

# Guidance for Flood Risk Analysis and Mapping

## General Hydraulics Considerations

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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](http://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](http://www.fema.gov/multimedia-library).

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## Table of Revisions

The following summary of changes details revisions to this document subsequent to its most recent version in November 2016.

Affected Section or Subsection	Date	Description
9.2 and 9.3	December 2020	Added language pertaining to floodway analyses completed based on 2-D models and evaluation lines.

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## 1.0 Introduction

This document describes the standards and methods to be applied by Mapping Partners in the performance, analysis, and presentation of results for riverine flooding analyses. The overall objectives of a hydraulic study are to:

- Identify areas subject to flooding and accurately define the flood-frequency relation at locations within those flood prone areas.
- Depict the data and analyses results with maps, graphs, tables, and explanatory narratives in order to support NFIP's flood insurance risk premium zones designation and sound floodplain management.
- Document data and analyses in a digital format to the extent possible to enable the results to be readily checked, reproduced, and updated.
- Maintain (or establish) consistency and continuity within the national inventory of Flood Insurance Rate Maps (FIRMs) and Flood Insurance Study (FIS) reports.

Riverine analysis consists of hydrologic analyses to determine discharge-frequency relations along the flooding source and hydraulic analyses to determine the extent of floodwaters (floodplain) and the elevations associated with the water-surface of each frequency studied. The base (1-percent-annual-chance) flood is delineated on the FIRM as the Special Flood Hazard Area (SFHA). When determined, the 0.2-percent-annual-chance floodplain and/or floodway are also depicted on the maps. 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. The analyses must be based on existing ground conditions in the watershed and floodplain. A community that conducts its own future-conditions analysis may request that FEMA reflect these results on the FIRM.

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## 2.0 Contributors to Riverine Flooding

A flood results when a stream runs out of its confines and submerges surrounding areas. Floods are a natural consequence of stream flow in a continually changing environment. Floods have been occurring throughout Earth's history and will continue as long as the water cycle continues to run. Overall, the water cycle is a balanced system. Sometimes the amount of water flowing in to one area is greater than the capacity of the system to hold it within natural confines. The result is a flood.

There are many influencing factors besides exceptional precipitation that can lead to or exacerbate flooding. Knowing the factors that influence the chances of flooding can help understand potential mitigation opportunities. Hydraulic analyses should consider these factors when attempting to model a stream's response to flooding and identify flooding hazards.

### 2.1 Natural Processes

The following lists some of the natural processes and watershed features that impact the intensity, timing and frequency of riverine flooding.

- Recent precipitation and snow pack

- Hydrologic characteristics (watershed slope, land cover, soil types)
- Channel shape, slope, sinuosity, depth vs. width
- Watershed size, shape, vegetation and sudden changes (ex., forest fires and landslides)
- Sediment deposition and erosion

## 2.2 Structural Processes

Man-made structures and development can significantly impact the flow of floodwaters through the hydrologic system. Properly designed systems can significantly reduce flooding, while undersized structures can increase flooding risks and frequency. The following is a list of manufactured structures that can impact flood risks:

- Levees, dams and other hydraulic structures
- Stormwater management systems
- Channel construction and modification (straightening, smoothing)
- Stream crossings (bridges, culverts) – address clogging, due to ice and debris
- Designed Basin transfers

## 2.3 Impoundments and Levees

Impoundments such as lakes and reservoirs occur as both natural and human constructed features. Natural features are created by volcanic events, geological construction, landslides, or blockage by ice. Human constructed dams are built for recreation, water storage, generation of electrical power, and flood control. All types of dams are subject to failure, suddenly releasing water into the downstream drainage system.

## 3.0 Study Methodology Overview

### 3.1 Watershed Studies

FEMA's Risk Mapping, Assessment, and Planning (Risk MAP) Multi-Year Plan: Fiscal Years 2010-2014 dated March 16, 2009, recognized the benefits of performing engineering and mapping analyses on a watershed basis and commits to, "Bring communities together to discuss joint risks and consequences around a shared watershed." To accomplish these goals, it was necessary to increase the integration of flood hazard analyses and data around a watershed framework.

The overarching principle for the watershed approach is to develop a complete, consistent, and connected flood engineering analysis within a watershed. This does not mean that there must be one model for an entire watershed or stream. An acceptable watershed-based study may include multiple hydrologic and hydraulic methods and models, but those methods and models must agree at the transition points between them. Frequently, these transition points occur at community boundaries. Guidance Document No. 45, Guidance for Flood Risk Analysis and Mapping: Contiguous Community Matching contains additional information regarding hydraulic connectivity across community boundaries. Gaps between analyses are to be analyzed and

addressed as a rule, but in certain watersheds there may continue to be some gaps in analyses for low-risk areas.

The U.S. Geological Survey (USGS) has defined and cataloged watersheds by unique Hydrologic Unit Codes (HUC). This classification system breaks down the U.S. into hydrologic units, with assigned numerical values. Oftentimes, the basis of FEMA's watershed-based analysis is the HUC-8 unit. The extent of a HUC-8 cataloging unit is defined by the Watershed Boundary Dataset (WBD), a companion dataset to the National Hydrography Dataset (NHD). Information on HUC-8 watersheds may be found at <http://water.usgs.gov/GIS/huc.html>. If utilizing a different sized watershed, close coordination with the communities and FEMA POC must be made to ensure consistency.

Both the NHD and WBD are discussed in detail in USGS Fact Sheet 2009–3054, Revised March 2010, and entitled "The National Map-Hydrography." The NHD and WBD can be viewed in The National Map at <https://viewer.nationalmap.gov/basic/> and downloaded for use in a Geographic Information System (GIS). The NHD and WBD also can be downloaded from a specialized hydrography portal at <http://nhd.usgs.gov/>.

