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GEOLOGY AND GROUND-WATER HYDROLOGY OF THE MOKELUMNE AREA, CALIFORNIA

BY

A. M. PIPER, H. S. GALE, H. E. THOMAS AND T. W. ROBINSON

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ABSTRACT

The Mokelumne River basin of central California comprises portions of the California Trough and the Sierra Nevada section of the Pacific Mountain system. The California Trough is divisible into four subsections—the Delta tidal plain, the Victor alluvial plain, the river flood plains and channels, and the Arroyo Seco dissected pediment. These four subsections comprise the land forms produced by the Mokelumne River and other streams since the Sierra Nevada attained its present height in the Pleistocene epoch.

The Victor alluvial plain rises eastward from the Delta plain and abuts on the dissected Arroyo Seco pediment; in the Mokelumne area it is 12 to 16 miles wide and slopes between 5 and 8 feet in a mile. It includes relatively extensive tracts that are intensively cultivated and irrigated with water pumped from wells. The Victor plain has been compounded of overlapping alluvial fans along the western base of the Sierra Nevada. It is prolonged eastward into the pediment by tongues of alluvium along several of the present streams; thus it seems likely that the present stream pattern in the eastern part of the area has been fixed since dissection of the pediment began.

Three of the four major streams—the Mokelumne and Cosumnes Rivers and Dry Creek—traverse the Victor plain in trenches which are 15 to 40 feet deep at the heads of their respective alluvial fans but which die out toward the west. The floors of these trenches, the historic flood plains, are from 100 yards to a mile wide. The exceptional major stream, which has not entrenched itself, is the Calaveras River.

The Arroyo Seco pediment, which lies east of the Victor plain, was initially at least 8 to 15 miles wide and lay along the western foot of the Sierra Nevada entirely across the Mokelumne area. Its numerous remnants decline 15 to 35 feet in a mile toward the west.

The Sierra Nevada section adjoins and lies east of the California Trough. Its major ridge crests define a volcanic plain whose westward slope is inferred to have been initially about 90 feet in a mile but is now about 180 feet in a mile, owing to tilting of the Sierra Nevada block in Pleistocene time.

In and near the Mokelumne area the Sierra Nevada and California Trough together are roughly coextensive with a single structural unit. The Sierra Nevada constitutes a block that has risen with respect to adjoining valley areas by simple rotation or tilting toward the west; it has not been warped or faulted extensively. It is inferred that this block extends westward beneath the thick alluvial deposits of the trough without material warping or faulting.

The oldest rocks of the Mokelumne region are the Carboniferous and Jurassic rocks that compose the crystalline core of the Sierra Nevada. These are overlain unconformably by sediments of Tertiary age—in upward succession the Ione, Valley Springs, Mehrten, and Laguna formations. Of these formations all except the Ione are newly discriminated, and type sections are described in the full text.

These Tertiary sediments form a great wedge, thinnest along the mountain front to the east, where they have been truncated by erosion. They dip about 2° W.

The Ione formation (Eocene) consists chiefly of sandstone, clay, and shale; its maximum thickness is 450 feet.

The Valley Springs formation (middle? Miocene) overlies the Ione formation unconformably. It is composed largely of greenish-gray clay, shale, and sandstone derived from rhyolitic ejectamenta. These rhyolitic deposits are confined to narrow channels in the higher part of the Sierra Nevada, but they spread fanlike over the lower western edge of the mountain block, where they attain a maximum thickness of 525 feet.

The Mehrten formation (upper? Miocene and lower Pliocene?) comprises the andesitic rocks that constructed the Sierran volcanic plain. In the Mokelumne area it consists chiefly of sandstone and siltstone but includes, as a minor though conspicuous part of the formation, layers and tongues of resistant breccia or agglomerate, which are presumed to have originated as mud flows. Nonfragmental andesite is not known to occur in the Mokelumne area, although several possible vents occur farther east. In the eastern part of the area the Mehrten formation truncates in turn the Valley Springs and Ione formations and the pre-Cretaceous rocks; in the western part the Mehrten formation (andesitic) interfingers with the underlying Valley Springs formation (rhyolitic). Its maximum measured thickness is 400 feet. Few of the irrigation wells are so deep that they can be said with assurance to reach the Mehrten formation.

The Laguna formation (Pliocene? and possibly lower Pleistocene) comprises poorly sorted, nonandesitic fluviatile sedimentary deposits that overlie the Mehrten formation. It is inferred to be essentially parallel to and tilted equally with the Mehrten formation and to be about 400 feet thick.

The Arroyo Seco gravel (presumably middle Pleistocene) veneers the Arroyo Seco pediment. At its easternmost outcrops the formation is composed of pebbles, cobbles, and boulders in a matrix of brick-red sand and silt; farther west, down the slope of the pediment, it becomes progressively finer. It is inferred that the Arroyo Seco gravel is a coarse fraction of the rock waste that was transported from the Sierra Nevada after the Sierran block was tilted in Pleistocene time. It is inferred further that the correlative of the Arroyo Seco gravel in the California Trough is a wedge-shaped mass of sediments whose base is the tilted Laguna formation and whose top can be interpolated by projecting a hypothetical surface through the remnants of the pediment.

The Victor formation comprises the fluviatile sand, silt, and gravel that built the Victor alluvial plain over the hypothetical equivalent of the Arroyo Seco gravel along the axis of the California Trough and against the western front of the dissected pediment to the east. The formation is thought to be about 100 feet thick along the western margin of the Mokelumne area, according to an estimate based upon projecting the slope of the Arroyo Seco pediment westward beneath the Victor plain.

The Mokelumne area lies on the fertile central plain along the Mokelumne River about the city of Lodi, in northern San Joaquin County, and has been intensively developed for the cultivation of grapes, deciduous fruits, and other crops. Of necessity its great productiveness is maintained by irrigation. Extensive irrigation from wells began about 1907 and has increased steadily until in 1932 about 50,000 acres (80 percent of the area) was watered in that manner. The specific question at issue is the extent to which the supply of ground water and hence the productiveness of the area are dependent upon the water flowing in the Mokelumne River and the extent to which that productiveness may be influenced by regulation of the stream—in particular, by the substantial regulation of the river that is accomplished by the Pardee Dam of the East Bay Municipal Utility District, which began to function in March 1929.

The depth of 1,447 irrigation wells in five townships in the central part of the area (T. 3 N., Rs. 6 and 7 E., and T. 4 N., Rs. 6 to 8 E.) ranges from 20 to 910 feet. About half the wells bottom within a 100-foot zone whose base is 75 feet below the projected Arroyo Seco pediment; essentially that zone constitutes the Victor formation. Only 6 percent of the wells bottom within the next lower 25-foot zone, but the percentage increases sharply for depths still greater; it is inferred that impervious strata are relatively persistent between 75 and 100 feet below the projected pediment and that these are the uppermost part of the Arroyo Seco gravel. Of 580 observation wells known to bottom in the Victor formation, essentially all appear to indicate a regional water-table stage; thus the water is essentially unconfined. On the other hand, nearly all wells so deep that they reach the Arroyo Seco gravel or some underlying formation tap confined water. Near the Mokelumne River the water levels in these deep wells stand below the water table, which is semiperched. In most deep wells remote from the river the water level stands above the water table except during the pumping season.

Fluctuations of ground-water levels are ascribed to moving or changing load on the land surface, earthquakes, variation of barometic pressure, ground-water draft by vegetation, infiltration of rain and certain indirect effects of rainfall, infiltration of water applied to the land for irrigation, variation in the discharge of streams, and pumping from wells.

In the eastern part of the central district, between Clements and the vicinity of Lockeford, it is inferred that (1) the river and the water in the alluvium of the flood plain are not insulated from the water in the sediments that form the adjacent Victor plain; (2) locally if not generally, however, there are discontinuities in pervious strata along the outer margin of the flood plain, where the water table passes from the alluvium into the enclosing sediments, so that percolation of ground water is impeded materially at that margin; (3) rising river stages set up ground-water waves that store relatively large volumes of water in the alluvium close to the river, whereas falling stages cause much of that stored water to percolate back into the river, weeks and even months lapsing before the ground-water stage becomes steady within the flood plain; and (4) seepage loss from the river into the alluvium tends to be intermittent and to alternate with seepage gain, the rate of loss or gain lagging weeks or months behind the fluctuations of river stage and lagging more for moderate changes at low stage. However, in the succeeding reach downstream as far as Woodbridge, it is inferred that percolation of ground water is not impeded generally along the outer margin of the flood plain and that the river tends to lose almost continuously by seepage rather than intermittently, although the rate of loss fluctuates somewhat in response to changing river stage.

The yearly pumpage for irrigation has been as much as 114,600 acre-feet (1928–29), and there have been as many as 2,500 wells equipped with irrigation pumping plants (1931). Commonly the wells are pumped only in daylight and are idle over week-ends and holidays, also during and after protracted rainstorms in the early part of the season. In a small district near Victor pumping in recent years has begun in January or February, has reached its height in March, and largely has passed by April. In outlying districts general pumping has begun as late as May, reached its height in June or July, and waned by September.

Since 1907 the water table appears to have declined steadily in most of the Mokelumne area except along the river. The decline was least in the Woodbridge Irrigation District, where in four typical wells the average decline from 1907 to 1937 was 3 feet, or 0.15 foot a year. Among 18 shallow wells in the district of most intensive pumping the average recession of the water table from 1907 to 1927 was 11 feet, or 0.55 foot a year; the greatest measured recession was 15 feet, or 0.75 foot a year. From 1927 to 1933 the water table declined 5 feet or more over most of the central pumping district except within 2 miles of the Mokelumne River, and the greatest measured decline was 9 feet. The area of material

recession extends 4 to 7 miles eastward beyond the central pumping district, whence it is inferred that pumping has drawn gradually on remote ground-water storage.

It is inferred that the Mokelumne River ordinarily has been a losing stream between the Mehrten dam site, near Clements, and the Woodbridge Dam, the area that received the percolate having been triangular with its apex upstream and having included about 5,200 acres of the flood plain and 36,500 acres in outlying districts to the north and to the south.

Mean fluctuations of the water table within the area receiving percolate from the river are believed to indicate that relatively little water is drawn from outside the area. Accordingly, simple storage methods are competent for a ground-water inventory. It is inferred that the rate of seepage loss from the river depends jointly upon river discharge, stage in the Woodbridge Reservoir, and ground-water pumpage.

The foregoing inferences lead to the following conclusions with respect to ground-water replenishment by seepage loss from the river in the intensively cultivated district about Lodi: (1) The annual replenishment has tended to increase for at least two decades, owing to the gradual increase in head between surface water and ground water as ground-water levels have been lowered progressively by pumping; (2) annual replenishment has tended to increase, especially in recent years, owing to gradually prolonged use of the Woodbridge Reservoir, for thereby a relatively large wetted area and great differential head have been maintained for an increasing term; (3) the rate of replenishment tends to be greater under regulation than under the so-called natural regimen, to the extent that regulation has maintained a moderately large wetted area and stage in the river through the later part of each pumping season, while the ground-water levels have been lowest. Moreover, for any particular yearly run-off below the Mehrten dam site, the replenishment by seepage would tend to be greater under the regulated regimen to the extent that fluctuations in discharge were suppressed, for the greatest yearly mean stage and mean wetted area would be afforded by constant discharge. Thus, diverting water out of the Mokelumne River Basin at the Pardee Dam does not necessarily entail a diminution in ground-water replenishment by seepage loss along the lower reach of the stream, at least in the replenishment beneath the Victor plain above the gaging station at Woodbridge. Rather, the Pardee Dam affords a means for so regulating the discharge as to effect a maximum ground-water replenishment with a given run-off in the natural channel.

Bodies of ground water perched above the regional water table are common in the Laguna formation, especially in its lower part. Conspicuous bodies occur about 3 miles south of Clay, in a district between 1 mile and 5 miles south of Clements, and along Dry Creek in T. 5 N., Rs. 7 and 8 E.

