Sacramento and San Joaquin river basins: Procedures for hydrologic analysis

September 9, 2008
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<tr>
<td>0</td>
<td>March 10, 2008</td>
<td>Draft completed, submitted to DWR</td>
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<td>1</td>
<td>September 9, 2008</td>
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Executive summary

Background
In late 2007, the California Department of Water Resources (DWR) estimated that 1.8 million Californians (5% of the State’s population) lived in the so-called 100-year floodplain (DWR 2007). DWR further estimated that almost 10% of residents of California’s Central Valley live or work in the 200-year floodplain (DWR 2007). A growing Californian population will increase this vulnerability to flooding, with more people and property moving into potentially inundated areas. A changing climate may expand the areas subject to inundation at a given risk level and may envelop more land and more people.

The flood control system that protects Californians in the Central Valley is aging and the information upon which floodplain management decisions must be made is incomplete or out of date.

In response to these concerns, in 2007 the state initiated the FloodSAFE California program, which aims to increase flood protection and improve flood preparedness and response. For the state to achieve its FloodSAFE goals, the data upon which it depends must be updated.

In support of these efforts, DWR has delegated to us, the US Army Corps of Engineers, Sacramento District (Corps), the task of completing a hydrologic analysis of the Sacramento and San Joaquin river basins.

In addition, DWR has commissioned a Hydrologic Advisory Committee (HAC), comprised of specialists in flood hydrology, to oversee the technical aspects of the hydrologic analysis.

Purpose of paper
The primary purpose of this document is to describe the methods and procedures we will use to complete the hydrologic analysis of the Sacramento and San Joaquin river basins. Specifically, we describe the required inputs, models, analysis, and anticipated results. This description will give the HAC an opportunity to review, in advance, the procedures for the hydrologic analysis.

The secondary purpose of this paper is to initiate development of a project management plan (PMP) by outlining specific procedural tasks to be completed in the hydrologic analysis.

Analysis overview
The goal of the hydrologic analysis is to develop the required frequency curves, which provide estimates of the annual exceedence probability of flows, to support DWR’s floodplain mapping effort. These curves are required at analysis points—locations at which frequency curves must be developed—to facilitate floodplain mapping of all areas.
protected by the federal-state levee system in the basin. These points must be of sufficient spatial resolution to map accurately the floodplain in accordance with current standards of practice. Floodplain maps will be developed for annual exceedence probabilities ranging from 0.10 (10-year) to 0.002 (500-year).

Requirements
The primary requirements of this hydrologic analysis include:

- Yielding sufficient resolution to permit DWR to prepare floodplain maps of areas protected by federal-state levees in the basin.
- Meeting requirements of the Federal Emergency Management Agency’s National Flood Insurance Program.
- Being consistent with the standard of practice, using well established, peer-reviewed, accepted procedures and methods.

The secondary requirements of this hydrologic analysis include:

- Using procedures that can be reproduced at a later time to update the frequency curves.
- Acknowledging and describing the uncertainty in the hydrologic results.
- Facilitating follow-up analyses, such as evaluating the effect of climate change on the areas subject to inundation at a given risk level. This may include use of models or procedures that can be adjusted or modified to assess possible changes to the frequency curves.

Procedure overview
To develop required frequency curves for floodplain mapping along and behind federal-state levees throughout the Sacramento-San Joaquin river basin, we will complete a floods-of-record analysis. To develop the required frequency curves, we will:

1. Process historic data to remove the effects of system regulation and develop a time series of unregulated flows at each of the required points. Follow consistent methods in fitting the frequency curve with the unregulated time series. This is illustrated in Figure 1(a).

2. Using the historic records, a reservoir operation simulation model, and an unsteady flow hydraulic model of the system, develop an unregulated-regulated flow transform curve for each analysis point. This curve is illustrated in Figure 1(b).

3. Combine the results from step 1 and step 2 to develop a regulated flow-frequency curve for each analysis point.

4. Using an unsteady flow hydraulic model to simulate the floods of record, develop a relationship between event peak flow and stage
for each analysis point. This curve is illustrated in Figure 1(c). This relationship captures the effect of downstream control and the timing of flows at confluences.

5. Combine the curves developed above to obtain a stage-frequency curve for each analysis point. This curve is illustrated in Figure 1(d).

Thus, at the completion of the analysis, we will have curves a, b, and c, and the ability to create d, in Figure 1 for each analysis point. These can then be used as input to the hydraulic analysis to develop floodplain maps. As needed, additional frequency analyses can be completed on the simulated record length to develop volume-frequency curves.

The chapters following describe these steps in more detail.

Figure 1. Overview of hydrologic analysis procedure
Introduction

Watershed description

The Sacramento and San Joaquin river basins, also known as California’s Central Valley, cover approximately 3/8 of the state. The basin is illustrated in Figure 2. Below we provided a brief description of the watershed and the hydrologic conditions. Detailed descriptions are available in the Sacramento and San Joaquin river basins comprehensive study interim report (USACE 2002a).

The Sacramento River watershed includes approximately 27,000 square miles upstream of Rio Vista, CA. The basin is 240 miles long and up to 150 miles wide. It is bounded by the Sierra Nevada on the east, the Coast Range on the west, the Cascade Range and Trinity Mountains on the north, and the Sacramento–San Joaquin Delta on the south. Major tributaries to the Sacramento River include the Feather and American rivers, which flow westerly from the mountains. Numerous smaller streams flow into the Sacramento River from both sides of the valley. The cities of Sacramento, Yuba City, Marysville, Chico, Colusa, Red Bluff, and Redding are in the basin.

The San Joaquin River watershed lies between the crests of the Sierra Nevada on the east and the Coast Range on the west, and extends from the northern boundary of the Tulare Lake basin, near Fresno, to the confluence with the Sacramento River in the Sacramento–San Joaquin Delta. The basin is approximately 16,700 square miles, including 13,500 square miles south of the Delta. The basin includes drainage from central Sierra rivers and streams, including the Mokelumne, Calaveras, Stanislaus, Tuolumne, Merced, and Fresno rivers. In addition, some flood flows from the Kings River are diverted north to the San Joaquin River. The cities of Stockton, Modesto, Fresno, Merced, and Firebaugh are in the basin.

Meteorological conditions in the basin vary significantly by season and elevation. In the valley and foothill areas, the summers are hot and dry, and the winters are cool and moist. At higher elevations, the summers are warm and slightly moist, and the winters are cold and wet. Mean annual precipitation varies widely throughout the basin, ranging from slightly more than 6 inches in valley areas to 90 inches in some mountain areas. In the valley, the summers are virtually cloudless. During the November through February rainy season, more than half of the annual precipitation falls, yet rain in measurable amounts occurs only about 10 days monthly during the winter (Martini 1993). Thunderstorms in the valley are few and usually occur in the late fall or in the spring.

