Guidance for Flood Risk Analysis and Mapping

Hydraulics:

Two-Dimensional Analysis

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

Affected Section or Subsection	Date	Description
Section 6.0	December 2020	Minor updates based on the revision of SID 65 pertaining to the allowable surcharge range.

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1.0 Introduction

This document discusses 2-D modeling as it pertains to National Flood Insurance Program (NFIP) regulatory products. NFIP regulatory products are used to determine if a structure is located in a Special Flood Hazard Area (SFHA), set the flood insurance risk premium rate, and enforce appropriate floodplain management regulations. The 1-percent-annual-chance flood is a regulatory standard for the NFIP. Flood Insurance Rate Maps (FIRMs) are regulatory maps, where the 1-percent and in some instances 0.2-percent-annual chance floodplain boundaries are shown. If a flood insurance study includes regulatory floodways, additional information such as average flood velocity and cross sectional area are provided at some modeled cross sections as well. It is important to note that although some communities might choose to use FIRMs as a flood risk management tool, the main purpose of these maps is still flood insurance rate determination and floodplain management. Therefore, the most critical information shown on FIRMs are the flood elevations associated with the 1-percent-annual-chance discharges in the flooding sources. This document is not a technical manual or reference for 2-D modeling techniques.

The underlying assumption for one-dimensional (1-D) hydraulic modeling is that the conveyances, velocities, and associated physical forces and variations are only significant in the stream direction (i.e. upstream and downstream); those in the lateral directions are negligible in modeling. As a result, the hydraulic parameters can be computed using cross sections placed perpendicular to the flow direction. Two-dimensional (2-D) modeling accounts for the transverse components. 2-D models solve depth-averaged equations of motion using a grid-based finite difference scheme, finite volume method, or apply finite element solution techniques. In a 2-D analysis, hydraulic properties of the floodplain are computed at the grids for the finite difference scheme and at the nodes, for the finite element scheme of solution. The governing equations of a 2-D solution assume that topography of the ground within a grid or element, and hence the water elevation, show mild variations. The hydraulic analysis in the vicinity of control structures is computed using steady flow analysis methods for the range of discharges the structure is likely to experience.

2-D models are most applicable to streams on flat terrain with broad floodplains where flow is moving in two or more directions, or flow is hydraulically disconnected between the main channel and the floodplain.

1.1 Background

The vast majority of the hydraulic modeling underlying the special flood hazard areas depicted on Flood Insurance Rate Maps (FIRMs) throughout the nation are steady-state flow, 1-D hydraulic models. However, in recent years, there has been an increasing number of unsteady flow, 1-D and 2-D hydraulic models being prepared to support revisions to the NFIP's special flood hazard areas.

1.2 Appropriate Use of 2-D Model

Steady-state models represent the flood with a constant discharge throughout time, whereas unsteady-state models have the flood wave represented as a function of time in every detail. In 1-D models, the inherent assumption is that the water flow occurs mainly in one direction, whereas in 2-D models two horizontal coordinates are used to represent the flow velocity vectors; the vertical velocity is assumed to be negligible (Cook, 2008). Therefore, from a theoretical point of view, and given that all other conditions are met, an unsteady-state, 2-D model would produce a more realistic prediction of the flooding extent, because more details of the flood wave and flooding patterns can be represented with horizontal resolution. Cook and Merwade (2009) found that it is reasonable to assume that inundation extent could be more accurately predicted using 2-D simulations, as influences of topographic and geometric features are more accurately represented. However, this straightforward approach for modeling floods does not work well in all cases. In general, the simplest model that can solve the problem with accuracy should be the one selected.

The available data used in a flood study can be a major deciding factor in whether to use a 1-D or 2-D model. Naturally, unsteady–state, 1-D and 2-D modeling approaches require both a higher level of input hydrologic data (time series of discharges or hydrographs, possibly at several locations), higher levels of output analysis, and more rigorous model calibration, as opposed to the steady-state counterparts (Hosseinipour et al., 2012). Data availability required to calibrate and validate a model is variable depending on the community where the study is being developed; the data may be absent in many cases and unfortunately most flooding models applied recently lack calibration.

