STREAMFLOW GAINS AND LOSSES AND SELECTED FLOW CHARACTERISTICS OF COTTONWOOD CREEK, NORTH-CENTRAL CALIFORNIA, 1982-85

By James C. Blodgett, James R. Walters, *and* James W. Borchers

---

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 92-4009

Prepared in cooperation with the

U.S. ARMY CORPS OF ENGINEERS

6228-07

Sacramento, California
1992

U.S. DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., *Secretary*

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, *Director*

For sale by the Books and
Open-File Reports Section
U.S. Geological Survey
Federal Center, Box 25425
Denver, CO 80225

For additional information write to:
District Chief
U.S. Geological Survey
Federal Building, Room W-2233
2800 Cottage Way
Sacramento, CA 95825

CONTENTS

FIGURES

TABLES

Conversion Factors and Vertical Datum

Conversion Factors

Multiply	By	To obtain
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per month (acre-ft/mo)	0.001233	cubic hectometer per month
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.59	square kilometer

Vertical Datum

Sea Level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

STREAMFLOW GAINS AND LOSSES AND SELECTED FLOW CHARACTERISTICS OF COTTONWOOD CREEK, NORTH-CENTRAL CALIFORNIA, 1982-85

By James C. Blodgett, James R. Walters, *and* James W. Borchers

Abstract

An 18-mile-long reach of Cottonwood Creek near Cottonwood, California, was studied to document streamflow characteristics for irrigation supply, effect of ground-water contribution, and possible flood control. Studies of streamflow data indicate that the primary source of flow gains of Cottonwood Creek downstream from the mouth of South Fork Cottonwood Creek is from tributary inflow and irrigation-return flow from canals.

Regression equations were prepared on the basis of streamflow data for gaging stations for annual, summer, and winter seasons for three reaches of Cottonwood Creek and South Fork Cottonwood Creek. These regression equations indicate that varying rates of flow gains and losses depend on the magnitude of streamflow and on the season.

Analyses of low-flow frequency relations for durations of 1, 7, and 30 days indicate that flows in South Fork Cottonwood Creek are less affected by contributions from ground water than are flows for other reaches in the study area. The reach downstream from the mouth of South Fork Cottonwood Creek gains more flow during the summer than during the winter.

The largest floods on Cottonwood Creek during the period of record (1941-86) were during January 1974 and February-March 1983. The January 1974 flood had the largest 1-day flow volume on record; the February-March 1983 flood had the largest 3- and 8-day volumes on record.

INTRODUCTION

In the early 1980's, the U.S. Army Corps of Engineers began a study of the feasibility of constructing several dams for flood control and irrigation storage on Cottonwood Creek near Cottonwood, California (fig. 1). Damsites that were considered are Dutch Gulch, which would be built on Cottonwood Creek about 10 mi upstream from the confluence with South Fork Cottonwood Creek, and Tehama, which would be built on South Fork Cottonwood Creek, about 7 mi upstream from the confluence with Cottonwood Creek (fig. 1).

There is concern that proposed dams could alter flood characteristics and that seepage from the proposed reservoirs could raise ground-water levels and increase streamflow in downstream reaches of Cottonwood Creek. Prior to this study, the network of gaging stations along Cottonwood Creek was inadequate to assess flow and possible influences of ground water on flows in downstream reaches. In addition, low-flow data were not available for tributaries to Cottonwood Creek and South Fork Cottonwood Creek.

As part of a study beginning in 1982, the U.S. Geological Survey, in cooperation with the U.S. Army Corps of Engineers, analyzed the hydrology of the Cottonwood Creek area. Data from several new gaging stations and observation wells, as well as periodic measurements at miscellaneous sites, were obtained so that a comprehensive study of streamflow and ground-water levels of selected downstream reaches of Cottonwood Creek could be made.

This report presents a description of the geohydrologic characteristics of the study area and discusses the seasonal variation of flow gains and losses and the frequency of low flow and floodflow for selected reaches of Cottonwood Creek. Data collected between 1940 and 1985 from stream-gaging stations and miscellaneous-measurement sites were used to estimate the inflow from tributaries to North, Middle, and South Forks Cottonwood Creek and the main channel of Cottonwood Creek. For gaging stations with adequate records, the frequency relations for low flows and floodflows were determined. These data, when combined with a statistical analyses of flow gains and losses for selected reaches, will permit comparisons of flow conditions for both before and after possible regulation. These data complement information on ground-water conditions in Cottonwood Creek basin previously collected and analyzed by the U.S. Geological Survey (Fogelman and Evenson, 1985; Evenson and Kinsey, 1985; and Johnson and others, 1989).

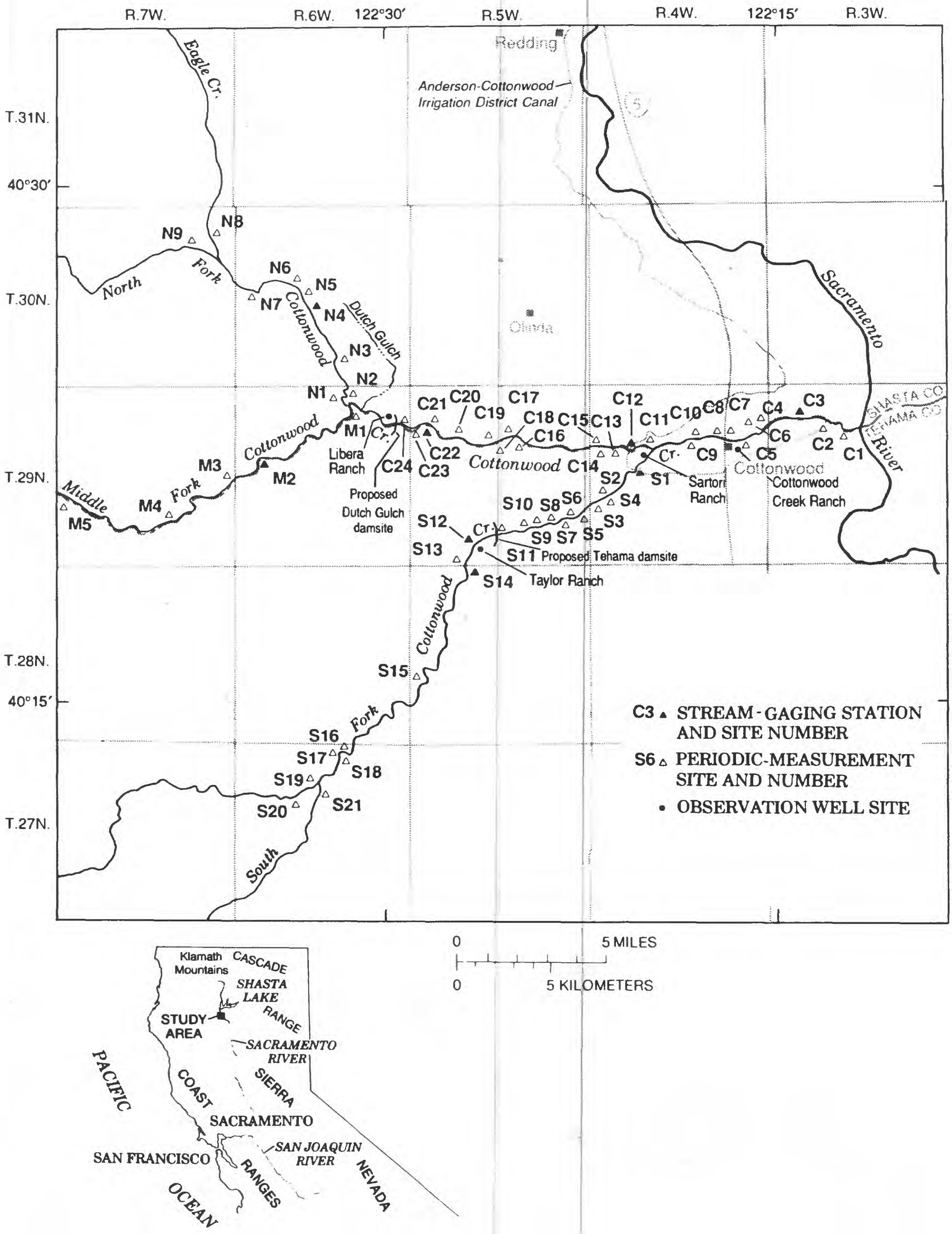

Figure 1. Cottonwood Creek study area and location of streamflow-measuring sites, observation-well sites, and proposed damsites.

DESCRIPTION OF STUDY AREA

Cottonwood Creek (drainage area, 930 mi^2) is about 100 mi northwest of Sacramento (fig. 1). The lower two-thirds of the Cottonwood Creek basin, including proposed damsites, lies in dissected uplands of the Central Valley geomorphic province (Poland and Evenson, 1966). Upstream parts of the Cottonwood Creek basin include steeper and more rugged terrain in the Coast Ranges and the Klamath Mountains (fig. 1).

