DRAFT

Guidelines and Specifications for Flood Hazard Mapping Partners

Appendix C: Guidance for Riverine Flooding Analyses and Mapping

November 2009

FEMA

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APPENDIX C

GUIDANCE FOR RIVERINE FLOODING ANALYSES AND MAPPING

C.1 Introduction [November 2009]

This Appendix describes the standards and methods to be applied by Mapping Partners in the performance, analysis, and presentation of results for riverine flooding analyses. The recommended approach for this analysis is to perform studies on a watershed basis. The overall objectives of a Flood Insurance Study (FIS) are:

- Identify areas subject to flooding from riverine sources and accurately define the flood-frequency relation at locations within those floodprone areas;
- Depict the data and analyses results with maps, graphs, tables, and explanatory narratives for purposes that support flood insurance decisions 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; and
- Maintain (or establish) consistency and continuity within the national inventory of Flood Insurance Rate Maps (FIRMs) and FIS reports.

A FIRM is the visual representation of the spatial components of the Digital FIRM (DFIRM) "data," the DFIRM database. In these *Guidelines*, Appendix J presents format and specifications for FIS reports; Appendix K presents graphical specifications regarding FIRM symbology; and Appendix L presents database specifications. Preliminary and Effective FIRM preparation is discussed in Volume 1 and further described in the FIRM Text Placement Guide.

Riverine analyses consist 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 shown 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. 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.

C.1.1 Numerical Models [November 2009]

All numerical models (computer programs) meeting the minimum requirements of the National Flood Insurance Program (NFIP) regulations are available as a list (accepted models list) at FEMA website http://www.fema.gov/plan/prevent/fhm/en_modl.shtm. The Mapping Partner must select computer programs from the accepted models list to conduct floodplain analyses. FEMA's policy for accepting new computer programs for use in the NFIP can also be found at this link. Computer shell programs enhancing the analysis efficiency by coupling pre- and/or post-processing data with the accepted models may be utilized if the source code of the accepted model has not been modified. Mapping Partners must not use shell programs that use different or modified source codes to imitate the accepted model.

Re-analyses of flood hazard information increase the precision and/or accuracy of the information reflected on the FIRM by including any 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 must maintain that floodway width and elevations, or document why this is not possible.

C.1.2 Identify Watersheds for Study [November 2009]

Watershed studies are identified through the scoping process described in Appendix I of these *Guidelines*. Several factors that affect the engineering analysis and determine the need for a new study are discussed in Appendix I.

C.1.3 Identify Study Type [November 2009]

The study type is determined during the scoping process as discussed in Appendix I of these Guidelines. The levels of study effort that should be considered for FISs differ based on the needs of the community. 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 Base Flood Elevations (BFEs) are collectively determined by FEMA, the Mapping Partner, the State, and/or the community.

The SFHA is the area subject to inundation by the base flood. The study type chosen is dependent on the level of risk from flooding, community needs, and the data available. Based on these factors, a commensurate level of study will be chosen. The level of study may range from regression equations to rainfall-runoff modeling, and from no structure information to detailed field surveys and complex modeling techniques. The results of the appropriate study type will also vary from not publishing BFEs on the FIRM or FIS to their inclusion.

C.1.4 Documentation [November 2009]

Anytime a FIRM is reviewed, such as during reviews of hydrologic and hydraulic analyses, comment periods, and validation evaluations, questions pertaining to the flood study may arise. Mapping Partners must prepare fully documented analyses, and documentation must be easily reproducible and include study methods, reasoning for study method selection, input data and parameters, sources of data results, and justifications for major changes in computed flood hazard parameters. The required data and analyses to be documented are described in Appendix M, *Data Capture Standards*, of these *Guidelines*.

Riverine analyses and mapping must be performed using established, well-documented approaches. Computer programs listed on the acceptable models list and techniques used by Federal agencies fall into this category. Using those models and techniques, including the user's manual and Federal publications, fulfills much of the documentation requirements. However, choices of options, data sources, assumptions, and methods of computing or measuring input parameters associated with those approaches must be documented in hydrology and hydraulics reports that are discussed in Appendix M.

The format of geospatial files, input and output files for hydrologic and hydraulic models, metadata, and other supporting files that are required to be submitted are described in Appendix M, for the various study types. The data and models must be organized by watershed and submitted to the Mapping Information Platform (MIP).

Methods are the means by which something is derived, calculated, or measured. Methods must be documented to the extent that the purpose and input data and parameter requirements are clear, and the results can be reproduced. When more than one method is available to accomplish the purpose, the documentation must include the reasoning for using the chosen method.

Documentation of input data must describe methods of measurements and sources from which data were obtained or measured. Documentation of parameters used in analyses, including initial and boundary conditions, must describe the derivation of those parameters, and methods of measurements and sources from which data supporting those parameters were obtained or measured.

The input data of computer models fulfill many documentation requirements. Selection of some parameters will be self-explanatory, such as the selection of "normal depth" method as the downstream boundary condition in a step-backwater hydraulic analysis. However, selection of many input parameters may depend on a number of physical, topographic, and hydrologic properties of the watershed and floodplain under study. For example, selection of Soil Conservation Service (SCS) Curve Numbers as loss parameters of a sub-watershed will depend on the geological, land use, and hydrologic properties. Therefore, documentation for the selection of Curve Numbers should provide all parameters used for the selection.

C.2 Hydrologic Analyses [November 2009]

Hydrologic analyses are performed to determine flood discharge-frequency relations in a watershed. Assigning frequencies to discharge values requires that at least some part of the analyses be stochastic. The following sections discuss the choice of hydrologic procedures, how to determine the statistical significance of flood discharges, hydrologic analysis requirements, hydrologic analysis procedures, hydrologic submittal standards, and hydrologic review procedures.

C.2.1 Choice of Hydrologic Procedures [November 2009]

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. However, the majority of the effective FISs are based on peak flow discharges estimated along the stream reach and steady flow hydraulic analyses of the floodplain. Except for special cases, estimates of peak flow discharges can be developed based on available stream gage analyses and regression equations (U.S. Water Resources Council, 1981).

For gaged streams, if sufficient stream gaging station data reflecting existing conditions is available, and the data is applicable to developing peak flow discharges along the study reach, this data must be used to estimate the flood discharge-frequency relations. Gaging station data are applicable to all study types if the record length is 10 years or longer. Flood discharges based on gaging station data can be transferred upstream and downstream from the gaging station, as described later.

For ungaged streams, regression equations are recommended for estimating existing-conditions flood discharges if a flood hydrograph is not required and the regression equations are applicable to the streams. The regression equations may not be applicable to watersheds with changing land use conditions in urban areas or where there are flood detention structures or significant temporary channel storage behind road embankments. Occasionally, FISs include watersheds with drainage areas outside of the recommended range of the hydrological parameters of the regression equations. Such watersheds would require the selection of another hydrologic procedure applicable for the watershed. For ungaged streams with existing rainfall-runoff models, the Mapping Partner performing the hydrologic analysis may use an existing rainfall-runoff model in lieu of regression equations, if that model was calibrated. Rainfall-runoff models are applicable and necessary for studies where a flood hydrograph is required, where the regional regression equations are not applicable, or where temporary storage behind road embankments is a factor in determining the flood discharges. Storage behind bridges and culverts with high road embankments can be reflected in the hydrologic analysis. If the effective hydraulic analysis for the floodplain utilized an unsteady flow hydraulic analysis, and the floodplain warrants an unsteady flow analysis to compute reliable flood elevations, a rainfall-runoff model must be developed to compute the hydrographs necessary. The computer program used in the effective hydrologic study or another computer program with equal capability can be used for the hydrologic study.

C.2.2 Determining Statistical Significance of Flood Discharges [November 2009]

A revised hydrologic analysis may be needed for a variety of reasons, such as:

- To reflect longer periods of record or data revisions;
- To reflect changed physical conditions;
- To take advantage of improved hydrologic analysis methods; or
- To correct an error in the hydrologic analysis performed for the effective study.

The factors noted above are discussed in more detail in Appendix I of these *Guidelines* as part of the validation evaluation. The Mapping Partner should consider revisions to the effective hydrologic analysis when a more recent hydrologic analysis yields flood discharges that are statistically different from the effective discharges, or when the new flood discharges yield significant differences in the BFEs. A hydrologic analysis could be performed before collecting the hydraulic data to determine if changes in the flood discharges alone are sufficient to warrant a new study.

The Mapping Partner performing the hydrologic analysis should base the test for significance on the confidence limits of the more recent analysis. Plus or minus one standard error, which is equivalent to a 68-percent confidence interval, should be used to determine if the effective and new base flood discharges are significantly different. If the effective base flood discharges are within the 68-percent confidence interval (one standard error) of the new base flood discharges, the new estimates are not considered statistically different and there is no need for a new study based only on changes in the flood discharges. If the effective discharges fall outside the 68-percent confidence interval (one standard error) of the new discharges, the estimates are considered significantly different and a new study may be warranted based on changes in the flood discharges.

When the effective flood discharges fall within the 68-percent confidence interval (one standard error), the Mapping Partner performing the hydrologic analysis may use the flood profiles for the effective study to evaluate the effect of new flood discharges on the effective BFEs. If the new flood discharges yield BFEs that differ from the effective BFEs by more than 0.5 foot or if the floodplain boundaries will be significantly changed in flat areas, a new study should be conducted. Often a new study is warranted without significant changes in flood discharges because of substantial changes in hydraulic conditions, like the channelization or construction of new hydraulic structures such as bridges.

Further discussion and examples of using the standard error to compare flood discharges for ungaged watersheds can be found at the web site of the Hydrologic Frequency Analysis Work Group of the Subcommittee on Hydrology of the Advisory Committee on Water Information (http://acwi.gov/hydrology/Frequency/pdf/ungaged_101602.pdf). As discussed in the cited paper, the standard error is recommended as a predefined error band for judging whether flood discharges are significantly different because this measure is:

- Easy to compute;
- Frequently used in hydrologic studies;
- Often reported in the literature, such as in U.S. Geological Survey (USGS) regional regression reports; and
- Better understood by engineers and hydrologists than most accuracy criteria.

The use of the standard error (68-percent confidence interval) for determining statistical significance offers some advantages over the joint use of the 50- and 90-percent confidence intervals. There is no subjectivity in evaluating the statistical significance such as when the effective discharge falls between the 50- and 90-percent confidence intervals of the new flood discharges. Furthermore, confidence intervals are estimated only for gaged streams whereas the standard error for regression estimates for ungaged streams is usually available, making the standard error more applicable for determining statistical significance. Finally, the use of standard error is consistent with criteria used in the hydrologic review procedures as discussed later.

C.2.3 Hydrologic Analysis Requirements [November 2009]

This section summarizes FEMA's requirements for hydrologic analyses. These requirements are further described in subsequent sections with additional guidance in an effort to assist Mapping Partners to better understand and comply with these requirements. The requirements listed below are not necessarily applicable for every study but are functions of the level of the study, the models used, and data available. The following requirements are generally listed in the order they are discussed in subsequent sections:

- If determining flood discharges at gaging stations, the Mapping Partner must use Bulletin 17B, *Guidelines for Determining Flood Flow Frequency* (Interagency

Advisory Committee on Water Data [IACWD], 1982) to determine peak flow data at gaging stations. A written justification and approval from the RPO must be obtained if analysis techniques other than those described in Bulletin 17B are to be applied. Additionally, no expected probability adjustments are allowed to the Bulletin 17B frequency curve or alternative analysis, if performed. See Section C.2.4.1 for additional information and guidance.

- If using regression equations, the Mapping Partner must use the most recently published USGS regional regression equations unless they are shown to be inappropriate. The Mapping Partner must verify that all parameter values fall within the range of basin and climatic characteristics used to derive the equations. If procedures to account for urbanized conditions are not available from USGS, the Mapping Partner must use the techniques described in *Flood Characteristics of Urban Watersheds in the United States* (USGS, 1983) to adjust the flood discharge values determined for the rural condition. Occasionally, flood discharge values computed with urban equations are lower than those computed with rural equations, especially in less-urbanized drainage areas. In those cases, the Mapping Partner must use the discharge values computed with rural equations. If regression equations other than those most recently published by USGS are to be used, the Mapping Partner must provide justification for the use of these equations. See Section C.2.4.3 for additional information and guidance.
- If using rainfall-runoff models, the Mapping Partner must use one of the rainfall-runoff models listed under "Numerical Models Meeting the Minimum Requirements for the NFIP," which is posted on FEMA's web site. Input and output files for the model and georeferenced spatial files showing hydrologic features used for the modeling must be submitted in accordance with Appendix M, *Data Capture Standards*, of these *Guidelines*. See Section C.2.4.4 for additional information and guidance.
- The Mapping Partner performing the hydrologic analysis must use depth-duration-frequency rainfall data developed by Federal, State, or Regional agencies or demonstrate that these data are not valid for use in hydrologic analyses. The Mapping Partner must use temporal storm distributions developed by Federal, State, or Regional agencies that reflect the local climatic conditions or justify why a different temporal distribution is applicable. The storm duration must exceed the time of concentration of the basin and be large enough to provide reasonable runoff and sediment volumes when performing storage analyses. In addition, the Mapping Partner must use areal reduction factors (if applicable) developed by Federal, State, or Regional agencies or demonstrate why these factors are not applicable. See Section C.2.4.4, Rainfall-runoff Models, for additional information and guidance.
- The Mapping Partner must not consider the storage capability below Normal Pool Elevation of reservoirs operated primarily for purposes other than flood control unless all the exceptions provided in Section C.2.4.4 (subsection for Reservoir Storage) are met.
- The Mapping Partner performing the hydrologic analysis must calibrate the rainfall-runoff model used in hydrologic analyses where practicable. The Mapping Partner

must compare results from modeling various frequency storms with discharge-frequency relations derived from stream gage data, if available, or with estimates from applicable regional regression equations, if applicable. See Calibration of Hydrologic Models under Section C.2.4.4 for additional information and guidance.

- If procedures other than those outlined in Bulletin 17B were applied for gaged streams, the Mapping Partner performing the hydrologic review must determine whether these procedures and the base flood discharges are reasonable. In cases where major flood events have occurred since the flood-frequency curves were published, the Mapping Partner performing the hydrologic review must confirm that the impacts of these events have been reflected in the flood discharge calculations. See Section C.2.6.3 for additional information and guidance.
- The Mapping Partner must submit georeferenced spatial files of sub-basins and nodes (discharge points) as described in Appendix M, *Data Capture Standards*.
- The Mapping Partner performing hydrologic analyses must document the following in the hydrology report:
  - Basic information such as the location and description of the watershed and study area, study limits, locations where the flood discharges were estimated, associated USGS gaging stations, climatic data, hydrologic features, and any other information that supports the hydrologic analyses;
  - Justification for any regression equations developed and used as part of the study other than those most recently published by the USGS;
  - The rainfall-runoff model used and all the assumptions and supporting computations associated with the model;
  - All data, assumptions, descriptions, and justifications used for rainfall analyses, including the antecedent moisture level modeled for each frequency, the methods used to compute the rainfall losses and areal reduction factor, the reasoning for using those methods, and the sources of data;
  - The reasoning for selecting a given synthetic unit hydrograph option and the methods for determining the hydrograph parameters. If a unit hydrograph is input to the model, documentation of its derivation including the sources of the rainfall and runoff data;
  - The routing methods used, including the values of input parameters, the derivation of those parameters, and methods of measurements and sources of data. The approach used for channel infiltration and the basis for any diversions from the watershed. The effect of encroachment on the computation of channel losses and storage, and the relation between storage and the extent of the floodplain;
  - The source and derivation of any inflow hydrographs that are estimated independent of the modeling process;
  - The methods or data used for estimating diversions from the watershed;
  - The elevation-storage-outflow relation when using reservoir storage, including sources of data, reservoir operations, etc.;

- The process for model calibration, including dates, measurements, and locations of measurements of historic storms; parameters revised and rationale for revising; and input and output data for the calibrated model;
- Comparison of the calibrated model outflow-drainage area values with gaging station and regression estimates (if applicable) and any adjustments made as a result. The documentation must include a discussion of the reasonableness of the model output; and
- The differences between the proposed flood discharges, obtained from the rainfall-runoff model and regression equations, and effective base flood discharges and an explanation as to why they are different.

