Guidance for Flood Risk Analysis and Mapping

General Hydrologic Considerations

February 2019

FEMA

Requirements for the Federal Emergency Management Agency (FEMA) Risk Mapping, Assessment, and Planning (Risk MAP) Program are specified separately by statute, regulation, or FEMA policy (primarily the Standards for Flood Risk Analysis and Mapping). This document provides guidance to support the requirements and recommends approaches for effective and efficient implementation. The guidance, context, and other information in this document is not required unless it is codified separately in the aforementioned statute, regulation, or policy. Alternate approaches that comply with all requirements are acceptable.

For more information, please visit the FEMA Guidelines and Standards for Flood Risk Analysis and Mapping webpage (https://www.fema.gov/guidelines-and-standards-flood-risk-analysis-and-mapping), which presents the policy, related guidance, technical references, and other information about the guidelines and standards development process.

Table of Revisions

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

Affected Section or Subsection	Date	Description
4.1, 4.3 and 7.3	February 2019	Revised references to United States Geological Survey Bulletin 17C and corrected several references to names of guidance documents or Technical References.

Table of Contents

List of Figures

List of Tables

1.0 Introduction

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

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

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. Discharges are to be developed for use by hydraulics models with multiple exceedance events in support of standard SID 84. The base (1-percent-annual-chance) flood is delineated on the FIRM as the Special Flood Hazard Area (SFHA). When determined, the 0.2-percent-annual-chance floodplain and/or floodway are also depicted on the maps. 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.

2.0 Contributors to Riverine and Inland Flooding

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

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

2.1 Natural Processes

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

- Recent precipitation and snow pack.
- Hydrologic characteristics (watershed slope, land cover, soil types).

- Channel shape, slope, sinuosity, depth verses. width.
- Watershed vegetation and sudden changes (e.g., forest fires and landslides).
- Sediment deposition and erosion.

2.2 Structural Processes

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

- Levees
- Filled floodplain
- Stormwater management systems
- Channel modification (straightening, smoothing)
- Stream crossings (bridges, culverts) – address clogging, due to ice and debris
- Basin transfers

2.3 Impoundments and Levees

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

3.0 Study Methodology Overview

3.1 Watershed Studies

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

The overarching principle for the watershed approach is to develop a complete, consistent, and connected flood engineering analysis within a watershed. The analysis should cover a geographic footprint, for example the U.S. Geological Survey (USGS) hydrologic unit code (HUC) 8 boundaries, that encompasses the hydrologic characteristics of the area of interest. HUC Boundary datasets can be found at nhd.usgs.gov/wbd.html. The National Water Information System (water.usgs.gov/wsc/index.html) is a good source of gage locations, gage data, and GIS data such as land cover, base flow, subsidence, National Hydrography Dataset (NHD) catchment, etc. Another good source of land cover data and impervious area computations is the Multi-Resolution Land Characteristics Consortium (MRLC) at

www.mrlc.gov/. This does not mean that there must be one model for an entire watershed or stream. An acceptable watershed-based study may include multiple hydrologic and hydraulic methods and models, but those methods and models must agree at the transition points between them. Gaps between analyses are to be analyzed and addressed as a rule, but in certain watersheds there may continue to be some gaps in analyses for low-risk areas.

The guiding principles for the watershed approach are described in the Discovery Guidance document. The assessments of needs are completed as part of the Coordinated Needs Management Strategy (CNMS) evaluation process. The Coordinated Needs Management Strategy Technical Reference contains information regarding the evaluation of streams validation status. Additional information and current validation status data are available at: msc.fema.gov/cnms.

