December 2002

Sacramento and San Joaquin River Basins Comprehensive Study

# TECHNICAL STUDIES DOCUMENTATION

## APPENDIX B

## SYNTHETIC HYDROLOGY TECHNICAL DOCUMENTATION

US Army Corps of Engineers
Sacramento District

# EXPECTATIONS OF USE

# SYNTHETIC HYDROLOGY
# DEVELOPED SPECIFICALLY FOR THE COMPREHENSIVE STUDY

## PURPOSE OF THE HYDROLOGY

The intent of the synthetic hydrology developed for the Sacramento and San Joaquin River Basins Comprehensive Study is to provide a basis for defining existing hydrologic conditions on a regional or generalized basis, and to support an array of systematic analyses for required or desired water resource development opportunities throughout the Central Valley of California. Specifically designed to support this particular study, the synthetic hydrology may or may not fulfill the technical requirements of site-specific investigations within the Central Valley. Prior to its use, the size and scope of each study, even at the pre-feasibility level, will need to be evaluated to determine if the Comprehensive Study hydrology can be directly applied. In most cases, more detailed hydrology will need to be performed.

Hydrologic analyses performed for such a large spatial area and at the level of detail documented herein present challenges and opportunities unique to such ambitious studies. The Comprehensive Study has made possible a system-wide update for Central Valley unregulated flood hydrology and an overall modernization of the models used by Sacramento District hydrologists and engineers. These accomplishments have proven valuable to the Comprehensive Study and will prove valuable to future studies undertaken by public and private organizations.

## RESPONSIBILITY OF USERS

1) The point of contact for comments and feedback is:

Mr. Robert Collins, District Hydrologist
U.S. Army Corps of Engineers
Sacramento District
(916) 557-7132

2) The complexity and intricacy in the development of the hydrology of this study require that it be used only by qualified hydrologic/hydraulic engineers and scientists familiar with proper applications of synthetically derived hydrology. Professional expertise and judgment should be exercised for all analyses conducted using this hydrology. The U.S. Army Corps of Engineers and the California State Department of Water Resources do not provide technical support for this hydrology.

## BASIC ASSUMPTIONS AND LIMITATIONS

The synthetic hydrology, as presented herein, was created to be "Comprehensive" in nature. Without further investigation, its development offers only enough detail in the storm centerings, local-flow contributions, and ungaged stream contributions to be applied in pre-feasibility applications. The models developed for the Comprehensive Study analysis were created with the following assumptions and limitations:

- The data are stationary.
- The natural flow frequency curves are strictly rainflood frequency curves. Snowmelt runoff is not directly incorporated into the analysis.
- Centering hydrographs are predicated on flood runoff, not precipitation. The approach was driven entirely by historic flow data; precipitation never entered into any portion of the methodology.
- Storm runoff centerings were formulated based on the Composite Floodplain concept.
- The unregulated frequency curves computed for the Comprehensive Study were created by following procedures outlined in Bulletin 17B.
- Travel times and attenuation factors (Muskingum Coefficients) are fixed for all simulated exceedence frequencies.
- Mainstem unregulated flow frequency curves were designed to quantify the total flows that the basins produced in rainfloods, not the average natural flows expected at mainstem locations during any of the synthetic exceedence frequency storm events.
- Patterns for synthetic floods are formulated based on historic storms.

# SYNTHETIC HYDROLOGY TECHNICAL DO CUMENTATION

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## REFERENCES

U.S. Army Corps of Engineers. 1977. San Joaquin River Basin, California; Hydrology Office Report, Lower San Joaquin River. Sacramento District. Sacramento, California.

U.S. Army Corps of Engineers. 1993. Sacramento River Flood Control Project, Hydrology Office Report. Sacramento District. Sacramento, California.

U.S. Army Corps of Engineers. 1999. Sacramento and San Joaquin River Basins, California; Post-Flood Assessment. Sacramento District. Sacramento, California.

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# CHAPTER I

# INTRODUCTION

## AUTHORITY

In response to extensive flooding and damages experienced in 1997, the United States Congress authorized the U.S. Army Corps of Engineers (USACE), Sacramento District to provide a comprehensive analysis of the Sacramento and San Joaquin River basin flood management systems. The Corps and the State Reclamation Board of California are leading this Comprehensive Study to improve flood management and restore the ecosystem in the Sacramento and San Joaquin River basins.

The authorization for the Comprehensive Study directed the development of hydrologic and hydraulic models for both river basins that will allow systematic evaluation. These models incorporate reservoir operations and flows on the major river systems to effectively evaluate the hydraulic performance of the flood management systems. The models can be used to assess the performance of the current systems or modified systems under a wide range of hydrologic conditions.

## PURPOSE OF DOCUMENTATION

This report documents the work conducted for the Sacramento and San Joaquin River Basins Comprehensive Study to develop hydrologic computer models and establish current, baseline condition floodplains. The main product components of this effort include: (1) a description of the hydrologic analysis methodology; (2) development of the models for the Sacramento River and San Joaquin River basins; (3) an illustration of existing conditions based on model results; and (4) conclusions drawn from this effort.

The scope of this document is limited to the use of hydrology to identify and describe baseline conditions. It does not include the formulation or evaluation of flood management alternatives. The performance of modified flood management strategies is not addressed. Future work will use this hydrology as a basis for analysis of alternatives to reduce flood damages in California's Central Valley.

## APPROVAL AND CERTIFICATION

Technical review guidelines mandate that individual report elements be reviewed for compliance with appropriate Public Laws, Engineering Reports, Circulars, Memos, and standard engineering and scientific practices appropriate for the corresponding discipline. The information contained within this appendix has been reviewed by an Independent Technical Review Team (ITRT) composed of individuals having expertise in, and representing all disciplines involved in the preparation of this appendix. Technical comments have been provided to the team members

*Note: Prior to use and application, reference the "Expectations of Use" preface.*

responsible for the derivation of information and data within this appendix and the report has subsequently been revised in accordance with suggestions made by the technical reviewer. Subsequent resolution of all issues has resulted in a Technical Certification and Findings document. To date, the development of the synthetic hydrology (Unregulated Frequency Curves, Historic Flood Event Matrices, Synthetic Flood Runoff Centerings, Computed and Adopted Statistics, Unregulated Rain Flood Flows, and Correlation Data) has surmounted this review process.

## STUDY AREA

The study area encompasses the watersheds of the two major river systems of California's Central Valley, the Sacramento River in the north and the San Joaquin River in the south. These river systems comprise a combined drainage area of over 43,000 square miles, an area nearly as large as the state of Florida. The Sacramento River basin and the San Joaquin River basin are illustrated in Plate 1.

Due to its climate and geography, flooding is a frequent and natural event in the Central Valley. Historically, the Sacramento River basin has been subject to floods that result from winter and spring rainfall as well as rainfall combined with snowmelt. The San Joaquin River basin has been subject to floods that result from both rainfall that occurs during the late fall and winter months, and unseasonable and rapid melting of the winter snowpack during the spring and early summer months.

Although the Tulare Lake basin is not part of the geographical focus area of the Comprehensive Study, some hydrologic modeling efforts will include this watershed because flows are exchanged between the San Joaquin and Tulare Lake basins.

*Note: Prior to use and application, reference the "Expectations of Use" preface.*

# CHAPTER II

# DESCRIPTIVE HYDROLOGY

## SACRAMENTO RIVER BASIN

### Basin Characteristics

The Sacramento River basin covers a 26,300 square mile area (above Rio Vista) about 240 miles long and up to 150 miles wide bounded by the Sierra Nevada on the east, the Coast Range on the west, the Cascade and Trinity Mountains on the north, and the Delta on the south. Major tributaries of the Sacramento River in the study area include the Feather and American rivers, which are tributaries from the east. Numerous other smaller creeks flow into the Sacramento from the east and west.

### Hydrography

The main drainage basins within the Sacramento Valley are the Sacramento, Feather, and American River basins, covering an area of more than 24,000 square miles in the northern portion of the Central Valley as shown in Plate 2. The Sacramento River basin encompasses the three major basins in the north: the McCloud River, Pit River, and Goose Lake; the Sacramento-San Joaquin River Delta in the south, the Sierra Nevada Mountains and Cascade Ranges in the east including the Feather, Yuba and American River basins, and the Coast Range and Klamath Mountains in the west. Plate 1 shows the Central Valley and surrounding mountain ranges. Drainage in the northern portion of the Central Valley is provided by the Sacramento, Feather, Yuba, and American rivers and major and minor streams and rivers that drain the east and west sides of the basin.

The Sacramento River flows generally north to south from its origin near Mount Shasta to its mouth at the Delta. As the Sacramento River travels to the Delta, it picks up additional flows from the Feather and American rivers. The Feather River flows generally north to south from its origin near Lassen Peak and joins the Sacramento River at Verona. The American River originates in the Sierra Nevada, flows generally east to west, and enters the Sacramento River at the City of Sacramento near I Street.

### Topography

Topography of the basin varies from flat valley areas and low rolling foothills, to steep mountainous terrain. Elevations in the Sacramento basin below Shasta and above Red Bluff range from about 280 feet to near 10,000 feet in the upper reaches of Battle Creek. In this reach, the main stem of the Sacramento River has a slope of about 5 ft/mi. In the reach from Red Bluff to Ord Ferry, elevations range from less than 100 feet at Ord Ferry to near 10,000 feet at the top of Mt. Lassen. Approximately 50% of the area is below 1,000 feet. The average slope of the Sacramento River is about 1 ft/mi. Below Ord Ferry and above Fremont Weir, elevations range from below 100 feet to near 3,000 feet in the Coast Ranges. The slope of the Sacramento River in this area is about 0.9 ft/mi. Below the Fremont Weir, the Sacramento River is fed by the Feather and American rivers. The elevations in the Feather and American rivers ranges from about sea level to near 10,000 feet in the upper reaches of the Sierra. The slope of the Sacramento River from Fremont Weir to Collinsville is about 0.4 ft/mi.

**Soils**

Soil cover in the Sacramento River Basin is moderately deep with classifications varying from sands, silts and clays in the valley areas to porous volcanic areas in the northern end of the basin. In the American and Feather River basins, the soils range from granitic rock in the upper elevations to alluvial deposits in the valley areas.

**Vegetation**

Vegetation in the higher elevations of the Sacramento River Basin is dominated by coniferous forest. The foothills and valley areas are dominated by an oak-brush-grassland environment. Many valley areas in the Sacramento River Basin are cultivated for agricultural purposes.

**Climate**

The climate in the Sacramento River Basin is temperate and varies according to 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.

**Temperatures**

Average annual temperatures in the Sacramento River Basin range from the middle 60's in the valley areas to the low 50's at the higher elevations. Temperature range from nearly 120 degrees in the northern valley to below zero in the Sierra Nevada Mountains. Average mean monthly minimum and maximum temperatures for Sacramento, Redding, Donner Summit State Park, and Blue Canyon are shown in Table 1.