Not having detailed enough terrain data to undertake the modeling effort is a major concern for 2-D models. If the data do not exist, it is not recommended to use a 2-D model because the model effort will not provide improved results over a 1-D representation. The 1-D model is a reasonable choice if the data do not support the 2-D model.

1.2.1 Decision Process

There are several factors that should be considered when multi-dimensional modeling is considered for flood insurance studies. These factors should go beyond technical aspects of the modeling to ensure that the added value of these models are commensurate with the added cost associated with data and the modeling effort.

Standard Engineering practice should be followed and in general, technical modeling factors to be considered include but are not limited to:

1. Topographic data availability and resolution
2. Cell size and computation time
3. Flooding from multiple sources
4. The prevalence of braided or split flow conditions as well as ineffective flow areas
5. Levees (overtopping and breach) or other lateral hydraulic structures
6. Dams or reservoirs
7. Shallow flooding
8. Hydraulic conditions (supercritical vs. critical)
9. Hydrologic and soil conditions (high infiltration rate, land use etc.)

10. Bridges, channels, culverts etc.
11. Boundary conditions
12. Model stability
13. Calibration
14. Data storage, transfer and management
15. Steady or unsteady
16. Data uncertainty

Additional factors that may more closely impact the FEMA products that should be considered include:

1. Population density
2. Level of expertise in community
3. Type of effective models up and downstream
4. Communities up and downstream
5. Up and downstream tie-ins
6. Ease of base flood elevation (BFE) and profile extraction
7. Regulatory floodway
8. Ease of reporting and review
9. Ease of reproducing results
10. Ease of maintenance and future map revision
11. Ease of communication to general stakeholders
12. Software licensing and versioning
13. Cost of modeling and maintenance

Considering the technical and FEMA-specific factors, the decision steps can be broken down into three main categories: Technical, Cost, and Programmatic. When deciding whether a 2-D model would be appropriate the following questions should be asked:

A. Technical (qualitative or quantitative assessment):

1. Will a 2-D analysis (as oppose to 1-D analysis) result in more accurate flood elevations on NFIP maps given the conditions on the ground?
2. Can the 2-D model be used for other purposes?
3. Is the best available topographic information sufficient for a 2-D analysis?
4. Can the effective hydrology be used or is a new hydrologic analysis is needed?

5. Are there hydraulic structures that need to be surveyed and modeled?
6. Is effective model calibrated? Is there enough data to calibrate a 2-D model?
7. Is a 1-D, 2-D hybrid more appropriate?
8. Do the potential model parameters work with the model limitations? (i.e., Some 2-D models are 1-D in channel and do not handle bridges well, other 2-D models have things built into their codes that make it run smoother but can affect accuracy).

B. Cost (qualitative or quantitative assessment):

1. Does the model need to be purchased and what is the cost to FEMA or the user, ensuring it adheres to requirements set forth in 44 CFR 65.6(a)(6)?
2. What is the cost of data development if needed? (topographic information, calibration data, hydrology, structure information…).
3. Is there a need for new IT equipment or systems and what would be the cost?
4. What level of expertise is needed to perform the modeling and how does it compare to 1-D modeling?
5. Is there additional cost associated with extracting profiles, BFEs or shapefiles from the 2-D model compared to a 1-D model?
6. What is the cost associated with developing a regulatory floodway and how does it compare to a 1-D model?
7. Cost of QC (no check-RAS)?
8. Does the entire area need to be in 2-D or can a small segment be broken out to handle that?