Snow is rare in the valley, but in the mountains that border the basin, precipitation often occurs as snowfall during the winter months. The annual snowmelt provides “a plentiful supply of water to the valley streams during the dry season” (Martini 1993).
Hundley (1992) points out that “the source of all this water is the Pacific Ocean. Vast clouds of moisture arise in the Gulf of Alaska or in the vicinity of the Hawaiian Islands and are driven ashore by the
prevailing easterly moving wind currents. When the heavily laden clouds strike first the Coast Range and later the Sierra Nevada, they are driven higher into colder elevations where their capacity to retain moisture decreases. As the clouds condense following their collision with the mountains, the higher elevations receive more precipitation than the valleys.”

This creates a situation in which torrential rain and heavy snow frequently fall on the western Sierra slopes, the southern Cascades, and to a lesser extent, the Coastal Range. However, with accurate, timely information about storms in the Pacific, the occurrence of large storms can be anticipated.

**Sacramento and San Joaquin river basin flood control system**

The cities and agricultural areas in the valley floor of the Sacramento and San Joaquin river basins are protected from flooding by the Central Valley flood control system. For completeness, we include a description of the system here.

The Central Valley flood control system, which includes the Sacramento River Flood Control Project (SRFCP) and the Lower San Joaquin River and Tributaries Flood Control Project (LSJFCP), protects more than 500,000 people and their property (Harder 2006). To accomplish this, the system relies on reservoirs, channels, bypasses, weirs, and levees.

Congress authorized the SRFCP in 1917 and construction occurred from 1918 through the 1950s. Specific facilities include (USACE 1999):

- 1000 miles of levees
- 440 miles of river, canal, and stream channels
- 5 major weirs
- 95 miles of bypasses comprising areas aggregating 100,000 acres
- 5 low-water check dams
- 50 miles of drainage canals and seepage ditches
- Numerous minor weirs and control structures, bridges, and gaging stations

Congress authorized the LSJFCP in 1944 and construction began in 1956. Specific facilities include (USACE 1955):

- 100 miles of levees
- New Hogan Dam on the Calaveras River
- New Melones Dam on the Stanislaus River
- Don Pedro Dam on the Tuolumne River
- Chowchilla and Eastside bypasses
Subsequent to authorization of the SRFCP and LSJFCP, additional major levees, bypasses, and multipurpose dams with flood control storage were constructed. These projects were the result of private developments, the federal Central Valley Project, the State Water Project, and several federal flood management projects in the San Joaquin Valley. These later projects are integrated with the SRFCP and LSJFCP, which remain central components of the Central Valley flood control system.

The Delta, lying between these 2 project areas, includes 60 islands and is protected by 1000 miles of non-project levees (DWR 2005).

Figure 3 shows locations of current Central Valley levees maintained by reclamation districts, levee districts, drainage districts, and municipalities. Delta levees and 300 miles of levees maintained directly by DWR are not shown.

Various agencies have constructed numerous reservoirs in addition to the Central Valley flood control system. These reservoirs provide water supply, recreation, and flood control. They are owned and operated by a federal, state, or local agency, but have designated flood control storage managed by the Corps. They are referred to as “Section 7” reservoirs (Flood Control Act of 1944). In the Sacramento River basin, approximately 3 million acre-ft of reservoir space are dedicated to flood control. In the San Joaquin River basin, approximately 2.4 million acre-ft of dedicated space are available for flood control.

**Situation**

In late 2007, the California Department of Water Resources (DWR) estimated that 1.8 million Californians (5% of the state’s population) lived in the so-called 100-year floodplain—the area subject to inundation with annual exceedence probability of 0.01 (DWR 2007). DWR further estimated that almost 10% of residents of California’s Central Valley live or work in the 200-year floodplain—the area subject to flooding with annual probability equal 0.005. A growing population will increase this vulnerability to flooding, with more people and property moving into the potentially inundated areas. Furthermore, a changing climate may expand the areas subject to inundation, encompassing more land and more people.

Historically, Californians have managed the flood hazard with structural water control measures, including levees adjacent to rivers and reservoirs upstream to manage flow rates and volumes in channels; and with floodplain management, including land use restrictions at the local level. However, the water control infrastructure—particularly the 6,000 miles of levees that 0.5 million Californians count on for protection—is aging, and the information upon which floodplain management decisions must be made is incomplete or, in some cases, outdated. This raises concerns about public safety and the level of protection afforded to property in the floodplain.
Figure 3. System levees and design flows (DWR 2003)
In response to these concerns, in 2007 the state initiated the FloodSAFE California program. Goals of FloodSAFE include:

- Increasing flood protection. The program, funded by Propositions 84 and 1E approved by voters in 2006, will reduce the likelihood of flood-related loss of life and damages to California communities, homes and property, and critical infrastructure.
- Improving preparedness and response. FloodSAFE promotes actions prior to flooding that will help reduce the adverse consequences of floods when they do occur and allow for quicker recovery after flooding.
- Supporting a growing economy. FloodSAFE provides continuing opportunities for prudent economic development that supports robust regional and statewide economies.
- Enhancing ecosystems. The program improves flood management systems in ways that enhance ecosystems and other public trust resources.
- Promoting sustainability. FloodSAFE prescribes actions to improve compatibility with the natural environment and reduce the expected costs to operate and maintain flood management systems into the future.

One key to achieving the FloodSAFE goals is availability of timely, accurate information about the flood hazard throughout the Central Valley. In particular, wise decision making to meet the FloodSAFE goals requires quantitative information about the frequency (probability) of flooding. When coupled with assessments of the vulnerability to and consequences of flooding (economic or otherwise), risk can be determined, tradeoffs can be weighed, decisions made, and appropriate actions taken.

Currently, the required up-to-date frequency information does not exist for the Central Valley. The bulk of the information that is available is at least 10 years old, and some of the information lacks resolution and robustness required of hydrologic studies related to FloodSAFE goals. Therefore, it is necessary to update the flood hazard information, and subsequently the risk assessment, for the Central Valley.

Accurate floodplain maps are the primary method of identifying and communicating flood hazards. They are required for risk assessments, which take into account the damageable property and lives at risk within the floodplain. In addition, such maps are a vital component of the National Flood Insurance Program (NFIP), which is administered by the Federal Emergency Management Agency (FEMA) (FEMA 2008).

**Task**

The first step in updating floodplain maps is completion of a detailed hydrologic study. Such a study defines the required flow or stage
frequency curves that are then used in a detailed hydraulic study. The hydraulic study, in turn, provides information with which we can map the floodplains.

DWR has delegated to us (the US Army Corps of Engineers [Corps], Sacramento District) the task of completing the aforementioned hydrologic study.

**Purpose of this report**

The primary purpose of this document is to describe the method and procedures we will use to complete the hydrologic analysis of the Sacramento and San Joaquin river basins. Specifically, we describe the required inputs, models, analysis, and anticipated results. This description is presented as a guide to analysts who are engaged in the study. It also provides reviewers and other interested parties an opportunity to participate in the process, offering insight into data and improved procedures.

The secondary purpose is to initiate development of a project management plan (PMP) by outlining specific procedural tasks to be completed in the hydrologic analysis.

