



# Guidance for Flood Risk Analysis and Mapping

Hydrology: Rainfall-Runoff Analysis

November 2024



**FEMA**

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

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

## Table of Revisions

The following summary of changes details revisions to this document subsequent to its most recent version in February 2019.

| Affected Section or Subsection | Date      | Description  |
|--------------------------------|-----------|--|
| 2.7                            | Nov. 2024 | Updated to clarify that road embankments should not be modeled as reservoirs except in rare cases coordinated with the FEMA Project Officer. |
| All                            | Nov. 2024 | Various minor style updates for improved consistency and clarity and correction of outdated links.   |

## Table of Contents

|   |           |
|---|-----------|
| <b>1. Introduction .....</b>                              | <b>1</b>  |
| <b>2. Rainfall-Runoff Model Components .....</b>          | <b>1</b>  |
| 2.1. Rainfall.....  | 2         |
| 2.2. Rainfall Losses .....                                | 4         |
| 2.3. Sub-Basin Response.....                              | 5         |
| 2.4. Routing.....   | 6         |
| 2.5. Input Hydrograph .....                               | 6         |
| 2.6. Channel Storage.....                                 | 7         |
| 2.7. Reservoir Storage.....                               | 7         |
| <b>3. Calibration .....</b>                               | <b>8</b>  |
| <b>4. Floodway.....</b>                                   | <b>9</b>  |
| 4.1. Floodway Storage.....                                | 9         |
| 4.2. Floodway Determination in Unsteady State Models..... | 9         |
| <b>5. 1-Percent Plus Calculation .....</b>                | <b>9</b>  |
| <b>6. Two-Dimensional Models.....</b>                     | <b>9</b>  |
| <b>7. Future Conditions.....</b>                          | <b>9</b>  |
| <b>8. Statistical Significance .....</b>                  | <b>10</b> |
| <b>9. Review of Rainfall-Runoff Models .....</b>          | <b>10</b> |
| <b>10. Documentation .....</b>                            | <b>11</b> |
| <b>11. Hydrology Submittal .....</b>                      | <b>11</b> |
| <b>12. References.....</b>                                | <b>12</b> |

## 1. 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 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 Identification Number (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. See Section 4.5 of the [General Hydrologic Considerations Guidance](#) for more discussion of future conditions modeling.

The [FEMA 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. More information about watershed studies is available in the [General Hydrologic Considerations Guidance](#).

## 2. Rainfall-Runoff Model Components

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 Base Flood Elevations (BFEs) for storage areas.

The Mapping Partner must submit georeferenced spatial files compliant with the [Data Capture Technical Reference](#); this means they must include but are not limited to:

- 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.

## 2.1. Rainfall

Rainfall input data consist of the 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, which can be obtained from <https://hdsc.nws.noaa.gov/pfds/>.

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 coordinate with the FEMA Regional Project

Officer (RPO) and fully document in the hydrology report the data used, including the gages used and the 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 might be incorporated into model calibration efforts after proper coordination and if appropriate. 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 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.

The United States Army Corps of Engineers (USACE) has developed a hypothetical storm distribution that can be used to sample rainfall durations (USACE, 1990; USACE, 2016). 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 that are appropriate for use in developing discharge hydrographs.

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 FIS reports. For example, the Huff distribution developed for Illinois and the temporal distributions that Florida water management districts developed are accepted for use in FIS reports.

The spatially-averaged depths of rainfall with large areal extents are, in general, less than those with relatively smaller areal extents. Published rainfall data (e.g., NOAA atlases) 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, publications of regional climate centers, or state and local agencies responsible for flood control.

The preceding discussion was related to the use of design storm rainfall (e.g., 1-percent-annual-chance event) for estimating the flood discharges. Continuous simulation rainfall-runoff models, such as Hydrologic Simulation Program – FORTRAN (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 FIS reports must be capable of predicting high flow events and should be verified against selected high-flood events observed within the watershed.

## 2.2. 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, which measure how dry or wet a watershed is at the beginning of a storm. Unless otherwise justified, wetted soil conditions should be considered when calculating rainfall losses. 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 runoff condition modeled for each frequency.

Several different infiltration methods are available to estimate losses and the associated runoff, including empirically based methods, such as the NRCS runoff curve number approach, to physically based methods, such as Green-Ampt. Physically based methods are more accurate. The choice of method 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. The [NRCS National Engineering Handbook](#) (USDA, 2004) provides guidance on estimating the NRCS runoff curve number. The land use and soils data needed to estimate the runoff curve number are available on United States Geological Survey (USGS) and NRCS websites. The NRCS runoff curve number computation is dependent on antecedent runoff conditions and assumes an initial abstraction that is a function of the soil properties.

