Natural and Human Factors in Recent Central Valley Floods

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ABSTRACT

Widespread and destructive flooding occurred in 1986 and 1997 along rivers flowing into California's Central Valley. The region is historically flood prone, but extensive flood control measures are designed to minimize damage. In recent years, land use changes and population increases have placed more people and property at risk, and the underperformance of flood control facilities exacerbate flood conditions. In 1986 and 1997, powerful subtropical storms delivered heavy rainfall over watersheds draining into the Central Valley and produced contrasting flood patterns. Precipitation occurrence and intensity and snowpack melting influenced peak discharge levels, but water management and land use decisions contributed to flood losses. Flooding in 1986 was most extensive in the Sacramento River Basin, where dams, levees, weirs, and other flood control structures were only partially successful in preventing flooding. The 1997 floods were most severe in the San Joaquin River Basin, where levee failures reduced river stages downstream but allowed flood waters to inundate Valley areas seldom associated with recent flooding problems. Despite early concerns, the timing and spatial characteristics of the 1998 ENSO-related precipitation produced only modest flooding in the Central Valley.

Introduction

ALONG WITH THE REST of northern and central California, Central Valley residents anticipated floods during the winter of 1997–98. The strong El Niño/Southern Oscillation (ENSO) event in the tropical Pacific Ocean was expected to influence the Pacific storm track and to deliver heavy rainfall to the region (Monteverdi and Null 1998). While flooding did occur in other areas of California, the Central Valley largely escaped damaging floods. The 1997–98 flood reprieve, along with the 1986 and 1997 floods, emphasizes the capricious nature of flooding in the region and the variety of circumstances contributing to Central Valley floods. Despite contemporary technology and an elaborate system of water management facilities, floods pose a continuing threat to life and property in the Central Valley.

Recent annual flood damage in California has been as high as $1.95 billion, and the Central Valley is often the focus of this damage. These flood losses occur even though flood abatement projects, including dams, reservoirs, levees, and flood bypass facilities, were initiated in the1880s (Kahrl 1979). Rivers draining into the Central Valley are regulated by 82 major reservoirs, but these facilities are unable to prevent periodic inundations somewhere along the stream courses. Intense rainfall, rapid snowmelt, or a combination of these weather-related events are the common causes of Central Valley floods. However, recent floods have emphasized that the spatial characteristics of inundated areas are also due to the success or failure of human efforts to control stream discharge. The characteristics of the 1986 and 1997 Central Valley floods are assessed to identify the relative roles of weather and flood management strategies in these two events. Precipitation associated with the 1998 ENSO illustrates the difficulty in forecasting the weather factor in producing Central Valley floods.

The Central Valley

The 20,800 mi^2 Central Valley occupies the structural depression between the Sierra Nevada and the Coast Ranges. All of the major rivers traversing the Central Valley drain the Sierra Nevada and enter from the east. The dominant drainage systems are the Sacramento River and its tributaries in the northern segment and the

Kern, Kings, Kaweah, and Tule rivers and the San Joaquin River and its tributaries in the southern Valley (Kahrl 1979). These river systems add 38,480 mi^2 to the area draining into the Central Valley, and they are the source areas for runoff producing floods throughout the Valley. Streams entering from the western side of the Central Valley drain the eastern slopes of the Coast Ranges and normally convey relatively little runoff (Figure 1). However, intense winter storms produce local flooding along these streams. The amount and