C. Programmatic (qualitative or quantitative assessment):

1. What are the benefits to the community and property owners from a 2-D analysis?
2. How many structures and how many people will be impacted?
3. Does the community support a 2-D analysis?
4. For floodplain management purposes, including floodway as applicable, does the 2-D model offer benefits compared to the effective model?
5. Is the requirement of 65.6(a)(8) met, demonstrating the effective model is no longer appropriate?
    a. 44 CFR 65.6 (a)(8): A revised hydraulic analysis for a flooding source with established base flood elevations must include evaluation of the same recurrence interval(s) studied in the effective FIS, such as the 10-, 50-, 100-, and 500-year flood elevations, and of the floodway. Unless the basis of the request is the use of an alternative hydraulic methodology or the requestor can demonstrate that the data of the original hydraulic computer model is

unavailable or its use is inappropriate, the analysis shall be made using the same hydraulic computer model used to develop the base flood elevations shown on the effective Flood Insurance Rate Map and updated to show present conditions in the floodplain. Copies of the input and output data from the original and revised hydraulic analyses shall be submitted.

6. What are the risks associated with using 2-D models in the community?
7. Does the community/CTP have the in-house capability to work with the 2-D model?
8. Will there be challenges with the appeal process?
9. Will there be software licensing challenges for LOMR requesters, the community or CTP?
10. See comments on floodways.

The results of the assessments above could provide the information necessary to make an informed decision that is technically, financially, and programmatically sound. Please note that additional categories or questions can be incorporated into the process.

1.3 Minimum Data Requirements for 2-D Model Use

Data requirements for flood inundation models fall into four groups: 1) topographic data of the channel and floodplain (model bathymetry), 2) time series of flow rates and stage data for model input and output boundary conditions, 3) roughness coefficients for channel and floodplain, and 4) data for model calibration and validation (Mason et al., 2010).

The creation of a 2-D model requires a detailed and accurate terrain model of the study area. The quality of the terrain model is one of the most limiting factors to the accuracy of the model. For more information about elevation data used in flood studies see the Elevation Guidance document. For significant flow paths within the model a terrain will need to be supplemented with channel and structure surveys to ensure that flow is routed correctly through the floodplain.

Discharge and stage data are another flood model data requirement which help provide the model boundary conditions and will be discussed in Section 4.5 of this document.

Flow across a floodplain is heavily affected by the type of land cover that is present along the grid. To ensure that significant variations in land cover are accounted for in the 2-D model Manning's roughness coefficients should very from cell to cell. Values of Manning's "n" (roughness) can be determined with the help of aerial or satellite imagery, textbooks, guidelines found in manuals, and site inspections (surveying).

2.0 Model Verification and Maintenance

2.1 Model Verification

When a currently effective model is updated or run within a new version / type of software testing and documentation of variations due to the model code should be made. If changes due to model code cause significant changes in BFE or SFHA results should be discussed with the regional project officer (RPO).

2.2 Model Maintenance

Models must be designed with ease of maintenance in mind, and should be created in discrete areas that allow for efficient modification and computation. There are many factors that can affect the efficiency of a model, number of pixels, pixel size, variation of model parameters between pixels, please refer to the models users guide to ensure that the model runs efficiently.

If a project or additional information affect a models parameter at a scale smaller than the effective model start by assessing if the changes modify the existing model inputs. An example would be if fill is placed in an amount that would change the elevation of pixels within the model, or ground cover is changed that would change the roughness values of pixels. If changes which are localized within a given cell do not change the effective parameters and multiple properties / structures are contained within the affected cell an effort should be made to evaluate localized impacts.

When a 2-D model is modified with new inputs, results from changes within the 2-D model need to be provided for the extent where resulting grid and /or cross section elevations tie in within 0.5 foot.

3.0 Two-Dimensional Hydraulic Analysis Procedures

The choice of hydraulic procedures for the analyses and presentation of flood hazard information is determined during project scoping. The level of effort and the amount of data collected determines whether flood elevations, or only floodplain boundaries, can be shown on the FIRM.

The approach used for the hydraulic analyses can generally be categorized as one of three types: 1-D steady flow, 1-D unsteady flow, and 2-D steady and unsteady flow analyses. The approaches require different level of effort. The following sections present more information about 2-D analysis.