The watershed approach requires an evaluation of the risk and need in the selected area to determine the flood study scope and scale. For flood engineering studies there is flexibility on the scale used for the study, based on the guidance below. The guiding principles for the watershed approach are described below. The assessments of needs are completed as part of the Coordinated Needs Management Strategy (CNMS) evaluation process. The Coordinated Needs Management Strategy (CNMS) Technical Reference contains additional information regarding the evaluation of streams validation status. The CNMS Technical Reference is accessible through the FEMA Guidelines and Standards for Flood Risk Analysis and Mapping webpage. Additional information and current validation status data are available at: <https://msc.fema.gov/cnms/>.

- A Risk MAP watershed project will be considered complete when the identified watershed has been evaluated, the watersheds or subwatersheds chosen for new or updated flood studies are studied, and:
  - All watersheds or subwatersheds requiring new or updated hydrologic or hydraulic analyses have been studied and mapped.
  - Hydraulic analyses will be performed for an entire stream segment when that segment is selected for study. This means that unstudied areas (or gaps) between studied stream segments must be studied unless those gaps consist of valid study that ties into the new study. There can be different levels of study for the different stream segments, as long as all the models tie-in.
  - Stream segments that are selected for study because they connect portions of watersheds that are to be studied for risk and need shall be accomplished using the most basic study method that is appropriate based on the risk and need of those areas. Additionally, it is not necessary to publish FIRMs for the connecting portions, unless risk or needs around those segments were to make publication appropriate.



- All other subwatersheds have been evaluated and do not require a new or updated study based on risk and need.
- All hydrology within the watershed is consistent. In watersheds where the hydrology is not consistent, additional study is required to create consistency.
- FEMA Program Standard ID (SID) 4 states that all newly initiated Flood Risk Projects must be watershed-based, with the exception of coastal and small-scale Flood Risk Projects related to levee accreditation status.
- FEMA Working Standard ID (SID) 5 states that no flooding source will receive a lower level of regulatory flood map product than what currently exists on effective maps. For example, areas with defined floodways will continue to have defined floodways. Areas with published Base Flood Elevations (BFEs) will continue to have published BFEs. The method of study chosen will be dependent on the level of risk for that flooding hazard.

### 3.2 Identify Study Areas

Hydraulic studies areas are typically identified through the Discovery process described in Guidance Document No. 5, Guidance for Flood Risk Analysis and Mapping: Discovery. Discovery is required for all new and updated Flood Risk Projects. Discovery is used for determining whether a Flood Risk Project is appropriate and will provide visibility to stakeholders as FEMA and Cooperating Technical Partners initiate flood risk and mitigation discussions and deliver flood risk information. The identification of flood sources to be studied should include a review of the CNMS status of the streams within the watershed.

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Except for coastal and levee accreditation status change projects, Discovery must occur on a watershed basis in accordance with the watershed approach. The Discovery area will consist of an entire watershed footprint, regardless of political or other regional, state, county, municipal, or other borders. The hydraulic analysis should start at the most downstream subwatershed where a new or revised study is identified and go all the way upstream to where there are no more new/updated studies identified.

Several factors that affect the engineering analysis and may indicate the need for a new study, making the CNMS status UNVERIFIED, are discussed below. More detailed information on how to perform a Mapping Needs Assessment is available in the [Coordinated Needs Management Strategy \(CNMS\) Technical Reference](#).

Mapping Partners should evaluate the following factors affecting hydraulic conditions of a stream when evaluating the community's flood data update needs:

- Comparing recent flooding events to effective mapping.
- Factors that affect the hydrologic conditions or analyses of a watershed, including the following:
  - Changes in land use in the watershed.
  - Publication of new regional regression equations.
  - Changes in design storm data.

- Increase in length of stream record.
- Construction of flood-control structures.
- Factors that affect the hydraulic conditions or analyses of a floodplain, including the following:
  - New bridges and culverts.
  - Changes in stream morphology and changes on banks.
  - Construction of flood-control structures.

### 3.3 Determine Study Level

Once the study area has been evaluated for risk, need, and data, and the study watersheds or subwatersheds have been determined, the next step is to determine the appropriate study methodologies for each study. The study level chosen for a specific location will depend on the type of study that is effective at that location, the type of need to be met, and the risk within to the study area. The levels of study are further described in this section below.

The level of effort expended in developing a floodplain analysis is generally related to the flood risk experienced by the community, study methodology, cost of acquiring necessary input data, level of calibration, and number of flood hazard parameters computed and extracted for publication. The selection of the level of study effort and the publication of the BFEs are collectively determined by FEMA, the Mapping Partner, the State, and/or the community. The existing effective study will be the baseline for future study. For example, if an area has published BFEs, it will continue to do so. Likewise, once a floodway has been defined, a floodway shall be maintained on future flood maps. An effective floodway cannot be eliminated or downgraded.

For each level of study described below, FEMA Program Standard ID (SID) 84 requires that “all riverine engineering Flood Risk Projects consist of a hydraulic model with multiple frequencies: 0.2-percent, 1-percent, 2-percent, 4-percent, and 10-percent-annual-chance exceedance events.

In addition, the “1-percent plus” flood elevation shall be modeled for all riverine analyses. The 1-percent plus flood elevation is defined as a flood elevation derived by using discharges that include the average predictive error for the regression equation discharge calculation for the Flood Risk Project. This error is then added to the 1-percent annual chance discharge to calculate the new 1-percent plus discharge. The upper 84-percent confidence limit is calculated for gage analyses and rainfall-runoff models for the 1-percent annual chance event.”