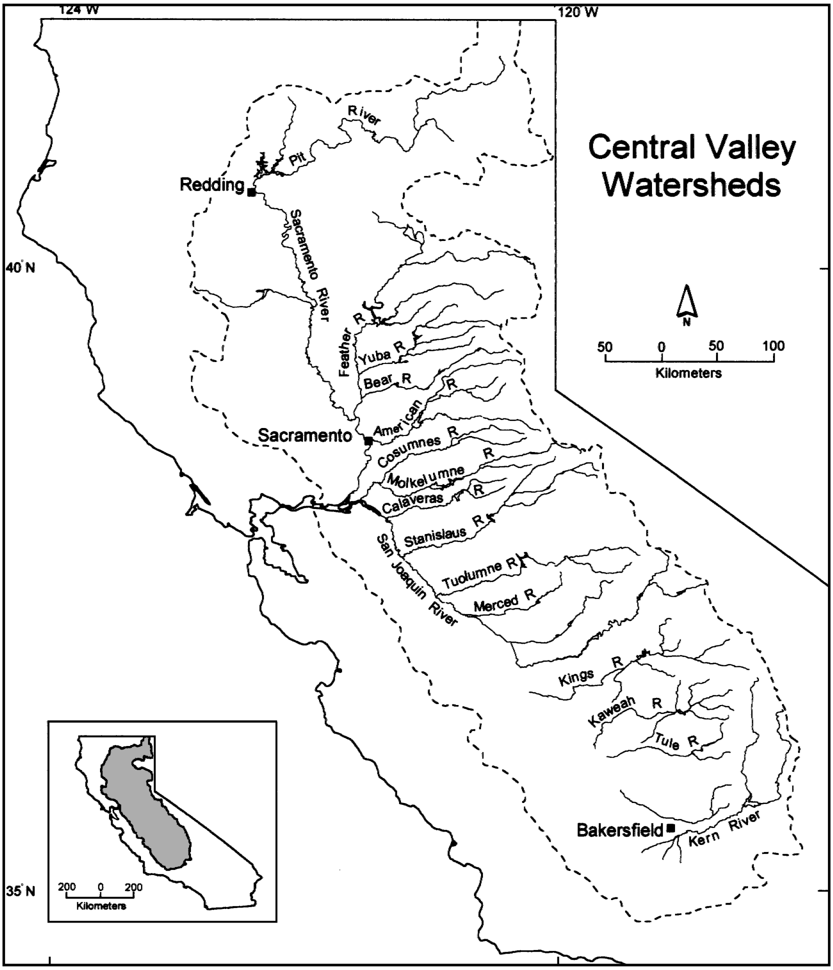

Figure 1: Central Valley watersheds.

intensity of rainfall are important for determining how much precipitation becomes runoff.

The majority of runoff entering the Central Valley occurs during the winter and spring months (Shelton 1995). Two dominant storm types produce two different runoff results. Cold arctic storms deliver snow at mid- to high elevations, and the snowpack delays periods of maximum runoff until late spring and early summer. Warm Pacific storms generate snowpack at the highest elevations and intense precipitation at mid- and lower elevations. These intense storms saturate the soil, creating overland flow that becomes the source of streamflow during most November-through-March floods.

About two-thirds of California's average annual precipitation of 200 million acre-feet (maf) falls in the northern third of the state draining into the Central Valley (Kahrl 1979). Normally, much of the rainfall is generated by four or five major winter storms, occurring between November and March. Some flooding is expected each year in areas where the precipitation is greatest, though hundreds of miles of levees have been constructed to protect developed areas. Levees are placed directly against rivers, rather than set back to allow a buffer zone. However, weirs, bypasses, agricultural easements, and levee setbacks create design failure mechanisms for levees.

The flood control systems for the Sacramento and San Joaquin basins evolved in response to different flood types in each watershed. Shasta Lake at the northern end of the Central Valley near Redding is California's largest flood control and water storage reservoir with a capacity of 4.5 maf. The Sacramento system was designed for rainfall-induced floods, having a large flow over a short duration and occurring predominantly in the winter. This flood control system has much larger channel capacities and a system of bypasses (Kahrl 1979). The Sacramento system has a 600,000-cubic-feet-per-second (cfs) capacity as it enters the Sacramento-San Joaquin Delta (CLAC 1997).

Unlike the Sacramento River, the San Joaquin River has no channel bypass and has experienced urban development in areas suitable to serve as a bypass. Furthermore, the San Joaquin River flood control system was designed to accommodate snowmelt in the spring and early summer. The peak flows associated with snowmelt normally are not as large as flows resulting from rain; however, the high flows last longer. Consequently, the San Joaquin River system has smaller channel capacities. At Mossdale, where the San Joaquin River enters the Delta, the system has a 52,000 cfs capacity. The entire San Joaquin River system has about 10 percent of the capacity of the Sacramento River system (CLAC 1997).