From the relation between the water table and the piezometric surface for water confined in deep aquifers, the area receiving percolate from the Mokelumne River may be divided roughly into (1) a central area, extending not more than half a mile beyond the flood plain, in which the piezometric surface is inferred to have stood below the water table throughout the term of the investigation and hence in which the difference in head has favored the percolation of water from shallow beds into deep beds in all seasons, and (2) an outlying area in which the difference in head likewise favors downward percolation into deep beds during the pumping season but favors upward percolation during the nonpumping season. This outlying area includes about 75 percent of the segment of the Victor plain that receives percolate from the river.

From 1927 to 1933 the subartesian head that existed during the nonpumping season in the area remote from the river tended to increase; it is therefore inferred that the relative opportunity for seasonal recharge of the shallow water-bearing beds by underfeeding has likewise tended to increase. On the other hand, the negative differential head in wells near the river also has tended to increase; thus in this central area the opportunity for discharge of water from shallow beds by downward percolation has probably tended to increase.

It is believed that ground-water storage within the area near the river is not decreased materially by discharge westward through deep pervious beds, also that the yearly addition to ground-water storage in the outlying area by deep percolation from a remote easterly source is scant and for all practical purposes is offset by downward percolation along the river.

INTRODUCTION

By A. M. Piper

LOCATION AND GENERAL FEATURES OF THE MOKELUMNE AREA

The Mokelumne River is one of the many streams that flow southwestward into the great central valley of California and that drain the westward-sloping volcanic plain of the Sierra Nevada. It joins the San Joaquin River near its confluence with the Sacramento River and about 20 miles east of the head of Suisun Bay, which is the extreme northeasterly segment of San Francisco Bay. As plate 2 shows, its drainage basin lies between 38° and 39° north latitude and approximately between 120° and 121°30′ west longitude.

The Mokelumne River is about 130 miles long and drains about 700 square miles. It rises at the crest of the Sierra in a relatively narrow headwater area in Alpine County, near the angle in the eastern boundary of the State; to the north lies the head of the American River, and to the south is the head of the Stanislaus River. Its three headwater branches—the North, Middle, and South Forks—occupy impressive canyons 1,000 to 4,000 feet deep and drain a rugged area which is about 47 miles long and 16 miles wide.

The largest branch, the North Fork, heads in the barren snow fields of the high Sierra, where the altitude ranges from 6,000 to 10,000 feet above sea level. However, much of the lower drainage area and most of the area drained by the Middle and South Forks is covered with a dense stand of conifers. Toward the west this type of vegetal cover grades into stunted hardwood trees and brush, which occupy all but the steepest rocky slopes. Below the junction of these branches no large tributaries enter the river within the Sierra Nevada section, and the area drained by the main river is confined within the two rims of its V-shaped canyon, which are generally less than 4 miles apart. In that reach the average grade of the river is about 50 feet in a mile.

The lower and western part of the Mokelumne River Basin lies on the central valley plain and comprises the northern part of San Joaquin County and the southern part of Sacramento County. There the river grade flattens sharply; it averages about 2 feet to the mile between the Sierran foothills and tidewater. In this reach the area that would naturally drain directly into the river is everywhere less than 2 miles wide and is commonly bounded by ill-defined remnants of natural levees along each rim of the river trench. Locally its natural drainage area has been materially reduced by artificial levees and flood-control works, so that even parts of the flood plain are no longer drained. Much of the flood plain is cleared and is cultivated in cereal, forage, and other crops,[1] but a minor fraction of the plain is covered with dense native brush.

This report is concerned primarily with a district that lies on the fertile central plain along the Mokelumne River and that centers about the city of Lodi, in northern San Joaquin County. That district has been intensively developed for cultivation of grapes, deciduous fruits, and other crops; of necessity, its great productiveness is maintained by irrigation. Extensive irrigation from wells began about 1907 and has increased steadily; in 1932 about 50,000 acres (80 percent of the district) was watered in that manner.

The largest settlement in the area is Lodi, whose population in 1930 was 6,776. In the contiguous rural districts the population averaged about 45 persons to the square mile. Stockton, the county seat, is 13 miles south of Lodi; Sacramento is about 35 miles to the north.

NATURE OF THE PROBLEM

Beginning in 1929 the East Bay Municipal Utility District of Oakland, Calif., has diverted water from the Mokelumne River Basin for municipal supply in the cities along the east side of San Francisco Bay. The diversion is effected at the Pardee Dam and reservoir, about 30 miles upstream from Lodi, in the Sierran foothills. The California Division of Water Resources, in authorizing the East Bay District to store water and to divert water from the basin, attached the following conditional clauses to its permit 2459, dated April 17, 1926:

1. The amount of water appropriated shall be limited to the amount which can be beneficially used and shall not exceed 310 cubic feet per second for direct diversion from January 1 to December 31 of each season and 217,000 acre-feet per annum for storage to be collected from about October 1 to about July 15 of each season, when there is unappropriated water available at the proposed point of diversion, the season of unappropriated water being in years of normal flow from about December 1 to about July 15; provided, however, that combined diversions from natural flow and storage shall not exceed the equivalent of 310 cubic feet per second, or approximately 200,000,000 gallons per day.

2. The maximum amount herein stated may be reduced in the license if investigation so warrants.

10. In order to determine the extent of prior vested rights to the use of Mokelumne River water which percolates into or supplies underground basins, permittee shall conduct such a study of the replenishment of and draft upon underground storage supply from the Mokelumne River as to determine with reasonable certainty the effect of the proposed diversion and storage upon the underground

[1] Areas covered by various species of vegetation on the bottom land of the Mokelumne River, Calif., between the Lancha Plana gaging station and the Woodbridge Dam: U. S. Geol. Survey typoscript rept., 17 pp., map, Feb. 25, 1932.

supplies and shall file such information as a matter of public record with the division of water rights from time to time and at any time upon demand by the said division.

Thus, the fundamental questions at issue in the Mokelumne area are the extent to which the supply of ground water and hence the productiveness of the area are dependent on the water flowing in the river and the extent to which this productiveness may be influenced by regulation of that stream.

NATURAL AND REGULATED REGIMENS OF THE MOKELUMNE RIVER

The Mokelumne River Basin lies in a region whose climate comprises a cool wet season and a warm dry season. Ordinarily the wet season begins in October or November and continues until the following May; in it occurs about 90 percent of the annual precipitation. January is ordinarily the wettest month. Further, the greater part of the drainage area lies in the mountainous headwater district, in which the altitude of the land surface ranges from 1,200 to 10,000 feet above sea level and the average annual rainfall ranges from 31 to 53 inches. At altitudes so high much of the precipitation is in the form of snow. Ordinarily, sufficient snow accumulates during the winter to induce a pronounced annual freshet in the river and to sustain a considerable flow far into the summer. However, as none of the snow fields are perennial, the natural run-off declines greatly by midsummer and remains relatively little throughout the autumn. These features are disclosed by the following table, which summarizes the monthly run-off in the Mokelumne River past the gaging station near Clements from 1905–6 to 1927–28. The 23-year term covered by this table precedes the diversion at the Pardee Dam, although the flow of the river was regulated in a relatively small degree throughout that period (pp. 8–10).

Range in monthly run-off in the Mokelumne River, measured at the gaging station near Clements, 1905–6 to 1927–28

[Based on publications of the United States Geological Survey]

Month	Run-off (acre-feet)		
	Maximum	Minimum	Average
October	17,000 (1907–8)	2,940 (1926–27)	8,140
November	56,600 (1909–10)	4,530 (1921–22)	14,500
December	92,200 (1909–10)	3,230 (1917–18)	22,900
January	179,000 (1908–9)	3,170 (1917–18)	50,900
February	154,000 (1906–7)	8,230 (1919–20)	62,700
March	300,000 (1906–7)	11,200 (1923–24)	96,200
April	264,000 (1906–7)	30,800 (1911–12)	141,000
May	318,000 (1921–22)	60,900 (1923–24)	201,000
June	358,000 (1905–6)	4,210 (1923–24)	154,000
July	218,000 (1905–6)	1,220 (1923–24)	43,700
August	43,200 (1906–7)	333 (1923–24)	9,720
September	15,300 (1906–7)	2,980 (1923–24)	7,080
The year	1,670,000 (1906–7)	182,000 (1923–24)	811,000

The following table and figures 1 and 2 show the relation between the yearly precipitation on the Mokelumne River Basin and the yearly run-off from the basin from 1905–6 to 1932–33.

Run-off from and precipitation on the drainage basin of the Mokelumne River above the gaging station near Clements, 1905–6 to 1932–33

Year (Oct. 1 to Sept. 30)	Run-off			Precipitation	
	Volume (acre-feet)	Depth on drainage area [1] (inches)	Percent of average	Mean on drainage area [2] (inches)	Percent of average
1905–6	1,350,000	40.2	184	50.06	135
1906–7	1,670,000	49.7	228	67.72	183
1907–8	480,000	14.3	65	27.12	73
1908–9	1,150,000	34.2	157	46.18	125
1909–10	906,000	27.0	123	42.24	114
1910–11	1,530,000	45.5	208	62.45	169
1911–12	393,000	11.7	54	29.10	79
1912–13	423,000	12.6	58	29.78	80
1913–14	1,080,000	32.1	147	46.11	125
1914–15	823,000	24.5	112	38.42	104
1915–16	1,030,000	30.7	140	42.77	116
1916–17	868,000	25.8	118	35.44	96
1917–18	521,000	15.5	71	33.53	91
1918–19	590,000	17.6	80	29.62	80
1919–20	464,000	13.8	63	29.11	79
1920–21	865,000	25.7	118	43.61	118
1921–22	919,000	27.3	125	38.37	104
1922–23	703,000	20.9	96	43.39	117
1923–24	182,000	5.4	25	17.61	48
1924–25	824,000	24.5	112	41.58	112
1925–26	374,000	11.1	51	23.33	63
1926–27	877,000	26.1	120	38.66	104
1927–28	639,000	19.0	87	32.52	88
1928–29	[3] 307,000	9.1	42	30.83	83
1929–30	[3] 351,000	10.4	48	33.17	90
1930–31	[3] 248,000	7.4	34	22.49	61
1931–32	[3] 548,000	16.3	75	35.14	95
1932–33	[3] 430,000	12.8	59	25.50	69
Average	733,800	21.82		36.99	

[1] Drainage area 630 square miles.
[2] Mean precipitation in each year assumed to be the arithmetic average of the precipitation recorded at Electra, West Point, and Tamarack (Twin Lakes beginning 1927-28), cooperative Weather Bureau stations.
[3] Sum of discharge measured near Clements and of net diversion from the Pardee Reservoir.

The water of the Mokelumne River was first put to beneficial use in the middle fifties of the last century, in connection with the exploitation of placer and lode deposits of gold. Since that time the discharge of the river has been artificially regulated in some degree, and the total capacity of the regulative reservoirs and works has increased steadily. The following table assembles the pertinent data on the reservoirs that were being operated in 1932–33 or were then proposed to be built; these data are drawn from Fowler,[2] Seel,[3] Steele,[4] Hall,[5] and Henning.[6]

[2] Fowler, F. H., Hydroelectric power systems of California: U. S. Geol. Survey Water-Supply Paper 493, p. 196, 1923.

[3] Seel, E. M., The story of the Mokelumne River, p. 13, San Francisco, Pacific Gas & Electric Co., 1929.

[4] Steele, I. C. (Pacific Gas & Electric Co., Division of Civil Engineering), written communication, Oct. 19, 1933.

[5] Hall, L. S. (East Bay Municipal Utility District, Division of Hydrography), written communication, Oct. 19, 1933.

[6] Henning, Clinton (city of Lodi, office of the engineer), written communication, Dec. 16, 1933.