C.2.4 Hydrologic Analysis Procedures [November 2009]

Hydrologic analyses establish discharge frequency relations along stream reaches. Those analyses are either stochastic, using stream gage record data; or deterministic, using a rainfall-runoff model. The following sections outline standards and procedures for performing the hydrologic analyses for FISs. A given study could utilize one or more of the following procedures.

C.2.4.1 Stream Gage Analyses [November 2009]

Maximum annual peak flow records are available for over 26,000 gaging station sites across the United States from the USGS at http://water.usgs.gov/nwis/sw. The length of record at those sites ranges from less than 10 to over 100 years. Data from those records are used to estimate flood frequency at or near the gage sites and the results of those analyses are used to estimate flood frequency at sites without gages.

The Mapping Partner must analyze peak flow data in accordance with those standards as presented in Bulletin 17B and subsequent modifications. Bulletin 17B recommends a minimum of 10 years of data for frequency analysis. The Mapping Partner must provide written justification and obtain approval from the RPO to use analysis techniques other than those described in Bulletin 17B. Discharge-frequency relations derived by the USGS in accordance with Bulletin 17B for gaged sites on unregulated streams may be obtained from published USGS reports.

Computer programs for performing stream gage analyses in accordance with Bulletin 17B are available from the U.S. Army Corps of Engineers (USACE) and the USGS. The programs include *HEC-FFA Frequency Analysis* (USACE, 1992) and *PEAKFQ, Annual Flood Frequency Analysis Using Bulletin 17B Guidelines* (USGS, 2006).

Note that gage record analyses are valid only for homogeneous periods of record in which the hydrologic response of the watershed is unchanged. In some cases where gage records contain short, discontinuous, or non-homogeneous periods, peak flow data may be revised within and/or added to a record using techniques described in Bulletin 17B. The Two Station Comparison method described in Bulletin 17B and the Maintenance of Variance

Extension method described by Hirsch (1982) can be used to augment and extend the record of short-term gaging stations using data for nearby long-term stations. Such enhancements to stream gage record data must be fully documented in the hydrology report. When analyzing gage records that are not homogeneous (mixed populations, e.g., annual flood peaks caused by rainfall and snowmelt floods), the Mapping Partner should refer to Appendix F of these *Guidelines* or USACE EM No. 1110-2-1415 (USACE, 1993).

USACE EM No. 1110-2-1415 (USACE, 1993) describes techniques for several situations in which the analyses may require adjustments to gage data to make a homogenous dataset. For example, guidance is available for analyzing gage records containing regulated and unregulated flow values.

The Mapping Partner must not make expected probability adjustments to the Bulletin 17B frequency curve or alternative analysis if performed (National Academy of Sciences, 1978).

Improved estimates of flood frequency can be obtained at gaging stations by weighting the gaged estimates with regional regression estimates. The weighting depends on the number of years of record at the gaging station and the accuracy of the regression estimates as described in Bulletin 17B (Appendix 8), statewide USGS reports, and documentation for the USGS National Flood Frequency (NFF) program (USGS, 2002).

Estimates of flood discharges from gaging stations can be used in hydrologic analyses for all study types.

C.2.4.2 Analyses for an Ungaged Location of a Gaged Stream [November 2009]

For a given frequency, flood magnitudes for ungaged sites on a gaged stream can be determined by weighting results from the appropriate regression equation with the results of gage analyses upstream and/or downstream of the reach under analysis. The weighted estimate can be transferred upstream and/or downstream and applied to reaches draining between 50- and 150-percent of the area drained by the gaging station. The weighting depends on the difference in drainage area between the gaging station and the ungaged site of interest. Weighting procedures, as recommended by the USGS, are described in most USGS regional flood-frequency reports, as well as in the documentation for the NFF program (USGS, 2002). Procedures other than those recommended by USGS may also be applicable if justification is provided.

Estimates of flood discharges made near gaging stations as described above can be used in hydrologic analyses for all study types.

C.2.4.3 Regional Regression Equations [November 2009]

USGS has published regional regression equations for rural watersheds for various frequencies throughout the United States. Those equations are published in Water

Resources Investigations Reports, Open File Reports, or Scientific Investigations Reports covering every State and several regions of the United States. Reports describing the regression equations and the NFF computer program (USGS, 1994; USGS, 2002) for applying these equations can be found at http://water.usgs.gov/software/nff.html. Although the NFF program is still available, the USGS has recently replaced it with the National Streamflow Statistics (NSS) computer program, and, therefore, Mapping Partners should use NSS in place of NFF. The NSS computer program has all the current regression equations for estimating flood discharges as well as equations for estimating other streamflow statistics like the 7-day, 10-year low flow or flow duration percentiles. The latest version of the NSS computer program can be found at http://water.usgs.gov/software/NSS.

The Mapping Partner must use the most recently published regional regression equations unless they are shown to be inappropriate. The Mapping Partner must verify that all parameter values fall within the range of basin and climatic characteristics used to derive the equations. If the parameters of the watershed under consideration do not fall within the recommended ranges, another hydrologic method applicable should be used to develop discharge frequency relationships. For several States, there is a map-based USGS web application called StreamStats (http://streamstats.usgs.gov) that makes it easier for users to obtain basin and climatic characteristics for use in the regional regression equations. StreamStats uses digital map data and a Geographic Information System (GIS) to automatically determine basin characteristics for ungaged sites that are used in the regression equations to estimate the flood discharges. StreamStats implements the same flood regression equations as NSS and eventually will replace NSS when StreamStats is implemented in all States.

USGS has published regional regression equations for estimating flood discharges for urban watersheds in several States. The list of reports for urban and rural watersheds by State can be found at http://water.usgs.gov/osw/programs/nss/pubs.html. Where the statewide reports do not contain procedures to account for urbanized conditions, the Mapping Partner must use the techniques described in *Flood Characteristics of Urban Watersheds in the United States* (USGS, 1983) to adjust the flood discharge values determined for the rural condition. Occasionally, flood discharge values computed with urban equations are lower than those computed with rural equations, especially in less-urbanized drainage areas. In those cases, the Mapping Partner must use the discharge values computed with rural equations.

The USGS has also developed the region-of-influence method to estimate flood discharges for a few States. The region-of-influence methods, if available, are described in the statewide regional reports available at http://water.usgs.gov/osw/programs/nss/pubs.html. In the region-of-influence method, basin similarity is accomplished by grouping gage records by basin and climatic characteristics rather than by region. The technique is to identify a certain number of gaged basins with characteristics closest in value to the watershed under investigation, and define various frequency discharges as functions of those values. For a given frequency, there is potentially a different equation for each reach in a study area. This method does not involve published regression equations. The NSS computer program allows users the opportunity to apply the region-of-influence method if it is available for a given State.

To use regional regression equations other than those most recently published by USGS, or derived by the region-of-influence method, the Mapping Partner must indicate why statewide regression equations published by the USGS are not applicable, obtain approval from the RPO, and fully document the derivation and application of the equations and justification for their use.

Area-specific flood frequency relationships can be estimated for ungaged stream reaches using the results of analyses of gages in the vicinity. Plotting, for example, the base flood discharge values derived from analyses of stream gages in the vicinity versus the corresponding drainage areas at the gage sites and fitting a curve to those points produces a means to estimate the base flood discharge as a function of drainage area. Adding other basin or climatic characteristics, such as main channel slope or mean annual rainfall, may improve the estimate. Such analyses are referred to as regional regression analyses.

Regional regression equations are valid only for basins where parameter values fall within the range of basin and climatic characteristics used to derive the equations.

Estimates of flood discharges from regional regression equations, if applicable, can be used in hydrologic analyses developed for all study types. Coordination with the local USGS office will be beneficial in establishing the need to develop a regional regression equation for the study area.

C.2.4.4 Rainfall-runoff Models [November 2009]

Rainfall-runoff models convert a spatial and temporal description of a given frequency storm over a watershed into a flood flow hydrograph at the outlet or concentration point of the watershed. A hydrograph represents the passage of a flood wave at a point usually expressed in terms of discharge as a function of time. In the design storm approach, the annual percent chance of exceeding the peak flow of the output hydrograph is taken to be the same as the annual percent chance of exceeding the total rainfall depth in the storm (EM 1110-2-1417, USACE, 1994). In addition, rainfall-runoff models are also useful in computing BFEs of storage areas. Computer programs included in the accepted models list must be used to develop FISs.

In rainfall-runoff models, watersheds are divided into sub-basins connected to the outlet through a system of stream reaches. For a given storm, the model computes runoff from each sub-basin and the outflow hydrograph at the sub-basin outlet. Those hydrographs are routed through the reach system and combined at points where reaches intersect (i.e., confluences).

The Mapping Partner must submit georeferenced spatial files showing the following and clearly label each feature shown on the map with the identification used in the model:

- Sub-basins;
- Locations of estimated flood discharges; and
- Flood control structures, such as reservoirs and diversions within the reach system that affect flood flow.

Rainfall-runoff models are, essentially, composed of the following parts:

- Rainfall;
- Rainfall Losses;
- Sub-basin response;
- Routing;
- Input hydrograph; and
- Channel and reservoir storage.

The parameters selected to represent the watershed characteristics are generally adjusted through a calibration process. Design rainfall is applied to the calibrated rainfall-runoff model to estimate the discharge hydrographs at concentration points necessary for the hydraulic analysis.

Rainfall

Rainfall input data consists of depth, temporal distribution, and duration of the design storm. The stochastic part of hydrologic analyses using a rainfall-runoff model is the rainfall. Depths of precipitation are recorded over various periods at thousands of locations nationwide. Those data are used to define depth-duration-frequency relations at gage sites. The depth values for a given frequency and duration are used to draw isohyets, or lines of constant depth, creating a map from which the rainfall depth for that particular frequency and duration can be found. The National Weather Service of the National Oceanic and Atmospheric Administration (NOAA) publishes precipitation depth-duration-frequency maps in various Atlases and Technical Papers, and these reports can be obtained from http://www.nws.noaa.gov/ohd/hdsc/currentpf.htm.

The Mapping Partner must use current depth-duration-frequency data developed by Federal or State agencies, Regional Climate Centers, or local flood control agencies, or provide justification for another data source. In the latter case, the Mapping Partner must fully document in the hydrology report the data used, including the gages used, and methods of fitting gage data to frequency curves and isohyets between gage sites.

For most applications reflected on FIRMs, the spatial distribution of rainfall is taken to be constant. If data are available regarding the spatial distribution of large recorded storms, those data should be incorporated into model calibration efforts.

Temporal storm distributions must be chosen to reflect the local climatic conditions. Most rainfall-runoff models contain options for using standard synthetic storm distributions or inputting a distribution. The choice of temporal storm distribution must be fully documented. If the source of the distribution is not a Federal, State, or Regional agency, the documentation must include a detailed description of the derivation of the distribution, including sources of data and the means of fitting those data to a particular distribution.

The storm duration chosen must exceed the time necessary for runoff everywhere in the basin to reach the outlet, also known as the time of concentration. The storm duration must also be large enough to provide reasonable runoff and sediment volumes when performing storage analyses. The Mapping Partner may use guidelines for storm durations developed by State and Regional agencies responsible for flood control or floodplain regulation.

USACE has developed a hypothetical storm distribution that can be used to sample rainfall durations (USACE, 1990; USACE, 2006). The hypothetical distribution centrally locates periods of the storm containing the precipitation depths associated with the durations of those periods for the frequency of storm under study. Procedures for developing these center-peaking distributions are included in many of the computer programs included in the accepted models list.

The Natural Resources Conservation Service (NRCS) has also developed hypothetical storm distributions similar to the USACE center-peaking storm (U.S. Department of Agriculture [USDA], 1983; USDA, 1986). The NRCS temporal distributions are frequently used in rainfall-runoff models. In addition, regional specific temporal distributions, developed by some State agencies or watershed management departments, have been approved for use in FISs. For example, Huff distribution developed for Illinois and the temporal distributions developed by Florida water management districts are accepted for use in FISs.

The spatially averaged depths of rainfalls with large areal extents are, in general, less than those with relatively smaller areal extents. Published rainfall data (NOAA Atlases, for example) describe depth-duration-frequency relations at points. In practice, an areal adjustment factor is applied to depth values derived from those relations. The Mapping Partner must document the use of areal reduction factors (or lack thereof). The areal reduction factor must be obtained from NOAA Atlases or publications of Regional Climate Centers, and State and local agencies responsible for flood control.

The preceding discussion was related to the use of a design storm rainfall (e.g., 1-percent-annual-chance event) for estimating the flood discharges. Continuous simulation rainfall-runoff models, such as HSPF, are occasionally used to estimate the flood discharges. These models account for changes in soil moisture between storm events, and they use observed rainfall and other climatic data to estimate flood discharges. Frequency analyses are then performed on the simulated peak flows to determine the design discharges such as the base flood discharge. This approach is applicable if long-term continuous rainfall data are available for the studied watershed. Continuous simulation models developed for FISs must be capable of predicting high flow events and should be verified against selected high flood events observed within the watershed.

Rainfall Losses

Runoff or effective rainfall is that portion of the rainfall that flows overland, into channels, and past the basin outlet. The portion that does not reach the outlet is the rainfall loss. Rainfall-runoff models typically offer several options for computing losses. Rainfall losses are attributed to an initial loss (from interception by vegetation and/or from ponding in local depressions in the ground surface) that must be satisfied before runoff occurs, and infiltration that is subtracted continuously from the rainfall. In practice, rainfall-runoff models compute the rainfall loss in a time step and subtract that amount from the rainfall in that time step, converting rainfall depth values to runoff depth values.

Rainfall losses depend on factors such as soil type, vegetation type and density, land use, percent of impervious area, and antecedent runoff conditions, a measure of how dry or wet a watershed is at the beginning of a storm. Runoff computations are generally performed at the sub-basin level, so input data are required for each sub-basin. The Mapping Partner must document in the hydrology report the methods used to compute rainfall losses, the reasoning for using those methods, and the sources of data and methods used to measure parameters. Because some parameters depend on the wetted condition of a watershed and infrequent events tend to follow wetter than usual conditions, the Mapping Partner must document the antecedent moisture level modeled for each frequency.

Several different infiltration equations are used to estimate losses and the associated runoff. These equations range from the NRCS runoff curve number that is empirically based to more physically based methods such as the Green-Ampt equation. The physically based methods are more accurate. The choice of methods is often based on the availability of data and models and guidelines recommended by State and Regional agencies.

The NRCS runoff curve number approach is a frequently used empirical method for determining rainfall losses. Guidance on estimating the NRCS runoff curve number is provided in the NRCS National Engineering Handbook (USDA, 2004). The land use and soils data needed to estimate the runoff curve number are available on USGS and NRCS web sites. The NRCS runoff curve number computation is dependent on antecedent runoff conditions and assumes an initial abstraction that is a function of the soil's properties.

Infiltration equations determine the rate at which the soil absorbs falling rain, melting snow or surface water. A closely related process is percolation defined as the rate at which soil moisture moves down through the lower soils layers or the permeable rock. If the underlying soil layers are different from the upper soil layers, the steady state infiltration rate may vary significantly from the percolation rate. This condition exists in watersheds with very sandy soils or karst terrains. Initial values of percolation rates should be estimated from field tests.

In areas with a high groundwater table, the total amount of infiltration and percolation is rather low even though the soil matrix is capable of higher infiltration and percolation rates. A hydrologic model used for simulating infiltration and percolation losses should account for all the flows entering, moving within, and leaving the system, as well as storage changes within the system. It is not acceptable to simply model the percolation as the amount of water disappearing from the system. If a perched groundwater table exists at or near an impermeable layer, it must be reflected in the model setup or parameter determination.

