Central Valley Hydrology Study (CVHS): Ungaged watershed analysis procedures

November 14, 2011

Prepared for California Department of Water Resources

Prepared by US Army Corps of Engineers, Sacramento District
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## List of revisions

<table>
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<th>Revision number (1)</th>
<th>Date of revision (2)</th>
<th>Description of revision (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>September 23, 2010</td>
<td>Draft submitted to DWR</td>
</tr>
<tr>
<td>1</td>
<td>February 18, 2011</td>
<td>Modified in response to comments from the HAC.</td>
</tr>
<tr>
<td>2</td>
<td>April 8, 2011</td>
<td>Further modification to update information in tables and provide additional response to comments from HAC.</td>
</tr>
<tr>
<td>3</td>
<td>September 13, 2011</td>
<td>Update temporal distribution procedure.</td>
</tr>
<tr>
<td>4</td>
<td>November 14, 2011</td>
<td>Specify use of TP-40 areal reduction factors. Update language for developing temporal distribution to reflect preference for synthetic distribution with historically-based time of peak intensity.</td>
</tr>
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</table>
Background

Situation

The Central Valley Hydrology Study (CVHS) is an undertaking by the Sacramento District of the US Army Corps of Engineers to develop estimates of the annual exceedence probability of flows and volumes for streams in the Sacramento and San Joaquin river basins. The CVHS is in support of an effort by the California Department of Water Resources to update hydrologic data and complete floodplain mapping along and behind the Federal-State levees in the Central Valley.

The document *Sacramento and San Joaquin river basins: Procedures for hydrologic analysis (Procedures document)*, dated September 9, 2008, describes the procedures to be used in the CVHS hydrologic analysis. Further details of this analysis can be found in *Central Valley hydrology study (CVHS): Technical procedures (Technical procedures document)*.

The floods-of-record analysis procedure described in the *Procedures document* can only be used for analysis points in gaged watersheds. For purposes of the CVHS, a gaged watershed is one for which the streamgage record is of sufficient length (preferably, at least 25 years of data), the data available from the gage(s) are of adequate quality, and 1 or more gages are located at or near the analysis point. Watersheds that do not meet the criteria for gaged watersheds require an alternative procedure for developing flow-frequency curves. We will use rainfall-runoff modeling of design storms for this purpose.

[For CVHS, an analysis point is a selected, agreed upon location, where frequency curves and flood volumes are required.]

The ungaged watersheds described in this document are not the same as the ungaged local flows developed as part of the unregulated time series, *Procedures document* Task 3. The analysis described here refers to Task 8 from the *Procedures document*.

A single ungaged watershed may contain multiple analysis points and their associated streams, as shown in Figure 1. In this example, the ungaged watershed is the Chico stream group, which contains Mud Creek, Sycamore Creek, and Big Chico Creek. Multiple analysis points are required to reflect the multiple streams and confluences in the area. When this watershed is analyzed, a similar approach and model for development of flow frequency curves will likely be used for all those analysis points shown.

Analysis of the ungaged watersheds must produce results that are compatible with the analyses of the gaged watersheds, as detailed in the *Procedures document* and *Technical procedures document*. 
Figure 1. Example of ungaged watershed with multiple analysis points

Purpose of this document

The purpose of this document, Ungaged watershed analysis procedures, is to detail the technical procedures for developing flow-frequency curves and volumes for the ungaged watersheds in the CVHS study area.

Pertinent guidance

The pertinent guidance for developing frequency functions for ungaged watersheds is found in EM 1110-2-1415 (USACE 1993), EM 1110-2-1417
Identification of CVHS ungaged watersheds

The preliminary list of the CVHS ungaged watersheds is included in Table 1. Additional watersheds may be added to this list once the quality of the available data is reviewed.