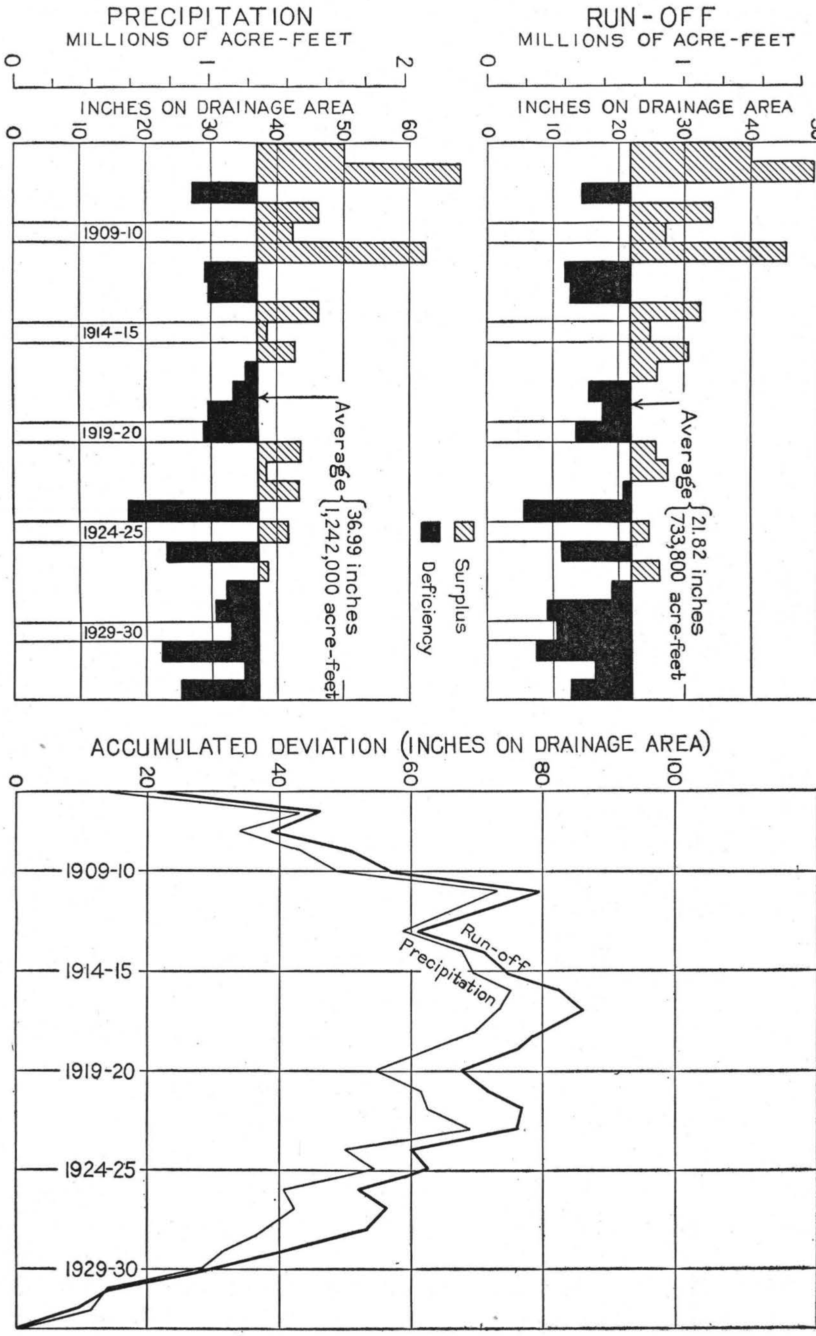

FIGURE 1.—Yearly and average run-off from the Mokelumne River Basin above Clements, Calif.; yearly and average precipitation; and accumulated deviations from the averages, 1905–6 to 1932–33.

Regulative works along the Mokelumne River above the gaging station at Woodbridge

Reservoir	Location of dam	Altitude of spillway (feet)	Maximum capacity (acre-feet)	Year completed	Owner
Upper Blue Lake	Sec. 18, T. 9 N., R. 19 E.[1]	8,126	7,700	1901 [2]	Pacific Gas & Electric Co.
Lower Blue Lake	Sec. 30, T. 9 N., R. 19 E.	8,037	4,340	1899 [3]	Do.
Deer Valley	Sec. 5, T. 8 N., R. 19 E.	7,350	9,400	Proposed	Do.
Twin Lakes	Sec. 25, T. 9 N., R. 18 E.[1]	8,168	1,340	1898	Do.
Meadow Lake	Sec. 27, T. 9 N., R. 18 E.[1]	7,768.5	6,110	1903 [4]	Do.
Salt Springs	Sec. 33, T. 8 N., R. 16 E.	3,947	130,000	1931	Do.
Bear River	Sec. 9, T. 8 N., R. 16 E.	5,875	6,712	1900	Do.
Lower Bear River	Sec. 18, T. 8 N., R. 16 E.	5,797	34,000	Proposed	Do.
Tiger Creek regulator	Sec. 8, T. 7 N., R. 14 E.	3,588	540	1931	Do.
Tiger Creek afterbay	Sec. 23, T. 7 N., R. 13 E.	2,340	3,800	do	Do.
Tabeaud forebay	Sec. 28, T. 6 N., R. 12 E.	1,958	1,158	1901	Do.
Petty forebay	Sec. 28, T. 6 N., R. 12 E.	2,160	12		Do.
Middle Bar	Sec. 16, T. 5 N., R. 11 E.	666	29,250	Proposed	East Bay Municipal Utility District.
Pardee	Sec. 26, T. 5 N., R. 10 E.	567.8	210,000	1929	Do.
	Sec. 33, T. 5 N., R. 10 E.	228.5	580	Proposed	City of Lodi.
Woodbridge	Sec. 35, T. 4 N., R. 6 E.	40.6	1,400	1901 [5]	Woodbridge Irrigation District.

[1] Unsurveyed.
[2] Earlier dam completed about 1881.
[3] Earlier dam completed 1874.
[4] Earlier dam completed 1885.
[5] Earlier dam completed 1891.

The dams of the Pacific Gas & Electric Co. are all situated on the North Fork of the Mokelumne River and are operated for the generation of hydroelectric power. Before March 1931, when the Salt Springs Dam began to impound water, the aggregate storage capacity of these regulative works (27,000 acre-feet) had been too small to effect any substantial reduction in the magnitude or duration of the annual freshet in the lower reaches of the stream. All water diverted by these works was returned to the main branch of the river below the Electra power plant, about 6 miles below the junction of the North and South Forks (pl. 1). Moreover, the monthly run-off to the lower reaches of the stream was not affected greatly except in the dry period of the late summer and autumn. On the other hand, the operation of the Salt Springs Reservoir, which has a maximum capacity of 128,000 acre-feet, has resulted in substantial regulation of the flow in the main stream, beginning in March 1931. The two dams proposed to be built on the North Fork by the company will provide an aggregate storage capacity of 43,400 acre-feet and will increase the capacity of all reservoirs in the basin of the North Fork to 199,000 acre-feet. With existing structures they will afford virtually complete regulation of the flow in the North Fork except during freshets of large magnitude.

The questions at issue in the Mokelumne area are concerned particularly with the substantial regulation of the main river, which is accomplished by the Pardee Dam of the East Bay Municipal Utility District (pl. 3, *A*). This structure is unique among those in the Mokelumne River Basin in that it has two functions—(1) to impound and divert water for municipal uses in a group of communities along the eastern shore of San Francisco Bay and (2) to impound water for the generation of hydroelectric power. The reservoir which it creates has a capacity of 210,000 acre-feet, a substantial fraction of the yearly

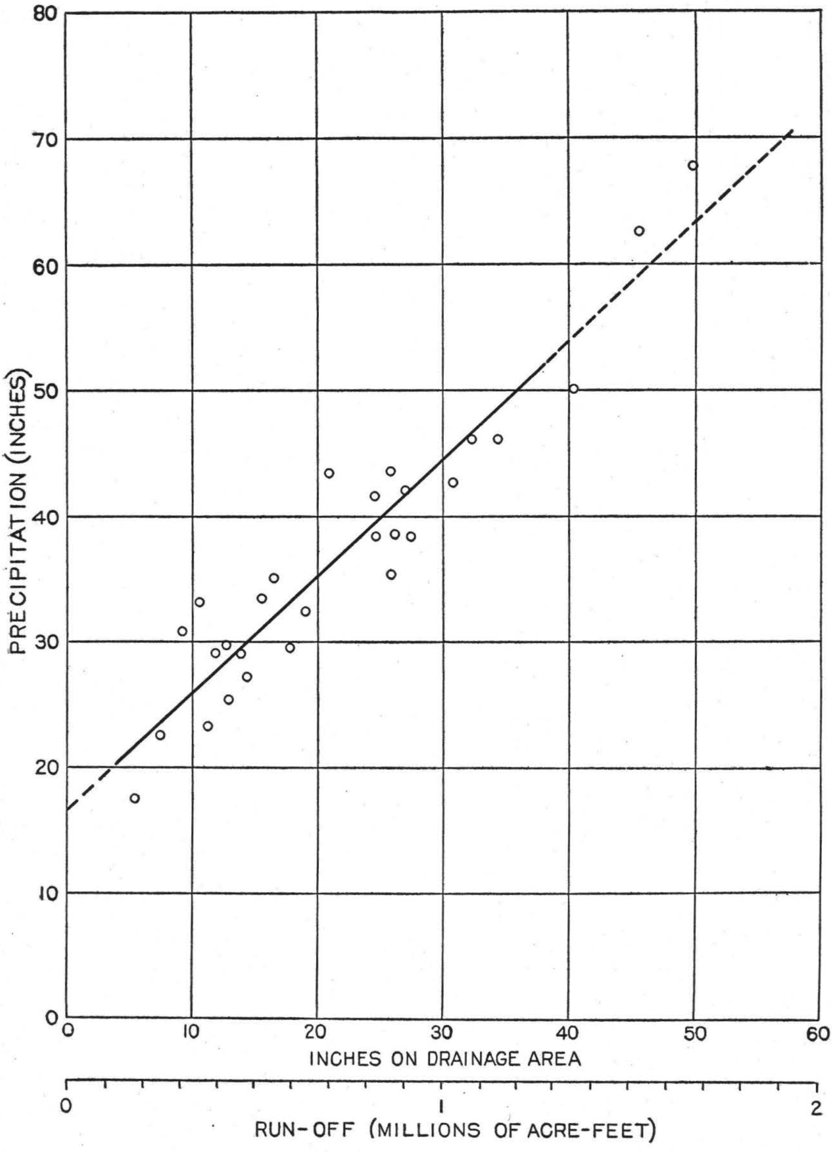

FIGURE 2.—Yearly run-off from the Mokelumne River Basin above Clements, Calif., in relation to the yearly precipitation, 1905-6 to 1932-33.

run-off. The aggregate transmission capacity of its sluiceways and of the draft tubes of its two hydroelectric turbines is about 4,000 second-feet, so that complete regulation of the discharge in the lower reach of the stream is possible except during the peak of the larger annual freshets. Water was first impounded above this dam on March 9, 1929; water was first diverted through the pipe line to the East Bay cities (pl. 2) on June 25, 1929.

Monthly diversions from the Mokelumne River Basin at the Pardee Dam, 1929 to 1932–33 [1]

[Quantities in acre-feet; based on records of the East Bay Municipal Utility District]

Month	1929	1929–30	1930–31	1931–32	1932–33
October		5,125	3,717	5,992	5,047
November		436	3,042	5,585	4,350
December		−7	2,945	4,885	3,961
January		−19	2,463	2,593	3,272
February		1,795	5,291	2,778	3,183
March	[2] 10	3,073	6,092	3,450	3,229
April	59	4,371	6,125	6,001	3,469
May	422	7,170	6,525	6,977	3,593
June	[3] 1,366	7,410	6,210	7,510	4,636
July	5,853	7,880	6,604	1,873	5,540
August	6,023	7,485	6,392	3,620	5,450
September	5,391	6,627	5,988	4,930	2,099
The year or period	19,100	51,300	61,400	56,200	47,800

[1] Discharge through pipe line plus evaporation from reservoir minus rainfall on the reservoir.
[2] Water first impounded Mar. 9, 1929.
[3] Water first diverted June 25, 1929.