Annual precipitation in the study area is about 37 in. (Pierce, 1983). Most of this precipitation falls between October and May as rain, although snow is common in the uppermost parts of the Cottonwood Creek drainage area. Winter temperatures are moderate; summer temperatures are high, commonly more than 100°F.

The dominant land use in the lower part of the Cottonwood Creek basin is cattle ranching, followed by cultivation of alfalfa, grain, field crops, and deciduous orchards (California Department of Water Resources, 1960). Pasturelands commonly are flood irrigated during the summer months. Irrigation water is diverted from the Anderson-Cottonwood Irrigation District Canal (fig. 1), pumped from wells, or diverted from stream channels.

GEOHYDROLOGIC SETTING

The ground-water reservoir in Cottonwood Creek basin consists of the unconsolidated continental sediments of the Tehama and Red Bluff Formations of Pliocene and Pleistocene ages, respectively, and the overlying Quaternary alluvium (fig. 2). The Tehama Formation is a clastic wedge of fluvial sediments deposited by coalescing alluvial fans that are thinnest to the west and thicken, due to subsidence during deposition, toward the center of the ancient Sacramento Valley to the east (Russell, 1931); the formation may be as thick as 2,500 ft near the valley trough. The Nomlaki Tuff Member, a unique horizon marker in the Tehama Formation, defines an eastward dip of about 1° for the Tehama Formation (U.S. Bureau of Reclamation, 1968).

In the study area, the Great Valley sequence outcrops to the west, underlies the water-bearing deposits (fig. 2), and is considered non-water bearing. The Great Valley sequence here consists of Pre-Cenozoic consolidated to semiconsolidated marine and nonmarine rocks (Norris and Webb, 1976).

Helley and Jaworowski (1985) described the top of the Tehama Formation as a pediment, a planar erosional surface, gently sloping from the Coast Range foothills on the west to the local base level of the Sacramento River near the center of the ancient Sacramento Valley. This erosional surface is mantled by as much as 40 ft of bright red sandy and silty gravel of the Red Bluff Formation and was deformed by mild uplift and folding during the Pleistocene Epoch. In most areas north of Cottonwood Creek, the Red Bluff Formation overlies the Tehama Formation. South of Cottonwood Creek, much of the Red Bluff Formation has been eroded, following mild uplift in the late Cenozoic, exposing the underlying Tehama Formation.

Steele (1980) differentiated five regional stream terraces in the northwestern Sacramento Valley that postdate the Red Bluff Formation and range in age from 4,000 to more than 250,000 years. The oldest terraces are topographically highest. The youngest terraces are lower and generally parallel the Holocene stream channel and fluvial deposits of Cottonwood Creek and its tributaries.

Pierce (1983) described the terrace deposits as moderately to highly permeable. Steele (1980) described many terraces, cut into the bedrock and covered by a veneer of stream deposits that seldom exceed the depth of flood scour at the time of their formation, as "strath terraces," which probably store negligible quantities of water. "Fill terraces" (Steele, 1980) are preserved stream terraces cut into the older unconsolidated alluvial fill along a stream. "Fill terraces" and Holocene stream-channel deposits include substantial volumes of alluvium that store ground water that interacts with streamflow in the Cottonwood Creek basin.

Nonmarine terrace deposits and the Holocene stream channel and fluvial deposits are mapped as a single unit--Quaternary alluvium. Generally, the Quaternary alluvium is less than 50 ft thick in the Cottonwood Creek area and thickens toward the mouth of the stream.

The Tehama Formation contains the principal water-bearing sediments from which most ground water in the area is withdrawn. Most wells are cased through the Quaternary alluvium and are less than 600 ft deep (Johnson and others, 1989). The eastward-flowing Cottonwood Creek drainages generally cut across the lines of strike of the gently eastward-dipping beds of the Tehama Formation and are a source of recharge to the more permeable beds (U.S. Bureau of Reclamation, 1968).

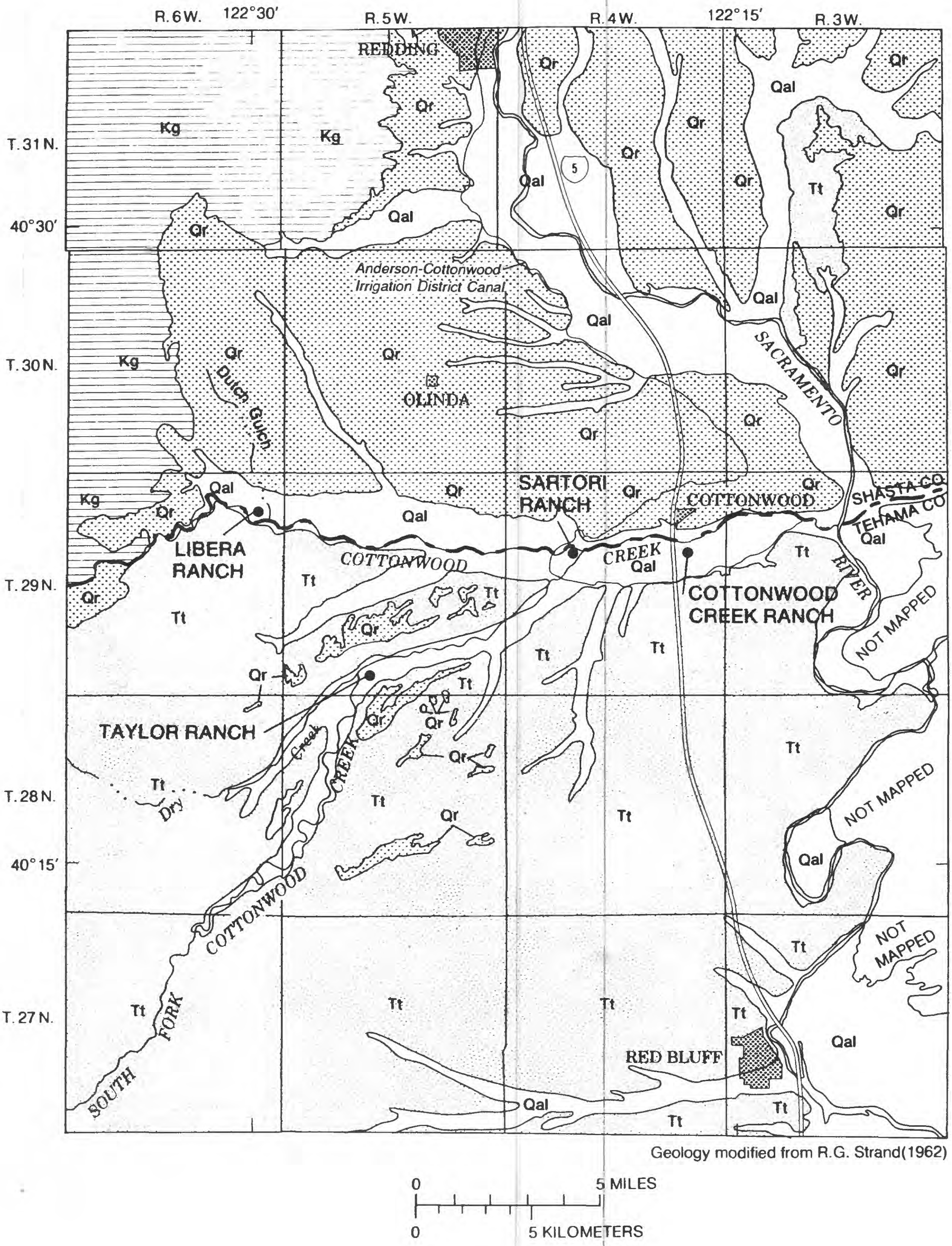

Figure 2. Geology of study area.

SOURCES OF DATA

Each gaging station and periodic-measurement miscellaneous site was given a designation based on the stream name and the number of sites upstream from the mouth (fig. 1). The station or miscellaneous site number, period of record, and drainage area are given in table 1. Ground-water levels were monitored at four observation sites near Cottonwood Creek and South Fork Cottonwood Creek (figs. 1 and 2). Water-level data for the wells at these sites are presented in Johnson and others (1989). The only interbasin transfer to Cottonwood Creek is by the Anderson-Cottonwood Irrigation District Canal (fig. 1), which delivers an average of about 18,000 acre ft/mo to the basin during the irrigation season (March through September) (Anderson and others, 1990).

CONTINUOUS RECORDS AT GAGING STATIONS

Continuous streamflow records are available for five U.S. Geological Survey gaging stations operated through the 1985 water year (Fogelman and others, 1984, 1985, 1986; and Mullen and others, 1987) and one gaging station discontinued in 1978 that was operated by California Department of Water Resources (table 1). Three gaging stations were operated during water year 1986. A water year begins October 1 and ends September 30; for example, the 1985 water year ended September 30, 1985.

Records for the gaging station at South Fork Cottonwood Creek near Cottonwood (S14) were not used in the analysis of low-flow characteristics because data collected by the California Department of Water Resources were not readily available for analysis. The stations, Cottonwood Creek above South Fork Cottonwood Creek, near Cottonwood (C12) and South Fork Cottonwood Creek at Evergreen Road, near Cottonwood (S1), were established in 1982 as part of this study.