**Study review and oversight**

Because of the potential significant impact of revised floodplain maps to land use, flood management, and other planning efforts, the analysis must be completed in an open, peer-reviewed manner. Thus, DWR has commissioned a Hydrologic Advisory Committee (HAC) to oversee the hydrologic analysis. The HAC includes specialists in flood hydrology studies who were selected by the Corps and DWR. These specialists are all familiar with California hydrology and the study requirements. The consultants in the committee were selected from contractors engaged by DWR for hydraulic analysis and mapping. The HAC will review the analysis to ensure it follows state-of-the-practice methods.
Analysis overview

Requirements of this hydrologic analysis

In this hydrologic study, we will develop frequency curves required for the floodplain mapping effort in the Sacramento-San Joaquin river basin. Specifically, we will prepare the necessary hydrologic inputs at analysis points in the basin. The analysis points are cross sections in the basin where frequency curves are required to map the floodplain. These analysis points include the upstream boundaries of the federal-state levees and points within the federal-state levee system where the regulated flow changes, such as at confluences, hydraulic structures, or areas with a large change in contributing watershed area. The required hydrologic inputs include peak flows and volumes for a given annual exceedence probability. We will develop the inputs for a range of annual exceedence probability from 0.10 to 0.002.

The primary requirements of this hydrologic analysis include:

- Yielding sufficient resolution to permit DWR to prepare floodplain maps of areas protected by federal-state levees in the basin.
- Meeting requirements of the Federal Emergency Management Agency’s National Flood Insurance Program (NFIP).
- Being consistent with the standard of practice, using well established, peer-reviewed, accepted procedures and methods.

The secondary requirements of this hydrologic analysis include:

- Using procedures that can be reproduced at a later time to update the frequency curves.
- Acknowledging and describing the uncertainty in the hydrologic results.
- Facilitating follow-up analyses, such as evaluating the effect of climate change on the floodplains. This may include use of models or procedures that can be adjusted or modified to assess possible changes to the frequency curves.

Pertinent FEMA guidelines

Floodplain maps created as a part of FloodSAFE will be used for NFIP-compliant floodplain management. Therefore, we must follow pertinent FEMA guidelines for hydrologic analysis that will lead to map making. The key guidelines that pertain to our analysis are listed in Table 1. These FEMA guidelines affect our starting storage assumed in the reservoirs in the Sacramento and San Joaquin river basins. In addition, FEMA guidelines (FEMA 2003) reference use of Corps Engineering Manual (EM) No. 1110-2-1415 (1993) for frequency analysis. Note that EM 1110-2-1415 provides guidance on flood flow-frequency analysis for regulated watersheds: “[R]outings should be made under reasonably conservative assumptions as to the initial reservoir stages.”
Previous system-wide hydrologic analysis

The Corps completed the last system-wide hydrologic analysis of the basin in 2002 as part of the greater Sacramento-San Joaquin Comprehensive Study (referred to herein and commonly as the Comp Study). Originally, the Comp Study was intended to provide a master plan for flood damage reduction and ecosystem restoration following the disastrous floods of 1997. For this, the Corps undertook a reconnaissance-level hydrologic and hydraulic analysis of the basin. The technical analyses completed for the Comp Study have served as the basis for recent local and system-wide flood management alternative evaluations by local flood control agencies, the State of California, and the Corps.

The hydrologic analysis component of the Comp Study included developing unregulated flow-frequency curves throughout the basin. In addition, the Comp Study used historical storm patterns to develop a series of design runoff hydrographs. These design hydrographs were used to stress specific tributary watersheds and system performance. These studies and procedures are documented in the technical appendices of the Comp Study report (USACE 2002b) and in technical journals (Hickey et al. 2002, Hickey et al. 2003). The technical appendices are available online at www.compstudy.net.

The procedures described herein build upon the Comp Study work and rely heavily on some of the fundamental products and procedures from that study, specifically the datasets and models developed.

Analysis strategy and results

To develop required frequency curves for floodplain mapping behind federal-state levees throughout the Sacramento-San Joaquin river basin, we will complete a floods-of-record analysis. Our strategy to develop the required curves is described in Table 2.

Thus, at the completion of the analysis, we will have curves $a$, $b$, $c$, and the ability to create $d$, in Figure 4 for each analysis point. These can be used in the hydraulic analysis to develop floodplain maps.

Table 1. Pertinent FEMA guidelines (FEMA 2003)

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<th>ID (1)</th>
<th>Guideline (2)</th>
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<tr>
<td>1</td>
<td>At a minimum, the hydrologic analysis should include the p=0.01 (100-year) annual exceedence probability event; however, FEMA often requires determinations of the p=0.10 (10-year), p=0.02 (50-year), and p=0.002 (500-year) flood discharges, as well.</td>
</tr>
<tr>
<td>2</td>
<td>The Mapping Partner performing the hydrologic analysis normally shall not consider storage capability below the normal pool elevation of reservoirs operated primarily for purposes other than flood control because the availability of such storage is uncertain.</td>
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</table>
needed, additional frequency analyses can be completed on the derived time series to develop volume-frequency curves.

Table 2. Summary of analysis strategy

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<tr>
<th>ID (1)</th>
<th>Task (2)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Analyze historical (unregulated) flow records to develop unregulated-flow time series for the same historical period, fitting a frequency curve with the unregulated series. This is illustrated in Figure 4(a).</td>
</tr>
<tr>
<td>2</td>
<td>Using the historical records, a reservoir operation simulation model, and an unsteady flow hydraulic model of the system, develop an unregulated-regulated flow transform curve for each analysis point. This curve is illustrated in Figure 4(b).</td>
</tr>
<tr>
<td>3</td>
<td>Combine the results from step 1 and step 2 to develop a regulated flow-frequency curve for each analysis point.</td>
</tr>
<tr>
<td>4</td>
<td>Using an unsteady flow hydraulic model to simulate the floods of record, develop an event peak stage-flow relationship for each analysis point to develop a stage transform. This curve is illustrated in Figure 4(c). Integrated into this relationship is the influence of downstream control and timing of flows at confluences, where appropriate.</td>
</tr>
<tr>
<td>5</td>
<td>Combine the curves developed above to obtain a stage-frequency curve for each analysis point. This curve is illustrated in Figure 4(d).</td>
</tr>
</tbody>
</table>

Figure 4. Overview of curves developed for hydrologic analysis
Procedure overview

We will use the floods-of-record to develop the frequency curves. The floods-of-record include the largest annual flow on each stream included in our study for the period of record. Given the size of the basin, this may result in one or more floods for any given year. The basic procedural tasks for completing the hydrologic analysis are described in Table 3 and illustrated in Figure 5.

Our first step is to collect relevant flow data. Next, these data, which represent regulated conditions in the system, are analyzed and processed to create an unregulated time series. This series represents the hydrologic response of the watersheds in the absence of storage associated with reservoirs and overbank areas. Using the unregulated time series, we next develop an unregulated flow-frequency curve. We will develop the unregulated flow time series using historical gage records as well as models of the Sacramento and San Joaquin river basin to help “fill in the gaps” in the available flow record.

