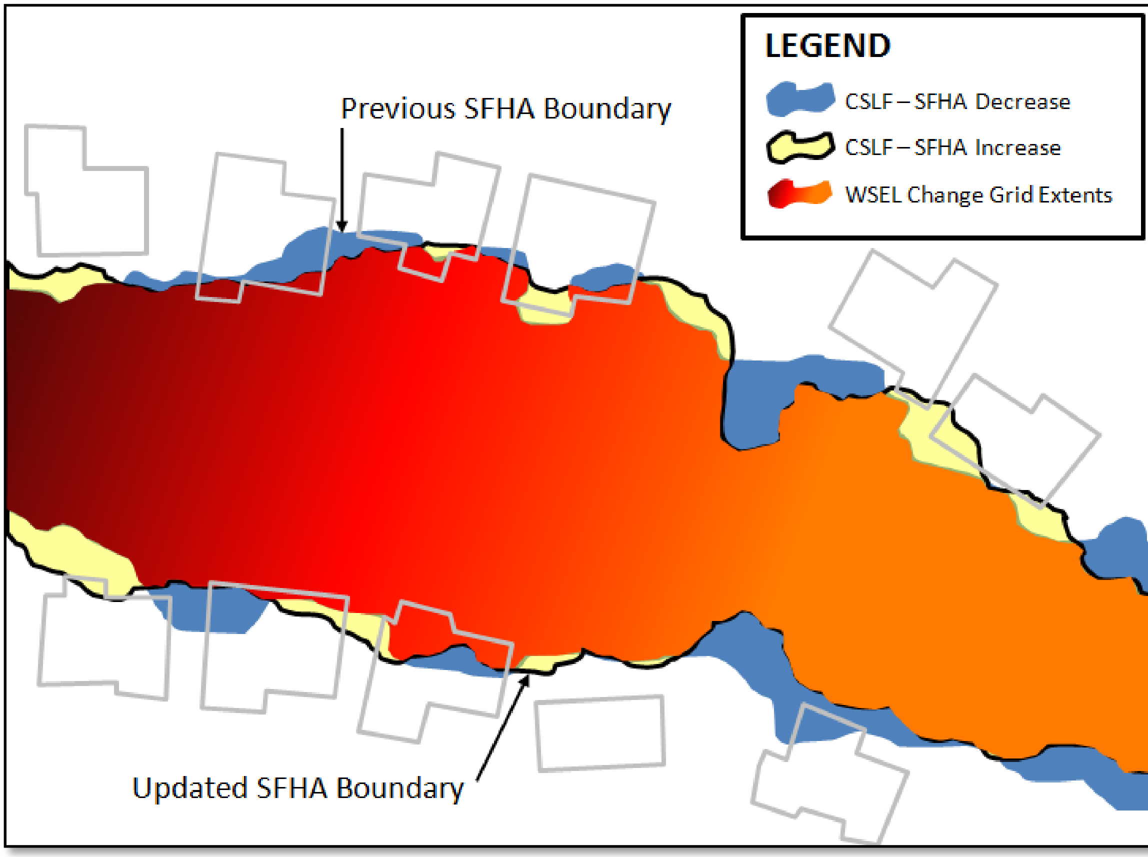
For areas where the new or effective model from which the Zone AO depths were derived is available and the associated WSEL raster has been created, the process for creating the depth raster is the same as described in Section 3. Each depth raster cell can be rounded to the nearest whole-foot value or to the tenth of a foot, provided that the values, when rounded, would equal the whole foot depth reported on the FIRM.

When depth rasters are created for areas where the new or effective model is not available, the 1-percent-annual-chance depth raster should be created to match what is shown on the effective FIRMs. The process in these cases is to simply convert the Zone AO polygons to a raster, with the raster values based on the Zone AO depths.

4.0 Water Surface Elevation (WSEL) Change Rasters

WSEL Change Rasters are the vertical equivalent of the horizontal Changes Since Last FIRM (CSLF) dataset, whereby areas of increase and decrease to the 1-percent-annual-chance water surface elevations from the previous to the new FIRM can be visualized and communicated. It is important to understand that the extent of the WSEL change raster should generally reflect only those areas that were both Special Flood Hazard Area (SFHA) before the revision and after the revision, as illustrated in Figure 25. Areas that reflect an SFHA increase and those that reflect an SFHA decrease do not need to be included in this dataset. This raster can be used in conjunction with the CSLF dataset to provide a more integrated picture of both the horizontal and vertical changes that have occurred to the floodplains within the project area since the previous study was completed.

Figure 25: Water Surface Elevation Change Raster Extents



The creation of a WSEL Change Raster is the result of subtracting the WSEL raster associated with the effective hydraulic study from the WSEL raster created from the revised study. The following are basic steps for creation of this dataset:

1. Using the WSEL raster derived from the existing hydraulic modeling and the WSEL raster derived from the revised hydraulic modeling, perform a subtraction of the two surfaces using the following formula:

   WSEL Change = *Revised WSEL - Effective WSEL*

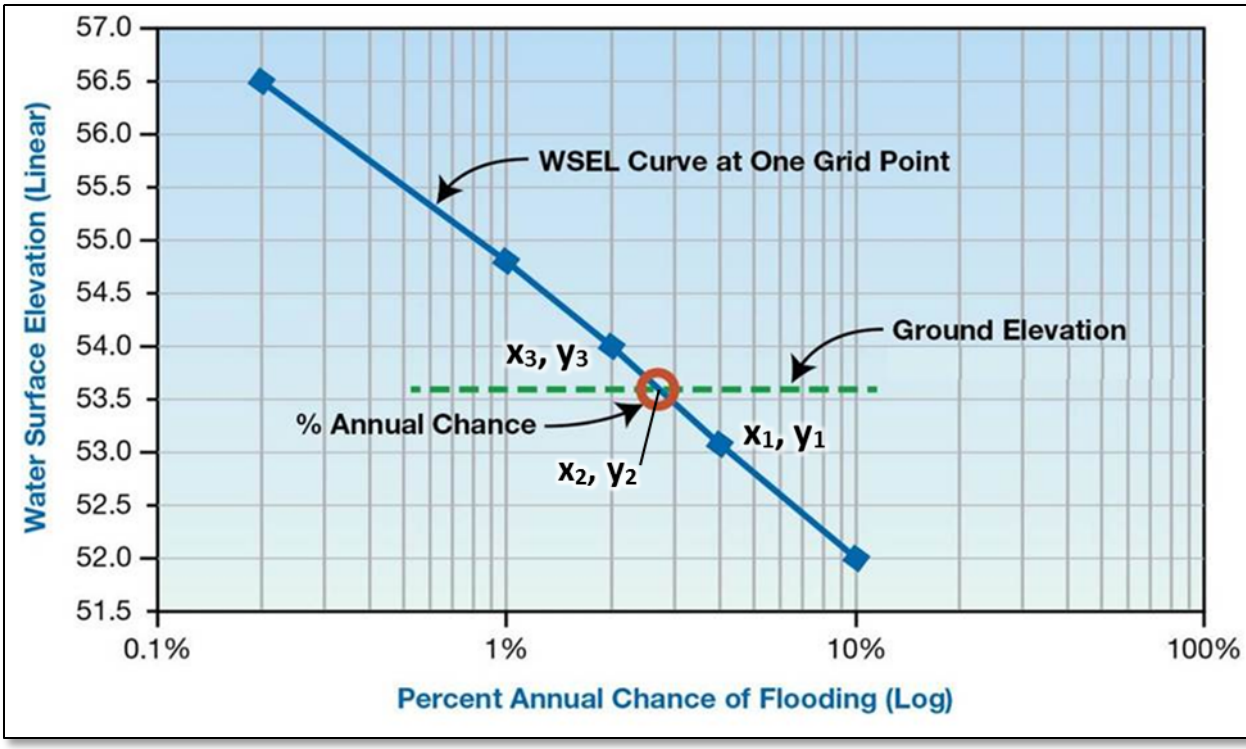
2. To limit the extents of the WSEL change raster to only those areas that were in the SFHA before and remain in the SFHA, other geospatial operations can be applied, such as using a separate polygon data layer as a mask to limit the area of output.

5.0 Percent-annual-chance of Flooding Raster

As an enhancement to the “in or out” format of the FIRM, the Percent-annual-chance raster provides local stakeholders with a better understanding of the relative probability of being flooded for any given location within the mapped floodplain. The raster is computed by using multiple water surface elevation results and their associated percent-annual-chance of exceedance (e.g. 0.2-percent, 1-percent, 2-percent, 4-percent, and 10-percent) and interpolating the percent-annual-chance of flooding at each raster cell based on those inputs coupled with the ground elevation at each specified point.

The percent-annual-chance flood event associated with inundating the ground elevation at each given location should be computed by interpolating the log-linear relationship between the associated flood elevations at each point and the ground elevation (linear interpolation of the Water Surface Elevations, log interpolation of the percent-annual-chance), as shown in Figure 26.

Figure 26: Log-Linear Relationship for Determining Percent-annual-chance Flood Event



This calculation is performed for each raster cell within the floodplain, using the equation shown in Figure 27.

As part of this analysis, there will be locations where these calculations are performed within the 10-percent-annual-chance floodplain. These values would mathematically yield a percent-annual-chance in excess of 10-percent. However, rather than extrapolate values beyond the 10-percent-annual-chance, estimates should be capped at 10-percent and considered as locations with at least a 10-percent-annual-chance of flooding. If more frequent flood events (such as the 20-percent or 50-percent-annual-chance floods) were analyzed as part of the Flood Risk Project and their results are available, the Percent-annual-chance raster can reflect values up to those higher percentages, but similarly, results should not be extrapolated out beyond those points.

Figure 27: Percent-annual-chance Equation

$$x_2 = 10^{[\frac{(y_2 - y_1)(\log(x_3) - \log(x_1))}{(y_3 - y_1)} + \log(x_1)]}$$

where

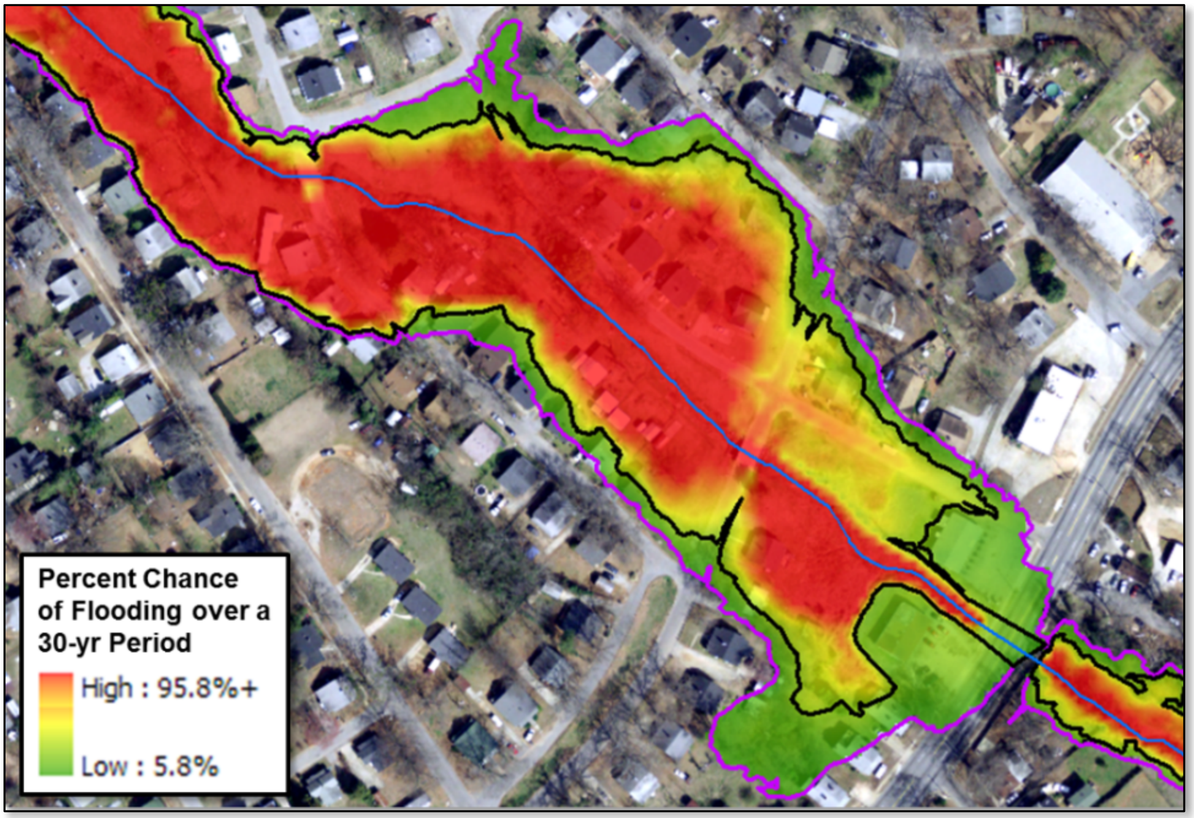
- x_1 = Percent annual chance corresponding to y_1 flood elevation
- x_2 = Percent annual chance at test point (red circle in Figure 13)