PERIODIC MEASUREMENTS AT MISCELLANEOUS SITES

Beginning in May 1982 and continuing through 1985, about 30 periodic measurements of inflow (table 2) were made about once a month at miscellaneous sites on Cottonwood Creek, South Fork Cottonwood Creek, and their tributaries. The criteria for selecting miscellaneous sites included (1) locations at the mouths of tributaries to determine surface inflow, (2) locations on Cottonwood Creek or South Fork Cottonwood Creek to define those reaches between sites that had large gains (inflow) or losses (outflow), and (3) easy access. Measurements made during the winter were timed to avoid peak-flow conditions because (1) data indicating winter low-flow conditions in a reach were needed to compare changes in flow regime with gains or losses that occurred during the summer, and (2) wading measurements could not be made during high flows at many sites. These miscellaneous sites were selected so gaining and losing reaches could be identified, and tributary inflow could be measured at the mouths of all tributaries. During the summer when precipitation was low, the tributaries dried up and streamflow was composed of inflow from the upstream reaches, discharge from the ground-water system (base flow), or a combination of base flow and seepage from irrigated fields and irrigation canals. The interaction of surface water with base flow was estimated by deducting tributary inflow into each reach.

Most precipitation falls during the winter; however, streamflow measurements at miscellaneous sites during this period were timed to lag peak flows by several days. Therefore, streamflows measured during the winter at miscellaneous sites represent higher base flow due to elevated ground-water levels, subsequent increased base flow to streams, and some inflow from tributaries. Data from high and low base-flow periods were used to describe the seasonal interaction of surface and ground water within each reach.

EXPLANATION

Qal	Alluvium	Holocene	QUATERNARY
Qr	Red Bluff Formation	Pleistocene	QUATERNARY
Tt	Tehama Formation	Pliocene	TERTIARY
	Unconformity		
Kg	Great Valley sequence		CRETACEOUS

——— CONTACT

● WELL LOCATION

Table 1. Gaging stations and periodic-measurement sites in the Cottonwood Creek basin

[Location shown in figure 1. Information in parentheses following station name indicates continuous U.S. Geological Survey gaging station number, period of record, and drainage area. mi^2, square mile]

Station or site name	Site No.
Cottonwood Creek	
Cottonwood Creek at mouth	C1
Patterson Creek on J.B. Ranch	C2
Cottonwood Creek near Cottonwood (11376000, 10-1-40 to present; 927 mi^2)	C3
Cottonwood Creek above powerlines	C4
Tributary at Holiday Ranch	C5
Tributary above Interstate Highway 5, on left bank	C6
Ditch No. 1 at Clark Ranch	C7
Ditch No. 2 at Clark Ranch	C8
Hooker Creek at Draper Road	C9
Cottonwood Creek below South Fork	C10
Tributary at South Fork Cottonwood Creek, on left bank	C11
Cottonwood Creek above South Fork Cottonwood Creek, near Cottonwood (11375815, 6-22-82 to 9-30-85; 478 mi^2)	C12
Tributary at Moore Ranch (Gas Point Road)	C13
Evergreen Road Creeks, Nos. 1-4	C14
Cottonwood Creek at Joanne Lane	C15
Little Dry Creek at Peterson Ranch	C16
Dry Creek below Steele Ranch	C17
Cottonwood Creek at Steele Ranch	C18
Antelope Creek at Meadow Oak Lane	C19
Tributary at Ponder Way	C20
Tributary at Mansee Drive	C21
Cottonwood Creek near Olinda (11375810, 8-16-71 to present; 395 mi^2)	C22
Tributary at Corkscrew Ranch, on right bank	C23
Dutch Gulch at Gas Point Road	C24
South Fork Cottonwood Creek	
South Fork Cottonwood Creek at Evergreen Road, near Cottonwood (11375900, 6-22-82 to 9-30-85; 397 mi^2)	S1
South Fork Cottonwood Creek near Bowman Store	S2
Tributary at Bowman Store	S3
Eighmy Road Creeks, Nos. 1-6	S4
Pine Creek at Bowman Road	S5
South Fork Cottonwood Creek above Pine Creek	S6
Mitchell Gulch at Bowman Hall	S7
Tributary below Shelter Haven Court	S8
Tributary below Farquhar Road, on left bank of South Fork Cottonwood Creek	S9
Tributary at Farquhar Road, on left bank of South Fork Cottonwood Creek	S10
South Fork Cottonwood Creek at Farquhar Road	S11
South Fork Cottonwood Creek near Olinda (11375870, 11-1-76 to present; 371 mi^2)	S12
Dry Creek near Olinda	S13
South Fork Cottonwood Creek near Cottonwood (11375820[1], 10-1-62 to 9-30-78; 217 mi^2)	S14
South Fork Cottonwood Creek at Highway 36	S15

See footnote at end of table.

Table 1. Gaging stations and periodic-measurement sites in the Cottonwood Creek basin--*Continued*

Station or site name	Site No.
South Fork Cottonwood Creek--*Continued*	
South Fork Cottonwood Creek below Wildhide Gulch	S16
Wildhide Gulch	S17
Red Bank Gulch	S18
Unnamed tributary	S19
Cold Fork at Vestal Road	S20
South Fork Cottonwood Creek at Vestal Road	S21
Middle Fork Cottonwood Creek	
Middle Fork Cottonwood Creek above North Fork Cottonwood Creek	M1
Middle Fork Cottonwood Creek near Ono (11374400, 1956-75, 1977-79; 249 mi^2)	M2
Middle Fork Cottonwood Creek above Hightower Gulch	M3
Middle Fork Cottonwood Creek below Wiley Flat Gulch	M4
Middle Fork Cottonwood Creek near Chickabally Mountain	M5
North Fork Cottonwood Creek	
Crow Creek	N1
North Fork Cottonwood Creek above Crow Creek	N2
North Fork Cottonwood Creek at Gas Point	N3
North Fork Cottonwood Creek near Igo (11375700, 1956-80; 88.7 mi^2)	N4
North Fork Cottonwood Creek below Huling Creek	N5
Huling Creek at North Fork Cottonwood Creek	N6
North Fork Cottonwood Creek below Bee Creek	N7
Eagle Creek (discontinued 6-1-84)	N8
North Fork Cottonwood Creek below Rector Creek	N9

[1]Gaging station operated by California Department of Water Resources.

Surface-water inflow from tributaries in the study reaches was measured at various times throughout the year. The average inflow ranged from 0 to 4.7 percent of the main-channel flow at the gaging stations for the study reaches (table 2). These data also indicate that, as a percentage of the flows in reach S12 to S1 on South Fork Cottonwood Creek, inflow is negligible for summer and winter. For reach C22 to C12, Cottonwood Creek above South Fork Cottonwood Creek, the similar percentages of inflow for summer and winter, 4.6 and 4.7 percent (table 2) are related to consistently proportional amounts of natural inflow from tributary streams. The high rate of inflow (4.1 percent) for summer, compared with the 1.8 percent for winter in reach (C12+S1) to C3, Cottonwood Creek above South Fork Cottonwood Creek, near Cottonwood, plus South Fork Cottonwood Creek at Evergreen Road, near Cottonwood, to Cottonwood Creek near Cottonwood (table 2), is attributed to return flow from the Anderson-Cottonwood Irrigation District Canal and infiltration of ground water originally applied as irrigation water upslope from the reach.

STREAMFLOW GAINS AND LOSSES

In this report, a gaining reach is defined as one in which the flow increases in a downstream direction as a result of in-channel flow, tributary inflow, ground-water inflow, or precipitation. A losing reach, defined as one in which the flow decreases in a downstream direction, is when a stream is subject to high rates of evapotranspiration or is contributing to ground water. As such, flow gains and losses in a reach represent the net effect of all hydrologic factors affecting flow.

MONTHLY FLOW DATA

The seasonal variation of flow gains and losses throughout the study area was determined by using monthly flow data obtained at gaging stations C3, C12, C22, S1, and S12 (fig. 1). The seasonal variation of monthly flow at station C3, Cottonwood Creek near Cottonwood (table 3), is indicative of the combined effect of in-channel flow, precipitation, evapotranspiration, tributary inflow, and ground-water inflow/outflow measured in the study reaches.

To evaluate the cumulative effects on streamflow of irrigation-return flow (drains), irrigation diversions, canal seepage, and evapotranspiration, each year was divided into summer and winter seasons. Low flow

Table 2. Surface-water inflow for selected reaches of Cottonwood Creek

[Location shown in figure 1. Site names given in table 1. Average flow at gaging station coincides with time when periodic measurements of tributaries were made; ft^3/s, cubic foot per second]

Season	Site No.	Average flow (ft^3/s)	Number of periodic measurements at sites in reach	Average inflow in reach (ft^3/s)	Percentage of average flow at gaging station
			Reach C22 to C12		
Annual	C22	885	33	27.1	3.1
Summer	C22	271	17	12.5	4.6
Winter	C22	912	16	42.6	4.7
			Reach S12 to S1		
Annual	S12	206	39	.38	.18
Summer	S12	100	18	.00	.00
Winter	S12	296	21	.71	.24
			Reach (C12+S1) to C3		
Annual	C3	1,010	26	25.1	2.5
Summer	C3	584	14	[1]23.7	4.1
Winter	C3	1,510	12	[2]26.8	1.8

[1]Equals 1,410 acre-feet per month.
[2]Equals 1,600 acre-feet per month.