We use reservoir and channel models to assess the effect of system regulation. Using these models and the floods-of-record time series, we construct a flow transform curve—a relationship of unregulated flow to the regulated flow at a given location. Reservoir operation is highly dependent on the timing of flow from adjacent watersheds. Capturing the temporal affects of storm variability—which drives runoff—is important in accurately representing the unregulated flows in the model. By using the large sample of historical events, we account for the inherent variability in storm patterns, and their relative coincident occurrences, in the Sacramento-San Joaquin river basin. The flow transform curve is therefore a measure of the physical properties of the watershed, flood management measures, and historical storm variability.
<table>
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<th>ID</th>
<th>Task (2)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Data collection and augmentation</td>
<td>We will collect the required data and information needed for the analysis. This includes identifying gages in the basin and collecting the associated historical flow and other data. In addition, we will collect the required watershed and reservoir information.</td>
</tr>
<tr>
<td>2.0</td>
<td>Model and computer program adoption</td>
<td>To complete the tasks of the hydrologic analysis, we will rely on computer models of the watershed, channels, and reservoirs. We will identify which models and computer programs will be used and adopt those models. This will help to ensure consistency throughout the analysis.</td>
</tr>
<tr>
<td>3.0</td>
<td>Development of unregulated flow time series</td>
<td>We will develop a floods-of-record unregulated flow time series for each basin, which includes identifying the largest event on each stream for each year in the period of record. As part of this task, we will estimate the flow contribution from the ungaged tributaries (Task 3.2 in Figure 5). We will accomplish this by using observed stage records—the best measure of historic events—that are available in the basin. Used in conjunction with an unsteady flow channel model, we can use observed stage hydrographs to estimate the local flow contribution between adjacent gages. For routing of unregulated flow through the basin, we will rely on unsteady flow channel models.</td>
</tr>
<tr>
<td>4.0</td>
<td>Flood flow-frequency analysis</td>
<td>Following the current standard of practice, we will fit frequency curves to the annual maximum unregulated flows at key locations in the basin. Development of this flow-frequency curve will allow us to estimate flows for events corresponding to selected exceedence probabilities.</td>
</tr>
<tr>
<td>5.0</td>
<td>Development of regulated flow time series</td>
<td>Using the unregulated flow time series and estimates of ungaged flows, we will employ reservoir simulation models to assess the effect of system regulation. In addition, we will use unsteady flow channel models to route reservoir releases through the channel network, accounting for attenuation due to overbank storage.</td>
</tr>
<tr>
<td>6.0</td>
<td>Development of flow transform</td>
<td>Using the model results from Task 3.0 and Task 5.0, we will extract information that represents the effect of system regulation. Specifically, we will build a dataset of pairs of event-maximum unregulated and regulated flows. Fitting a most likely curve through these data pairs will yield a flow transform curve. To help define the extreme end of the flow transform curve, we will extract data pairs from a uniformly scaled, then simulated, floods-of-record dataset. This flow transform curve will allow us to convert our unregulated flow-frequency curve to a regulated flow-frequency curve.</td>
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<tr>
<td>7.0</td>
<td>Development of stage-flow transform</td>
<td>Taking advantage of our previous unsteady flow channel routings of regulated conditions, we will extract pairs of event maximum stage–maximum flow values. Fitting a most likely curve through these pairs of values will yield a stage-flow transform. This relationship will allow us to convert our regulated flow-frequency curve to a stage-frequency curve.</td>
</tr>
<tr>
<td>8.0</td>
<td>Analysis of ungaged streams</td>
<td>For ungaged tributaries, the proposed procedure is not applicable. Thus, for ungaged tributaries, we expect to develop the frequency curves through region-specific regression equations or through rainfall–runoff modeling of hypothetical events, calibrated to frequency curves developed for gaged streams as described above.</td>
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</table>
Figure 5. Overview of steps for hydrologic analysis procedure
Combining the unregulated flow-frequency curve and the flow transform curve, we develop a regulated flow-frequency curve.

Using an unsteady flow channel model to route our reservoir release through the channel network, allows us to extract pairs of event-based maximum stage-maximum flow values. Fitting a most likely curve through these points yields a stage-flow transform that accounts for both the channel characteristics and the hydraulic effects of downstream conditions. The stage-flow transform is used to convert the regulated flow-frequency curve to a stage-frequency curve. Quantiles from this analysis serve as the inputs for mapping activities.

**Precedence of analysis procedure**

EM 1110-2-1415 (USACE 1993) identifies the hydrologic analysis method and procedure described herein as an appropriate strategy for defining frequency curves.

The Corps used this procedure in *The Upper Mississippi flood frequency study* (USACE 2003) to compute flood profiles along the major rivers (the Missouri, Mississippi, and Illinois) in the Upper Mississippi Basin. The analysis covered a drainage area of approximately 700,000 square miles from the basin headwaters to the USGS gage at Thebes, Illinois, downstream of St. Louis, Missouri. The frequency analysis was completed with consultation from a technical advisory group and interagency advisory groups, members of which came from universities, consultants, FEMA, the United States Bureau of Reclamation (USBR), the National Weather Service, and the United States Geological Survey (USGS).
Step-by-step analysis procedure

In this chapter, we describe in detail the tasks and steps required to complete the hydrologic analysis. In application of this procedure, we have identified several technical challenges which we must address during the study. However, such challenges are a part of any large watershed-scale analysis. Appendix C lists these technical challenges and our anticipated approach for addressing them in the study.

The illustration in Figure 5 graphically illustrates the hydrologic analysis procedure. The task numbers shown in Figure 5 are used in subsequent documentation of this study.

1.0 Data collection and augmentation

The first task is to collect the data required for the analysis. These include:

- Time series of unregulated flows in the system for use in frequency analysis and system performance analysis.
- Time series of flows for unregulated watersheds for use in supporting studies, including a regional skew analysis.

In addition, we will collect the required information to assemble and verify reservoir and channel models.

A large data collection effort was completed as part of the Comp Study. We will review and revise data collected for the Comp Study, particularly in light of the additional 10 years of gage data recorded since the Comp Study collection effort.

Subtasks of this task include:

1.1 Identify gages

The first step is to identify the locations and types of gages in the watershed. This includes, for example, identifying reservoir level and stream gages in both the headwaters portion of the watershed as well as the valley floor.

1.2 Filter gage list by record length, collect data

Once all gages are identified, we will filter this list to those gages that will be useful for the study, specifically those with a long record length – the critical common record length is expected to be 50 years. We will collect the available data for the gages and store the data following the conventions defined in this study's Data management plan (2007).

For this analysis, we are interested in collecting data for the floods-of-record. These floods include the largest annual flood on each stream included in our study for the common record length. This may result in more than a single event for a given year. These additional events
must be included to construct a series of annual maximum flows on each stream in our study for later frequency analysis.

1.3 Filter gage list by unregulated watershed, collect data
From step 1.2, we will identify the subset of gages for unregulated watersheds. This subset of gage data will be useful for supporting analyses.