- x_3 = Percent annual chance corresponding to y_3 flood elevation
- y_1 = next closest modeled WSEL just lower than the Ground elevation
- y_2 = Ground elevation at test point (red circle in Figure 13)
- y_3 = next closest modeled WSEL just higher the Ground elevation

6.0 Percent Chance of Flooding over a 30-yr Period Raster

The Percent Chance of Flooding over a 30-year Period raster represents the percent chance of flooding at least one time during a 30-year period for a given cell, or location, within the mapped floodplain (see Figure 28). Although a 30-year interval was chosen for this dataset, other time periods may also be selected, and the likelihood can be computed for other floodplain management and risk assessment/communication applications.

Figure 28: Example of a Percent-annual-chance of Flooding Over a 30-yr Period Raster



The process for developing the Percent 30-Year Chance Raster is not complex, assuming that the Percent-Annual-Chance Raster has been developed. Once the Mapping Partner has the Percent-annual-chance Raster developed, the process for developing the Percent 30-year Chance Raster uses the following statistical equation:

$Probability = 1 - (1-p)^{n}$ where…

- p = percent-annual-chance of flooding (values derived from the Percent-annual-chance raster layer)
- n = time period in years (30 years for this dataset)

7.0 Velocity Rasters

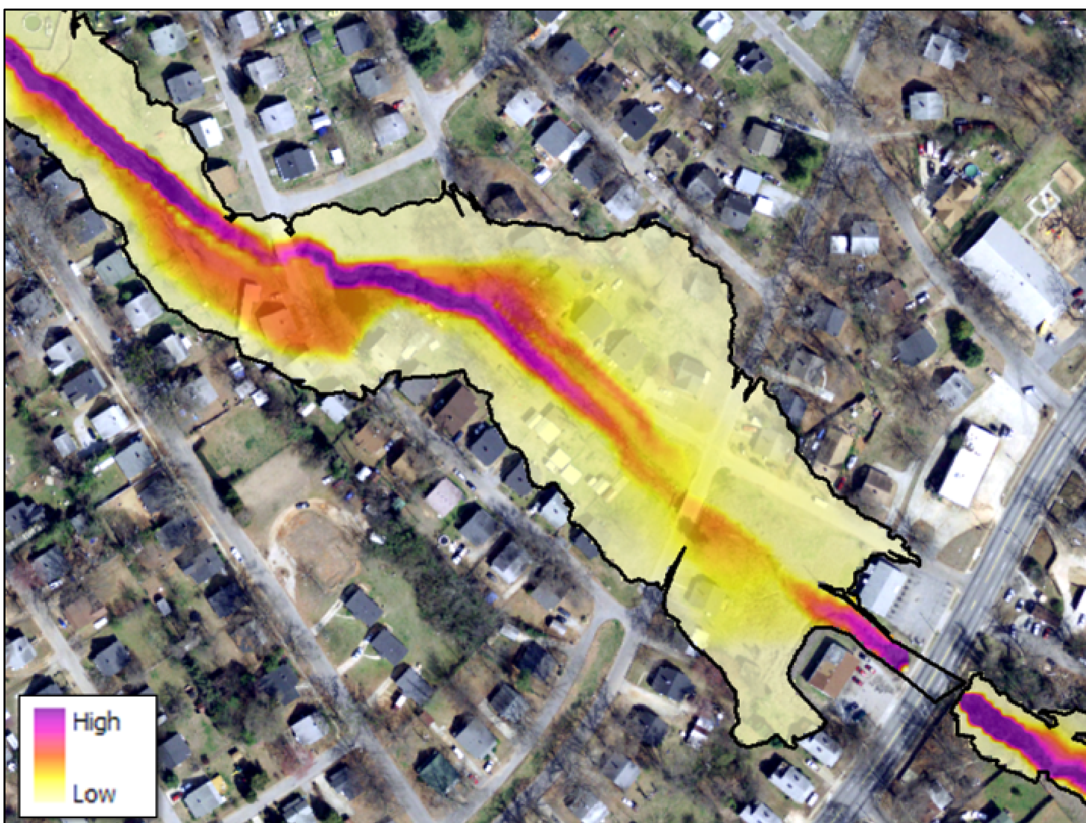
Velocity data provides additional information about the flood hazard and can offer a wide range of other floodplain management and risk communication benefits that may be difficult to convey with flood depths alone. The Velocity Raster dataset is comprised of a digital representation of flood velocity distribution throughout the floodplain. Any point on the raster describes the average flood velocity for that floodplain location for a given flood frequency. The extents of each velocity raster (10-percent, 1-percent, etc.) produced should align with the extents of its corresponding WSEL and depth raster. In addition to the guidance below, additional velocity raster guidance can be found in the FEMA publication entitled Recommended Procedures for Flood Velocity Data Development, published in November 2012.