Table 3. Seasonal variation of flow at gaging station Cottonwood Creek near Cottonwood (C3)

[Location shown in figure 1. Average annual flow 1940-85, 54,000 acre-feet per month; average flow, winter season (November-April 1982-85), 137,000 acre-feet per month; average flow, summer season (May-October 1982-85), 19,400 acre-feet per month. Values are in thousands of acre-feet]

Water year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Annual
1982	9.06	88.8	241	136	153	143	162	52.4	22.6	12.9	6.36	6.79	1,034
1983	10.5	36.4	153	278	398	662	183	150	50.9	22.5	10.4	9.76	1,964
1984	11.7	100	33.4	87.8	48	48.5	34.2	22.1	8.51	5.10	4.08	5.82	409
1985	8.86	109	67	25.8	33.9	27.6	37.5	15.2	8.37	3.56	3.10	4.94	345

generally occurred during the summer (May through October), and high flow occurred during the winter (November through April). During some winters, low-flow conditions did occur, such as those measured January 8, 1983, and January 16, 1985. Average flows at gaging station C3 during the winter for 1982-85 were 137,000 acre-ft/mo; average flows during the summer were 19,400 acre-ft/mo (table 3).

Regression equations for estimating average monthly flow for various reaches and seasons, based on streamflow data for gaging stations in Cottonwood Creek basin (table 1), are given in table 4. At gaging station C12, Cottonwood Creek above South Fork, near Cottonwood, only 8 months of data could be obtained during periods of high flow that occur during winter months of November through April for most years. In the development of these regression equations, data for the upstream gaging station were considered the independent variable, and data for the downstream gaging station were the dependent variable. Flow data for gaging stations C22 and S12 were used to estimate flow for periods of missing record at gaging stations C12 and S1.

The regression equations in table 4 were used to estimate the average monthly flow during periods of missing record at gaging stations at the downstream ends of the reaches. Because these regression equations were developed on the basis of streamflow characteristics for present basin conditions, any changes in the basin, such as reservoir construction, will alter the historical flow regime. As such, the regression equations in table 4 could be compared with new regression equations that may be derived on the basis of newly altered basin conditions. However, a comparison of this type requires that the changes in flow regime for the altered basin be larger than the errors inherent in the regression analyses.

Table 4. Regression equations for estimating average monthly flows at gaging stations in the Cottonwood Creek basin for various seasons

[Location shown in figure 1. acre-ft/mo, acre-foot per month]

Reach	Regression equation	Number of months	Flow (acre-ft/mo)		Correlation coefficient, r^2 (percent)
			Maximum	Minimum	
		Annual			
C22 to C12	C12 = -389+1.06 C22	28	60,000	673	99.7
S12 to S1	S1 = -1,632+1.16 S12	39	199,000	1	99.5
(C12+S1) to C3	(C12+S1) = -4,216+0.918 C3	28	109,000	3,560	99.3
		Summer season (May-October)			
C22 to C12	C12 = 124+0.931 C22	20	23,800	673	99.2
S12 to S1	S1 = -8.71+0.903 S12	21	56,900	1	99.9
(C12+S1) to C3	(C12+S1) = -3,772+0.918 C3	20	50,900	3,560	98.7
		Winter season (November-April)			
C22 to C12	C12 = -1,160+1.09 C22	8	60,000	15,400	99.7
S12 to S1	S1 = -2,388+1.18 S12	18	199,000	7,030	99.6
(C12+S1) to C3	(C12+S1) = -2,522+0.965 C3	8	109,800	25,900	98.9

Regression equations in table 4 indicate that variability of flow gains and losses in study reaches is highly dependent on the season and discharge. The reach downstream from the mouth of South Fork Cottonwood Creek [reach (C12+S1) to C3, curve A, fig. 3] is a gaining stream throughout the year on the basis of average annual flows. The reaches upstream from the mouth of South Fork Cottonwood Creek (reach C22 to C12, curve B, and reach S12 to S1, curve C) indicate flow losses when flows are less than about 10,000 acre-ft/mo (fig. 3).

A summary of flow gains and losses by month for the reaches from Cottonwood Creek near Olinda (C22) to Cottonwood Creek above South Fork, near Cottonwood (C12), from South Fork Cottonwood Creek near Olinda (S12) to South Fork Cottonwood Creek at Evergreen Road, near Cottonwood (S1), and from the confluence of Cottonwood Creek and South Fork Cottonwood Creek (C12+S1) to Cottonwood Creek near Cottonwood (C3) is shown in table 5. The data indicate that the reaches Cottonwood Creek above South Fork (C22 to C12) and South Fork Cottonwood Creek above the mouth (S12 to S1) both gain and lose flow, depending on the season. Only the lower reach of Cottonwood Creek [(C12+S1) to C3] consistently indicates a flow gain.

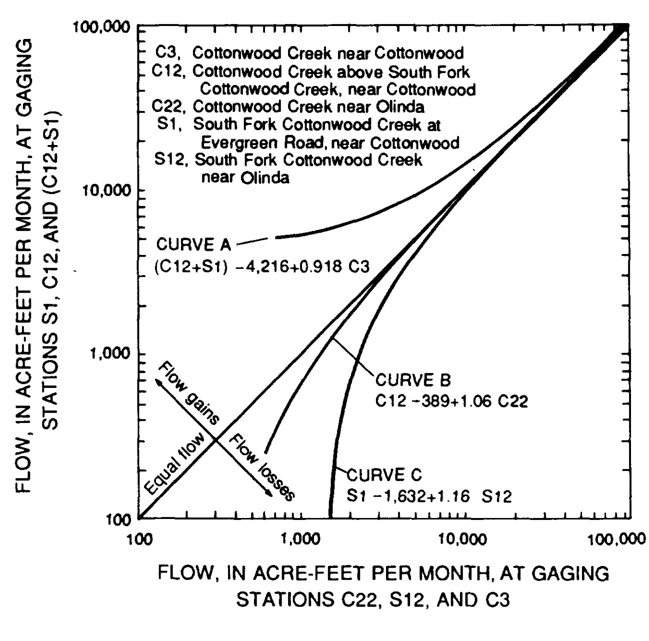

Figure 3. Relation of monthly flow gains and losses for selected reaches of Cottonwood Creek as a function of average annual flows.

Flow gains based on data for 1982-85 in reach C22 to C12 (table 5) show averages of 1,497 acre-ft/mo for the winter months (November through April and using 1985 water-year data for November through February). In the summer months (May through October), the stream loses an average of 181 acre-ft/mo, based on data for 1982-85.

On the basis of data for 1982-85, average gains for reach S12 to S1 were 5,960 acre-ft/mo during the winter months (most of this gain is attributed to runoff, precipitation, and tributary inflow) and average losses were 726 acre-ft/mo during the summer months. In this reach, gains and losses during both seasons are highly dependent on the magnitude of streamflow.

For the reach downstream from the mouth of South Fork Cottonwood Creek [(C12+S1) to C3], the stream gains an average of 4,670 acre-ft/mo during the year (using monthly data for November through February for the 1985 water year). The relations of monthly flow gains and losses for summer and winter seasons in the reach downstream from the mouth of South Fork Cottonwood Creek (C12+S1 to C3) are shown in figure 4. These curves are based on regression equations given in table 4. The apparent increase in inflow during the summer (fig. 4) compared with the winter, which is usually affected by inflow from tributaries, is attributed to irrigation return flow from the Anderson-Cottonwood Irrigation District Canal (fig. 1) during the summer.

DAILY FLOW DATA

The relations of flow gains and losses for selected reaches using mean daily discharge (table 6) were determined by regression analyses based on annual, summer, and winter seasons. The resulting regression equations with correlation coefficients averaging 98 percent are given in table 6 and are shown in graphic form in figures 5 through 7.

The flow curves in figure 5 for the reach between gaging stations Cottonwood Creek near Olinda (C22) and Cottonwood Creek above South Fork Cottonwood Creek, near Cottonwood (C12) indicate that the flow gains or losses throughout the reach do not vary more than about 3 percent of the gaging station flow, regardless of the discharge or season.

Table 5. Flow gains and losses for selected reaches of Cottonwood Creek

[Location shown in figure 1. Values in thousands of acre-feet. Gains are positive; losses are negative. --, no data]

Reach C22 to C12

Water year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1982	--	--	--	--	--	--	--	--	--	0.340	-0.030	-0.150
1983	-0.360	--	--	--	--	--	--	--	-1.44	-1.990	-.320	.350
1984	.230	--	--	--	--	-0.210	0.11	-0.23	.020	-.030	-.106	-.110
1985	-.040	4.60	2.09	0.62	0.88	.45	1.23	.49	.12	-.122	-.236	.00
Average	-0.057	--	--	--	--	0.12	0.67	0.13	-0.433	-0.451	-0.173	0.022

Average annual loss, 668 acre-feet per month; average gain, winter season, 1,497 acre-feet per month; average loss, summer season, 181 acre-feet per month.