Table 1. Ungaged watersheds included in CVHS

<table>
<thead>
<tr>
<th>ID (1)</th>
<th>Ungaged watershed (2)</th>
<th>HUC8(^1) (3)</th>
<th>Approximate drainage area (sq mi) (4)</th>
<th>Number of analysis points (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mud Creek and Big Chico Creek Diversion</td>
<td>18020103 18020119 18020120</td>
<td>124</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>Butte Creek, Little Chico Creek</td>
<td>18020105 18020120</td>
<td>158</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Dry Creek Cherokee Canal</td>
<td>18020105 18020120</td>
<td>117</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>North Fork Honcut Creek South Ford Honcut Creek</td>
<td>18020106 18020124</td>
<td>212</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>Wadsworth Canal</td>
<td>18020106</td>
<td>58</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>Jack Slough</td>
<td>18020106</td>
<td>56</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>Bear River tributaries: Reeds Creek and Best Slough (WPI C), Dry Creek (near Wheatland), and Yankee Slough</td>
<td>18020106 18020108 18020126 18020127</td>
<td>217</td>
<td>11</td>
</tr>
<tr>
<td>8</td>
<td>Natomas Cross Canal Pleasant Grove Creek Steelhead Creek Arcade Creek</td>
<td>18020109 18020111</td>
<td>485</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>Bear Creek near Lockeford</td>
<td>18040005</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>Colusa Basin Drainage</td>
<td>18020104 18020126</td>
<td>1619</td>
<td>3</td>
</tr>
<tr>
<td>11</td>
<td>Cache Creek</td>
<td>18020116 18020106</td>
<td>1145</td>
<td>3</td>
</tr>
<tr>
<td>12</td>
<td>Willow Slough bypass</td>
<td>18020109</td>
<td>208</td>
<td>4</td>
</tr>
<tr>
<td>13</td>
<td>Ulatis Creek, Cache Slough, Hass Slough, Lindsey Slough</td>
<td>18020109</td>
<td>252</td>
<td>6</td>
</tr>
</tbody>
</table>

Note:
1. The 8-digit hydrologic unit code assigned to the watershed by the US Geological Survey used for uniquely categorizing drainage areas.
Analysis procedure

Because regression analyses are not appropriate for estimating flow quantiles in watersheds with regulating features such as cutoff levees and diversion weirs, rainfall-runoff modeling using frequency-based hypothetical storms will be used to analyze the CVHS ungaged watersheds. Further, use of rainfall-runoff modeling will facilitate development of the required flow hydrographs required for floodplain mapping for these watersheds.

Figure 2 is a generalized representation of an ungaged watershed within the context of this study. In the figure, (A) is a stream that is analyzed using the “floods of record” method described in the Procedures document. Stream (B) in the figure is a smaller tributary to stream (A) that includes an analysis point, and thus requires a flow-frequency analysis. However, since the stream (B) is ungaged, it will be analyzed using rainfall-runoff modeling and design storms rather than the “floods of record” method. Note that following the study procedures, the ungaged watershed contribution between the upstream and downstream streamgages is included in the floods of record analysis of the downstream gage on stream (A). However, the inferred local flow hydrograph is not necessarily adequately defined for frequency analysis of stream (B).

Figure 2. Generalized representation of an ungaged watershed analyzed with rainfall-runoff modeling
We will follow standard procedures described in Corps guidance to develop flow frequency curves for the ungaged watersheds using rainfall-runoff modeling. The various analysis steps are described in detail in Attachment A. In summary, these steps include:

1. Identify the ungaged watersheds that require frequency analysis.
2. Gather information about each watershed.
3. Delineate watershed subbasins.
4. Select rainfall-runoff modeling methods, parameter values, and model time steps.
5. Assess availability of data for model calibration. Calibrate model parameters if sufficient data exists.
6. Develop precipitation input including event duration, temporal and spatial distribution, and frequency.
7. Compute runoff for specified quantiles.
8. Confirm the flow-frequency curves developed.
10. If needed, integrate ungaged watershed analysis with floods-of-record analysis.

Specific information about rainfall-runoff models and their application is presented in Table 2. There we list methods to be adopted, unless alternate methods are justified based on previous studies.
### Table 2. Summary of CVHS rainfall-runoff modeling of ungaed watersheds