Monthly regulated run-off in the Mokelumne River measured at the gaging station near Clements, 1929 to 1932–33

[Quantities in acre-feet]

Month	1929 [1]	1929–30	1930–31	1931–32	1932–33
October		3,350	28,300	3,570	31,500
November		23,900	19,500	3,750	32,400
December		1,810	15,700	6,460	33,900
January		1,990	7,500	17,300	36,600
February		1,680	7,220	34,900	29,500
March		5,890	8,120	39,900	31,400
April		20,100	13,700	37,700	31,100
May	129,000	98,400	13,600	91,600	30,900
June	50,900	64,900	14,300	156,000	26,700
July	9,470	24,500	20,100	38,300	32,500
August	7,320	26,300	32,300	31,000	32,600
September	5,080	26,900	6,430	31,400	33,200
The year		300,000	187,000	492,000	382,000

[1] Water first impounded in Pardee Reservoir on Mar. 9, 1929, and first diverted from reservoir on June 25, 1929; effect of regulation on monthly run-off first appreciable in May of that year.

The table just presented shows some long-term regulative effects of the Pardee Dam when compared with the table of range in monthly run-off from 1905–6 to 1927–28 (p. 7). Thus, within 5 years after operation at the Pardee Dam began new maxima were established for the monthly run-off below the dam in September and October and new minima were established for the run-off in each month from November to May. This substantial regulation has been accomplished during a period in which the yearly run-off, including the diversions at the dam, ranged from 248,000 to 548,000 acre-feet (p. 8)—that is, from one-third to two-thirds of the average from 1905–6 to 1927–28.

Some regulation of the Mokelumne River is accomplished by the diversion dam of the Woodbridge Irrigation District, which is near the western edge of the area described in this report. The storage capacity of the Woodbridge Reservoir is about 1,400 acre-feet; the maximum transmission capacity of the diversion canal is about 300 second-feet, or about 18,000 acre-feet a month. Thus, these works are competent to divert all or a large portion of the discharge of the river in the months of little run-off. Commonly they have been manipulated over a relatively wide range of storage and of diversion and have regulated the discharge in the lower reach of the stream in a complex fashion.

SCOPE OF THE INVESTIGATION AND REPORT

The investigation in the Mokelumne area by the United States Geological Survey, which began in 1926, has been made to determine the basic relation between regulation of the flow in the Mokelumne River and the safe yield of the contiguous ground-water basin and thus to formulate sound principles for adjudication of the surface-water and ground-water rights that are involved. The investigation has been made under the direction of N. C. Grover, chief hydraulic engineer, and the supervision of O. E. Meinzer, geologist in charge of the division of ground water, and H. D. McGlashan, district engineer of the division of surface water.

Beginning about 1930 intensive investigations have been made in the Mokelumne area by several agencies that are concerned with the utilization and development of its water resources—namely, the East Bay Municipal Utility District, the city of Lodi, and the Pacific Gas & Electric Co. In large part, the voluminous data gathered by these agencies have been available to the United States Geological Survey to supplement its observations.

The Geological Survey has issued several fact-finding and analytical reports covering its work in the Mokelumne area prior to June 30, 1933. A preliminary report [7] was published in 1930 to summarize and interpret data gathered prior to June 30, 1929. Manuscript reports that have been released periodically for public inspection have assembled data on ground-water and surface-water stage, areas irrigated by pumping from wells, diversions from the Mokelumne River by pumps, turbidity and temperature of the Mokelumne River, and meteorologic data. Interpretative manuscript reports have described the geology of the Mokelumne area,[8] pumpage of ground water for irrigation,[9] seepage loss and gain of the Mokelumne

[7] Stearns, H. T., Robinson, T. W., and Taylor, G. H., Geology and water resources of the Mokelumne area, California: U. S. Geol. Survey Water-Supply Paper 619, 402 pp., 1930.

[8] Gale, H. S., Piper, A. M., and Thomas, H. E., Geology of the Mokelumne River basin, California: U. S. Geol. Survey typoscript report, 259 pp., Dec. 23, 1932.

[9] Piper, A. M., Pumpage of ground water for irrigation in the Mokelumne area, California, 1927–1932: U. S. Geol. Survey typoscript report, 69 pp., Nov. 13, 1933; Pumpage of ground water for irrigation in the

River below the Pardee Dam,[10] and general hydrology of the area.[11]

The present report comprises the substance of the two manuscripts that describe the geology and the general ground-water hydrology of the Mokelumne River Basin. In these two fields the discussions are extended rather broadly beyond the area that is influenced directly by regulation of the flow in the Mokelumne River, in order to afford an adequate basis for judgment of the evidence available within the smaller district, also to demonstrate that the geologic and hydrologic conditions of the smaller district are not unique within the region. Field and office study of the geology was pursued intensively between November 1931 and August 1932, chiefly by H. S. Gale and H. E. Thomas; some bits of critical data have been gathered subsequently as incidental products of hydrologic studies. The chapter on ground-water hyrology is based largely on the factual data gathered by the United States Geological Survey from April 1926 to June 30, 1933, when its intensive field studies ended. Contributions to those data were made by B. R. Colby, C. A. McClelland, A. M. Piper, T. W. Robinson, G. M. Sherwood, H. T. Stearns, G. H. Taylor, H. E. Thomas, and L. K. Wenzel, of the Survey staff, and by T. F. Baun, F. B. Blanchard, and R. C. Cady, temporary employees. The main lines of approach to the hydrologic problems were extended to September 30, 1933, by drawing on the data of the non-Federal agencies, and a few critical phenomena were studied in the field by the Geological Survey as late as May 1935. Altogether, the data available permit a searching analysis of the questions at issue and seem to afford a rational approach toward composing conflicting rights to beneficial use of the water resources of the Mokelumne River Basin.

GEOLOGY

By H. S. Gale, A. M. Piper, and H. E. Thomas

GEOMORPHOLOGY

Central California, which includes the Mokelumne area, comprises parts of three physiographic sections as delimited by Fenneman.[12] These are, in order from west to east, the California Coast Ranges and California Trough sections of the Pacific Border province and the Sierra Nevada section of the Sierra-Cascade Mountains province. Commonly, the California Trough is also termed the "Great Valley of California" or simply the "Great Valley." The area described in this

Mokelumne area, California, 1933, and revised estimates of pumpage, 1927 to 1932: U. S. Geol. Survey typoscript report, 28 pp., Apr. 9, 1934.

[10] Pritchett, H. C., Bue, C. D., and Piper, A. M., Seepage loss and gain of the Mokelumne River, California: U. S. Geol Survey typoscript report, 217 pp., June 5, 1934. Pritchett, H. C., Seepage loss from the Mokelumne River, California, in the year ending Sept. 30, 1934: U. S. Geol. Survey typoscript report, 10 pp., Jan. 26, 1935.

[11] Piper, A. M., Thomas, H. E., and Robinson, T. W., Ground-water hydrology of the Mokelumne area, California: U. S. Geol. Survey typoscript report, 241 pp., Oct. 30, 1935.

[12] Fenneman, N. M., Physiographic divisions of the United States, 3d ed.: Assoc. Am. Geographers Annals, vol. 18, No. 4, map, December 1928.

report comprises parts of the California Trough and Sierra Nevada sections; the Coast Ranges lie 15 or more miles farther west. (See pl. 2.)

CALIFORNIA TROUGH

The part of the California Trough that lies within and adjacent to the Mokelumne area is divisible into four natural subsections—the so-called Delta country or Delta tidal plain, the Victor alluvial plain, the river flood plains and channels, and the Arroyo Seco dissected pediment. These four divisions comprise the land forms produced by the Mokelumne River and other streams since the Sierra Nevada block was tilted in the Pleistocene epoch (pp. 26–27).

DELTA PLAIN

The Delta plain forms the western and lowest part of the Mokelumne area. Under natural conditions it was a tidal marsh traversed by the meandering interlacing sloughs of the San Joaquin, Mokelumne, and Sacramento Rivers where those streams unite just east of the head of Suisun Bay (the northeasternmost extension of San Francisco Bay). However, most of the sloughs have been confined by artificial levees and the enclosed "islands" reclaimed in large part. These "islands"—if the sloughs and levees are disregarded—define an extensive fertile plain of which the greater part is between 1 and 6 feet below mean sea level and which slopes locally away from the sloughs at rates between 1 foot and 20 feet in a mile.

Along the eastern edge of the Delta plain and between the Mokelumne and San Joaquin Rivers there are six "blind" sloughs that head near the zero or sea-level contour and extend westward to the South Fork of the Mokelumne River. These are believed to be remnants of former distributary channels of the Mokelumne that have been abandoned successively by the river as it built up the Victor plain and established its present course farther north.

The Delta plain, although a distinct geomorphic unit, is not sharply delimited by the adjacent land forms. In the Mokelumne area its eastern edge is somewhat arbitrarily fixed at the zero or sea-level contour of the land surface.

VICTOR ALLUVIAL PLAIN

Lying east of and rising from the Delta plain is an extensive alluvial plain that forms the surface of most of the California Trough in and about the Mokelumne area. Within the Mokelumne area this alluvial plain is 12 to 16 miles wide and rises eastward between 5 and 8 feet in a mile—that is, somewhat more steeply than most of the contiguous Delta plain. Upon it are situated the cities of Lodi and Victor and other principal settlements of the Mokelumne area. It includes most of the land that is intensively cultivated in grapes and fruit and that is irrigated by water pumped from wells. In this report this feature is designated the Victor alluvial plain. Its altitude is about 50 feet above sea level at the longitude of Lodi, 75 feet at Victor, and 100 feet still farther east at Lockeford.

The standard topographic maps [13] of the region show that the Victor plain forms a relatively flat cone in the central part of the Mokelumne area, between Laguna Creek on the north and the Calaveras River on the south. The apex of this cone falls close to the Mokelumne River where it flows out from its canyon in the harder rocks. As nearly as can now be recognized, it is just below the narrows at the Mehrten dam site, near Clements, near the northeast corner of T. 4 N., R. 8 E. From this place the plain extends westward between two radiating but curving margins. The northern margin passes just south of Dogtown (1½ miles north of Clements), courses northwestward approximately parallel to Coyote Creek, and extends to or beyond Dry Creek; the southern margin may be traced toward the southwest along another curving line that coincides approximately with Bear Creek. Between these radiating margins, if the trenches of the major streams are disregarded, the contours on the plain are very nearly arcuate and approximately concentric about the apex of the cone. Thus, the cone is a typical alluvial fan built at the exit of a mountain stream, an ancestral Mokelumne River.

Impressed upon this fan is a system of ill-defined intermittent and ephemeral drains that radiate westward from the apex near Clements. Presumably these are the channels of consequent distributary streams that flow on the initial slope of the plain. The principal channels of this class are those of Bear Creek, which lies south of the Mokelumne River, and Jahant Slough, which lies north of the river. The extensive interstream tracts are undrained in large part, although they include some shallow closed depressions that are perhaps the products of wind erosion in the sandy soil. Most of these interstream tracts do not appear to have been modified appreciably in form since they were constructed.

To the north the alluvial fan of the Mokelumne River merges into a corresponding and similar fan developed by the Cosumnes River. These and related alluvial forms that extent beyond the Mokelumne area are evidently the product of one general epoch. They have compounded the Victor plain by mutual interference.