Percolation is a relatively slow process compared to surface runoff. An event-based model typically simulating surface runoff hydrographs for a rainfall duration of 24 hours or shorter is usually not sufficient to reflect the impact of percolation, especially changes of groundwater levels. To fully simulate the impacts of percolation, the simulation period should be determined by physical conditions such as the watershed size and soil characteristics. The simulation period should be at least 48 hours longer than the surface runoff hydrograph associated with the design rainfall event.

Sub-basin Response

The sub-basin response is the outflow from the sub-basin expressed as a function of time (outflow hydrograph) resulting from the runoff generated over the sub-basin, also expressed as a function of time (effective rainfall hyetograph). Sub-basin response can be modeled as a series of hydraulic processes, such as overland flow into small collector channels that, in turn, convey flow to a main channel that conveys flow to the sub-basin outlet or concentration point; or as a response function, the unit hydrograph, which is characteristic of the sub-basin. The unit hydrograph approach is preferred for developing FISs, if applicable. If the Mapping Partner uses an option to model the response as hydraulic processes, that option must be fully documented in the hydrology report, including the reasoning for choosing it in lieu of a unit hydrograph approach.

Most models offer several well-known, synthetic, unit hydrograph options. Those options require one or more parameters that set the shape and timing of the unit hydrograph. The NRCS unit hydrograph is an example of a commonly used approach (USDA, 2007). Mapping Partners must document in the hydrology report the reasoning for using a particular option and the sources and methods for measuring data and determining the input parameters.

A unit hydrograph may be input as a table of flow values corresponding to a unit of runoff for a period equal to the input time increment for the rainfall. In that case, the unit hydrograph is derived from runoff and outflow data. If a unit hydrograph is input as a table, the Mapping Partner must document its derivation, including the sources of rainfall and runoff data and the outflow hydrograph.

Routing

As a flood wave travels downstream along a stream reach, it tends to spread out due, in part, to storage in the channel and floodplain. The hydrograph at the downstream end of the reach is not only shifted by the amount of time it takes to traverse the reach (lag time), but its shape is also changed (attenuation). Routing is the way that rainfall-runoff models account for the change in shape and timing of hydrographs as the computations move through the stream reach system, including reservoirs and lakes within the system. The Mapping Partner must fully document the routing methods used, including the values of input parameters, the derivation of those parameters, and methods of measurements and sources from which data supporting those parameters were obtained or measured.

Some models include an option to account for channel infiltration (USDA, 2007). If channel infiltration is modeled, the Mapping Partner must fully document the approach for calculating losses and the sources and methods of measurement of parameters used in the approach. If considering encroachment into the floodplain affects the computation of channel losses, the effects must be clearly documented in both the submitted report and the model input. The documentation must include mapping where applicable and identification of all regulatory floodways shown on FIRMs that overlap the infiltration areas. If such overlaps exist, the Mapping Partner must prepare a revised model of the base flood, removing infiltration considerations within floodways.

Diversions are defined as water leaving the watershed. The methods or data used for estimating diversions in the model must be fully documented.

Input Hydrograph

Rainfall-runoff models usually provide for introducing an inflow hydrograph into the stream reach system. Inflow hydrographs, in this context, are user-supplied and independent of rainfall, runoff, and sub-basin response portions of the model. However, input hydrographs are subject to the routing and combining functions of the model and, therefore, must be synchronous with the model (the input hyetograph, in particular).

The Mapping Partner must clearly document the source of inflow hydrographs in the hydrology report. The Mapping Partner must ensure that the derivations of input hydrographs meet the documentation requirements and standards set forth herein, including synchronization with the input rainfall.

Channel Storage

Some channel routing techniques do not account for storage, but do result in attenuated hydrographs. The Mapping Partner should use routing techniques that account for storage. In many cases, the amount of attenuation depends on the number of sub-reaches or the number of steps by which a reach is divided.

When using channel storage routing techniques, the parameter documentation should explain the relation between storage and the extent of floodplain. If considering encroachment into the floodplain that can affect the computation of storage, the effects must be clearly documented in the hydrology report. The documentation must include mapping where applicable and identification of all regulatory floodways shown on FIRMs that overlap storage areas. If such overlaps exist, the Mapping Partner must prepare a revised model of the base flood removing storage considerations within floodways.

Reservoir Storage

The effects of reservoir storage on inflow hydrographs are accounted for through direct routing or an elevation-storage-outflow relation or equivalent that describes the operation of the reservoir. The Mapping Partner must fully document the elevation-storage-outflow relation if used, including sources of data regarding reservoir operation, the outlet structure, and methods, sources, and measurements of data used to define the relation. The Mapping Partner must not consider the storage capability below Normal Pool Elevation of reservoirs operated primarily for purposes other than flood control because the availability of such storage is uncertain. The exception is when all of the following have been met:

- Operation of the project in accordance with its documented water control plan could affect the BFEs in a community by 1 foot or more.
- The storage capability to be considered is totally dedicated to flood control. Where different amounts of storage can be totally dedicated during different parts of the year, the Mapping Partner must obtain flood discharges from the joint probability combination of frequency curves established for each part of the year that the different storage levels are dedicated. Joint use storage based on forecasted inflow is not acceptable for NFIP purposes.
- A project water control plan providing explicit details of operation during flooding conditions is in effect and has been reviewed and approved by FEMA or another Federal agency responsible for Federal flood-control activities. The Mapping Partner must contact the RPO to discuss the review and approval process.
- A written commitment to dedication of the flood-storage capacity and to the approved reservoir operation plan is assured through a mandatory condition of Federal or State licensing or through a direct agreement between the project operator and FEMA for non-Federal projects.

The information regarding the operation of reservoirs should have been obtained and evaluated during the scoping process. Whether and how a reservoir is to be analyzed is decided at the scoping meeting. If hydrologic analyses commence without those directions, the Mapping Partner should perform the required analyses, present those analyses to the RPO, and obtain direction on how to proceed.

The impoundment of floodwaters caused by undersized culverts and high road embankments can be modeled using reservoir modeling procedures.

Calibration of Hydrologic Models

Calibration of runoff, sub-basin response, and routing parameters are performed through modeling major historic storms over the watershed where rainfall and outflow data are available. By comparing the measured outflow from a storm to the modeled outflow, 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 modeling parameters.

The Mapping Partner must calibrate the model where practicable and fully document the process in the hydrology report, including dates, measurements, and locations of measurements of historic storms; parameters revised and rationale for revising; and input and output data for the calibrated model. This calibration should be performed using historic storms that exceed the 10-percent-annual-chance event where practicable.

The Mapping Partner must compare results from modeling various frequency storms with discharge-frequency relations derived from stream gage data, if available, or with estimates from applicable regional regression equations, if applicable, and document the comparison and any resulting adjustments. The Mapping Partner should plot the peak outflows associated with the base flood for all sub-basin outlets and confluences in the model on the discharge-drainage area graphs in the hydrologic report. The Mapping Partner should compare the model outflow-drainage area values with those based on gaging station and regression estimates (if applicable), and document the comparison and any adjustments made as a result. The documentation must include a discussion of the reasonableness of the model output.

If reasonable agreement cannot be reached by maintaining calibration parameters within acceptable ranges, the Mapping Partner should review the data, the model methodology, and its application to the watershed. Where models are calibrated against historic storms and the modeled flood discharges do not agree with frequency estimates from stream gage data or regression estimates, the Mapping Partner may consider adjusting the design rainfall volume and distribution.

C.2.5 Hydrology Submittal Standards [November 2009]

The Mapping Partner must submit all hydrologic data in digital format as described in Appendix M, *Data Capture Standards*. The Mapping Partner must submit files by uploading them to the MIP (https://hazards.fema.gov), or other media may be acceptable if coordinated with FEMA.

C.2.6 Hydrologic Review Procedures [November 2009]

The goal of the hydrologic review is to provide an assessment of the "reasonableness" of the proposed base flood discharges and, if necessary, to suggest alternative methods that may provide more reasonable flood discharges. The reasonableness of a flood discharge depends on the study requirements and hydrologic conditions in the region of interest. The Mapping Partner reviewing the hydrologic analysis must evaluate the reasonableness of the proposed flood discharges using procedures described below.

C.2.6.1 Review of Rainfall-Runoff Models [November 2009]

The Mapping Partner reviewing hydrologic analyses based on rainfall-runoff models must compare the proposed base flood discharges to the flood discharges from USGS regional regression equations (if applicable); to flood discharges at gaging stations in the vicinity of the study; to the effective discharges; and to other hydrologic estimates as appropriate. If the rainfall-runoff model was calibrated to discharge-frequency relations (stream gages and/or regional regression equations), most of the hydrologic review has been completed. If not, the reviewing Mapping Partner must plot the flood discharge estimates from these sources against drainage areas on logarithmic paper to determine if the proposed base flood discharges are reasonable. The proposed base flood discharges from the rainfall-runoff model are considered reasonable if they are generally within one standard error (68-percent confidence interval) of the regression and gaging station estimates. Differences between the proposed and effective discharges must be documented in the hydrology report and an explanation given as to why they are different.

If the proposed discharges are determined to be unreasonable, the model parameters should be reviewed to determine if they are within the range of engineering practice. The model parameters should either be revised to conform to engineering practice or their values justified.

C.2.6.2 Review of Regional Regression Equations [November 2009]

The Mapping Partner reviewing hydrologic analyses based on regional regression equations must compare the proposed base flood discharges to gaging station estimates in nearby watersheds having similar characteristics (such as drainage area, mean basin elevation, or mean annual precipitation) to those of the studied streams, to the effective discharges, and other hydrologic estimates as appropriate. The reviewing Mapping Partner must plot the base flood discharge estimates from these sources against drainage area on logarithmic paper to determine if the proposed flood discharges are reasonable. The proposed base flood discharges from the regression equations are considered reasonable if they are generally within one standard error (68-percent confidence intervals) of the gaging station estimates. Differences between the proposed and effective discharges must be documented in the hydrology report and an explanation given as to why they are different.

C.2.6.3 Review of Stream Gage Analyses [November 2009]

Proposed base flood discharges based on gaging station data must be reviewed for conformance to the guidelines in Bulletin 17B (IACWD, 1982). If procedures other than those outlined in Bulletin 17B were applied, the reviewing Mapping Partner must determine whether these procedures and the base flood discharges are reasonable. At least 10 years of record are needed to define the base flood discharge. In more arid regions, there are often many years when the annual peak flow is zero. For these conditions, at least 10 years of non-zero flows are recommended for defining the base flood discharge.

Flood-frequency curves for gaging stations are routinely published by the USGS as part of regional flood studies. The reviewing Mapping Partner can compare these published flood discharges to the proposed flood discharges to judge their reasonableness. In cases where major flood events have occurred since the flood-frequency curves were published, the reviewing Mapping Partner must confirm that the impacts of these events have been reflected in the flood discharge calculations.

C.2.6.4 Example of Hydrologic Review Procedures [November 2009]

The restudy for Lake County, California, is used to illustrate the hydrologic review procedures. Three streams were studied in Lake County, including two unregulated streams and one regulated stream. Two of the studied streams have gaging stations on unregulated reaches. The effective base flood discharges, gaging station estimates, and USGS regression estimates (USGS Water Resources Investigation [WRI] 77-21) are compared to the proposed base discharges from a HEC-1 model in Figure C-1. Plus and minus one standard error bars are shown around the gaging station estimates and plus one standard error for the regression estimates. As illustrated in Figure C-1, the proposed HEC-1 discharges for the unregulated streams are generally within one standard error of the gaging station and regression estimates. The proposed HEC-1 discharges that plot significantly below the other data are for the regulated reaches of streams where the discharges are reduced by upstream flood control structures.

The standard errors for the gaging station estimates can be estimated using the 68-percent confidence interval as defined in Appendix 9 of Bulletin 17B (IACWD, 1982) or by procedures described in Kite (1999) or Stedinger and others (1993). The standard errors for the USGS regression equations are given in USGS WRI 77-21.

Based on the comparisons to the effective discharges, the gaging station and regression estimates as shown in Figure C-1, the proposed HEC-1 base flood discharges for the unregulated streams are considered reasonable and suitable for use in the hydraulic analysis. The regulated flood discharges are also considered reasonable if the peak inflows to the flood control reservoirs are reasonable and acceptable reservoir routing procedures are used.

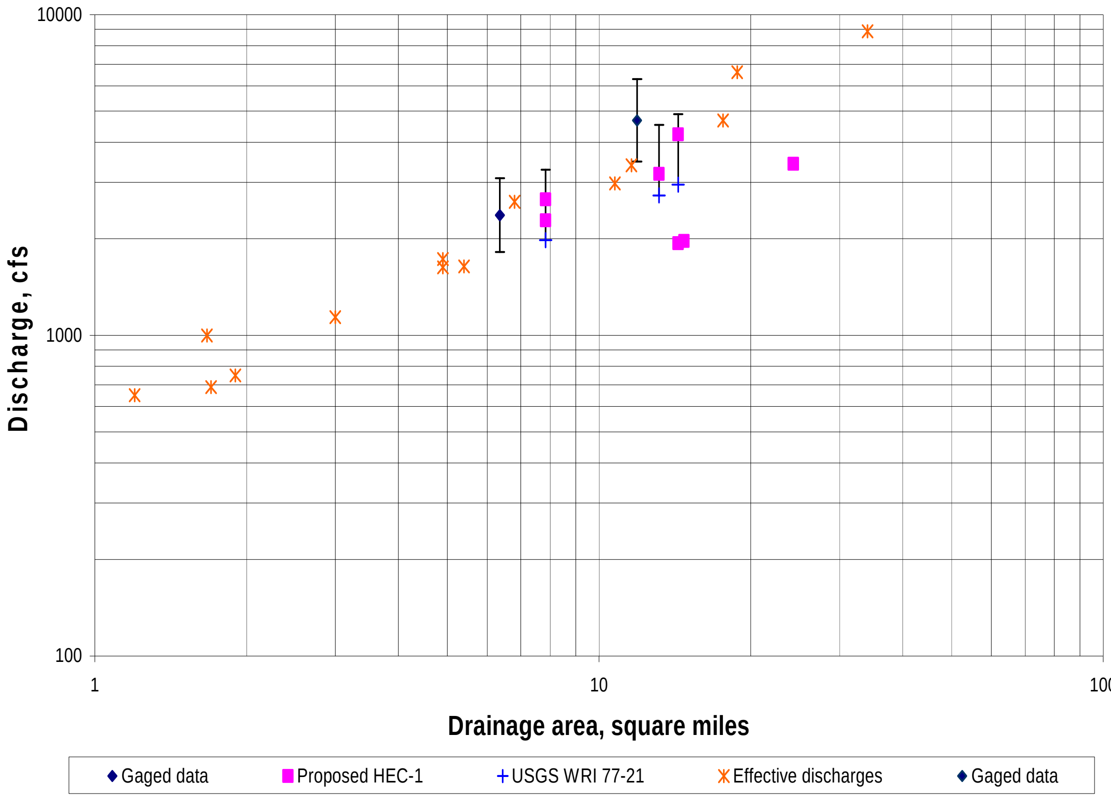


Figure C-1 Comparison of the proposed base flood discharges to gaging station, regression, and effective discharges for streams in Lake County, California.

C.2.6.5 Hydrologic Review Documentation [November 2009]

The reviewing Mapping Partner must document the results of the review in a memorandum or letter and deliver it to the Mapping Partner that performed the hydrologic analysis. The documentation must describe the review approach and conclusions (whether flood discharges are reasonable or unreasonable) and should provide options for resolving any concerns. This report should be uploaded to the MIP as described in Appendix M, *Data Capture Standards.*

If the proposed flood discharges are determined to be unreasonable, the options may include, but are not limited to the following:

- Requesting further justification or documentation that the proposed base flood discharges should be used;
- Suggesting an alternate method; or
- Revising the analysis to obtain more reasonable results.