#### 3.3.1 Automated Engineering

Automated Engineering is a process that can be used to validate Zone A studies and the availability of flood risk data in the early stages of a Flood Risk Project. The Automated Engineering process involves using best available data and automated techniques to produce estimates of flood hazard boundaries for multiple recurrence intervals. Although the cost for developing the data and estimates resulting from the Automated Engineering process should be lower than standard flood production costs, the Automated Engineering may be scalable for eventual production of regulatory and non-regulatory products. See Guidance Document No. 5,

Guidance for Flood Risk Analysis and Mapping: Automated Engineering for additional information on Automated Engineering.

### **3.3.2 Base Level Analysis**

Base Level Analysis is the most basic level of study that should be used for the production of regulatory and non-regulatory products. Base level analyses should be used in areas of low to moderate development (Risk Class B or C).

The base level study type entails using topographic data, typically without bathymetry or bridge/culvert dimensions, to conduct approximate hydrologic and hydraulic analyses. While the hydraulic impact of bridges and culverts may not be evaluated in a base level study, the impact of dams should always be considered, although the methods used to do so may vary.

A base level analysis that is mapped as a Zone A SFHA results in the delineation of a 1-percent-annual-chance floodplain and the determination of water surface elevations for each of the five flood frequency events and the 1-percent plus flood elevation, but may or may not include the mapping of the 0.2-percent event, BFEs or the development of Flood Profiles. In some cases, more robust base level analyses may be of sufficient detail to warrant the delineation of a Zone AE SFHA. See Table 1 for additional information on when this may be appropriate. In this case, the 0.2-percent event, BFEs and Flood Profiles would also need to be developed.

Base level analyses are typically conducted using a one-dimensional steady state flow approach (see Section 4 for more information on hydraulic modeling approaches), which typically requires less effort and cost to perform. The hydraulic modeling software HEC-RAS is the most common model used to perform a base level analysis, due to its wide availability, relatively low input requirements and the ability to utilize readily available GIS datasets as input data through the HEC-GeoRAS program.

Generally, base level study methods are appropriate for areas where flood hazards have not been identified but which are thought to be flood prone. If these areas are experiencing light to moderate development (Risk Class B or C) and these trends are expected to continue, then base level study methods are appropriate. Likewise, base level study methods may be used for areas that were already mapped based on an effective base level study and where development is minimal to moderate, but where experience indicates that the current SFHA delineation is inadequate. Base level study methods are not to be used for flooded sources that have already been studied using enhanced study methods.

### **3.3.3 Enhanced Analysis**

The enhanced analysis update method entails using topographic data, channel bathymetry, and bridge/culvert opening geometry to conduct detailed hydrologic and hydraulic analyses and floodplain mapping. Enhanced analyses should always consider the impact of the hydraulic structures using either field surveyed data, field measured (sometimes referred to as limited-detailed structures) or as-built information. Similarly, the geometry of the channel bathymetry should be considered in enhanced studies, whereas the area below the water surface (as captured by Lidar) is sometimes not considered in base level studies. The channel bathymetry may be from field survey data, field measurements or as-built documents (for areas near structures).

Enhanced analysis methods involve the determination and publication of BFEs and Flood Profiles. The SFHA for an area studied by enhanced analysis methods will typically be designated an AE, AO or AH zone on the FIRM. Normally, a regulatory floodway will be determined if a flooding source is studied by enhanced methods. If a regulatory floodway along a particular flooding source has been developed and is shown on the FIRM, and if the flooding source is being restudied, the new detailed study must include the regulatory floodway.

Enhanced-study methods may be used regardless of the current flood insurance risk premium zone designation. They may be used to update a previous enhanced study, to upgrade the analysis of an area previously studied using base level methods, or to map the SFHA in areas that were previously unmapped.

If areas are experiencing or expected to experience moderate to dense development, then enhanced studies are important to provide BFEs and regulatory floodways to regulate safe construction in these areas. This applies to residential, industrial, or commercial areas where growth is beginning and/or subdivision is underway, and where these trends are likely to continue. They include areas that are likely to be developed within five years following the completion of the enhanced study.

Within the base and enhanced level analysis study types, there are various options or assumptions that can be made to control the effort and cost to identify flood hazards. The following table presents a set of approaches and assumptions for various levels of base level analysis and the typical flood zone designation that may be mapped on a FIRM. Table 1 describes common methods of developing hydraulic modeling input data, but should be considered guidance, not a required approach. The Mapping Partner and FEMA Program Manager should discuss what options will be used for a study when establishing the scope of a project. The final approach should be selected considering the needs and risk of the community, availability of input data and project funding.