7.1 Riverine Velocity Rasters

The following general guidance is provided for the creation of Velocity Rasters for studies where digital models are available.

- Floodplain conveyance for 1-D hydraulic models should be subdivided and included in the model output of each cross section. For a model such as the Hydrologic Engineering Center's River Analysis System (HEC-RAS), this can be done by using the flow distribution option. The scale or number of velocity points or subdivisions to be specified per cross section should be representative of the variation of velocity across the channel and overbank areas.
- It may be necessary to augment user-defined cross sections with interpolated cross sections in order to obtain sufficient flood depth velocity data at areas of interest such as known flooding "hot spots," existing flood prone structures, critical facilities, populated areas, etc.
- For older or un-modernized studies where the flow distribution option may not be readily available, the flood velocity at specific locations along a cross section can be approximated using average flow velocities provided in the Floodway Data Tables of Flood Insurance Study (FIS) Reports in conjunction with generalized patterns of velocity distribution for different channel shapes (see Figure 29).

Figure 29: Riverine Velocity Raster



While Mapping Partners may utilize differing hydraulic models and geospatial software, velocity rasters can often be developed directly as an output of the modeling software itself. For example, velocity rasters are an output that can typically be automatically generated from 2-D hydraulic modeling software. Velocity data generated from 2-D models is often more accurate than from a 1-D model, especially for 1-D models whose cross-sections may be widely spaced. Because 2-D-based velocity data is more accurate than 1-D, Mapping Partners are encouraged to look for creative ways to leverage this type of data as a way to provide communities with at least a high-level awareness of the velocities within their mapped floodplains. For example, Base Level Engineering (BLE) data that is generated from 2-D models can use its velocity raster outputs as a way to provide relative velocity information (e.g. Low, Medium, High, etc.) within mapped floodplains. Thresholds of 5 feet/second and 10 feet/second are often used by construction and design publications to distinguish between these areas of low, moderate, and high velocities.

For flooding sources modeled by 1-D methods, care should be taken when using the velocity rasters to communicate specific velocity values in between cross-sections. Velocity distributions and values generated from 1-D models are typically linearly interpolated from cross-section to cross-section, whereas there is likely more variation of flood velocities in reality. The velocity raster can, however, provide a general awareness of areas within the floodplain where flood velocities are likely to be higher than their surrounding areas.

7.2 Coastal Velocity Rasters

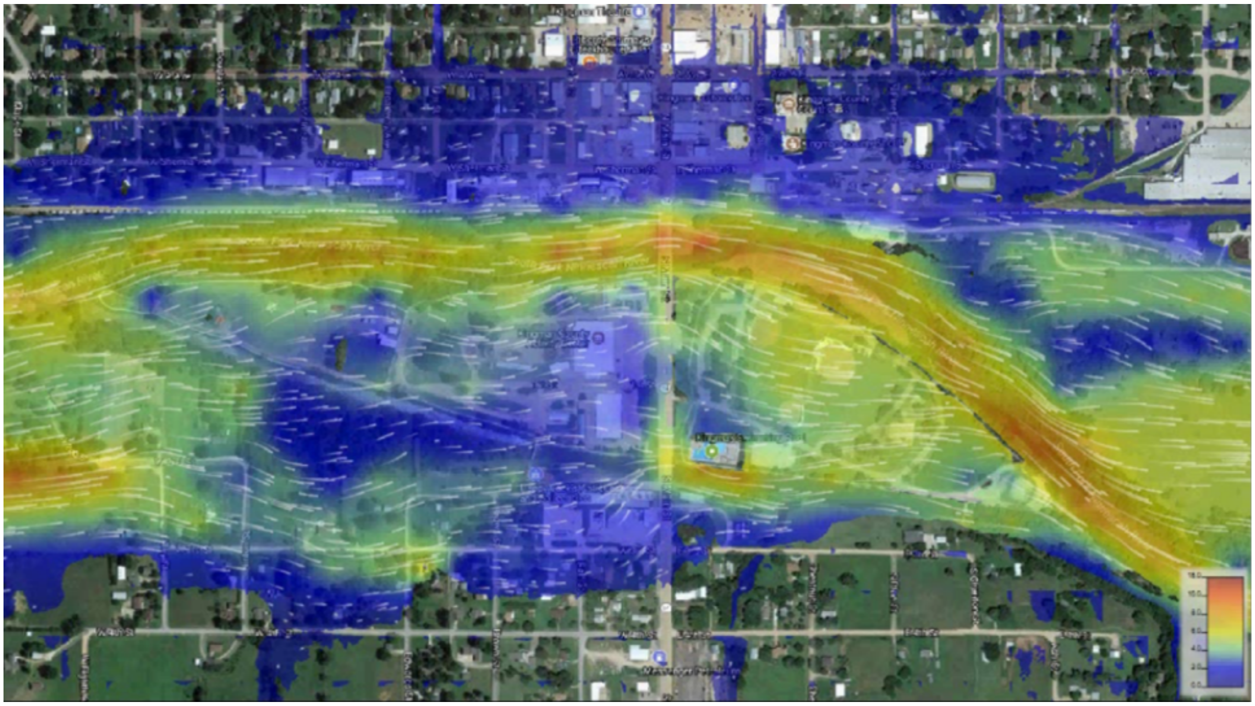
Velocity rasters produced from coastal flooding are intended to provide general information about circulation patterns and magnitudes of open water and onshore flooding. They are not used to delineate regulatory VE zones and should not be expected to align to VE zone delineations on the FIRMs.

Although methods have been developed in the past to approximate coastal velocities based on stillwater depths, these procedures are crude and provide limited value. It is, therefore, recommended that coastal velocity data be model-based if it is being provided. If 2-D storm surge modeling is being undertaken for the study area, the water velocity will be included in the output and can be used to develop the velocity raster.