On the east the Victor plain generally abuts against or merges into an undulating terrane, a part of the Arroyo Seco dissected pediment (p. 20), approximately along the east boundary of R. 7 E. From Lockeford, however, a tongue of the plain originally extended eastward into the dissected pediment along the present course of the Mokelumne River and is now partly preserved in terraces along the river valley. These terraces are well defined as far east as Clements,

[13] U. S. Geol. Survey topographic maps of Bruceville, Castle, Clay, Galt, Headreach, Lockeford, New Hope, Waterloo, and Woodbridge quadrangles; scale 1:31,680.

where they are about 130 feet above sea level and where the tongue was originally about 1½ miles wide. Still farther east the terrace becomes narrower and discontinuous and in part seems to be cut on rock, but it can be traced with fair assurance as far as the former town site of Lancha Plana, 15 miles from Lockeford. At Lancha Plana its altitude is about 230 feet above sea level. These altitudes indicate that the existing remnants of the tongue decline westward about 9 feet in a mile between Lancha Plana and Lockeford. In the tributary valleys of the Lancha Plana district and in the main river valley farther east the tonguelike extension of the Victor plain has not been traced, for the topographic forms are complex and the resultant of several partial erosion cycles whose products can scarcely be separated without detailed topographic maps.

Presumably other tongues that correspond to the plain at Victor originally extended eastward along each of the streams that flow from the Sierra Nevada—that is, along the Calaveras River to the south of the Mokelumne River and along Dry Creek, Laguna Creek, and the Cosumnes River to the north (pl. 1). Along the Calaveras River such a tongue of the Victor plain extends eastward from Linden to and beyond the boundary between San Joaquin and Stanislaus Counties. In this reach of the river the tongue is the present flood plain and has not been reduced to terrace remnants, as in the valley of the Mokelumne River. Along Laguna Creek, which drains the area between Dry Creek and the Cosumnes River, remnants of a corresponding tongue can be traced about 15 miles upstream, as far as Carbondale. The average width of this tongue is about 1 mile; the average gradient is 9 feet to the mile. In the valleys of Dry Creek and the Cosumnes River, however, no remnants of tongues of the Victor plain have been recognized where those streams traverse the dissected pediment. These two streams seem to have lowered their respective valley floors entirely below the projected altitude of the Victor plain.

Figure 3 shows a profile of the Victor plain in relation to the profiles of the Mokelumne River and of the other geomorphic divisions of the Mokelumne area.

RIVER FLOOD PLAINS AND CHANNELS

The streams of the Mokelumne area, with the exception of the Calaveras River, traverse the Victor plain in trenches whose floors are adjusted approximately to the tidewater of the Delta country but rise eastward more gradually than the Victor plain. Thus, along the lower reach of the Mokelumne River below Woodbridge the trench is ill defined, beginning about at the crossing of the 20-foot contour and increasing in depth upstream to about 10 feet at Woodbridge. (See pl. 1.) The floor of the trench—the flood plain or bottom land—ranges from 300 to 1,500 feet in width along this reach. Upstream from Woodbridge the trench widens to about half a mile at Victor and

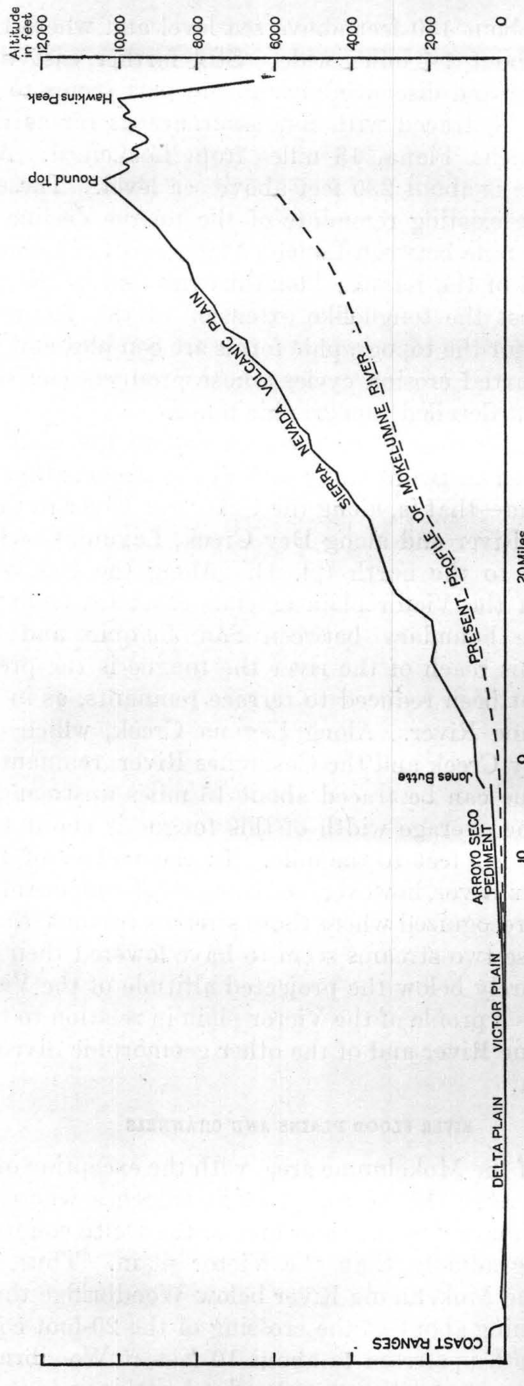

FIGURE 3.—Composite profile trending N. 65°–85° E. through Suisun Bay and Round Top, showing relation of the physiographic divisions of the Mokelumne area to one another.

to about 1 mile near Lockeford and Clements; in this reach its walls are steep cut banks. Its floor is 25 to 30 feet below the Victor plain at Victor and 40 feet below the plain at Clements; thus its grade is from 2 to 6 feet to the mile. In this reach across the Victor plain the course of the trench is presumed to have been inherited from the initial distributary drainage system by integration of the segments whose grades were most favorable. It has no rational dependence on the courses of former distributaries that are represented by buried tongues of sand and gravel. Upstream from Clements, where it traverses the dissected pediment, the river trench is formed in the more resistant rocks of Tertiary age (pp. 57–84) and there its flood plain narrows to a quarter of a mile. Still farther upstream, above Camanche, near the eastern boundary of the area represented by plate 1, the flood plain is discontinuous, and it dies out altogether about a mile east of Lancha Plana, where the river flows out from the resistant crystalline rocks of the Sierra Nevada. In this reach the stream has swept away all but a few remnants of the former tongue of the Victor plain.

The flood plain of the Mokelumne River is by no means featureless, for it includes many shallow but continuous flood channels, a number of oxbow lakes, and many undrained potholes. The oxbow lakes and potholes are especially numerous between Victor and Woodbridge. One of the larger ill-drained parts of the flood plain has been utilized for the reservoir of the Woodbridge Irrigation District at Woodbridge.

Across its flood plain the Mokelumne River ordinarily flows in a sinuous inner channel, which is 75 to 150 feet wide and 15 to 30 feet deep, even as far upstream as Clements. This inner channel contains the river at all ordinary stages. In its natural regimen the river would overflow this inner channel during freshets and would occupy its intermittent flood channels and at times inundate much of its fertile flood plain. This natural regimen, however, has been modified by the construction of levees, especially between Clements and Lockeford and in and near the Delta country west of Lodi, so that the river is artificially confined to its inner channel except during freshets of unusual magnitude, such as that of 1907 and that of 1928, which is described by Stearns.[14]

The streams that join the Mokelumne River on the north—Dry Creek and the Cosumnes River—are intermittent but both have post-Victor trenches about as wide as that of the Mokelumne River. Generally, however, their floors are not more than 20 feet below the Victor plain. Like that of the Mokelumne River, these trenches terminate upstream about where their streams flow out from the crystalline rocks at the western edge of the Sierra Nevada. Those of the two principal forks of Dry Creek terminate near Buena Vista and Ione;

[14] Stearns, H. T., Robinson, T. W., and Taylor, G. H., Geology and water resources of the Mokelumne area, California: U. S. Geol. Survey Water-Supply Paper 619, pp. 188–190, 1930.

that of the Cosumnes River near Michigan Bar (pl. 1). Unlike that of the Mokelumne River, however, the floors of these trenches—the flood plains of the present streams— do not comprise intermittent flood channels and abandoned oxbows and potholes. Rather, they are essentially featureless and are but ineffectively drained by a discontinuous network of sinuous shallow channels. Under natural conditions, therefore, the flood plains are overflowed by freshets of even moderate size. The natural regimen of the Cosumnes River has been modified locally by levees that confine the stream and permit cultivation of its fertile flood plain.

The Calaveras River, which parallels the Mokelumne River on the south, is unique in the Mokelumne area in that it does not occupy a post-Victor trench and that its flood plain is an extension of the Victor plain. Downstream from Bellota, where it emerges onto the main Victor plain, this intermittent stream naturally would occupy several braided sinuous channels from 10 to 15 feet deep. As a means of flood control however, it has been confined to one artificial channel, which has been made by deepening the natural channel of Mormon Slough and by erecting levees along both its banks.

ARROYO SECO DISSECTED PEDIMENT

North and east of Clements, in the district that adjoins the Victor plain on the east, the interstream divide between the Mokelumne River and Laguna Creek is composed of flat-topped ridges whose summits broaden locally to poorly drained flats as much as 2 miles wide. Commonly these flats have a thin sterile soil and are strewn with coarse gravel and cobbles 2 to 5 inches in diameter. Characteristically the soil is a rich reddish brown, a color that gives to the uplands their common local name "red lands." The soil also seems unusually impervious, for it becomes boggy during each rainy season and upholds many pools that persist for weeks or even months and waste slowly by evaporation. In many places the flats are pitted by bowl-shaped depressions a few feet or yards across and 1 or 2 feet deep. These depressions, which are known locally as hog wallows, are commonly floored with gravel and cobbles; in part at least they are presumed to be a product of wind erosion which in favorable places has carried away the finer particles of the original soil. The sterile flats are generally treeless and are used chiefly for grazing; they contrast sharply with the fertile Victor plain to the west and with the oak-covered slopes of the Sierra Nevada to the east.

The interstream flats just described are remnants of a plain of denudation that initially was at least 8 to 15 miles wide and that lay at the western foot of the Sierra Nevada entirely across the Mokelumne area. Thus they are remnants of a pediment. Though now intricately dissected in many parts of the Mokelumne area, its present remnants that stand above the Victor plain are considered to constitute a geomorphic unit. This unit is herein termed the Arroyo Seco dissected pediment, because of its extensive remnants on the Arroyo Seco land grant, in the northern part of the Goose Creek quadrangle. The remnants of the pediment are coextensive with the outcrops of the Arroyo Seco gravel. (See pl. 1.)

Between the Mokelumne River and Laguna Creek the most westerly remnants of the Arroyo Seco pediment occur at the longitude of Lockeford; in this district they are 135 to 210 feet above sea level and 30 to 100 feet above the Victor plain. About 12 miles farther northwest, in the vicinity of Elk Grove, occurs the most westerly remnant of the pediment in the Mokelumne area; there it is but 80 to 90 feet above sea level and 25 feet above the Victor plain. Toward these remnants the pediment declines from the east and northeast as much as four times as steeply as the Victor plain. In the Clements-Wallace district east of Lodi it declines S. 70°–80° W. from 20 to 35 feet in a mile; in the Elk Grove-Slough House district, in the northern part of the Mokelumne area, it slopes S. 50°–65° W. between 10 and 20 feet in a mile. Between Dry Creek on the north and the Calaveras River on the south it attains an altitude of 350 feet above sea level at its eastern edge, near the eastern boundary of San Joaquin County. North of Dry Creek its eastern edge occurs about at the longitude of Clements and attains an altitude of 270 to 320 feet above sea level. Here its smoothness is broken by a number of scattered knobs and ridges of resistant rock that rise as much as 250 feet above the plain.

Between the conspicuous remnants of the Arroyo Seco pediment and the Victor plain to the west there is a belt 4 to 8 miles wide that is made up of rounded hills and ridges. Among these are certain flat-topped forms whose summits coincide in altitude with that of the projected plane of the Arroyo Seco pediment. Farther south, in the district between the Mokelumne and Calaveras Rivers, there are similar but less extensive mesalike uplands within a belt of rounded hills. It is evident that these flattish summits are remnants of the Arroyo Seco pediment and that the belt of rounded hills against which the Victor plain abuts are products of the intricate dissection of that pediment.