**Precipitation**

Normal annual precipitation (NAP) varies widely throughout the basin, ranging from the low teens in valley areas to 90 inches in some mountain areas. Average monthly and annual precipitation are shown in Table 2 for Sacramento, Redding, Blue Canyon and Mc Cloud.

***Orographic Influence***

The Sierra Nevada and Coast Ranges have an orographic effect on the precipitation. Precipitation increases with altitude, but basins on the east side of the Coast Ranges lie in a rain shadow and receive considerably less precipitation than do basins of similar altitude on the west side of the Sierra Nevada.

## TABLE 1

## AVERAGE MONTHLY TEMPERATURES FOR SELECTED LOCATIONS IN THE SACRAMENTO RIVER BASIN

| Month | Sacramento (1941-2000) | | Redding (1931-1979) | | Donner Summit State Park (1953-2000) | | Blue Canyon (1948-2000) | |
|---|---|---|---|---|---|---|---|---|
| | Min. (°F) | Max. (°F) | Min. (°F) | Max. (°F) | Min. (°F) | Max. (°F) | Min. (°F) | Max. (°F) |
| January | 37.8 | 53.1 | 37.4 | 54.9 | 13.7 | 40.3 | 30.7 | 43.5 |
| February | 41.1 | 59.7 | 40.5 | 59.7 | 15.4 | 43.4 | 31.5 | 45.1 |
| March | 42.9 | 64.4 | 43.3 | 65.2 | 20.1 | 46.7 | 31.6 | 45.5 |
| April | 45.9 | 71.7 | 47.9 | 72.5 | 24.8 | 53.4 | 36.2 | 52.2 |
| May | 50.5 | 79.8 | 54.9 | 81.7 | 31.1 | 62.7 | 43.3 | 60.7 |
| June | 55.1 | 87.1 | 62.3 | 90.2 | 36.7 | 72.3 | 51.4 | 69.6 |
| July | 58.0 | 92.9 | 68.1 | 98.4 | 40.8 | 80.8 | 58.7 | 77.4 |
| August | 57.7 | 91.5 | 65.9 | 96.4 | 39.6 | 80.0 | 57.5 | 76.7 |
| September | 55.8 | 87.6 | 61.3 | 90.7 | 34.3 | 73.5 | 53.2 | 72.0 |
| October | 50.2 | 77.9 | 53.2 | 78.7 | 27.7 | 63.0 | 45.8 | 62.8 |
| November | 42.7 | 63.6 | 44.4 | 64.6 | 21.9 | 49.1 | 37.3 | 51.2 |
| December | 38.0 | 53.5 | 38.8 | 55.7 | 15.0 | 40.8 | 32.7 | 45.8 |
| *Average* | *48.0* | *73.6* | *51.5* | *75.7* | *26.8* | *58.8* | *42.5* | *58.5* |

## TABLE 2

## AVERAGE MONTHLY PRECIPITATION FOR SELECTED LOCATIONS IN THE SACRAMENTO RIVER BASIN

| Month | Sacramento (in) | Redding (in) | Blue Canyon (in) | Mc Cloud (in) |
|---|---|---|---|---|
| *Data Period* | (1941-2000) | (1931-1979) | (1948-2000) | (1948-2000) |
| *Location Elevation* | 20 ft | 580 ft | 5280 ft | 3250 ft |
| January | 3.8 | 8.0 | 13.0 | 9.7 |
| February | 3.1 | 5.9 | 10.5 | 8.1 |
| March | 2.4 | 5.0 | 9.3 | 6.9 |
| April | 1.1 | 3.0 | 5.1 | 3.5 |
| May | 0.5 | 1.5 | 2.7 | 2.4 |
| June | 0.2 | 1.0 | 0.8 | 1.0 |
| July | 0.0 | 0.2 | 0.3 | 0.2 |
| August | 0.1 | 0.3 | 0.5 | 0.4 |
| September | 0.3 | 0.8 | 1.1 | 1.1 |
| October | 0.9 | 2.2 | 3.9 | 3.0 |
| November | 2.2 | 4.7 | 9.6 | 6.7 |
| December | 2.8 | 7.0 | 11.7 | 8.2 |
| *Annual Total* | 17.2 | 39.4 | 68.4 | 51.1 |

*Note: Prior to use and application, reference the "Expectations of Use" preface.*

### Snowpack

During winter and early spring months, precipitation is often in the form of snow at higher elevations in the Sacramento River Basin. Plate 2 illustrates the area of the Sacramento River Basin above 5,000 feet. The ground surface elevations in northern portion of the Sacramento Valley reach nearly 14,000 feet in the headwaters of the Sacramento River. Lassen Peak, which exceeds 10,000 ft in the Cascade Range, receives as much as 90 inches of precipitation, primarily as snow.

### Flood Damage Reduction System

The basic flood damage reduction system in the Sacramento Valley consists of a series of levees and bypasses, placed to protect specific areas and take advantage of the natural overflow basins. The management system includes levees along the Sacramento River south of Ord Ferry; levees along the lower portion of the Feather, Bear, and Yuba rivers; and levees along the American River. Additionally, the system benefits from three natural drainage basins: Butte, Sutter, and Yolo. These basins run parallel to the Sacramento River and receive excess flows from the Sacramento, Feather, and American rivers via natural overflow channels and over weirs. When the Sacramento River is high, the three basins form one continuous waterway connecting the Butte, Sutter, and Yolo basins. During low stages on the Sacramento River, water in these basins can reconnect with the Sacramento at several points: the Butte Slough Outfall Gates, the terminus of the Sutter Bypass at Verona, and the east levee toe drain at the terminus of the Yolo Bypass above Rio Vista.

In addition to the leveed system, the flood damage reduction system uses reserved flood storage space in selected reservoirs on the Sacramento, Feather, and American rivers. These reservoirs help to reduce damaging rain flood peaks by holding back floodwater and, ideally, releasing water into the rivers at a slower rate.

## SAN JOAQUIN RIVER BASIN

### Basin Characteristics

The San Joaquin River Basin lies between the crests of the Sierra Nevada and the Coast Range and extends from the northern boundary of the Tulare Lake Basin, near Fresno, to the Delta near Stockton, as shown in Plate 1. It is drained by the San Joaquin River and its tributary system. The basin has an area of about 13,500 square miles (at the Vernalis Gage), extending about 120 miles from the northern to southern boundaries.

### Hydrography

The San Joaquin River Basin extends from the Delta in the north to the Kings River in the south, and from its headwaters upstream from Friant Dam in the Sierra Nevada in the east to the Coast Range in the west. The river basin encompasses about 13,000 square miles at the southern boundary of the Delta, and a total watershed area of 16,700 miles (including the Delta).

The San Joaquin River flows approximately 270 miles from Friant Dam to the river mouth, 4.5 miles below Antioch. The San Joaquin River originates in the Sierra Nevada at an elevation of

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more than 10,000 feet, flows into the San Joaquin Valley at Friant Dam, then flows westward to the center of the valley floor, turns sharply northward near Mendota, and flows through the San Joaquin Valley to Vernalis, which is generally considered to represent the southern limit of the Delta. The San Joaquin River receives flows from the Fresno and Chowchilla rivers, Bear and Owens creeks, and several smaller streams through the Chowchilla and Eastside Bypasses. Along the valley floor, the San Joaquin River receives additional flow from the Kings, Merced, Tuolumne, and Stanislaus rivers. Within the Delta, the San Joaquin River receives flows from the Calaveras, Cosumnes, and Mokelumne rivers. Streams on the west side of the basin include Panoche, Los Banos, Orestimba, and Del Puerto creeks. West side streams are intermittent, and their flows rarely reach the San Joaquin River except during large floods. Flood management facilities are found on all major tributaries except the Cosumnes River. Locations along the San Joaquin River are referenced by River Mile (RM), with RM 0 beginning at the mouth of the San Joaquin River (4.5 miles below Antioch), and RM 270 at Friant Dam.

The San Joaquin River Basin and Tulare Lake Basin, shown in Plate 1, are hydrologically connected through the Kings River. In the past, most water in the Kings River naturally drained into the Tulare Lakebed, and small quantities of flood flows would flow north into the San Joaquin River. When the Tulare Lake exceeded capacity, water would overflow into the Fresno Slough and make its way to the San Joaquin River. Today, these basins are connected where part of the Kings River flow is diverted to the Kings River North, then through the James Bypass, Fresno Slough, Mendota Pool, and into the San Joaquin River.

The watersheds of the San Joaquin, Merced, Tuolumne, Stanislaus, and Mokelumne rivers include large areas of high-elevation terrain along the western slope of the Sierra Nevada. As a result, these rivers experience significant snowmelt runoff during the late spring and early summer months. Before construction of water supply and flood management facilities, flows typically peaked in May and June and snowmelt runoff caused flooding in most years along all of the major rivers. When these snowmelt floodflows reached the valley floor, they spread out over the lowlands, creating several hundred thousand acres of permanent tule marshes and more than 1.5 million acres of seasonally flooded wetlands.

## Topography

In the San Joaquin River Basin, the Sierra Nevada Mountains have an average crest elevation of about 10,000 feet with occasional peaks as high as 13,000 feet. The Coast Range crest elevations reach up to about 5,000 feet. The valley area measures about 100 miles by 50 miles and slopes gently from both sides towards a shallow trough somewhat west of the center of the valley. Valley floor elevations range from 250 feet at the south to near sea level at the Delta. The trough forms the channel for the lower San Joaquin River and has an average slope of about 0.8 feet per mile between the Merced River and Paradise Cut.

## Soils

The basin lies within parts of the Sierra Nevada, California Coast Ranges, and Great Valley geomorphic provinces. Its sedimentary, metamorphic, and igneous rocks range in age from pre-Cretaceous to Recent, being dominated by nonwater-bearing crystalling rocks. In the California Coast Ranges, Jurassic and Cretaceous sandstones and shale dominate. In the valley, upper

Tertiary and Quarternary sediments in places contain fresh water as deep as 2,000 feet. And, in most of the area, impermeable Corcoran clays confine the lower water-bearing zone.

Soils in the valley basin bottoms are poorly drained and fine textured. Some areas are affected by salts and alkali and require reclamation before they are suitable for crops. Bordering and just above the basin are soils of the fans and floodplains. They are generally level, very deep, well drained, non-saline and non-alkaline, and well suited to a wide variety of crops. The soils of the terraces bordering the outer edges of the valleys generally are of poorer quality and have dense clay subsoils or hardpans at shallow depths. These soils are generally used for pasture and rangeland.

### Vegetation

The types of vegetation occurring in the San Joaquin River basin consist of a combination of cultivated crops and pasture grasses and forbs, hardwood forests, chapparal mountain brush, and coniferous forests. The distribution of these vegetation types is primarily a function of elevation with the cultivated crops located entirely on the valley floor areas, the hardwood forests and chapparal brush located at the mid-elevations, and the coniferous forests located at the higher elevations.