7.3 Velocity Raster Display

Magnitude and direction are both important components of velocity. However, the velocity raster only stores the magnitude of the velocity, and not the direction. For flooding sources that have been modeled in 2-D, it can be beneficial to share velocity information with a community by showing flow animations, or to provide snapshots of the velocity with flow vectors overlaid, as illustrated in Figure 30. This can help to provide communities with a fuller sense and appreciation of their flood hazards that they are exposed to than just the raster alone. Once again, rather than show actual velocity values as Figure 30 demonstrates, certain applications may benefit from displaying velocity data in ranges (e.g. <5 feet/second, 5-10 feet/second, >10 feet/second, etc.) instead.

Figure 30: 2-D Model-Based Velocity Raster with Flow Vectors



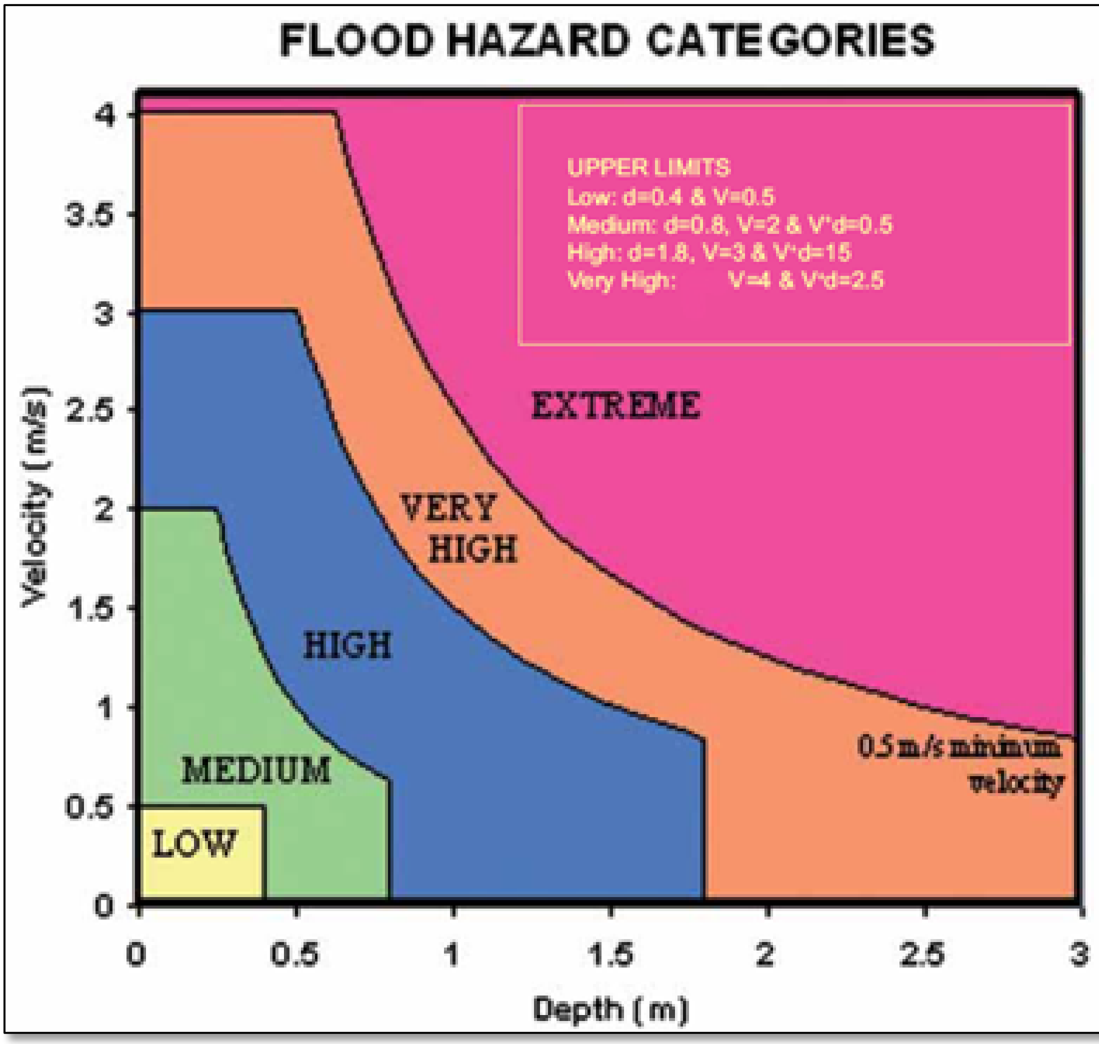
8.0 Flood Severity Raster

The flood severity raster represents the combined effect of depth and velocity, most often communicated in categories of Low, Medium, High, Very High and Extreme Hazard. Studies have been performed in multiple countries to categorize the depth x velocity result into various flood hazard or flood severity classifications. The example graph in Figure 31 is based on studies in Australia and published in the 2006 Designing Safer Subdivisions - Guidance on Subdivision Design in Flood Prone Areas (http://www.ses.nsw.gov.au/media/2249/subdivision_guidelines.pdf) manual, which was derived from earlier work from the New South Wales Floodplain Development Manual (2005).

Other flood hazard classifications exist, such as the US Bureau of Reclamation ACER Technical Memorandum No. 11, to communicate the combined effects of flood depth and velocity on structures, mobile homes, varying types of vehicles, and pedestrians. Mapping Partners may utilize an alternate classification method, although documentation and explanation of the calculations, classification breaks, etc., should be provided.

The creation of the flood severity raster is very simple. Once the depth raster and velocity raster for a particular flood event (such as the 1-percent-annual-chance event) have been produced, the severity raster is created by multiplying the depth raster times the velocity raster. The dataset can then be symbolized by the different flood severity categories as shown in Figure 32, or by some other user-defined criteria.