Intrusion of commercial and residential development into the floodplain and raised levees change the floodplain for all major rivers in the Central Valley. For example, the Army Corps of Engineers built Folsom Dam in the 1950s, estimating the dam would provide 250 years of protection given the existing development near Sacramento. Today, with the same system, there is approximately 70 years of protection (CLAC 1997).

The 1986 Flood

January 1986 was one of the warmest Januarys in California since records began in the 1850s. Most locations were more than 4°F above normal. Blue Canyon (5,280 ft) averaged 4.2°F above normal and remained above freezing for the entire month. Mid-January rain in northern California was the heaviest since November 1984. Warm rains originating from a subtropical storm system just north of Hawaii began on February 11, raising snow levels to above 7,000 feet in the Sierra Nevada (DWR 1988).

Precipitation totaled as much as 6 inches in the upper Feather River Basin during this early storm. On February 13, another very strong storm produced nearly 5 inches of rain at Redding (Figure 2), more than 11 inches at Bucks Lake (5,750 ft) in the Feather River Basin, and 1.5 inches at New Melones Dam (Figure 3) on the Stanislaus River. On February 16–17, rainfall of 0.5 to 0.75 inches per hour was reported for many locations, Redding received another 5 inches, New Melones added 6.5 inches, and totals at many Sierra stations exceeded 10 inches. As much as 24 inches of rain fell at Four Trees (5,150 ft) in the Feather River Basin and the snow line remained above 7,000 feet. The ground was saturated by previous storms and runoff was almost immediate. Rain continued through February 18 and 19, but cooler storms dropped the snowline to about 5,000 feet (DWR 1988). The 7-day increase in the snowpack at the Central Sierra Snow Laboratory near Soda Springs after February

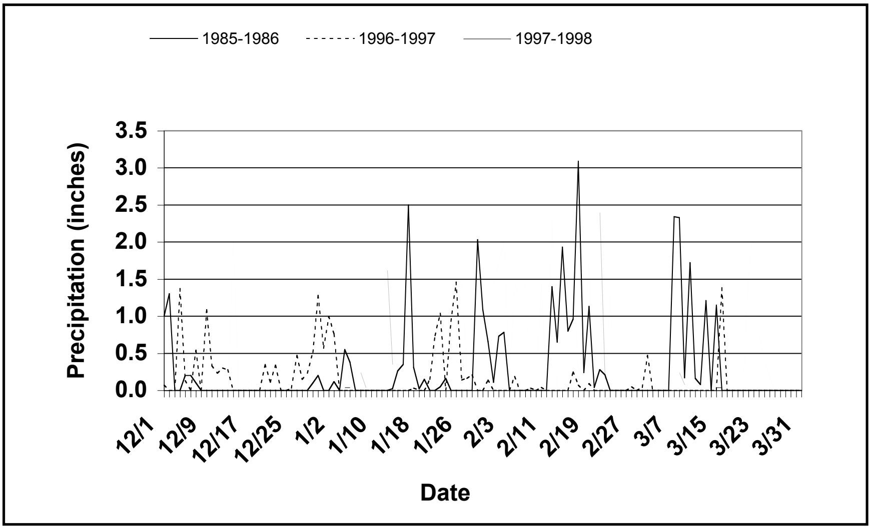

Figure 2. Redding daily precipitation. (Sources: NOAA 1986, 1996, 1997; NOAA 1998).