**Table 1: Base and Enhanced Level Analysis Approach Options**

Option	Cross Sections	Flow Paths (Left, Right and Channel)	Manning's "n" Values	Structures	Flood Zone
A	Auto-placed; may be unnaturally straight with computerized look to them adjusted or auto-placed by "intelligent" methods.	Reach lengths are assumed equal.	Single value for each cross section.	Not included; cross sections placed as if structures don't exist or cross sections placed appropriately for structure modeling.	A
B	Auto-placed and hand adjusted or auto-placed by	Reach lengths computed by offsetting	Overbanks from Land Use Land Cover (LULC) data, channel	Not included; but cross sections placed appropriately for structure modeling.	A

Option	Cross Sections	Flow Paths (Left, Right and Channel)	Manning's "n" Values	Structures	Flood Zone
	"intelligent" methods.	stream centerline.	value estimated separately.		
C	Each section reviewed by engineers.	Reach lengths adjusted based on draft floodplain.	Overbanks LULC data, channel value estimated separately.	Included; structure data from national, state or other data source. Estimated base on topography and aerial photos for those not available.	A
D	Each section reviewed by engineers.	Reach lengths adjusted based on draft floodplain.	Overbanks from LULC data, channel value estimated separately and calibrated where possible.	Included; structure data from as-builts, design plans, "measured" in the field, or other community datasets with opening information.	or AE
E	Each section reviewed by engineers; Channel bathymetry included in sections.	Reach lengths adjusted based on draft floodplain.	Overbanks from LULC data and field data, channel value estimated separately from field data and calibrated where possible.	Included; structure data from field survey, as-builts, design plans, "measured" in the field.	AE

### 3.3.4 Floodway Analysis

A floodway is a tool to assist communities in balancing development within the floodplain against the resulting increase in flood hazard. Typically, a regulatory floodway will be determined if a flooding source is studied by enhanced methods. It may be developed, as needed, for a base level study in Category D as well. Additional information and requirements associated with floodway determinations are provided in Guidance Document No. 79, Guidance for Flood Risk Analysis and Mapping: Floodway Analysis and Mapping.

### 3.4 Choose Modeling Software

Per FEMA Program Standard ID (SID) 90, the methods and models used to evaluate the flood hazard must be technically reliable, must be appropriate for flood conditions and produce

reasonable results. All computer models must adhere to 44 CFR 65.6 a (6). Hydraulic modeling software meeting the minimum requirements of the NFIP regulations are listed on the website: <https://www.fema.gov/hydraulic-numerical-models-meeting-minimum-requirement-national-flood-insurance-program>. Hydraulic models include one-dimensional steady flow, one-dimensional unsteady flow, two-dimensional steady/unsteady flow and floodway analysis models. For further information on these regulations and to learn how to get a model added to this list, please refer to the [Policy for Accepting Numerical Models for Use in the NFIP](#).

Please visit the Numerical Models No Longer Accepted by FEMA for NFIP Usage, at <https://www.fema.gov/numerical-models-no-longer-accepted-fema-national-flood-insurance-program-usage> page for a list of unaccepted models.

Effective hydraulic models may be updated to increase the precision and/or accuracy of the information reflected on the FIRM by including physical, climatic, or engineering methodology changes in the watershed. In such cases, the Mapping Partner must consult the effective floodplain analyses and obtain the hydrologic and hydraulic models used to develop the information shown on the FIRM (effective models). If a model used to develop the FIRM is not available or its use is inappropriate, the Mapping Partner must document why the effective model cannot be used and document why the new model is more appropriate. If an effective floodway has been designated, a new study should maintain that floodway width and elevations, or document why this is not possible.

Along a stream, various hydraulic modeling methods and/or models may be used. However, the continuity of the computation of water surface elevations will be maintained. The water surface elevations for all recurrence intervals from the different models must tie-in within 0.5-feet.

## 4.0 Hydraulic Analysis Procedures

Hydraulic analyses are performed to determine the peak water-surface elevations associated with a given flood frequency at specific locations within a floodplain. Water-surface elevations shown on the FIRMs must be based on hydraulic models identified in FEMA's acceptable models list. The Mapping Partner should follow the procedures and guidance given in the most up-to-date user's manual of any model used.

For each stream segment being studied, the Mapping Partner must document the model to be applied; the source and method of measuring cross-section data; the source and method of measuring hydraulic structures; the method of estimating loss parameters and starting water-surface elevations; and whether flood profiles will be included in the FIS Report and BFEs shown on the FIRM.

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.

Although 1-D steady state model accurately analyzes much of the riverine flooding with well-defined open channels with gradually varying flow, unsteady flow simulations of a 2-D model have



the capability to more accurately account for the movement of water and storage within a wide area of the floodplain. The 2-D solution has the ability to accurately model unsteady, unconfined flows; however, rating curves are necessary to reflect control structures within the floodplain.

2-D hydraulic models are used to determine flood elevations for wide floodplains caused by flat topography; for these floodplains, the basic assumption of unidirectional flow is violated, and 1-D models may not provide reliable results. An example is when the flow is moving in two or more directions, with the flow moving downstream in the main channel and out of the channel into the floodplain. The floodplain flow may be hydraulically disconnected from the channel flow or may be exchanged at multiple locations. Similarly, 2-D models may be required to analyze clusters of split and/or diverted flow paths and to do so at scales beyond the practicable use of 1-D models, such as analyzing widespread street flooding.

One of the most important aspects of flood studies is determining whether to use a 1-D steady-state, 1-D unsteady-state, 2-D steady-state, or 2-D unsteady-state model. Decision between unsteady-state vs. steady-state model solutions is more of an issue when it comes to smaller streams/rivers with presence of hydraulic structures. The decision on 1-D vs. 2-D hydraulic modeling is dependent on many factors within the study area. There are certain applications where 2-D modeling can give better results than 1-D modeling.

- Modeling an area behind a levee
- Bays and Estuaries
- Highly Braided streams
- Inactive Alluvial Fans
- Very wide and flat flood plains
- Shallow Flooding

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The following subsections briefly describe categories of hydraulic modeling approaches. More detailed guidance regarding the methods and requirements for conducting hydraulic analyses and a decision matrix to support a flood study may be found in Guidance Document No. 80, Guidance for Flood Risk Analysis and Mapping: Hydraulics: One-Dimensional Analysis, and Guidance Document No. 81, Guidance for Flood Risk Analysis and Mapping: Hydraulics: Two-Dimensional Analysis.