### Climate

The climate of the San Joaquin River Basin is characterized by wet, cool winters, dry, hot summers, and relatively wide variations in relative humidity. In the valley area, relative humidity is very low in summer and high in winter. The characteristic of wet winters and dry summers is due principally to a seasonal shift in the location of a high pressure air mass ("Pacific high") that usually exists approximately a thousand miles west of the mainland. In the summer, the high blocks or deflects storms; in the winter, it often moves southward and allows storms to reach the mainland.

### Temperatures

Temperatures in the basin vary considerably due to seasonal changes and the large range of elevation. Temperatures in the lower elevations are normally above freezing but range from slightly below freezing during the winter to highs of over 100 degrees during the summer. At intermediate and high elevations the temperature may remain below freezing for extended periods during the winter. Average mean monthly minimum and maximum temperatures for Stockton, Los Banos, Hetch Hetchy, and Huntington Lake are shown in Table 3.

### Precipitation

Normal annual precipitation in the basin varies from 6 inches on the valley floor near Mendota to about 70 inches at the headwaters of the San Joaquin River. Most of the precipitation occurs during the period of November through April. Precipitation is negligible during the summer months, particularly on the valley floor. Average monthly and annual precipitation are shown in Table 4 for Stockton, Los Banos, Hetch Hetchy, and Huntington Lake.

*Note: Prior to use and application, reference the "Expectations of Use" preface.*

### *Orographic Influence*

Similar to the Sacramento River Basin, the Sierra Nevada and Coast Ranges have an orographic effect on the precipitation. Precipitation increases with altitude, but basins on the east side of the Coast Ranges lie in a rain shadow and receive considerably less precipitation than do basins of similar altitude on the west side of the Sierra Nevada.

**TABLE 3**

**AVERAGE MONTHLY TEMPERATURES FOR SELECTED LOCATIONS IN THE SAN JOAQUIN RIVER BASIN**

| **Month** | **Stockton** 1948-2000 | | **Los Banos** (1948-2000) | | **Hetch Hetchy** (1931-2000) | | **Huntington Lake** (1948-2000) | |
|---|---|---|---|---|---|---|---|---|
| | **Min. (°F)** | **Max. (°F)** | **Min. (°F)** | **Max. (°F)** | **Min. (°F)** | **Max. (°F)** | **Min. (°F)** | **Max. (°F)** |
| January | 36.3 | 54.0 | 36.3 | 55.0 | 28.5 | 48.0 | 23.5 | 43.8 |
| February | 39.5 | 61.1 | 39.9 | 62.4 | 29.9 | 52.4 | 23.2 | 44.7 |
| March | 42.1 | 66.0 | 42.6 | 67.9 | 32.4 | 56.4 | 24.0 | 45.4 |
| April | 45.3 | 72.8 | 46.3 | 75.1 | 37.2 | 62.8 | 28.0 | 50.2 |
| May | 49.9 | 80.0 | 51.5 | 82.3 | 43.0 | 69.5 | 34.0 | 56.5 |
| June | 54.4 | 87.2 | 56.4 | 89.7 | 49.2 | 77.6 | 41.2 | 65.8 |
| July | 56.8 | 92.3 | 60.3 | 96.3 | 55.6 | 86.1 | 47.9 | 73.5 |
| August | 55.9 | 91.1 | 59.2 | 94.8 | 55.0 | 85.8 | 47.4 | 72.9 |
| September | 53.5 | 87.4 | 56.0 | 90.0 | 50.3 | 80.9 | 43.1 | 67.4 |
| October | 47.6 | 78.5 | 49.4 | 80.3 | 42.1 | 71.4 | 36.8 | 59.3 |
| November | 40.8 | 65.0 | 41.3 | 66.1 | 34.0 | 57.9 | 29.7 | 49.8 |
| December | 36.0 | 54.6 | 36.0 | 55.2 | 29.7 | 49.1 | 25.2 | 44.6 |
| *Average* | 46.5 | 74.2 | 47.9 | 76.3 | 40.6 | 66.5 | 33.7 | 56.1 |

**TABLE 4**

**AVERAGE MONTHLY PRECIPITATION FOR SELECTED LOCATIONS IN THE SAN JOAQUIN RIVER BASIN**

| **Month** | **Stockton (in)** | **Los Banos (in)** | **Hetch Hetchy (in)** | **Huntington Lake (in)** |
|---|---|---|---|---|
| *Data Period* | (1948-2000) | (1948-2000) | (1931-2000) | (1948-2000) |
| *Elevation* | 10 ft | 120 ft | 3870 ft | 7020 ft |
| January | 3.3 | 1.9 | 6.0 | 7.7 |
| February | 2.7 | 1.8 | 5.8 | 7.3 |
| March | 2.3 | 1.4 | 5.2 | 6.6 |
| April | 1.3 | 0.7 | 3.2 | 3.3 |
| May | 0.5 | 0.4 | 1.8 | 2.0 |
| June | 0.1 | 0.1 | 0.8 | 0.6 |
| July | 0.0 | 0.0 | 0.2 | 0.3 |
| August | 0.0 | 0.0 | 0.2 | 0.2 |
| September | 0.3 | 0.3 | 0.7 | 1.3 |
| October | 0.8 | 0.5 | 2.0 | 1.8 |
| November | 2.0 | 1.2 | 4.2 | 4.3 |
| December | 2.5 | 1.4 | 5.7 | 5.8 |
| *Annual Total* | *15.9* | *9.5* | *36.0* | *41.2* |

## Snowpack

During winter and early spring months, precipitation is often in the form of snow at higher elevations in the San Joaquin River Basin. Plate 2 illustrates the area of the San Joaquin River Basin above 5,000 feet. The ground surface elevations in southern portions of the San Joaquin River Basin reach nearly 14,000 feet in the headwaters of the San Joaquin River.

## Flood Damage Reduction System

The flood damage reduction system includes levees along the lower portions of Ash and Berenda sloughs; Bear Creek; Fresno, Stanislaus, and Calaveras rivers; and leveed sections along the San Joaquin River. The Chowchilla Canal Bypass diverts excess San Joaquin River flow and sends it to the Eastside Bypass. In addition to the Chowchilla Canal Bypass flow, the Eastside Bypass intercepts flows from minor tributaries and rejoins the San Joaquin River between Fremont Ford and Bear Creek. Channel capacity on the San Joaquin River decreases moving downstream until the confluence of the Merced River, where it then begins to increases downstream of the confluence of the Merced River. The San Joaquin River levee and diversion systems are not designed to contain the objective release from each of the project reservoirs simultaneously. Flows in the San Joaquin River that are less than design flow may cause damage to levees.

The travel time for moving floodflows down the river system complicates the management of the flood system. The travel time for water released from Friant Dam on the San Joaquin River is more than 5 days to the Merced River confluence at Newman and about 7 days to Vernalis. On the Merced River, water released from New Exchequer Dam takes 42 hours to reach the San Joaquin River confluence at Newman. The travel time from Don Pedro Dam on the Tuolumne River to Vernalis is almost 2 days. Flow released from New Melones Dam on the Stanislaus River takes just over a day to reach Vernalis.

The San Joaquin River basin also receives floodflows from the Tulare Lake Basin. The Kings River Weirs divert floodflows north via the Kings River North, James Bypass, Fresno Slough, and Mendota Pool system into the San Joaquin River basin. Flows greater than flood management operating policies are sent into Tulare Lake Basin via Kings River South.

*Note: Prior to use and application, reference the "Expectations of Use" preface.*

# CHAPTER III

# HYDROLOGIC ANALYSES

## INTRODUCTION

One of the primary missions of the U.S. Army Corps of Engineers (USACE) is to plan, design, build, and operate water resources and other civil works projects. Among them are projects related to navigation, flood damage reduction, environmental protection, and disaster response. A critical ingredient, common to each of these pursuits is water. Ever too much or too little, society is always seeking a water resources balance that is elusive due to both the unpredictability of nature and the constant changes in public and private demands. This is especially true in California, where the hydrologic cycle is distinctly seasonal and tends towards the extremes and the demand for water is high and often filled with controversy.

An important step in planning studies is establishing "without-project conditions." This step defines the system that exists or will exist before any possible improvements proposed by a study are implemented. As the Comprehensive Study focuses on system operations that are driven in part by the hydrologic cycle, definition of baseline hydrology is central to the establishment of without-project conditions.

In support of the Comprehensive Study, the Water Management Section of the Sacramento District, USACE, has developed synthetic 50-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent chance exceedence flood events. These seven synthetic exceedence frequency events will provide a basis for defining existing conditions and eventual alternatives analysis and plan formulation. In this sense, this hydrology study will serve as a cornerstone for future Comprehensive Study investigations.

This report includes details of the methodology used by the Water Management Section of the USACE, in performing this study, including: 1) updated natural flow frequency curves for locations within the basins; 2) a retrospective of historic floods that have impacted Central Valley rivers and the synthetic flood runoff centerings developed to represent flood events of a specific exceedence frequency; and 3) construction of seven synthetic exceedence frequency flood hydrographs.

Ultimately, results from this hydrologic investigation will feed into other Comprehensive Study models and drive parameter development for related aspects of the study.

## FLOODPLAIN BACKGROUND

Before entering into a discussion of methodology details, it is important that the reader clearly understand the ultimate goal of this effort, which is to prepare flood runoff centerings and flood hydrographs that feed into reservoir system and hydraulic models, whose simulations culminate in delineation of Central Valley floodplains. Recognition that this hydrology shapes floodplains is a critical concept considering the complexity of floodplains in large spatial areas with numerous contributing tributaries. It is intuitive that flows create floodplains, but more involved than it first appears.

### Composite Floodplain

The "Composite Floodplain" concept recognizes that the floodplains generated through modeling of the seven synthetic exceedence frequency events are not created by a single flood event, but by a combination of several events, each of which shapes the floodplain at different locations as shown in Plate 3 and further described in Appendix D – Hydraulic Technical Documentation. As one moves downstream in a watershed, the Composite Floodplain becomes increasingly complex. With the confluence of each additional tributary, the number of possible scenarios of flow combinations that could shape the floodplain grows. The role of tributaries in shaping floodplains individually and as a system is the foundation of the Composite Floodplain concept and a cornerstone of the Synthetic Hydrology Analysis. It is a theme that guides the methodology and is discussed throughout this report.