- A Risk MAP watershed project will be considered complete when the geographic footprint that was included in the watershed-based discovery been evaluated, the watersheds or subwatersheds chosen for new or updated flood studies are studied, and:
    - All watersheds or subwatersheds requiring new or updated hydrologic or hydraulic analysis have been studied and mapped.
    - Hydraulics will be performed for an entire stream segment when that stream is selected for study. This means that unstudied areas (or gaps) between studied stream segments must be studied unless those gaps consist of valid study that ties into the new study. There can be different levels of study for the different stream segments, as long as all the models tie-in.
    - All other subwatersheds have been evaluated and do not require a new or updated study based on risk and need.
    - All hydrologic data within the geographic footprint has been determined to be consistent. It is without discrepancies when evaluated as a single hydrologic system. In watersheds where the hydrology is not consistent, additional study is required to create consistency.
- All newly initiated studies will be watershed-based, with the exception of studies related to Provisionally Accredited Levee (PAL) status, and flooding sources related to issue resolution for litigation or federal legislative or executive inquiries.
- A study within a geographic footprint will be initiated once within the Risk MAP lifecycle. All watersheds or subwatersheds within the geographic footprint will be evaluated, scoped, and have work initiated within that project period. It is understood that coordination with levee and coastal studies may prove challenging, and exceptions to the once per lifecycle guidance here will be considered under those circumstances.
- No stream segment or subwatershed will receive a lower level of regulatory flood map product than what currently exists on effective maps. For example, areas with defined floodways will continue to have defined floodways. Areas with published Base Flood Elevations (BFEs) will continue to have published BFEs. The method of study chosen will be dependent on the level of risk for that flooding hazard.

- Stream segments that are selected for study because they connect portions of watersheds that are to be studied for risk and need shall be accomplished using the most basic study method that is appropriate based on the risk and need of those areas. Additionally, it is not necessary to publish FIRMs for the connecting portions, unless risk or needs around those segments were to make publication appropriate.

3.2 Identify Study Areas

Hydrologic studies areas are typically identified through the Discovery process described in the Discovery Guidance document. Discovery is required for all new and updated Flood Risk Projects. Discovery is used for determining whether a Flood Risk Project is appropriate and will provide visibility to stakeholders as FEMA and Cooperating Technical Partners initiate flood risk and mitigation discussions and deliver flood risk information. The identification of flood sources to be studied should include a review of the CNMS status of the streams within the watershed. More detailed information on the discovery process may be found in the Discovery Guidance document.

The hydrologic analysis should start at the most downstream subwatershed where a new or revised study is identified and go all the way upstream to where there are no more new/updated studies identified. Results from the updated hydrologic analysis within the revised study should be checked for consistency with other discharge values within the watershed. More detailed information on evaluating hydrologic consistency may be found in the Contiguous Community Matching Guidance document.

Several factors that affect the engineering analysis and may indicate the need for a new study, making the CNMS status UNVERIFIED, are discussed below. More detailed information on how to perform a mapping needs assessment can be found in the Coordinated Needs Management Strategy Technical Reference.

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

- Comparing recent flooding events to effective mapping.
- Changes in land use in the watershed.
- Publication of new regional regression equations.
- Changes in design storm data.
- Increase in length of stream record.
- Construction of flood-control structures.

3.3 Choose Modeling Software

Per FEMA Standard #90, the methods and models used to evaluate the flood hazard must be technically reliable, must be appropriate for flood conditions and produce reasonable results. All computer models must adhere to Title 44, Code of Regulations (44 CFR) 65.6 a(6). Hydrologic modeling software and Statistical Numerical Models meeting the minimum requirements of the National Flood Insurance Program (NFIP) regulations are listed on the website:

hwww.fema.gov/numerical-models-meeting-minimum-requirements-national-flood-insurance-program. Hydrologic models include single event and continuous simulation models. For further information on these regulations and to learn how to get a model added to this list, please refer to the Accepting Numerical Models for Use in the NFIP Guidance document.

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

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

Throughout the watershed, various hydrologic modeling methods and/or models may be used. However, results of the various modeling techniques need to be consistent throughout the watershed. More detailed information on evaluating hydrologic consistency may be found in the Contiguous Community Matching Guidance document.

When a study methodology and modeling software is selected community notification will take place as specified in FEMA Standard 620 and described in Section 12.0 of the Discovery Guidance document. Notification will be documented in the Flood Elevation Determination Document (FEDD) File as seen in the Technical Support Data Notebook and Flood Elevation Determination Docket Guidance document.

4.0 Hydrologic Analysis Procedures

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.

Discharge values used to determine water-surface elevations shown on the FIRMs must be based on hydrologic or statistical 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 determining model parameters.

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.

The following subsections briefly describe categories of hydrologic modeling approaches. More detailed guidance regarding the methods and requirements for conducting various unique aspects of a hydrologic analysis can be found in the documents referenced in Table 1.