The easternmost known remnants of the Arroyo Seco pediment are two outliers just south of the Mokelumne River. The larger of these is the flattish gravel-veneered upland between Wallace and Camanche, in T. 4 N., R. 9 E.; it rises to about 425 feet above sea level. The smaller outlier, whose correlation with the pediment is doubtful, lies about 5 miles farther east, about midway between Valley Springs and Burson; this doubtful remnant is about 650 feet above sea level.

The eastern edge of the Arroyo Seco pediment overlooks an elongate bipartite basin that extends eastward to the base of the Sierra Nevada and that trends somewhat east of south entirely across the Mokelumne area—that is, from the Cosumnes River on the north to and beyond the

Calaveras River on the south. Its northern segment is the conspicuous depression that contains the town of Ione. It is 6 to 8 miles wide and 14 miles long. Its floor is rolling, and its lowest points are less than 300 feet above sea level and nearly 100 feet below the projected Arroyo Seco pediment. Only a few summits within it stand noticeably above the projected pediment; outstanding among these are Jones Butte and Buena Vista Peak. This northern segment of the basin is drained in part by Laguna Creek and in part by the Jackson Creek and Sutter Creek forks of Dry Creek. The southern segment is a depression of similar magnitude that extends southward from Lancha Plana and contains the towns of Wallace, Valley Springs, and Milton. In it only Valley Springs Peak and some of the surrounding tableland stand noticeably above the projected pediment. It is drained by the Mokelumne and Calaveras Rivers and Bear Creek. At the longitude of Lancha Plana these two segments of the basin are separated by the conspicuous divide between the Mokelumne River and Dry Creek. However, for much of its length the crest of this divide is lower than the projected pediment.

It seems likely that the pediment initially extended eastward entirely across the bipartite basin. Accordingly, the basin is considered in this report as a hypothetical subdivision of the dissected pediment.

SIERRA NEVADA SECTION

The Sierra Nevada section, which adjoins the California Trough on the east and extends eastward beyond the Mokelumne area (pl. 2), is a block mountain range tilted toward the west and deeply carved on its western slope in the fashion that is characteristic throughout central California. It comprises a monotony of parallel ridges of accordant height whose crests decline gently westward, impressive steep-walled canyons, and numerous alpine peaks and mountains that rise above the ridge crests. The relation of these major features to one another has been well pictured by Turner [15] in these words:

> The general aspect of the country, as seen from such an elevation [the crest of a ridge], is that of a somewhat uneven, gently sloping plain, below the surface of which the present canyons have been excavated. * * * If the present canyons were once more filled up with the solid rock which in the course of Pleistocene time has been disintegrated and carried down as sediment to the Great Valley, and if the lava cappings of the ridges were extended so as again to cover the filled-in canyons, there would be reproduced a surface nearly identical with that upon which the existing streams began their work. It would be a great desolate lava plain, sloping gently to the southwest. Its surface, however, would be somewhat uneven, and above it would project several summits, such as Blue Mountain, composed of unusually resistant rocks belonging to the Bedrock series [pre-Cretaceous crystalline rocks (pp. 88–89)] and which, on account of the durability of their materials, formed hills too lofty to be buried beneath the lavas.

The plain defined by the major ridge crests rises about 2° NE. It is about 500 feet above sea level just east of the Arroyo Seco pediment,

[15] Turner, H. W., U. S. Geol. Survey Geol. Atlas, Big Trees folio (no. 51), p. 1, 1898.

at the longitude of Ione, and about 9,000 feet above sea level near the crest of the Sierra Nevada, 50 to 55 miles farther east. Conspicuous remnants of this plain along the eastern edge of the Mokelumne area are the crest of the ridge 3 miles northeast of Jackson and that which extends from the town of Mokelumne Hill to Golden Gate Hill. Extensive remnants also exist farther east above an altitude of 4,000 feet.

At the latitude of the Mokelumne area this summit plain is constructed of andesitic sediments and breccias and is essentially the final product of the volcanism that occurred in upper (?) Miocene time (pp. 61, 69). The remnants of this constructional volcanic plain are a conspicuous feature of the Sierra Nevada in an extensive region about the Mokelumne area. Its present inclination is presumably the resultant of the initial slope of construction plus the effect of tilting in the Pleistocene epoch (p. 31). In other parts of the Sierra Nevada, according to Matthes,[16] there are several upland plains, or remnants of them at different levels. These are of destructional rather than constructional origin; none of them have been discriminated in the Mokelumne area.

Conspicuous among the knobs and peaks that stand above the restored volcanic plain in and near the central-eastern part of the Mokelumne area are Valley Springs Peak, Buena Vista Peak, Jackson Butte, and Golden Gate Hill (pl. 4). These rise 200 to 500 feet above the plain. Most conspicuous in the area represented by plate 1, however, are Gopher Ridge and Bear Mountain; these are southeast of the town of Valley Springs and south of the Calaveras River. Farther north at the same longitude and just north of the Cosumnes River is Logtown Ridge. These are bold strike ridges composed of resistant crystalline rocks. They stand 500 to 1,000 feet above the restored volcanic plain and together constitute a topographic barrier that in the Mokelumne area trends north to N. 30° W. along the western flank of the Sierra Nevada. Other conspicuous peaks that occur farther east are the rough and jagged Pyramid Peak Range, which forms the crest of the Sierra Nevada southwest of Lake Tahoe and attains an altitude of 10,020 feet; the sharp and rocky Mokelumne Peak; and Blue Mountain. These also are composed of the resistant crystalline rocks; they rise 1,000 to 1,200 feet above the volcanic plain. Eleven other masses of crystalline rocks that stand above the volcanic plain are indicated on plate 4; none cover more than 6 square miles.

Gopher Ridge and Bear Mountain are essentially colinear with Logtown Ridge. The gap between them, about 20 miles wide, is the only gateway through the barrier of crystalline rocks opposite the Mokelumne area. Through it pass the Calaveras, Mokelumne, and Cosumnes Rivers and Dry Creek. This gateway existed in about its present form at the beginning of the Miocene volcanic epoch. Con-

[16] Matthes, F. E., written communication, Oct. 26, 1932.

sequently, the lowest gaps in its floor have in large measure controlled the distribution of the Miocene volcanic rocks and of the unconsolidated post-Miocene rocks in the Mokelumne region. Thereby it has influenced indirectly the distribution of those rocks that are so permeable as to be potential sources of ground water in the Mokelumne area.

The impressive steep-walled canyons of the Mokelumne River and other streams of the region head in the Sierra Nevada and trend southwestward down the initial slope of the volcanic plain. Hence they are the products of consequent streams. That of the Mokelumne River heads at the very crest of the range, is 1,000 to 4,000 feet deep, and does not have an alluvial floor. Though it has been in part sculptured by glaciers in the summit area, no vestiges of glaciation along its rim are visible below an altitude of 5,000 feet, and most of the canyon cutting can be ascribed to fluvial processes. The canyons of the other major streams are similar in form and of comparable magnitude, but the tributary canyons are commonly much shallower, for they head farther down the slope of the mountain block.

Within a belt 5 to 20 miles wide along the western edge of the mountain block, where it adjoins the California Trough, the tributary streams have ramified so minutely as to destroy nearly all remnants of the volcanic plain. Most of the summits in this district stand below the projected altitude of the plain, and the ridge crests are sharp rather than flat. The valleys are characteristically V-shaped, as in the dissected upland farther east, but commonly they do not conform to the southwest course that is characteristic higher on the slope of the mountain block. Conspicuous examples among the major stream canyons are afforded by the North Fork of the Cosumnes River and the South Fork of the Calaveras River. These canyons are the products of subsequent streams eroding along the eastern flanks of Logtown Ridge and of Bear Mountain, respectively. In several places, however, the streams cut across resistant members of the crystalline rocks and clearly were superposed on them from an initial consequent course. Such are the reach of the Cosumnes River that transects the southern tip of Logtown Ridge and the reach of the Calaveras River that skirts the northern tips of Bear Mountain and Gopher Ridge.

GEOMORPHIC HISTORY

GENERAL FEATURES

The sculpture of the present land forms in the Mokelumne area may be said to have begun in the late (?) Miocene or possibly the early Pliocene epoch. By that time the west flank of the Sierra Nevada east of the Mokelumne area had been almost completely mantled by volcanic (andesitic) detritus (pp. 69–71). That detritus had filled and obliterated the older stream valleys, had buried all but the highest monadnocks or peaks of the older land surface, and had disorganized the older drainage system. Previously, the ancestral Mokelumne, Calaveras, and Stanislaus Rivers, for example, appear to have been parts of one stream, as Lindgren [17] has pointed out. The channel of this stream was completely filled by the volcanic detritus and in many places, as between Mokelumne Hill and Campo Seco, has not since been reexcavated. At the culmination of the volcanic activity the upper surface of the detritus was an evenly sloping constructional plain whose grade, estimated to have been initially about 100 feet in a mile, represented equilibrium between the carrying power of its streams and the quantity of fresh detritus available to load them. As volcanism waned and the quantity of detritus decreased, the streams became able to cut.

Presumably a system of consequent drains was quickly organized on the initial slope of the Sierra Nevada volcanic plain. Over most of the upper part of the mountain block—that is, east of the longitude of Ione—the principal segments of the present stream pattern apparently were established then and in all subsequent time have incised themselves without major derangement. Bear Mountain and Logtown Ridge (monadnocks on the prevolcanic land surface that were never covered by the volcanic detritus) locally prohibited a consequent drainage pattern. Doubtless the tributary streams have reorganized their courses locally as they cut down into the steeply dipping crystalline rocks that lie beneath the volcanic detritus, but there seems no reason to believe that such changes have been general or that major segments of the drainage systems have been involved in them. Even after the Sierra Nevada block was tilted in early or middle Pleistocene time (p. 26), the major streams in that part of the Mokelumne area seem only to have deepened the canyons that had been established earlier. Their courses have shifted somewhat, as is indicated by gravel terraces at different altitudes close along the present channels, but material changes are not known. The many tributaries of the major streams have likewise deepened their channels and have reworked successively many of the deposits of earlier stages. Some have formed well-defined cobble or gravel terraces at several altitudes. These terraces, which commonly are dissected, constitute an intricate and complex record of geomorphic substages.

West of Ione, however, the detritus swept from the higher part of the mountain block was deposited as weak fluvial sediments; in these sediments the stream patterns have been less stable.

LAGUNA EPOCH

It is thought that the volcanic plain of the Sierra Nevada initially lay at a relatively low altitude and that in the Mokelumne area it stood somewhat above sea level and drained westward toward the

[17] Lindgren, Waldemar, The Tertiary gravels of the Sierra Nevada: U. S. Geol. Survey Prof. Paper 73, pl. 1, 1911.

ocean. From the higher part of this Sierran plain the newly formed consequent streams transported their detritus to be deposited west of Ione, presumably as a wedge of sediment lapping against the lower part of the plain. These sediments, which constitute the Laguna formation (p. 57), are believed to be the upper part of alluvial and possibly deltaic deposits of the streams that drained across the Sierran volcanic plain. Some of them are evenly bedded and suggest deposition in quiet water. The courses and heads of the presumed distributary streams by which the Laguna formation was deposited are unknown in the present outcrop area. Thus, by the culmination of the epoch the land surface of the region about the Mokelumne area was a moderately smooth plain that formed the aggradational surface on the Laguna sediments and, farther east, the constructional volcanic plain of the Sierra Nevada with its consequent drains. The cycle of erosion and sedimentation that constituted the Laguna epoch appears to have continued without interruption into the earliest part of the Pleistocene epoch, but the part of Pleistocene time that may have been included is relatively very short. It is inferred to be correlative with the later part of the mountain-valley stage of the Yosemite region as described by Matthes.[18]

MAJOR DEFORMATION OF THE SIERRA NEVADA

The Laguna epoch was terminated by mountain building on a major scale, which gave to the Sierra Nevada its present altitude and general form. At many places in California the rocks were closely folded and complexly faulted in this epoch of deformation, but in the Mokelumne area the deformation appears to have accomplished only a simple tilt or rotation of the Sierran block, with consequent displacement along the faults that bound the block on the east. Differential warping within the block is unknown. The beginning of this epoch is ascribed by the senior writer (Gale) to middle Pleistocene time (Yarmouth interglacial stage), although Matthes [19] feels that it began somewhat earlier—that is, not later than the Aftonian interglacial stage.