An example location to illustrate the composite floodplain concept is the reach of Tuolumne River between New Don Pedro Dam and Reservoir and its confluence with the San Joaquin River near Maze Road Bridge. Don Pedro Reservoir is a flood damage reduction project that regulates flows from the entire upper basin of the Tuolumne River. Directly below the reservoir, the floodplain associated with a 1-percent chance exceedence event is shaped by a 1-percent chance exceedence outflow from Don Pedro, the existing operational criteria for that facility, and the channel shape below the dam. The combined influence of these factors continues until the Tuolumne courses through the City of Modesto and joins with flows from Dry Creek. At this point, the floodplain becomes two-pronged with inundated areas extending up both Dry Creek and the Tuolumne River. Here, the shape of the floodplain is a function of the timing and magnitude of flow from two tributaries, hydraulic (including backwater) influences of each upon the other, and channel and inundated landforms. This changes again when the Tuolumne comes within the realm of influence of the San Joaquin River mainstem and, thereby, the twelve other tributaries that join the mainstem above Maze Road.

Ultimately, the floodplain associated with a 1-percent chance exceedence flow in the Lower Tuolumne River may not be entirely shaped by the 1-percent chance exceedence outflow from Don Pedro. A different storm scenario may generate flows on the San Joaquin mainstem that create larger extents of inundation (despite a lower exceedence frequency event on the Tuolumne River) through backwater effects or by simply introducing large out-of-channel flows to adjacent floodplain areas. The synthetic hydrology for the Comprehensive Study was developed to ensure that such characteristics are reflected and that the composite floodplain represent the maximum extent of inundation possible at all locations for any of the simulated seven synthetic exceedence frequency storm events.

## METHODOLOGY

### Study Approach

The Synthetic Hydrology Analysis investigated three fundamental subjects during the formulation of synthetic flood events: 1) the amount of runoff produced during each of the seven

*Note: Prior to use and application, reference the "Expectations of Use" preface.*

synthetic exceedence frequency flood events; 2) the contribution of individual tributaries to this total volume; and 3) translating these flood volumes and distributions to hourly time series ready to feed into the Reservoir Simulations Model.

# ANALYSIS

## General

Unregulated frequency curves were developed at key mainstem and tributary locations in both the Sacramento and San Joaquin River basins. Unregulated frequency curves plot historic points and statistical distributions of unimpaired flows (no reservoir influence). Curves display volumes or average flow rates for different time durations over a range of annual exceedence probabilities. These curves can be used to translate: 1) hydrographs to frequencies (i.e., in 1997, the 3-day natural inflow to Friant Dam, San Joaquin River was roughly 50,000-cfs, which translates to a 1.54-percent chance exceedence event); and 2) frequencies to flood volumes (i.e., according to the curves, the 3-day natural inflow to Friant Dam associated with an annual 10-percent chance exceedence event is approximately 20,000 cfs). After a curve is developed, the runoff volume for any of the seven synthetic exceedence frequency flood events can be obtained from the plot for that curve's specific location.

## Natural Flow Analysis/Unregulated Frequency Analysis

### *Methodology for Deriving the Unregulated Frequency Curves*

The unregulated frequency curves computed for the Comprehensive Study were created by following procedures outlined in Bulletin 17B, Guidelines for Determining Flood Flow Frequency, U.S. Department of the Interior, dated March of 1982. This report directs Federal agencies to use the procedures included therein for all "planning activities involving water and related land resources." Bulletin 17B requires the use of a Pearson Type III distribution with log transformation of the data (Log Pearson Type III distribution) as the method to analyze flood flow frequency.

In this report, charts containing frequency curves display two types of information. The frequency curve itself is one of these. The curve is derived from a statistical analysis of the recorded data after it has been transformed to log values. The mean, standard deviation and skew of the log-transformed data, are computed for the stream gage or reservoir. The data are screened for high and low outliers and if found, adjustments to the statistics are computed as outlined in Bulletin 17B. In addition, the resulting statistics are reviewed and sometimes adjusted or smoothed to account for sampling error differences among the various durations, or after comparison with similar gages in the watershed or region. The second type of information found on each frequency curve is the plot of the historical events given their estimated frequency. To determine its location on the frequency paper, the peak of each annually recorded event or peak flow value is given a hypothetical frequency based upon its assigned plotting position using a Log Pearson Type III distribution. In some instances, visual examination of the unregulated frequency curves contained in this report reveal a significant difference between the statistical frequency curve and the imaginary curve that would be formed if a pencil line were hand-drawn through the historical data points. For some curves in this report in which the characteristic described above was apparent, further examination was made. In addition, a few frequency curves were re-computed using alternative distributions such as Gumble type III or lognormal. The result was that the other distributions did not result in an improved fit. Bulletin 17B directs the use of a Log Pearson III Distribution unless compelling and substantive evidence can be found that other distributions are more appropriate.

Development of the unregulated frequency curves for the tributaries as shown in Attachment B.1 required daily natural flow data for all target locations. Data were obtained from USACE archives or computed by routing daily change in storage from upstream reservoirs and adding this routed value to the gage record at the location of interest. Most required storage time series were available through USGS publications. Other data were obtained directly from Central Valley and federal water agencies, including U.S. Bureau of Reclamation, U.S. Geological Survey, Oroville-Wyandotte Irrigation District, South Sutter Water District, Placer County Water Association, Nevada Irrigation District, Surface Water Data Inc., Southern California Edison, Sacramento Metropolitan Utility District, and Pacific Gas and Electric.

Data from tributaries were routed to downstream locations for use in constructing mainstem "index" frequency curves. The frequency curves that characterize the total flows through the mainstem index locations represent "at-latitude" flows (i.e., any and all diverted or channelized flows that pass through a particular gage's geographic latitude). Muskingum routings with travel times (in hours) and reach-specific attenuation factors were used to transport daily hydrographs through the basins, as shown in Table 5 for the Sacramento River Basin and Table 6 for the San Joaquin River Basin. Travel times and attenuation factors (Muskingum Coefficients) were obtained from past studies, through communication with local water agencies, or through comparisons of historic flood data. If no information was available from these sources, variables were estimated based on length of reach, average slope, and other channel characteristics. All river routings were assumed to be conservative (routings were simulated with indefinitely large channels); no flow was lost in overbank areas during transit.

This procedure was not intended to reflect the natural dynamics of the Central Valley, where large flood flows often discharge to out-of-bank areas and are lost or greatly attenuated. The unregulated flow frequency curves were designed to quantify the total flows that the basins produced in rain floods throughout the period of record, rather than the average natural flows expected at mainstem locations during any of the seven synthetic exceedence frequency storm events.

Historical data were plotted using moving averages of the daily time series for 3-, 5-, 7-, 10-, 15-, and 30-day duration natural flow at all points of interest. Wintertime maxima were picked from the moving average for each water year. All snowmelt-driven events were screened out from these duration maxima; screened events were replaced with the highest rainflood, or rainfall driven, maxima experienced during that water year, which included any rain-on-snow events occurring during the obvious rainflood season of a particular annual record. Values were sorted, ranked, and graphed with median plotting positions. Statistics were computed for these samples of annual rainfloods with USACE statistical analysis tools (FFA and REGFREQ). Sample mean, standard deviation, and skew were computed and, in some cases, smoothed to better represent the values for each duration. The Pearson Type III Distribution with log transformation of the data and final statistics were used to construct best-fit curves for all durations and were plotted on the same graph as the historic values for each location.

Unregulated frequency curves were prepared for 43 tributary locations and 8 mainstem locations, as shown in Attachment B.2. In all cases, curves were developed or updated to reflect post-1997 hydrology. For any location, the amount of runoff volume produced during simulation of any one of the seven synthetic exceedence frequency flood events can be read off of the family of best-fit curves or computed directly from the final statistical distribution of each duration.

Flood volumes at mainstem index locations represent the sum of volumes contributed by all upstream tributaries, but do not offer any information regarding how each provides to the whole. In this sense, these index curves can provide exceedence frequency targets, in terms of volumes, at mainstem locations for any of the seven synthetic exceedence frequency flood patterns that involve a number of upstream tributaries. During the development process, it was assumed the effects of increased urbanization occurring throughout the period of record was insignificant on the timing of runoff within the watersheds of the Sacramento and San Joaquin rivers. For a further investigation of this assumption, please reference the "Watershed Impact Analysis" done by HEC.

The approach formulated and described above was driven entirely by historic flow data. Each year of record included the influence of snowmelt, infiltration, interception, precipitation distribution, timing of runoff, storm development characteristics, and physical basin attributes for that annual rainflood event. Historic flow data records provided a sufficient sample of flood events to characterize hypothetical flood volumes and tributary-system relationships.

No synthetic precipitation events were required. In fact, precipitation never entered into any portion of the methodology.

## TABLE 5

## ROUTING PARAMETERS FOR SACRAMENTO RIVER BASIN INDEX POINTS

| Source | From | To | Travel Time (Hours) | Muskingum Coefficient. |
|---|---|---|---|---|
| Sacramento | Bend-Bridge | Ord Ferry | 18 | 0.2 |
| Mill Creek | Gage near Los Molinos | Ord Ferry | 14 | 0.2 |
| Elder Creek | Gage near Paskenta | Ord Ferry | 20 | 0.2 |
| Deer Creek | Gage near Vina | Ord Ferry | 14 | 0.2 |
| Thomes Creek | Gage at Paskenta | Ord Ferry | 20 | 0.2 |
| Big Chico Creek | Gage near Chico | Ord Ferry | 6 | 0.2 |
| Stony Creek | Black Butte | Ord Ferry | 11 | 0.2 |
| Sacramento | Ord Ferry | Moulton Weir | 13 | 0.2 |
| Sacramento | Moulton Weir | Colusa Weir | 3 | 0.2 |
| Sacramento | Colusa Weir | Tisdale Weir | 9 | 0.2 |
| Sacramento | Tisdale Weir | Knights Landing | 7 | 0.2 |
| Sacramento | Knights Landing | Fremont Weir | 2 | 0.2 |
| Ord Ferry Overflow | Ord Ferry | Highway 162 | 32 | 0.1 |
| Butte Creek | Gage at Chico | Highway 162 | 7 | 0.2 |
| Butte Creek and Ord Ferry Overflow | Highway 162 | Moulton Weir | 10 | 0.1 |

*Note: Prior to use and application, reference the "Expectations of Use" preface.*