Table 1: References of Hydrologic Guidance

Modeling Consideration	Location within Guidance
	Analysis Procedures
Gage Analysis	Section 4.1 of this Document (General Hydrologic Considerations)
Regression Equations	Section 4.2 of this Document (General Hydrologic Considerations)
Rainfall-Runoff Models	Hydrology: Rainfall-Runoff Analysis (Guidance Document 91)
Future Conditions	Section 4.5 of this Document (General Hydrologic Considerations)
	Hydrologic Aspects of Hydraulic Models
Steady Flow	Guidance: Hydraulics: One-Dimensional Analyses (Guidance Document 80)
Unsteady Flow	Guidance: Hydraulics: One-Dimensional Analyses (Guidance Document 80)
Two-Dimensional Models	Guidance: Hydraulics: Two-Dimensional Modeling Analyses (Guidance Document 81)
Split Flow	Guidance: Hydraulics: One-Dimensional Analyses (Guidance Document 80)
Floodway Storage	Floodway Analysis and Mapping (Guidance Document 79)
Shallow Flooding	Shallow Flooding Analysis and Mapping (Guidance Document 84)
Ice Jam	Ice-Jam Analyses and Mapping (Guidance Document 94)
Alluvial Fan	Alluvial Fans (Guidance Document 75)
Interior Drainage	Levees Guidance (Guidance Document 95)
Lake Levels and Closed Basins	Section 4.4.10 of this Document (General Hydrologic Considerations)

Modeling Consideration	Location within Guidance
Karst Flooding	Section 4.4.11 of this Document (General Hydrologic Considerations) and Hydrology: Rainfall-Runoff Analysis (Guidance Document 91)

4.1 Stream Gage Analysis

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 should 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.

Maximum annual peak flow records are available for over 26,000 gaging station sites across the United States from the USGS at 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 should analyze peak flow data in accordance with USGS Bulletin 17C and subsequent modifications. Bulletin 17C recommends a minimum of 10 years of data for frequency analysis. The Mapping Partner should coordinate with their Regional Project Officer (RPO) to use analysis techniques other than those described in Bulletin 17C. Discharge-frequency relations derived by the USGS in accordance with Bulletin 17C for gaged sites on unregulated streams may be obtained from published USGS reports.

Computer programs for performing stream gage analyses in accordance with Bulletin 17C are listed in the accepted Statistical models list and are available from the U.S. Army Corps of Engineers (USACE) and the USGS.

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 17C. The Two Station Comparison method described in Bulletin 17C 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. As stated in Bulletin 17C this augmented record will be introduced into the Expected Moments Algorithm (EMA) calculations and will be subject to the potentially influential low floods (PILF) criteria. 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 the mixed population section of Bulletin 17C, *Guidance: Ice Jams*, or USACE Hydrologic Frequency Analysis 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 17C 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 17C (Appendix 9), statewide USGS reports, and documentation for the USGS National Flood Frequency (NFF) program (USGS, 2002).

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.

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

4.1.1 1-percent + Calculation for Stream Gage Analysis

The 1-percent-plus flood elevation is defined as a flood elevation derived by using discharges that are at the upper 84-percent confidence limit as calculated in the gage analysis for the 1-percent-annual-chance event for the Flood Risk Project. Methods for estimating synthetic statistics outlined in Bulletin 17C Appendix 7 are used to estimate the upper 84 percent confidence limit of the Log Pearson III frequency Curve at the 1-percent-annual-chance event.

4.2 Regional Regression Equations

For ungaged streams, and gaged streams where a stream gage analysis is inappropriate, 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.

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 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 water.usgs.gov/software/NSS.

The Mapping Partner must use the most recently published regional regression equations unless they are shown to be inappropriate. 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. Documentation will be included in the data development section of the TSDN as documented in the Technical Support Data Notebook and Flood Elevation Determination Docket Guidance document. 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.

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 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 method, if available, are described in the statewide regional reports available at https://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.

4.2.1 1-percent + Calculation for Regression Analysis

The 1-percent-plus flood elevation is defined as a flood elevation derived by using discharges that include the predictive error for the regression equation discharge calculation for the Flood Risk Project. This error is then added to the 1percent annual chance discharge to calculate the new 1 percent plus discharge.

4.3 Lake Levels for Closed Basins

Conventional floodflow-frequency analysis, such as that described in Bulletin 17C and subsequent modifications, 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 (auto correlated) 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 auto correlated 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. Closed basin lakes occur 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.

