Reconnaissance Study of the Chemical Quality of Surface Waters in the Sacramento River Basin, California

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1619-Q

Prepared in cooperation with the California Department of Water Resources

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By ROBERT BRENNAN

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

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CONTENTS

ILLUSTRATIONS

[Plates are in pocket]

TABLES

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES

RECONNAISSANCE STUDY OF THE CHEMICAL QUALITY OF SURFACE WATERS IN THE SACRAMENTO RIVER BASIN, CALIFORNIA

By Robert Brennan

ABSTRACT

The Sacramento River and its tributary streams furnish water for the production of large quantities of hydroelectric power in the mountain areas of the Sacramento River drainage basin and for irrigation in the Sacramento Valley. A knowledge of the chemical quality of the water is important for the planning of present and future projects in the area.

The Sacramento River drainage basin is the largest drainage area in northern California. In includes the Sacramento Valley, which is about 150 miles long and 40 miles wide at the widest part, and parts of the surrounding Klamath and Cascade Mountains, the Coast Ranges, and the Sierra Nevada. The topography of the drainage basin consists of flat valley land, which rises from only a few feet above sea level to about 200 feet; low lying hills which range in altitude from 200 to 300 feet; and rugged mountains rising from 6,000 to 9,000 feet above mean sea level.

The climate is one of extremes in temperature and precipitation. The mountain areas have below freezing temperatures during the winter months, and the valley occasionally has temperatures in excess of 100°F during the summer months. In the mountains the average annual temperature is 54°F and in the valley it is 62°F. Most of the precipitation occurs from November to April. The west slope of the Sierra Nevada receives the greatest amount of precipitation, which at times has exceeded 100 inches in a year. Depths of snow in excess of 300 inches a year have been recorded above the 4,000-foot level in these mountains. The Sacramento Valley occasionally receives less than 10 inches of rainfall annually. The average annual precipitation for the Sacramento River drainage basin is approximately 30 inches.

The Sacramento River drainage basin contains igneous, sedimentary, and metamorphic rocks that range in age from pre-Tertiary to Recent. The mountain areas have been uplifted with accompanying folding and faulting. The Sacramento Valley is a structural depression that has received both marine and continental sediments from Late Jurassic to Recent time. The batholithic intrusion of the Sierra Nevada took place in Tertiary time. Volcanic activity has occurred in all the mountain areas and has been extensive in the Cascade Range from Tertiary to Recent time.

The chemical quality of the water in the Sacramento River basin is directly related to the geology of the area. The streams draining the crystalline rocks of the mountains north and east of the Sacramento Valley are low in dissolved solids and have specific conductance values ranging from 29 to 332 micromhos, while the streams draining the sedimentary rocks of the Coast Ranges west of the Sacramento Valley have a higher dissolved-solids content and specific conductance values ranging from 89 to 968 micromhos. At the present time, the chemical quality of the water in the Sacramento River is considered suitable for all uses. Estimates show that a threefold increase in irrigation use should not change the mineral quality sufficiently to make the water unsuitable for export to other areas in California. Two streams in the basin, Cache Creek and Putah Creek, have high boron concentrations that limit their use for irrigation.

INTRODUCTION

PURPOSE AND SCOPE OF INVESTIGATION

The overall plan for the development of the water resources of the Sacramento River drainage basin, as set forth in the California Water Plan, includes the regulation and control of flood waters, irrigation of additional lands, and production of hydroelectric power. A basic requirement for the planning of these projects is a knowledge of the chemical quality of the surface streams in the valley. This report gives the results of a study by the U.S. Geological Survey of the dissolved minerals that are transported by the Sacramento River and its tributary streams.

Successful irrigation depends not only on soil type, drainage, and climate but also on the chemical quality of the water used. The chemical-quality data obtained in the Sacramento River basin over a period of 7 years have been interpreted to show the variation in the quality of the water by area and with time. Also, insofar as possible, the quality and quantity of dissolved constituents of the main streams have been correlated with geologic, climatic, hydrologic, and cultural characteristics of the drainage basin.

Samples analyzed for dissolved constituents were collected periodically at stations operated by the California State Department of Water Resources and daily at three stations operated by the U.S. Geological Survey. The analytical results of these samples and of samples collected from the major tributary streams of the basin for a special salinity study serve as the basis for the chemical-quality discussions in this report.

Calcium, magnesium, sodium, potassium, bicarbonate, chloride, boron, hardness, specific conductance, and percent sodium were usually determined on the periodic samples. In addition, silica, sulfate, nitrate, fluoride, and dissolved solids were determined on the May and September periodic samples and on all composite samples from daily station.

The information on the geology of the area considered in this report has been obtained from the work of Olmsted (1956), Bryan (1923), and Reed (1951).

PREVIOUS INVESTIGATIONS

Prior to 1950, chemical analyses of waters in the Sacramento River drainage basin were made by the Southern Pacific Railroad Company, the California University Agricultural Experimental Station, and the U.S. Geological Survey. The results of these analyses may be found in the U.S. Geological Survey Water-Supply Papers 237 and 274, and Professional Paper 135.

Since 1946 the California State Department of Public Works (now the Department of Water Resources) has published the yearly reports of Sacramento-San Joaquin Water Supervision. These reports contain chemical-quality, discharge, and water-use data for the major streams in the area. Many reports on the geology of the Sacramento River basin have been published.

ACKNOWLEDGMENTS

This study was made by the U.S. Geological Survey in cooperation with the California State Department of Water Resources. It was conducted under the general supervision of Eugene Brown, District Chemist, Sacramento, Calif. This report was prepared under the immediate supervision of R. P. Orth, Assistant District Chemist, Sacramento, Calif.

Periodic stream samples were collected by the employees of the State Department of Water Resources, Sacramento, Calif.

Chemical analyses of surface-water samples were made by the personnel of the Branch of Quality of Water, Sacramento, Calif.

Unpublished stream flow records were furnished by the area engineer, Branch of Surface Water, Geological Survey, Sacramento, Calif., and by the California State Department of Water Resources.

SACRAMENTO RIVER BASIN

GEOGRAPHY

The Sacramento River drainage basin lies in the northern half of California. It includes the east slope of the Coast Ranges, a part of the Klamath Mountains, and the west slopes of the Cascade Range and the Sierra Nevada. The Sacramento Valley is continuous with the San Joaquin Valley to the south.

The Sacramento River rises in Gumboot Lake in the Trinity Mountains, which are a part of the Klamath Mountains. It flows eastward for about 12 miles, then south into Shasta Reservoir; from Shasta Reservoir it flows south to the delta area, then westward into the eastern arm of San Francisco Bay, which is known as Suisun Bay.

The fall of the Sacramento River is approximately 5,700 feet in the 50 miles above Shasta Reservoir (whose spillway is 1,037 feet above mean sea level) and 267 feet in the 56 miles between Shasta Reservoir and Red Bluff. The fall of the remaining 250 miles of its course is 250 feet.

The interested reader will find more detailed information on the geography of the Sacramento River basin in Bryan (1923, p. 7–20), California Division of Water Resources (1931, p. 63–65), and Olmsted and Davis (1961).

TOPOGRAPHY

Topographically, the Sacramento River basin ranges from valley lands and low hills to high mountain peaks. The Sacramento Valley, which is the northern part of the Great Central Valley of California, extends south from Red Bluff to the delta lands and Suisun Bay, a distance of about 150 miles. The maximum width of the valley is about 40 miles. The flat appearing valley rises gently from below sea level in the delta area to the mountain foothills.

Surrounding the Sacramento Valley on three sides are the mountains of the Coast Ranges, the Klamath and Cascade Mountains, and the Sierra Nevada. The Coast Ranges, about 35 miles wide, extend in a narrow belt along the west boundary of the Sacramento River drainage basin from Suisun Bay north to Stony Creek. Altitudes in these mountains rarely exceed 6,000 feet. The east slope of the Coast Ranges is steep and has been deeply incised by the streams that drain it.

North of Stony Creek the Coast Ranges merge with the Klamath Mountains, which extend across the upper end of the valley and join the Cascade Mountains to the northeast. The Klamath Mountains are higher than the Coast Ranges and range in altitude from 7,000 to 8,000 feet. The streams draining the east slopes of these mountains have cut deep V-shaped valleys.

The northeastern section of the Sacramento River drainage basin lies in the Cascade Mountain area. This area is a broad volcanic plateau surmounted by volcanic peaks, the most prominent of which are Mount Shasta and Mount Lassen. The west slope of this volcanic plateau has been dissected by westward-flowing streams into V-shaped channels. The Cascade Mountains extend southward to the North Fork Feather River.

South of the Cascade Mountains, the Sierra Nevada forms the eastern section of the Sacramento River drainage basin. This mountain province is about 65 miles wide and slopes from the valley floor to about 9,000 feet altitude. The streams draining the west slopes of the Sierra Nevada have cut deep, well-defined channels.

In the center of the Sacramento Valley, the remnants of an old laccolith, the Sutter Buttes, project about 2,000 feet above the surrounding valley sediments. These buttes are a rugged, circular mass about 12 miles in diameter. Figure 1 shows the topography and extent of the Sacramento River drainage basin.

CLIMATE

The Sacramento Valley has characteristically warm, dry summers and mild, wet winters. Surrounding mountain areas also have warm, dry summers, but much colder winters with temperatures frequently falling below freezing. The average annual temperature in the mountains is 54°F. Although summer temperatures in the valley occasion-

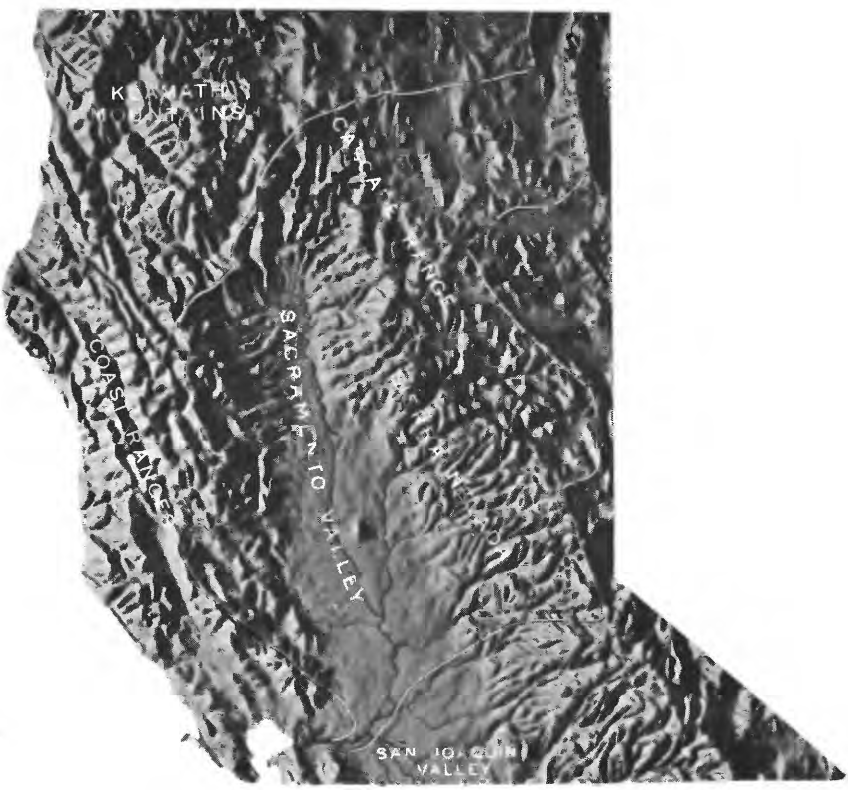

FIGURE 1.—Map showing the topography and extent of the Sacramento River drainage basin, California.

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ally exceed 100°F, the average annual temperature is 62°F. A subtropical, high-pressure area off the coast keeps the basin without rainfall during the summer months, but in the winter this high-pressure area moves southward and allows Pacific Ocean storms to enter the valley and deposit their moisture. The Pacific Ocean has a moderating effect upon the winter temperatures, and the Sierra Nevada acts as a barrier to the cold air masses of the interior of the country.

Most of the precipitation falls between November and April, as rain in the lowlands and as snow in the mountains. The remaining months of the year are generally free of precipitation. With topography the major controlling factor, the amount of precipitation that falls in the winter varies greatly with location. The heaviest precipitation, which has exceeded 100 inches in a year, occurs on the west slope of the Sierra Nevada; the lowest precipitation, which has been less than 5 inches in a year, occurs in the valley. Heavy snowfall occurs in the mountains above 4,000 feet. Depths of snow exceeding 300 inches a year have been recorded. Plate 1 shows the normal annual temperature and precipitation at selected weather stations in the Sacramento River drainage basin.