From the profiles of the ancient channels of the Merced River and other streams, the magnitude of the tilt suffered by the Sierra Nevada block in this major deformation has been estimated by Lindgren [20] and Matthes.[21] According to these estimates the tilt added about 6,000 feet to the altitude of the crest of the range. Expressed in angular magnitude, the tilt amounted to about 90 feet in a mile. This magnitude is confirmed in a general way by other lines of evi-

[18] Matthes, F. E., Geologic history of the Yosemite Valley: U. S. Geol. Survey Prof. Paper 160, pp. 31–32, 1930.

[19] Matthes, F. E., written communication, Oct. 26, 1932.

[20] Lindgren, Waldemar, The Tertiary gravels of the Sierra Nevada of California: U. S. Geol. Survey Prof. Paper 73, pp. 46–48, pl. 10, 1911.

[21] Matthes, F. E., op. cit. (Prof. Paper 160), pp. 43–44.

dence. This tilt is but half the present inclination of the west slope of the Sierran volcanic plain.

ARROYO SECO EPOCH

The grades of the consequent streams that had been established on the volcanic plain of the Sierra Nevada in the Laguna epoch were steepened several fold by the tilting of the mountain block. Thus the streams abruptly acquired large competence to transport detritus and, it might be inferred, would begin to cut rapidly in their upper reaches, would become heavily loaded, and might begin to plane widely or to aggrade at relatively steep gradients in their lower reaches. These characteristics seem to be reflected in the land forms and sediments produced. On the higher part of the Sierran block the streams incised the channels in which they found themselves at the beginning of the deformation and destroyed nearly all vestiges of the former channel forms. The lower reaches of the gorges that descend the western slope of the Sierra Nevada were deepened to fully two-thirds of their present impressive size. Glaciers presumably sculptured the land surface in the highest part of the Sierra Nevada during this epoch and perhaps supplied a material part of the detritus. However, the relative amounts of cutting performed by the two agents—glaciers and streams—were not established in this investigation. Farther west the streams were able to widen their valleys by planation in the weak Tertiary sedimentary rocks that lay along the flank of the mountain block and ultimately to swing widely to the north and south, planation continuing until the Tertiary sedimentary rocks had been truncated and thoroughly leveled. Most of the large volume of detritus was transported westward across the truncated sedimentary beds and deposited, at least in part, in alluvial fans or deltas along the axis of the California Trough. Only the coarser detritus was left as a mantle over the surface of truncation; this mantle constitutes the Arroyo Seco gravel (p. 49). Thus, at the culmination of this epoch a broad gravel-capped plain of uniform gradient had been formed at the western foot of the Sierra Nevada entirely across the Mokelumne area. This plain was the Arroyo Seco pediment. Its formation had engaged the ancestral Mokelumne, Cosumnes, and Calaveras (?) Rivers and Dry Creek—all the present streams of the area. Although the courses of these ancestral streams are not known, their apices of planation must have been very near the present canyon mouths. Toward the culmination of the Arroyo Seco epoch, when leveling was complete, the Mokelumne River may have swung so widely as to join the Calaveras River on the south or the Cosumnes River on the north. Strong physical evidence that the streams were so interbraided at that time is entirely lacking, but certain beds of gravel about a mile east of Burson suggest a possible channel that may have passed temporarily from the present course of the Mokelumne River, along the valley of Cosgrove Creek, and thence southwest to the Calaveras River. It seems certain, however, that this channel did not divert the whole flow of the river for a period of material length, because it is poorly graded and relatively narrow. Also, the divide at its head is but little lower than the initial altitude of the Arroyo Seco pediment at that place. It appears more likely that this possible channel is a local feature produced by a tributary of the Calaveras River.

The Arroyo Seco epoch appears to correspond to the early part of the so-called canyon stage of the Yosemite Valley, the stage to which Matthes [22] has ascribed all the stream cutting accomplished in the Yosemite Valley since the major deformation of the Sierra Nevada. It might presumably have coincided in time with one of the cycles of glacial and interglacial stages that constitute the Pleistocene epoch, but definite correlation seems not justified by the data now available. The present inclination and form of the Arroyo Seco pediment suggest that the baselevel of local erosion, the sea, has risen somewhat with respect to the present land surface since the pediment was formed. The suggested rise is inferred to be of the order of 100 feet. The relation of the pediment to the other land forms of the area suggests further that this rise of the baselevel ended the epoch of pediment cutting.

VICTOR EPOCH

In the partial cycle of erosion and sedimentation that succeeded the epochs of pediment cutting and of rising baselevel, the streams of the Mokelumne area achieved much flatter gradients. In the Sierra Nevada they deepened still further the canyons that had been established in the Laguna epoch and deepened in the epoch of pediment cutting. Thus a material part of the present impressive depth of the Mokelumne River canyon was produced in the Victor epoch. At Lancha Plana, at the present mouth of the canyon, near the western edge of the resistant crystalline rocks, the canyon was deepened about 250 or 300 feet in the Victor epoch before sedimentation at that place began. Presumably the amount of deepening would have decreased upstream, but it does not seem justified to state where it may have died out, for in most places it is not possible to discriminate sharply those parts of the canyon that were not deepened.

In the western part of the area, on the other hand, the streams trenched and dissected the Arroyo Seco pediment and built broad alluvial fans that lapped eastward upon it. The pediment was most extensively dissected along its higher eastern edge, where certain of the tributary streams occupied courses across the nonresistant Valley Springs and Ione formations (pp. 71, 80). In rocks so weak the streams were able to deepen and widen their valleys rather rapidly and in

[22] Matthes, F. E., op. cit. (Prof. Paper 160), pp. 31-32.

this way to form the Wallace-Ione basin (pp. 21–22). This basin constitutes the most conspicuous of the Victor erosion forms that is preserved in the present topography of the Mokelumne area. Toward the west the depth of dissection diminished. In the vicinity of Clements, for example, the Mokelumne River incised its relatively narrow channel 100 or perhaps 150 feet below the pediment. Still farther west, perhaps beneath the area that is irrigated by ground water, it is presumed that the trenching of the pediment by the ancestral Mokelumne River and other streams died out entirely (p. 45).

Presumably detrital sediments were deposited in the Mokelumne area throughout the Victor epoch. It is inferred that sedimentation occurred first along the axis of the California Trough beyond the mouths of the stream trenches that were being cut into the pediment; there sedimentation had proceeded without an appreciable halt at the beginning of the epoch. Gradually, however, the sediments of the Victor epoch were built higher and higher by the streams, and the apices of alluviation migrated eastward along the respective stream trenches. Ultimately the alluvial fans were built so high that they coalesced, buried the western part of the dissected Arroyo Seco pediment, and formed a single extensive alluvial plain that occupied all but the axial tidal portion of the Califorina Trough. This is the Victor alluvial plain that has been described above.

The courses of the distributaries by which the Mokelumne River built its Victor fan westward from Clements are very imperfectly known. One main channel whose position was relatively stable is suggested by a triangular body of coarse sand and fine gravel that is postulated to define the thickness of the Victor sediments between Victor and Lodi (p. 48). It is inferred that as far west as Lodi this channel passed somewhat south of the present stream; near Lodi it appears to have swung northwestward and passed beneath Woodbridge (fig. 5). The lower reaches of other Victor channels are suggested by the six blind tidal sloughs along the western edge of the Mokelumne area (p. 15). The final pattern of the distributaries on the surface of the fan is defined by the shallow ephemeral drains that radiate westward from Clements between Bear Creek on the south and Coyote Creek on the north. These two creeks define approximately the margins of the Victor fan and bound the area over which the distributaries of the river swung.

Between the mouth of its canyon near Lancha Plana and the apex the Victor fan near Clements, the Mokelumne River is confined on the north by the dissected Arroyo Seco pediment, part of which is the conspicuous ridge between Lancha Plana and Buena Vista. The crest of this ridge, which is formed for the most part of relatively resistant rocks, is but little lower than the projected Arroyo Seco pediment. On the south the river is likewise confined except for a few possible water gaps so narrow that they could never have diverted the whole flow of the Mokelumne River for any material length of time. Small gaps of this sort in the vicinity of Valley Springs Peak may thus have diverted some water into Cosgrove Creek, a tributary of the Calaveras River. Farther west, in the vicinity of Washington School, 4 miles east of Clements, is an ill-defined gap through which part of the flow of the river may have spilled into the present channel of Bear Creek late in the Victor epoch. No major gaps are known on either side of the river. Clearly the Mokelumne River has followed its present course, except for possible minor deviations, since the trenching of the Arroyo Seco pediment began in the Victor epoch. The other streams of the Mokelumne area seem to have been confined likewise between the mouths of their canyons in the crystalline rock of the Sierra Nevada and the apices of alluviation along the eastern margin of the Victor plain. It seems likely that their present courses in that district are those that they happened to occupy on the Arroyo Seco pediment at the beginning of the Victor epoch and that they incised those courses without rearrangement. The pattern of the streams on the west flank of the Sierra Nevada is believed to have been established before the major tilt of the mountain block and to have undergone little if any rearrangement since the tilt. Thus it is inferred that the relative extent of the present drainage basins is an index of the volumes of detritus transported by the respective streams of the Mokelumne area in the Victor epoch.

RECENT EPOCH

Since the Victor plain was built the Mokelumne River and other major streams of the area have entrenched their channels. Apparently this trenching has been accomplished without appreciable change in baselevel.

STRUCTURAL DIVISIONS OF CENTRAL CALIFORNIA

The Mokelumne area and the adjacent region include parts of three of the major structural units or crustal blocks of central California—the Sierra Nevada, the California Trough, and the California Coast Ranges. In a sense the Sierra Nevada and the California Trough may be considered parts of one structural unit. These structural units are essentially coextensive with the geomorphic divisions of the corresponding names.

SIERRA NEVADA BLOCK

The Sierra Nevada is sculptured from an elongated crustal block that trends about N. 30° W. throughout central California. This block is bounded on the east by the bold escarpment that faces the Great Basin; on the west its rocks are continuous with those that underlie the California Trough. This block has risen with respect to adjoining valley areas, by revolving or tilting toward the west, accompanied by block faulting that is especially pronounced along the east front.[23] This tilting seems to have been accomplished without appreciable warping within the block. The westward extension of the block has suffered a corresponding depression, though of less magnitude, where it is now covered by the alluvial deposits of the San Joaquin and Sacramento Valleys. There are some major faults along the west front of the Sierran block, particularly toward the south end,[24] but none are known to occur in or near the Mokelumne area. These movements are believed to have occurred in two relatively short epochs of diastrophism that correspond to epochs of much more violent and extensive deformation elsewhere in California and on the Pacific continental border.

In large areas, particularly in the central part that includes the Mokelumne area, the Sierra Nevada block has, since the beginning of the Tertiary period, behaved as a rigid mass together with the sediments that were deposited upon it during that period. This central area of the Sierra Nevada, which is now tilted westward with remarkably constant inclination of the strata, is at least 150 miles long and 65 miles wide from the summit of the mountains to the eastern edge of the San Joaquin Valley. Its southern limit lies opposite the city of Fresno; its northern limit opposite Sacramento. It is singularly free from the faults that form so conspicuous a feature of the geologic structure of most other parts of California.

CALIFORNIA TROUGH

The California Trough or Great Valley of California lies between the Sierra Nevada on the east and the Coast Ranges on the west. Its form is determined primarily by the geologic structure but is reflected at the surface by the great interior valley plain that is occupied by the Sacramento and San Joaquin Rivers. The origin of this trough has been discussed recently by Clark,[25] with references to the views of previous writers. As a regional feature the trough is properly considered a product of faulting, for its western margin is generally defined by a series of faults; nevertheless, in and near the Mokelumne area its eastern limb is a prolongation of the tilted Sierra Nevada block without known discontinuities of the strata. Although there is a possibility that faults may at some time be found beneath the alluvium along the eastern edge of the trough in the Mokelumne area, the presumption is strongly in favor of structural continuity. Lindgren [26] draws the contrast between the trough and the Sierra Nevada and Coast Ranges.