## TABLE 5 (CONTINUED)

## ROUTING PARAMETERS FOR SACRAMENTO RIVER BASIN INDEX POINTS

| Source | From | To | Travel Time (Hours) | Muskingum Coefficient |
|---|---|---|---|---|
| Moulton Weir Spill | Sacramento River | Butte Creek | 4 | 0.10 |
| Butte Basin Flow | Moulton Weir/Butte Creek | Colusa Weir | 4 | 0.10 |
| Butte Basin Flow | Colusa Weir | Butte Sink | 16 | 0.10 |
| Butte Basin Flow | Butte Sink | Tisdale Weir | 8 | 0.10 |
| Sutter Bypass/Tisdale Flow | Tisdale Weir | Fremont Weir | 20 | 0.10 |
| Feather River | Oroville | Gridley | 3 | 0.20 |
| Feather River | Gridley | Honcut | 1 | 0.17 |
| Feather River | Honcut | Yuba City | 4 | 0.17 |
| North Yuba River | Bullards Bar Dam | Englebright | 3 | 0.15 |
| Yuba River | Deer Creek | Dry Creek | 2 | 0.15 |
| Yuba River | Dry Creek | Marysville | 1 | 0.15 |
| Yuba River | Marysville | Mouth | 1 | 0.15 |
| Feather River | Yuba River | Bear River | 8 | 0.35 |
| Bear River | Wheatland | Mouth | 5 | 0.35 |
| Feather River | Bear River | Nicolaus | 2 | 0.35 |
| Feather River | Nicolaus | Fremont Weir | 4 | 0.20 |
| Sacramento River | Verona | Sacramento Weir | 5 | 0.20 |
| American River | Folsom Dam | Fair Oaks | 2 | 0.40 |
| Folsom Inflow | Folsom Dam | Sacramento Weir | 8 | 0.30 |
| Sacramento River | Sacramento River | Freeport | 4 | 0.20 |
| Sacramento River | Freeport | Rio Vista | 9 | 0.20 |
| Colusa Drain | Ord Ferry Overflow | Yolo Bypass | 72 | 0.10 |
| Fremont Overflow | Fremont Weir | Colusa Drain Con. | 6 | 0.20 |
| Yolo Bypass Flow | Colusa Drain | Interstate 5 | 2 | 0.20 |
| Cache/Clear Lake | Clear Lake | Rumsey | 8 | 0.28 |
| NFK Cache Creek | Indian Valley Reservoir | Rumsey | 7 | 0.20 |
| Cache Creek | Rumsey | Yolo Bypass | 3 | 0.30 |
| Yolo Bypass Flow | Interstate 5 | Putah Creek | 6 | 0.20 |
| Putah Creek | Berryessa Dam | Putah Div. Dam | 3 | 0.00 |
| Putah Creek | Putah Diversion Dam | Yolo Bypass | 24 | 0.00 |
| Yolo Bypass Flow | Putah Creek | Lisbon | 16 | 0.20 |

*Note: Prior to use and application, reference the "Expectations of Use" preface.*

## TABLE 6

## ROUTING PARAMETERS FOR SAN JOAQUIN RIVER BASIN INDEX POINTS

| Source | From | To | Travel Time Hours | Muskingum Coefficient |
|---|---|---|---|---|
| Kings River | Piedra | Army Weir | 24 | 0.25 |
| Kings River | Army Weir | Crescent Bypass | 48 | 0.25 |
| Kings River-North | Crescent Bypass | James Bypass Gage | 20 | 0.20 |
| Kings River-North | James Bypass Gage | Unet Handoff Point | 3 | 0.20 |
| Kings River-North | James Bypass Unet | Mendota Gage | 10 | 0.20 |
| San Joaquin River | Friant Dam | Confluence w/ Little Dry Creek | 4 | 0.25 |
| Big Dry Creek Outflow | Dam | Little Dry Creek | 7 | 0.20 |
| San Joaquin River/ Full Natural Flow | Little Dry Creek | Gravelly Ford | 32 | 0.25 |
| San Joaquin River/ Channel Capacity | Gravelly Ford | Eastside Bypass | 14 | 0.15 |
| San Joaquin River/Channel | Eastside Bypass | Mendota | 14 | 0.15 |
| San Joaquin River In-Channel | Mendota | El Nido | 44 | 0.17 |
| Eastside Bypass Flow | | Fresno River | 12 | 0.10 |
| Fresno River | Hidden Dam | Madera Canal | 4 | 0.20 |
| Fresno River | Madera Canal | Unet Handoff Point | 14 | 0.20 |
| Fresno River In-Channel | Unet | Eastside Bypass | 8 | 0.20 |
| Eastside Bypass Flow | Fresno River | Chowchilla River | 14 | 0.25 |
| Chowchilla River | Buchanan Dam | Madera Canal | 4 | 0.20 |
| Chowchilla River In-Channel | Madera Canal | Eastside Bypass | 20 | 0.20 |
| Eastside Bypass In-Channel | El Nido | Mariposa Bypass | 24 | 0.20 |
| Eastside Bypass/ In-Channel | Mariposa Bypass | Merced Stream Group | 6 | 0.30 |
| Mariposa Creek | Mariposa Dam | Owens Diversion | 6 | 0.30 |
| Owens Creek | Owens Dam | Mariposa Creek | 5 | 0.30 |
| Mariposa Creek In-Channel | Owens Diversion | Deadman/Dutchman | 12 | 0.20 |
| Mariposa Creek In-Channel | Deadman/Dutchman | Eastside Bypass | 14 | 0.20 |
| Miles Creek | | Owens Creek Channel/Below Owens Bypass | 10 | 0.20 |
| Miles Creek In-Channel | Below Owens Bypass | Eastside Bypass | 10 | 0.20 |
| Bear Creek | Bear Dam | Black Rascal Diversion | 8 | 0.30 |
| Burns Creek | Burns Dam | Black Rascal Diversion | 8 | 0.30 |
| Bear Creek In-Channel | Below Black Rascal Diversion | McKee Road | 3 | 0.30 |
| Note: All routing assumed to remain in channel. | | | | |

*Note: Prior to use and application, reference the "Expectations of Use" preface.*

**TABLE 6 (CONTINUED)**

**ROUTING PARAMETERS FOR SAN JOAQUIN RIVER BASIN INDEX POINTS**

| Source | From | To | Travel Time Hours | Muskingum Coefficient |
|---|---|---|---|---|
| Bear Creek In-Channel | McKee Road | R.M. 8.6 | 22 | 0.20 |
| Bear Creek In-Channel | R.M. 8.6 | Eastside Bypass | 8 | 0.20 |
| San Joaquin River | El Nido | Mariposa Bypass | 20 | 0.20 |
| San Joaquin River | Mariposa Irrigation Canal | End of Eastside Bypass | 6 | 0.20 |
| Los Banos Creek | Los Banos Dam | Local Flow | 24 | 0.20 |
| Los Banos Flow | Local Irrigation Project | San Joaquin River | 11 | 0.02 |
| San Joaquin River/ In-Channel | Los Banos Creek | Newman Gage | 7 | 0.15 |
| Merced River In-Channel | Exchequer | Dry Creek | 20 | 0.20 |
| Merced River In-Channel | Unet | San Joaquin River | 18.5 | 0.20 |
| Merced River In-Channel | Cressey | Unet Handoff Point | 3.5 | 0.20 |
| Del Puerto Creek | Interstate 5 | San Joaquin River | 5.5 | 0.20 |
| Orestimba Creek | Interstate 5 | San Joaquin River | 10 | 0.10 |
| San Joaquin River In-Channel | Newman Gage | Maze Road Bridge | 20 | 0.15 |
| Tuolumne River In-Channel | Don Pedro Dam | Dry Creek/Near Modesto | 20 | 0.20 |
| Dry Creek/Near Modesto | | Tuolumne River | 2 | 0.20 |
| Tuolumne River In-Channel | Modesto | Maze Road Bridge | 8 | 0.20 |
| San Joaquin River In-Channel | Maze Road Bridge | Vernalis | 8 | 0.20 |
| Stanislaus River | New Melones Dam | Tulloch Dam | 2 | 0.20 |
| Stanislaus River In-Channel | Tullock | Orange Blossom Bridge-Inflow | 4 | 0.20 |
| Stanislaus River In-Channel | Orange Blossom Bridge | Ripon | 15 | 0.10 |
| Stanislaus River In-Channel | Ripon | Vernalis | 16 | 0.20 |
| Note: All routing assumed to remain in channel. | | | | |

## Historic Flood Event Analysis

With the completion of the natural flow data analysis and compilation of the 51 curve sets (43 tributary and 8 mainstem), the amount of flood volumes at discrete locations within the basins were quantified. At mainstem locations, total volumes reflected the combined flows of between 5 and 20 individual tributaries (depending on location). To perform simulations with the reservoir and hydraulic models, this total volume needed to be redistributed into the system of tributaries through a flood pattern.

In nature, storms trigger high flows on isolated tributaries and large-scale river systems as a function of storm structure, air temperature, water content, storm path, orographic influence, basin alignment, and a host of other geophysical and meteorological variables. Ultimately, all storms are unique, but certain dynamics tend to be common to a variety of storm types,

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especially those that trigger productive (in terms of volume) events within the Central Valley. Development of patterns is possible through a number of methods, including random generation, use of a singular historic event, and uniform or ramped concurrencies.

The most realistic patterns for synthetic floods are formulated based on historic storms. A detailed analysis of several events was undertaken to identify flood trends and distributions that could be incorporated into generalized patterns.

## Retrospective of Historic Flood Events

Nineteen historic flood events were analyzed. Events were chosen based on the natural 3-day rain flood volumes produced at Central Valley flood damage reduction reservoirs. On a project by project basis, any event that was both the largest 3-day natural flow experienced during that water year and one of the five largest 3-day natural flows in the gage history of that project was selected for analysis. Though this selection process focused on tributary events, often the same year was selected for multiple projects. This was especially true for the largest flood years on record (i.e., 1997, 1986, and 1956). Therefore, the 19-storms represent a mixed population of storms that were focused on individual tributaries as well as those that had a powerful system-wide effect.

For each year, a time window was set that contained both the tributary event, which had been elected for inclusion that year, and provided additional time allowing the storm pattern to complete its influence throughout the basin. Duration flows (1-, 3-, 7-, 15-, and 30-day average flows) within this event window were analyzed for all significant tributaries and several mainstem locations. These flows were translated into annual percent chance exceedence values based on the unregulated flow and index frequency curves developed for tributary and mainstem locations during the natural flow analysis.

By comparing annual percent chance exceedences instead of flow rates, the distribution of storm patterns is normalized spatially. Percent chance exceedences provide a consistent measure of intensity from basin to basin, while flow rates, as a function of drainage area, alignment, and others, are tributary specific. Investigating chance exceedences clarifies patterns, in terms of how individual storm systems impacted a system of tributaries. Considering multiple storm events1 highlights trends linking tributary responses and orographic influence in rare events, which form the basis for, and can be incorporated into, the development of generalized storm patterns.

## Flood Matrix

All annual chance exceedence events, locations of interest, flood durations, and year of event were tabulated into Sacramento and San Joaquin Basin storm matrices referred to jointly as the Matrix, as shown in Attachment B.3.

The Matrix is a valuable product of this study; it provides the nineteen historic flood events analyzed for comparison of runoff for all major tributaries in a complex hydrologic system. The matrices are laid out in upstream to downstream fashion, allowing storm and tributary dynamics to be looked at in diverse permutations of flood durations, storm combinations, and tributary sets.