The interested reader is referred to Bryan (1923, p. 45–48) and the U.S. Weather Bureau (Annual Summaries) for further information on climate in the Sacramento River basin.

GENERAL GEOLOGIC STRUCTURE AND HISTORY

The Sacramento River drainage basin lies within five geologic provinces: the Sacramento Valley, the Coast Ranges on the west, the Klamath Mountains on the northwest, the Sierra Nevada on the east, and the Cascade Range on the northeast. A generalized geologic map of the Sacramento basin is presented in plate 2.

In Late Jurassic and Early Cretaceous time, a sea occupied the structural basin of the Sacramento Valley. The axis of this ancient valley was farther west than it is now, and the present site of the Coast Ranges was covered by the sea. The ancestral Sierra Nevada to the east was eroded during the Cretaceous period, and the debris from this erosion was deposited in the sea. At the end of the Cretaceous period, a regional uplift of the area now occupied by the Coast Ranges caused the withdrawal of the sea.

During the Eocene period the Sacramento Valley was again inundated by a sea. Owing to the erosion of the mountain areas, the Sierra Nevada was planed down to a surface of low relief. During the middle or late Eocene, volcanic activity deposited rhyolite, andesite, and basalt near the present crest of the Sierra Nevada.

By Miocene time the sea had completely withdrawn from the Sacramento Valley, and a period of erosion ensued. In the northern Sierra Nevada and southern Cascades, volcanic activity occurred in the late Miocene and continued into the middle Pliocene. During the middle or late Pliocene, the Sierran block was faulted and tilted westward, and the Coast Ranges were uplifted. Erosion of the mountains resulted in the deposition of sediments in the valley depression at a rate sufficient to keep pace with the slowly sinking valley floor.

During the late Pliocene, extensive volcanic activity occurred in the southern Cascade Range. The volcanic rocks deposited were continuously eroded and the resulting sediments were deposited as far west as the present axis of the Sacramento Valley.

The intrusion of a laccolith in the valley took place during the late Pliocene. The valley sediments were pushed up, and erosion as well as later intrusions helped to form the Sutter Buttes.

Further uplift of the Sierran block and the Coast Ranges occurred in Pleistocene time. Folding and faulting occurred in the Coast Ranges, and the flat-lying sediments north of Red Bluff were deformed into hills of low relief. The erosion of the mountains was vigorous, and glaciation occurred in the Sierra Nevada. Deposition of sediments in the valley continued until recent time. Volcanism occurred at Mount Lassen in the Cascade Ranges as recently as 1917.

A more detailed discussion of the geology of the Sacramento River basin is available in Olmsted and Davis (1961) and in Reed (1933).

PHYSICAL CHARACTERISTICS OF THE STREAMS

SACRAMENTO RIVER

In the reach above Shasta Reservoir, the Sacramento River is a small, swift stream. It flows in a well-defined channel through the ultramafic intrusive and the pre-Cretaceous metamorphic rocks of the Klamath Mountains. From Redding to Suisun Bay, the river flows through Recent sediments; however, just north of Red Bluff it flows through a small area of Tertiary and Quaternary, slightly to moderately deformed, nonmarine sediments. At Red Bluff the river enters the Sacramento Valley and becomes a sluggish, meandering stream as it flows through the valley toward the bay.

The Sacramento River is joined by many tributary streams as it flows through the valley. The major tributary streams originate on the broad western slope of the Sierra Nevada and contribute the largest flow to the Sacramento.

PIT RIVER

The Pit River is formed near Alturus by the union of its north and south forks. The South Fork rises south of Emerson Peak at about 7,500 feet altitude and flows northward for about 35 miles. It joins the North Fork approximately 3 miles south of Alturus. The North Fork rises in Goose Lake and flows south to the point near Alturus where it joins the South Fork. From this junction the Pit River flows southwest to Shasta Reservoir where it joins the Sacramento River. Although the Pit River comprises about 23 percent of the total drainage of the Sacramento River basin, it is considered a tributary, not an extension, of the Sacramento River.

The Pit River flows through the Modoc Plateau of the Cascade Range. The average elevation of the plateau is about 4,000 feet. The northern part of the Pit River basin consists mainly of barren lava beds and small valley meadows. West of Fall River the Pit River enters the National Forest areas of Mount Shasta and Mount Lassen and shares part of the drainage from those two peaks.

The principal tributaries of the Pit River are McCloud and Fall Rivers, Squaw, Burney, Hat, Beaver, and Ash Creeks. Goose Lake, tributary to the North Fork, seldom overflows to the river, though some water may reach it as underflow through permeable lava.

Most of the tributary streams are fed by springs issuing from the crevices in the lava beds; a few of these springs discharge several hundred feet of water per second.

COTTONWOOD CREEK

Cottonwood Creek rises in the marine sedimentary rocks on the east slope of the Klamath Mountains and is composed of the North, Middle, and South Forks. The North Fork rises in Rainbow Lake, which is south of Shasta Bally Mountain, and flows southeast to its junction with the Middle Fork. The Middle Fork rises just north of North Yolla Bolly Mountain, flows northeast, and joins the main stem of Cottonwood Creek about 5 miles west of the city of Cottonwood. The upper reaches of Cottonwood Creek are in steep mountain country, and its channels are deeply cut and well defined. Above their junction in Recent valley alluvium, Cottonwood Creek and South Fork flow successively through areas underlain by marine sedimentary rocks and slightly to moderately deformed nonmarine sediments.

STONY CREEK

Stony Creek rises in the marine sedimentary rocks of the Coast Ranges. It flows north for about 30 miles; then northeast through an area underlain by marine sedimentary rocks, Jurassic to Tertiary in age; and finally, southeast through the undeformed nonmarine sediments of Recent age of which the valley is composed. It joins the Sacramento River near Hamilton City.

CLEAR LAKE—CACHE CREEK

Clear Lake lies near the center of Lake County in the marine sedimentary rocks of the Coast Ranges. The mountains along its southeast shore are of volcanic origin; the lake is elsewhere surrounded by high mountains composed mainly of sandstones, shales, and limestone. The lake is about 20 miles long and is about 7 miles wide at the widest point. It narrows at the southeastern end and overflows into Cache Creek.

Cache Creek has cut a deep, well-defined channel—Cache Creek Canyon—through the sandstones and shales east of Clear Lake. The main tributary to Cache Creek is North Fork Cache Creek, which joins the main stream near the upper end of Cache Creek Canyon. The North Fork drains the marine sandstones and shales of the Coast Ranges northeast of Clear Lake.

As Cache Creek leaves Cache Creek Canyon, it enters the long, narrow, southeastward-trending Capay Valley. This valley is wider than Cache Creek Canyon and is filled with sediments of Recent age. Cache Creek flows eastward across the Sacramento Valley and empties into the Yolo-by-pass, an artificial drainage system along the west side of the Sacramento River; it then flows south through the bypass to Cache Slough, which in turn flows into the Sacramento River below Isleton, Calif.

PUTAH CREEK

Putah Creek rises in marine sandstones and shales south of Clear Lake and drains the area south of Cache Creek. The upper reaches of the stream are in mountain country and have characteristic steep-sloped, well-defined channels. Putah Creek enters the Sacramento Valley near Winters. It flows through Recent sediments to the Yolo-by-pass and from there to its junction with the Sacramento River.

MILL AND DEER CREEKS

Mill and Deer Creeks rise in the volcanic rocks south of Mount Lassen. They flow southwest through volcanic sediments to the Sacramento River. About 6 miles above their confluence with the Sacramento River, the creeks enter the Sacramento Valley and their velocity decreases rapidly in the flat valley. Several springs issuing from the volcanic rocks help to maintain the flow of these creeks throughout the year.

BIG CHICO CREEK

Big Chico Creek rises at an altitude of about 6,000 feet in the volcanic rocks of the Sierra Nevada approximately 5 miles north of Philbrook Reservoir. It flows to the Sacramento River in a rugged canyon cut in the volcanic rocks. On leaving the canyon about 6 miles east of Chico, the creek enters the Sacramento Valley and flows across the flat valley alluvium to its junction with the Sacramento River.

BUTTE CREEK

Butte Creek rises in the volcanic rocks south of Big Chico Creek. After flowing southwest through the volcanic and pre-Cretaceous metamorphic rocks of the Cascade Mountains, it leaves the mountains about 6 miles southeast of Chico and enters the Sacramento Valley, where the stream joins the Sacramento River below Colusa. Its velocity decreases rapidly in the flat valley land. Most of the flow of Butte Creek is diverted for irrigation above the junction with the Sacramento River. The returning irrigation water flows into the Sutter-by-pass, a major irrigation drain and floodway on the east side of the Sacramento River.

FEATHER RIVER

The Feather River rises on the crest of the Sierra Nevada and flows southwest to a point slightly beyond Oroville. From there it flows south to its junction with the Sacramento River just below Knights Landing. It is formed by the North, Middle, and South Forks, and its main tributaries are the Yuba and Bear Rivers.

The North Fork, which heads in Lake Almanor, drains the northern half of the rugged mountain country of the Feather River basin. The eastern tributaries of the North Fork drain volcanic rocks of Tertiary and Quaternary age and pre-Cretaceous metamorphic rocks; they also flow through some areas underlain by ultramafic intrusive rocks before joining the North Fork. Below this junction, the North Fork flows through pre-Tertiary intrusive rocks and pre-Cretaceous metamorphic rocks to its junction with the Middle Fork near Oroville.

The Middle Fork rises in the volcanic rocks on the west slope of the Diamond Mountain Range of the Sierra Nevada near the Nevada-California border and approximately 12 miles north of Beckwourth. It flows south through Beckwourth Pass and enters the rather large Sierra Valley. After leaving Sierra Valley, the Middle Fork flows westward through areas underlain successively by pre-Cretaceous metamorphic, ultramafic intrusive, and pre-Tertiary silicic intrusive rocks. It joins the North Fork near Oroville.

The South Fork of the Feather River is much shorter than either the North or Middle Forks. It flows through the igneous rocks south of and approximately parallel to the Middle Fork and joins the Middle Fork just east of Oroville. Above Oroville the Feather River flows swiftly through steep, rugged mountain canyons, but below Oroville it enters the flat lands of the Sacramento Valley. The Feather River flows south from Oroville to its junction with the Sacramento River and is slow and meandering in its passage through the valley.

Many springs flow into the Feather River, especially from the volcanic rocks. These springs help to maintain the flow in the river during the dry months of the year. Some of the larger springs discharge water at about 100 cubic feet per second into the river.

YUBA RIVER

The Yuba River rises on the crest of the Sierra Nevada and flows westward to the Feather River. It is composed of the North, Middle, and South Forks. The three forks, which roughly parallel each other, have cut deep channels in the igneous and metamorphosed sedimentary rocks of the Sierra Nevada. Near French Corral, just a few miles from the area where the river emerges from the mountains and enters the Sacramento Valley, the three forks merge to form one stream. The Yuba River joins the Feather River at Marysville.

BEAR RIVER

The Bear River drains the mountain area between the Yuba River and the American River. It rises in pre-Cretaceous metamorphic rocks near Emigrant Gap and flows generally southwest. The Bear River enters the Sacramento Valley just above Wheatland and flows through the Recent valley deposits to its junction with the Feather River about 15 miles below Marysville.

AMERICAN RIVER

The American River rises on the crest of the Sierra Nevada southwest of Lake Tahoe and is composed of the North, Middle, and South Forks. The North and Middle Forks head in pre-Cretaceous metamorphic rocks and flow southwest to their junction near Auburn. The Rubicon River, tributary to the Middle Fork, rises in pre-Tertiary silicic intrusive rocks and flows northwest through pre-Cretaceous metamorphic rocks to its junction with the Middle Fork. The South Fork also rises in pre-Tertiary silicic intrusive rocks and flows west through pre-Cretaceous metamorphic rocks to Folsom Reservoir, where it joins the previously combined North and Middle Forks. Above Folsom Reservoir the American River is a swift stream in rugged mountain country. Below Folsom Reservoir, it enters the Sacramento Valley and flows more slowly through Recent valley deposits to its junction with the Sacramento River just north of the city of Sacramento.

The reader is referred to Bryan (1923, p. 52–68) for additional information on the physical characteristics of these streams.

RUNOFF

Streamflow measurements in the Sacramento River drainage basin were made at 127 stations by the U.S. Geological Survey, and at 44 stations by the California State Department of Water Resources.

Flow in the streams of the basin is usually maintained throughout the year, but it varies greatly depending on the season. The heaviest flow occurs during the rainy season from November to April. Because of the snowmelt from the Sierra Nevada, the streams draining the east side of the basin generally have a greater sustained flow than have the streams draining the west side.