1.4 Augment gage data
In some cases, the time series of gage data may have gaps or may need to be extended. For these cases, we will use procedures that were followed and documented for the Comp Study.

1.5 Collect reservoir properties and rule curves
For development of reservoir simulation models, we will collect reservoir physical properties, such as elevation-volume relationships. We also will collect information on operation policies and rule curves, referring to each reservoir's water control manual. Data gathered and collected from the Comp Study will also be used.

1.6 Collect properties of stream networks and channels
For development of a channel routing model, for both unregulated and regulated conditions, we will collect available information about stream networks and channel geometry. This information will likely be in the form of existing channel models used in the Comp Study or other recent watershed studies.

2.0 Model and computer program selection and acceptance
Here, we identify and adopt the required hydrologic and hydraulic models and computer programs necessary to complete the study. The result of this step will be a suite of models, with common information exchange points within the system; these models will be used to complete this hydrologic analysis.

Subtasks of this task include:

2.1 Accept reservoir simulation models
A reservoir simulation model will be used in this hydrology analysis to convert the floods-of-record unregulated flow time series to a floods-of-record regulated flow time series. For this analysis, we will use the computer program HEC-ResSim (USACE 2006) to develop a model of the system. We expect to create 2 complete reservoir simulation models of the system. The first model will be of the Sacramento River basin, including reservoirs in the reservoir simulation model from the Comp Study (UASCE 2002c). These are the 33 largest reservoirs in the basin. The second model will be of the San Joaquin River basin. Again,
the model will include the same reservoirs used in the Comp Study model—the 29 largest reservoirs in the basin.

Before acceptance of the models, we will simulate a selected historical flood event with the reservoir models. The appropriate Corps water manager will review the reservoir simulation for accuracy. The standard for comparison will be the currently authorized water control manual for each reservoir.

Given that this study focuses on flood management issues, the reservoir models will be configured with flood management rules only. Water supply operation and minimum flow requirements will not be included in this reservoir simulation model.

2.2 Accept hydraulic models

For the analysis, we require an unsteady flow hydraulic model to route flows through the channel networks. Two different channel routing models are required. These are:

- A channel routing model representing regulated, with-project conditions. This model must reflect the regulating conditions that will be in place for the floodplain mapping effort. Thus, the regulated model must include the ability to simulate the effects of levee overtopping and potential levee failure. We will also use this channel routing model to estimate the ungaged-watershed flow contribution.

- A channel routing model representing unregulated conditions. For routing of the floods-of-record unregulated flow time series, we require a second channel routing model that contains the flow within the channels and routes it through the system.

As with the reservoir simulation model, we expect to create channel routing models for the Sacramento River basin and for the San Joaquin River basin. Note that for the regulated channel model, an assumption of levee overtopping or failure is required. This is addressed in Appendix C.

We will review the status of current basin-wide channel models, select the appropriate model and computer program, and modify the model configuration, as appropriate, to reflect each condition. The UNET and/or HEC-RAS computer programs will be used to create the channel models.

3.0 Development of unregulated flow time series

The goal of this task is to develop an unregulated flow time series at all analysis points within the basin. We will use this unregulated flow time series for the following two purposes: (1) as the basis of the unregulated flow-frequency analysis and (2) as the input to our regulated-condition analysis. The result of this step will be an unregulated flow time series at each required analysis point in the
basin that accounts for all upstream contributing area. We develop this based on the data gathered in Task 1.0.

Subtasks of this task include:

3.1 Develop reservoir inflows

Since inflow is not measured directly at reservoirs in the system, we must estimate the inflow into each reservoir for the floods-of-record. To estimate the reservoir inflows for each event, we will use the data collected in Task 1.0, such as reservoir elevation and reservoir release, along with a water accounting model. For these computations, we will use HEC-ResSim as well as custom scripts and spreadsheets.

This estimated reservoir inflow will be checked to ensure that the influence of upstream regulation is absent and that the derived series therefore represents the unregulated flow time series. (Gage records that are influenced by regulation, such as those from a reservoir farther upstream, must be transformed to unregulated flow time series, thus removing the effects of all reservoirs in the records.)

3.2 Develop flows from ungaged watersheds

For development of the unregulated flow time series, we must estimate the contribution of the ungaged portions of the watershed. These ungaged portions may include the portion of the watershed between 2 reservoirs in series, small tributaries that flow into larger streams, or local runoff along major streams. This contribution must be included in curves to be developed in subsequent tasks, such as the unregulated flow-frequency curve and flow transform. For estimation of the ungaged flow, we will rely on our best measure of historical hydrologic conditions, observed stage hydrographs, in conjunction with our channel routing model (regulated conditions).

The procedures for estimating ungaged flow are described in Appendix B. In summary, the process includes setting a gage location with a stage hydrograph, for example, Gage A in Figure 6, as an upstream reach boundary in the channel routing model. The channel model converts the stage hydrograph to a flow hydrograph and routes it from Gage A to Gage B, a gage location with an observed stage hydrograph. By comparing the routed stage hydrograph at Gage B to the observed stage hydrograph at the same location, we can infer the contribution of the ungaged tributary due to the contributing area between A and B in the Figure 6. Appropriate lag adjustments in the inferred local flow can then be made based on the travel time from the confluence of the ungaged tributary to Gage B, as appropriate.

We will review the results from this ungaged flow method for reasonableness by comparing the results to standard rules used for hydrologic analysis in the basin, such as ratios of local flows to mainstem flows or flow per area estimates.
Once the step is complete, we will have estimates of the total flow contributed to the major streams in the Sacramento and San Joaquin river basins. These local (or lateral) flow estimates will be used in later analysis steps when simulating system-wide regulated and unregulated conditions.

Figure 6. Example of unaged tributary

3.3 Complete unregulated flow time series

We will combine the local flow estimates from Task 3.2 with our headwater reservoir inflow estimates to develop a complete unregulated flow time series. For this computation, we rely on our unregulated condition channel routing model. We use this channel model to simulate the floods-of-record, adding the inferred local flow from Task 3.2 at the appropriate locations. The result of this hydraulic simulation is an unregulated flow time series at every cross section in the model. This is illustrated in Figure 7.

Figure 7. Illustration of unregulated flow time series at an analysis point

4.0 Flood flow-frequency analysis

With the floods-of-record unregulated flow time series at essentially every location in the valley along the major streams (for every cross section for the extent of the channel model), we can develop unregulated flow-frequency curves wherever needed. By developing an
unregulated flow-frequency curve, we can estimate the unregulated flow for each of the annual exceedence probabilities required for the floodplain mapping. As needed, unregulated flow-frequency curves can also be developed for various durations of volumes, such as the 3-day or 7-day volumes (or corresponding average flow rate for that duration).

For the flow-frequency analysis, we will follow the standard-of-practice procedures. At present, those are described in Bulletin 17B (Interagency Advisory Committee on Water Data 1982).