Documentation of 2-D models must include a georeferenced spatial file showing the locations of the stream under study, major flow paths emanating from and adjacent to the study stream, hydraulic structures adjacent to and crossing the stream, and the grid of cells. The location of each cell must be readily ascertained from the spatial file either through labeling or a labeling scheme (e.g., row and column numbers). Model settings and tolerances should be documented also to ensure that rerunning the model will reproduce previous results.

3.1 Topographic Information

2-D models require digital terrain models as input. Peak water-surface elevations are determined at cells, either evenly spaced squares or irregularly spaced geometric elements, composing a grid or mesh (below both will be referred to as a grid). The model grid should be carefully examined to ensure that linear features, such as embankments and ditches that effect the travel of water through the model are accounted for. The grid must cover the entire project area and the derivation or development of the grid must be clearly documented. For more information about elevation data used in flood studies see the Elevation Guidance document.

The Mapping Partner should carefully select cell size, not only considering the accuracy of the topographic data and computational efficiency of the model, but also mapping and floodplain management needs. Too small a cell size not only slows computations, but also creates too many elevation grids, which may not practically be presented on the floodplain map. Too large a cell size either creates flat water-surface elevations over a large area or does not accurately define the flood boundaries. Cell size and orientation are important attributes to ensure that linear features are represented correctly in the grid. Portions of the grid should be further refined as necessary to ensure that these features are not lost within the grid. In spacing the cells, Mapping Partners should maintain gradual changes in elevation from one cell to adjacent cells to avoid numerical instability; they should not use too many cells along a cross section to avoid unnecessary difficulty in maintaining surcharge in the floodway calculation. More details are discussed in the Floodway Guidance document. The Mapping Partner should not size cells specifically to remove certain structures or lots from the floodplain.

3.2 Hydraulic Structures

The effects of hydraulic structures including bridges and culverts are typically input as rating tables at specified cells. The Mapping Partner must document the modeling of each hydraulic structure. That documentation must include a list of each cell associated with the structure and a description of the rating table including the derivation, sources of data, and the information required in the Hydraulic Structures heading under Section 2.2.3, Hydraulics: One-Dimensional Analysis Guidance.

3.3 Non-Conveyance Areas

Because 2-D models simulate flow in all horizontal directions, the modeler does not, in general, have to identify non-conveyance areas in the input data. However, there may be reasons (e.g., cell size) to identify non-conveyance areas through input data.

The modeling technique should be chosen to reflect the natural conditions (topography and roughness) as closely as practical. Artificially removing cells from computation (e.g., removing cells for areas that were not inundated during the calibration event) may be used to reflect natural conditions in model calibration, but this practice should not be used when developing BFEs for mapping. This approach should also not be used for removing a structure from the floodplain or forcing flow toward or away from a particular area. Similarly, the approach of turning off the cells at the edge of the grids to accelerate model computational time should not be used in runs that develop BFEs for mapping.

The Mapping Partner must fully document the reasoning for, location of, and technique used to model non-conveyance areas through input data. The documentation must include a clear explanation of the natural conditions where artificial data have been used. The Mapping Partner must ensure that non-conveyance areas that should be included in the floodplain are mapped as such.

3.4 Energy Loss Coefficients

Cells are analogous to intervening reaches between cross sections in 1-D models. For example, each cell is assigned a roughness coefficient. As in 1-D modeling, roughness is described by

Manning's "n." Mapping Partners must document roughness coefficients as described in Loss Parameters under Section 2.2.5 of Hydraulics: One-dimensional Analysis. Roughness coefficient ranges available for different land cover categories are established through 1-D steady flow computations. Therefore, the roughness coefficients applied in a 2-D analysis should be validated through calibration.