Reach S12 to S1

Water year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1982	--	--	--	--	--	--	--	--	--	0.43	-0.112	-0.160
1983	-0.29	-0.45	7.83	24.1	16.90	29.50	2.27	-5.32	-3.29	-.81	-.51	-.200
1984	-.040	11.6	17.6	.55	.94	1.37	-.77	-.52	-.51	-.439	-.064	.001
1985	-.531	4.37	-1.19	-1.62	-.67	-1.86	-3.24	-.51	-.46	-.106	.00	-.148
Average	-0.287	5.17	8.08	7.68	5.72	9.67	-0.58	-2.12	-1.42	-0.231	-0.172	-0.127

Average annual loss, 2,620 acre-feet per month; average gain, winter season, 5,960 acre-feet per month; average loss, summer season, 726 acre-feet per month.

Reach (C12+S1) to C3

Water year	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.
1982	--	--	--	--	--	--	--	--	--	4.58	4.30	5.81
1983	5.84	--	--	--	--	--	--	--	7.10	7.40	4.29	4.71
1984	6.65	--	--	--	--	-0.51	5.85	5.24	2.00	3.44	3.25	4.56
1985	6.05	5.39	9.19	4.39	2.59	2.84	3.88	4.48	4.42	2.94	2.66	3.60
Average	6.18	--	--	--	--	1.16	4.86	4.86	4.51	4.59	3.62	4.67

Average annual gain, 4,670 acre-feet per month; average gain, winter season, not determined; average gain, summer season, 4,738 acre-feet per month.

Flow gain-and-loss curves for the reach between South Fork Cottonwood Creek near Olinda (S12) and South Fork Cottonwood Creek at Evergreen Road, near Cottonwood (S1) (fig. 6) indicate that flow losses occur during all seasons when flows are less than about 300 ft^3/s. Only when flows exceed this amount is there evidence of gaining flows in this reach.

Flow gains for the reach Cottonwood Creek above South Fork Cottonwood Creek (C12) and South Fork Cottonwood Creek at Evergreen Road (S1) and the gaging station Cottonwood Creek near Cottonwood (C3) generally are least during the winter and greatest during the summer seasons (fig. 7). Flow gains during the summer season in this reach average more than winter flow gains for all discharges. No flow losses in this reach have been measured during both winter and summer seasons, indicating that ground water contributes to the stream regardless of possible irrigation seepage or return flows from Anderson-Cottonwood Irrigation District Canal.

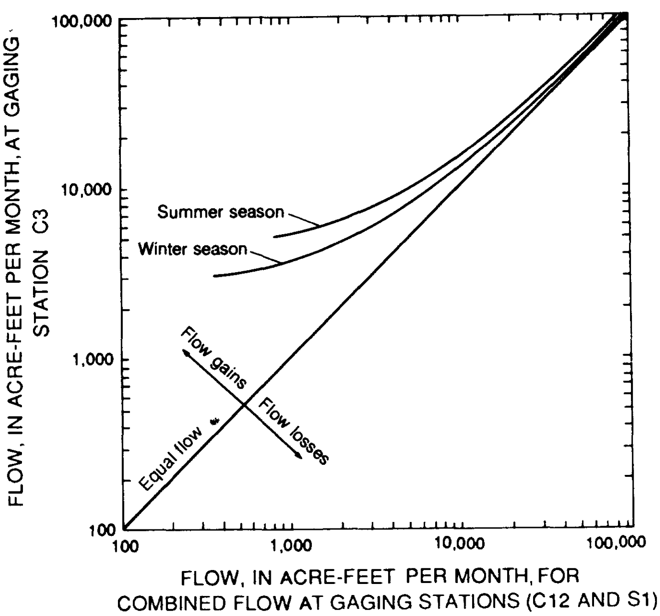

Figure 4. Relation of monthly flow gains and losses for reach Cottonwood Creek above South Fork Cottonwood Creek, near Cottonwood (C12) and South Fork Cottonwood Creek at Evergreen Road, near Cottonwood (S1) to Cottonwood Creek near Cottonwood (C3) as a function of average seasonal flows.

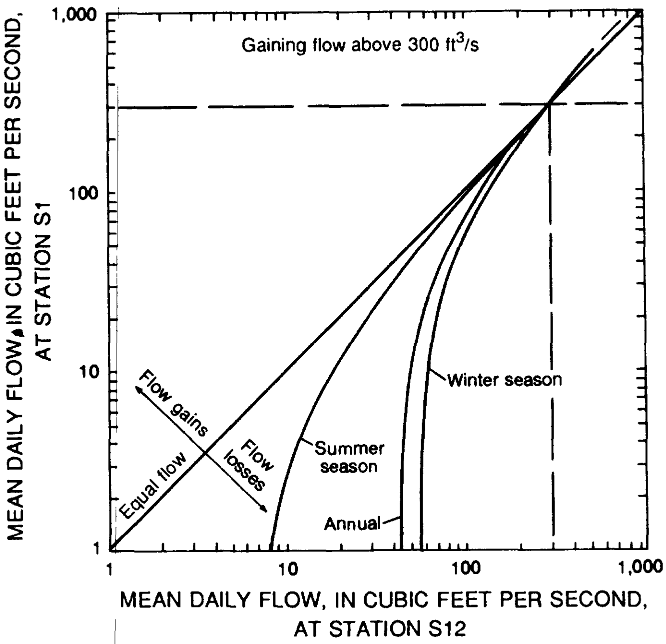

Figure 6. Relation of daily flow gains and losses between gaging stations South Fork Cottonwood Creek near Olinda (S12) and South Fork Cottonwood Creek at Evergreen Road, near Cottonwood (S1).

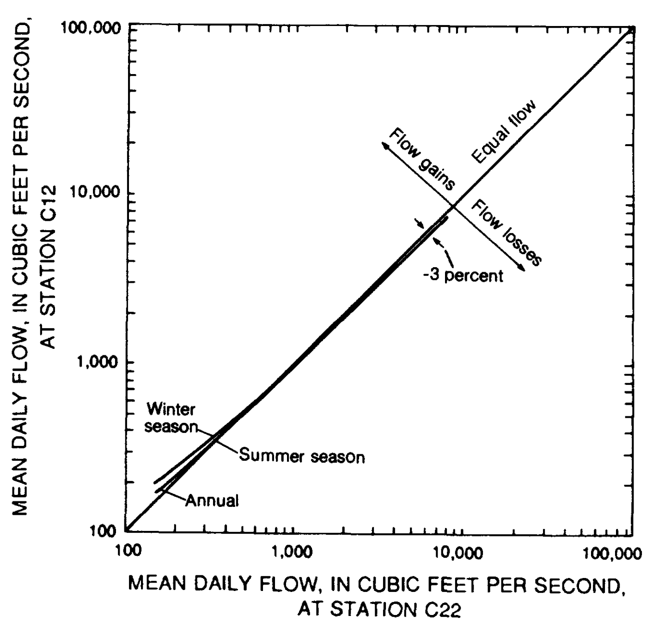

Figure 5. Relation of daily flow gains and losses between gaging stations Cottonwood Creek near Olinda (C22) and Cottonwood Creek above South Fork Cottonwood Creek, near Cottonwood (C12).

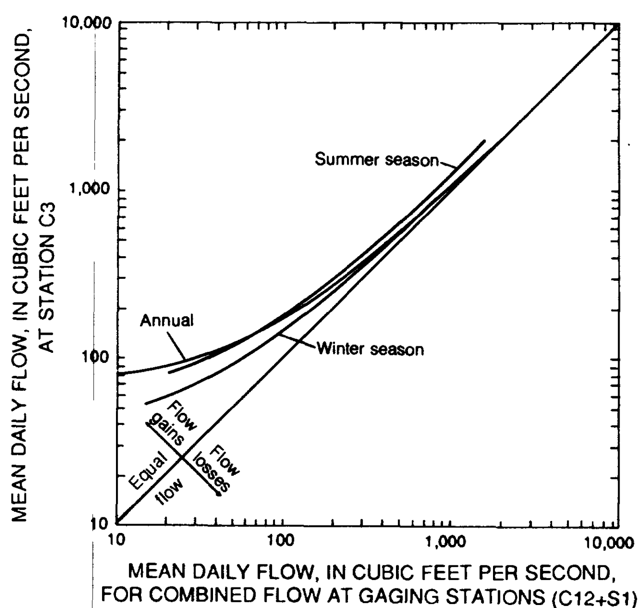

Figure 7. Relation of daily flow gains and losses between combined flows at gaging stations Cottonwood Creek above South Fork Cottonwood Creek, near Cottonwood (C12) and South Fork Cottonwood Creek at Evergreen Road, near Cottonwood (S1) and gaging station Cottonwood Creek near Cottonwood (C3).