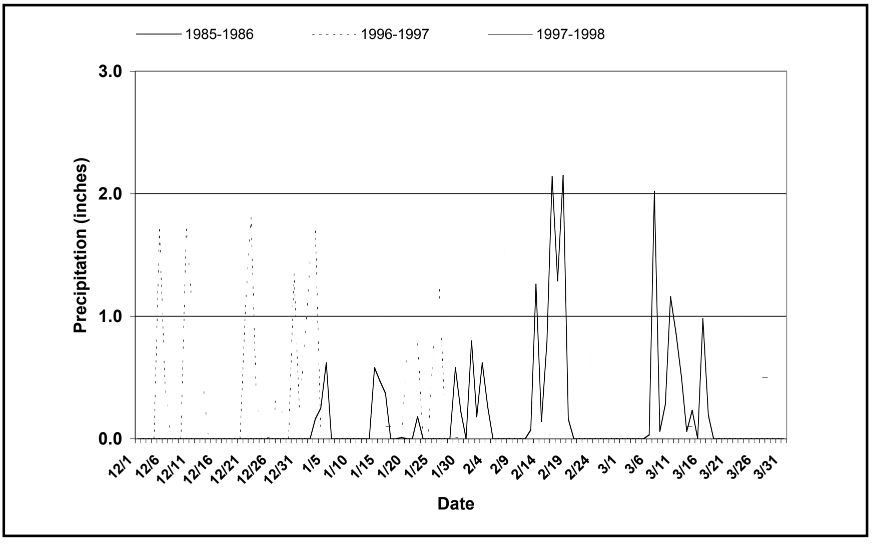

Figure 3. New Melones daily precipitation. (Sources: NOAA 1986, 1996, 1997; NOAA 1998).

14 illustrates the nearly 50 percent increase in the snow accumulation typical of the high Sierra (Figure 4).

Comparison of precipitation at two stations, Placerville (Figure 5) in the American River Basin and Redding in the Sacramento River Basin, illustrates the 1986 flood was not solely the result of the amount of precipitation, but was also a result of the interplay between precipitation, runoff timing, and the location of the watershed. Placerville received 3.42 inches of rain on February 17 and the total precipitation for February 11–22 of 16.11 inches was 60 percent greater than the rainfall at Redding for the same period.

Flooding was most prevalent north of the Sacramento-San Joaquin Delta, though some of the Delta islands were inundated. From February 16 to February 25, 7.77 maf of water passed through the Sacramento River system. Only 4.7 maf had flowed down the river during the 138 days since October 1, 1985. On February 20, 1.3 maf surged through the Sacramento River and Yolo Bypass to become the flood of record for that date. The highest flow measured was 665,000 cfs, a flow that would fill an empty Folsom Lake in less than 19 hours (DWR 1986a). Inflow to Lake Oroville reached a high

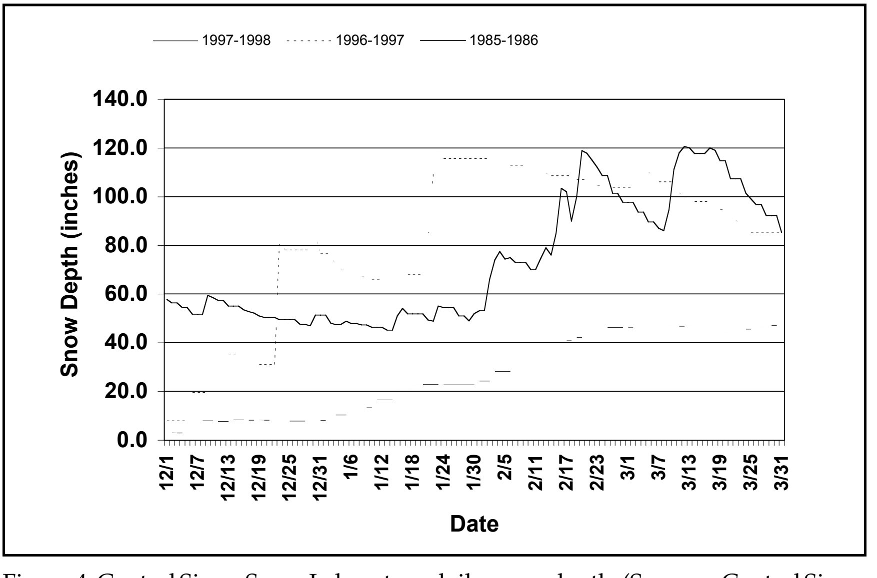

Figure 4. Central Sierra Snow Laboratory daily snow depth. (Sources: Central Sierra Snow Laboratory 1986,1996–97; DWR 1997a).