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.

4.4 Karst Flooding

Determining the flood hazard of depressions and sinkholes within Karst topography is a unique situation. In an area where a depression is being studied best available terrain information is used to determine stage – storage curves and contributing drainage area for the depression. Then, the runoff volume for the contributing drainage area is determined using techniques described in the Hydrology: Rainfall-Runoff Analyses Guidance document. Estimated flood stage is determined by comparing runoff volume minus any outflow (if known) to the stage-storage curve. Examples of karst flooding calculations can be found in various counties in Kentucky including Barren County. For the Kentucky Division of Water (KDOW) Barren County methodology see Attachment A.

4.5 Future Conditions

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 as seen in Federal Register Volume 66, Number 228 titled Changes to General Provisions and Communities Eligible for the Sale of Insurance Required to Include Future-Conditions Flood Hazard Information on Flood Maps published in the Federal Register on November 27, 2001.

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)”.

In considering watershed development, the term “future” itself can be defined in several different ways: 10 or 20 years projected into the future, for example, or the maximum development planned for a given watershed. For the purposes of this discussion, we will consider future conditions to be those land-use conditions shown on the current zoning maps or comprehensive land-use plans. Future-conditions hydrology is then defined as the flood discharges that would occur if the land-use conditions shown on the current zoning maps or comprehensive land-use plans were realized. There are two instances where existing conditions are equivalent to future conditions (1) no significant development is planned for an area, and (2) areas currently developed to the extent shown on the current zoning maps or comprehensive land-use plans of local governments within the watershed. Under these conditions, no additional hydrologic analyses are needed.

Watershed development can include hydrologic as well as hydraulic modifications. The changes in the watershed that can influence the hydrology and flood discharges are the increase in impervious area and the improvements in the drainage network that accompany urbanization. For example, as buildings and parking lots are constructed, the amount of impervious land within the watershed increases, which increases the amount or volume of direct runoff. The construction of storm sewers and curb and gutter streets usually cause an increase in the peak rate of direct runoff. These modifications can have drama tic effects on the flood frequency characteristics of a watershed, resulting in significantly increased base flood discharges and elevations.

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 technical procedures and 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.

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.

4.6 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 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.

5.0 Data Requirements

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

Significant cost savings can be realized if existing spatial data sources are used. Possible sources of existing topographic, land use, soils and aerial photography data include regional Light Detection and Range (LiDAR) consortiums, USGS, NOAA, local planning departments, GIS coordinators, engineers, and directors of public works, FEMA archives (particularly for

cross-section data from effective hydrologic and hydraulic models); and State Departments of Transportation (e.g., bridge plans). Guidance for specific data input requirements for rainfall-runoff analysis may be found in the Hydrology: Rainfall-Runoff Analyses Guidance document.

Guidance on the submission of the hydrologic analysis inputs and outputs can be found in the Data Capture – General Guidance document and Data Capture Technical Reference. Formatting and organization of required spatial files is discussed in the FIRM Database Technical Reference.

As part of the submission 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.
- 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.

6.0 Determining Statistical Significance of Flood Discharges

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 (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.

- 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 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.

7.0 Hydrologic Analysis Quality Control

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 base flood discharges using procedures described below.

7.1 Review Rainfall Run-Off Models

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.

7.2 Review Regional Regression Equations

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.

7.3 Review of Stream Gage Analysis

Proposed base flood discharges based on gaging station data must be reviewed for conformance to the guidelines in Bulletin 17C. If procedures other than those outlined in Bulletin 17C 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.

7.4 Hydrologic Review Documentation

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. Guidance on the submission of the hydrologic review can be found in the Data Capture – General Guidance document, and the Data Capture Technical Reference.

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.
- Revising the analysis to obtain more reasonable results.

8.0 Related Topics Covered by Other/Future Guidance

Below is a list of related topics that have been developed or are planned, to provide additional guidance related to hydraulic modeling riverine flooding analyses and mapping:

- Hydrology: Rainfall-Runoff Analyses
- Hydraulics: One-Dimensional Analyses
- Hydraulics: Two-Dimensional Analyses

- Floodway Analysis and Mapping
- Shallow Flooding
- Alluvial Fans
- Ice Jams
- Riverine Mapping and Floodplain
- Combined Coastal and Riverine Floodplain
- Base Flood Elevations
- Flood Profiles

9.0 Attachment A: Kentucky Division of Water (KDOW) Sinkhole Methodology

9.1 Hydrologic Analysis

Hydrologic analysis was carried out to establish peak flow for the 100-year event for each of the studied sinkholes.