Subtasks of this task include:

4.1 Coordinate with USGS on regional frequency analysis study

The standard-of-practice for flood flow-frequency analysis calls for fitting a log Pearson type III probability distribution to a series of unregulated flow annual maximums. The 3 parameters used in the probability distribution are estimated from the mean, standard deviation, and skew coefficient of the sample series. As a component of the parameter estimation process, an attempt to regionalize the analysis is made. This regionalization attempts to pool information based on previous studies in the area using gage data. This regionalization could come from the development of a regional skew value or regional estimates of flow quantiles. The US Geological Survey (USGS) is working currently on a regional frequency analysis study. We will coordinate with USGS staff on the approach and methods used for that study, and use those results for this hydrologic analysis.

4.2 Complete unregulated flow-frequency analysis

Using the results of the regional skew analysis, we will use our unregulated flow values to fit unregulated flow-frequency curves, such as the one shown in Figure 8, at all analysis points. These points are expected to be at the upstream extents of the federal-state levee system and at locations downstream where the flow is expected to increase or decrease.
5.0 Development of regulated flow time series

We must assess the effect of regulation in the system. To do this, we will develop a companion regulated flow time series to our unregulated flow time series, using our reservoir simulation model, our regulated-condition channel model, our estimate of ungaged local flows (from Task 3.2), and our unregulated flow time series. At the completion of this task, we will have a regulated flow time series at each location for which we have an unregulated flow time series. The regulated flow time series will be used in the development of our flow transform curves (unregulated flows to regulated flows) and our stage-flow transform. With these, the unregulated flow-frequency curves will be transformed to regulated flow-frequency curves.

Subtasks of this task include:

5.1 Route flows through reservoir simulation model

The first step in developing the regulated flow time series is to simulate the floods-of-record using the adopted reservoir simulation model. As input flows to our reservoir simulation model, we will use the ungaged local flows, as needed, and our unregulated flow time series. The result of the floods-of-record simulation is a set of time series of reservoir releases.

Following FEMA requirements on starting storages in reservoirs, this reservoir simulation will not be a pure period-of-record analysis where, for example, in a given year vacant storage in the conservation pool may provide flood control benefit. For the simulation, each year the reservoirs will be considered such that flood control reservoirs are at the top of the conservation pool (bottom of flood control pool) and headwater reservoirs are at normal pool (top of conservation pool).
As noted above, we will configure the reservoir models for flood control operations only. Thus, the resulting regulated flows are assured to be valid only for high flow periods.

### 5.2 Route flows through channel model (regulated condition)

The next step is to route the reservoir releases from Task 5.1 through the system using our regulated-condition, unsteady flow channel model. (The ungaged local flows from Task 3.2 will be added in the channel model as appropriate.) The channel model will simulate the effects of hydraulic structures and operable weirs and diversions as well as the effects of levee overtopping and potential levee failure.

The information obtained from the channel model floods-of-record analysis will be a regulated flow time series that corresponds to an unregulated flow time series developed in Task 3.0. This regulated flow time series is illustrated in Figure 9.

![Figure 9. Illustration of regulated flow time series](image)

### 6.0 Development of flow transform curves

Here, we develop a relationship of unregulated flow to regulated flow for all locations within the floodplain mapping extents, using the unregulated and regulated time series developed previously. The purpose of this step is to develop a relationship that captures the effects of:

- Reservoir operation.
- Historic storm patterns and timing, including coincidence and concurrence of flood events explicitly accounted for.
- Impact of storm patterns on reservoir operations.
- Impact of water control features such as channels, levees, weirs, and bypasses.

The result of this task is a relationship, based on common historical events, of unregulated flow and regulated flow. This relationship can be used to convert the unregulated flow-frequency curve from Task 4.0 to a regulated flow-frequency curve.
Subtasks of this task include:

**6.1 Identify regulated and unregulated event maxima**

Using the time series developed from Task 4.0 and Task 5.0, we will identify maximum flows from each time series for common high flow events throughout the entire set of historic events. The peak from the regulated flow time series and the peak from the unregulated flow time series for the same event represent 1 data point in the flow transform curve. Note that these are not simply contemporaneous values from each time series. As a result of on- and off-stream storage associated with the regulated condition, the peak flows from the regulated time series may lag the corresponding unregulated peak flows.

**6.2 Extend the unregulated-regulated flow transform**

We expect that our data points gathered in Task 6.1 will not extend far enough to allow us to convert unregulated flow to regulated flow for extreme events such as the p=0.002 event. Therefore, we will extend the flow transform relationship to include events greater than those that have been recorded, thus expanding the storm sample size for purposes of the unregulated-regulated flow modeling.

To extend the flow transform relationship, we will use the procedure called for in EM 1110-2-1415 (USACE 1993). That is, we will uniformly scale our unregulated flow floods-of-record dataset and repeat Task 5.0. By scaling the historical unregulated flow time series and simulating it with the reservoir and channel routing models, we will be able to assess system response to extreme events and extend the flow transform relationship. Note that EM 1110-2-1415 suggests that a scaling factor no larger than 2 or 3 be used. As noted in the EM, this procedure “assures consistency in the analysis and gives a graphical presentation of the variability of the regulated events for a given unregulated flow.”

By scaling all the floods-of-record rather than just a few of the largest events, we are able to capture the effect of the various historic storms’ spatial and temporal distributions. This will limit the bias of the results toward any one historic event.

Scaling the floods-of-record and simulating extends only the relationship that indicates system response to regulating factors. This is independent of the unregulated flow-frequency curve and does not affect the probability of a given unregulated flow.

After we have scaled the historic events, the scaled unregulated and regulated time series must be used to develop information points for the flow transform curve as described in Task 6.1. The result is a set of data points relating unregulated and regulated flow for all the historic events and the scaled historic events.
6.3 Fit flow-transform curve

The paired values of event unregulated and regulated flows, from the floods-of-record time series and the scaled time series, will be used to fit a flow transform curve. This is illustrated in Figure 10. Here, the points shown in the figure represent matched event peaks from the unregulated and regulated time series.

We will fit an interpolating polynomial to estimate the flow transform from the paired data as follows:

1. Examining a plot of the flow transform points, identifying and deleting anomalies.
2. Developing a statistical procedure to fit a mathematical curve with the points.
3. Examining the curve for reasonableness.

![Figure 10. Illustration of unregulated-regulated flow transform curve](image)

6.4 Apply flow-transform curve

The flow-transform curve is combined with the unregulated flow-frequency curve from subtask 4.2 to develop a regulated flow-frequency curve at each analysis point.

7.0 Development of stage-flow relationships

Conditions in adjacent and downstream channels affect water surface profiles (stages) in the Sacramento and San Joaquin river basin channels, especially within the extents of the federal-state levee system. For example, the stage at a given cross section upstream from a confluence with a tributary stream may be influenced by the coincident event and timing of flows on that tributary. This effect must be considered when estimating the stage of a given annual exceedence probability at the cross section.

To account for this downstream effect, EM 1110-2-1415 suggests identifying stage-flow relationships from historic events and fitting a
most likely curve. These stage-flow relationships would come from
simulation of historic events. We will follow this guidance here.

Once developed, this stage-flow relationship can be used in
conjunction with the regulated flow-frequency curve from Task 6.0 to
develop a stage-frequency curve.