C.3 Hydraulic Analyses [November 2009]

Hydraulic analyses should be updated on a watershed basis to achieve consistent analyses on a given stream and minimize the effects of any mismatches across community, county, and State boundaries. Hydraulic analyses are performed to determine elevations associated with the water-surface of each flood frequency studied and to determine the extent to which the floodwaters for those events inundate otherwise dry land. Choice of hydraulic procedures, hydraulic analysis requirements, and hydraulic analysis procedures are described in this section.

The Mapping Partner must obtain the hydraulic models used to develop the information shown on the effective FIRM. If the effective computer program is not available or its use is inappropriate to reflect the existing floodplain, the Mapping Partner must document why the effective computer program cannot be used and why the new computer program is more appropriate. The Mapping Partner should identify methodologies and data that have been updated or changed since the analyses reflected on the FIRM were performed. Major factors influencing the new study include:

- Hydraulic modeling computer program that upgrades or supersedes computer program used to develop the FIRM;
- Topographic information that is more accurate and/or of higher resolution than the topographic information reflected in the hydraulic analyses used to develop the FIRM and reflects physical changes;
- Discharge-frequency relations different from those reflected in the hydraulic model used to develop the FIRM.

Detailed guidance on identification of methodologies and data is provided in Appendix I of these *Guidelines*.

The Mapping Partner must incorporate floodplain changes in the hydraulic model that may affect the water-surface elevations reflected on the FIRM. These changes should have been identified during validation of the engineering data and include (but not limited to):

- Development within floodplains shown on the FIRM;
- Changes in the alignment of the stream, the carrying capacity of the channel, and other geo-morphological changes;
- Construction, modification, or removal of flood-control structures, including dams, certified levee systems, and diversion facilities;
- Construction, modification, or removal of other hydraulic structures, particularly culverts and bridges;
- Revised operating procedures of existing flood control structures, diversion, or levee system projects.

In addition, the Mapping Partner should identify and incorporate data and regulation changes, such as

- More accurate and detailed topographic data;
- Changes in Federal/State/local regulations; and
- Changes in community needs and priorities.

C.3.1 Choice of Hydraulic Procedures [November 2009]

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 study types are differentiated by the acquisition and measurement of the data used in the hydraulic model as well as the choice of the hydraulic procedure.

The choice of hydraulic analyses can generally be categorized as one of three types: one-dimensional steady flow, one-dimensional unsteady flow, and two-dimensional steady and unsteady flow analyses. Each of these approaches can be approached with varying levels of effort. Each approach is defined and its standards are specified in Section C.3.3, Hydraulic Analysis Procedures. The factors described below determine the appropriate modeling approach for the study.

- Developing the hydraulic model
  - 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.
  - One-dimensional unsteady flow models are most applicable to urban systems with both open channels and closed conduits; and stream systems with significant storage changes, reversed flow, or subject to rapidly varied flow and wave changes. For such streams, storage-discharge curves are usually looped.
  - Two-dimensional 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.
- Acquisition and measurement of data used in the model include,
  - Placement (number) of cross sections
  - Surveyed cross-section data
  - Cross-section data from interpretation of other topographic mapping (contoured or digital) or aerial photographs

- “Typical” cross section(s) adjusted to vertical datum, if necessary
- Surveyed bridge data
- “As-built” bridge plans
- Bridge opening dimensions adjusted to vertical datum
- “Typical” bridge configuration(s)

- Assigning or deriving parameters used in the model
  - Adjustment through model calibration
  - Loss coefficient estimates from on-site inspection
  - Loss coefficient estimates from aerial photographs

C.3.2 Hydraulic Analysis Requirements [November 2009]

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

- For all areas within the continental United States, elevations must be referenced to the North America Vertical Datum of 1988 (NAVD88), unless a waiver is granted based upon requests from community CEOs for all jurisdictions included on the flood map.
- The Mapping Partner must use the effective model unless justification can be provided as to why the new model is more appropriate. The Mapping Partner must use one of the hydraulic models listed under “Numerical Models Meeting the Minimum Requirements for the NFIP” which is posted on FEMA’s web site. Input and output files for the model and georeferenced spatial files showing hydraulic features used for the modeling must be submitted in accordance with Appendix M, *Data Capture Standards*, of these *Guidelines*.
- Cross sections must be placed perpendicular to flood flow and extend beyond the 0.2-percent-annual-chance floodplain boundaries on either side of the stream. See Section C.3.3.1 for additional information and guidance.
- Hydraulic structures that are designated to divert flood flow from its natural path, such as flood gates and diversion channels, must be included in the hydraulic modeling and clearly labeled on all maps. See Section C.3.3.1 for additional information and guidance.
- Unless where a clearly identified change in flood characteristics or an error in the existing data can be shown, BFEs for the stream reach studied must agree with those of other contiguous studies of the same flooding source within 0.5 foot. See Section C.3.3.1 for additional information and guidance.
- The Mapping Partner must inform the RPO when split flow paths lead into another jurisdiction where a regulatory floodway has not been computed, thus necessitating that the split flow or overbank flow paths remain unencroached.

- If split or diverted flow paths are identified in the model, the Mapping Partner must plot the applicable profiles for each of those paths separately. For all study types that require the computation of SFHA, the locations of political boundaries, if involved, must be shown. See Section C.3.3.1 for additional information and guidance.
- The Mapping Partner must coordinate with the RPO and refer to Appendix G for more guidance when using a 2-D hydraulic model on alluvial fans.
- Hydraulic models must be calibrated to all available high-water marks.
- The Mapping Partner must document in the hydraulics report the following:
    - Basic information such as the location and description of the study area, study limits, location of structures that affect water-surface elevations, including models used, hydraulic features, and any other information that supported the hydraulic analyses.
    - For each stream reach being studied with one- or two-dimensional models, documentation must include the hydraulic model to be applied including all data sources used to develop the model; the source and method of generating cross-section data; the source and method of data collection for hydraulic structures; the method of estimating loss parameters and starting water-surface elevations.
    - One-dimensional models must include a georeferenced spatial file showing the location, orientation, and extent of each cross section and each hydraulic structure adjacent to or crossing the stream. Each cross section must be labeled with a unique identifier corresponding to the same cross section used in the hydraulic model.
    - Unless surveyed in the field, include an explanation of how the hydraulic structure data were tied to a vertical datum and how the alignment of the structure relative to the stream and floodplain was determined. Where stream crossing dimensions are approximated, the reasoning leading to the approximation and the sources and means of measuring any data used in the approximation must be documented.
    - Documentation of two-dimensional 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. For models using 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).
    - For a two-dimensional analysis, the modeling of each hydraulic structure must be documented to include a list of each grid or element 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 C.3.3.1.

- The simulation history of two-dimensional models including justification of reasonableness of the initial condition must be provided. The documentation must also include a discussion of the sensitivity of the results of two-dimensional models with respect to storm history and the implications regarding the frequency assigned to the results.
- For hydraulic structures that are designated to divert flood flow from its natural path, such as flood gates and diversion channels, include the owners and operators of the structure; the date it became operational; operation, inspection, and maintenance plans; and as-built plans describing the dimensions and identifying any moving parts.
- The location and the technique used to model ineffective flow areas or storage areas (non-conveyance areas) must be provided including a clear explanation of the natural conditions where artificial data have been used. The need and use of roughness coefficients to define ineffective flow areas must be clearly documented in the FIS report.
- Explanation of how roughness coefficients were selected, including roughness coefficients to define ineffective flow areas. On-site observations must include photographs. If "n" values were adjusted based on calibration, a summary of the values before and after the adjustments must be included.
- For each stream crossing modeled, the dimensions of the crossing, values of loss coefficients, and the reasoning behind those values must be provided including a clear statement of whether those values and corresponding reasoning are based on observation, measurement, or assumption.
- For split flow and diverted flow analyses, the documentation must include a description of how the amount of flow analyzed was determined, the location along the main channel of the split or diversion, and the location of the downstream limit of analysis. The paths (profile baselines) of each split or diverted flow must be shown on the FIRM and labeled with a name that clearly associates it with the main channel.
- The effects of supercritical flow velocity on the flood carrying capacity and stability of natural or improved channels must be fully documented. Any findings on the risk of stability or flood carrying capacity of natural or improved channels during a flood must be reported to the RPO.
- For one-dimensional unsteady modeling, the downstream boundary conditions must be documented including the sources of data and the reasoning used to assign frequencies to the hydrographs. In addition, the sources for all inflow hydrographs must be provided.
- Any elevation-storage relations used in modeling of off-channel storage areas, including the methods, sources, and measurements of data used to define the relations must be fully documented.
- Digital terrain model grids developed for two-dimensional modeling must cover the entire project area.

- The derivation or development of the digital model grids must be clearly documented.
- When flow in sinuous reaches crosses the floodplain to form a more direct flow path, the flow path must be documented, shown on the FIRM, and labeled "Profile Baseline."

C.3.3 Hydraulic Analysis Procedures [November 2009]

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 reach 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.

C.3.3.1 One-dimensional Steady Flow [November 2009]

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.

Specifications for performing subcritical flow modeling are discussed below; modeling of supercritical flow will be discussed in a later section.

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; and
- Peak flow discharge.

Documentation of one-dimensional models must include a georeferenced topographic file showing the location, orientation, and extent of each cross section and each hydraulic structure adjacent to or crossing the stream. Each cross section must be labeled with a unique identifier corresponding to the same cross section used in the hydraulic model. River miles should be used as cross-section identifiers for major streams.

Profile Baseline

The profile baseline is the horizontal distance along the Flood Profile as represented on the FIRM and shown in the Floodway Data Table. The profile baseline can be the distance between cross sections or nodes in a one-dimensional model. The profile baseline may be the same as the stream centerline, which is the channel configuration shown on the base map.

The flood path is, in most cases, the stream channel. However, under flooding conditions, flow in sinuous reaches may cross the floodplain to form a more direct flow path. Such cases must be documented and the flow path shown on the FIRM and labeled “Profile Baseline.” Flow distances in one-dimensional models must be referenced to the profile baseline.

Cross Sections

Cross sections must be placed perpendicular to flood flow and extend beyond the 0.2-percent-annual-chance floodplain boundaries on either 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 general slope of the flow path between adjacent cross sections should be approximately constant. Cross sections should be located at all major breaks in the streambed profile, at points of minimum and maximum cross-sectional areas, and at points where channel roughness and channel shape changes abruptly (USGS, 1984). Cross sections may be spaced further apart for types of studies that require only the SFHA parameter to be computed.

Underwater portions of cross sections need to be surveyed in the field by conventional surveying techniques for studies that require the publication of BFEs; for studies conducted for the development of the SFHA only, cross-section data can be obtained from interpretation of aerial photographs or topographic mapping. Some hydraulic models may need approximated “typical” cross sections to reflect the conveyance of flow. Cross-section data above water are obtained through conventional survey techniques, by interpretation of aerial photographs, from remotely sensed topographic data, either digital or in the form of contour maps, or approximated as a “typical” cross section. Additional details on surveying cross sections are provided in Appendix A, *Guidance for Aerial Mapping and Surveying*, of these *Guidelines*.

For each reach studied, the sources of cross-section data and methods of measurement must be fully documented. Where more than one technique is used to acquire cross-section data, the documentation must include an explanation of how the data were merged. Where cross-section geometry is approximated as “typical,” the documentation must include an explanation of how each typical cross section was developed; the sources of data used in the approximation and means of measuring those data; and how typical cross sections are aligned vertically with topographic information used for mapping.

Hydraulic Structures

Flow in the vicinity of hydraulic control structures may exhibit a combination of free surface flow, pressure flow, and weir flow. The hydraulic analysis in the vicinity of control structures generally uses a combination of simple steady flow hydraulic theory and discharge coefficients.

The dimensions of hydraulic structures crossing the stream must be surveyed in the field for some study types that require computation of many flood hazard parameters and flood profiles for additional frequency storms. Dimensions of hydraulic structures may be estimated by either direct measurement in the field or taken from as-built plans for some study types that require base flood and one higher frequency flood studied. The effects of the structure can be ignored if the study type requires only the SFHA boundary to be computed. The phrase “Measured in the Field” means measuring the relative dimensions of the structure without relating the structure’s elevations to a known vertical datum, as is implied by “Surveyed in the Field.” Additional details on surveying hydraulic structures are provided in Appendix A, *Guidance for Aerial Mapping and Surveying*, of these *Guidelines*.

The sources of data and means of measurement must be fully documented. Unless surveyed in the field, the documentation must include an explanation of how the data were tied to a vertical datum and how the alignment of the structure relative to the stream and floodplain was determined. Where stream crossing dimensions are approximated, the Mapping Partner must document the reasoning leading to the approximation and the sources and means of measuring any data used in the approximation.

Bridges are the most common hydraulic structure crossing a stream and may significantly affect water-surface profiles. Federal Highway Administration (FHWA) has published a series of hydraulic engineering guidelines which addressed bridge hydraulic calculations and provided detailed technical guidance. For example, FHWA Hydraulic Design Series No. 1 (HDS1, 1978) addressed a broad range of hydraulic issues of bridged waterways including water-surface profile of skewed bridges, and FHWA Hydraulic Engineer Circular No.18 (HEC-18, 2001) addressed scour at bridges. It is important to note that bridge scouring may result in significant changes in cross sections from the original design conditions; use of outdated as-built plans as the source for bridge cross sections should be avoided.

Hydraulic structures that are designated to divert flood flow from its natural path, such as flood gates and diversion channels, must be clearly labeled on all mapping and fully documented. The documentation must include identification of the owners and operators of the structure; the date it became operational; operation, inspection, and maintenance plans; and as-built plans describing the dimensions and identifying any moving parts. The structures can also be measured in the field.

As a general rule, hydraulic structures are assumed free of blockage, and debris loading is not modeled in hydraulic analysis for NFIP studies. At locations where there is evidence that a structure is likely to be blocked by siltation, structure blockage may be modeled as requested by the community and approved by the RPO. FHWA HEC-9 (2005) provides general guidelines for analyzing debris accumulations on a bridge structure and determining the impacts the debris would have on the water-surface profile.

Hydraulic structures that are a part of a levee system are addressed in Appendix H, *Guidance for Mapping of Areas Protected by Levee Systems*, of these *Guidelines*.

Ineffective Areas

Conveyance areas are those portions of cross sections through which floodwaters flow. An area adjacent to a floodplain where floodwater collects as a pond of standing water is not a conveyance area. Inundated areas adjacent to flowing floodwaters, but through which floodwaters are not conveyed, are referred to as ineffective flow areas (also as non-conveyance areas). In addition, ineffective flow areas can be used to reflect the non-conveyance flow areas created upstream and downstream of high grounds within the floodplain and those caused by the flow constriction and expansion due to topography of the floodplain. Portions of cross sections are, in general, modeled as ineffective areas in one of two ways:

- Removing the ineffective area and wetted perimeter computations through artificial data (e.g., vertical walls) incorporated in cross-section geometry or through ineffective flow, blocked obstruction, or encroachment options entered into the model; or
- Assigning artificially high roughness coefficients to the area, thereby reducing the computed flow through the area to a negligible value (if the hydraulic model does not have other capabilities to reflect ineffective flow).

The modeling technique should be chosen to reflect the natural conditions (topography and roughness) as closely as practical. The Mapping Partner must fully document the location and the technique used to model non-conveyance areas. The documentation must include a clear explanation of the natural conditions where artificial data have been used.

Energy Loss Coefficients

Friction losses are usually computed using Manning's equation, and, therefore, channel and floodplain roughness are usually expressed as Manning's "n" values. Values of "n" are estimated by observing irregularities, ground cover, and vegetation in stream channels and overbank areas and comparing those observations with channel and overbank areas that have known values. Guidance on selecting n values is given in almost any treatment of open channel hydraulics. The HEC-RAS Hydraulic Reference Manual (USACE 2001 and 2008) and the FHWA report FHWA-TS-84-202 (1984) are the most commonly used documents. Water-Supply Papers 1849 and 2339, published by the USGS (1967, 1989), are also applicable and dedicated specifically to guidance on selecting “n” values in natural channels and floodplains.