Table 6. Regression equations that relate gains and losses between gaging stations in the Cottonwood Creek basin

[Location shown in figure 1. Regression equations based on mean daily discharge at gaging stations. ft^3/s, cubic foot per second]

Reach	Regression equation	Number of measurements	Flow (ft^3/s)		Correlation coefficient, r^2 (percent)
			Maximum	Minimum	
		Annual			
C22 to C12	C12 = 2.69+0.967 C22	967	757	17.6	95.2
S12 to S1	S12 = 43.8+0.830 S1	1,003	672	0	98.4
(C12+S1) to C3	(C12+S1) = -68.4+0.989 C3	682	1,780	62	96.7
		Summer season (May-October)			
C22 to C12	C12 = 1.33+0.941 C22	610	436	15.5	97.0
S12 to S1	S12 = 7.51+1.05 S1	459	575	0	97.5
(C12+S1) to C3	(C12+S1) = -45.3+0.829 C3	413	714	62	92.2
		Winter season (November-April)			
C22 to C12	C12 = 4.75+0.986 C22	315	757	113	95.6
S12 to S1	S12 = 56.6+0.825 S1	544	672	58	98.4
(C12+S1) to C3	(C12+S1) = -34.5+0.960 C3	278	1,720	114	95.4

SURFACE- AND GROUND-WATER INTERACTION

Hydrographs of daily mean discharge (fig. 8) and a review of hydrogeologic data collected (Johnson and others, 1989) reveal some characteristics of the surface- and ground-water interaction in the Cottonwood Creek basin. South Fork Cottonwood Creek at Evergreen Road, near Cottonwood (S1) commonly dries up during the summer. The narrow South Fork Cottonwood Creek valley contains only shallow deposits of alluvium that overlie the Tehama Formation; therefore, it has minimal ground-water storage capacity that might sustain streamflow during periods of no precipitation. For example, for the test hole drilled at Taylor Ranch (fig. 2) the lithologic log described the Tehama Formation as silty, sandy clay that overlies tight clay which in turn overlies a sandy zone from 91 to 101 ft (Johnson and others, 1989). The potentiometric head in the sandy zone was reported between 1.5 and 6.7 ft below the bottom of the South Fork Cottonwood Creek channel from June 1984 through June 1985 (Johnson and others, 1989). The test-hole data indicate that a hydraulic potential exists throughout the year for flow from South Fork Cottonwood Creek to the shallow ground-water system at the Taylor Ranch site. As shown by the relation of flow for this reach (gaging stations S12 to S1, fig. 3), South Fork Cottonwood Creek in the vicinity of Taylor Ranch is considered a losing reach.

The hydrographs for gaging stations C22, C12, and C3 (fig. 8) show that Cottonwood Creek was flowing at these sites even when there was no flow at the gaging station on the South Fork Cottonwood Creek (S1). Some summer baseflow at gaging stations C22, C12, and C3 may be contributed by ground water stored in Quaternary alluvium in the wide Cottonwood Creek Valley.

The ground-water flow in the Quaternary alluvium at Libera Ranch (fig. 2) was toward the stream. Johnson and others (1989) found that ground water tended to move upward from the Tehama Formation

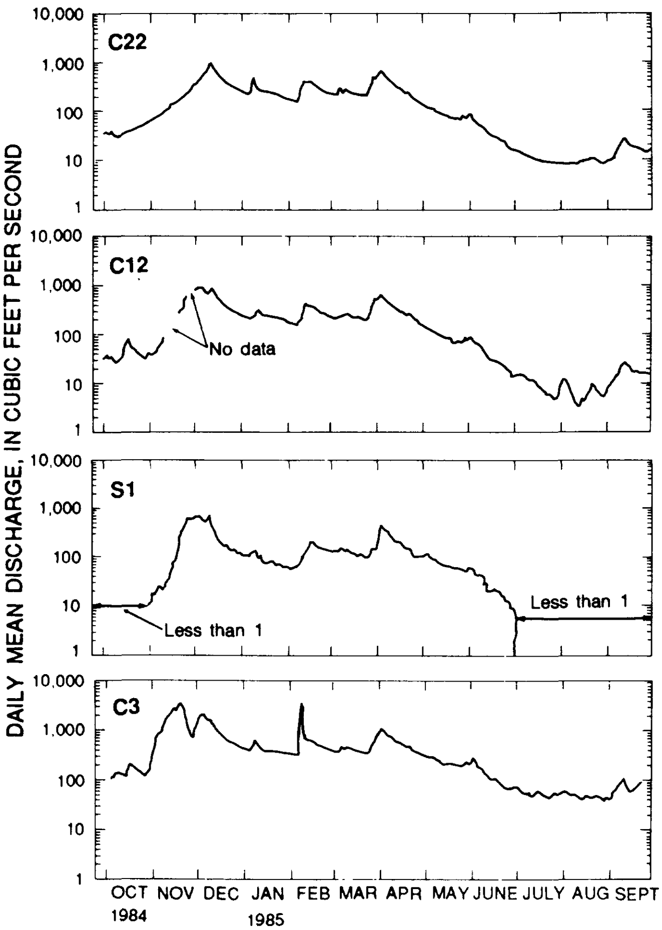

Figure 8. Discharge at selected streamgaging stations for water year 1985. Names of stations given in table 1.

to the overlying alluvial deposits throughout most of the year (June 1984 to June 1985). They also reported that a well screened at 60 ft below land surface in the Tehama Formation flowed year-round. These data indicate that Cottonwood Creek near the Libera Ranch is a gaining stream much of the time.

At Sartori Ranch (fig. 2), the water level in the Quaternary alluvium is below the level of the adjacent stream bottom throughout the year (Johnson and others, 1989). The potentiometric head, at a point 160 ft below land surface in the Tehama Formation, is always at least 10 ft lower than the water level in the alluvium. This indicates that there is potential for surface water to infiltrate to the ground-water system near the Sartori Ranch. The hydrographs and relation of flow losses for the upstream reach (between gaging stations C22 and C12, curve B fig. 3) indicate that the net transfer of water in this reach is from the stream to the ground-water system during much of the year.

During the summer, Cottonwood Creek seems to gain significant flow between stations [(C12+S1) and C3] (figs. 4 and 7). Johnson and others (1989) reported that ground-water levels in the Quaternary alluvium at Cottonwood Creek Ranch are above the stream-channel bottom year-round, as is the potentiometric head in the Tehama Formation measured in a well screened 85 ft below land surface. These data, as well as the relation between flow gains and losses (figs. 4 and 7), indicate that Cottonwood Creek between stations C12 and C3 may gain significant flow from the ground-water system. Water-level contour maps for October 1982 and March 1983 indicate that ground water flows toward and into Cottonwood Creek between the mouth of South Fork Cottonwood Creek and the town of Cottonwood (Fogelman and others, 1985). Ground water discharging to the stream from the alluvium in this area is partly responsible for the increased flow (fig. 7) downstream from the mouth of South Fork Cottonwood Creek.

FLOW CHARACTERISTICS

VOLUME OF FLOW

For average flows of 19,400 acre-ft/mo during the summer at gaging station Cottonwood Creek near Cottonwood (C3) (table 3), the corresponding volume for Cottonwood Creek below South Fork (S1+C12) was about 14,000 acre-ft/mo (see equations in table 4). However, surface inflow from tributaries in this reach during the summer averages about 1,410 acre-ft/mo (23.7 ft^3/s, table 2). Applying a flow-volume budget for this reach, ground-water inflow, which may include irrigation seepage, would be 19,400–14,000–1,410 = 3,990 acre-ft/mo, which is 20 percent of the average monthly summer flow at gaging station Cottonwood Creek near Cottonwood.

LOW-FLOW FREQUENCY

Analyses of low-flow data for the three long-term gaging stations on Cottonwood Creek were made by developing frequency curves for durations of 1, 7, and 30 days, as shown in figures 9-11. The convex shape of the curves for gaging stations C22 and S12 is attributed to losses to ground water and possibly to irrigation pumpage. Lower return periods for a given discharge are smaller for gaging station Cottonwood Creek near Cottonwood (C3) because of probable ground-water discharge to the channel and irrigation-return flow and seepage attributed to the Anderson-Cottonwood Irrigation District Canal (fig. 1). As seen in figure 11, flows at gaging station South Fork Cottonwood Creek near Olinda (S12) less than 1 ft^3/s for periods as long as 30 days have a recurrence interval of about 2 years. However, at gaging station Cottonwood Creek near Cottonwood (C3), low flows of 60 ft^3/s for periods as long as 30 days have a recurrence interval of 2 years; this indicates that low flows are maintained by contributions from ground water. The steep slopes of the curves for South Fork Cottonwood Creek in figures 9-11 indicate that there is less ground water available to maintain flows in the South Fork Cottonwood Creek basin.