<table>
<thead>
<tr>
<th>Aspect (1)</th>
<th>Details (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer program</td>
<td>HEC-HMS, with support GIS files including subbasin delineation and watershed characteristics.</td>
</tr>
</tbody>
</table>
| Subbasin delineation| - Delineate where flow is needed or significant change in topography or rainfall characteristics, such as analysis points that do not have sufficient gage records (availability and quality).  
- Number of subbasins should be minimized, but sufficient for evaluating Federal-State levee system.  
- 10 m digital elevation model (DEM) used for topographic input; better if available.  
- Not intended to support local drainage studies or master plans. |
| Modeling methods:   |                                                                             |
- Spatial distribution – Uniform application of areal reduction factors over contributing area to each point of interest/frequency curve location (not ellipsoid or other centering, unless specific analysis completed to demonstrate need).  
- Temporal distribution – Balanced hyetograph constructed of NOAA-14 depth-duration pairs corresponding to the event probability of interest. Areal reduction factors are applied to the balanced hyetograph.  
- Set runoff frequency equal to rainfall frequency. |
<p>| Evapotranspiration  | Not included in modeling.                                                   |
| Snowmelt            | For watersheds having more than 1/3 of the basin area above 5,000 feet, effects of snow on runoff will be considered in the analysis. The approach for accounting for snow effects will be determined on a case by case basis, and will consider the effect of snowmelt in historical events in the watershed. |
| Runoff-volume       | Initial and constant rate loss model.                                       |
| Direct-runoff transform | Select appropriate s-graph developed by Corps.                           |
| Baseflow            | Most likely, none, unless a specific analysis is completed to demonstrate need. |
| Routing             | Use appropriate routing technique per HEC-HMS technical reference manual (HEC 2000) and EM 1110-2-1417 (USACE 1994); see Table 3 in Attachment A. Since the majority of the routing reaches will be on ungaed, steep streams, it is expected that Muskingum-Cunge will be the preferred method. |
| Calibration         | When supported by available historical data.                              |
| Water control structures | As required given the definition of the subbasins and the significance of the controlling structure. |</p>
<table>
<thead>
<tr>
<th>Aspect (1)</th>
<th>Details (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model time step</td>
<td>Choose an appropriate time step given the time of concentration ($T_c$) of smallest subbasin.</td>
</tr>
<tr>
<td>Confirmation of results</td>
<td>Compare computed flow quantiles with another source as check for reasonableness. Sources include: USGS peak flow regression equations (under development), historical flow information if available, or unregulated flow frequency curves from Procedures document Task 4 at nearby sites.</td>
</tr>
<tr>
<td>Integration with other study results</td>
<td>Develop stage-flow transform by coupling stages at location of interest with estimated tributary flows from &quot;floods of record&quot; analysis of the mainstem. Flows on the mainstem will also be considered if the location of interest is subject to backwater conditions.</td>
</tr>
</tbody>
</table>
## Glossary

**Analysis point**

Locations in the basin where frequency curves are required to assess the Federal-State levee system. These are locations that have been agreed upon between USACE and DWR. They include upstream boundaries of the Federal-State levees and points within the Federal-State levee system where the regulated flow changes, such as at confluences, or areas with a large change in contributing watershed area.

**Floods-of-record analysis procedure**

The floods-of-record analysis procedure for gaged watersheds includes the following steps for each analysis point:

1. Develop a time series of unregulated flows.
2. Using historical records, an unsteady flow hydraulic model, and statistical analysis tools, fit a set of unregulated flow frequency curves.
3. Using historical records, a reservoir simulation model, and an unsteady flow hydraulic model, develop an unregulated-regulated flow transform curve.
4. Combine steps 2 and 3 to develop a regulated flow-frequency curve.
5. Using the regulated flow series from step 3 from the unsteady flow hydraulic model simulations, develop a relationship between event peak flow and stage.
6. Combine the curves developed in the preceding steps to obtain a stage-frequency curve.

For more information, see the *Procedures document* (USACE 2008).

**Gaged watershed**

A watershed for which the streamgage record is of sufficient length, the data available from the gage(s) are of sufficient quality, and one or more gages are located at or above the analysis point.

**Ungaged watershed**

A watershed that does not meet all 3 criteria of a gaged watershed.
References


Attachment A. Analysis procedure details

This attachment provides details about the following aspects of the analysis:

- Identifying the ungaged watersheds that require frequency analysis.
- Gathering information about each watershed.
- Delineating watershed subbasins.
- Selecting rainfall-runoff modeling methods, parameter values, and model time steps.
- If sufficient data are available for calibration to one or more events, calibrate model parameters.
- Developing precipitation input including event duration and runoff frequency.
- Computing runoff.
- Confirming the flow-frequency curves developed.
- Adopting flow-frequency curves.
- If needed, integrating ungaged watershed analysis with floods-of-record analysis.

1.0 Identify the ungaged watersheds requiring frequency analysis

The steps to identify ungaged watersheds needing frequency analysis are:

1. Identify analysis points (locations where frequency functions must be developed).
2. Delineate CVHS watersheds using GIS tools.
3. Identify the locations and types of gages in the watersheds.
4. Identify which watersheds meet the CVHS criteria for gaged watersheds, i.e., gages that:
   - Have a record length of 25 or more years, per EM 1110-2-1415 guidance.
   - Provide data of adequate quality.
   - Are located at or near (upstream or downstream of) the analysis point.
5. Compile a list of ungaged watersheds, as defined for the purposes of the CVHS.