#### **4.1 One-Dimensional Steady Flow**

Hydraulic analysis is most commonly performed using a one-dimensional, steady flow, step-backwater model for subcritical flow. The governing assumption applied in a one-dimensional model is that the flow properties can be based on cross sections placed perpendicular to the direction of flow. The basic approach is to compute the energy of water passing through a cross section as equal to the energy of the water passing through the cross section immediately downstream plus the energy lost to friction and turbulence in the reach between the cross sections. One-dimensional steady flow step backwater models are most applicable to channels with mild to moderate slopes and gradually varied flow that is not dominated by storage; they should not be used in channels with reversed flow conditions during flooding.

There are essentially four types of input data required:

- Cross-section geometry (including hydraulic structures).
- Loss coefficients.
- Water-surface elevation at the most downstream cross section (starting water-surface elevation).
- Peak flow discharge.

One-dimensional steady flow models are applicable to streams with well-defined open channels with gradually varied flows. Steady flow models are best used where flow peaks are not dominated by significant storage changes, where the channel storage-discharge relationship can be reasonably represented by a single-valued rating curve instead of a looped rating curve, and water-surface profiles are not affected by reversed flow conditions.

Additional guidance and specifications for performing one-dimensional steady flow modeling can be found in Guidance Document No. 80, Guidance for Flood Risk Analysis and Mapping: Hydraulics: One-Dimensional Analysis.

## 4.2 One-Dimensional Unsteady Flow

In unsteady flow models, depth of flow and/or velocity of flow vary with time. FEMA-approved unsteady state models include (1) unsteady state channel routing models, which utilize inflow hydrographs produced by separate hydrologic analysis, and (2) hydrodynamic models, which include a rainfall-runoff modeling component to simulate both watershed hydrographs and channel routing.

Some one-dimensional unsteady state models describe the drainage system as a nodal network, consisting of nodes (junctions) and links (conduits); others use channel network features by cross sections, similar to 1-D steady state models. 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. Nodal system models are most applicable to urban drainage systems including open channels, storm sewers, and other structures, or natural streams with significant on- and off-channel storage such as swamps and wetlands where flow may change direction during a flood event. Typical channel network models are mostly applicable for larger rivers where open channel flow is the predominant source of flooding. These models are suitable for simulating flood waves in large rivers, tidal flows, and waves generated by operation of control structures, as well as rapid flow changes such as flows that would result by failure of a dam.

Unlike steady state models, which assume flow peak is constant within a stream reach and consider only conveyance, unsteady state models also compute storage along with conveyance within the floodplain. Changes in storage in an upstream reach directly affect flow and water-surface elevations in the downstream direction.

Additional guidance and specifications for performing one-dimensional steady flow modeling can be found in Guidance Document No. 80, Guidance for Flood Risk Analysis and Mapping: Hydraulics: One-Dimensional Analysis.



### 4.3 Two-Dimensional Models

The underlying assumption for one-dimensional 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 modeling accounts for the transverse components. Two-dimensional models solve depth-averaged equations of motion using a grid-based finite difference scheme or apply finite element solution techniques. In a two-dimensional 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 two-dimensional 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.

Unsteady flow simulations of a two-dimensional model have the capability to more accurately account for the movement of water and storage within a wide area of the floodplain. The two-dimensional solution has the ability to accurately model unsteady, unconfined flows; however, rating curves are necessary to reflect control structures within the floodplain.

Two-dimensional hydraulic models are used to determine flood elevations for wide floodplains caused by flat topography; for these floodplains, the basic assumption of unidirectional flow is violated, and one-dimensional models may not provide reliable results. An example is when the flow is moving in two or more directions, with the flow moving downstream in the main channel and out of the channel into the floodplain. The floodplain flow may be hydraulically disconnected from the channel flow or may be exchanged at multiple locations. Similarly, two-dimensional models may be required to analyze clusters of split and/or diverted flow paths and to do so at scales beyond the practicable use of one-dimensional models, such as analyzing widespread street flooding.

Although using a two-dimensional model can remove much of the iterative nature of stream modeling, results should be verified as reasonable within the context of the input data. Two-dimensional models may be run in either the steady or unsteady flow mode and may include rainfall-runoff modeling capabilities.

As with all models, calibration is highly recommended for two-dimensional models.

More detailed guidance on two-dimensional modeling can be found in Guidance Document No. 81, Guidance for Flood Risk Analysis and Mapping: Hydraulics: Two-Dimensional Analysis.

### 4.4 Ice Jams

An ice jam may be defined as an accumulation of ice in a river, stream, or other flooding source that reduces the cross-sectional area available to carry the flow and increases the water-surface elevation. Ice usually accumulates at a natural or man-made obstruction or a relatively sudden change in channel slope, alignment, or cross-section shape or depth. Ice jams are common in locations where the channel slope changes from relatively steep to mild, and where a tributary

stream enters a large river. Ice jams often cause considerable increases in upstream water surface elevation, and the flooding often occurs quite rapidly after the jam forms.

In the northern U.S. where rivers can develop relatively thick ice covers during the winter, ice jams can contribute significantly to flood hazards. Although flow discharges may be low relative to free flow flood, the stages of ice jam flooding may be among the highest on the record. Ice jams typically occur repeatedly in the same locations and ice jam flooding tends to be local and highly site specific.