Infiltration equations determine the rate at which the soil absorbs falling rain, melting snow, or surface water. A closely related process is percolation, which is the rate at which soil moisture moves

down through the lower soil 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 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.

### **2.3. 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 often used for developing FIS reports, if applicable. If the Mapping Partner uses an option to model the response as a series of hydraulic processes (e.g., Kinematic-wave models or nonlinear reservoir models), 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. If methods or parameters are outside normal ranges, coordination with the FEMA RPO is necessary before finalizing analysis.

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.

## 2.4. 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. Any significant reduction in peak discharges due to routing must be noted and communicated to FEMA RPO prior to mapping. The reduction must be explained, justified, and documented.

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. Unless otherwise justified, wetted conditions should be considered when calculating channel infiltration. If floodplain encroachments are factored into 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.

“Diversion” is defined as water leaving the watershed. The methods or data used for estimating diversions in the model must be fully documented.

## 2.5. Input Hydrograph

Rainfall-runoff models usually provide for introduction of 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 hydrograph).

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.

## 2.6. Channel Storage

Some channel routing techniques do not account for storage but do result in attenuated hydrographs. The Mapping Partner could use routing techniques that account for storage if appropriate. 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 relationship between storage and the extent of the floodplain. If floodplain encroachments are factored into the computation of storage, the effects must be clearly documented in the hydrology report. The documentation must include mapping where applicable and identify 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.

## 2.7. 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 to which the storage levels are dedicated. Joint use storage based on forecasted inflow is not acceptable for National Flood Insurance Program (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 Discovery 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.

Reservoir modeling procedures should not be used for the impoundment of floodwaters caused by undersized culverts and high road embankments, except in rare cases first coordinated and approved by the RPO.

### **3. Calibration**

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 feasible 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 feasible.

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.

## 4. Floodway

### 4.1. Floodway Storage

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. As discussed in Routing and Channel Storage under Sections 2.4 and 2.6 of this document, if hydrologic modeling includes channel storage areas that reduce flood discharges, these areas should be designated as part of the floodway. See the [Floodway Analysis and Mapping Guidance](#) for more discussion of storage considerations within floodways.

### 4.2. Floodway Determination in Unsteady State Models

Steady state models do not consider lost storage in effective and ineffective flow areas or 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. See the [Floodway Analysis and Mapping Guidance](#) for more discussion of floodway determination in unsteady state models.

## 5. 1-Percent Plus Calculation

The 1-percent plus flood elevation for a study that uses rainfall-runoff methodology is defined as a flood elevation derived by using discharges at the upper 84-percent confidence limit for the 1-percent-annual-chance flood. 1-percent plus discharges can be estimated using methods outlined in [Bulletin 17C](#), which can be implemented in various software such as the USGS PeakFQ program or the Hydrologic Engineering Center (HEC) Statistical Software Package (SSP).

## 6. Two-Dimensional Models

For information about hydrologic analysis for two-dimensional hydraulic models, see the [General Hydrologic Considerations Guidance](#) and [Hydraulics: Two-Dimensional Analysis Guidance](#).

## 7. 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. See Section 4.5 of the [General Hydrologic Considerations Guidance](#) for more discussion of future conditions modeling.

## 8. Statistical Significance

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 reflect the impact of flow regulations;
- To take advantage of improved hydrologic analysis methods; and
- To correct an error in the hydrologic analysis performed for the effective study.

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. Guidance for the determination of statistical significance may be found in the [General Hydrologic Considerations Guidance](#).

## 9. Review of Rainfall-Runoff 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 a logarithmic scale 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 the prediction error 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 have their values justified.

## 10. Documentation

Whenever 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 the [Data Capture Technical Reference](#) and [Data Capture – Workflow Details Guidance](#).

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. Use of those models and techniques, including the user's manual and federal publications, fulfills many 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 the [Data Capture Technical Reference](#) and [Data Capture – Workflow Details Guidance](#).

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.

## 11. Hydrology Submittal

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 the [Data Capture Technical Reference](#) and [Data Capture – Workflow Details Guidance](#). The data and models must be organized by watershed and submitted to the Mapping Information Platform.



## 12. References

U.S. Army Corps of Engineers, Flood Runoff Analysis: Engineering Manual No. 1110-2-1417, Davis, CA, 1994.

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U.S. Army Corps of Engineers, Risk-Based Analysis for Flood Damage Reduction Studies: Engineering Manual No.1110-2-1619, Washington, DC, 1999.