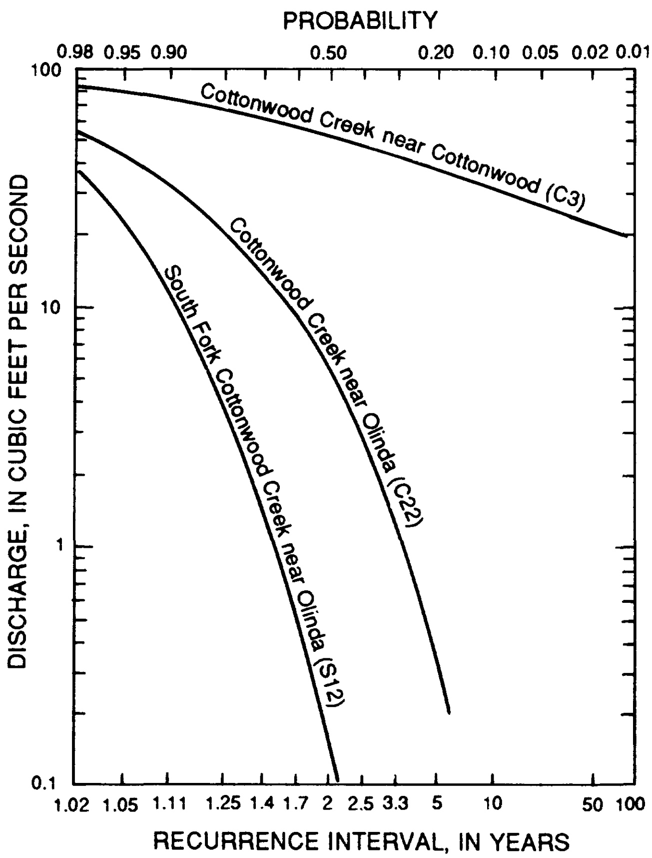

Figure 9. Frequency curve of annual lowest 1-day mean discharge for selected gaging stations.

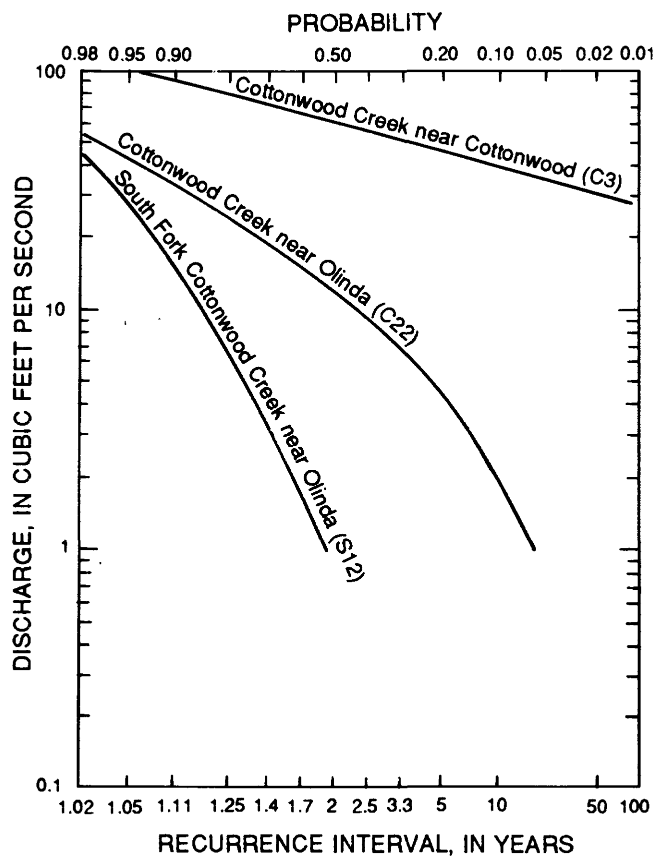

Figure 10. Frequency curve of annual lowest 7-day mean discharge for selected gaging stations.

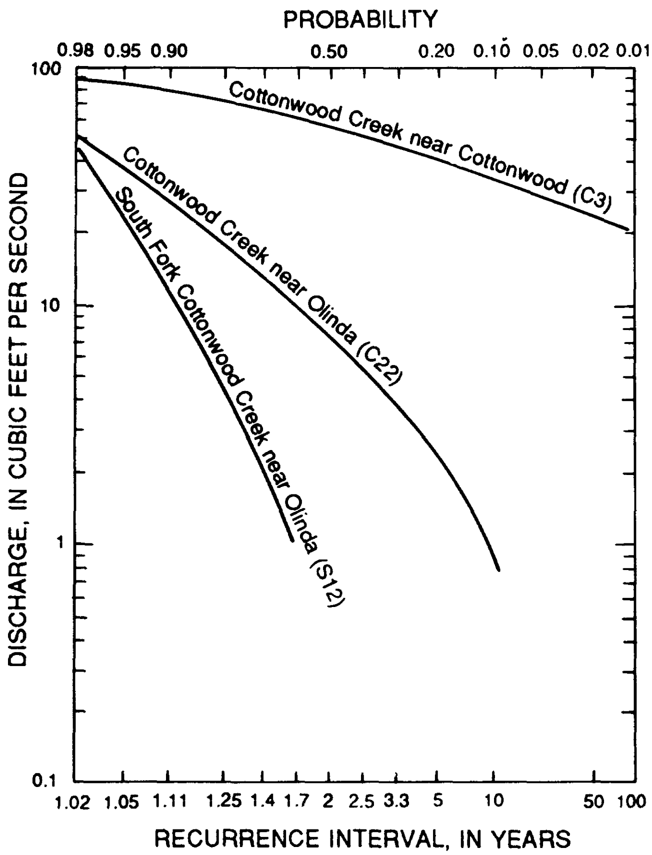

Figure 11. Frequency curve of annual lowest 30-day mean discharge for selected gaging stations.

FLOODFLOW FREQUENCY

Three gaging stations in the Cottonwood Creek basin, C22, S12, and C3, had the most complete records of the six stations used in the study. Annual peak data for the period of record at these stations are shown in table 7. Floodflows at these stations generally are unaffected by regulation or diversion; only during the drought of 1976-77, when annual peaks were very small, were floods possibly affected by diversions. A comparison of the timing of annual peaks at the three stations indicates that the average traveltime for reach C22 to C3 is 4.4 hours, and for reach S12 to C3 is 2.4 hours. The recurrence intervals of selected annual peaks at gaging stations Cottonwood Creek near Olinda (C22) and Cottonwood Creek near Cottonwood (C3) are given in table 8; the frequency analyses are based on procedures given by the U.S. Water Resources Council (1981). The recurrence interval is the average interval of time within which a given size event (flood or low flow) will be equaled or exceeded once (Langbein and Iseri, 1960). The recurrence interval of peak flows for gaging station South Fork Cottonwood Creek near Olinda (S12) was not determined because the length of record is only 10 years. At gaging station Cottonwood Creek near Cottonwood (C3), the floods of February-March 1983 (recurrence interval about 47 years) and January 1974 (recurrence interval about 24 years) are the largest recorded during the 46 years of operation.

Another procedure for evaluating the significance of floods is on the basis of the volume of flow for selected durations. Because major storms and subsequent flood runoff in the Cottonwood Creek basin generally last up to 8 days, intervals of flow used in this study are durations of 1, 3, and 8 days. The 1-day volume may be compared with peak flows. The 3- and 8-day volumes were selected to identify the segment of runoff that is associated with the storm duration.

Flood data for durations of 1, 3, and 8 days at gaging station Cottonwood Creek near Cottonwood (C3) indicate that the floods of January 1974 and February-March 1983 are the largest on record (table 8). For the 8-day volume, the February 1986 flood is the third largest on record and has an 18-year recurrence interval.

Table 7. Annual peak data for the period of record for three gaging stations in the Cottonwood Creek basin

[Location shown in figure 1. ft, foot; ft^3/s, cubic foot per second]