Drainage areas for studied sinkholes were delineated on a 10 m digital elevation model (USGS). Sinkholes intersecting scoped streams and sinkholes mapped on previous effective FIRMS were selected for Hydrologic and Hydraulic analysis. Curve number was computed based on percent impervious estimated using aerial imagery. Since flooding of sinkholes is based on total volume of water draining into the sinkhole, a reasonable value for time of concentration was estimated for this approximate study. Precipitation depth for Barren County was obtained from NOAA Atlas 14, Volume 2. SCS Hydrology within XP SWMM along with the SCS Type 2 rainfall distribution was used to simulate runoff for each of the drainage basins delineated.

The northern portion of Barren County is located in the Pennyroyal Plateau, which consists of sinkhole plain topography. This topography is characterized by numerous depressions throughout its lower elevations. These depressions are sometimes represented by one large sinkhole in the Kentucky statewide sinkhole database as shown in Figure 1.

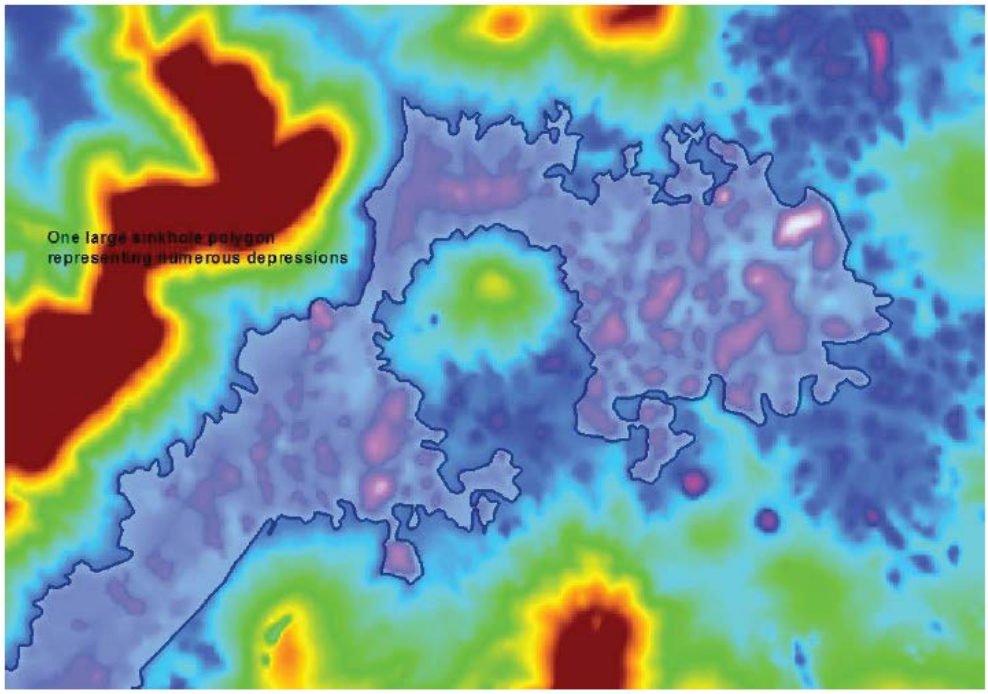

Figure 1: Large Sinkhole Polygon Representing Numerous Depressions

Large sinkhole polygons representing numerous depressions are divided into individual polygons, each representing one depression. Drainage basins are delineated, and stage-storage curves are developed for each individual depression. Depressions intersecting the 1 square mile statewide stream drainage network are selected as sinkholes for modeling. A calculation is performed to determine which surrounding depressions' drainage basins contribute to the modeled sinkhole. The calculation is as follows:

$$D_o = V_s / DA$$

Where: D_o = Rainfall Overtopping Depth
V_s = Depression Storage Volume
DA = Depression Drainage Area

If D_o is greater than the 1-percent-annual-chance rainfall depth, then the 1-percent-annual-chance event is contained within the sink. If D_o is less than the 1-percent-annual-chance rainfall depth, then the 1-percent-annual-chance event will overtop the sinkhole and drainage area is consider as contributing to the overall drainage area of the modeled sinkhole. A final sinkhole shape is determined based on the total contributing drainage basin. A final stage-storage curve is determined for the modeled sinkholes. Figure 2 shows the smaller sinkholes resulting from the contributing drainage area analysis.