When estimating roughness coefficients, the Mapping Partner should consider the size and makeup of streambed and bank material, the slope of the channel, the type and density of vegetation in the floodplain, the degree of meandering, and the expected depth of flooding. The Mapping Partner should consider variation of roughness coefficient values with flood stage, depending upon factors such as the width-to-depth ratio of streams, vegetation in the channel and overbanks, and materials of the river bed. The Mapping Partner should carefully select roughness coefficients in overbank areas to represent the effective flow in those areas. There is a general tendency to overestimate the amount of flow occurring in overbank areas, particularly in broad, flat floodplains. The Mapping Partner must document clearly the use of roughness coefficients to define ineffective-flow areas in the documentation submitted for inclusion in the FIS report.

The most detailed observations are made in the field, and the most reliable estimates are those calibrated to historic events. An on-site visit is required to estimate roughness values for studies where results are used to define additional frequency flood profiles. Manning’s roughness values may be assigned by consulting aerial and/or oblique photographs for studies that require the computation of SFHA boundary or only one flood profile for the base flood.

The Mapping Partner must fully document how roughness coefficients were selected and computed. Documentation of on-site observations must include photographs as well as the computations used to estimate roughness coefficients. If “n” values were adjusted based on calibration, the documentation must include a summary of the values before and after the adjustments. Calibrating hydraulic models in general is discussed in Section C.3.3.4.

Most models include a calculation of eddy losses to be added to friction losses and the downstream energy. Those losses are computed as a fraction of the difference in velocity head. The fractions are typically referred to as the contraction coefficient if velocity increases in the downstream direction and as the expansion coefficient if velocity decreases in the downstream direction. Values are typically 0.1 and 0.3 for gradual contraction and expansion, respectively; and 0.3 and 0.5 at bridge structures (USACE, 2008). If warranted and approved by the RPO, the Mapping Partner may use other values for these coefficients instead of taking those standard values. The Mapping Partner must document this deviation, including justification for the different value (e.g., abrupt expansion) and the location or extent of where that reasoning applies.

Energy losses through bridges are typically calculated by subroutines in the hydraulic model or by consulting graphs and nomographs for various bridge types and openings published by the FHWA (1978, 1985). Additional information and guidance on selection of loss coefficients and other coefficients is provided in user's manuals of the hydraulic models, such as the HEC-RAS program developed by USACE (2008).

For each stream crossing modeled, the Mapping Partner must document the dimensions of the crossing, values of loss coefficients, and the reasoning behind those values. The documentation must clearly state whether those values and corresponding reasoning are based on observation, measurement, or assumption.

Starting Water-Surface Elevations

The downstream boundary condition in a one-dimensional, steady flow, step-backwater model should, whenever possible, be taken from a previously established water-surface elevation (accounting for any required vertical datum correction), such as a contiguous effective FIS immediately downstream. The Mapping Partner may need to extend the model downstream of the proposed downstream limit of study to tie into an established elevation. Except where a clearly identified change in flood characteristics or an error in the existing data can be shown, the proposed BFEs must agree with those of other contiguous studies of the same flooding source within 0.5 foot. In rare cases, if an agreement within 0.5 foot cannot be achieved, this mismatch should be identified as an unmet need, and reasons for the mismatch must be documented.

If no downstream elevation has been established, the Mapping Partner should identify any "control" cross sections in the immediate downstream vicinity of the downstream limit of study. A control cross section is a cross section at which the computed water-surface elevation is unaffected by (reasonably expected) changes in the downstream flood elevation, and the reach upstream can be treated as hydraulically independent. A control cross section can be manmade, such as a drop structure, culvert, or a bridge; or a naturally occurring constriction and/or change in grade where the flow regime passes through critical depth.

Absent established downstream elevations or a control cross section, the Mapping Partner should compute starting water-surface elevations using normal depth calculations (or slope area) at a cross section sufficiently distant downstream from the downstream limit of study so as to render the effects of uncertainties in the starting water-surface elevation negligible. For normal depth calculations, the friction slope (energy slope as defined in HEC-RAS) should be the slope of the water surface measured along the flood path (EM 1110-2-1416, USACE, 1993).

For starting conditions on tributaries, the Mapping Partner should use normal depth unless a coincident peak situation is assumed, or the tributary flow depths are higher than the corresponding mainstream events.

The assumption of coincident peaks may be appropriate if <u>all</u> of the following are true:

- The ratio of the drainage areas lies between 0.6 and 1.4;

- The times of peak flow are similar for the two combining watersheds; and
- The likelihood of both watersheds being covered by the storm being modeled is high.

If gage records are available for the basins, the Mapping Partner performing the hydraulic analysis should obtain guidance from the RPO on coincidence of peak flows using streamflow records.

When the downstream boundary of a modeled stream is within a costal tidal reach, the tidal boundary of the model is taken as equal to the Mean Higher High Water (MHHW) level of the nearby tide station. Location of tide station(s) must be verified to represent true downstream conditions. The tide level can be transferable to other locations along open coast; however, tide level at an estuary station is not transferable to locations beyond the estuary.

Split Flow, Diverted Flow

When two (or a finite) major flow directions are identified, split flow or diverted flow conditions exist. Split flow, generally, rejoins the main stream, while diverted flow is lost to the floodplain being modeled.

Split flow is the situation where floodwaters following a single well-defined flow path split and follow two or more paths separated by areas of dry land or relatively shallow flooding. In this Appendix, split flow refers to floodwaters that are separated from the main channel or primary flow path for some distance and then merge with the floodwaters from the main channel. Procedures for analyzing split flows associated with uncertain flow paths on alluvial fans are described in Appendix G of these *Guidelines*.

The Mapping Partner should examine the topography to establish that major flow directions exist and the momentum transfer between these flow paths occurs within a clearly defined area where the split flow path deviates from the main channel and joins downstream. The discharge transfer between the main stream and the split flow path is computed using an appropriate hydraulic method. Spill over flows with a nappe that contain a critical flow section can be estimated reliably using lateral weir flow equations. The discharges estimated for the diverted flow should be checked to ensure that the flow direction is from the mainstream to the floodplain; this can be achieved by selecting an appropriate weir coefficient. Selection of the appropriate location of the lateral weir profile is crucial in obtaining realistic results.

When a weir flow situation is not evident, the Mapping Partner should analyze the split flow as an additional study reach. That analysis should meet the level of effort requirements of the originating reach (main channel). Unless the split flow re-enters the main channel through a control cross section, the downstream limit of analysis should be the first cross section in the main channel downstream of the point where the paths merge.

In that case, the starting water-surface elevation for the split flow analysis should be the corresponding (same frequency) elevation at that cross section. This type of split flow is referred to as divided flow in the HEC-RAS manual (USACE, 2008) where an island or other obstruction separates flow into two or more channels over a substantial length. In this analysis, the quantity of water passing on each side of the island or obstruction should be determined because the total energy loss should be the same for both flow paths.

The Mapping Partner should verify that the flow value in the main channel and split flow path is constant. If the flow values are not constant, the Mapping Partner should verify that the results indicate shallow flooding between the main channel and overflow paths and adjacent cross sections sufficient to allow the transfer of sufficient floodwaters between the paths to account for the difference in flows.

Floodwaters overtopping low-lying basin divides, leaving the floodplain of the studied reach and flowing into an adjacent stream or body of water, are referred to herein as diverted flow; the Mapping Partner should consider possible increases in flood discharges on the adjacent stream or water body due to diverted flow, if coincident peaking conditions between the diverting and receiving streams are evident. Discharges in the diverted flow reaches are determined by applying methods applicable for split flows. Diverted flows should be analyzed as tributaries to the adjacent stream or water body. Those analyses should meet the level of effort requirements of the originating reach.

The Mapping Partner should ensure that the overland flow segment on the mainstream remains open by determining a separate regulatory floodway for the overflow path, or by a note on the FIRM stating that the overflow area should remain unencroached until a detailed hydraulic analysis is performed to establish a regulatory floodway. The Mapping Partner must inform the RPO when overland flow paths lead into another jurisdiction where a regulatory floodway has not been computed, thus necessitating that the overflow area remain unencroached.

The RPO may approve, as an alternative, that the Mapping Partner determine the regulatory floodway on the main channel downstream of the overflow area by determining the floodway profile with the total flow (including the flow lost as overflow). The Mapping Partner should compare the water-surface elevations from the floodway profile to the water-surface elevations of the 1-percent-annual-chance Flood Profile reflecting existing conditions (whose discharges in the main channel have been reduced because of flow lost as overflow) to determine surcharges. If the calculated surcharge is less than or equal to the allowable surcharge, the regulatory floodway is depicted on the main channel only. Otherwise, a separate regulatory floodway is defined for the overflow path. The Mapping Partner should add a note to the Floodway Data Table or the FIRM to identify the segment of floodway where the surcharge was computed using the reduced flow. The floodway should be revised when the diverted flow does not occur anymore and the flow is fully carried by the main stream.

Split flow and diverted flow analyses must be fully documented. The documentation must include a description of how the amount of flow analyzed was determined, the location along the main channel of the split or diversion, and the location of the downstream limit of analysis. The paths (profile baselines) of each split or diverted flow must be shown on the FIRM and labeled with a name that clearly associates it with the main channel.

Supercritical Flow

The standard step-backwater approach is an iterative process. For subcritical flow, when a steep reach is encountered where the flow would be supercritical, subsequent iterations do not converge to an answer. In such cases, calculations typically reach a limit of iterations and, then, default to the minimum energy (critical depth) and move on to the next upstream cross section. Elevations associated with supercritical flow for natural streams are not plotted on flood profiles or reflected on FIRMs. With the approval of the RPO, supercritical flood profiles may be shown for concrete lined chutes, specifically designed and constructed to carry supercritical flow.

Where supercritical flow exists in natural channels, elevations associated with critical depth should be used if subcritical flow analysis indicates critical or supercritical flow to exist for long reaches of the channel. The Mapping Partner must verify that, when calculations default to minimum energy, the maximum number of allowable iterations was not exceeded for some reason other than flow regime.

Concrete-lined channels should be analyzed by supercritical flow regime; man-made or improved channels where supercritical flow is likely should be analyzed for both subcritical and supercritical flow regimes. The hydraulic analysis should extend both upstream and downstream of the project area to have a smooth transition between subcritical and supercritical profiles. The water-surface elevations from the subcritical run are drawn downstream of the project horizontally until they cross the supercritical profiles to eliminate drawdowns. The Mapping Partner should check the effects of supercritical flow velocity on the flood carrying capacity and stability of improved channels, including erosion and super elevation of floodwaters at bends in the channel. The findings resulting from those considerations must be fully documented. The Mapping Partner must report to the RPO any findings that the stability or flood carrying capacity of improved channels may be jeopardized during a flood.

C.3.3.2 One-dimensional Unsteady Flow Modeling [November 2009]

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 would result by failure of a dam.

Unlike steady state models, which assume flow peak is constant within a stream reach and only consider 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.

Input requirements to one-dimensional unsteady state channel routing models include inflow hydrograph(s), geometry data for channel cross sections or other conduits, junctions and/or other storage areas, energy loss coefficients, and downstream boundary conditions. In addition to direct measurement, geometry data for urban watersheds are often available from databases managed by public utility agencies, such as the community's Department of Public Works. The Mapping Partner must document such data sources used to develop the hydraulic model, including name of database, format, accessibility, and contact information.

Boundary Conditions for Unsteady Flow Computations

The downstream boundary condition is usually a flood stage hydrograph or, less commonly, a flood flow hydrograph. The Mapping Partner must fully document the downstream boundary conditions including the sources of data and the reasoning used to assign frequencies to the hydrographs.

In addition, for all the frequencies studied for the FIS, the one-dimensional unsteady flow models require inflow hydrographs as upstream boundary conditions, as well as corresponding inflow hydrographs from significant tributaries, and lateral inflow hydrographs representing local direct inflow to the channel. The Mapping Partner must clearly document the source of these inflow hydrographs. The derivations and supporting documentation of input hydrographs should meet the requirements and standards set forth in Section C.2.4.4, Rainfall-runoff Models, including synchronization of all input hydrographs. Observed historical hydrographs provide valuable reference for synchronization and can be used in model calibration; however, they should not be assigned any frequency unless frequency of the historical event has been established through separate studies. In such a case, the Mapping Partner must provide documentation of the study.

Non-conveyance Areas for Unsteady Flow Computations

Non-conveyance portions of cross sections for unsteady flow computations can be designated as ineffective areas in modeling; these cross-section areas can still be considered in the storage computations.

Many one-dimensional unsteady flow models have the capability to explicitly model off-channel storage areas connected to the channel. These storage areas are usually defined by elevation-volume or elevation-surface area relations or modeled by user-defined flow allocation ratios. Such areas should be clearly labeled with a unique identifier corresponding to the storage area used in the model. The Mapping Partner must fully document any elevation-storage relationships used in the analysis, including the methods, sources, and measurements of data used to define the relationships.

C.3.3.3 Two-dimensional Models [November 2009]

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 are 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.

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.

Within a stream channel, flow depths within a computational grid or element are likely to vary and the flow is more likely to have one general flow direction. For wide floodplains with defined channels, one-dimensional cross-section based analysis may be appropriate to represent the channel flow. Several of the two-dimensional computer programs in the accepted models list include the capability to provide one-dimensional unsteady flow solutions within the stream channel and two-dimensional flow solutions for the wide overbank floodplains. They have the capacity to model channel flow as one-dimensional and overbank floodplain flow as two-dimensional. Such models should be used for floodplains with clearly defined channel systems.

Two-dimensional models may be used to model areas subject to alluvial fan flooding, or flat terrain where runoff occurs as shallow flow over the floodplain. The Mapping Partner must coordinate with the RPO and should refer to Appendix G, *Guidance for Alluvial Fan Flooding Analyses and Mapping*, for more guidance when using two-dimensional hydraulic models on alluvial fans.

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. Reliable guidance is not available to select roughness coefficients to represent two-dimensional flow; until such data evolves through acquired experience, every effort should be taken to calibrate the hydraulic model to observation.

Topographic Information

Two-dimensional 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 grid must cover the entire project area and the derivation or development of the grid must be clearly documented.

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. 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 Section C.4.4.2, Floodway Determination Using Two-dimensional Models. The Mapping Partner should not size cells specifically to remove certain structures or lots from the floodplain.

Documentation of two-dimensional 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).

Hydraulic Structures in Two-dimensional Models

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 C.3.3.1, One-dimensional Steady Flow.

Non-conveyance Areas in Two-Dimensional Models

Because two-dimensional 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. Non-conveyance areas are modeled through input data in one of two ways:

- Removing the cells covering the area from computations through options provided by the model ("turning the cells off") or by incorporating artificial data (high elevations); or
- Assigning artificially high values of roughness coefficients or other appropriate parameters to the cells covering the area and thereby reducing the computed flow through the cells to a negligible value.

The modeling technique should be chosen to reflect the natural conditions (topography and roughness) as closely as practical. Artificially removing cells from computation (for example, 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.

Energy Loss Coefficients in Two-dimensional Models

Cells are analogous to intervening reaches between cross sections in one-dimensional models. For example, each cell is assigned a roughness coefficient. As in one-dimensional modeling, roughness is described by Manning's "n." Mapping Partners must document roughness coefficients as described in Loss Parameters under Section C.3.3.1, One-dimensional Steady Flow. Roughness coefficient ranges available for different land cover categories are established through one-dimensional steady flow computations. Therefore, the roughness coefficients applied in a two-dimensional analysis should be validated through calibration.

Initial Conditions in Two-dimensional Models

Initial conditions in two-dimensional hydraulic models are typically established by preliminary simulations (warm-up runs) until reasonable initial values are established. Two-dimensional 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 two-dimensional 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.

Boundary Conditions in Two-dimensional Models

Boundary conditions for two-dimensional models are similar to those for one-dimensional models. Rather than being associated with cross sections, boundary conditions in two-dimensional models are associated with boundary cells. The Mapping Partner should meet the requirements described in Starting Water-Surface Elevations under Section C.3.3.1, One-dimensional Steady Flow; and Boundary Conditions for Unsteady Flow Computations under Section C.3.3.2, One-dimensional Unsteady Flow, for all cells where boundary conditions are user supplied.