To assess the quality of the data from a given streamgage, we inspect the data visually to identify any anomalies or inconsistencies. We then confirm data quality with those familiar with the streamgage in question, such as Corps water managers or DWR staff.

Factors which may make streamgage records inappropriate for frequency analysis include:

- Recurring errors in data values.
- Backwater effects.
- Streamgage subsidence, if resulting in distorted flow record.
- Land use changes.
- Urbanization.
- Missing data.

The analysis points and study reaches were finalized on 9/20/2009.

Some flexibility is allowed in comparing analysis points and gage locations. For example, when the gage is slightly downstream from the analysis point, and the incremental area between the analysis point and the gage is small, then the gage may be deemed appropriate for use in developing the required frequency curve. The presumption is that the difference in flow between the 2 points is small in comparison to the total flow at the point of interest.

A preliminary list of the CVHS ungauged watersheds has been developed, and is shown in Table 1. It is subject to revision as the analysis progresses. Note that the final list of ungauged watersheds has potential ramifications for users of the study products and the definition of the “unregulated condition” channel model as described in the Technical procedures document.

2.0 Gather readily available information about each watershed

We will gather information about the properties and characteristics of each ungauged watershed. Specifically, we will:

- Review the physical properties of the watershed such as elevation, average slope, soil type, and land use.
- Review the physical configuration of the watershed such as catchment areas and stream channels.
- Identify the presence of regulating features such as cutoff levees and diversion weirs.

We will examine the locations of analysis points within each ungauged watershed in relation to the physical features of the watershed. Specifically we must understand which analysis points are affected by regulating features or backwater.

We will also review previous studies of each ungauged watershed, if available, to determine: (1) what analysis methods were used, and (2) if the results and associated models are consistent with, and can be used for, the CVHS analysis. The latest study completed of a given watershed is likely to contain information useful for the present study and information regarding the appropriate modeling techniques for that ungauged watershed.

In review of these studies and any associated models, we will note:

- The purpose of the study.
- The analysis methods used.
- The analysis assumptions made, if any.
- The modeling parameters used, if any.
- The applicability of study results to the CVHS.
Based on a cursory review of the watersheds listed in Table 1 we have identified several previous studies which may contain information relevant to the analysis of these watersheds. These studies are summarized in Attachment B.

As the purpose of the model is to develop flow-frequency curves at analysis points, additional effort that does not lead to significant improvement in these curves is not warranted. There may be cases, however, wherein additional detailed information is required. Such cases may require field visits to assess channel dimensions and roughness for estimation of routing parameters, or identification of significant drainage features. A description of the additional data needed, supporting sensitivity analysis to justify the collection effort, and estimate of required resources should be documented before the decision is made to gather additional data. Readily available information sources, including previous studies and underway efforts (CVFED included) should also be considered.

3.0 Delineate watershed subbasins

Subbasins in the ungaged watersheds will be delineated using GIS-based tools. Note that a 10-meter digital elevation model (DEM) is sufficient for watershed delineation within the context of the CVHS; however, a DEM with a finer spatial resolution may be used if available.

We will delineate subbasins using the following 3 criteria:

- The number of subbasins within the watershed should be minimized.
- The outlet of each subbasin should correspond to a location where flow information is needed, i.e., an analysis point.
- The outlet of a subbasin may correspond to the location of a stream gage, to facilitate calibration of subbasin model parameters.
- The precipitation and topographic characteristics should be relatively homogenous over a given subbasin.

4.0 Select modeling methods and parameter values

We will use rainfall-runoff modeling using frequency-based design storms to develop frequency curves for all the ungaged watersheds. To do this, the first step is to develop and configure rainfall-runoff models for the required tributaries. For CVHS, computer program HEC-HMS will be used. Development of HEC-HMS models is well documented in the HEC-HMS technical reference manual (HEC 2000), and the HEC-HMS applications guide (HEC 2002).

The modeling methods we intend to use are described below. However, we will consider alternative methods if previous studies suggest that is warranted. Similarly, if sufficient historical data are available for calibration of model parameters, then this information should be considered in the adoption of final model parameters.

4.1 Runoff volume

We will use the initial and constant loss model for rainfall-runoff modeling of the ungaged watersheds. To develop the event-specific loss model boundary conditions, we will select parameter values using previous studies and other regional information, such as from local drainage manuals. Initial losses will be estimated from Table 5-1 of Sacramento City/County Drainage Manual.
Volume 2: Hydrology Standards (Sac County, 2006). Constant losses may be estimated from NRCS soil survey data. The Soil Survey Geographic (SSURGO) database (USDA-NRCS 2010) can be used to determine the Hydrologic Soil Group, and the HEC-HMS technical reference manual (Chapter 5) provides guidance for determining constant loss rates.