3.5 Hydrologic Inputs

The choice of hydrologic procedures is associated with the size and characteristics of the watershed, the study type, the effective FIS methods, the availability of data, the requirements from the hydraulic study, and the allocated funds. In addition, information on any relevant hydrologic studies developed by other Federal or State agencies would be of use in selecting the hydrologic procedure. Hydrologic analyses, to determine the discharge characteristics along stream reaches under study, can be developed based on statewide regression equations, statistical analysis of stream gage data, or hydrologic models developed for the watershed. Unsteady flow analyses of the floodplain require the development of hydrographs using hydrologic models of the watershed. For more information about hydrologic analysis see the General Hydrologic Guidance.

For many of the 2-D models hydrologic inputs are entered as initial conditions and boundary conditions. Generally, you'll see it input two ways, as a flow hydrograph on a bounding cell or channel section originating from another basin (discussed in Section 4.5.2) or as rainfall or rainfall excess that is input directly on the 2-D flow area. Care should be taken if rainfall is used to know whether total rainfall or rainfall excess (rainfall minus losses due to interception / infiltration) is required for the model. the models user's manual should define which is required.

If the rainfall-runoff modeling capabilities of the model are utilized for initial or boundary conditions for the hydraulic computations. Mapping Partners utilizing those capabilities should meet the analysis and documentation requirements of the rainfall-runoff input as described in the applicable parts of Hydrology: Rainfall-Runoff Analysis Guidance. Until this new guidance documents are final, please continue to use Sections C.2.4.4 of the Guidelines and Specifications for Flood Hazard Mapping Partners, Appendix C: Guidance for Riverine Flooding Analyses and Mapping.

3.5.1 Initial Conditions

Initial conditions in 2-D hydraulic models are typically established by preliminary simulations (warm-up runs) until reasonable initial values are established. 2-D hydrodynamic models usually have the capability to generate initial conditions through the rainfall-runoff process. Flow is then routed through the system for a warm-up period to establish the initial water-surface elevation. In either situation, using a separate warm-up run or development of a warm-up period through rainfall-runoff and routing simulations, the Mapping Partner should fully evaluate and ensure reasonableness of the initial conditions before performing the runs that develop water-surface elevations for mapping. The Mapping Partner must document the simulation history including justification of reasonableness of the initial condition.

Rainfall-runoff modeling usually establishes antecedent conditions through input data (antecedent moisture conditions, elevations in reservoirs, etc.). The rainfall-runoff step in the 2-D modeling process often establishes starting conditions by simulating a "typical" recent history of storms.

The Mapping Partner should investigate the ramifications of using other reasonable simulated histories and document that investigation. The documentation must include a discussion of the sensitivity of the results with respect to storm history and the implications regarding the frequency assigned to the results.

For areas with distinct dry and wet seasons, the Mapping Partner should use the average wet season condition, either average rainfall for the rainfall-runoff process of the hydrodynamic model or average channel flow for the hydraulic routing model, to establish the initial condition to develop water-surface elevations for mapping.

3.5.2 Boundary Conditions

Boundary conditions for 2-D models are similar to those for 1-D models. Rather than being associated with cross sections, boundary conditions in 2-D models are associated with boundary cells. The Mapping Partner should meet the requirements described in Starting Water-Surface Elevations, and Boundary conditions for unsteady flow in Hydraulics: One-Dimensional Analysis Guidance; for all cells where boundary conditions are user supplied.

Flow hydrographs that originate from other basins should be modeled as inflow at boundary cells. Mapping Partners must document crossing basin flow hydrographs to meet the requirements for inflow hydrographs described General Hydrologic Considerations Guidance.

3.6 Flow Paths

An advantage of using 2-D models is their capacity to identify separate flow paths in addition to the mainstream channel. Velocity, flow rate, and flow volume can identify flow paths. The Mapping Partner may create separate flood profiles for significant flow paths. Details of water-surface profiles are described in the Flood Profiles Guidance.

The profile baseline is the horizontal distance along the Flood Profile as represented on the FIRM. The profile baseline can be the distance between centers of cells along flow direction in the 2-D model. Graphic specifications for profile line types can be found in the Flood Insurance Study (FIS) Report Technical Reference.