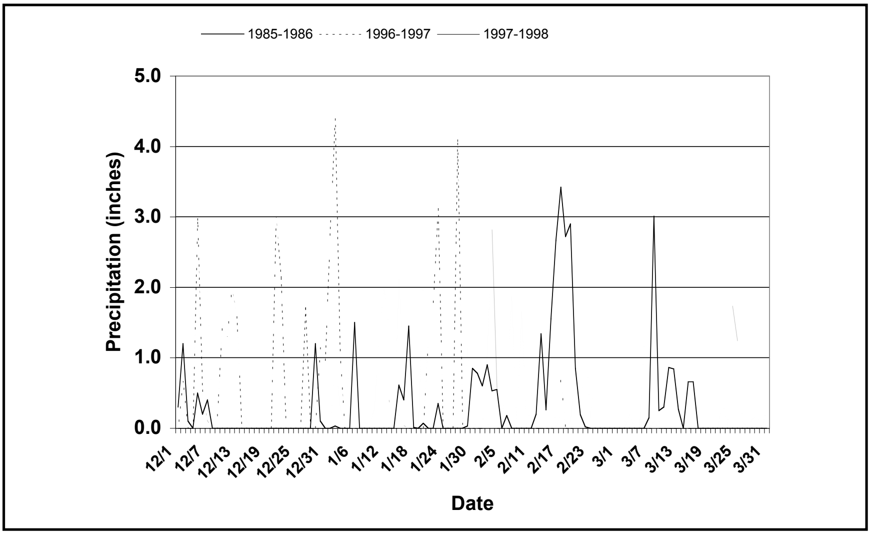

Figure 5. Placerville daily precipitation. (Sources: NOAA 1986, 1996, 1997; NOAA 1998).

of 266,450 cfs on February 17 and record releases of 150,000 cfs were required to maintain mandated operational standards (Kelley 1989). Table 1 shows selected flood peaks for the February 1986 flood that established new records at sites along the Sacramento, Feather, American, and Cosumnes rivers. However, many of these record flows were subsequently exceeded.

Peak inflows to the flood control reservoirs (Shasta, Black Butte, Oroville, Bullards Bar, and Folsom) above Sacramento totaled 789,000 cfs in 1986. The maximum releases from these reservoirs totaled 425,000 cfs. Without these flood control reservoirs, about 1,000,000 cfs would have been directed at Sacramento and into a levee and bypass system designed to accommodate 590,000 cfs. At its peak inflow, Shasta Lake received over 150,000 cfs, but downstream releases were limited to 70,000 cfs. Folsom Lake's largest inflow reached in excess of 200,000 cfs. The peak flow was briefly augmented by the failure of an upstream coffer dam near Auburn. Folsom maintained releases at 130,000 cfs (Kelley 1989).

Flooding occurred in a broad band 200 miles north and 100 miles south of a line extending from San Francisco to Sacramento to Lake Tahoe. River systems outside the Central Valley, such as the Russian River in Sonoma County and the Truckee River in Reno, Nevada, also flooded. Within the Central Valley, vast expanses were inundated including 30,000 acres of the Sacramento-San Joaquin Delta and 10,000 acres of agricultural land along the Yuba River as the result of a levee break (DWR 1986a). In addition, 30 mi^2 in and around Linda and Olivehurst along the Yuba Rriver were also flooded (DWR 1986b).

Along the Sacramento River below Shasta Dam, $17.4 million in estimated damage occurred in 1986. Damage totaling $133 million occurred along the Feather, Yuba, and American rivers. However, in the heavily urbanized area along the American River alone, it is estimated that flood damage would have approached $5 billion if Folsom Dam and the river levees had not existed. Despite the 50,000

Table 1. Selected Flood Peaks for 1986, 1997, and 1998 (all units in feet)

Station	Feb. 1998	Jan. 1997	Feb. 1986	Previous Record
Sacramento River				
Above Bend Bridge	27.9	30.6	32.8	36.6 Jan. 1970
Ord Ferry	118.2	118.7	118.3	119.8 Jan. 1970
Colusa	68.3	68.6*	68.0	68.5 Mar. 1983
Fremont	38.5	42.5*	41.7	41.7 Feb. 1986
Sacramento, I St.	25.2	30.4	30.7	30.7 Feb. 1986
Feather River				
Yuba City	54.9	78.2*	76.3	76.3 Feb. 1986
Nicolaus	n/a	50.4*	49.1	49.1 Feb. 1986
American River				
H Street	33.4	42.7	43.4	43.4 Feb. 1986
Cosumnes River				
Michigan Bar	13.2	18.3*	14.8	14.8 Feb. 1986
Tuolumne River				
Modesto	56.6	70.9*	55.2	69.2 Dec. 1950
San Joaquin River				
Newman	64.6	66.1*	64.7	65.9 Feb. 1969

*New Record

(*Source*: DWR 1997b, DWR 1999)

people forced from their homes and the dozen flood-related deaths, the local, state, and federal flood protection facilities largely withstood flows exceeding the system's theoretical capacity (Kelley 1989).