4.2 Direct runoff transform

We will use the s-graph method developed by the Corps and used extensively in the Central Valley. Three s-graphs are identified for use in the CVHS: mountain, foothills, and valley. These are provided in LAPRE-1: Los Angeles District preprocessor to HEC-1 (USACE 1989). The valley s-graph is recommended for areas with a basin slope less than 200 feet per mile, the foothill s-graph is recommended for areas with a basin slope between 200 and 400 feet per mile, and the mountain s-graph is recommended for areas with a basin slope greater than 400 feet per mile. Additional regional or location specific s-graphs may be used if previously developed for gaged watersheds with characteristics similar to that of the ungaged area.

Lag for each subbasin will be computed as described in Improved procedures for determining drainage area lag values (USACE 1962) using the equation:

\[ T_{lag} = 24 \text{h} \left( \frac{L_{ca}}{S_{ave}} \right)^{0.5} \]

where:
- \( T_{lag} \) = basin lag time (hrs)
- \( n \) = basin roughness coefficient
- \( L \) = longest flow path length (mi)
- \( L_{ca} \) = centroidal flow path length (mi)
- \( S \) = overall basin slope (ft/mi)

The length of the longest flow path (\( L \)), centroidal flow path length (\( L_{ca} \)) and the overall basin slope (\( S \)), can be obtained during delineation of the watershed (Section 3.0). The basin roughness coefficient (\( n \)) can be estimated from land use data following the guidance of Chapter 7 of the Sacramento City/County Drainage Manual (Sac County, 2006). Land use data will be obtained from the USGS National Land Cover Database (http://landcover.usgs.gov; Homer et al., 2007), last updated in 2001, unless more detailed data is available.

For areas with groundcover consisting of cultivated crops (or similar vegetation), no drainage improvements, and with surface characteristics such that channelizing does not occur, it may be appropriate to assign a basin \( n \) of 0.20 as recommended in Section E of the County of San Joaquin Hydrology Manual (1997).

4.3 Baseflow

We do not anticipate needing baseflow methods for most watersheds because the flood runoff from the design storms is likely to be large, and thus the contribution of baseflow to the peak runoff small.
4.4 Routing
We will follow the guidelines for selecting flow routing methods provided in chapter 8 of the HEC-HMS technical reference manual (USACE 2000). Table 8-3 of the technical reference manual is reproduced herein as Table 3, where $T$ = hydrograph duration, $u_o$ = reference mean velocity, $d_o$ = reference flow depth, and $g$ = acceleration due to gravity. A consistent recommendation table is available in EM 1110-2-1417 (USACE 1994).

Table 3. Guidelines for selecting a channel routing method (USACE 2000)

<table>
<thead>
<tr>
<th>If this is true...</th>
<th>...then consider this HEC-HMS routing method</th>
</tr>
</thead>
<tbody>
<tr>
<td>No observed hydrograph data available for calibration</td>
<td>Kinematic wave; Muskingum-Cunge</td>
</tr>
<tr>
<td>Significant backwater will influence discharge hydrograph</td>
<td>Modified Puls</td>
</tr>
<tr>
<td>Flood wave will go out of bank, into floodplain.</td>
<td>Modified Puls, Muskingum-Cunge with 8-point cross section</td>
</tr>
<tr>
<td>Channel slope &gt; 0.002 and $\frac{TS_o u_o}{d_o} \geq 171$</td>
<td>Any</td>
</tr>
<tr>
<td>Channel slopes from 0.002 to 0.0004 and $\frac{TS_o u_o}{d_o} \geq 171$</td>
<td>Muskingum-Cunge; modified Puls; Muskingum</td>
</tr>
<tr>
<td>Channel slope &lt; 0.0004 and $TS_o \left( \frac{g}{d_o} \right)^{0.5} \geq 30$</td>
<td>Muskingum-Cunge</td>
</tr>
<tr>
<td>Channel slope &lt; 0.0004 and $TS_o \left( \frac{g}{d_o} \right)^{0.5} &lt; 30$</td>
<td>None</td>
</tr>
</tbody>
</table>

4.5 Computation time step
The time step of the simulation will be chosen so it adequately captures the runoff peak. Generally, the simulation time step should not exceed 1/6th the time of concentration ($T_c$) of the smallest subbasin. Consideration of the temporal resolution of the design storm should also be given in selecting a time step. For example, the minimum time step should be less than that of the precipitation data. However, it may be shorter as indicated by the time of concentration metric. Upon selecting the computation time step, care must be taken to ensure that any routing parameters dependent on the time step are defined consistently.