Water-storage reservoirs in the mountain areas of the Sacramento River basin have been very effective in regulating the runoff. Releases from storage areas are made during the summer and fall; therefore, the streams have a greater sustained flow than they normally would have without the upstream storage reservoirs. A large percentage of this water is diverted for irrigation use, either through canals from the reservoirs or by pumps along the streams. A large proportion of the irrigation water is either consumed by the crops or percolates to the ground-water zone and does not return to the streams as runoff. This has caused a reduction in the amount of runoff from the Sacramento River basin, and future increases in irrigation will further reduce the total runoff from the basin.

A large percentage of the basin area is mountainous country with steep slopes and little water retention. For this reason, most of the precipitation in the Sacramento River drainage basin soon leaves the basin unless it can be stored. During the period 1897–1947, the average annual runoff for the basin was 22,390,000 acre-feet of water from a total drainage area of 26,548 square miles. Calculated as inches of water, the runoff is 15.8 inches for the entire basin.

The average precipitation for the Sacramento River basin has been calculated to be approximately 30 inches a year. The method used for this calculation is as follows: Average annual precipitation figures from the several weather stations in the basin were plotted on a map of the drainage basin. Isohyetal lines were then drawn allowing 10 inches of precipitation between lines. After these lines were drawn, the areas encompassed by the lines were cut from the map and weighed on a balance. Using an average precipitation for each area, the weight figures were used to approximate the average precipitation for the entire Sacramento River drainage basin. Table 1 presents the calculations made.

TABLE 1.—*Calculation of average precipitation for the Sacramento River basin*

Precipitation (inches	Weight of paper (grams)	Percent of total	Average precipitation of area (inches)	Average precipitation contributed (inches)
10–20	2. 9722	40. 21	15	6. 03
20–30	1. 3297	17. 99	25	4. 50
30–40	1. 0256	13. 88	35	4. 86
40–50	1. 0726	14. 51	45	6. 53
50–60	. 5265	7. 12	55	3. 92
60–70	. 2932	3. 97	65	2. 58
70+	. 1717	2. 32	75	1. 74
Total	7. 3915	100. 00	----------	30. 16

This calculation is considered to be sufficiently accurate for use in this report.

At the present time, the runoff in the Sacramento River drainage basin is about 53 percent of the total precipitation in the basin.

GEOCHEMISTRY OF THE WATER

Water begins dissolving minerals before it reaches the ground, and although it will dissolve small amounts of all the gases in the air, those gases that will react with the water chemically are the most soluble. Rain water dissolves relatively large quantities of carbon dioxide and smaller amounts of the oxides of sulfur and nitrogen. These oxides in combination with the rain water form weak acids and greatly aid in the solution of rocks and soils. The quantity of minerals that the water can dissolve depends upon the solubility of the minerals, the length of time the water is in contact with the rocks and soils, and the temperature of the water. Soluble minerals are not plentiful in the Sacramento River basin because it is composed mainly of igneous and metamorphic rocks.

The igneous rocks of the Klamath and Cascade Mountains and the Sierra Nevada are resistant to solution by water; hence, the surface water draining from these areas is characteristically low in dissolved solids. Most of the dissolved solids that are found in this water are derived from feldspathic materials. Because calcium feldspars are more soluble than sodium feldspars, calcium is usually the major cation of the water. The potassium that dissolves along with the sodium does not long remain in solution because it is so readily adsorbed by clay materials. Thus, in surface water, sodium generally is present in larger amounts than potassium. Carbon dioxide dissolved from the air and from decaying organic matter in the soil forms the bicarbonate ion, the most abundant anion of the water; small amounts of sulfate and chloride are also present.

Streams draining the Coast Ranges have a higher concentration of dissolved solids than do the streams draining the Klamath and Cascade Mountains and the Sierra Nevada. This difference is the result of the solution of calcium from the limestones and dolomites found scattered throughout the sedimentary deposits; the solution of sodium from the marine sediments; and the solution of magnesium from the ultramafic instrusive rocks in the sediments.

Some streams draining the mountain areas of the Sacramento River basin contain more salts in solution than would normally be expected from the solution of rocks alone. This higher concentration of dissolved solids is attributed to the many mineral springs that are found in the basin and to returning irrigation water. The springs can be grouped into three classes on the basis of dissolved solids: in about half the springs, dissolved solids range from 300 to 1,500 ppm (parts per million) total concentration; in most of the remaining springs they range from 1,500 to 5,000 ppm; and in a few they range from 13,000 to 27,000 ppm (Waring, 1915).

Springs contributing water to the Sacramento River above Shasta Lake contain dissolved solids ranging from 500 to 26,000 ppm. The water generally is the sodium carbonate type containing substantial quantities of chloride ion. Shasta Spring has 9.9 ppm boron as BO_2, and Neys Spring contains hydroxide and sulfide ions.

Many hot springs contribute water to the Pit River, and dissolved solids range in concentration from 140 to 750 ppm. Some water is sodium sulfate or bicarbonate type, and some is calcium bicarbonate type. Spring water flowing into Mill Creek originates in the volcanic rocks near Mount Lassen. Dissolved solids in the water range from 300 to 4,300 ppm and silica ranges from 124 to 286 ppm. Except for the water from Devils Kitchen hot spring, which contains a very high concentration of dissolved aluminum, the water generally is of the sodium chloride or sodium sulfate type.

The Feather River and its tributaries are fed by many springs, some of which are hot springs. Dissolved solids range from 500 to 1,400 ppm in the hot springs, and the water ranges from sodium carbonate or sulfate type to calcium carbonate type. Several hot springs have high concentrations of iron and aluminum.

Water from springs flowing into the American River generally is of the sodium bicarbonate type, with appreciable amounts of calcium. Dissolved solids range from 900 to 6,000 ppm, and one spring (Summit Soda) has concentrations of iron and aluminum of 22 and 10 ppm, respectively.

Springs are more numerous on the west side of the Sacramento River basin than on the east side, and the water quality of the two areas differs. The geology of the Coast Ranges is the major cause for this difference.

Water from springs in the Stony Creek drainage area generally is of the sodium bicarbonate type, but some springs contain considerable quantities of magnesium. Dissolved solids in this water ranges from 700 to 13,000 ppm. Minor constituents include iron, aluminum, ammonia, and iodide.

Springs are numerous in the vicinity of Clear Lake. In general, these springs produce a magnesium bicarbonate type water, but one or two have sodium or calcium as the major cation. Dissolved solids in this water ranges from 1,200 to 5,000 ppm. Most of the springs yield water high in dissolved iron and aluminum. Other constituents found in these springs include ammonia, hydrogen sulfide, barium, and boron. Sulfur Bank Spring water has a high boron content (800 ppm as BO_2).

In the Cache Creek drainage area, the springs yield bicarbonate type water containing sodium, calcium, and magnesium in almost equal amounts. Minor constituents include boron, hydrogen sulfide, lithium, ammonia, iodide, iron, and aluminum. Dissolved solids range from 300 to 23,000 ppm.

Water from springs flowing into Putah Creek ranges from magnesium bicarbonate to sodium sulfate and chloride types. Dissolved solids range from 350 to 3,500 ppm, and the silica content is high. Minor constituents include iron, aluminum, manganese, hydrogen sulfide, and arsenic.

Most of the springs in the Sacramento River basin yield flows of from 1 to 10 gallons per minute; but from some, the flow exceeds 100 gallons per minute. The flow of these springs is considerably less than the overall flow of the streams in the drainage basin and so causes only a minor change in the chemical composition of the streams. Generally, the springs are found near the headwaters of the streams. Their effect on stream quality could not be ascertained because of insufficient time and a lack of the funds required to enable collection of the necessary data.

CHEMICAL QUALITY OF THE WATER

CHEMICAL-QUALITY RECORDS

This report is based on data obtained from analyses of samples collected between 1951 and 1958 at 26 periodic and 3 daily sampling stations and for a low-flow salinity survey. These data are summarized in tables 2, 3, 4, 5, and 6. The analyses of surface water in this area appear in U.S. Geological Survey Water-Supply Papers 1200, 1253, 1293, 1353, 1403, 1453, 1523, and 1574.

All the major streams tributary to the Sacramento River have been sampled periodically since 1951. Since 1953 the sampling at most of these stations has been on a monthly basis. The principal exceptions are streams in the high mountain areas that are inaccessible during the winter months and streams that do not flow during the dry season. Through September 1958, approximately 65 samples had been collected at each of the periodic stations and analyzed. These stations are shown in plate 3.

Sampling during low-flow periods was adequate, but peak flows, frequently missed by monthly sampling, were not as well represented. Although periodic sampling has been sufficient to indicate major changes in chemical character and normal ranges in concentration of the major ions in solution, complete definition of quality in all stages of discharge would require more frequent sampling over a longer period of time.

The three daily sampling stations, in operation since 1951, are located on the Sacramento River at Knights Landing, on the Feather River at Nicolaus, and on the American River at Fair Oaks. Samples were obtained during all variations in flow that occurred during the sampling period, and it was possible to develop cumulative frequency curves for the major ions in solution.

Specific conductance was determined for all daily samples. These data were then used in the compositing of the daily samples for more complete analysis. In general, the daily samples were composited by combining equal volumes of the daily samples for a 10-day period. The composite samples give an average analysis and therefore tend to mask the high and low values. By correlating the constituents to electrical conductivity, the high and low values can be estimated from the daily conductance values.

Yearly weighted averages have been calculated for the daily sampling stations. The weighted-average analysis is weighted by flow and therefore approximates the water quality that would result if all the water was impounded in a reservoir and thoroughly mixed.

The samples for the special salinity survey were collected during the summer and represent the quality of the Sacramento River and its major tributary streams during a low-flow period. These samples indicate the effect of the tributary flow on the quality of the Sacramento River. The data from this study are presented in table 2.

EXPRESSION OF RESULTS

The analytical results are expressed in accordance with the methods prescribed by the U.S. Geological Survey (Rainwater and Thatcher, 1960).

The dissolved mineral constituents are reported in parts per million. A "part per million" is a unit weight of a constituent in a million unit weights of water. An "equivalent per million" is a unit chemical combining weight of a constituent in a million unit weights of water and is calculated by dividing the concentration in parts per million by the chemical combining weight of the constituent. For convenience in making this conversion, the reciprocals of the chemical combining weights of the most commonly reported constituents (ions) are given in the following table:

Constituent	*Factor*
Calcium (Ca^{+2})	0.0499
Magnesium (Mg^{+2})	.0822
Sodium (Na^{+1})	.0435
Potassium (K^{+1})	.0256
Carbonate (CO_3^{-2})	.0333
Bicarbonate (HCO_3^{-1})	.0164
Sulfate (SO_4^{-2})	.0208
Chloride (Cl^{-1})	.0282
Fluoride (F^{-1})	.0526
Nitrate (NO_3^{-1})	.0161

Hardness, as calcium carbonate, is calculated from the equivalents of calcium and magnesium. The hardness caused by calcium and magnesium (and other ions if significant) equivalent to the carbonate and bicarbonate is called carbonate hardness; the hardness in excess of this quantity is called noncarbonate hardness.

In the analyses of most irrigation water, the quantity of dissolved solids is given in tons per acre-foot as well as in parts per million.

Percent sodium is calculated by dividing the equivalents per million of sodium by the sum of the equivalents per million of calicum, magnesium, sodium, and potassium, and then multiplying the quotient by 100.

Specific conductance values are expressed in reciprocal ohms times 10^6 (micromhos at 25°C).

Hydrogen-ion concentration on the pH scale is given as the negative logarithm of the number of moles of ionized hydrogen per liter of water.

The weighted average of the analyses is computed by multiplying the discharge for the sampling period by the quantities of the individual constituents for the corresponding period and by dividing the sum of the products by the sum of the discharge.

SALINITY SURVEY

Spot samples were taken from the Sacramento River and its major tributary streams and drain canals from July 18 to 21, 1955. These samples were taken during a period of low flow and are not applicable to periods of flood or other high runoff. The return flow from irrigation drains was generally low except that of Colusa Drain and Sacramento Slough. The location of sampling sites is shown in plate 3; the data are presented in table 2; and the principal mineral constituents are shown graphically in figure 2.

It will be noted from figure 2 that the main stem of the Sacramento River does not increase greatly in dissolved solids from the Delta station downstream to the station at Colusa; the first major increase in dissolved solids occurs at Knights Landing. The specific conductance at Colusa is 132 micromhos while at Knights Landing it has increased to a little over 200 micromhos. This indicates approximately a 50 percent increase in dissolved solids. The water from two large irrigation drains that discharge into the Sacramento River upstream from Knights Landing causes this increase. The dissolved solids in the Sacramento River at Sacramento only slightly exceed those of the Sacramento River at Knights Landing. This slight increase is explained by the fact that the water from several irrigation drains that flow into the Sacramento River above Sacramento is diluted by the large flow of the Feather and American Rivers.