Matrix investigations pointed to several trends that were eventually incorporated into the synthetic flood runoff centerings. Among the first dynamics noticed was the presence of spatial trends and storm bull's eyes within individual storm events. Bull's eyes were created as historic storms impacted certain spatial areas with greater intensity than surrounding areas. Nearly all events in the Matrix displayed some sort of spatial trend or bias towards a specific area. The floods of February 1986, for example, were most intense over the mid-latitudes of the Central Valley, including the lower Sacramento Basin (Feather, Yuba, Bear, and American rivers), Delta (Mokelumne and Cosumnes rivers), and Lower San Joaquin rivers (Stanislaus River). Perhaps the most isolated storm centering occurred in 1967 in the southern end of the Central Valley, where Success Reservoir, on the Tule River, filled and spilled overnight. During this event, the Kings River at Pine Flat Reservoir, a neighboring tributary to the north, experienced a 1-day, 1.69-percent chance exceedence event. The chance exceedence exceedence on the San Joaquin River, just one watershed further north, equated to less than an annual 5-percent chance exceedence event. No other tributary north of this point registered higher than an annual 16.67-percent chance exceedence event.

Mainstem locations below these "bull's eyes" experienced greater exceedence frequencies, because here the intensity of flooding is a function of all upstream tributaries, not just those that were especially intense. In this sense, the mainstem acts as a buffer, which absorbs and moderates localized extremes because they alone do not add enough volume to the system to maintain the larger, less frequently occurring storm events.

A key finding was that orographic effects were most pronounced in the rarest, least frequently occurring events. The January 1997 floods were the maximum on record in the lower San Joaquin Basin. In this event, as well as 1982, 1967, 1951 and, to a lesser extent, 1986 and 1956, storm events were consistently more extreme in the higher elevation San Joaquin basins than in the foothill tributaries. This relationship highlights the effects of the high Sierra in the San Joaquin and Tulare basins.

Orographic effects in the Sacramento Basin were definitely visible, but not as well defined as those in the San Joaquin. Still, higher basins in the floods of 1974 and 1956, and to a lesser extent in 1997 and 1986, displayed distinctively more extreme storm events than the lower basins. It is likely that the more pronounced orographic influence in the southern Central Valley is related to the average ridge crest elevation along the Sierras, which is generally lower in the Sacramento Basin than in the San Joaquin and Tulare, but this remains uncertain.

The years cited above for both the Sacramento and San Joaquin basins basically comprise a subset of the Matrix containing the most severe historical events analyzed in this study. For storms that were generally less intense, orographic effects were muted at best and basically not visible. Storms tended to become more and more evenly distributed until any dynamics that could potentially be tied to orographics were just as likely attributed to random noise.

The Matrix also points out that natural dynamics are highly variable. Storm cells nested within the larger storm structure are powerful and have the ability to trigger individual tributaries significantly (i.e., the 1986 flood on the Bear River). Even with the supporting evidence for orographic influence, there are Matrix examples of floods that demonstrate a consistently opposite bias; in the San Joaquin Basin during the March 1995 floods and in the Sacramento Basin during the 1983 floods, annual percent chance exceedences for foothill tributaries were lower than those of neighboring higher basins.

*Note: Prior to use and application, reference the "Expectations of Use" preface.*

## SYNTHETIC FLOOD RUNOFF CENTERING

### General

Based on trends identified in the historic storm analysis and in keeping with the concept of the Composite Floodplain, guidelines for centering development were formulated and synthetic flood runoff centerings were constructed.

In the context of this study, a flood runoff centering is defined simply as a set of synthetic exceedence frequencies assigned to a set of tributaries. Centerings were developed separately for the Sacramento and San Joaquin basins. Each tributary was included in all centerings within its basin.

Two basic types of flood runoff centerings were analyzed. The first consists of basin-wide flood events (mainstem centerings), which are significant on a regional basis and produce large runoff volumes throughout the system. The second are tributary specific floods (tributary centerings), which generate extremely large floods on individual rivers, but are not widespread enough to produce the runoff volumes typical of basin-wide events.

Mainstem centerings were prepared at Ord Ferry, Sacramento, El Nido, Newman, and Vernalis; tributary centerings were prepared for 18 individual rivers (8 in the Sacramento Basin and 10 in the San Joaquin) to represent synthetic annual 50-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent chance exceedence events. Flood runoff centering tables for mainstem and tributaries are located in Attachment B.4.

Due to the differences in flood character, mainstem and tributary centerings needed to be addressed with separate sets of governing guidelines. There are similarities between rule sets, but in general, approaches are dissimilar.

### Mainstem Flood Runoff Centering

Mainstem centerings were designed to stress widespread valley areas. Index frequency curves were prepared at Ord Ferry and Sacramento in the Sacramento River Basin, and at El Nido, Newman, and Vernalis in the San Joaquin River Basin. These curves provide the hypothetical volumes that the basin will produce during simulations of each of the seven synthetic exceedence frequency flood events. The role of the mainstem centerings is to distribute these volumes back into the basin, tributary by tributary, in accordance with patterns visible in historic flood events. Once the volume is distributed it will be translated into hydrographs and routed through reservoir simulation models (Appendix C) to produce the seven synthetic exceedence frequency regulated hydrographs needed to construct floodplains throughout the system.

Mainstem centerings reflect a generalized flood pattern based on a number of historic events. Through the incorporation of multiple floods into one characteristic pattern, relationships between tributaries become more stable and the influence of powerful, but isolated, storm cells are downplayed.

Characteristic patterns were developed for each mainstem location. Where available, historic events that displayed flood "bull's eyes" in the watershed above the mainstem location of interest were used to formulate synthetic patterns. The orographic effects noted in the Matrix analysis

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were also incorporated, especially for the largest, less frequently occurring synthetic exceedence frequency events.

To assure that patterns were developed consistently, guidelines for mainstem pattern construction were formulated and are presented in Table 7. A key guide and concept is that the exceedence frequency of any single tributary cannot be less than that of the mainstem target location. This constraint was established to accommodate two points of logic. First, concurrent events of the same annual percent chance exceedence (i.e., a 1-percent chance exceedence event) occurring on all tributaries will lead to a mainstem flood more extreme than a storm event of the same percent chance exceedence occurring without any other tributary or upstream contributions. The second point is related to the Composite Floodplain Concept and takes into account that these hydrologic results are intended for use in floodplain delineation and estimation of without-project damages.

Use of the generalized pattern is not necessarily representative of historic flooding. In nature, and as reflected by the Matrix, floods display localized extremes which exceed that of the overall system. However, if a mainstem flood runoff centering was used that incorporated a tributary annual percent chance exceedence lower than the targeted mainstem location, the floodplain delineated would not be directly usable in the Composite Floodplain, because the extent of inundation along the tributary would be larger than that of the simulated synthetic exceedence frequency event.

A potential solution to this would be to use the centering, but to omit that tributary's extent of inundation from the Composite Floodplain and characterize damages along that stretch with an annual percent chance exceedence event equal to that of the target location. This remedy becomes convoluted when one considers how best to represent the influence of that particular tributary. This is especially true in areas where the influence shaping the floodplain begins to transition from this mainstem centering to other centerings, either tributary or mainstem. In these transition zones, it is difficult to isolate the influence of any single tributary and the decision regarding whether to screen out inundation and damages proves to be difficult and subjective. These approaches, all centered around the direct use of a singular historic pattern, were considered and discarded in favor of generalized mainstem patterns.

After an initial pattern was formulated, hydrographs were constructed at tributary locations (in accordance with the pattern) and routed back to the mainstem location with the same procedure used during construction of the index frequencies as shown in Attachment B.4. Duration maxima (1-, 3-, 7-, 15-, and 30-day) were computed for the mainstem hydrograph and compared with the average flows from the index curve. The initial pattern was then increased or decreased by a fixed percentage and the comparison process was repeated. This iterative procedure continued until the final centering produced flood volumes at the mainstem location that were roughly equal to the hypothetical volumes specified by the index curves. A detailed sample mainstem centering development is presented in Attachment B.4.

## TABLE 7

## GUIDELINES FOR THE PREPARATION OF MAINSTEM CENTERINGS FOR THE SACRAMENTO AND SAN JOAQUIN RIVER BASINS

| Guidelines for the Preparation of Mainstem Centerings |
|---|
| 1) All mainstem centerings must be supported by patterns visible in historic floods.<br>2) Flood volumes produced by a mainstem centering must be roughly equal to the hypothetical volumes specified by the index volume curves.<br>3) The annual percent chance exceedence event of any individual tributary cannot be less than that of the mainstem centering being developed.<br>4) Orographic effects are most pronounced in the rarest, less frequently occurring events.<br>a) Basins higher in elevation experience less frequent exceedence events than do lower elevation basins during mainstem centering simulations of 1-, 0.5-, and 0.2-percent chance exceedence events.<br>b) During 4- and 2-percent chance exceedence events, orographic effects are less pronounced and mainstem centerings begin to reflect a more evenly distributed pattern.<br>c) In simulating 50- and 10-percent chance exceedence events, mainstem centerings reflect an evenly distributed pattern.<br>5) As an individual tributary becomes more distant from the mainstem location of interest, the annual percent chance exceedence of that tributary is increased. For example, the percent chance exceedence assigned to the Sacramento River at Shasta Dam must be lower during the simulation of a 1-percent chance exceedence storm runoff centering at Verona than during a 1-percent chance exceedence storm runoff centering at Ord Ferry.<br>This relationship is maintained within the context of the first rule (i.e. if Shasta is reduced for a downstream 1-percent chance exceedence storm runoff centering, Battle Creek must be reduced proportionately to assure that Shasta, as the higher basin, still has a lower annual percent chance exceedence due to orographic influences. |

### Tributary Flood Runoff Centering

Tributary centerings were designed to stress individual tributary systems. Whereas the mainstem centerings were formulated as spatially distributed events that were productive on a system-wide basis, tributary centerings were designed to simulate extreme floods on individual rivers generated by storm systems that were not widespread enough to produce runoff volumes typical of basin-wide events. In this sense, tributary centerings seek to reflect the powerful and isolated storm cells intentionally downplayed by the mainstem centerings.

Preparation of tributary centerings, as shown in Table 8, was more straightforward than those prepared for the mainstem, because in any tributary centering, the exceedence frequency of the target tributary was set equal to the desired chance exceedence event (i.e., development of a 1-percent chance exceedence storm runoff centering for the Tuolumne River includes a 1-percent chance exceedence inflow to Don Pedro Reservoir). Also, all other tributaries experienced a greater (in frequency) chance exceedence event and, as there were no downstream target volumes, no iterative procedure was required. Considering these inherent features, the only remaining step was to determine how neighboring rivers were related to the target tributary.