Date	Stage (ft)	Flow (ft^3/s)
Cottonwood Creek near Olinda (C22) (Gage datum 498.01 feet above sea level)		
January 23, 1972	9.02	2,620
January 16, 1973	14.95	10,700
January 16, 1974	21.44	36,900
February 12, 1975	15.59	13,200
February 26, 1976	10.35	4,500
September 19, 1977	7.53	827
January 16, 1978	16.08	13,600
February 20, 1979	11.36	5,580
February 17, 1980	16.73	16,000
February 14, 1981	16.04	14,100
December 19, 1981	19.18	24,300
February 28, 1983	20.19	33,000
December 11, 1983	15.46	15,900
November 27, 1984	11.30	6,040
February 17, 1986	17.86	23,800
South Fork Cottonwood Creek near Olinda (S12) (Gage datum 501.28 feet above sea level)		
March 16, 1977	2.79	486
January 9, 1978	10.86	16,500
March 27, 1979	7.54	7,700
February 17, 1980	9.35	12,100
January 28, 1981	9.95	13,400
December 19, 1981	11.88	20,400
February 28, 1983	15.38	35,800
December 11, 1983	11.52	20,200
November 27, 1984	5.26	4,350
February 17, 1986	11.30	19,500
Cottonwood Creek near Cottonwood (C3) (Gage datum 363.80 feet above sea level)		
March 1, 1941	15.40	52,300
February 5, 1942	14.10	42,600
January 21, 1943	13.42	32,000
February 3, 1944	6.70	5,800
February 2, 1945	9.88	16,100
December 27, 1945	12.06	22,000
February 12, 1947	9.84	13,200
April 29, 1948	8.40	9,870
Cottonwood Creek near Cottonwood (C3)--*Continued*		
March 19, 1949	12.04	21,900
February 6, 1950	8.63	10,700
December 14, 1950	10.31	14,800
December 27, 1951	14.15	32,600
December 7, 1952	12.03	20,300
January 28, 1954	11.82	19,500
January 19, 1955	7.59	7,020
December 22, 1955	15.23	4,900
February 24, 1957	10.80	15,900
February 19, 1958	15.20	48,600
February 16, 1959	11.40	18,900
February 8, 1960	12.78	26,100
January 31, 1961	10.80	16,700
February 15, 1962	11.26	18,300
January 31, 1963	12.28	23,100
January 20, 1964	13.25	13,000
December 22, 1964	19.24	60,000
January 5, 1966	13.88	14,700
January 31, 1967	14.70	22,800
February 20, 1968	14.14	19,400
January 13, 1969	15.48	23,500
January 24, 1970	19.46	58,500
January 16, 1971	15.57	31,300
January 23, 1972	9.39	4,670
January 16, 1973	15.43	27,400
January 16, 1974	20.15	70,000
March 7, 1975	15.88	30,600
February 26, 1976	8.99	3,220
August 20, 1977	8.52	2,210
January 9, 1978	17.92	39,100
March 27, 1979	12.94	13,200
February 17, 1980	17.27	36,300
January 28, 1981	15.97	27,500
December 19, 1981	19.70	64,400
March 1, 1983	21.59	86,000
December 11, 1983	16.39	32,800
November 27, 1984	11.22	8,660
February 17, 1986	17.64	53,000

Table 8. Peak flow, flow volume, and recurrence interval during various durations for selected floods for three gaging stations in the Cottonwood Creek basin

[Location shown in figure 1. Flow volumes in thousands of acre-feet. ft^3/s, cubic foot per second; yr, year]

Date	Peak flow (ft^3/s)	Recurrence interval (yr)	1-day volume		3-day volume		8-day volume	
			Flow	Recurrence interval (yr)	Flow	Recurrence interval (yr)	Flow	Recurrence interval (yr)
Cottonwood Creek near Olinda (C22)								
January 16, 1974	36,900	16	4.64	17	84.0	12	134	10
February 28, 1983	33,000	8	40.1	12	98.4	18	172	20
February 17, 1986	23,800	4	35.1	9	67.9	7	126	9
South Fork Cottonwood Creek near Olinda (S12)								
January 16, 1974[1]	18,700	([2])	29.8	([2])	57.2	([2])	86.3	([2])
February 28, 1983	35,800	([2])	28.8	([2])	50.4	([2])	75.8	([2])
February 17, 1986	19,500	([2])	29.2	([2])	73.0	([2])	155	([2])
Cottonwood Creek near Cottonwood (C3)								
March 1, 1941	52,300	6.7	57.5	7	135	9	234	9.5
December 22, 1955	49,000	6	73.2	13	125	7	230	9
December 22, 1964	60,000	12	79.7	18	161	17	238	10
January 16, 1974	70,000	24	108	63	199	37	289	20
March 1, 1983	86,000	47	85.9	24	224	67	362	50
February 17, 1986	53,000	7.8	70.6	11	151	12	282	18

[1]Data from station South Fork Cottonwood Creek near Cottonwood (S14).
[2]Period of record too short to estimate recurrence interval.

SUMMARY

A study of streamflow data for 5 continuous-record gaging stations and flow measurements at periodic sites was done to determine gains and losses in flow for selected reaches of Cottonwood Creek. Regression equations prepared for annual, summer, and winter conditions indicate that rates of gains and losses in flow depend on the season and magnitude of streamflow. The reach downstream from the mouth of South Fork Cottonwood Creek gains more flow during the summer than during the winter. Surface-water inflow from tributaries in the basin ranges from 0 to 5 percent of the flow in the main channel, depending on the reach and season.

The gain in flow downstream for the mouth of South Fork Cottonwood Creek is attributed to ground-water inflow and irrigation-return flow. For gaging station South Fork Cottonwood Creek near Olinda, flows are less than 1 ft^3/s for periods up to 30 days with an average recurrence interval of about 2 years. For gaging station Cottonwood Creek near Cottonwood, low flows for durations up to 30 days are about 60 ft^3/s for an average recurrence interval of 2 years; the peak and 8-day flow of the February-March 1983 flood is the largest on record (1940-86), and the recurrence interval of this flood is about 47 years.

References Cited

Anderson, S.W., Mullen, J.R., and Shelton, W.F., 1990, Water resources data--California, water year 1989. Volume 4. Northern Central Valley basins and the Great Basin from Honey Lake basin to Oregon State line: U.S. Geological Survey Water-Data Report CA-89-4, 315 p.

California Department of Water Resources, 1960, Northeastern counties investigation: California Department of Water Resources Bulletin 58, 312 p.

Evenson, K.D., and Kinsey, W.B., 1985, Maps showing ground-water conditions in the Cottonwood Creek area, Shasta and Tehama Counties, California, 1983-84: U.S. Geological Survey Water-Resources Investigations Report 85-4184, scale 1:50,000.

Fogelman, R.P., and Evenson, K.D., 1985, Water-resources monitoring in the Cottonwood Creek area, Shasta and Tehama Counties, California, 1982-83: U.S. Geological Survey Water-Resources Investigations Report 84-4187, 70 p.

Fogelman, R.P., Mullen, J.R., Shelton, W.F., and Simpson, R.G., 1984, Water resources data--California, water year 1982. Volume 4. Northern Central Valley basins and the Great Basin from Honey Lake basin to Oregon State line: U.S. Geological Survey Water-Data Report CA-82-4, 319 p.

Fogelman, R.P., Mullen, J.R., Shelton, W.F., Simpson, R.G., and Grillo, D.A., 1985, Water resources data--California, water year 1983. Volume 4. Northern Central Valley basins and the Great Basin from Honey Lake basin to Oregon State line: U.S. Geological Survey Water-Data Report CA-83-4, 361 p.

_____1986, Water resources data--California, water year 1984. Volume 4. Northern Central Valley basins and the Great Basin from Honey Lake basin to Oregon State line: U.S. Geological Survey Water-Data Report CA-84-4, 277 p.

Helley, E.J., and Jaworowski, Cheryl, 1985, The Red Bluff Pediment; a datum plane for locating Quaternary structures in the Sacramento Valley, California: U.S. Geological Survey Bulletin 1628, 13 p.

Johnson, M.J., Houston, E.R., and Neil, J.M., 1989, Test holes for monitoring surface-water/ground-water relations in the Cottonwood Creek area, Shasta and Tehama Counties, California, 1984-85: U.S. Geological Survey Water-Resources Investigations Report 88-4090, 28 p.

Langbein, W.B., and Iseri, K.T., 1960, General introduction and hydrologic definitions, *in* Manual of Hydrology: Part 1. General surface-water techniques: U.S. Geological Survey Water-Supply Paper 1541-A, 29 p.

Mullen, J.R., Shelton, W.F., Simpson, R.G., and Grillo, D.A., 1987, Water resources data--California, water year 1985. Volume 4. Northern Central Valley basins and the Great Basin from Honey Lake basin to Oregon State line: U.S. Geological Survey Water-Data Report CA-85-4, 289 p.

Norris, R.M. and Webb, R.W., 1976, Geology of California: New York, John Wiley, p. 255-256.

Pierce, M.J., 1983, Ground water in the Redding Basin, Shasta and Tehama Counties, California: U.S. Geological Survey Water-Resources Investigations Report 83-4052, 37 p.

Poland, J.F., and Evenson, R.E., 1966, Hydrogeology and land subsidence, Great Central Valley, California, *in* Bailey, E.H., ed., Geology of northern California: California Division of Mines and Geology Bulletin 190, p. 239-247.

Russell, R.D., 1931, The Tehama Formation of northern California: Berkeley, California, University of California, unpublished Ph.D dissertation.

Steele, W.C., 1980, Quaternary stream terraces in the northwestern Sacramento Valley, Glenn, Tehama, and Shasta Counties, California: U.S. Geological Survey Open-File Report 80-512, 167 p.

Strand, R.G., 1962, Geologic map of California--Redding sheet: California Division of Mines and Geology, scale 1:250,000.

U.S. Bureau of Reclamation, 1968, Ground-water geology and resources appendix of reconnaissance study of Cottonwood Creek Service Area, Cottonwood unit, lower Trinity River division, North Coast Project, California: 27 p.

U.S. Water Resources Council, 1981, Guidelines for determining flood-flow frequency: U.S. Water Resources Council Hydrology Bulletin 17B, 206 p.

☆U.S. GOVERNMENT PRINTING OFFICE: 1992 - 687-018/79130