For the most part, the water of the Sacramento River basin is of the calcium and magnesium bicarbonate type. Dissolved solids range from 41 to 418 ppm, and the silica content ranges from 7 to 38 percent of the total dissolved solids.

Figure 2 shows graphically the comparison of the mineral content of the Sacramento River from Delta to Sacramento with that of its tributary streams. Even though several of the tributary streams, such as Antelope Creek and Deer Creek, contain nearly twice as many dissolved solids as the Sacramento River, their effect upon the dissolved solids content of that river is not discernible. The reason for this becomes apparent when the flows of these streams are compared. On July 19, 1955, Antelope Creek and Deer Creek had flows of 32 and 94 cfs (cubic feet per second), respectively, whereas the Sacramento River just below Deer Creek had a flow of 11,300 cfs. Thus, the highly concentrated small quantity of water from Antelope and Deer Creeks is negligible in comparison with the flow of the Sacramento River.

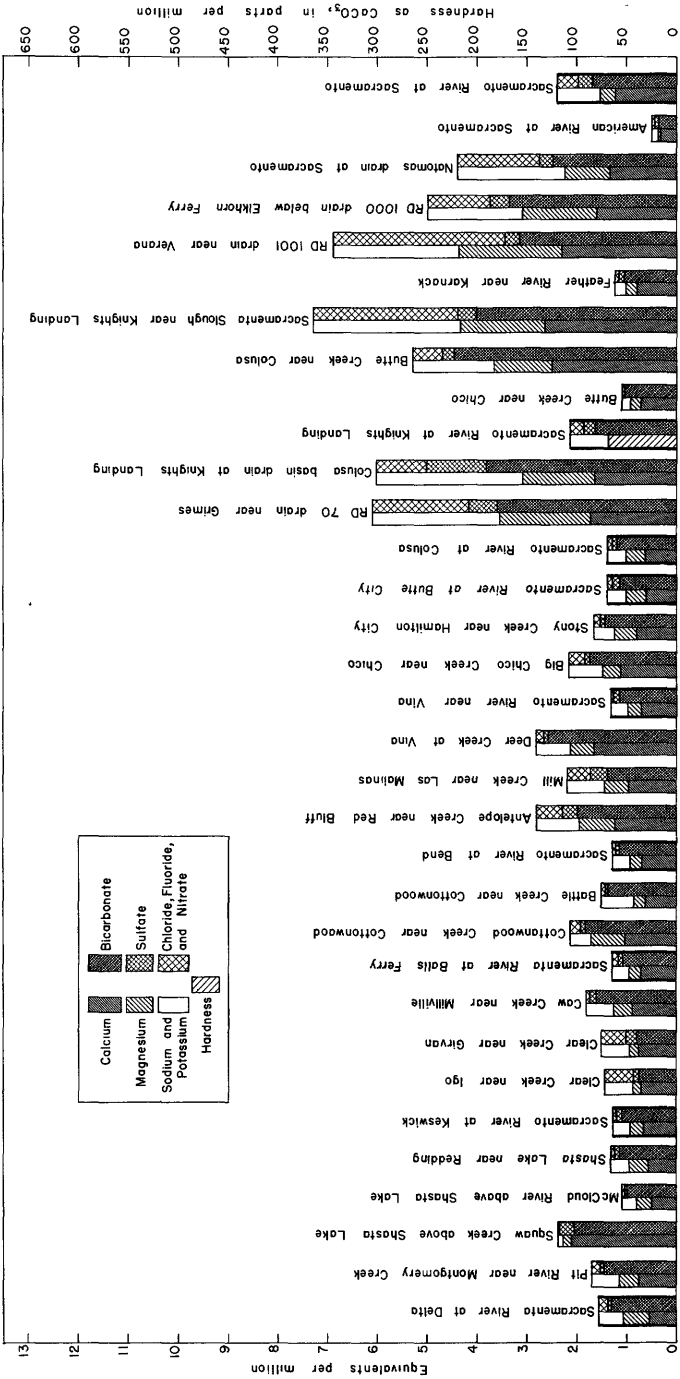

FIGURE 2.—Principal mineral constituents in surface water, salinity survey, July 18 to 21, 1955, Sacramento River basin, California. Sacramento River at Knights Landing shows combined calcium and magnesium as "hardness."

TABLE 2.—*Mineral constituents and related physical measurements, salinity survey, July 18 to 21, 1955*

[Analytical results in parts per million except as indicated]

Station	Date of collection	Discharge (cfs)	Silica (SiO_2)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Boron (B)	Dissolved solids (Sum)		Hardness as $CaCO_3$		Percent sodium	Specific conductance (micromhos at 25° C)	pH
														Parts per million	Tons per acre-foot	Calcium, magnesium	Noncarbonate			
Sacramento River at Delta	7-18-55	230	25	10	6.9	9.5	1.0	80	2.9	6.2	0.0	0.0	0.19	101	0.14	53	0	27	146	8.2
Pit River near Montgomery Creek	do	3,930	28	15	4.9	11	2.0	89	4.0	4.5	.0	.0	.16	114	.16	58	0	28	159	7.7
Squaw Creek above Shasta Lake	do	33	14	41	1.2	3.7	.2	126	14	.8	.0	.0	.02	137	.19	107	4	7	220	8.2
McCloud River above Shasta Lake	do	988	33	10	3.9	5.4	1.5	62	1.8	1.5	.0	.0	.01	88	.12	41	0	22	99	8.1
Shasta Lake near Redding	do	(1)	23	11	4.6	7.8	1.4	71	4.3	2.9	.0	.0	.07	90	.12	46	0	26	143	7.5
Sacramento River at Keswick	do	11,200	23	13	3.1	7.0	1.4	68	4.7	2.3	.0	.0	.05	88	.12	45	0	24	123	7.9
Clear Creek near Igo	7-19-55	42	18	14	2.0	12	1.0	47	9.2	17	.1	.2	.00	96	.13	43	4	37	146	7.8
Clear Creek near Girvan	do	----------	19	15	2.1	12	1.0	49	11	17	.1	.2	.00	101	.14	46	6	35	153	7.6
Little Cow Creek near Iugot	7-18-55	----------	------	------	------	9.6	------	93	------	11	------	------	------	------	------	71	0	------	186	7.4
Cow Creek near Millville	7-19-55	15	38	18	4.6	11	2.2	99	6.4	2.0	.1	.4	.01	132	.18	64	0	26	180	7.5
Sacramento Rover at Balls Ferry	do	10,800	24	14	2.8	7.0	1.5	68	3.8	38	.0	.2	.02	90	.12	46	0	24	125	7.8
Cottonwood Creek near Cottonwood	do	73	26	21	8.2	8.6	1.5	112	5.4	6.7	.0	.5	.00	133	.18	86	0	18	206	7.8
Battle Creek near Cottonwood	do	123	44	13	5.1	8.4	2.5	86	1.0	3.6	.0	.4	.05	120	.16	54	0	24	149	8.2
Sacramento River at Bend	do	11,200	23	14	3.0	7.3	1.5	70	4.1	2.9	.0	.2	.03	90	.12	47	0	24	128	7.6
Antelope Creek near Red Bluff	do	32	44	24	8.4	17	4.1	121	15	18	.3	.5	.45	192	.26	94	0	21	280	7.8
Mill Creek near Los Molinos	do	121	37	19	5.7	15	3.7	85	17	16	.0	.2	.41	156	.21	71	1	33	223	7.6
Dear Creek at Vina	do	94	37	33	5.8	14	2.8	159	3.8	5.4	.0	.1	.12	180	.24	106	0	22	261	8.0
Sacramento River near Vina	do	11,300	25	14	3.0	7.3	1.5	70	6.7	1.7	.0	.1	.00	93	.13	47	0	24	129	7.9
Big Chico Creek near Chico	7-20-55	26.5	38	22	4.4	14	1.3	107	4.9	11	.0	.1	.16	149	.20	73	0	29	205	7.8
Stony Creek near Hamilton City	7-19-55	----------	25	16	5.2	8.4	1.3	88	5.1	4.5	.0	.1	.06	109	.15	61	0	22	159	8.2
Sacramento River at Butte City	7-20-55	8,650	26	12	4.8	7.3	1.4	70	6.8	3.3	.1	.4	.03	96	.13	50	0	24	127	7.9
Sacramento River at Colusa	do	8,020	26	13	4.6	7.3	1.4	73	5.4	2.9	.1	.3	.04	97	.13	51	0	23	132	7.9
Drainage Water RD 70, pump, near Grimes	do	----------	31	34	22	56	1.2	221	27	67	.2	1.6	.12	349	.47	174	0	41	583	8.1
Colusa Basin Drain at Knights Landing (Back Borrow Pit)	do	496	23	33	18	66	1.6	233	58	34	.4	.9	.32	350	.48	156	0	48	571	8.0
Sacramento River at Knights Landing right bank	do	6,960	------	------	------	21	------	108	------	11	------	------	------	------	------	74	0	------	240	7.2
Sacramento River at Knights Landing, right of center	do	6,960	------	------	------	18	------	100	------	10	------	------	------	------	------	69	0	------	216	7.1
Sacramento River at Knights																				

Landing, left of center	do	6,960				15		95		8.0						65	0		197	7.2
Sacramento River at Knights Landing, left bank	do	6,960				15		92		8.0						64	0		194	7.1
Butte Creek near Chico	do	148	17	14	2.3	3.8	.9	64	28	.0	.0	.1	.01	74	.10	44	0	15	105	7.8
Butte Creek near Colusa	do	137	36	49	14	36	1.3	271	12	21	.2	10	.24	304	.41	180	0	30	470	8.2
Sacramento Slough near Knights Landing	do	451	33	53	21	67	1.4	246	18	102	.2	.9	.13	418	.57	217	15	40	712	
Feather River near Karnack	do		17	16	2.8	4.6	1.1	64	5.6	2.8	.1	.2	.00	82	.11	51	0	16	125	7.8
Drain, RD 1001, near Verona	7-21-55		29	46	25	56	2.0	193	14	121	.3	.9	.19	389	.53	219	61	36	700	7.8
Drain 3, RD 1000, below Elkhorn Ferry	do	[2] 26	30	32	18	42	1.5	204	20	42	.3	2.1	.18	288	.39	155	0	37	469	7.9
East Borrow Pit (Natomas Drain) at Sacramento	do		58	26	11	45	5.6	151	13	55	.6	3.7	.26	292	.40	110	0	46	444	7.6
American River at Sacramento	do	3,220	14	6.4	.3	2.4	.8	22	4.0	.9	.1	10	.03	41	.06	17	0	22	45	
Sacramento River at Sacramento Tower Bridge, Sta. 1	do	[3] 9,270				18		103		14						76	0		233	7.0
Sacramento River at Sacramento Tower Bridge, Sta. 2	do	[3] 9,270	26	24	3.5	19	1.9	103	13	15	.1	.3	.06	154	.21	74	0	35	230	8.0
Sacramento River at Sacramento Tower Bridge, Sta. 3	do	[3] 9,270				12		74		9.5						53	0		165	7.0

[1] Reservoir capacity 3, 277,300 acre-feet.
[2] Mean discharge.
[3] Estimated mean discharge.

Below Colusa, two major irrigation drains return concentrated water in considerable quantities to the Sacramento River. The effect of this water can be seen from the analyses of the Sacramento River at Knights Landing. (See fig. 2.)

Between Knights Landing and Sacramento, three drains returning concentrated water to the river were sampled. As can be seen from figure 2, the Sacramento River at Sacramento shows little increase in the content of dissolved solids. This is probably due to the large quantity of relatively dilute water from the Feather and American Rivers that flows into the Sacramento River between the Knights Landing station and Sacramento.

SACRAMENTO RIVER AT DELTA

Samples were collected periodically from the station at the town of Delta from April 1951 to September 1958.

The relation between stream flow and mineral composition for the Sacramento River at Delta for the period October 1953 to September 1954 is shown in figure 3.

During periods of low stream flow, the dissolved solids content of the water is indicative of the quality of the ground water inflow to the stream; during periods of high flow, the surface runoff dilutes the stream and the content of dissolved solids decreases. The water at the Delta station is generally of the calcium and magnesium bicarbonate type, resulting from the solution of the pre-Cretaceous metamorphosed marine sediments and the igneous rocks that underlie this area. The magnesium content is derived largely from the ultramafic intrusive rocks present in the drainage area.