Intertributary relationships were defined using historical patterns visible in the Matrix. For each tributary centering, the 19 historic events were analyzed to determine if any were focused most intensely over that specific tributary. Once suitable historic events were found, exceedence frequencies for tributaries neighboring the target river were increased by the highest rate visible in the historic flood patterns. Tributary frequencies were reduced in this manner until reaching a

*Note: Prior to use and application, reference the "Expectations of Use" preface.*

maximum chance exceedence event or until the tributary was distant enough from the target river to have no possible influence on that tributary's floodplain (at which point it was also increased to a maximum exceedence frequency). The exceedence frequencies of concurrent events on the distant tributaries were assumed to be approximately 10 times the target tributary's exceedence frequency. Again, all tributaries within the Sacramento or San Joaquin Basin were included in each flood runoff centering regardless of proximity to the target location. A detailed sample of tributary centering development is presented in Attachment B.4.

**TABLE 8**

**GUIDELINES FOR THE PREPARATION OF TRIBUTARY CENTERINGS FOR THE SACRAMENTO AND SAN JOAQUIN RIVER BASINS**

| **Guidelines for the Preparation of Tributary Centerings** |
|---|
| 1. All tributary centerings must be supported by patterns visible in historic floods.<br>2. Generic patterns not supported by the historic flood analysis may need to be applied to tributaries, which have not been the focal basin in any of the 19 historic events.<br>3. The exceedence frequency of the target tributary is always set equal to the desired annual chance exceedence event.<br>4. No other tributary can have an exceedence frequency as large as that specified for the target tributary.<br>5. a) Exceedence frequencies for adjacent tributaries are reduced by the highest rate visible in historic flood patterns. This maximum reduction rate defines the relationship between those tributaries as the target tributary moves further and further away.<br>b) Tributary exceedence frequencies are reduced in this manner until reaching a maximum chance exceedence event, which is a function of the target exceedence frequency, or until the tributary is distant enough from the target tributary to have no possible influence on that tributary's floodplain, at which point it would also be increased to the established maximum chance exceedence event. |

In some cases, individual tributaries were not the focal basin in any of the 19 historic events and did not occur in greater frequency than events of neighboring tributaries consistently enough to formulate a centering. Here, generic patterns unsupported by the historic flood analysis were applied. Tributaries that needed to be simulated with these patterns were typically small foothill or west-side basins.

Once a tributary centering was prepared it was deemed complete pending a test that translated centerings to hydrographs and routed tributary flows to the nearest downstream index curve location. Duration maxima (1-, 3-, 7-, 15-, and 30-day) were then computed for each of the resultant seven synthetic exceedence frequency natural flow hydrographs and compared with the average flows from the corresponding index frequency curves. For each tributary centering, it was confirmed that the flows experienced at the mainstem points were lower than those generated by the corresponding mainstem centering. This affirmed that the floodplains in mainstem locations are more likely to be shaped by the widespread floods simulated with mainstem centerings.

### Development of Seven Synthetic Exceedence Frequency Natural Flow Hydrographs

To this point, the discussion has focused primarily on flood frequencies, not on flood flows. The final topic in the Synthetic Hydrology Methodology is the translation of frequencies to hourly

*Note: Prior to use and application, reference the "Expectations of Use" preface.*

flood hydrographs for use in reservoir simulations (Appendix C) and hydraulic modeling (Appendix D). The translation process is depicted in Plate 4 and involves 3 steps: 1) obtaining the average flood flow rates from the unregulated frequency curves; 2) separate these average flows into wave volumes; and 3) distributing volumes into the 6 wave series. This process is performed only at the tributary locations. Mainstem flood hydrographs always result from the routed contributions of upstream tributaries.

### *Average Flood Flows*

The process of preparing flood hydrographs begins by using unregulated frequency curves to translate all of the exceedence frequencies in the synthetic patterns to average flow rates. In this study, a spreadsheet was developed that used the adopted statistics for the 5-, 10-, 15-, 20-, 25-, and 30-day durations to translate specific annual chance exceedence events to flows. This approach produces the same results as would be obtained by manually reading average flows off of individual curves for each chance exceedence event. By using the adopted statistics to quantitatively describe the frequency curves, the process was automated.

Often, the unregulated frequency curves had been prepared using 1-, 3-, 7-, 15-, and 30-day durations. In these cases, values for the 5-, 10-, 20-, and 25-day durations were obtained through interpolation.

### *Separation of Average Flows into Wave Volumes*

The values from the frequency curves represent the average flow anticipated over a specific time interval. For instance, the 5-day value is the average flow expected during the highest 5-days of flooding during any of the seven synthetic exceedence events. Likewise, the 10-day value is the average over the highest 10-days of flooding. Though not always the case, it is typical for the highest 5- day period to be part of the highest 10-day period as well as part of the highest 15-day, 20-day and so on. Essentially, shorter durations tend to fall within the longer.

Holding this to be true, flood volumes were computed by multiplying the average flows by their respective durations. These values represented the total volumes of water anticipated during the highest 5-, 10- 15-, 20-, 25-, or 30-days of flows. Furthermore, these volumes were portioned into time segments by subtracting volumes of the shorter durations from the next longer duration. For example, the 5-day volume was subtracted from the 10-day volume and the remainder was equal to the amount of flood volume that is produced by the tributary between the extents of the 5-day and 10-day maximum periods.

This procedure was repeated for the 10-, 15-, 20-, 25-, and 30-day durations and resulted in a set of seven synthetic exceedence frequency flood volumes produced by the tributary. These 6 volumes were treated as wave volumes in a series of 5-day waves.

### *Distribution of Volumes into Hourly Flood Hydrographs*

In this study, the basic pattern of all synthetic flood hydrographs was a 30-day hourly time series consisting of 6 waves, each 5-days in duration. Volumes were ranked and distributed into the basic pattern. The highest wave volume was always distributed into the fourth, or main, wave. The second and third highest volumes preceded and followed the main wave, respectively. The fourth highest volume was distributed into the second wave and the fifth highest was distributed into the final of the six waves. The sixth and smallest wave volume was distributed into the first wave of the series. The shape of each wave is identical and the magnitude is determined by the total volume that the wave must convey.

The presence of six distinct waves in the constructed series appears to be unnatural. While there are examples in the gage record which display this multiple wave dynamic, it is also important to keep in mind that the series of six 5-day waves is first and foremost a method used to redistribute volumes from the frequency curves into hydrographs for further analysis.

### *5-Day Pattern*

In the Sacramento River Basin, no extensive archives of hourly natural patterns existed. Five-day wave patterns were constructed by adjusting regulated gage records for the 1997 flood event in accordance with changes in upstream storage. Natural series were computed for all tributaries locations except the Sacramento River at Shasta Dam, Feather River at Oroville, and Deer Creek near Smartsville. At these sites, insufficient data at headwater reservoirs precluded the accurate computation of natural flows; regulated flows were used as pattern hydrographs.

The distribution of tributary flood volumes into these 5-day wave patterns was automated within the same spreadsheet that translated frequencies to average flows. In fact, the process was mechanized to the point where generation of the 30-day hourly series was entirely driven by entering the exceedence frequencies of the tributaries within each centering into the spreadsheet. Hydrographs were automatically computed and could be copied into text files for direct entry into HEC-DSS (HEC, Data Storage System).

## QUALIFICATION OF BASE CONDITION RESULTS

In defining baseline hydrologic conditions for the occurrence of 50-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent chance exceedence events, 70 Sacramento and 91 San Joaquin Basin flood runoff centerings have been analyzed. As each centering involved the construction of at least 20 hydrographs, over 3,220 flood series have been prepared. All work was performed with consistent approaches while maintaining the vision that tools capable of replicating the process and testing the methodology must support definition of the baseline. This hydrology provides a sound basis for feasibility level, regional plan formulation as well as regional reservoir, hydraulic, and economic modeling, but does not necessarily provide the detail required for project implementation.

Hydrologic analyses performed for such a large spatial area, and at the level of detail documented herein, present challenges and opportunities unique to such an ambitious study. The Comprehensive Study has made possible a system-wide update for Central Valley unregulated flood hydrology and an overall modernization of the models used by Sacramento District hydrologists and engineers. These accomplishments will prove valuable to the Comprehensive Study and to future studies undertaken by public and private organizations.

One product not discussed in this report is the hydrologic data set that has been compiled in the process of investigating and defining the baseline hydrology. A massive data collection effort was undertaken to support the construction of unregulated frequency curves and model development and calibration. Data were obtained directly from Central Valley and federal water agencies, including U.S. Bureau of Reclamation, U.S. Geological Survey, U.S. National Weather Service, California Department of Water Resources (Northern, Central, and San Joaquin Districts), California Irrigation Management Information System, Oroville-Wyandotte Irrigation District, South Sutter Water District, Placer County Water Association, Nevada Irrigation District, Surface Water Data, Sacramento County, East Bay Municipal Utility District, Fresno Metropolitan Flood Control District, Tri-Dams, City of Roseville, Southern California Edison, Sacramento Metropolitan Utility District, and Pacific Gas and Electric. It is anticipated that this data will be made available to all interested parties via the Internet and it is further recommended that these archives be maintained in cooperation with all involved organizations to expedite future studies and research.

Recent developments in policy have advocated the use of watershed approaches in hydrologic studies. The Riverine Ecosystem Restoration and Flood Hazard Mitigation Initiative (Challenge 21) provides funding and expanded authority for the USACE to undertake studies with a broad focus on entire watersheds and possible implementation of nonstructural flood damage reduction projects and floodplain and riverine restoration. The Sacramento and San Joaquin River Basins Comprehensive Study, and specifically the Synthetic Hydrologic Analysis, has embraced this holistic watershed emphasis.