5.0 Model calibration
While the subject watersheds are referred to as “ungaged”, there may be cases in which sufficient information exists for calibration. A streamgage may exist near the watershed outlet, or well upstream of the outlet. If the gage is upstream of the outlet, consideration should be given to subdividing the watershed at the gage location to support calibration. An assessment of whether sufficient data exists to support calibration must be made for each watershed.
If sufficient precipitation and streamgage data exist, model parameters can be calibrated to historical events. If only streamgage data is available, then it may be possible to develop a flow-frequency curve for the gage site. The appropriate method for developing the frequency curve will depend on gage record length and whether or not the site is unregulated. A frequency-based design storm can then be developed and applied, and model parameters adjusted to improve the comparison of computed runoff with the quantile flow estimate indicated by the frequency curve.

6.0 Develop precipitation input

Using the rainfall-runoff models developed as described above, we will use frequency-based design storms to develop frequency curves for all the ungaged watersheds. To do this, we will develop and configure design storms in HEC-HMS, compute runoff hydrographs, and assign the frequency of the design storm to the runoff hydrograph.

As needed, the peak and various volume-duration pairs at key locations will be extracted from the simulated results to then develop flow-frequency-duration curves.

Development of frequency curves using rainfall-runoff modeling is well documented in the literature. See, for example, EM 1110-2-1415 (USACE 1993), EM 1110-2-1417 (USACE 1994), the HEC-HMS technical reference manual (HEC 2000), and the HEC-HMS applications guide (HEC 2002).

To develop the design storm boundary conditions, we will:

- Use the precipitation-frequency data published in NOAA-14 Volume 6 to develop design storms for the ungaged watersheds.

- Develop balanced temporal distributions. A balanced hyetograph exhibits the same probability for all depth-duration pairs and is an established Corps method (USACE 1994) for specifying a design precipitation temporal distribution. The balanced temporal distribution may be either synthetic or historically-based.

  A synthetic balanced hyetograph may be developed directly from NOAA-14 depth-duration-frequency data. The time of maximum precipitation intensity (center balanced, front loaded, or other) should be historically justified if sufficient supporting information exists. Otherwise a center balanced event is acceptable.

  A historically-based balanced hyetograph may be developed by applying scale factors for various durations to a historical hyetograph. The historically hyetograph should be from a large event for which adequate precipitation data exists to well define the temporal distribution.

  The synthetic balanced hyetograph with historically-based time of peak intensity is the preferred method for defining the temporal distribution.

- Apply TP-40 areal reduction factors (ARFs) to balanced hyetographs to obtain design hyetographs. For watersheds having multiple analysis points, areal reduction factors will be spatially distributed to simulate events centered above the various analysis points.
Updated ARFs are being developed as part of NOAA-14, however, as of this writing the effort has been put on hold. Because waiting for these values will adversely impact the CVHS schedule we must use ARFs from alternative sources. Therefore, where ARFs are not published as part of NOAA ATLAS 14, ARF values from the TP-40 will be used.

7.0 Compute runoff and develop flow frequency curves

After the design storms have been developed and configured in the HEC-HMS models, the runoff hydrographs will then be computed. We will assign a runoff frequency equal to the rainfall frequency. Thus peak flow-frequency curves at analysis points, with the associated runoff hydrographs, will be developed.

8.0 Confirm frequency curves

We will confirm the frequency curves developed using rainfall-runoff modeling by comparing with 1 of the following 3 sources: (1) USGS regional regression equations (under development), (2) the unregulated flow frequency curves from nearby analysis points developed using the "floods of record" method, or (3) historical precipitation or discharge information.

We will use the USGS regional regression equations to estimate peak flow quantiles where appropriate. These will then be compared to those developed using the rainfall-runoff modeling and checked for reasonableness.

Where the regression equations are not appropriate, we will use the unregulated flow frequency curves as part of Procedures document Task 4 from nearby analysis points to confirm the flow-frequency curves. This confirmation will be done by comparing flow quantiles, for example on a flow per square mile basis, to those of the closest gaged point. Here, we will also compare the results to previous frequency analyses and watershed studies in the area.