During the period from October 1951 to September 1958, the specific conductance of the water ranged from 56 to 163 micromhos, hardness from 26 to 56 ppm as $CaCO_3$, percent sodium from 9 to 38, and boron from 0.00 to 0.28 ppm. (See table 3.) These ranges of concentration were obtained from monthly samples and therefore may not be the true ranges in the concentrations of the constituents. Since these samples were collected only once a month, the possibility is quite remote that the actual maximum and minimum concentrations occurred at the times of sampling. The longer the sampling period, the better the chances are of sampling the true maximum and minimum concentrations. However, the values obtained are probably sufficiently close to the true maximum and minimum to be usable with little error.

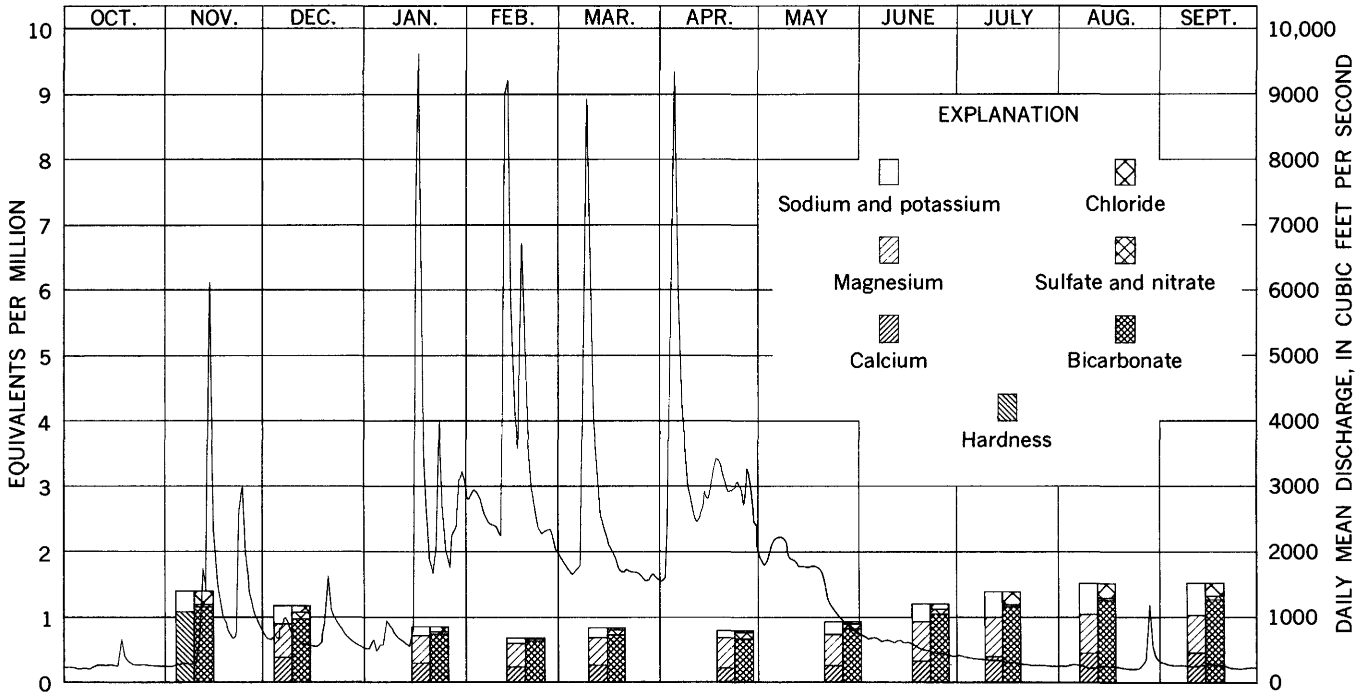

FIGURE 3.—Relation between chemical composition and discharge, Sacramento River at Delta, October 1953 to September 1954. November record shows combined calcium and magnesium as "hardness."

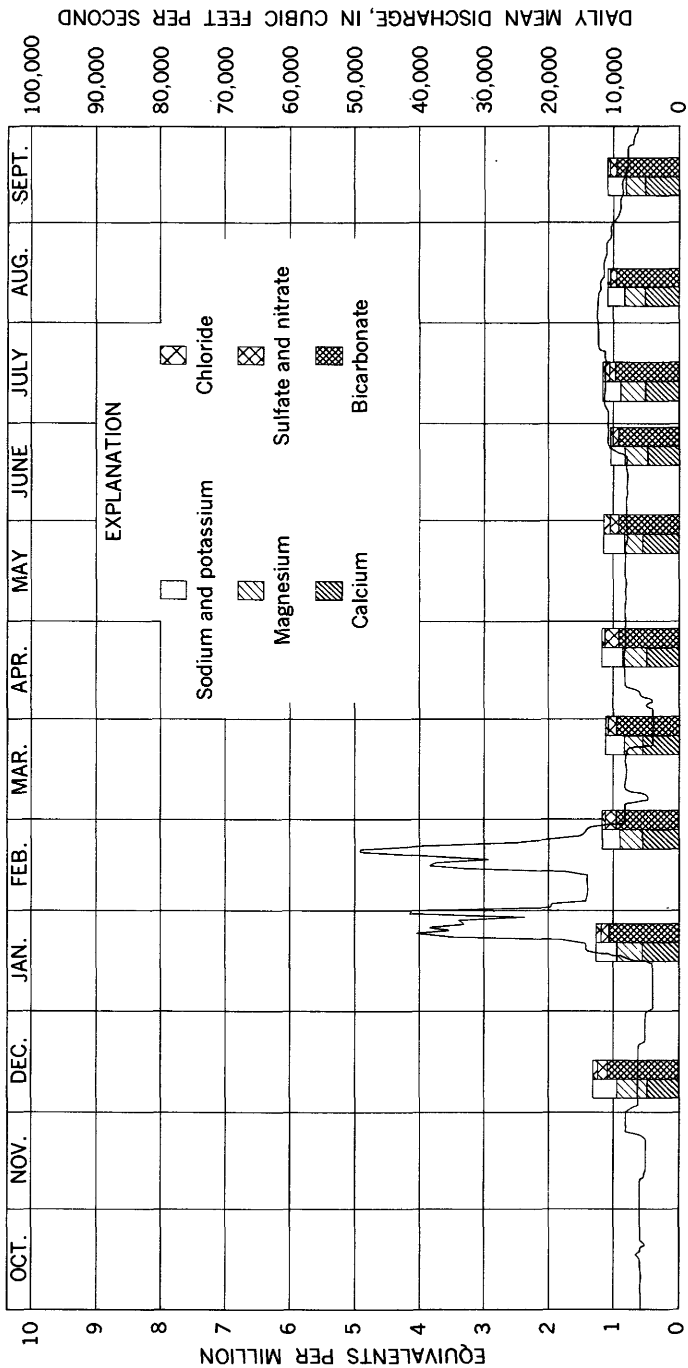

FIGURE 4.—Relation between chemical composition and discharge, Sacramento River near Keswick, October 1953 to September 1954.

TABLE 3.—*Ranges of specific conductance, hardness, percent sodium, and boron for streams in the Sacramento River basin, 1951–58*

Stream	Specific conductance (micromhos at 25°C)		Hardness as $CaCO_3$ (ppm)		Percent sodium		Boron (ppm)	
	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.
Sacramento River at Delta	163	56	56	26	38	9	0.28	0.00
Pit River near Montgomery Creek	183	101	63	40	34	20	.19	.00
McCloud River above Shasta Reservoir	150	79	54	31	28	15	.72	.00
Sacramento River at Keswick	139	86	66	36	30	17	.18	.00
Cottonwood Creek near Cottonwood	389	89	150	41	23	12	.20	.00
Mill Creek near Los Molinos	252	70	88	22	43	22	.73	.00
Deer Creek at Hwy. 99E Bridge near Vina	332	56	149	22	34	17	.71	.00
Sacramento River near Hamilton City	161	95	68	37	32	18	.35	.00
Big Chico Creek near Chico	223	65	86	27	33	14	.24	.00
Stony Creek near Hamilton City	404	188	170	81	24	14	.64	.00
Colusa Trough near Colusa	1,670	269	418	76	58	34	.44	.00
Sacramento River at Knights Landing	447	99	114	36	46	15	.31	.00
Butte Creek near Chico	127	47	55	21	23	11	.21	.00
Feather River at Nicolaus	245	50	114	22	27	8	.19	.00
American River at Sacramento	112	29	41	12	28	8	.23	.00
Sacramento River at Sacramento	299	63	97	23	38	14	.32	.00
Cache Creek near Lower Lake	490	140	200	56	23	14	2.2	.08
N. Fk. Cache Creek near Lower Lake	884	181	344	76	37	14	7.4	.16
Cache Creek near Capay	968	210	348	83	42	16	5.0	.15
Putah Creek near Winters	868	146	371	67	33	6	1.7	.00

Table 3 lists the maximum and minimum concentrations for the main tributary streams in the Sacramento basin. This table has been included so that the values for the entire basin can be more easily compared.

SACRAMENTO RIVER AT KESWICK

Samples were collected periodically from the station at Keswick between April 1951 and September 1958. Figure 4 shows the relation between mineral composition and stream flow for the period October 1953 to September 1954. The flow in the Sacramento River at the Keswick station is controlled by releases from Keswick Reservoir, which is only a short distance upstream from the station. Because of this control, the usual variations of chemical quality with stream flow do not occur. Some dilution of the stream does occur during periods of high surface runoff. However, these changes are small because the station is only 0.6 mile downstream from the reservoir, and therefore, only the small part of the drainage area above the station is uncontrolled.

The water at this station is a mixture of the water of the Sacramento, Pit, and McCloud Rivers, and Squaw Creek. The drainage area of these streams is steep mountain country. It is underlain by pre-Cretaceous metamorphic rocks and pre-Cretaceous and Tertiary igneous rocks that produce water low in dissolved solids and generally of the calcium and magnesium bicarbonate type.

For the period October 1951 to September 1958, the specific conductance of the Sacramento River water at Keswick ranged from 86 to 139 micromhos, hardness from 36 to 66 ppm as $CaCO_3$, percent sodium from 17 to 30, and boron from 0.00 to 0.18 ppm. (See table 3.)

SACRAMENTO RIVER NEAR HAMILTON CITY

Samples were collected periodically at the station near Hamilton City from April 1951 to September 1958. The relation between mineral composition and stream flow for the period October 1953 to September 1954 is shown in figure 5.

The water in the Sacramento River near Hamilton City is a mixture of water from the Sacramento River, Clear Creek, Cottonwood Creek, Deer Creek, and Mill Creek; it is similar to the water at Keswick. Cottonwood Creek water flows across the marine sedimentary rocks of the Coast Ranges and has a high concentration of dissolved solids. Mill Creek contributes water that is higher in sodium and chloride content than is the water of the Sacramento River.