The 1997 Flood

December 1996 was the second wettest December since 1922, when records began for the "Northern Sierra" 8-Station Index, which serves as a wetness index for the northern Sierra Nevada and southern Cascade Mountains of the Sacramento River Basin. Only precipitation for December 1955, also a flood year, is greater in this record (DWR 1996). In addition, December 1996 and January 1997 were the two wettest consecutive months on record, with a combined total of 47.6 inches of precipitation (DWR 1997b). These storms delivered heavy rainfall from Shasta Dam in the north into the southern Sierra, as illustrated by the 12 inches of rainfall at New Melones Dam (Figure 3). Along with the heavy precipitation, a cold storm delivered heavy snowfall to low elevations in December 1996. Snow at the Central Sierra Snow Laboratory (Figure 4) nearly tripled on December 22 and 23. Precipitation was well above normal by Christmas at most northern California locations, and runoff during December approached three times the December monthly average.

A series of storms related to an atmospheric circulation pattern known as the "pineapple express" produced about 40 percent of an average water year's total precipitation (49.8 inches) between December 26 and January 2. Placerville (Figure 5) received 4.4 inches of rain on January 2 and over 12 inches during the period December 27 to January 3. Blue Canyon received over 30 inches of rain, and most of the existing snowpack melted. However, the middle and higher elevation snowpack remained as illustrated by the 84 inches at the Central Sierra Snow Laboratory (Figure 4) on December 30. The Snow Laboratory, at an elevation of 6,950 feet, had a snowpack greater than 66 inches throughout January.

Overall, snow sensors showed nearly as much snow water content after the storms as was present before the storms. When the storms ended in early January, the snowpack was 85 percent of normal for that date at the lower elevations of the northern Sierra, but well above normal at the higher elevations of the central and southern Sierra. Sudden snowmelt was not primarily responsible for 1997

Central Valley flooding. Snowmelt, partly from lower elevations, added approximately 15 percent to runoff, but the bulk of the runoff was from rain (RAC 1997).

Estimated runoff during January was 390 percent of average, probably a record for the month. Ironically, February 1997 runoff was only about 20 percent of average statewide and was one of the driest Februarys on record (DWR 1997b). Usually the Sacramento River Basin or the San Joaquin River Basin experiences flooding separately depending on the type of storm. In 1997, the entire east side of the Valley over both the San Joaquin River and the Sacramento River watersheds was drenched. Table 1 indicates the numerous new records established by the January 1997 storms. Table 2 shows that the unregulated runoff for January 1997 is higher than for February 1986 for both the maximum 1-day estimate and the average 3-day flow estimate.

On December 26, 1996, the U.S. Bureau of Reclamation started releasing water at Folsom Dam on the American River. Maximum outflow peaked at 115,000 cfs, the channels' design capacity, on January 2. The heaviest precipitation fell over the Feather River Basin, rather than the American River Basin, and this proved to be an important factor in Folsom Dam releases remaining below channel capacities (CLAC 1997). The brunt of the storm dropped approximately 15 inches of rain in the Oroville area. The DWR warned that releases from Lake Oroville could exceed channel capacity, threatening major downstream flooding. Inflow peaked at 277,000 cfs on January 1. Peak outflow was maintained at 160,000 cfs, utilizing maximum storage, but avoiding uncontrolled spillway releases that would flood downstream communities. At Sacramento, 80 percent of the flood waters flowed through the Yolo Bypass, with the remainder flowing past the City of Sacramento in the river channel.

The DWR and the Army Corps of Engineers reported that some of the levees that failed along the Sacramento River in January 1997 had been recently inspected and appeared to be well maintained. This included a levee along the Sutter Bypass that broke along a 150-foot section. The majority of levee breaches developed from erosion caused by overtopping because the river exceeded channel capacity (CLAC 1997).