Per FEMA Program standard (SID) 141, in regions where ice jams are typical, the project shall include investigation of historical floods for evidence of ice jam contribution and coordination of the methodology with the impacted communities and state as part of the Discovery process. Additionally, SID 142 specifies that where ice jams occur, backwater effects must be taken into account.

the Guidance Document No. 94, Guidance for Flood Risk Analysis and Mapping: Ice-Jam Analysis and Mapping provides detailed information on the analysis of flooding sources impacted by ice jams.

#### **4.5 Calibration of Hydraulic Models**

Historic flood data are necessary to calibrate a hydraulic model. 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 user's manuals for most models provide guidance and, in many cases, optimization options for calibrating friction loss (roughness) coefficients.

The Mapping Partner must calibrate the model where practicable and fully document the process, including dates, measurements, and locations of measurements of historic floods; parameters revised and rationale for revising; and the calibration model input and output data. The most useful data relative to historic floods are high-water marks, and these data can be used to calibrate the Manning's "n" values. Wherever possible, the Mapping Partner should calibrate hydraulic models using measured profiles, reliable high-water marks, or reliable stage information at stream gages for past floods. Models should match known high-water marks reflective of the studied recurrence interval within 0.5 feet.

The Mapping Partner should not revise explicitly measurable input data to values other than those measured unless fully documented and justified (as in artificial data used to define non-conveyance areas). The Mapping Partner should not calibrate against data that result in roughness coefficients out of the realm of published roughness coefficients for similar observed conditions. If such data are lacking or are out of date, the Mapping Partner should determine the roughness coefficients using Cowan's method (FHWA, 1984) based on a field inspection of the channel and floodplain and compare the new roughness coefficients to roughness coefficients published in Federal agency documents and hydraulic text books.

In case high-water marks are not available, the Mapping Partners should compare aerial photos of inundation areas from flood events with known frequencies with the inundation areas resulting

from the hydraulic modeling. Although such a comparison cannot be used to directly calibrate a hydraulic model, it illustrates the reasonableness of model results. The hydraulic model should be closely examined if any unreasonable results are discovered through such comparisons.

## **5.0 Data Requirements**

The following provides a brief description of typical input data requirements for hydraulic analysis. In many cases, additional guidance is or will be available on these topics. Generally, FEMA Program SID # 93 requires that Flood Risk Projects use the best available, quality-assured data that meets the needs of the study methodology.

Significant cost savings can be realized if existing topographic data sources are used because 50- percent of the cost of a map update may be to acquire new topographic, channel and structure data. Possible sources of existing topographic data include regional LiDAR consortiums, USGS, the National Oceanic and Atmospheric Administration, local planning departments, GIS coordinators, engineers, and directors of public works, FEMA archives (particularly for cross-section data from effective hydrologic and hydraulic models); and State Departments of Transportation (e.g., bridge plans).

### **5.1 Topography**

Topographic data are required for each method of updating flood data: Automated Engineering, base level and enhanced study. Please refer to the Guidance Document No. 47, Guidance for Flood Risk Analysis and Mapping: Elevation Guidance for more information on the selection and use of topographic data. In evaluating the suitability of existing topographic data, the Mapping Partner shall consider the following factors:

- Contour interval — should be 4 feet or less (2 feet in flat terrain).
- Currency of data—whether significant changes (e.g., highways, subdivisions, and mining) have occurred since the data were developed. It may be possible to update only “pockets” of the data. If a question about the currency of the data exists, “spot checks” should be performed to verify the accuracy.

In some cases, the Mapping Partner and the FEMA Regional Project Officer may decide to use the best available data, even though it may not meet the preferred accuracy specifications, but it will improve the quality of the effective analysis and identification of flood hazards. If suitable existing topographic data are not available, it will be necessary to develop new topographic and/or survey data. The Guidance Document No. 47, Guidance for Flood Risk Analysis and Mapping: Elevation Guidance, provides the requirements for developing new topographic data.

The following FEMA Program Standards ID must be met; SID 44 requires all elevation data to be processed to the bare earth terrain in the vicinity of floodplains that will require hydraulic modeling.

### **5.2 Bathymetry, Channel Data and Structure Geometry**

As discussed above, bathymetry or channel data are typically used to support an enhanced level study but may also be utilized on base level analyses. Existing data may be available to help support a new flood study. In evaluating the suitability of existing data, the Mapping Partner shall consider the following factors:

- Currency of data - Whether significant changes (e.g., new bridges, culverts, geomorphologic changes) have occurred since the data were developed. If there is a question about the currency of the data, “spot checks” should be performed to verify the accuracy.
- Density of cross sections—whether an adequate number are located in the project area.
- It may be possible to supplement existing cross-section and structural data with additional and/or updated cross sections at selected locations.

When used in hydraulic models, cross sections must be placed perpendicular to flood flow, must not intersect other cross sections of the same flooding source, and must extend beyond the 0.2-percent-annual-chance floodplain boundaries on each side of the stream. Cross sections must be spaced so that the geometry and hydraulic roughness of the reach between adjacent cross sections varies gradually and that variation can be estimated as linear. The Guidance Document No. 80, *Guidance for Flood Risk Analysis and Mapping: Hydraulics: One-Dimensional Analysis* and the *Data Capture Technical Reference*, will provide the requirements for performing cross-section and structure surveys.

### 5.3 Hydrologic Data

In order to perform a hydraulic analyses, hydrologic or flow data must be available each of the five flood frequency events and the 1-percent plus flood. The methods and requirements for developing the flow data to support a flood study may be found in the guidance documents for Rainfall-Runoff Analyses, Regression Equation Analyses and Stream Gage Analyses, once developed. Until these new guidance documents are final, please continue to use Sections A.4.6, A.4.7, A.5 and A.6 of the *Analyses*. Until this new guidance document is final, please continue to use Section C.2 of the Guidelines and Specifications for Flood Hazard Mapping Partners, Appendix C: Guidance for Riverine Flooding Analyses and Mapping.