Owing to the controlled flow of the Sacramento River, the usual variations in dissolved solids content with stream flow are obscured at this station. During low-flow period, the more highly mineralized

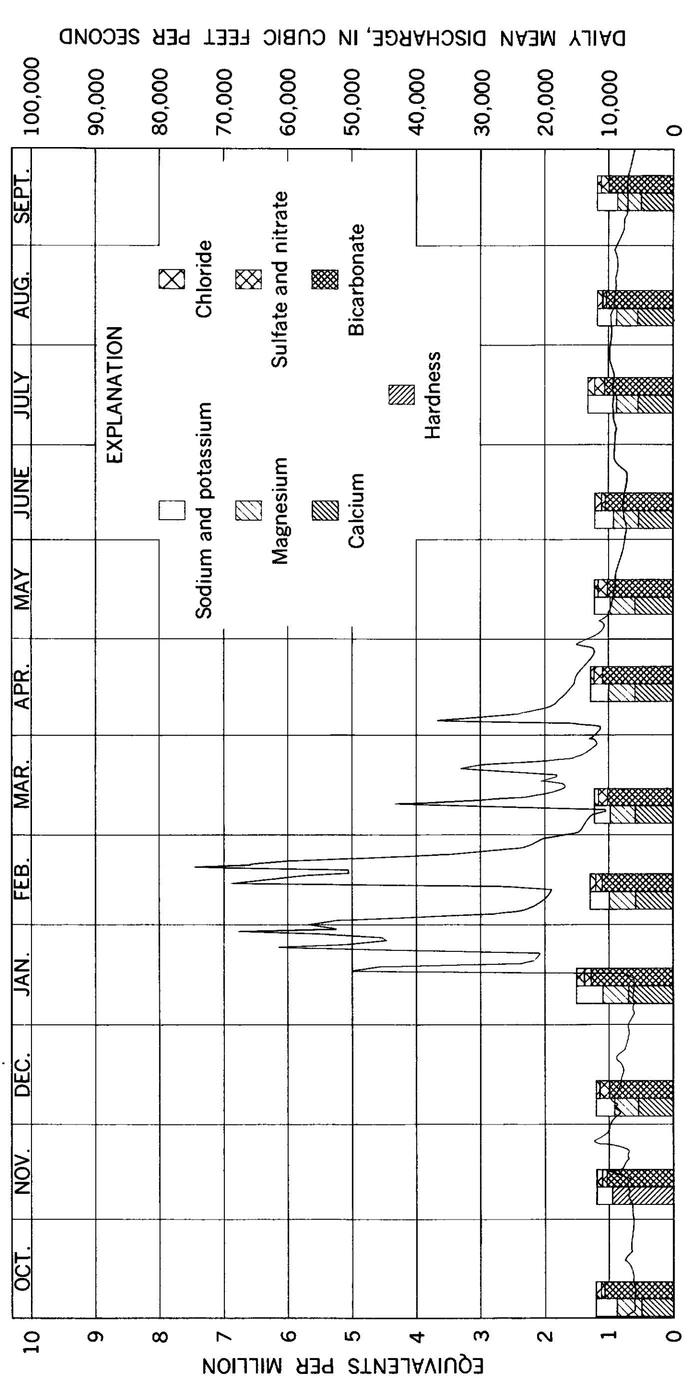

FIGURE 5.—Relation between chemical composition and discharge, Sacramento River at Hamilton City, October 1953 to 1954. November record shows combined calcium and magnesium as "hardness."

water of the tributary streams does not effect a noticeable change in the dissolved solids content of the Sacramento River because of the large flow maintained in the river. However, a slight increase in ions can be noted in the Sacramento River at Hamilton City. Mineral springs in the Lassen Peak area, where Mill and Deer Creeks head, contribute to the sodium and chloride as well as to the boron concentrations in these streams. Boron is usually associated with volcanic activity, and this has been an area of such activity to recent time.

For the period October 1951 to September 1958, the specific conductance at Hamilton City ranged from 95 to 161 micromhos, hardness from 37 to 68 ppm as $CaCO_3$, percent sodium from 18 to 32, and boron from 0.00 to 0.35 ppm. (See table 3.)

SACRAMENTO RIVER AT KNIGHTS LANDING

Periodic samples were collected at this station from September 1951 to September 1958, and daily samples were collected about a quarter of a mile below this station from March 1951 to September 1958.

The water in the Sacramento River at Knights Landing is more highly concentrated than the water at Hamilton City. Colusa Basin drain is the main drain for most of the irrigated lands on the west side of the Sacramento River above Knights Landing. It contributes as much flow to the Sacramento River as do several of the major tributary streams above Colusa. The water of the Sacramento River and Stony Creek that is used for irrigation in this area is concentrated by evaporation and transpiration; therefore, the water returned to the Sacramento River via the Colusa drain is from three to five times more highly concentrated with dissolved solids than the applied water. The concentration of chloride and sulfate ions has been increased, and calcium ions have been exchanged for sodium ions in the soil. Some calcium probably has been lost by precipitation as calcium carbonate.

Big Chico Creek, which drains the Sierra Nevada, contributes typical mountain water of low mineral content, predominantly calcium bicarbonate type. Hot springs near the headwaters of Big Chico Creek contribute some sodium and chloride ions to this stream.

Stony Creek drains the pre-Cretaceous marine sedimentary rocks of the Coast Ranges and contributes water of moderate dissolved solids content to the Sacramento River above Knights Landing.

The relation between stream flow and mineral content of the Sacramento River at Knights Landing is given in figure 6.

The main increase in dissolved solids content occurs during the irrigation season from May to December, the period of normally low flow in the Sacramento River and its tributary streams. However, the major factor affecting the increase at this station is probably the

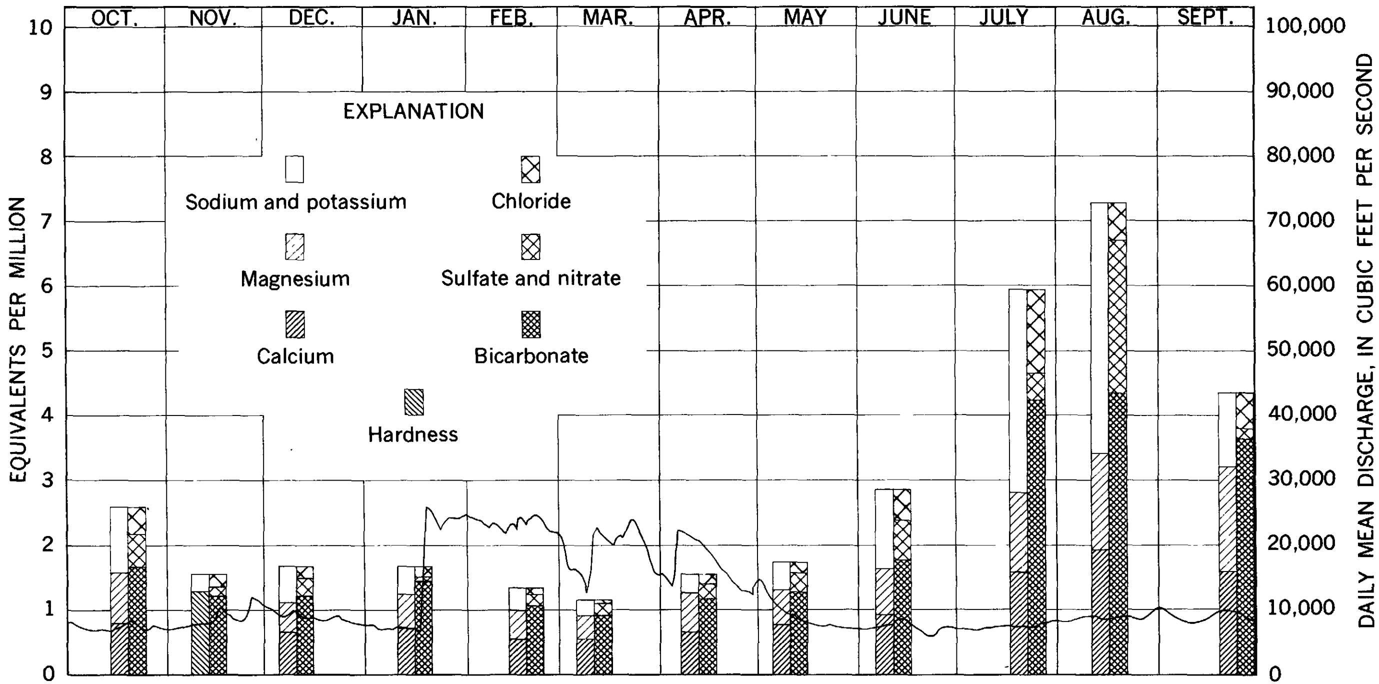

FIGURE 6.—Relation between chemical composition and discharge, Sacramento River at Knights Landing, October 1953 to September 1954. November record shows combined calcium and magnesium as "hardness."

irrigation return water from above Knights Landing. The July analysis shown in figure 6 has a higher dissolved solids concentration than the July analysis obtained during the salinity survey. This anomaly is caused by the following factors: The analyses illustrated in figures 2 and 6 were collected during different years; the monthly samples shown in figure 6 were collected from a station 0.2 miles upstream from the sampling location used for the salinity survey; the return water from Colusa drain is not as well mixed at the monthly station as it is further downstream where the salinity survey was made. Table 4 shows the summary of data for the Sacramento River at Knights Landing for the period October 1952 to September 1958.

TABLE 4.—*Summary of data for Sacramento River at Knights Landing from October 1952 to September 1957*

Period	Tabulated value equaled or exceeded for indicated percent of days				
	1	10	50	90	99
Conductivity [1] *(micromhos at 25°C)*					
Oct. 1952–Sept. 1953	385	266	185	143	116
Oct. 1953–Sept. 1954	315	252	190	135	111
Oct. 1954–Sept. 1955	395	260	206	167	112
Oct. 1955–Sept. 1956	260	230	180	130	98
Oct. 1956–Sept. 1957	273	227	190	136	119
Average	320	250	190	145	114
Hardness [2] *(ppm $CaCO_3$)*					
Oct. 1952–Sept. 1953	102	85	67	55	48
Oct. 1953–Sept. 1954	94	80	62	52	46
Oct. 1954–Sept. 1955	114	86	72	62	44
Oct. 1955–Sept. 1956	88	79	65	50	41
Oct. 1956–Sept. 1957	92	78	68	52	47
Average	106	85	68	54	45
Bicarbonate [2] *(ppm)*					
Oct. 1952–Sept. 1953	126	108	84	66	52
Oct. 1953–Sept. 1954	138	113	82	63	53
Oct. 1954–Sept. 1955	160	116	95	80	51
Oct. 1955–Sept. 1956	126	111	86	61	44
Oct. 1956–Sept. 1957	126	105	89	63	57
Average	127	110	88	67	53
Temperature [1] *(°F)*					
Oct. 1952–Sept. 1953	72	70	60	48	46
Oct. 1953–Sept. 1954	70	67	59	48	45
Oct. 1954–Sept. 1955	72	70	57	45	43
Oct. 1955–Sept. 1956	74	71	59	46	44
Oct. 1956–Sept. 1957	75	71	57	46	43
Average	74	70	59	46	43

[1] Based on daily samples.
[2] Estimated from frequency of specific conductance and conductivity-concentration relationship.

For purpose of comparison, the periodic samples collected 0.2 mile upstream from the daily station at Knights Landing have been included in table 3 with those from the tributary streams of Big Chico Creek, Stony Creek, and Colusa Trough. These data show that the specific conductance of the Sacramento River at Knights Landing ranged from 99 to 447 micromhos, hardness from 36 to 114 ppm as $CaCo_3$, percent sodium from 15 to 46, and boron from 0.00 to 0.31 ppm for the period October 1951 to September 1958.

SACRAMENTO RIVER AT SACRAMENTO

Sampling was conducted at the Sacramento station periodically from April 1951 to September 1958.

Water in the Sacramento River at Sacramento is less concentrated with dissolved solids than the water sampled upstream at Knights Landing. This is due largely to the dilution of the river by its two major tributary streams, Feather River and American River. Both of these rivers have calcium bicarbonate type water that is generally low in dissolved solids. (See tables 5 and 6.)

The Feather River drains a large area underlain by igneous rocks in the Sierra Nevada. It joins the Sacramento River just below Knights Landing and dilutes the more concentrated water of that river.

The American River, which enters the Sacramento River just above Sacramento, contributes a large quantity of dilute water that further reduces the concentration of dissolved solids in the Sacramento River. South of the Feather River basin, the American River drains an area of the Sierra Nevada that is underlain by igneous rocks. The resulting water is low in dissolved solids and is predominantly a calcium bicarbonate type water.

Table 3 shows that the specific conductance of the American River water at Sacramento ranged from 29 to 112 micromhos, hardness from 12 to 41 ppm as $CaCO_3$, percent sodium from 8 to 28, and boron from 0.00 to 0.23 ppm for the period October 1951 to September 1958. Tables 5 and 6 show the summary of daily data for the period October 1952 to September 1958 for the two main streams tributary to the Sacramento River. These streams flow into the Sacramento River between Knights Landing and Sacramento and are a major factor in determining the chemical quality of the Sacramento River at Sacramento.

Figure 7 shows the relation between chemical composition and stream flow for the period October 1953 to September 1954.