Figure 31: Example of Flood Severity Raster Classification



To produce a flood severity raster that exactly matches the categorization shown in Figure 31, additional rules would need to be applied when calculating the depth * velocity product, to take into account the depth and velocity upper limits of each category. Additionally, the flood severity thresholds are different depending on whether they are being considered related to the impact on humans, vehicles, or buildings. As a simplified approach, the following depth * velocity categories can be applied when symbolizing the results of the dataset (see Table 1). However, other categorizations of this data may be used where desired, and users are encouraged to customize the symbolization ranges shown in Table 1 if doing so would better communicate the hazard.

Figure 32: Flood Severity Raster Example

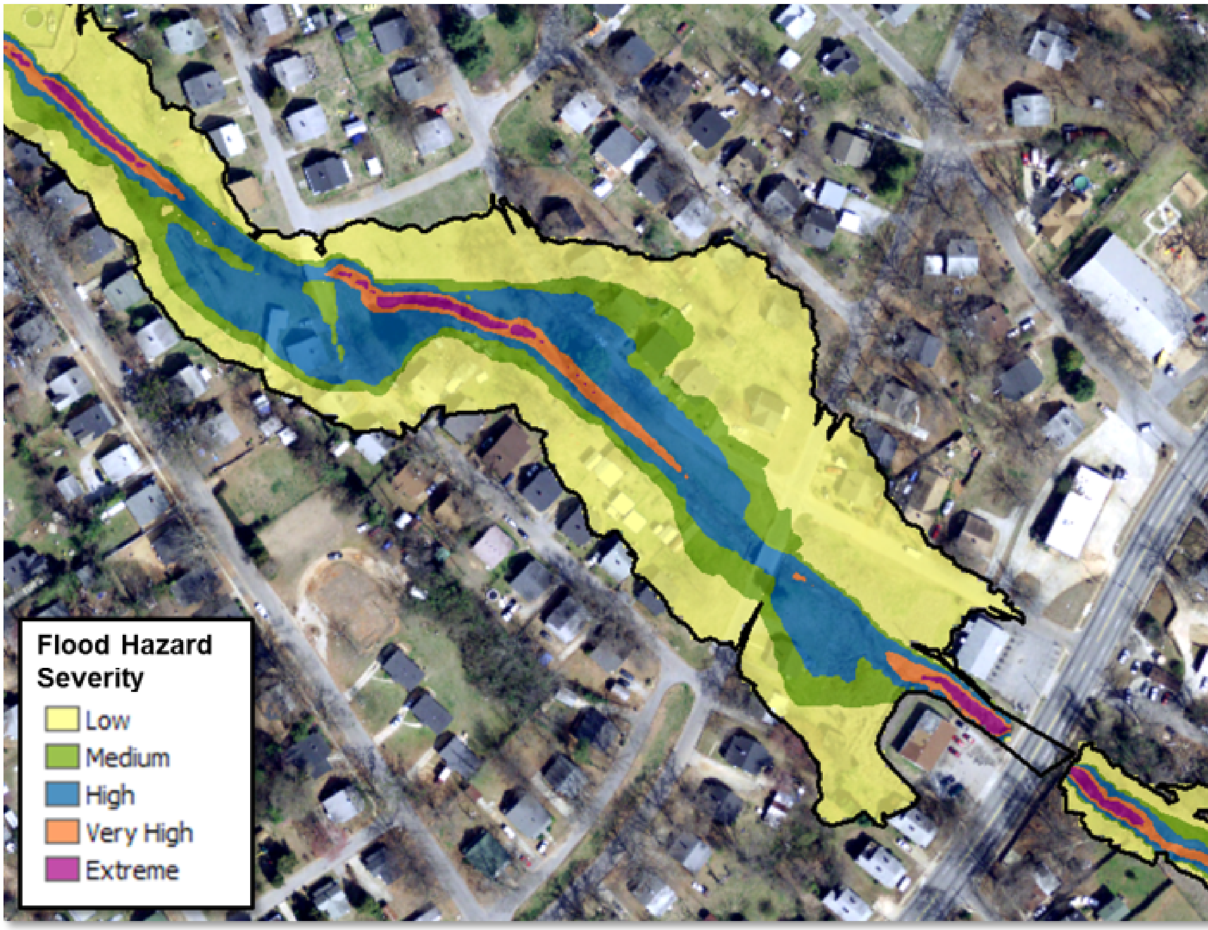


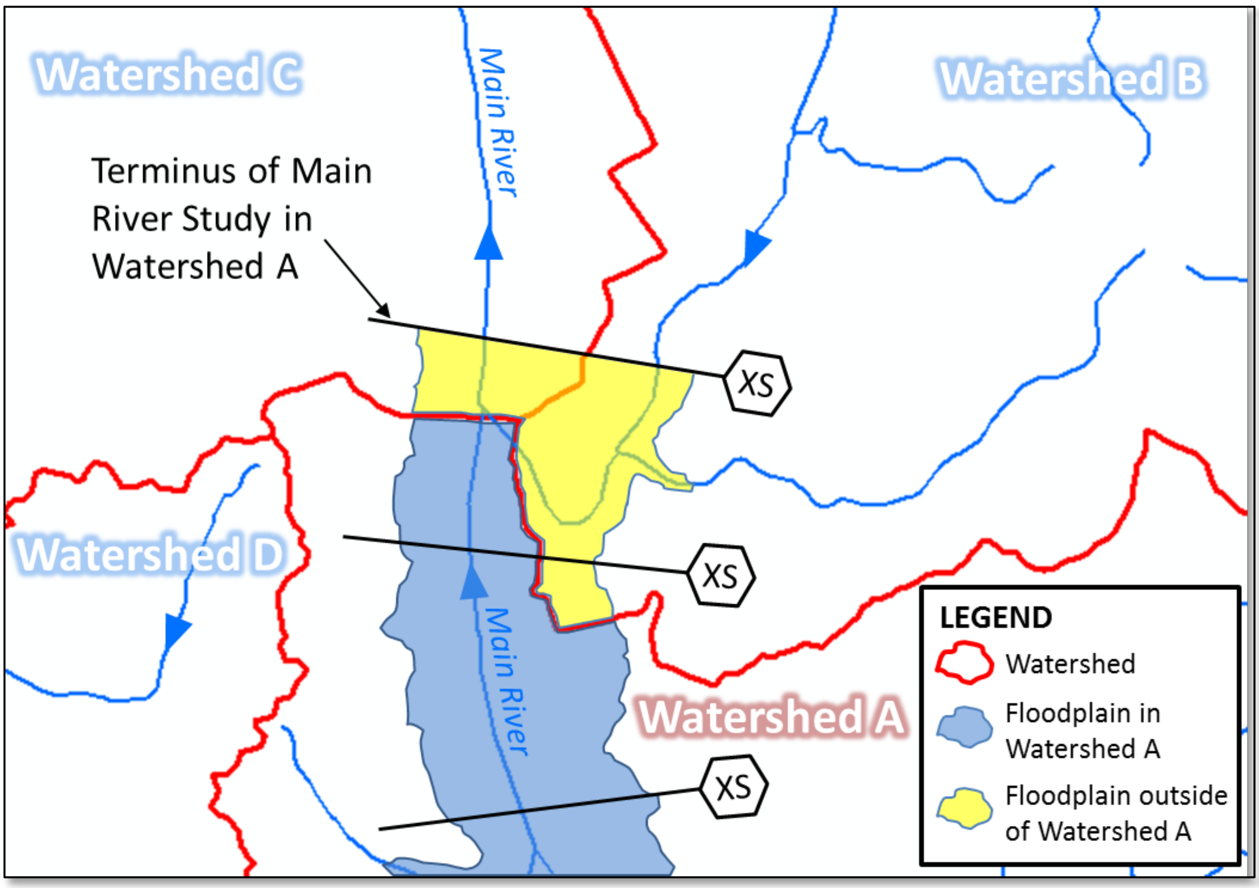
Table 1: Simplified Flood Depth and Velocity Severity Raster Symbolization Categories

Flood Severity Category	Depth * Velocity Range (ft^2/sec)	Depth * Velocity Range (m^2/sec)
Low	< 2.2	< 0.2
Medium	2.2 – 5.4	0.2 – 0.5
High	5.4 – 16.1	0.5 – 1.5
Very High	16.1 – 26.9	1.5 – 2.5
Extreme	> 26.9	> 2.5

9.0 Dataset Spatial Extents

Certain flood risk datasets will naturally extend beyond the limits of the Flood Risk Project footprint. This additional data may be needed to ensure a complete picture of flood risks within the project area. Figure 33 provides an example of a typical scenario that will regularly occur at the outlet of watersheds that are being studied. In these cases, the depth and analysis rasters should not be clipped to the project footprint but should remain in their entirety to cover the full extent of the modelled area.

Figure 33: Flood Risk Data Outside of the Project Area



Raster datasets are rectangular in shape by design. For those cells whose centroid is outside the project area, the value of each cell is set to "NODATA" (see Figure 34). For those cells whose centroid is inside the project area, the value of each cell is calculated based on the data being represented (e.g., depth, velocity, percent chance, etc.) Similarly, for a project composed of multiple, non-contiguous study areas, the depth and analysis rasters should cover the maximum footprint of the multiple study areas (see Figure 35). Each raster dataset should include all studied flooding sources within the project area, as opposed to delivering separate raster datasets by flooding source. For example, there should only be one 1-percent-annual-chance depth raster delivered within the FRD for the riverine flooding sources. There should not be multiple 1-percent-annual-chance depth rasters delivered by individual flooding sources, or as several groups of flooding sources.