If historical data are available, comparisons between computed quantiles and observed data may be useful for confirming estimates of frequency. For example, if historical data are available in parts of the watershed, these observations could be compared against the inputs used to develop these computed frequency curves by fitting statistical distributions to the data or by comparing precipitation and runoff volumes.

Based on expert judgment, modifications to the watershed model or candidate frequency curve may be made if necessary.

9.0 Adopt flow-frequency curves

Using the information of the peak flow and volume-duration flow quantiles identified using rainfall-runoff modeling, we will adopt the flow-frequency curve for a given analysis point within an ungaged watershed.

10.0 Integrate ungaged watershed analysis with floods-of-record analysis

The results of rainfall-runoff analysis of ungaged watersheds must be integrated with the other study products of the CVHS, including flow-frequency and stage-frequency estimates for the major rivers in the Central
Valley. The key to this integration is the flow-stage transform developed through the “floods of record” analysis.

Here, we refer to the reaches analyzed with the “floods of record” method as the mainstem, and the reaches using the rainfall-runoff method described herein as the tributary. Thus, the integration described is needed for cases where information from the mainstem affects flows and stages on the tributary. This is illustrated in Figure 3. In the figure, stream (A) is the mainstem and stream (B) is the tributary. Thus, here, the integration is required where stages on stream (B) are influenced by stream (A). If stages on stream (B) are not influenced by stream (A), then integration of methods is not required.

Figure 3 highlights, as compared to Figure 2 previously, the total incremental area between the upstream and downstream streamgage. A portion of this incremental area is made up with the ungaged watershed (B), but the remaining portion also contributes flow. As described in the Technical procedures document, Attachment B, the incremental flow between the 2 streamgages would be distributed in cases such as this as a combination of uniformly-distributed lateral inflows and point lateral inflows for development of the unregulated and regulated flow time series. Thus, given that a representation of the stream (B) is included in the CHVS system routing models, a stage-flow transform would be developed for the lower portion of stream (B). This relationship is not tied to the frequency of any 1 specific event.

Thus, using the stage-flow transform developed on the downstream end of stream (B) through the “floods of record” analysis, stages along stream (B) can be computed following steps described in the CVHS product uses document.
Figure 3. Example integration of uniformly distributed and point inflow local flows
Attachment B. Summary of previous watershed studies

Table 4 summarizes the results of an investigation on previous studies known to the Corps for the preliminary set of ungaged watersheds. These studies may be used during model development and for analyzing the interim study products.
<table>
<thead>
<tr>
<th>ID (1)</th>
<th>Ungaged watershed name (2)</th>
<th>Study report title (3)</th>
<th>Report author (4)</th>
<th>Report date (5)</th>
<th>Notes (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mud Creek and Big Chico Creek Diversion</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Butte Creek, Little Chico Creek</td>
<td>Comprehensive Study</td>
<td>SPK</td>
<td>2002</td>
<td>Flow Frequency Curve at Butte Creek near Chico</td>
</tr>
<tr>
<td>3</td>
<td>Dry Creek, Cherokee Canal</td>
<td>Cherokee Canal, Butte County CA: Section 1135 Hydrologic, Hydraulic, and Sediment Yield/Transport Study</td>
<td>URS/ SPK</td>
<td>January 2003</td>
<td>Cherokee Canal modeled to provide concurrent flows for the &quot;Standard Project Floods, Sacramento River &amp; Tributaries above Ord Ferry, Sacramento River, CA, dated 4 March 1963.</td>
</tr>
<tr>
<td>4</td>
<td>North Fork Honcut Creek, South Fork Honcut Creek</td>
<td>Sutter County Feasibility Study, F3 Milestone, Appendix A</td>
<td>SPK</td>
<td>March 2004</td>
<td>Sutter Basin feasibility study presently underway by the Corps.</td>
</tr>
<tr>
<td>5</td>
<td>Wadsworth Canal</td>
<td>Survey Report For Flood Control, Jack And Simmerly Sloughs Area, California</td>
<td>SPK</td>
<td>March 1968</td>
<td>Includes general area description, 2-hour unit hydrographs, and flow/stage frequency curves.</td>
</tr>
<tr>
<td>6</td>
<td>Jack Slough</td>
<td>Lower Feather River Flood Plain Mapping Study: Bear River Hydrology</td>
<td>SPK</td>
<td>April 2004</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>Bear River tributaries: Reeds Creek and Best Slough (WPI C), Dry Creek (near Wheatland), and Yankee Slough</td>
<td>Lower Feather River Flood Plain Mapping Study: Bear River Hydrology</td>
<td>SPK</td>
<td>April 2004</td>
<td>-</td>
</tr>
</tbody>
</table>