Subtasks of this task include:

7.1 Identify regulated and unregulated stage-flow maxima

Here, we will use the results from the channel routing in Task 5.2 to
develop event maximum stage–maximum flow data points from the
historic events. As with development of the flow transform curve, we
will select the largest event each year to define 1 point on the stage-
flow relationship. If we need to extend the information points for the
larger events, we will extract points from the scaled floods-of-record
channel routing in Task 6.2.

7.2 Fit stage-flow transform

After extracting the stage-flow data points, we will establish a
relationship between event maximum flows and maximum stages,
similar to development of the flow transform curve in Task 6.3. We will
fit this curve by examining the stage-flow points, fitting a curve using
a statistical analysis procedure, and examining the results. This fitted
curve will be used to develop a rational relationship between the
stage-flow points.

The stage-flow transform developed through the system-wide floods-
of-record analysis includes more information than a typical rating
curve. Typically, a rating curve is developed based on a given flow,
channel geometry, channel roughness, and a presumed downstream
boundary condition. In addition to the typical information associated
with a rating curve, the stage-flow transform developed as part of this
study incorporates timing and magnitude of downstream flows or
stages and the likelihood of a specific downstream condition.

7.3 Apply stage-flow transform

The stage-flow transform is combined with the regulated flow-
frequency curve from subtask 6.4 to develop a stage-frequency curve
at each analysis point.

8.0 Analysis of ungaged watersheds

The hydrologic analysis procedure described in Task 3.0 through Task
7.0 does not facilitate development of frequency curves for smaller,
ungaged tributaries or those with limited stream flow data. The
contribution of such a tributary is included in the total flow in the main
channels. However, we may lack sufficient data to fit a frequency
curve, following the procedures in Task 3.0 through Task 7.0, to the
channel on that tributary. Therefore, for these cases, a complementary
hydrologic analysis procedure is required to supplement the procedure described above.

At this time, 2 options for this supplementary procedure are considered. We describe these in Task 8.2 and Task 8.3 below. In either case, the result of this supplementary analysis will yield the remainder of the required frequency curves for floodplain mapping.

To the extent possible, this analysis will be completed simultaneously with Task 3.0 through Task 7.0. Subtasks of this task include:

**8.1 Identify ungaged watersheds requiring frequency curves**

Our first step is to identify which ungaged tributaries require frequency curves. After the data collection effort of Task 1.0, we will review the gage locations and the location of the federal-state levees to identify which tributaries require this supplementary analysis. We will categorize the characteristics of the ungaged watersheds, such as watershed area, land use, and topography.

**8.2 Develop regression equations for the Central Valley**

Our preferred option is to develop region-specific regression equations for quantiles of the required annual exceedence probabilities. To do this, we would use data identified and collected in Task 1.3. There, we identify gages on unregulated watersheds and collect that data. We would extract the physical properties of the contributing watersheds based on available topographic data. Using quantiles from the frequency curves developed from Task 4.0 for these gages, and the physical watershed properties, we would develop the required regression equations. We would develop these regression equations for various flow durations, such as for peak flow, 1-day flow, 3-day flow, and as needed. Where hydrographs are required, we would take an historical hydrograph and scale it using the regression equations.

This regression analysis would be completed with cooperation from USGS.

**8.3 Develop rainfall-runoff models**

Where a clear need for rainfall-runoff modeling is demonstrated, such as in areas of urbanization, we would develop rainfall-runoff models with hypothetical precipitation events. To do this, we would configure rainfall-runoff models for the required tributaries. To estimate the model parameters, we would complete a regional parameter estimation analysis. For the hypothetical precipitation, we would use the regional precipitation depth-duration-frequency (DDF) function analysis from the National Weather Service (NWS). (The NWS is currently updating the existing DDF function, and will publish the results in NOAA 14. If they are available at the time of this hydrologic analysis, we will use the updated functions.) All such rainfall-runoff modeling efforts will follow current standards of practice for similar studies. Computer program HEC-HMS will be used.
Conclusion

This document outlines the overall procedure that will be used to complete the hydrologic analysis of the Sacramento and San Joaquin river basins by the Corps for DWR. The step-by-step analysis procedure describes how the different curves will be developed. It also shows how these curves will be combined to produce required regulated flow-frequency curves and stage-frequency curves.

Per the analysis requirements defined within this document, the procedure must:

- Yield sufficient resolution to permit DWR to prepare floodplain maps of areas protected by federal-state levees in the basin.
- Be consistent with the standard of practice, using well established, peer-reviewed, accepted procedures and methods.
- Use procedures that can be used later to update the frequency curves as additional data are available.
- Acknowledge and describe the uncertainty in the hydrologic results.
- Facilitate follow-up analyses, such as evaluating the effect of climate change on the areas subject to inundation at a given risk level. This may include use of models or procedures that can be adjusted or modified to assess possible changes to the frequency curves.

The procedure we describe herein meets the requirements as follows:

- By proper selection of the analysis points, and agreement on those analysis points with DWR, the study will produce the required resolution needed for floodplain mapping efforts.
- By following the FEMA and Corps guidelines, specifically Appendix C of Guidelines and specification for flood hazard mapping partners (FEMA 2003) and EM 1110-2-1415 (USACE 1993), the procedure and its results will meet the requirements for FEMA’s NFIP.
- By following the appropriate guidelines, as well as continued coordination of the analysis with the HAC, the procedure and results will be consistent with the standard of practice and will represent the results of a peer-reviewed and accepted procedure.
- By establishing a step-by-step process that defines clearly the inputs, analysis algorithms, and outputs, the procedure sets a standard that can be followed to update the resulting curves as additional years of record become available. As we move forward in time, each of the curves can be updated with the additional floods of record. In addition, as new channel and reservoir models become available, they can be incorporated into the procedure.
• By retaining the data pairs that are used as the basis of fitting the curves, such as the dataset of unregulated-regulated peak flows, we can assess the variability of the system. Although these values do not represent confidence bands, they help to describe the uncertainty in the analysis.

• By developing the models to implement the procedure, tools will be available to assess later the sensitivity of the system to climate change. If additional models need to be developed, for example, rainfall-runoff models above the reservoirs or analysis points, then frequency curves will be established to aid calibration of these models to existing conditions.