Table 2. Unregulated Runoff at Selected Dams

River	Location	Date	Unregulated Runoff Estimates Maximum 1 Day (cfs)	Unregulated Runoff Estimates Average 3 Day (taf)
Sacramento	Shasta	Feb. 86	126,000	681
		Jan. 97	216,000	1,000
		Feb. 98	60,775	106
Feather	Oroville	Feb 86	217,000	1,113
		Jan 97	298,000	1,392
		Feb 98	57,156	77
American	Folsom	Feb 86	171,000	988
		Jan 97	249,000	977
		Feb 98	45,462	53
Mokelumne	Camanche	Feb 86	28,000	149
		Jan 97	76,000	233
		Feb 98	3,852	8
Stanislaus	New Melones	Feb 86	40,000	246
		Jan 97	73,000	298
		Feb 98	11,168	14
Tuolumne	New Don Pedro	Feb 86	53,000	294
		Jan 97	120,000	248
		Feb 98	23,077	27
San Joaquin	Friant	Feb 86	33,000	176
		Jan 97	77,000	313
		Mar 98	13,663	19

(*Sources*: RAC 1997; NOAA 1986,1996,1997; NOAA 1998)

On the San Joaquin River system, the runoff volume exceeded the flood control capacity of Don Pedro Reservoir on the Tuolumne River and Millerton Reservoir on the upper San Joaquin River. A major constraint in the San Joaquin system is a flow limit of 9,000 cfs at the Ninth Street Bridge in Modesto. Usually, Don Pedro Reservoir stores most of the water inflow and releases it after the storm passes. On December 26, flood storage space was already encroached upon by 16 percent; on January 2 Don Pedro reached maximum capacity and water spilled over the emergency spillway. Releases from the dam measured 59,000 cfs, over six times the in-stream flow capacity at the Ninth Street Bridge (CLAC 1997). Areas of new urban development, not previously viewed as flood-prone, became under these circumstances the focus of severe flooding.

Reservoir releases, especially those from Friant Dam on the upper San Joaquin system, brought most channel flows up to maximum design capacity (CLAC 1997). Along with northern portions of the Central Valley, there was severe flooding along the Tuolumne River, Stanislaus River, and the San Joaquin River and its tributary, the Merced River. Nearly 300 mi^2 of agricultural land was flooded (RAC 1997). The San Joaquin River narrows as it enters the Delta. This contributed to high water flows and numerous levee breaks. Thirty-six Federal Project levees failed on the San Joaquin River system and significant damage such as wave wash and sloughing occurred on others, causing severe damage and threatening their integrity. At least 12 Federal Project levees broke on the Sacramento River system. In addition, many boils and sink holes, erosion, sloughing, and heavy seepage occurred (RAC 1997). Delta islands for the most part were spared because levee failures in tributary areas relieved pressure and reduced river stages as the water moved downstream. Nevertheless, Central Valley flood damage reached $1.8 billion (Null 1999b).

In post-flood evaluations, it was concluded there was no evidence to suggest major communication lapses between federal, state, and local agencies impaired the 1997 flood response nor that dams had been operated independently of system-wide considerations. In addition, no evidence indicated levee failures could be attributed to application of endangered species or environmental quality regulations (CLAC 1997).

ENSO and California

An ENSO is characterized by temporary warming of the surface waters in the eastern and central equatorial Pacific Ocean related to a weakening of the trade winds. ENSO has become synonymous with large-scale, climatically significant, warm events, occurring at intervals of about 2 to 7 years. During strong ENSOs, mid-latitude low pressure systems tend to be more vigorous than normal in the eastern North Pacific and southern United States.

In California, an ENSO year usually means a wet winter, with flooding in coastal areas and lower elevations as numerous storms pass through the region (Monteverdi and Null 1998). Rains tend to start earlier in the fall, and once soils are saturated there is a greater risk of increased runoff, flooding, and landslides, especially in historical problem areas where land movement is reactivated. In the Sacramento-San Joaquin Delta, there is increased risk of wave damage during high tides and increased levee problems. Although major floods on the large rivers draining the Sierra Nevada are not always associated with ENSO events, the prospect of an ENSO year raised concerns about damage to both public and private property. Heavy rains during the 1982–83 ENSO caused about $30 million of property damage in San Mateo County alone. In comparison, the Loma Prieta earthquake caused about $20 million in property damage in the County (Wilson 1998).