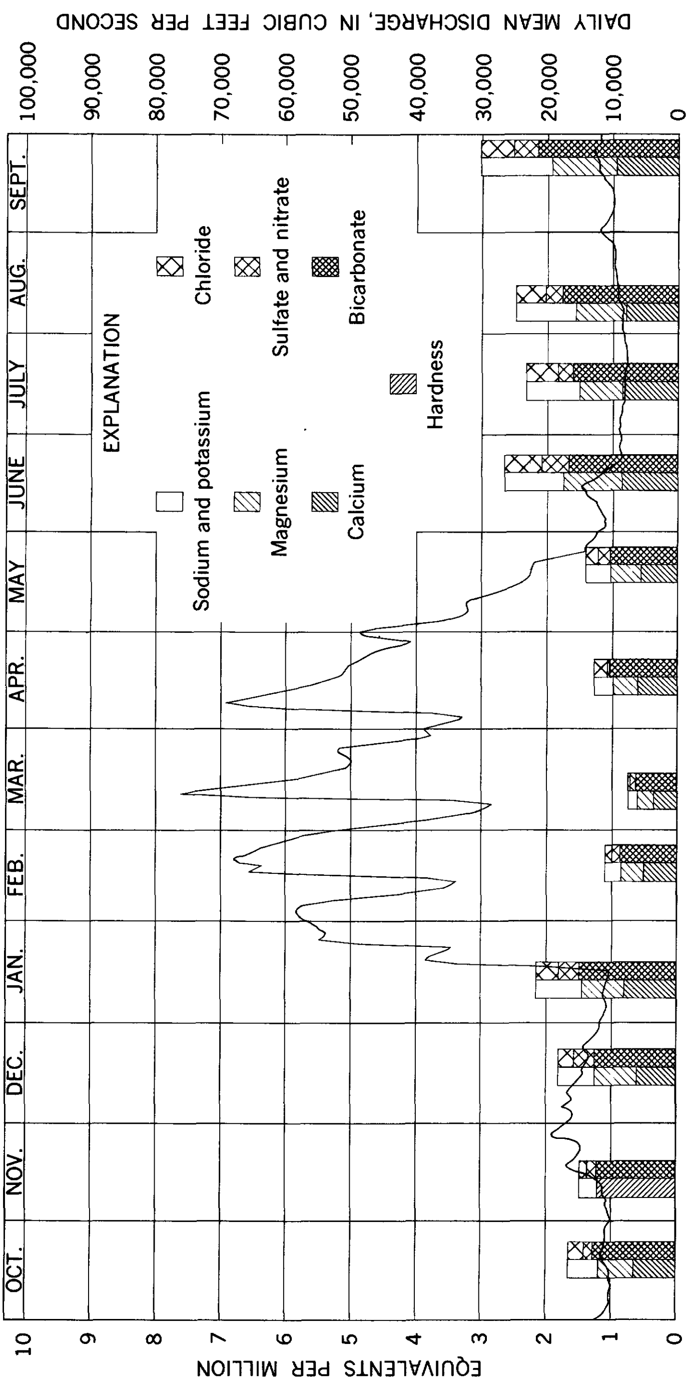

FIGURE 7.—Relation between chemical composition and discharge, Sacramento River at Sacramento, October 1953 to September 1954. November record shows combined calcium and magnesium as "hardness."

The ranges in concentration of the major mineral constituents of the Sacramento River at Sacramento for the period October 1951 to September 1958 are given in table 3. This table shows that the specific conductance of the Sacramento River at Sacramento ranged from 63 to 299 micromhos, hardness from 23 to 97 ppm as $CaCO_3$, percent sodium from 14 to 38, and boron from 0.00 to 0.32 ppm. It can be seen from table 3 that the water at Sacramento has a higher concentration of dissolved solids than the water at Hamilton City and that it is less concentrated than the water at Knights Landing. The diluting effect of the Feather and American Rivers is clearly indicated.

TABLE 5.—*Summary of data for Feather River at Nicolaus from October 1952 to September 1958*

Period	Tabulated value equaled or exceeded for indicated percent of days				
	1	10	50	90	99
Conductivity [1] *(micromhos at 25°C)*					
Oct. 1952–Sept. 1953	160	130	105	68	59
Oct. 1953–Sept. 1954	148	140	113	71	61
Oct. 1954–Sept. 1955	170	145	118	84	65
Oct. 1955–Sept. 1956	225	170	133	67	58
Oct. 1956–Sept. 1957	200	160	127	80	66
Oct. 1957–Sept. 1958	260	145	103	69	58
Average	200	148	115	72	60
Hardness [2] *(ppm $CaCO_3$)*					
Oct. 1952–Sept. 1953	73	59	46	29	23
Oct. 1953–Sept. 1954	62	60	47	30	26
Oct. 1954–Sept. 1955	68	60	48	35	28
Oct. 1955–Sept. 1956	112	76	56	27	24
Oct. 1956–Sept. 1957	91	68	51	34	30
Oct. 1957–Sept. 1958	126	61	42	29	25
Average	92	63	47	29	25
Bicarbonate [2] *(ppm)*					
Oct. 1952–Sept. 1953	80	67	54	35	30
Oct. 1953–Sept. 1954	79	75	60	37	31
Oct. 1954–Sept. 1955	88	78	63	46	36
Oct. 1955–Sept. 1956	141	98	73	38	35
Oct. 1956–Sept. 1957	112	88	67	39	30
Oct. 1957–Sept. 1958	147	77	51	30	24
Average	115	80	59	34	28
Temperature [1] *(°F)*					
Oct. 1952–Sept. 1953	76	72	54	45	43
Oct. 1953–Sept. 1954	80	73	57	45	42
Oct. 1954–Sept. 1955	78	74	55	43	40
Oct. 1955–Sept. 1956	79	74	65	48	45
Oct. 1956–Sept. 1957	78	74	56	42	39
Oct. 1957–Sept. 1958	78	74	56	45	43
Average	78	74	58	44	40

[1] Based on daily samples.
[2] Estimated from frequency of specific conductance and conductivity-concentration relationship.

TABLE 6.—*Summary of data for American River at Fair Oaks from October 1952 to September 1958*

Period	Tabulated value equaled or exceeded for indicated percent of days				
	1	10	50	90	99
Conductivity [1] *(micromhos at 25°C)*					
Oct. 1952–Sept. 1953	101	89	66	38	31
Oct. 1953–Sept. 1954	105	96	72	46	36
Oct. 1954–Sept. 1955	100	90	70	42	39
Oct. 1955–Sept. 1956	79	73	56	40	37
Oct. 1956–Sept. 1957	70	66	58	48	47
Oct. 1957–Sept. 1958	78	70	59	38	37
Average	100	85	61	40	33
Hardness [2] *(ppm $CaCO^2$)*					
Oct. 1952–Sept. 1953	41	37	28	16	13
Oct. 1953–Sept. 1954	43	39	29	19	14
Oct. 1954–Sept. 1955	40	36	28	16	15
Oct. 1955–Sept. 1956	31	29	22	16	15
Oct. 1956–Sept. 1957	31	26	22	18	18
Oct. 1957–Sept. 1958	31	27	23	14	13
Average	40	33	24	15	11
Bicarbonate [2] *(ppm)*					
Oct. 1952–Sept. 1953	46	41	32	20	18
Oct. 1953–Sept. 1954	48	44	34	23	18
Oct. 1954–Sept. 1955	47	43	34	23	21
Oct. 1955–Sept. 1956	41	38	31	24	22
Oct. 1956–Sept. 1957	32	30	27	23	22
Oct. 1957–Sept. 1958	34	31	26	17	17
Average	47	40	30	21	18
Temperature [1] *(°F)*					
Oct. 1952–Sept. 1953	78	73	53	46	43
Oct. 1953–Sept. 1954	80	74	57	46	42
Oct. 1954–Sept. 1955	75	70	56	42	40
Oct. 1955–Sept. 1956	71	65	56	46	43
Oct. 1956–Sept. 1957	67	63	45	45	43
Oct. 1957–Sept. 1958	66	61	54	44	33
Average	78	69	53	44	39

[1] Based on daily samples.
[2] Estimated from frequency of specific conductance and conductivity-concentration relationship.

SUITABILITY OF THE WATER FOR IRRIGATION

The suitability of water for irrigation depends not only upon the content of dissolved solids in the water, but also upon the type of soil and the drainage characteristics of the land. A description of the variations in soil types and drainage characteristics found throughout the Sacramento Valley is beyond the scope of this report; however, if good soil, drainage, and irrigation practices are assumed, the suitability of the water alone can be discussed.

Dissolved solids, percent sodium, and concentration of boron are the important considerations in determining whether or not a water supply is suitable for irrigation. In an otherwise acceptable water, if the equivalents of the alkalinity expressed as bicarbonate exceed the equivalents of calcium and magnesium by more than 1.25 epm (equivalents per million), the water may develop residual sodium carbonate and may be classed as unsuitable for irrigation (Eaton, 1950).

Of the several classifications of water for irrigation that have been developed, most investigators rely upon specific conductance and percent sodium. The more recent classifications have placed greater emphasis upon the composition of the water. The United States Salinity Laboratory Staff (1954) released a classification embodying the desirable features of earlier classifications into more recent developments, such as the sodium-adsorption ratio. This classification is the one used in this report and is quoted from p. 89–91 as follows:

Conductivity

Low-salinity water (C_1) can be used for irrigation with most crops on most soils with little likelihood that soil salinity will develop. Some leaching is required, but this occurs under normal irrigation practices except in soils of extremely low permeability.

Medium-salinity water (C_2) can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control.

High-salinity water (C_3) cannot be used on soils with restricted drainage. Even with adequate drainage, special management for salinity control may be required, and plants with good salt tolerance should be selected.

Very high-salinity water (C_4) is not suitable for irrigation under ordinary conditions but may be used occasionally under very special circumstances. The soils must be permeable, drainage must be adequate, irrigation water must be applied in excess to provide considerable leaching, and very salt-tolerant crops should be selected.

Sodium

Low-sodium water (S_1) can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium. However, sodium-sensitive crops such as stonefruit trees and avacados may accumulate injurious concentration of sodium.

Medium-sodium water (S_2) will present an appreciable sodium hazard in fine-textured soils having high cation-exchange-capacity, especially under low-leaching conditions, unless gypsum is present in the soil. This water may be used on coarse-textured or organic soils with good permeability.

High-sodium water (S_3) may produce harmful levels of exchangeable sodium in most soils and will require special soil management—good drainage, high leaching, and additions of organic matter. Gypsiferous soils may not develop harmful levels of exchangeable sodium from such waters. Chemical amendments may be required for replacement of exchangeable sodium, except that amendments may not be feasible with waters of very high salinity.

Very high-sodium water (S_4) is generally unsatisfactory for irrigation purposes except at low and perhaps medium salinity * * * where gypsum or other amendments may make the use of these waters feasible.

Figures 8, 9, and 10 show the water of the Sacramento River drainage basin classified according to this method. The data used in this classification are the periodic samples collected from October 1951 to September 1958. Rather than plotting points for these data, the areas covered by the indivdual analyses were plotted.

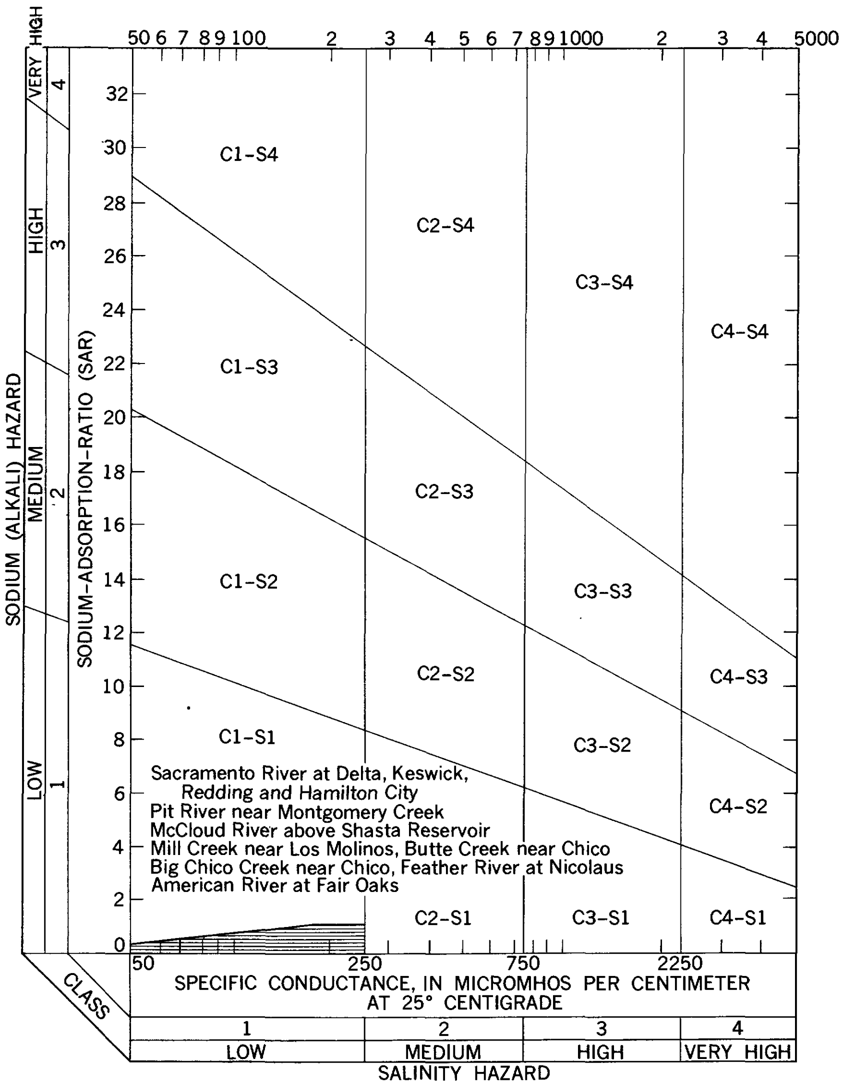

FIGURE 8.—Classification of water for irrigation (after U.S. Salinity Laboratory Staff, 1954, p. 80).