Computer programs that offer 2-D and 1-D solution capability compute flow parameters in a form suitable to develop flood profiles and floodway data published in the FIS, because the stream channel can be modeled using cross sections based on 1-D analysis.

4.0 Calibration of Hydraulic Models

Calibration of hydraulic model parameters is performed through modeling major historic floods on stream reaches where flood flow and elevation data are available. By comparing the measured water surface elevation from a flood to the modeled water-surface elevation, the modeler can judge the reliability of the model and adjust input parameters accordingly. The parameters adjusted are usually energy loss coefficients. The user's manuals for most models provide guidance and, in many cases, optimization options for calibrating friction loss (roughness) coefficients. For more information on calibration of Hydraulic Models see Section 4.5 of the General Hydraulics Guidance**.**

5.0 Alluvial Fan Analysis

Alluvial fans, and flooding on alluvial fans, show great diversity because of variations in climate, fan history, rates and styles of tectonism, source area lithology, vegetation, and land use. 2-D models are a good way of defining the 1-percent-annual-chance flood elevation on inactive areas of the alluvial fan. For more information, specific to Alluvial Fan Analysis, please see Alluvial Fan Guidance.

6.0 Floodway Determination

A floodway is a tool to assist communities in balancing development within the floodplain against the resulting increase in flood hazard. The Mapping Partner must coordinate with the community when developing floodways.

A regulatory floodway is defined as the channel of a river or other watercourse and the adjacent land area that is reserved from encroachment in order to discharge the base flood without cumulatively increasing the water-surface elevation by more than a designated height, or surcharge. A maximum height of 1.0 feet based on NFIP regulations should be used unless the project resides within a state or other jurisdiction that has established more stringent regulations. The portions of the floodplain beyond the floodway are called the floodway fringe. The community is responsible for maintaining the floodway to mitigate flood hazards; the community must not allow any activities causing a rise in the BFE in the regulatory floodway. For more information about conducting a floodway analysis see the Floodway Analysis and Mapping Guidance.

7.0 Hydraulic Review Requirements

The reviewing Mapping Partner will be responsible for performing hydraulic reviews as described in section 9 of the General Hydraulics Guidance. The reviewing Mapping Partner is responsible for determining whether the proposed analyses are reasonable. Section 9 provides requirements and criteria that should be used to determine if the hydraulic analyses are reasonable.

8.0 Deliverable Products

The Mapping Partner must submit the hydraulic and floodway data in digital format as described in Technical Reference: Data Capture. The Mapping Partner must submit files via the mapping information platform (MIP); other media may be acceptable if coordinated with FEMA. For more information about the Calibration of hydraulic models see the General Hydraulic Considerations Guidance.

8.1 Special Mapping Considerations

As 2-D modeling becomes used for more applications around the country additional resources are being developed. The following white papers / references are good sources for additional information:

- One-Dimensional Unsteady and Two-Dimensional Models: Issues for Regulatory Use, ASFPM 2014.
- On the issues associated with 2-D modeling for flood mapping purposes, Devinder S. Dhillon, Fabián A. Bombardelli, Wm. E. Fleenor and Kaveh Zamani 2014.

- Hunter, NM, Bates, PD, Neelz, S, Pender, G, Villanueva, I, Wright, NG, Liang, D, Falconer, RA, Lin, B, Waller, S, Crossley, AJ and Mason, D (2008) Benchmarking 2-D hydraulic models for urban flood simulations. Proceedings of the Institution of Civil Engineers: Water Management, 161 (1). 13-30.

References

Hosseinipour, E.Z. 2-D Fine Grid Hydrodynamic Modeling for More Accurate Floodplain Mapping in Southern California. 2012.

Mason, D. C., Schumann, G. J-p., Bates, P.D. 2010. Data Utilization in Flood Inundation Modeling. Flood Risk Science and Management, doi: 10.1002/9781444324846.ch11.