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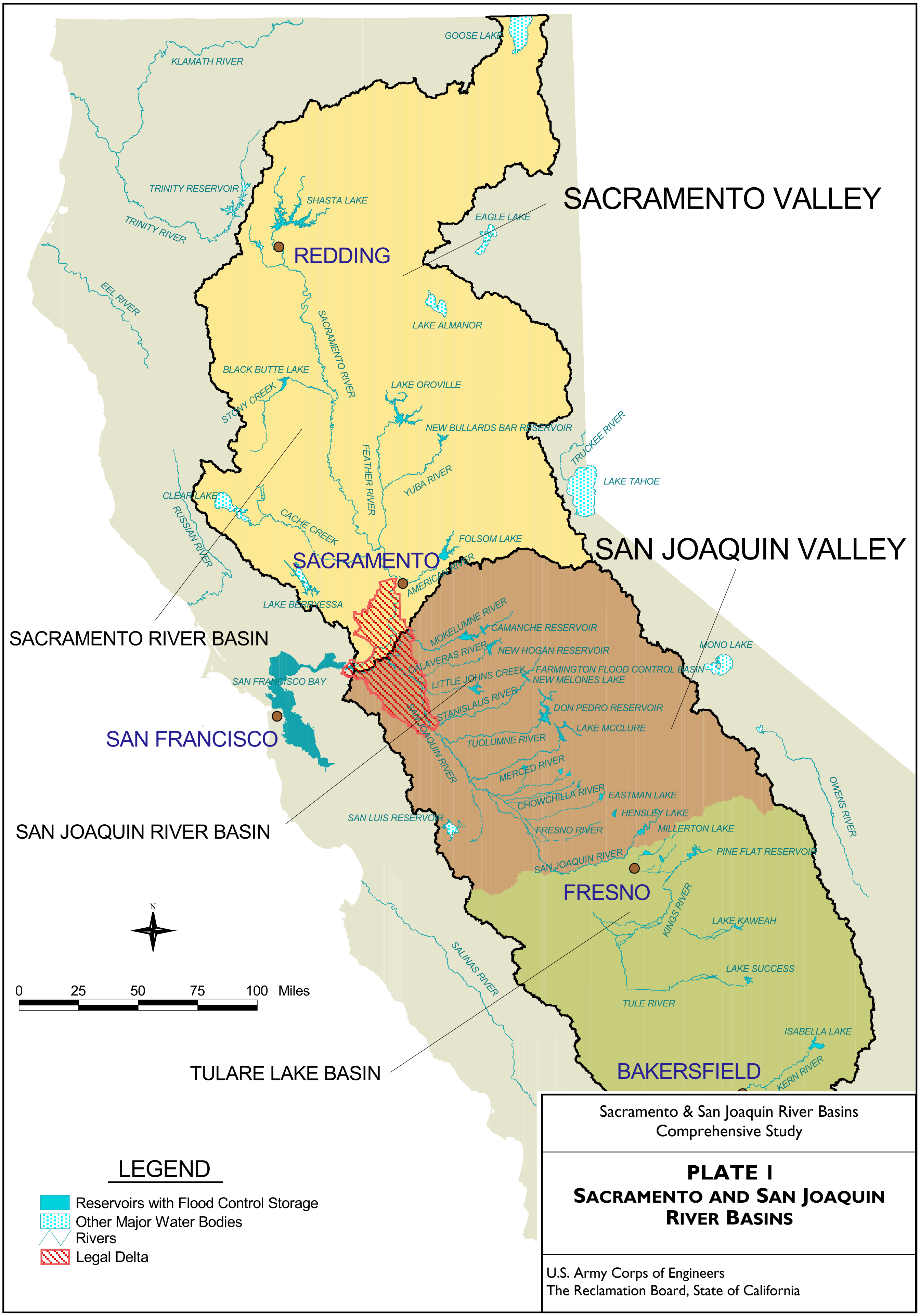



Sacramento & San Joaquin River Basins
Comprehensive Study

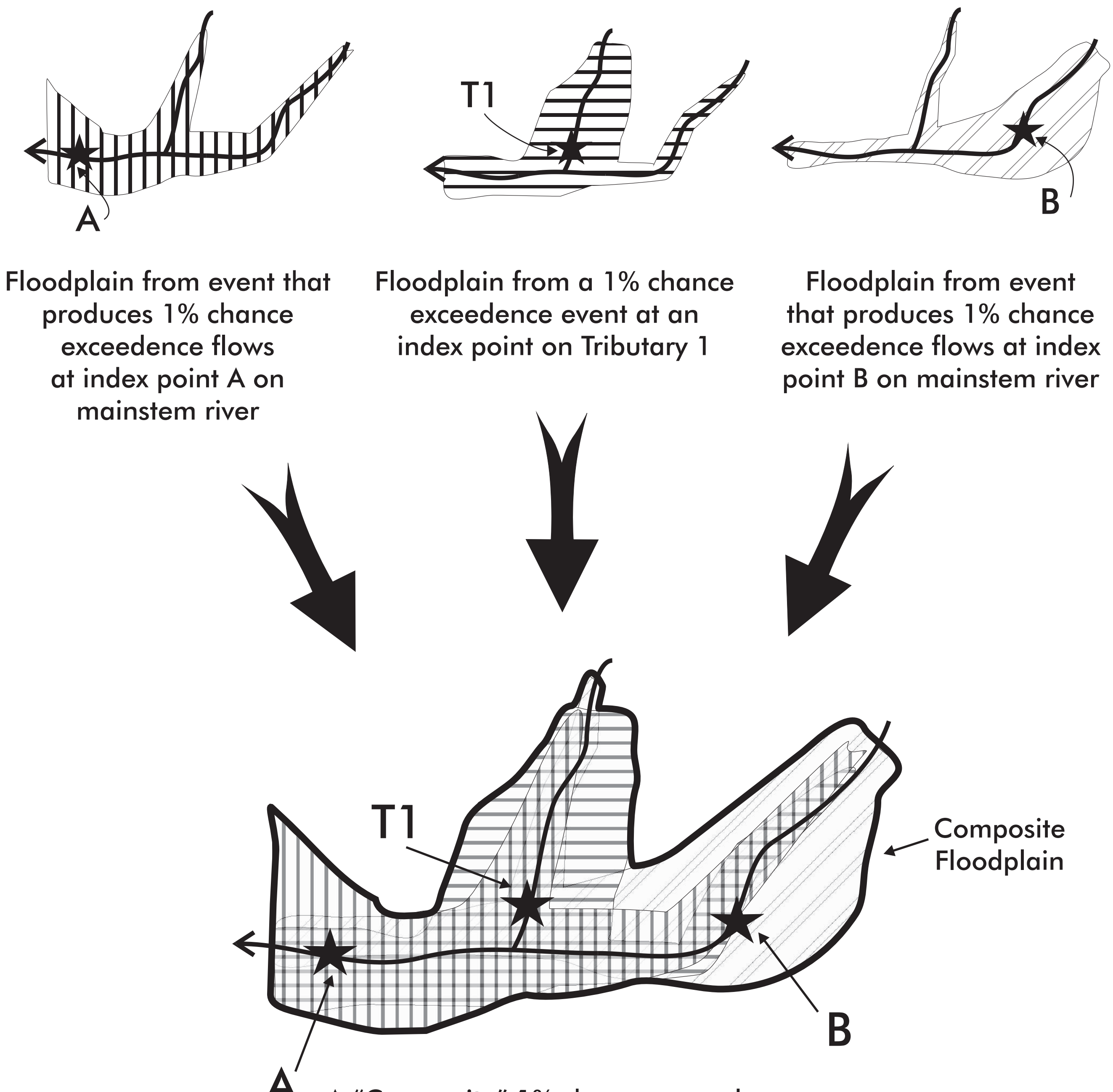
**PLATE I**
**SACRAMENTO AND SAN JOAQUIN RIVER BASINS**

U.S. Army Corps of Engineers
The Reclamation Board, State of California


Sacramento & San Joaquin River Basins
Comprehensive Study

# PLATE 2
## WATERSHED AND SNOWPACK AREAS ABOVE MAJOR CENTRAL VALLEY FLOOD MANAGEMENT DAMS

U.S. Army Corps of Engineers
The Reclamation Board, State of California




A "Composite" 1% chance exceedence floodplain is the maximum extent of floodplains resulting from 1% chance exceedence events at all index points

Sacramento & San Joaquin River Basins
Comprehensive Study

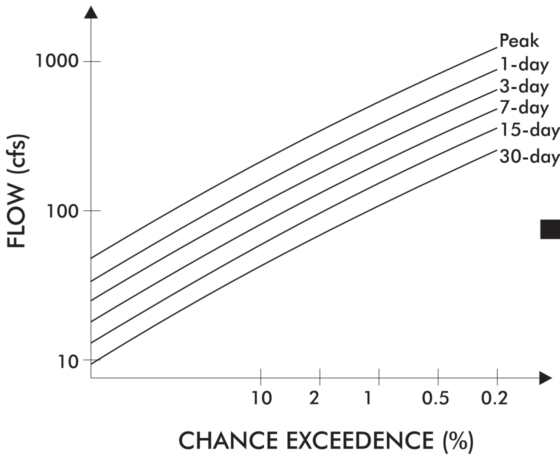
**PLATE 3**

**COMPOSITE FLOODPLAIN CONCEPT**

U.S. Army Corps of Engineers
Reclamation Board, State of California

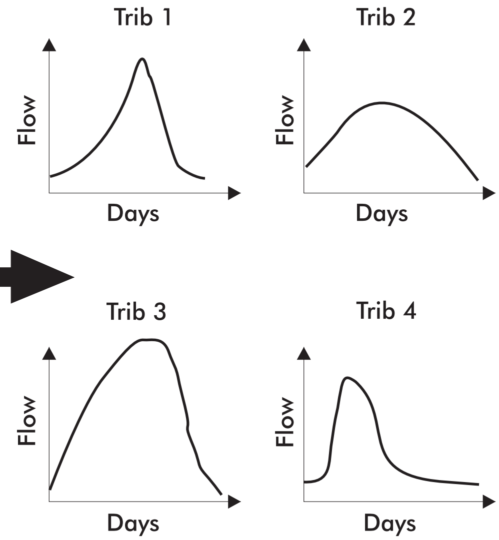
June 2002

## Full Natural Flow



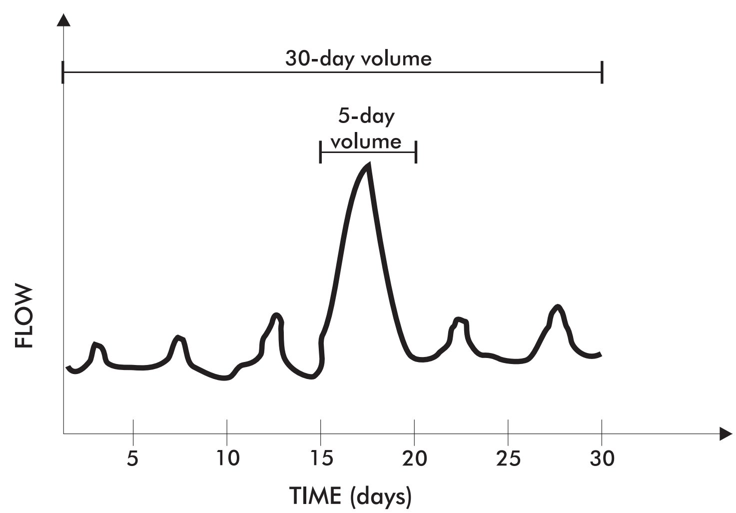

Full natural flow volumes were developed for each of 7 synthetic exceedence events on each tributary

## Tributary-Specific Patterns




Tributary-specific hydrograph patterns were used to translate 5-day incremental volumes to flow patterns

Flow Patterns were combined to develop a 30-day period




Resulting 30-day hydrographs for each of the 7 exceedence events on each tributary

Sacramento & San Joaquin River Basins
Comprehensive Study

**Plate 4**

**HYDROGRAPH CONSTRUCTION**

U.S. Army Corps of Engineers
Reclamation Board, State of California

July 2002