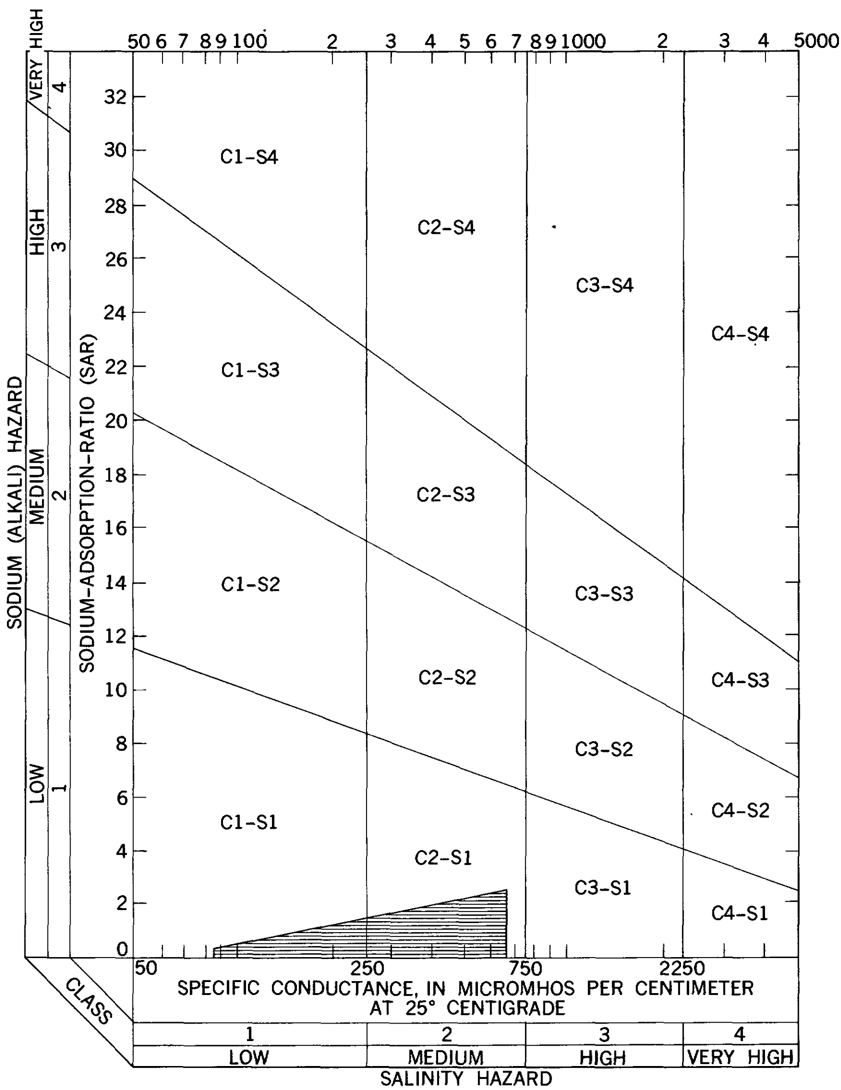

FIGURE 9.—Classification of water for irrigation (after U.S. Salinity Laboratory Staff, 1954, p. 80).

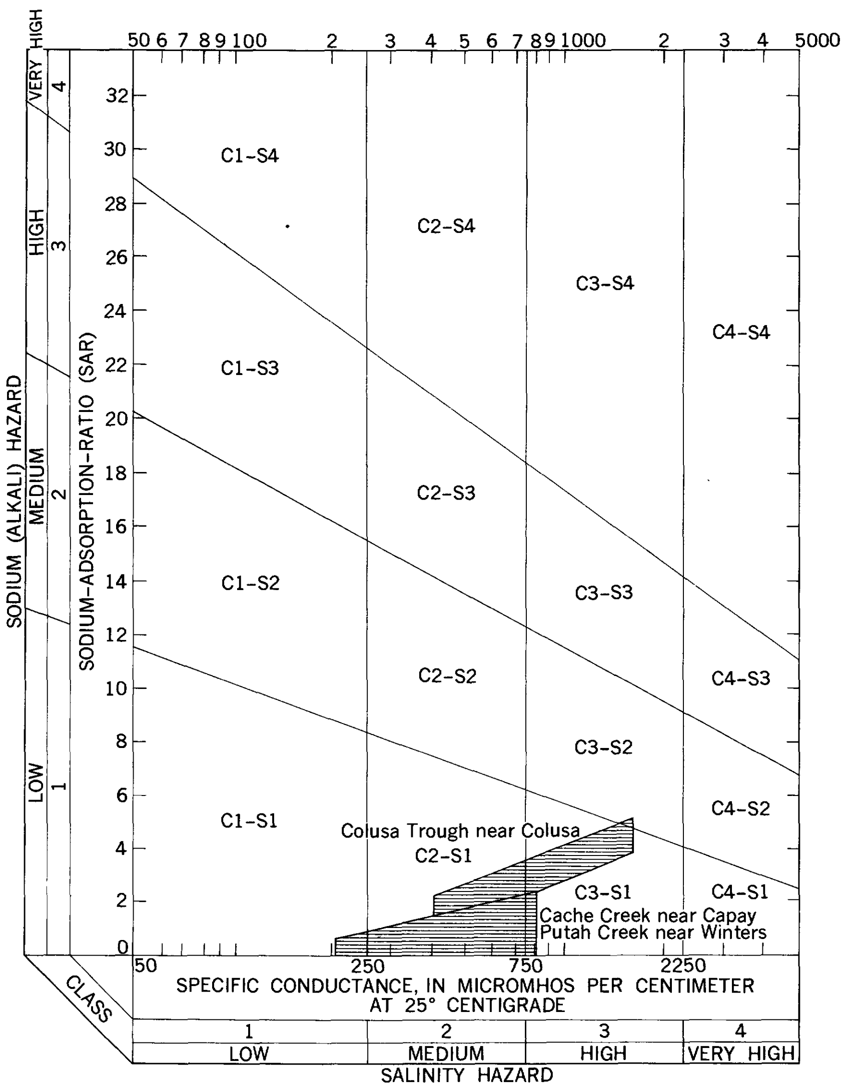

FIGURE 10.—Classification of water for irrigation (after U.S. Salinity Laboratory Staff, 1954, p. 80).

All water in the Sacramento River drainage area is classed as S_1 water except the irrigation return flow from Colusa Trough (fig. 10), which is classed occasionally as S_2. Water classed as S_1 can be used on almost all soils with little danger of the development of harmful levels of exchangeable sodium.

The salinity classification of water in the drainage basin range from C_1 to C_3. The water that is classed as C_1 for all periods includes the Sacramento River down to Hamilton City and most of the eastern tributary streams (fig. 8). The exceptions are the Pit River at Canby and Deer Creek near Vina, which are classed as C_2 during periods of low stream flow. Those streams that are classed as C_2 include the Sacramento River from Knights Landing to Rio Vista and all western tributary streams (fig. 9). Most of these streams are classed C_1 during periods of high stream flow but increase to class C_2 during periods of low stream flow. Since the major portion of the flow is class C_1, this water if impounded in a reservoir would be class C_1. Cache Creek near Capay and Putah Creek near Winters are occasionally classed as C_3 during periods of low flow (fig. 10).

Water classed C_1 can be used with most crops and on most soils with little likelihood that soil salinity will develop. Water classed as C_2 can be used on most soils if a moderate amount of leaching occurs. Water classed as C_3 cannot be used on soils with restricted drainage. Even with adequate drainage of the soil, special management for salinity control may be required, and plants with good salt tolerance should be planted.

As of 1954, approximately 850,000 acres of land in the Sacramento Valley was being irrigated. Of this area, about 500,000 acres was irrigated with surface water, mainly from the Sacramento River. Slightly more than 2,000,000 acre-feet of water was diverted from surface flow during the irrigation season. Approximately one-third of this water was returned to the Sacramento River as irrigation drainage. Although the return water contains more dissolved solids than the original irrigation water, the dissolved solids of the Sacramento River increase very little as a result of the mixing. Analyses of water from the Sacramento River at Knights Landing show an increase in dissolved solids; therefore, that station located about a quarter of a mile down stream from the outlet of the Colusa Basin drain, readily reflects the effect of irrigation return. The largest tributaries to the Sacramento River, the Feather and American Rivers, flow into the Sacramento River below Knights Landing and above Sacramento. The analyses of the water at Sacramento show that the dilution effect of the tributaries is such that the water of the Sacramento River at

Sacramento has only about twice the dissolved solid content of the water in Shasta Reservoir.

The ultimate extent of irrigation envisioned for the Sacramento Valley by the State of California in the California Water Plan will be about 2.5 times the present acreage. At the present time, about one-half of the irrigation in the valley utilizes surface water. Therefore, if the additional irrigation utilizes only surface water, a 2.5 times increase in acreage will require a fivefold increase in surface water diversion.

What effect will the use of this large quantity of water have on the quality of the water in the Sacramento River? By assuming the quality of the Sacramento River at Hamilton City to be representative of natural quality, and the quality of the Sacramento River at Sacramento to be representative of quality effected by irrigation, an estimate of the effect of increased irrigation can be made. The 90th percentile value has been taken for the high dissolved solids value in the calculations. This value has been used because it was felt that the maximum value tabulated from the monthly data could have been anomolous. The 90th percentile values for the Hamilton City and Sacramento stations are 147 and 278 micromhos, respectively. The difference between these values, 131 micromhos, is considered to be the effect of present irrigation return flow. By adding 3 and 5 times this difference to the quality at Sacramento, the values of 671 and 933 micromhos are obtained.

These values are very rough estimates and do not take into consideration the increased stream flow that could result when the Trinity River Diversion is completed; or the decrease, if any, caused by the Feather River Project. An increase in water use will reduce the present flow in the Sacramento River, but this may be offset by the additions from the Trinity Diversion. All of the improvements that are planned will affect the concentration of dissolved solids in the Sacramento River, but at the present time their effect cannot be estimated accurately. The calculated specific conductance for a fivefold increase in surface water diversion exceeds the limit recommended by the Board of Water Quality Consultants for water to be exported south of the delta area. Some increase in dissolved solids can be expected between Sacramento and the southern boundary of the delta area, but because this boundary is outside the area of this report, the data at Sacramento must be used.

At the present time, slightly less than 1,250,000 acre-feet of ground water is used for irrigation in the Sacramento Valley. Approximately one-third of this water is returned to surface streams as drainage water. Large amounts of this drainage water flow into Cache Slough, which enters the Sacramento River well below the reach from which irrigation water is pumped, but a considerable portion is returned to the Sacramento River within the reach presently used for irrigation. This return water has an increased mineral concentration and does affect the present dissolved solids content of the Sacramento River.

Cache and Putah Creeks are the tributary streams which have the poorest quality of water for irrigation. Weighted-average values calculated for these streams indicate that the water would be of better quality if it were impounded in a reservoir where the concentrated water of the low-flow periods would be diluted by the less concentrated water of the high-flow periods.

Table 7 shows the permissible limits of boron in irrigation water with respect to the tolerance of crops.

With the exception of Cache and Putah Creeks, the boron content of most of the streams in the Sacramento River basin can be classed as excellent for sensitive crops. The boron content of these two streams must be classed as unsuitable for sensitive crops.

At times, the high boron content of Cache Creek water changes the classification of the stream to unsuitable, even for tolerant crops. If all the flow of Cache Creek were stored in a reservoir, the boron content of the stored water would be reduced sufficiently to permit its use on some sensitive and all semitolerant crops. It should be understood that this comparison is based upon a weighted-average analysis calculated from monthly data.

The discharge-weighted boron concentration of Putah Creek water indicates that storage of the water would improve its classification to excellent.

TABLE 7.—*Permissible limits of boron, in parts per million, for irrigation water*

[After Wilcox, 1948]

Water rating	Sensitive crops	Semitolerant crops	Tolerant crops
Excellent	<0. 33	<0. 67	<1. 00
Good	0. 33–0. 67	0. 67–1. 33	1. 00–2. 00
Permissible	. 67–1. 00	1. 33–2. 00	2. 00–3. 00
Doubtful	1. 00–1. 25	2. 00–2. 50	3. 00–3. 75
Unsuitable	>1. 25	>2. 50	>3. 75

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INDEX

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