Figure 34: Raster Extents

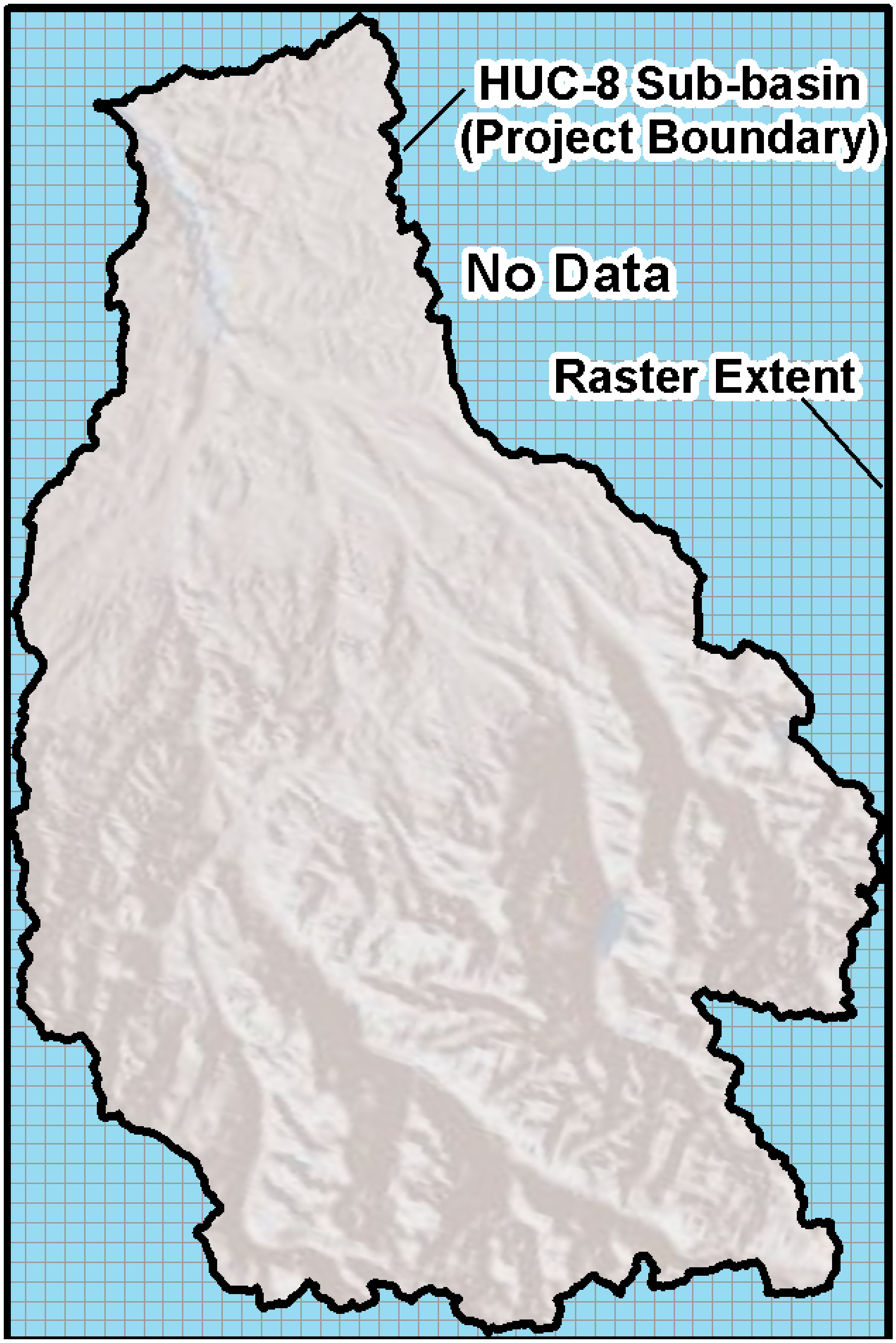
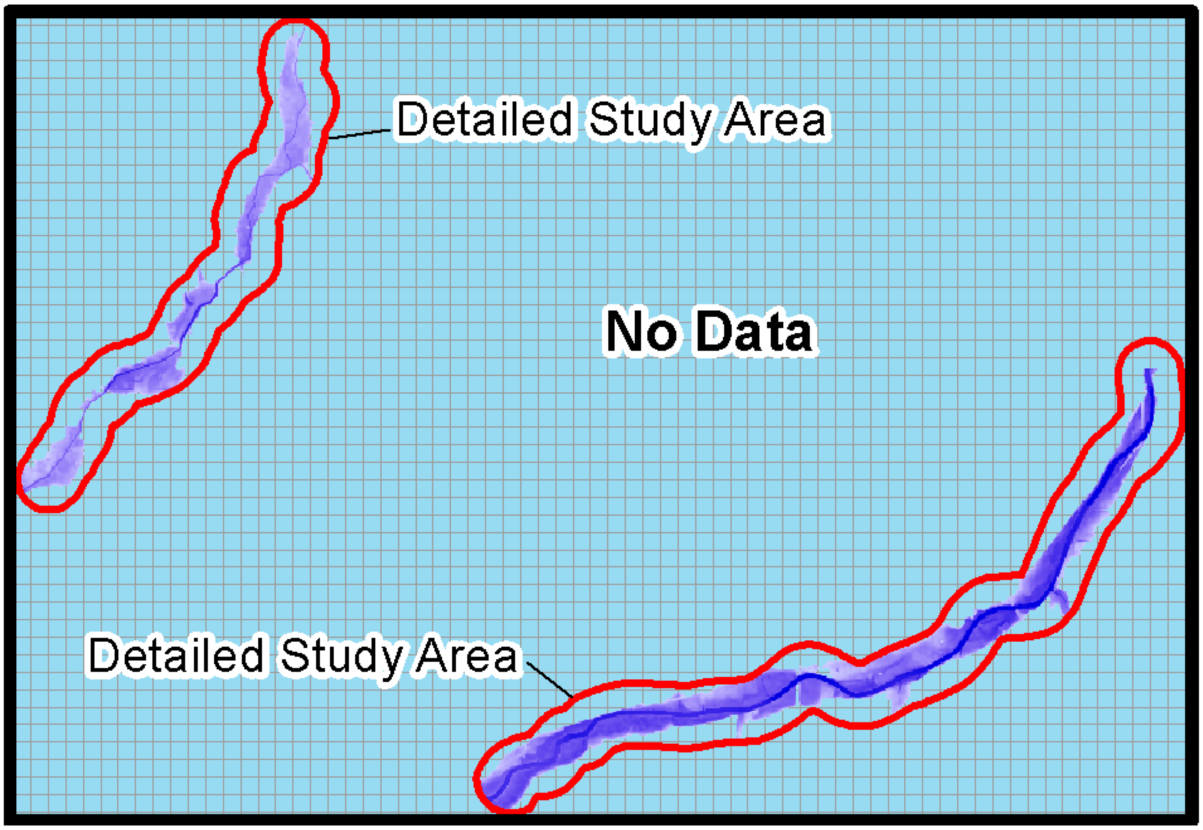


Figure 35: Raster Extents for Multiple Study Areas



10.0 Data Delivery Timeline

The Flood Risk Database Guidance provides recommendations as to when the flood depth and analysis rasters should generally be provided to communities during the life of a Flood Risk Project, and the conditions under which it should be updated after its initial delivery.

11.0 Uses in Outreach, Collaboration, and Flood Risk Communication

The value of all the flood depth and analysis rasters lies in their ability to communicate varying degrees of risk within the mapped floodplains. This allows community officials, emergency responders, and other stakeholders to identify specific areas and buildings within the floodplain where flood hazards and risks are most significant. Some of the various uses of these rasters include the following:

- Flood depth rasters can help identify potentially compromised evacuation or emergency routes in the event of a flood.
- WSEL rasters can help inform mitigation efforts and the elevation of individual structures. Some building codes, for example, require that certain building types and occupancies be elevated to the 0.2-percent-annual-chance flood elevation or higher.
- Velocity rasters can help identify areas of swift-moving water where scour or erosion may be an issue.

- Percent chance rasters can help identify the areas within the floodplain that are most likely to flood first, and the frequency with which they may flood.

Used in conjunction with one another, these raster datasets are helpful in communicating flood risk that can be more personalized to individual property owners within the floodplain. In meetings with local officials and stakeholders, it is most effective to use the raster datasets within GIS to look at specific areas where mitigation opportunities may be warranted.