The most commonly used ENSO indices indicated the 1998 event reached unusual strength by April or May 1997 and continued at high levels until April or May 1998 (Wolter and Timlin 1998). The 1997–1998 winter season was one of the wettest on record across California, with typically twice the normal precipitation. San Francisco experienced its second wettest rainfall season (47.22 inches) in the past 149 years. Perhaps more importantly, there was a record 119 days with measurable rainfall, providing a moisture input to streams and soil, with no opportunity for drying between storms (Null 1999a). The 1998 ENSO brought severe winter storms and flooding to many parts of California, starting about February 2. By the end of February, 27 California counties were declared federal disaster areas and were eligible for federal aid. Approximately $550 million in flood and storm damage occurred statewide.

The 1998 ENSO and the Central Valley

Coming on the heels of two major Central Valley floods in 12 years, there was considerable public concern about the possible effects of ENSO in 1998 and considerable media attention was directed toward its possible impact on the Central Valley. Residents were braced for the possibility that ENSO would bring another season of serious floods. Instead, 1998 was a quiet flood year in the Central Valley.

The absence of extensive 1998 Central Valley floods was not due to a lack of precipitation. At Davis, January 1998 was the 25th wettest in the record and February 1998 was the wettest for that month. Rain occurred at Davis on all but 3 of the first 24 days of February. Rainfall in January and February 1998 was greater than in either 1986 or 1997 at Redding (Figure 2), New Melones Dam (Figure 3), and Placerville (Figure 5). The comparatively drier conditions in December 1997 at all stations appear to have been an important characteristic in the absence of widespread 1998 Central Valley flooding.

River stage data (Table 1) and the unregulated runoff (Table 2) at dams clearly indicate the non-flood character of the 1998 season, in contrast to the previous year and to events elsewhere in California. The discharge peaks at Ord Ferry and Colusa on the upper Sacramento River probably are related to reservoir releases in response to an expected deluge that never arrived. Unregulated runoff at reservoirs for 1998 is strikingly small compared to 1986 and 1997.

Central Valley flooding that occurred during 1998 was localized. Merced, San Joaquin, Sutter, and Yolo counties were eligible for federal disaster relief due to flooding. Redding and Sacramento were among the Central Valley cities that experienced road closures due to water over roads and highways. The Federal Emergency Management Agency and the Governor's Office of Emergency Services issued warnings for residents to be alert to conditions and to be prepared to evacuate flood-prone areas. However, flood-producing storms did not visit the Central Valley. Data for the Central Sierra Snow Laboratory (Figure 4) illustrates that 1998 snow to support melt and runoff was as little as one-third the amount present in 1986 or 1997. For the Central Valley, the great 1998 ENSO flood was a nonevent.

Conclusions

The 1986 Central Valley flood was a rain-induced event resulting from heavy precipitation concentrated in early February, particularly at the most northern Central Valley stations. Precipitation was focused on the Sacramento River system, where flood control facilities are designed for rainfall-induced floods.

Despite initial assumptions that rain falling on snow triggered 1997 Central Valley flooding, this was also a rain-induced flood. Precipitation was significantly greater than during the 1986 flood, and the precipitation occurred over both the Sacramento and the San Joaquin basins. San Joaquin Basin flood control facilities, designed to accommodate snowmelt, were unable to handle rapid inflows of rainfall-induced runoff in 1997. Design problems, such as the bottleneck at the Ninth Street Bridge in Modesto, levee structure and maintenance problems, and channel capacity limits, intensified 1997 flood problems.

Although February 1998 produce record precipitation amounts at many stations, it produced localized rather than widespread Central Valley flooding. Significantly less snow was present in the Sierra Nevada to contribute melt to stream flow that would have exacerbated the heavy rainfall contributions.

The 1986 and 1997 floods reminded the public of the potential for flooding in the Central Valley. Enhanced forecast capabilities and media attention on the 1998 El Niño highlighted the possibility that 1998 might be another flood year. This awareness encouraged public officials to undertake levee maintenance, dredging, and other projects designed to improve water flow through the channels. In hindsight, public fears for the 1998 ENSO flood in the Central Valley were exaggerated. However, personal and civic preparedness is not wasted simply because a disaster is averted.

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