Some two-dimensional hydrodynamic models include rainfall-runoff modeling capabilities that produce the 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 Section C.2.4.4, Rainfall-runoff Models.

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 in Section C.3.3.2, One-dimensional Unsteady Flow Model.

Flow Paths in Two-dimensional Models

An advantage of using two-dimensional models is their capacity to identify separate flow paths in addition to the mainstream channel. Flow paths can be identified by velocity, flow rate, and flow volume. The Mapping Partner should create separate flood profiles for significant flow paths. Details of water-surface profiles are described in Section C.3.4, Water-Surface Profiles.

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 two-dimensional model.

Computer programs that offer two-dimensional and one-dimensional 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 one-dimensional analysis.

C.3.3.4 Calibration of Hydraulic Models [November 2009]

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.

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 within 0.5 foot.

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.

C.3.4 Water-Surface Profiles [November 2009]

Water-surface profiles are plots of elevation versus stream distance. The studies may require the development of flood profiles for each reach and flood frequency studied, a profile of the streambed, and the location and cross sections of the control structures located on the stream. The profiles are plotted with a constant slope between cross sections and with stream distances referenced to the profile base line. If split or diverted flow paths are identified in the model, the Mapping Partner must plot the applicable profiles for each of those paths separately. The profiles should be plotted as the projection of the terrain model or flood surfaces onto the flow path. The plots should show the locations of and clearly label:

- Each cross section;
- Splits and diversions;
- Confluences with tributaries and split flows;
- Each stream crossing with symbology depicting the top of road and low chord elevations of bridges and culverts along with the name of the bridge/culvert (e.g., Pine Street) ;
- Extents of hydraulic structures adjacent to the floodplain;
- Up- and downstream limits of study or restudy;

- Jurisdiction boundaries, if coincident with the beginning or end of the profile; and
- Extent of backwater or flooding controlling the receiving stream and depiction of the backwater elevation along the profile.

For studies for which flood profiles are included in the FIS report, the locations of political boundaries must be shown. The specifications for including water-surface profiles in an FIS report are given in Appendix J, *Format and Specifications for Flood Insurance Study Reports*, of these *Guidelines*.

C.3.5 Hydraulic Modeling for Future Hydrologic Conditions

[November 2009]

Hydraulic modeling can be used to estimate impacts of watershed changes in the future, as described in Section C.7, Future-Conditions Flood Mapping. Such hydraulic models input peak flows (for steady flow modeling) and inflow hydrographs (for unsteady flow modeling) generated by hydrologic models that reflect future watershed conditions, along with the existing geometric and topographic data. Such hydraulic models do not reflect any hydraulic changes that may occur in the future and should not be referred to as a "future-conditions hydraulic model." Water-surface elevations estimated by such models are not used to map the regulatory BFEs.

C.4 Floodway [November 2009]

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 areas 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 NFIP regulations designate a maximum height of 1.0 foot. 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.

If the State in which the mapping project is being performed has established more stringent regulations for the maximum allowable rise in water-surface elevations, through legally enforceable statutes, these regulations take precedence over the NFIP regulatory standard. In the case of streams that form the boundary between two or more States, the 1.0-foot maximum allowable rise criterion should be used unless the States have previously agreed on a lesser rise criterion. The Mapping Partner must obtain written approval of the RPO before computing or mapping a second regulatory floodway based on a criterion established by the community.

The base model for the allowable surcharge is the model used to determine the BFEs the first time a floodway was adopted for the reach. Unless it is demonstrated that the model should be revised for reasons other than encroachments into the floodplain, all subsequent revisions to the floodway are limited to the maximum allowable surcharge above the elevations determined in the base model. That way, as hydraulic models are updated to reflect encroachments into the floodway fringe, the cumulative effect of those and future encroachments is limited to the maximum allowable surcharge. If the model is revised for reasons other than encroachments into the floodplain (such as increased discharges), the revised model, excluding any revisions attributable to loss of conveyance areas resulting from floodplain encroachment, is the base model for future floodway analyses.

Regulatory floodways are not normally delineated in coastal high-hazard areas (i.e., Zones V1-30, VE, and V). The computation of regulatory floodways on riverine flooding sources in coastal floodplains is based on the base flood discharge and elevations of the riverine flooding source only. The regulatory floodway must be terminated at the boundary of the V1-30, VE, or V Zone or where the mean high tide exceeds the 1-percent-annual-chance riverine flood elevation, whichever occurs further upstream.

The following sections provide guidance and requirements associated with floodway determinations.

C.4.1 Floodway Requirements [November 2009]

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

- Mapping Partners must coordinate all regulatory floodway determinations with community officials, as well as the State NFIP Coordinator and FEMA, as early as possible in the study process. Refer to Section C.4.2 for additional information and guidance.
- If a State has established more stringent regulations for the maximum allowable rise in water-surface elevations, through legally enforceable statutes, these regulations take precedence over the NFIP regulatory standard for floodway determinations.
- In the case of streams that form the boundary between two or more States with different allowable rise, the Mapping Partner must obtain written approval of the RPO before computing or mapping a second regulatory floodway based on a criterion established by the community.
- The regulatory floodway must be terminated at the boundary of the Zone V1-30, VE, or V or where the mean high tide exceeds the 1-percent-annual-chance riverine flood elevation, whichever occurs further upstream.
- The technique of using artificially high roughness coefficients <u>must not</u> be used to determine encroachment stations for floodway analyses in one-dimensional steady flow analysis.
- If a floodway exists upstream or downstream of the study reach, the floodway data for the study reach must match the floodway data for the existing study.
- If a floodway does not exist immediately downstream of the study reach or if the study reach begins at the mouth of the stream, the Mapping Partner must start the encroachment analysis at a width yielding the maximum allowable surcharge for a normal depth calculation using the same friction slope as the unencroached profile. Refer to Section C.4.3.1 for additional information and guidance.
- Surcharge values must be between zero (0.0) and the maximum allowable value in the respective community. Refer to Section C.4.3.4. for additional information and guidance. Negative surcharge values in the floodway modeling are not acceptable.
- For floodway determinations that use alternative methodologies other than steady-state, one-dimensional models, Mapping Partners must receive approval from the RPO and agreement from the communities involved. Refer to Section C.4.4 for additional information and guidance.
- The interpolated floodway boundaries between cross sections must be smooth lines following the general flow direction of floodwaters. The floodway must be shown in a georeferenced spatial file submitted as part of the hydraulics submittal. A floodway data table must be created as described in Section C.4.5 to document the floodway analysis. Refer to Section C.4.5 for additional information and guidance.

- The Mapping Partner must document in the hydraulics report and submit the following:
  - All discussions and decisions regarding floodway development with community officials, as well as the State NFIP Coordinator and FEMA, must be documented. Refer to Section C.4.2 for additional information and guidance.
  - Where there are discrepancies identified between the floodway data table and floodway model, the Mapping Partner must document the magnitude of and reason for the mismatch and suggest remedies to the RPO. Refer to Section C.4.3.1 for additional information and guidance.
  - The Mapping Partner must submit the hydraulic and floodway data in digital format to the MIP as described in Appendix M, *Data Capture Standards*, of these *Guidelines*.

C.4.2 Floodway Coordination [November 2009]

Because the floodway is the community's tool to mitigate flood losses by restricting encroachments into the floodplain, Mapping Partners must coordinate all regulatory floodway determinations with community officials, as well as the State NFIP Coordinator and FEMA, as early as possible in the study process.

Where communities have adopted a regulatory floodway, the Mapping Partner must use the configuration of the adopted floodway to the extent practical to compute floodway data along restudied streams. If the surcharge values are greater than the maximum allowable above the base condition, the Mapping Partner must inform the RPO and community. In such cases, the Mapping Partner must coordinate a revised configuration with the community and the RPO.

Where communities have not adopted a regulatory floodway or where the scope of work calls for a revised configuration, the Mapping Partner must coordinate the floodway configuration with the community and RPO. The Mapping Partner must discuss options for determining the floodway with community officials and the RPO. Those discussions should include:

- The establishment of the base condition for this floodway determination and future floodway revisions;
- The effects of high velocities on fill, and structures and preferences the community may have for restricting encroachments into high velocity areas or encroachments that may result in high velocities elsewhere;
- The restrictive nature of the regulatory floodway and means to distribute the restrictions evenly, such as determining the limits through equal conveyance reduction on both sides of the channel; and
- The use of public land such as parkland to offset restrictions in other parts of the floodplain.

The agreed upon approach must be fully documented in the hydraulics report including the reasoning leading to the encroachment methods and minutes of coordination meetings. Meeting minutes must include the date, time, and location of the meeting and a list of attendees. If the community cannot agree upon an approach, the Mapping Partner must consult the RPO for direction.

If more than one community is affected by the floodway, all affected communities must be included in the discussions. In the case that one of the communities sharing the same reach has more stringent allowable maximum surcharges, the Mapping Partner must describe any differences in maximum allowable surcharge values and facilitate an agreement among the communities as to the maximum surcharge and the floodway configuration to be applied to the shared reaches. That agreement must be fully documented including the date, time, and location of the meeting, and signed by all parties in attendance. If such an agreement cannot be reached, the Mapping Partner must seek guidance from the RPO. When the floodway has been established for either or both upstream or downstream communities, the Mapping Partner must coordinate with all involved communities to create a smooth transition of floodway surcharges and ensure the surcharges are within the maximum allowable limit. Detailed guidance for such transitions is described in Section C.4.3, Floodway Analyses- Steady State.

C.4.3 Floodway Analyses – Steady State [November 2009]

Floodways are determined by modeling the floodway fringe as a non-conveyance area. The technique of using artificially high roughness coefficients must not be used for floodway analyses in one-dimensional steady flow analysis. The Mapping Partner should use the most recent existing conditions model and limit surcharges to the maximum allowable above the base conditions 1-percent-annual-chance profile. Typically, the Mapping Partner should use an equal conveyance reduction method to establish the regulatory floodway.

When flow is in the supercritical regime for manmade channels, or where velocity conditions are such that normal encroachment analyses are not possible or are inappropriate, the encroachment stations should be computed so that the allowable rise in water-surface elevation matches the target water surface without exceeding the target energy.

C.4.3.1 Boundary of Floodway Analyses [November 2009]

Most floodways are determined using a step-backwater model. If a floodway exists at the downstream limit of study on the same stream as the study reach, the floodway must be configured so that the floodway data at the downstream limit of study match the floodway data at the upstream limit of the existing study.

In case a discrepancy is identified between the floodway data table and floodway model, the Mapping Partner must document the magnitude of and reason for the mismatch and suggest remedies to the RPO. Once the data match, the floodway analysis is based on a starting water-surface elevation associated with the maximum allowable surcharge. That way, future (allowable) revisions to the downstream floodway should not create surcharges greater than the maximum allowable in the study reach.

If a floodway does not exist immediately downstream of the study reach or if the study reach begins at the mouth of the stream, the Mapping Partner must start the encroachment analysis at a width yielding the maximum allowable surcharge for a normal depth calculation using the same friction slope as the unencroached profile. If a floodway does not exist immediately downstream of the study reach, the Mapping Partner should start the analysis sufficiently downstream of the downstream limit of study so that differences in the starting conditions do not create surcharges greater than the maximum allowed within the study reach. That way, future floodway designations downstream should not create surcharges greater than the maximum allowable in the study reach.

If a floodway exists at the upstream limit of study, the floodway must be configured so that the floodway data at the upstream limit of the study match the floodway data at the downstream limit of the existing study.

C.4.3.2 Storage [November 2009]

Storage considerations in hydrologic and hydraulic modeling of the unencroached condition should be revised to reflect any encroachment into storage areas indicated by the floodway configuration.

If designated storage areas behind structures are accounted for in the flood discharge computations by routing the base flood hydrograph, no encroachment is to be allowed; the floodway encroachment stations should be equal to the base floodplain boundary of the storage area. In this case, the Mapping Partner should use the same flood discharge for the unencroached and encroached profiles in the step-backwater analysis to determine the surcharge values. However, if the storage capacity exists but is not accounted for in the routing base flood hydrograph, it can be encroached; the Mapping Partner should determine the flood discharges for the encroached profile downstream of the structure by routing the 1-percent-annual-chance flood hydrograph through the reduced storage area. In this case, the flood discharge for the encroached profile may be greater than the flood discharge for the unencroached profile in the step-backwater analysis.

As discussed in Routing and Channel Storage under Section C.2.4.4, Rainfall-runoff Models, if hydrologic modeling includes channel storage areas that reduce flood discharges, these areas should be designated as part of the floodway.

When using an unsteady state model to determine a floodway for a reach with a previously determined steady-state floodway, it is possible that the surcharge in the unsteady flow model will be higher due to loss of storage resulting from encroachment. Refer to

Floodway Determination Using Unsteady State Modeling under Section C.4.4.1 for detailed discussion.

C.4.3.3 Tributary, Split, and Diverted Flows in Floodway Analyses [November 2009]

The regulatory floodway on a tributary stream is based on the base (1-percent-annual-chance) flood discharge and elevation of that stream only and normally should not include consideration of any backwater flooding from the main stream. Therefore, the floodway elevations in the lower reach of a tributary subject to backwater flooding may be lower than those used to plot the Flood Profiles.

The Mapping Partner should re-compute flood flow values along each flow path associated with reaches with split and/or diverted flow situations, as described in Split Flow under Section C.3.2.1, One-dimensional Steady Flow, under encroached (floodway) conditions. If the primary flow path (originating reach) can safely carry the entire base flood flow without increasing flood heights more than the maximum allowable surcharge, only the primary flow path requires a floodway. If not, other flow paths require floodways.

C.4.3.4 Negative Surcharge Values [November 2009]

Surcharge values must be between zero (0.0) and the maximum allowable value in the respective community. Negative values in output data generally indicate excessive changes in velocity, conveyance capacity, or floodway width at or downstream of the cross section with the negative surcharge. Floodway configurations should be revised until all surcharge values are between zero and the maximum allowable value. Reasons for deviating from this practice should be coordinated with the RPO.

C.4.4 Floodway Analyses – Unsteady State [November 2009]

The equal conveyance reduction approach is most applicable to a steady state, one-dimensional model. In certain situations, equal conveyance reduction cannot be practically achieved in defining the floodway configuration. The Mapping Partner may use one of the alternative methods discussed below to determine the regulatory floodway configuration. Use of an alternative method must be approved by the RPO and agreed to by the communities involved.

C.4.4.1 Floodway Determination Using Unsteady State Modeling [November 2009]

Steady state models do not consider lost storage in both effective and ineffective flow areas and its impacts on flow rates and timing. However, for unsteady state models, encroachment into the floodway fringe would increase flow rates; the degree depends on the amount of storage lost. Encroachments result in storage decreases in both off-channel storage modeled with an elevation-storage curve, and in non-conveyance areas modeled with artificially high roughness coefficients. Input data for the elevation-storage curve or the values of roughness coefficients should be revised to reflect the lost storage

Due to accounting for loss of storage on floodway fringe, the volume of discharge resulting from unsteady state floodway models will likely be larger than that in the unencroached analyses. The flow rate increases are likely to cause elevation increases downstream even if the base flood is fully within the channel. If surcharges increase when unsteady state modeling is used for a reach with a previously determined steady-state floodway, the floodway width should be increased to meet the maximum allowable surcharge limit.

The equal conveyance reduction method can be performed in unsteady state modeling through an iterative process.

In general, the Mapping Partner should follow procedures described in the HEC-RAS User's Manual (HEC, 2008) to perform unsteady flow floodway analyses. The procedure uses a steady flow encroachment analysis to establish an approximate floodway and import the encroachment stations to the unsteady flow model to verify that the surcharge is within the maximum allowable limit. The Mapping Partner should incorporate peak flows from unsteady flow runs to the steady flow model to estimate the encroachment stations. When rerunning the steady flow model with encroachment stations, Mapping Partners should adjust downstream boundary conditions to reflect increases of water-surface elevation due to encroachment.