## 6.0 Related Topics Covered by Other/Future Guidance

The following is a list of related topics that have been developed to provide additional guidance related to hydraulic modeling riverine flooding analyses and mapping.

- –Hydrology Rainfall-Runoff Analyses
- –General Hydrologic Considerations
- Hydraulics: One-Dimensional Analysis
- Hydraulics: Two-Dimensional Analysis
- Floodway Analysis and Mapping
- Shallow Flooding
- Alluvial Fans
- Ice Jams
- Automated Engineering
- Base Level Engineering (BLE)

- Riverine Mapping and Floodplain Boundaries
- Combined Coastal and Riverine Floodplain
- Mapping Base Flood Elevations on Flood Insurance Rate Maps
- Flood Profiles
- Levee
- Dams / Reservoirs and Non-Dam Features
- Data Capture

Data Capture - General

## 7.0 Hydraulic Modeling for Future Hydrologic Conditions

Hydraulic analyses must be based on existing ground conditions in the watershed and floodplain. Communities experiencing urban growth and other changes often use future-conditions hydrology in regulating watershed development. While some communities regulate based on future development, others are hesitant to enforce more restrictive standards without FEMA support. To assist community officials, FEMA has decided to allow the inclusion of flood hazard data based on future-conditions hydrology and hydraulics on FIRMs and in FIS reports for informational purposes at the request of the community. When this is completed, it is usually shown as a shaded Zone X to reflect future conditions. More information regarding the inclusion of future conditions hydrology can be found in the document Modernizing FEMA's Flood Hazard Mapping Program: Recommendations for Using Future-Conditions Hydrology for the National Flood Insurance Program, and Guidance: General Hydrologic Considerations.

## 8.0 Hydraulic and Floodway Submittal

The Mapping Partner must submit the hydraulic and floodway data in digital format as described in Data Capture Technical Reference, Guidelines and Standards for Flood Risk Analysis and Mapping. The [Data Capture Technical Reference](#) is accessible through the FEMA Guidelines and Standards for Flood Risk Analysis and Mapping webpage.

The Mapping Partner must submit files via the MIP; other media may be acceptable if coordinated with FEMA.

The required data files for hydraulic analyses are described in Section 6.7 of the Data Capture Technical Reference and include geospatial files that describe, for example, the stream channel network, locations of cross sections and floodway and flood boundaries, input and output files for the hydraulic models, and reports that describe and document the hydraulic floodway analyses.

Per FEMA Program standard (SID) 74, hydraulic analyses must be certified by a registered professional engineer.

As part of the project narrative, the Mapping Partner should provide documentation of the following:

- Methodology and results
- Reasoning for method selection
- Input data and parameters
- Sources of data
- Quality Reviews
- Validation evaluations
- Comparison and justification of major changes

## 9.0 Hydraulic and Floodway Analyses Quality Control

The reviewing Mapping Partner will be responsible for performing hydraulic and floodway reviews as described below. The reviewing Mapping Partner is responsible for determining whether the proposed analyses are reasonable. The following sections provide requirements and criteria that should be used to determine if the hydraulic and floodway analyses are reasonable.

### 9.1 Hydraulic and Floodway Review Requirements

This section summarizes FEMA's requirements for hydraulic and floodway reviews. These requirements are further described in the subsequent sections with additional guidance in an effort to help Mapping Partners better understand and comply with these requirements:

- The Mapping Partner performing the analyses and the reviewing agency or organization must ensure that conditions outlined in Sections 9.2 through 9.7 are met.
- The reviewing Mapping Partner must document the results of the review in a memorandum or letter, send it to the Mapping Partner that performed the hydraulic analysis and post it to the MIP through the Independent QA/QC of Hydraulic Analyses task. The review document must present specific comments and may include any new calculations or model runs in support of the review.

### 9.2 Regulatory Requirements and Consistency Checks

The Mapping Partner reviewing the hydraulic analyses should check the following conditions are met:

- Methods and models used to evaluate the flood hazard must be technically reliable, must be appropriate for flood conditions and produce reasonable results. All computer models must adhere to 44 CFR 65.6 a (6), see Section 3.4 for more information.
- BFEs must agree with those of other contiguous studies of the same flooding source within 0.5 foot unless it is demonstrated that it would not be appropriate. Please see 44 CFR 65.6a (2).
- Elevations in the new model should tie into the elevations of the effective model exactly at the downstream end of the new model when backwater computations are used.
- Any existing mismatches in floodplains and flood hazard information between communities and counties must be resolved as part of a FIS Report/FIRM update.

- Floodplain widths at the upstream and downstream ends of the studied reach match those shown on the effective FIRM.
- Floodway surcharge values reported for at cross sections for floodways based on 1-D models and averaged along evaluation lines for 2-D models, throughout the area of study, must be within acceptable limits, typically between zero and 1.0 ft. Floodways based on 2-D models should also meet guidance specified in Section 5 of the Floodway Analysis and Mapping Guidance document for surcharge at insurable structures. If the state (or other jurisdiction) has established more stringent regulations, these regulations take precedence over the NFIP regulatory standard. Further reduction of maximum allowable surcharge limits can be used if required or requested and approved by the communities impacted.
- With-floodway elevations at the downstream end of the new model match those in the effective model.
- With-floodway elevations at the upstream end of a revised model and beyond do not create surcharge values greater than the allowable limits.
- Revised floodway data must match any effective floodways at the downstream and upstream end of the Flood Risk Project.
- A floodway run is included in the new model if the effective model included one.
- Hydraulic and floodway modeling results are all in the same datum, preferably NAVD88.