As noted, this document describes the overall process. Subsequent technical memorandums will be prepared and distributed. These technical memorandums will describe how each of the steps will be implemented. For example, a technical memorandum will describe how the unregulated flow time series will be developed.
## Appendix A. Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>US Army Corps of Engineers (Corps or USACE)</td>
<td>An agency of the US Army that serves the armed forces and the nation by providing engineering services and capabilities across a spectrum of operations in support of the national interest. Corps missions include five broad areas: water resources, environment, infrastructure, homeland security, and warfighting.</td>
</tr>
<tr>
<td>data</td>
<td>Observed events, values, or quantifiable behavior that are unmodified from their original recording.</td>
</tr>
<tr>
<td>State of California Department of Water Resources (DWR)</td>
<td>A unit of the California state government responsible for various regulatory functions regarding water supply, water use, and flood management.</td>
</tr>
<tr>
<td>Federal Emergency Management Agency (FEMA)</td>
<td>An agency of the federal government charged with reducing loss of life and property from disasters.</td>
</tr>
<tr>
<td>floodway</td>
<td>An area identified on a FEMA Flood Boundary Floodway Map that represents the portion of the floodplain that carries the majority of the flood flow and often is associated with high velocity flows and debris impact.</td>
</tr>
<tr>
<td>HEC</td>
<td>Hydrologic Engineering Center. An office of the Corps’ Institute for Water Resources charged with supporting the nation in its water resources management responsibilities.</td>
</tr>
<tr>
<td>HEC-HMS</td>
<td>HEC’s Hydrologic Modeling System. Computer program to predict watershed runoff and to simulate channel behavior. HEC-HMS was used for watershed runoff prediction in the Comprehensive Study.</td>
</tr>
<tr>
<td>HEC-RAS</td>
<td>HEC’s River Analysis System. Computer program to model channel hydraulics and to simulate water surface profiles for given river cross sections’ geometry.</td>
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<tr>
<td>HEC-ResSim</td>
<td>HEC’s Reservoir System Simulation. Computer program to simulate reservoir operation.</td>
</tr>
<tr>
<td>information</td>
<td>The results of applying tools or processes to data.</td>
</tr>
<tr>
<td>National Flood Insurance Program (NFIP)</td>
<td>A program of the federal government that subsidizes insurance for properties in designated floodplains.</td>
</tr>
<tr>
<td>National Weather Service (NWS)</td>
<td>Part of the Department of Commerce, National Oceanic and Atmospheric Administration (NOAA). The federal governmental agency that provides weather, hydrologic, and climate forecasts and warnings for the United States.</td>
</tr>
<tr>
<td>observed</td>
<td>Obtained through the senses or by instrumentation for measuring condition or state.</td>
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<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
<td>regulated flow</td>
<td>Change in a river's natural flow due to the influence of hydraulic constriction(s) or manmade influence(s). In this study, regulation includes reservoir storage and overbank storage as a result of levee overtopping and/or failure.</td>
</tr>
<tr>
<td>results</td>
<td>Information that is the output from a toolset or process.</td>
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<tr>
<td>simulated</td>
<td>Developed through the use of a computer program designed to model hydrology, hydraulics, reservoir operation, etc.</td>
</tr>
<tr>
<td>unregulated flow</td>
<td>A river's “natural” streamflow, which occurs when a channel is devoid of regulating structures. In this study, the unregulated condition corresponds to the absence of reservoir and overbank storage.</td>
</tr>
<tr>
<td>US Geological Survey (USGS)</td>
<td>Part of the Department of the Interior. The sole science agency for the Department of the Interior, serving as an independent fact-finding agency that collects, monitors, analyzes, and provides scientific understanding about natural resource conditions, issues, and problems.</td>
</tr>
<tr>
<td>UNET</td>
<td>A computer program developed by the Corps’ HEC to model channel hydraulics and to simulate water surface profiles for given river cross sections’ geometry.</td>
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</tbody>
</table>
Appendix B. Estimation of ungaged-flow contribution

Estimation of ungaged-watershed contribution

Here, we describe the steps for estimating ungaged runoff for watershed area between 2 gages. To do so, we use stage hydrographs and an unsteady flow hydraulic model. Figure 6 illustrates such a scenario. Here we must estimate the contribution of the portion of the watershed between Gage A and Gage B.

For the computation, we require an unsteady flow channel model that represents accurately the channel conditions. To estimate the flow, we specify the observed-stage hydrograph at Gage A as the upstream boundary condition for the reach between Gage A and Gage B.

The model converts this observed-stage hydrograph to a flow hydrograph, based on the channel geometry and the hydrodynamics of the reach. At Gage B, the observed-stage hydrograph is also specified in the model. Again, based on the channel geometry and hydrodynamics of the reach, this observed-stage hydrograph is converted to a flow hydrograph.

With the model, the flow hydrograph at Gage A is routed downstream to Gage B. During the computation, a computed flow and stage hydrograph is developed for each cross section. The routed flow hydrograph at Gage B is then compared to the observed-flow hydrograph at Gage B. The difference in the hydrographs is the contribution of the ungaged flow to that reach.

Results of this flow estimation are reviewed for appropriateness. This review may consider knowledge of the local hydrologic and hydraulic conditions, estimates of flow per area, and estimates of flow ratios from other watersheds. If needed, the estimated ungaged flow may be adjusted.

This capability is currently in computer program UNET (USACE 2001) and may be added to computer program HEC-RAS (USACE 2006).

Distribution of local flow upstream

Once we estimate the contribution of the ungaged watershed at our downstream location (for example Gage B from Figure 6), we distribute those flows upstream.

This determination of distributing the local flow within the upstream reach will be made at the discretion of the analyst. However, once an appropriate distribution is decided upon, it must be kept consistent for all subsequent tasks in the hydrologic analysis.
Appendix C. Technical issues

Overview

The hydrologic analysis procedure described herein approaches the challenge of developing frequency curves in the Sacramento-San Joaquin River basin in a comprehensive, integrated way. This approach is required because of the complexities involved in analyzing a system this large. The traditional “boundaries” between hydrologic and hydraulic analysis begin to overlap as traditional hydraulic models are used for flow routing, for example.

This document describes the basic approach that we will follow. It does not attempt to describe in detail all the technical issues that will be involved in implementing these procedures. Below, we acknowledge and list several of the key technical issues that we have identified and our current approach for addressing these issues:

- **Assumption for upstream levee failures.** In leveed systems, with large floodplains, such as in the Sacramento-San Joaquin system, levee failures affect the flows and water surface elevations downstream. For modeling and analysis, the assumptions made about upstream levee failures can significantly change the results. Deciding upon a levee failure assumption is not a trivial task, and the final assumption must be consistent through all levels of analysis. Our strategy is to work with the HAC, DWR, and the hydraulic modelers to agree upon a consistent analysis assumption.

- **Availability of historic event data.** The procedures described herein rely heavily on historic data, specifically for development of unregulated flows at reservoirs and for estimation of local flows. Our strategy is to first assess data availability and to collect and organize the data per the study’s Data management plan. We recognize that for some locations, we may have missing data or the gage record length may not extend far enough to cover the required historic events. When necessary, we will follow Comp Study procedures to extend data record lengths or “fill in” data gaps.

- **Assessment of climate variability.** A requirement of the overall Sacramento-San Joaquin hydrologic and hydraulic analysis is to include an assessment of the effect of climate variability. This will be addressed in this hydrologic analysis, but after the requirements for the floodplain mapping are met. A separate procedures document will be prepared describing the process for assessing climate variability. To the extent appropriate, the tools and results from this study will be utilized.
Appendix D. List of references


US Army Corps of Engineers (USACE). (1955). Design memorandum no. 1, lower San Joaquin River and tributaries project, California, San Joaquin River levees general design, Sacramento, CA.


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