An alternative method is to perform floodway analysis using an unsteady state model directly. The Mapping Partner should use the base flood hydrograph as the inflow hydrograph and determine encroachment stations by the equal conveyance reduction method.

Equal storage reduction may be applied in the floodway determination for streams with flooding dominated by storage. In such systems, the difference between the equal conveyance reduction method and equal storage reduction method is usually not significant. The equal storage reduction method is simpler in both concept and application, and could be considered as an alternative approach for floodway determination.

C.4.4.2 Floodway Determination Using Two-dimensional Models [November 2009]

None of the FEMA-approved, two-dimensional models includes a routine to perform equal-conveyance reduction floodway analysis. Certain two-dimensional unsteady state models incorporated floodway computation procedures; however, the computation focuses on impacts of encroachment on water-surface elevation and storage in floodway fringe.

When a hydrograph is routed downstream and constrained within the floodway with a given surcharge, it moves more water downstream. If the floodway fringe is encroached, the water that previously inundated the floodway fringe areas is pushed downstream due to reduction of storage and may result in increased flow volume and water-surface elevation on the downstream floodplain. The storage routing floodway procedure fills the floodplain grid elements up to the maximum allowable surcharge before distributing flow to contiguous floodplain grid elements. Because the maximum allowable surcharge is defined by the user, this procedure can easily satisfy the floodway surcharge requirement. The method does not explicitly compute and compare conveyance reductions; the Mapping Partner must get pre-approval from the RPO to use this method and coordinate with the communities to get an approved floodway configuration.

If the floodway was previously determined by a one-dimensional model, the Mapping Partner should incorporate the encroachment stations into a two-dimensional model and run the two-dimensional model to verify that the maximum allowable surcharge is not exceeded.

C.4.5 Floodway Delineation and Data Table [November 2009]

Floodways are delineated at the encroachment stations (limits of conveyance) at cross sections and interpolated between cross sections. The interpolated boundaries must be smooth lines following the general flow direction of floodwaters, gradually widening or narrowing to reflect the changes in width between cross sections. The floodway must be shown in a georeferenced spatial file submitted as part of the hydraulics and floodplain submittal. The floodway boundaries should be mapped at the channel bank stations when the floodway surcharged elevation is lower than the channel bank elevations and the base flood is contained within the channel.

For each floodway determined under the scope of work, the Mapping Partner must create a floodway data table. The floodway data table developed as part of this analysis must contain an entry for each cross section in the model to fully document the floodway analysis (this does not imply that all cross sections will be shown in the FIS report). Each entry must include the following information:

- Cross-section identification shown in a georeferenced spatial file;
- Stream or profile baseline station of the cross section;
- Width of the floodway at the cross section;
- Wetted area of the cross section under encroached conditions;
- Average velocity of the floodwaters at the cross section under encroached conditions;
- The greater of BFEs from all flooding sources, including from backwater, affecting the cross section (regulatory elevation);
- The BFE from the existing conditions model (without floodway elevation);
- The BFE from the encroached existing conditions model (with floodway elevation);and
- Difference between with and without floodway elevations (surcharge).

Existence of high grounds in the middle of a cross section would reduce the floodway width, computed as distance between two encroachment stations. In such a case, the width of floodway should be the width as mapped and a note should be added to the Floodway Data Table (FDT) to explain the difference.

Where the floodway is mapped differently than the model results in order to meet State requirements, the Mapping Partner should document the State requirements and the location(s) that discrepancies occur.

When creating a Floodway Data Table (FDT) based on a HEC-RAS unsteady flow floodway analysis, the Mapping Partner should use floodway parameters (floodway width, section area, mean velocity of with floodway and without floodway water-surface elevation) associated with the maximum discharge at each cross section from the unsteady floodway run.

For one-dimensional, unsteady flow models with a nodal system that do not compute BFEs at cross sections, nodes and links should be used to identify locations and the flow peak of the base flood hydrograph should be presented in the floodway table. An example of a floodway data table based on a link-node model is presented in Table C-1.

Most two-dimensional models do not use cross sections. In those cases, the Mapping Partner should create a set of cross sections and an associated FDT. The cross sections should be placed at BFE contour lines and extend into the floodway fringe on both sides of the floodway. Cross sections should be placed at changes in floodway width, spaced adequately to represent stream characteristics, and with enough numbers to sufficiently represent the variation in floodway data.

Guidelines of floodway re-delineation are discussed in C.6: Floodplain Boundaries.

FLOODING SOURCE			FLOODWAY[1]			BASE FLOOD WATER-SURFACE ELEVATION			
NODES	LINKS	DISTANCE	WIDTH (FEET)	PEAK FLOW (CFS)	VELOCITY (FEET PER SECOND)	REGULATORY (FEET NAVD)	WITHOUT FLOODWAY (FEET NAVD)	WITH FLOODWAY (FEET NAVD)	INCREASE (FEET)
RALEIGH CREEK									
A		13,551				924.0	924.0	924.0	0.0
	A-B		148	2240	3.1				
B		14,488				928.1	928.1	928.1	0.0
C		15,707				932.9	932.9	933.1	0.2
	C-D		180	3280	4.5				
D		16,213				937.8	937.8	937.9	0.1
E		16,998				943.6	943.6	943.9	0.3
	E-F		42	3680	5.7				
F		17,876				955.1	955.1	955.4	0.3

[1]Values represent maximum along link

TABLE 4

FEDERAL EMERGENCY MANAGEMENT AGENCY

SWMM COUNTY, MN AND INCORPORATED AREAS

FLOODWAY DATA

EXAMPLE CREEK

Note: In a node-link model, such as SWMM, flood elevations are computed at nodes and cross sections (and hydraulic properties of flow, velocity, and flow area are defined at links that connect nodes. Selected links and corresponding nodes are shown on the table.

Table C-1 Example of Floodway Data Table based on a Link-Node Model

C.4.6 Hydraulic and Floodway Submittal [November 2009]

The Mapping Partner must submit the hydraulic and floodway data in digital format as described in Appendix M, *Data Capture Standards*, of these *Guidelines*. 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 Appendix M 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.

C.5 Hydraulic and Floodway Review [November 2009]

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.

C.5.1 Hydraulic and Floodway Review Requirements [November 2009]

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 C.5.2 through C.5.7 are met.
- The reviewing Mapping Partner must document the results of the review in a memorandum or letter and send it to the Mapping Partner that performed the hydraulic analysis. The review document must present specific comments and may include any new calculations or model runs in support of the review.

C.5.2 Regulatory Requirements and consistency Checks [November 2009]

The Mapping Partner reviewing the hydraulic analyses must ensure the following conditions are met:

- The hydraulic analysis must be performed using a FEMA-approved computer model listed under "Numerical Models Meeting the Minimum Requirements for the NFIP," which is posted on FEMA's web site;
- Elevations in the new model must tie into the elevations of the effective model within 0.5 foot at the upstream end of the new model when backwater computations are used;
- Elevations in the new model must tie into the elevations of the effective model exactly at the downstream end of the new model when backwater computations are used;
- Floodplain widths at the upstream and downstream ends of the studied reach match those shown on the effective FIRM;
- 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;

- Regulatory floodway widths at the downstream and upstream end of the new model match the effective model;
- The surcharge throughout the area of study is within acceptable limits
- A floodway run is included in the new model if the effective model included one; and
- Hydraulic and floodway modeling results are all at the same datum of NAVD88.

C.5.3 Profile, Map, and Model Agreement [November 2009]

The Mapping Partner reviewing the hydraulic analyses must ensure 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;
- 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 do not cross one another; and
- The water-surface profiles do not show drawdowns (i.e., water-surface elevation at an upstream cross section must be higher than a water-surface elevation at a downstream cross section).

C.5.4 Flood Discharges [November 2009]

The Mapping Partner reviewing the hydraulic analyses must ensure the following conditions are met:

- Flood discharges used as inputs in the new hydraulic modeling correlate with the hydrologic analysis being used (whether it is a new hydrologic analysis or an effective hydrologic analysis); and
- All frequencies of flood discharges used to prepare the effective FIS Report and FIRM are included in the new model.

C.5.5 Starting Conditions [November 2009]

The Mapping Partner reviewing the hydraulic analyses must ensure the following conditions are met:

- Starting water-surface conditions for the profiles are simulated; and
- Starting water-surface conditions and encroachment methodology for the floodway run are appropriate.

C.5.6 Basic Hydraulic Modeling [November 2009]

The Mapping Partner reviewing the hydraulic analyses must ensure 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
- The hydraulic parameters for the submitted flooding sources are spot checked against topographic maps.

C.5.7 General Review considerations [November 2009]

The Mapping Partner reviewing the hydraulic analyses must ensure 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. Design flows for the bridge and culvert provide reference for the reality check;
- 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 are calibrated where high-water marks are available, and elevations in the new model are reasonable relative to high-water marks; and
- 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.

C.5.8 Hydraulic Review Documentation [November 2009]

The reviewing Mapping Partner must 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 must 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. 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, and
- Elevations in the model tie into the elevations of tributaries that confluence with the studied reach for those tributaries not studied.

C.6 Floodplain Boundaries [November 2009]

Upon completion of the hydrologic and hydraulic analyses and the hydrologic and hydraulic reviews, the new or revised floodplains are determined, as well as the floodplain boundaries that are being revised to reflect new topographic data and/or a new base map. Subsequently, BFEs are plotted to reflect the results of the hydraulic analyses. The following sections provide guidance and requirements associated with floodplain boundary determination.

C.6.1 Floodplain Boundary Determination Requirements [November 2009]

This section summarizes FEMA's requirements for floodplain boundary determinations. 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:

- All floodplain boundaries mapped in FIRMs must meet the Floodplain Boundary Standards described in Volume 1 of these *Guidelines*;
- The Mapping Partner must delineate and display on the FIRMs floodplain boundaries for the base flood. If calculated, floodplain boundaries associated with the 0.2-percent-annual-chance flood must also be delineated and shown on the FIRMs;
- The flood boundaries mapped and flood surface contour lines must be provided in a georeferenced spatial file;
- When re-delineating effective flood hazard data, if data are not available for all cross sections, the Mapping Partner must generate the missing data using the Flood Profiles exhibit in the FIS report. The cross sections must traverse the floodplain and be oriented perpendicular to the direction of flow. If flood elevation data are not available, the elevations must be obtained from the effective profile. The Mapping Partner must use the complete set of cross sections to develop the required flood profiles. If the re-delineation topographic data indicates that the effective hydraulic analyses are no longer valid, the Mapping Partner must coordinate further actions with the RPO. Refer to Section C.6.5 for additional information and guidance;
- BFE lines must be shown in a georeferenced spatial file as specified in Appendix M of these *Guidelines* and placed along the study reach so that linear interpolation between two lines is minimally different from the base flood profile (and nowhere more than 0.5 foot). BFE lines must traverse the floodplain and be oriented perpendicular to the direction of flow. BFE lines must not cross each other or cross sections delineated in the georeferenced spatial file. Refer to Section C.6.6 for additional requirements and guidance.
- The Mapping Partner must document in the hydraulics report the following:

- The Mapping Partner must fully document the methods used to develop the flood surface and to determine flood boundaries; and
- If inspection of this file does not demonstrate that the cross sections are aligned perpendicular to the flow, the Mapping Partner must document why, contrary to what may be indicated, the flow direction is in fact perpendicular to each cross section.

C.6.2 One-dimensional Models [November 2009]

At a minimum, the Mapping Partner must delineate the floodplain boundaries of the base flood. The Mapping Partner must also delineate the floodplain boundaries associated with the 0.2-percent-annual-chance flood, if it is calculated. In addition, the magnitude of a projected base flood under future hydrologic conditions, as determined by the community, may be mapped. For those communities experiencing urban growth, flood hazards from future hydrologic conditions data may be included on the FIRMs and in the FIS reports for informational purposes, upon request of the communities. Additional information on the use of future hydrologic conditions is given in Section C.7, Future-Conditions Flood Mapping.

Floodplain boundaries are delineated on the best available topographic mapping using the water-surface elevations determined at cross sections. Between cross sections, water-surface elevations are interpolated. The interpolation is linear along smooth lines following the general direction of the flow close to the boundary. The topographic mapping should be digital, accommodating an automated or semi-automated floodplain mapping algorithm; manual delineation should be used only if digital topographic data are not available.

Except at places where floodwaters overtop low-lying basin divides and flow into an adjacent drainage basin, floodplain boundaries should be continuous.

The floodplain boundaries must be shown in a georeferenced spatial file. If inspection of this file does not demonstrate that the cross sections are aligned perpendicular to the flow, the Mapping Partner must document why, contrary to what may be indicated, the flow direction is in fact perpendicular to each cross section.

C.6.3 Two-dimensional Models [November 2009]

Two-dimensional flood analysis results in a (regular or irregular) grid of flood elevation values. Each cell in the model is attributed with a flow direction and flood elevation or is designated as not flooded or dry. The floodplain is delineated using the collection of cells with flood elevations. Note that collection may not include non-conveyance cells. The Mapping Partner should ensure that such cells are used to delineate the floodplain.

If the flood elevation grid cannot be used directly in GIS software as a digital surface, the Mapping Partner should develop such a surface. Most GIS software contains options to develop such a surface. The flood boundaries are delineated by either finding the intersection of the ground surface defined by the underlying digital terrain model and the flood surface, or subtracting the ground surface grid from the flood surface grid and finding the boundaries of those cells with differences (i.e., flood depths) greater than zero. The Mapping Partner must fully document the methods used to develop the flood surface and to determine flood boundaries.

The Mapping Partner should delineate BFE contour lines using the digital flood surface. The contour interval should be sufficient to discern the flow direction at any point within the floodplain. The Mapping Partner should verify that the flow directions indicated by the contour lines agree with the flow directions in the output grid.

The flood boundaries and flood surface contour lines must be provided in a georeferenced spatial file as defined in Appendix M of these *Guidelines*. If necessary for presentation purposes, the Mapping Partner should smooth the boundaries and contour lines.

C.6.4 Final Mapping Considerations [November 2009]

The results of hydraulic and floodway analyses are published on FIRMs. FIRMs show the flood hazard and floodplain management information, including revisions to maps affected by Letters of Map Change, or updated using methodologies provided in this Appendix.

The Mapping Partner tasked with preparing the preliminary FIRM incorporates the data documented and delineated per this Appendix into the FIRM and DFIRM database. Preliminary FIRM preparation, including reformatting from community-specific to countywide presentation, selecting data for visual presentation (such as which cross sections to show), and copying unrevised flood hazard information is discussed in Volume 1 of these *Guidelines*.

C.6.5 Re-delineating Effective Flood Hazard Data [November 2009]

This section presents standards for mapping floodplain boundaries with updated topographic information along reaches that have not been reanalyzed, and mapping BFE contour lines.

Topographic information may be available that is more accurate and/or of higher resolution than the topographic information reflected in the hydraulic analyses used to develop the FIRM. If the scope of work requires the re-delineation of effective flood hazard data instead of a restudy, the Mapping Partner should obtain copies of the backup data for the analysis shown on the FIRM and the more accurate or higher resolution topographic information.

Re-delineating the floodplain requires defining the spatial orientation of each cross section used in the hydraulic model reflected on the FIRM and the flood elevations associated with each floodplain to be re-delineated. If both the spatial orientation and water-surface elevation data of each cross section used in the model reflected on the FIRM is available, the set of cross sections is complete.

If data are not available for all cross sections, the Mapping Partner must generate the missing data using the Flood Profiles exhibit in the FIS report. Missing cross-section data are evident where flood profiles change slope, but no cross section is identified on the FIRM or the exhibit. The Mapping Partner must delineate such cross sections at the position along the stream or profile baseline indicated by the flood profile station. The cross sections must traverse the floodplain and be oriented perpendicular to the direction of flow. If flood elevation data are not available on the FIRM, the elevations must be obtained from the effective profile.