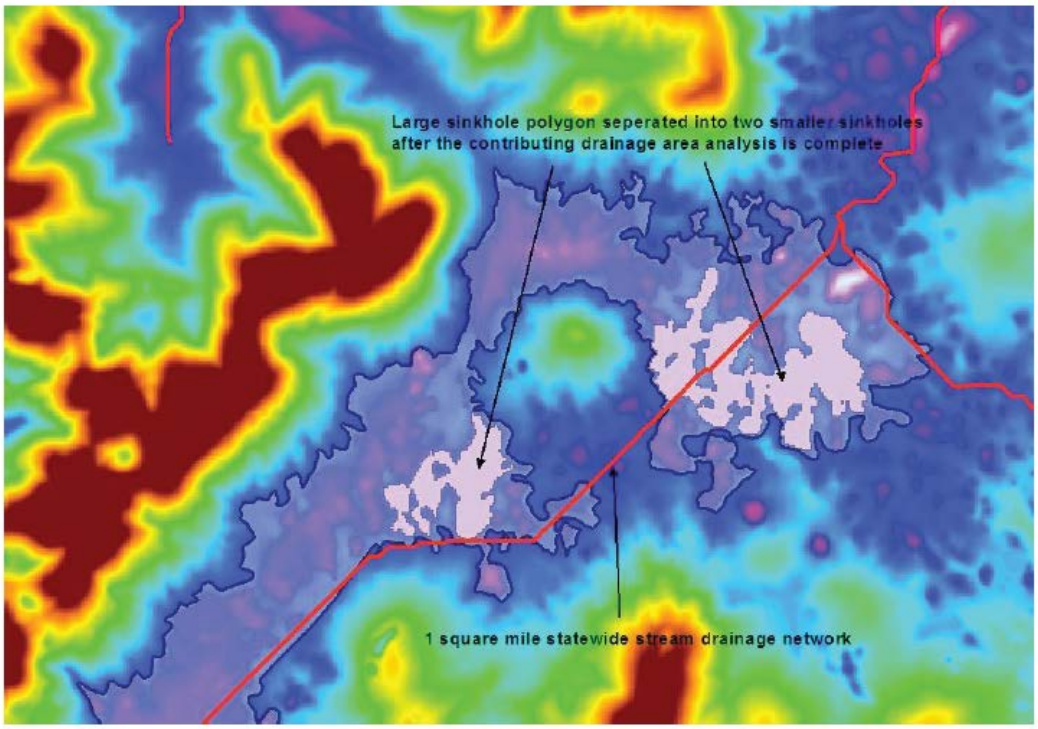

Figure 2: Final Sinkholes for Modeling

It is necessary to account for extra storage in addition to the storage provided by the modeled sinkhole in cases where depressions exist in the upper reaches of a drainage basin. In those cases, the basin is divided into subbasins in the XPSWMM model, and stage-storage curves are determined for the subbasin depressions. Accounting for this additional storage reduces the total runoff volume contributing to flooding in the modeled sinkhole.

9.2 Hydraulic Analysis

Hydraulic Analysis was carried out to establish peak stage elevation for the 100-year event for each of the studied sinkholes. Each of the sinkholes was treated as a Hydraulic node within XP-SWMM software. Node invert elevation was set to the bottom elevation of the sinkhole. Stage-Storage (Depth-Elevation) relation was established for each of the sinkholes using the 10 m digital elevation model (USGS). Links were established between individual sinkholes based on the DEM to account for any overflow from one sinkhole to the other. Extran block within XP-SWMM was used to compute maximum water surface elevation for the 100- year event for each of the studied sinkholes. Dry wells providing outflow for sinkholes were represented in the model by links connecting sinkhole nodes to outfall nodes. Dry wells were only input into the model where well location and size data was available. Dry well data was only available in Cave City. The dry well inventory was provided by the City of Cave City. Sink IDs 171859, 172348, 173496, 174967,191329, 203318 and 204014 were previously modeled with Metcalfe County and are included in Metcalfe XP-SWMM model in the Barren County submittal.