### 9.3 ~~Profile, Map, and Model Agreement~~ **Map and Model Agreement superseded. For reference only**

The Mapping Partner reviewing the hydraulic analyses should check the following conditions are met:

- The results of the new model match the work maps and revised Flood Profiles, including the distances between cross sections, water-surface elevations, regulatory floodway widths, and surcharges.
- The FIRM, Flood Profiles and Floodway Data Tables must all agree with each other as it relates to the depiction of flood hazards and hydraulic structures.
- Any backwater flooding is properly reflected in the Flood Profiles.
- All hydraulic structures in the model are reflected on the work maps and vice versa.
- The water-surface profiles of different flood frequencies must not cross one another. Exceptions may be allowed where profiles are generated based off of the results of a 2-D or 1-D, 2-D hybrid model.
- The water-surface elevations shown on the Flood Profiles shall not rise from an upstream to downstream direction. Flood Profiles should be adjusted to show the water-surface elevation at an upstream cross section must be equal to or greater than the water-surface elevation at a downstream cross section, even if minor drawdowns are indicated in the model. However, drawdowns in the vicinity of bridges often indicate errors in the hydraulic modeling of the structure and these modeling errors should be corrected before profiles



are revised. Exceptions may be allowed where profiles are generated based off of the results of a 2-D or 1-D, 2-D hybrid model.

#### **9.4 Flood Discharges**

The Mapping Partner reviewing the hydraulic analyses should check the following conditions are met:

- Flood discharges used as inputs in new hydraulic modeling correlate with the hydrologic analysis being used (whether it is a new hydrologic analysis or an effective hydrologic analysis).
- All frequencies of flood discharges (0.2-percent, 1-percent, 2-percent, 4-percent, and 10-percent-annual-chance exceedance events and the “1-percent plus”) are included in the new model, unless an exception has been approved by the Region Project Officer.

#### **9.5 Starting Conditions**

The Mapping Partner reviewing the hydraulic analyses should check the following conditions are met:

- Starting water-surface conditions for the profiles are simulated, not hard coded.
- Starting water-surface conditions and encroachment methodology for the floodway run are appropriate.

#### **9.6 Basic Hydraulic Modeling** This document has been superseded. For reference only

The Mapping Partner reviewing the hydraulic analyses should check the following conditions are met:

- Cross sections, Manning’s roughness coefficients, transition loss coefficients, and loss coefficients at structures are modeled in accordance with the scoping agreement or the user’s manual of the model and should be within published or otherwise acceptable values;
- Ineffective and non-conveyance areas should be designated to reflect the actual conditions (such as topography and surface roughness) as closely as practical; and
- The hydraulic parameters used in the models are in agreement with topographic data, aerial imagery and other spatial data as appropriate. This should be verified through spot checking.

#### **9.7 General Review Considerations**

The Mapping Partner reviewing the hydraulic analyses should check the following conditions are met:

- The 1-percent-annual-chance water-surface profile has been compared to the bottom slope. For long, straight channels, the water-surface profile should be parallel to the bottom slope, because open channel flow tends toward the normal depth, and a problem likely exists if the profile and bottom slope are not parallel.



- The water-surface elevations at bridges or culvert sections have been compared to the top-of-roadway elevations. If a bridge or culvert is not designed to carry the base flood discharge, yet the base flood model shows low flow, a problem likely exists. On the other hand, many culverts and bridges are designed to pass the 10-percent-annual-chance flood. If the 10-percent-annual-chance water-surface elevation overtops the bridge or culvert, bridge modeling may not be appropriate, or bridge dimensions may not match with the existing structure.
- The hydraulic models were developed in accordance with State Professional Engineering board requirements and are signed and sealed by an engineer.
- The hydraulic models are calibrated where high-water marks are available, and elevations in the new model are reasonable relative to high-water marks.
- The hydraulic model results are compared with aerial photos of inundation areas from flooding with a known frequency, if available, and the modeled results are considered reasonable relative to the comparison with known inundation areas.

## 9.8 Hydraulic Review Documentation

The reviewing Mapping Partner should document the results of the review in a memorandum or letter that will be sent to the Mapping Partner that performed the hydraulic analysis if there are concerns with any aspect of the review. The document should present specific comments and may include any new calculations or model runs that the reviewing Mapping Partner has made in support of the review. Differences should be resolved between the reviewing Mapping Partner and Mapping Partner that performed the hydraulic analysis before the results are used for mapping or presented to communities. All review documentation should be uploaded to the MIP through the Independent QA/QC of Hydraulic Analyses task. Concerns may be related to, but not limited to, the following:

- Acceptability of the model used in the analysis.
- Water-surface elevation and floodway width tie-ins at the downstream and upstream end of the studied area.
- Increase in BFE if the effective regulatory floodway is encroached.
- Agreement of structures, distances, water-surface elevations, and regulatory floodway widths among the map, profile, and model.
- Acceptability of surcharge values.
- Water-surface profiles crossing each other.
- Proper documentation of the study and application/certification forms.
- Agreement in discharges between hydrologic and hydraulic analysis.
- Selection of starting water-surface elevation options.
- Deviation of hydraulic parameters from recommended values.
- Agreement (or discrepancy) between modeled water-surface elevations with high- water marks.

- Elevations in the model tie into the elevations of tributaries that confluence with the studied reach for those tributaries not studied.

This document has been superseded. For reference only