**Table 4. Summary of previous watershed studies of the unaged watersheds**
<table>
<thead>
<tr>
<th>ID (1)</th>
<th>Ungaged watershed name (2)</th>
<th>Study report title (3)</th>
<th>Report author (4)</th>
<th>Report date (5)</th>
<th>Notes (6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>Natomas drainage: Cross Canal Pleasant Grove Creek Steelhead Creek Arcade Creek</td>
<td>Natomas GRR/Lakeview Farms GR Report</td>
<td>SPK / Civil Solutions</td>
<td>Unknown</td>
<td>Natomas GRR utilized proprietary HEC-1 models developed by Civil Solutions for the Natomas East Main Drainage Canal (NEMDC) tributaries: Coon Creek, Bunkham Slough, Markham Ravine, Auburn Ravine, King Slough, Pleasant Grove Creek, and Curry Creek. Models are very finely subdivided and complex. Land use reflects projected development, so runoff is flashier than under existing conditions, which required modification of the outflow hydrographs for the Natomas GRR hydrology.</td>
</tr>
<tr>
<td></td>
<td>Completed in conjunction with 1 of the COE Dry Creek near Roseville studies in the 1980s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dry Creek Watershed Flood Control Plan</td>
<td>Placer County Flood Control &amp; Water Conservation District</td>
<td>SPK</td>
<td>post-Feb 1986 flood</td>
<td>Model includes Coon Creek, Markham Ravine, Auburn Ravine, Pleasant Grove Creek, Curry Creek, King Slough Model is not very complex, and was representative of the watershed when it was rural.</td>
</tr>
<tr>
<td></td>
<td>Dry Creek Hydrology</td>
<td>SPK</td>
<td>July 1984 (updated 2006)</td>
<td>HEC-1 model developed for the Dry Creek watershed as part of a Flood Control Plan. Used by USACE for Natomas GRR. Loss rates vary from 0.41 to 0.1 for the 2yr to 100yr. Snyder’s Cp varies from 0.60 to 0.75 among the 129 subbasins.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrology Office Report Supplement No. 1</td>
<td>SPK</td>
<td>March 1985</td>
<td>Hydrology data presented as basis for flood control projects. Description of development of standard project flood. Updated for 2006 urbanized conditions for AR Common Features Study</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Bear Creek near Lockeford</td>
<td>-</td>
<td>-</td>
<td>March 1985</td>
<td>Supplemental report to above report, detailing more frequent floods and cloudburst floods.</td>
</tr>
</tbody>
</table>

Part of the lower San Joaquin River feasibility study area being modeled by PBI.
<table>
<thead>
<tr>
<th>ID</th>
<th>Ungaged watershed name</th>
<th>Study report title</th>
<th>Report author</th>
<th>Report date</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>Colusa Basin Drainage</td>
<td>Colusa Basin Drain Hydrologic Investigation</td>
<td>SPK</td>
<td>August 1990</td>
<td>Model only includes a portion of the total drainage--mostly west-side subbasins below HWY 20</td>
</tr>
<tr>
<td>11</td>
<td>Cache Creek</td>
<td>Hydrology Appendix For Lower Cache Creek Feasibility Study</td>
<td>SPK</td>
<td>2001</td>
<td>HEC-1 model developed.</td>
</tr>
<tr>
<td>12</td>
<td>Willow Slough bypass</td>
<td>Westside Tributaries Yolo Basin Recon</td>
<td>SPK / Borcalli &amp; Associates</td>
<td>1993</td>
<td>An HEC-1 model was developed by Borcalli and Associates in 1992. Model was not calibrated but was verified by direct observation of flows in 1993. SPK review of model for Yolo BP Westside Tribs recon study determined that the model assumptions are reasonable. Lag times using USACE Snyder formula, with watershed roughness of 0.05</td>
</tr>
<tr>
<td>13</td>
<td>Ulatis Creek, Cache Slough, Hass Slough, Lindsey Slough</td>
<td>Alamo &amp; Ulatis Creeks nr Vacaville FPI Study</td>
<td>SPK</td>
<td>1972</td>
<td>Flood plain information study completed in 1972 for Alamo and Ulatis Creeks. No hydrologic model developed, hydrograph ordinates computed, routed, and combined by hand.</td>
</tr>
</tbody>
</table>