The Mapping Partner must use the complete set of cross sections to develop the required flood profiles. In the case that the re-delineation topographic data indicate that the effective hydraulic analyses are no longer valid, the Mapping Partner must coordinate further actions with the RPO. The effective hydraulic analyses may not be valid if:

- The effective floodway is outside the re-delineated floodplain,
- The effective profile baseline or stream centerline is outside the re-delineated floodplain.

Under these conditions, the mapping partner must inform the RPO.

C.6.6 Base Flood Elevation Lines [November 2009]

Contour lines of the whole-foot 1-percent-annual-chance flood elevations are called Base Flood Elevations (BFEs) or BFE lines. BFE lines are placed on FIRMs to assist users in determining the BFE anywhere within the floodplain. BFE lines are labeled with the corresponding BFE, rounded to the nearest whole foot. BFE lines must be shown in a georeferenced spatial file as specified in Appendix M of these *Guidelines* and placed along the study reach so that linear interpolation between two lines is minimally different from the base flood profile (and nowhere more than 0.5 foot). BFE lines must traverse the floodplain and be oriented perpendicular to the direction of flow. BFE lines must not cross each other or cross sections delineated in the georeferenced spatial file.

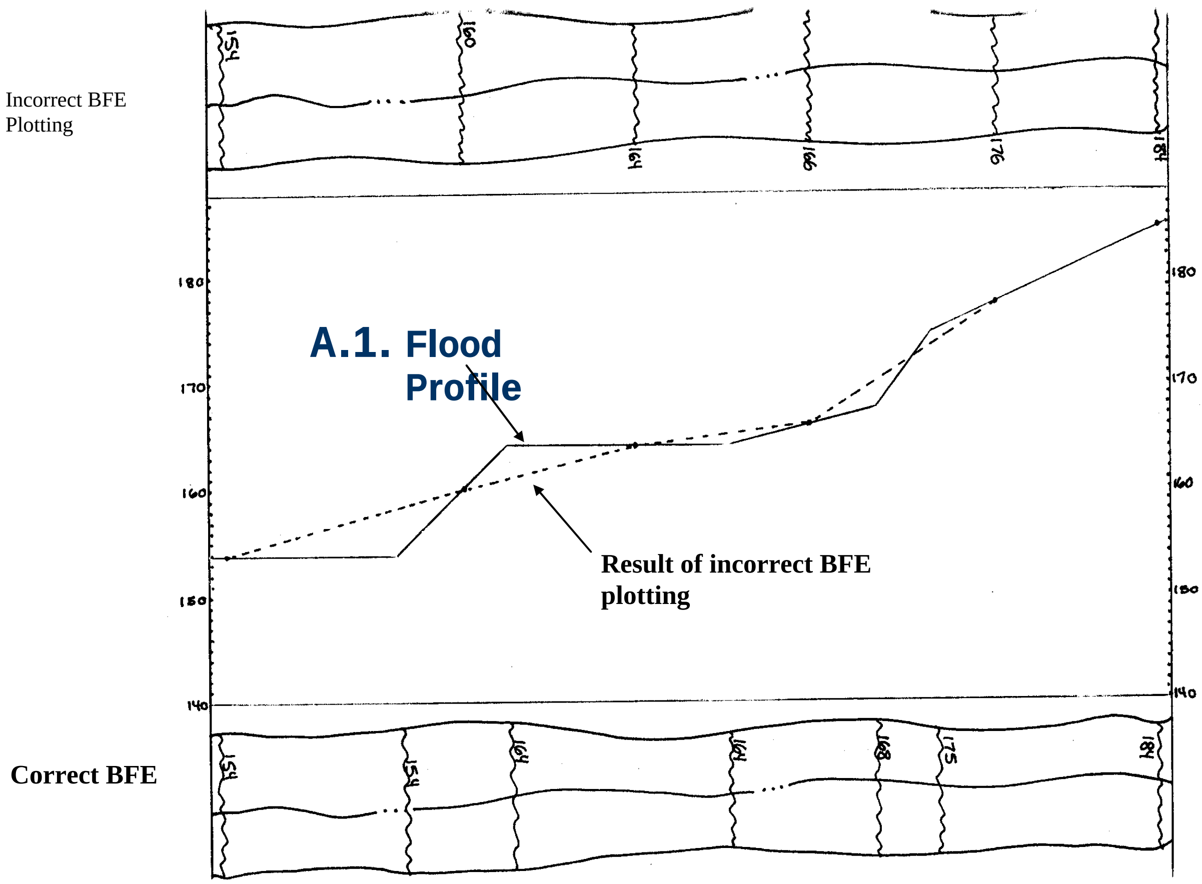
BFEs are to be plotted at significant profile inflection points (Profile breaks), or as close to them as possible. These points are critical to the accuracy of the FIRM, because the Flood Profiles could not be reproduced accurately without them, as described below.

Intermediate BFEs are to be plotted between inflection points. The profile slope (gradient) should be relatively constant between inflection points, and intermediate BFEs are to be placed at whole-foot elevations whenever possible. The main factor in determining the proper interval at which intermediate BFEs are to be plotted is the profile slope (gradient). The general guidelines below are to be followed, keeping in mind that the profile slope should be relatively constant between inflection points.

- Gentle Gradient – If BFEs rise less than 1 foot per 1 inch of map distance, the BFEs shall be plotted at every whole foot of elevation rise.
- Moderate Gradient – If BFEs rise more than 1 foot, but less than 5 feet per 1 inch of map distance, the BFEs shall be plotted at approximately 1-inch intervals.
- Steep Gradient – If BFEs rise 5 feet or more per 1 inch of map distance, the BFEs shall be plotted at 0.5-inch intervals of map distance or at 5-foot intervals, whichever is greater (i.e., whichever results in a wider BFE spacing).

To determine the proper method for the intermediate BFE interval, the amount of BFE rise is divided by the map distance over which it rises. For example, in the case where 10 inches of map distance has a 30-foot BFE rise, the gradient equals a 3-foot BFE rise per inch, and the Moderate Gradient method would be used to plot the BFEs.

Once all BFEs have been plotted, the Mapping Partner should test whether all significant inflection points have been plotted. It is critical that the FIRM reflect the BFEs shown on the Flood Profile to within a 0.5-foot tolerance. The diagram shown below demonstrates how the FIRM could show accurate BFEs, but still not reflect the BFEs shown on the Flood Profile to within the required tolerance. As demonstrated in the diagram, the difference between the line drawn to reflect the FIRM and the actual BFEs could be significantly skewed if BFEs are not plotted at significant inflection points, even if the BFE values shown on the FIRM are correct where they are plotted.



The following general rules are to be applied to the plotting of BFEs on FIRMs:

- BFEs must not rise more than 1 foot across panel edges (unless the stream gradient is very steep at the panel edge);
- The maximum rise between plotted BFEs must not exceed 10 feet;
- Extreme BFEs at corporate limits and Limits of Detailed Study do not have to be shown if graphically impossible (e.g., when the elevation is 65.5 at the corporate limits, BFE 65 may be plotted within 0.5 inch of the corporate limits); and
- In a static base flood insurance risk zone (tidal or lacustrine flooding), elevation numbers under zone labels must be used in lieu of BFE lines. For tidal flooding only, a zone break (or gutter) must be placed at the point where the static zone becomes a rising elevation zone, and a BFE line of the same elevation as the static zone must be placed immediately upstream of the gutter.

C.7 Future-Conditions Flood Mapping

[November 2009]

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 include flood hazard data based on future-conditions hydrology on FIRMs and in FIS reports for informational purposes at the request of the community. This decision was documented in a Final Rule published in the *Federal Register* on November 27, 2001.

Because multiple options exist for presenting future-conditions floodplains and related data on the FIRM and in the FIS report, interested community officials should contact the appropriate RPO to discuss the available options and agree on the approach to be taken. For information on these options, FEMA encourages interested community officials to review the November 27, 2001, Final Rule and the FEMA report titled "Modernizing FEMA's Flood Hazard Mapping Program: Recommendations for Using Future-Conditions Hydrology for the National Flood Insurance Program" (FEMA, 2001). That report contains one possible scenario/example of depicting future-conditions flood hazard information on a FIRM and in an FIS report and may be downloaded from the FEMA web site by searching the title of report.

At the request of a community and with the approval of FEMA, FIRMs and FIS reports may include, for informational purposes, flood hazard areas based on projected- or future-conditions hydrologic and hydraulic analyses. If community officials request that FEMA show the future-conditions base floodplain on the FIRM, the future-conditions floodplains and flood insurance risk zone should be shown on the FIRM and referenced in the accompanying FIS report. Although graphic specifications are flexible for the mapping of this flood insurance risk zone, the zone label will be “Zone X (Future Base Flood).”

The future-conditions flood insurance risk zone is defined in the FIRM legend and in the FIS report as follows:

> Zone X (Future Base Flood) is the flood insurance risk zone that corresponds to the 1-percent-annual-chance floodplains that are determined based on future-conditions hydrology. No BFEs or base flood depths are shown within this zone.

FEMA opted to use the Zone X (shaded) screen, in lieu of a new flood hazard zone designation, to depict the future-conditions base floodplain to minimize confusion by users of the FIRM who make determinations regarding Federal mandatory flood insurance purchase requirements. Those users now recognize that areas designated as Zone X (shaded) are floodprone, but that the mandatory flood insurance purchase requirement does not apply. Because the risk premium rates for buildings located in the future-conditions base floodplain will be the rate comparable to other areas outside the SFHA, FEMA believes designating these areas as “Zone X (Future Base Flood)” will be a sufficient distinction.

FEMA may develop graphic specifications for the presentation of future-conditions flood hazard data on the FIRM and specifications and guidelines for the inclusion of support information in the accompanying FIS report. However, it is FEMA’s intent, as indicated in the previously referenced Final Rule, to have flexibility in the implementation of this community-requested mapping option. Because multiple options for presenting the future-conditions flood hazard data exist, FEMA intends to work closely with each community to develop the presentation format that best meets community and FEMA needs. For the time being, FEMA, in coordination with the affected community and the Mapping Partner that is preparing the Preliminary FIRM and FIS report, will establish the presentation specifications on a case-by-case basis.

Once future-conditions flood hazard data have been included on the FIRM and in the FIS report for a community, all revision submittals should incorporate the future-conditions data developed by the community. The community is entirely responsible for developing and maintaining this data layer on a FIRM.

C.8 Hydrologic and Hydraulic Analyses of Lake Levels for Closed Basins [November 2009]

Conventional floodflow-frequency analysis, such as that described in Bulletin 17B (IACWD, 1982), is based on the assumption that the data used to prepare the analysis are stationary and independent. These conditions are usually satisfied when analyzing annual maximum peak discharges on a river. However, some notable exceptions do occur. For example, annual maximum lake levels or lake volumes are usually significantly correlated with time (autocorrelated) and hence violate the independence requirement.

In the presence of autocorrelation, floodflow-frequency analysis takes on a new meaning. The floodflow-frequency curve depends on an initial condition and evolves over time to a steady-state or equilibrium distribution. As a result, when conventional floodflow-frequency analysis methods are applied to autocorrelated lake data, the results should be interpreted as the long-term or steady-state distribution of annual maximum lake levels. This is in marked contrast to a conventional analysis of independent riverine data where a single floodflow-frequency distribution applies at all times. This fundamental difference between conventional floodflow-frequency analyses for lakes and rivers has important ramifications in developing sound floodplain management strategies for lakeshore communities.

A closed-basin lake, as defined by FEMA, is a natural lake from which water exits primarily through evaporation and whose surface area exceeds or has exceeded 1 square mile at any time in the recorded past. Many closed-basin lakes are in the western half of the United States, where annual evaporation exceeds annual precipitation and where lake levels and surface areas are subject to considerable fluctuation due to wide variations in the climate. In accordance with NFIP regulations, these lakes may overtop their basins on rare occasions. Because of the unique type of flooding, special policy and procedural considerations are warranted and have been documented in Sections C.8.1 through C.8.3 of this Appendix.

C.8.1 Insurance and Ordinance Issues [November 2009]

FEMA has amended the Standard Flood Insurance Policy to address the closed-basin lake continuous flooding circumstance. FEMA has added an endorsement to all policies allowing policyholders to file a total loss claim for an insured building that is actually damaged or under imminent threat of flooding, without the requirement for the building to be continuously inundated for 90 days. Policyholders should use claim payments minus salvage value to relocate their structures to a site outside the area subject to flooding. This special floodprone area around closed basin lakes is referred to in this Appendix and on the affected FIRM panels as an Area of Special Consideration (ASC). The insurance claim provision provides the means for homeowners and commercial business interests to relocate outside the ASC, thereby affording the community and its residents a permanent means of eliminating future flood losses in these areas.

The special endorsement for closed-lake basins is established in Paragraph 61.13(d) of the NFIP regulations. The insurance claim provisions are described in Appendices A(1), A(2), and A(3) of Section 61.17 of the NFIP regulations. Local and State governments should establish ordinances and building restrictions as described in Section 61.17 to be eligible for the special insurance claim provisions.

C.8.2 Mapping Protocol [November 2009]

As mentioned earlier, FEMA established the ASC to accommodate the unique type of flooding around closed-basin lakes. The ASC may include the 1- and 0.2-percent-annual-chance floodplains and additional areas to account for the continuous and often uncertain fluctuations in the water-surface elevation due to the closed-basin lake phenomenon. The ASC is an area subject to flooding, but the percent chance of being flooded in any given year is not defined. For example, the elevation shown within the ASC may be determined by using the natural spill elevation of the closed lake, the historical (or geological) elevation of record, and other criteria. The FEMA Regional Office should determine whether closed-basin lake flooding conditions exist and should implement the closed-basin lake policy accordingly.

FEMA should exclude from the ASC those areas that are landward of certified levees that provide protection from flooding. In determining the ASC, FEMA and its Mapping Partners should not take into account all flood hazards that may exist from other flooding sources, such as local streams or other floodwaters that are not hydraulically connected to the closed-basin lake.

C.8.3 Technical Methodologies [November 2009]

Multiple methods have been used to determine lake levels for closed basins. The Mapping Partners should analyze lake conditions to select the best applicable method. Several applicable methods are described below.

For large closed-basin lakes, such as Devils Lake in North Dakota and the Great Salt Lake in Utah, historical water level data and other data are available to estimate the 1-percent-annual-chance lake level. If the data are available, autoregressive moving average models can be used to model annual lake levels and volumes.

In North Dakota, Wiche and Vecchia developed a stochastic water balance model to estimate the 1-percent-annual-chance lake elevation (USGS, 1995). Wiche and Vecchia used long-term seasonal precipitation, evaporation, and inflow to Devils Lake to develop a stochastic water balance model for generating possible future lake-level elevations, namely 10,000 traces of 50 years in length. Wiche and Vecchia determined the chance that a given lake level will be exceeded in any given year by evaluating the proportion of the generated annual maximum lake levels that exceeded the given level.

The chance that a given lake level will be exceeded in any given year is dependent on the current or existing water level in the lake. The equilibrium level corresponding to a given percent chance of exceedance is reached when the current lake level has no effect on the given percent chance of exceedance. The equilibrium levels for the 1- and 0.2-percent-annual-chance floods are mapped on the FIRM.

Closed-basin lakes in the Southeast tend to have smaller drainage basins and size. With distinguished dry and wet seasons, annual maximum lake levels are unlikely to have significant autocorrelation. Lake level records are usually collected and maintained by regional and local agencies. Frequency analysis methods, either graphic or numerical, are applicable to such closed-basin lakes.

If the historical annual maximum lake level records are too short for frequency analyses, continuous simulation by a rainfall-runoff model may be used to generate a synthetic time series of flow and lake elevations. Frequency analyses can be performed upon the simulated annual maximum levels. To apply this method, the Mapping Partner must use a well-calibrated rainfall-runoff model able to generate reliable peak lake levels, and carefully assess the independency of the annual maximum lake level.

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