[23] Louderback, G. D., Period of scarp production in the Great Basin: California Univ., Dept. Geol. Sci., Bull., vol. 15, pp. 1-44, 1924.

[24] Hake, B. F., Scarps of the southwestern Sierra Nevada, California: Geol. Soc. America Bull., vol. 39, pp. 1017-1030, 1928.

[25] Clark, B. L., Tectonics of the Valle Grande of California: Am. Assoc. Petroleum Geologists Bull., vol. 13, pp. 199-238, 1929.

[26] Lindgren, Waldemar, The Tertiary gravels of the Sierra Nevada of California: U. S. Geol. Survey Prof. Paper 73, pp. 15-16, 21-22, 50, 1911.

Ransome [27] discusses the rigidity of the Sierran block and concludes that the whole mass may have behaved as a unit and that the trough may have subsided contemporaneously with the uplift of the Sierra Nevada. Viewed in this aspect the California Trough in the Mokelumne area is a geomorphic division but not a structural unit.

COAST RANGES

The Coast Ranges, broadly classed as a unit, are much more complex in structure than the Sierra Nevada, include a much thicker series of strata, and disclose a more continuous record of sedimentation. A general concept of the geologic history of any part of the Sierran region cannot be obtained without considering also the geology of the Coast Ranges. In the present paper, consideration of the geology of the Coast Ranges is mainly limited to references to the Diablo Range, which forms the southwestern border of the San Joaquin Valley and which is the eastern unit of the Coast Range system opposite the Mokelumne area.

STRATIGRAPHY OF THE MOKELUMNE AREA AND ADJACENT REGION

AGE AND GENERAL DISTRIBUTION OF THE ROCKS

The geology of the Mokelumne area is concerned chiefly with the record of the Tertiary and Quaternary periods, for it is only the Tertiary and Quaternary strata—with an unknown thickness of Upper Cretaceous deposits that are reached in deep wells—that overlap and lie upon the basement of older Mesozoic and Paleozoic rocks. The rocks of the Tertiary system form a great wedge that is thickest beneath the axis of the San Joaquin Valley and thinnest toward the east, along the mountain front, where the rocks are uptilted and truncated by erosion. The sediments of the Quaternary system lie in similar form above the Tertiary and likewise thicken westward. Below the Quaternary, only Tertiary strata have been reached by any of the deeper wells that have yet been drilled in the Mokelumne area, though rocks of Cretaceous age have been penetrated in a deep well near Oakdale, south of this area (p. 87). Rocks of Cretaceous age also crop out near Folsom, north of the area, and in the Diablo Range, to the west (pp. 86–87).

The rocks of the Tertiary system crop out in orderly succession in roughly parallel north-south belts or zones and range in age from a thin Eocene formation that lies in overlap against the older rocks of the Sierra on the east through strata of Miocene and Pliocene (?) age.

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[27] Ransome, F. L., The Tertiary orogeny of the North American Cordillera and its problems, in Problems of American geology, pp. 371–373, Yale Univ. Press, 1915.

The contact of the Tertiary rocks with the older rocks of the Mokelumne region was mapped by Turner,[28] and little modification of that mapping can be suggested from the present work. However, the subdivisions of the Tertiary system now in common use are somewhat different from those used by Turner.

The general character and succession of the rocks in the Mokelumne area and the adjacent region, as now interpreted, are summarized by the following table. A more detailed description of the stratigraphic units and of their geologic classification in given in succeeding pages, for it is upon the physical character and continuity of these units that the interpretation of hydrologic conditions must be based. The usual order of description has been inverted, in that the youngest unit is described first; thus the sequence of description is the same as the order in which the units are encountered by the well driller. Moreover, in the agricultural district of the Mokelumne area the extent to which the stratigraphic units control the intake and circulation of ground water is roughly inverse to their geologic age.

The distribution of the formations in the Mokelumne area is shown on the geologic map (pl. 1).

Stratigraphy of the Mokelumne area and adjacent region, California

Geologic age		Formation and symbol on pl. 1	Thickness (feet)	General character
Quaternary	Recent.	Alluvium (Qal).	0–25	Sand, silt, and gravel in present stream channels and beneath flood plains.
	Pleistocene.	Victor formation (Qv).	0–125	Sand, silt, and gravel, in small part well sorted and well stratified; deposited by the Mokelumne River and adjacent streams in building the Victor alluvial plain on which the settlements of Lodi, Lockeford, and Clements are situated.
		Arroyo Seco gravel (Qas).	0–19	Water-worn cobbles, gravel, and sand derived chiefly from pre-Cretaceous crystalline rocks; a pediment gravel that mantles the dissected Arroyo Seco pediment along the west front of the Sierra Nevada; contemporaneous sediments presumably exist to much greater thickness beneath cover in the axis of the California Trough.
		Gravel deposits of uncertain age (Qtu).	0–40	Water-worn cobbles and gravel on remnants of stream terraces and capping remnants of upland plains along the west front of the Sierra Nevada; in part possibly of Arroyo Seco age; in part perhaps as old as early Pleistocene or late Pliocene.
------	------(?) ------	Unconformity		
Tertiary	Pliocene(?).	Laguna formation (Tl).	0–400	Stream-borne silt and sand, with some gravel and clay, nonandesitic, poorly bedded and poorly exposed; laid down presumably in Pliocene but perhaps in early Pleistocene time — that is, after the Miocene andesitic epoch and before the major tilting of the Sierra Nevada in the early Pleistocene.

[28] Turner, H. W., U. S. Geol. Survey Geol. Atlas, Jackson folio (no. 11), 1894.

Stratigraphy of the Mokelumne area and adjacent region, California—Continued

	Geologic age	Formation and symbol on pl. 1		Thickness (feet)	General character
Tertiary	Miocene(?).	Mehrten formation (Tm).		75–400	Fluviatile sandstone, siltstone, and conglomerate, commonly well assorted and well stratified; encloses layers of coarse agglomerate of mud-flow origin; dominantly of andesitic detritus associated with andesitic eruptions in the high Sierra Nevada; in part contemporaneous and in part subsequent to regional diastrophism.
		-Unconformity			
		Valley Springs formation (Tv).		75–525	Pumice and fine siliceous ash, with much greenish-gray clay and some vitreous tuff, glassy quartz sand, conglomerate; commonly well bedded; derived largely from rhyolitic ejectamenta thrown out in the high Sierra Nevada.
		-Unconformity			
	Eocene.	Ione formation (Ti).		0–450	White or light-colored clay and clayey quartzose sand and sandstone; shale and some lignite beds in the lower part.
		(Unnamed).		200+	Dark-gray and brown shale and fine gray sand containing carbonaceous streaks or flakes; fossiliferous; do not crop out in or near the Mokelumne area but known from the records of a few deep wells.
Cretaceous	Upper Cretaceous.	Chico group	Moreno formation.	(?)	Argillaceous shale and fine dark clay shale; exposed in the Diablo Range and presumed to underlie the Mokelumne area, which lies about 40 miles to the northeast.
			Panoche formation.	(?)	Arenaceous shale and thin-bedded sandstone with hard concretionary beds and local conglomerate lentils; exposed in Diablo Range; upper part may underlie the Mokelumne area.
			-Unconformity		
Carboniferous and Jurassic					Slate, argillite, limestone, quartzite, and greenstone; closely folded and intruded by granite, granodiorite, and associated plutonic rocks; form core of the Sierra Nevada.

QUATERNARY SYSTEM

RECENT SERIES

The Recent alluvium comprises those sediments to which further additions are being made periodically by the streams or would be made under natural conditions. Over most of the Mokelumne area, therefore, it includes the deposits of the inner channels and flood plains of the streams. Only these deposits are now subject to periodic overflow, for all the streams except the Calaveras River are entrenched so deeply that they no longer overflow the Victor plain. Also, all the streams are in places so confined by levees that the natural regimen is upset and alluviation no longer takes place over the flood plains. In the Delta country, which lies farther west, beyond the longitude of Woodbridge and Galt, the land is but little above or below mean sea level, and all the surficial deposits are classed as Recent alluvium. There, except for the effect of levees, all the land would normally be overflowed during high stages of the streams or intermittently exposed in tidal marshes, and stream-borne alluvium becomes more or less intermingled with tidal muck and peat.

The Recent alluvium in bars along the Mokelumne River east of Lodi is composed of ill-sorted sand and fine gravel with subordinate quantities of silt and cobbles. The gravel pits operated by Langley & Flockhart in the river channel northeast of Clements, in the SW¼ sec. 11, T. 4 N., R. 8 E., are replenished each year by the river during its high stages. Thus during the winter and spring of 1932 one pit was filled with a 2-foot layer of unsorted mud and sand overlain by another 2-foot layer of gravel and cobbles as large as 4 inches in diameter. Here the alluvium is known to be 8 to 10 feet thick. Though such material may be deposited along the main channels during freshets, only fine sand and silt are commonly handled by the stream during low stages. Such fine sediments may remain as a thin but continuous blanket over the coarser sand and gravel of the river bed until a succeeding freshet.

The alluvium that floors the inner channels of the other streams generally resembles that of the Mokelumne River in texture. The channel floors of Dry Creek are covered chiefly with silt, but sand and gravel are not uncommon. During each yearly freshet this stream commonly inundates its entire flood plain and consequently drops thereon a large portion of its detrital load. The channel alluvium of the Cosumnes River consists of unconsolidated silt, sand, and gravel. That of the Calaveras River is commonly somewhat finer, contains few cobbles, and in places is capped by a crust of dark-red silty sand that is cemented tightly by iron oxide. These crusts are as much as 2 feet thick and extend for half a mile or more; they occur in the main channel and in the secondary channels that have been permanently abandoned by the stream. Obviously they reduce the perviousness of the stream bed.

The flood plain of the Mokelumne River ranges in width from a quarter of a mile to 1 mile and is 10 to 15 feet above the floor of the inner channel. That of the Cosumnes River is approximately as wide but is only 5 to 8 feet above the channel floor. Dry Creek, although it drains a much smaller area, has a flood plain about as wide as those of the Mokelumne and Cosumnes Rivers. The flood plains of these three streams are entrenched 10 to 40 feet below the Victor plain.

The Recent alluvium that has been spread in historic time over the flood plain of the Mokelumne River consists of sand and silt. Some freshets have spread sand extensively in the Delta country; others have deposited only silt even farther upstream than Victor.

The channel of the Mokelumne River is not stable, for in places it has shifted appreciably in the last 25 years, and in late geologic time it has swung to and fro in a belt as much as a mile wide to scour its trench in the Victor plain. Hence, all the alluvium that underlies its flood plain must be compounded of sediments whose texture is similar to that of the present channel deposits and of finer sediments such as have been spread in historic time on the flood plain. Heterogeneity and discontinuity of beds are characteristic. The channel bank at the Langley & Flockhart gravel pit northeast of Clements discloses the following section:

Top of bank and section.	Feet
Soil, chiefly fine sand and medium sand	3
Coarse sand, gray, cross-bedded	10
Concealed (to bottom of section)	2
Total	15

The bed of coarse sand can be traced westward about 100 feet without noticeable change in texture. Other small scattered outcrops on the grass-covered banks of the channel show that in general the alluvium underlying the flood plain consists of sand that is commonly cross-bedded, silt and clayey silt, and gravel. The beds, as shown by samples taken from observation wells and test borings, are 2 to 8 feet thick. They are so discontinuous and differ so much in texture from place to place that commonly the same succession of beds does not exist in two borings 20 feet apart. Some beds even pinch out between borings only 5 feet apart.

Upstream from Clements much of the flood plain of the Mokelumne River is stacked with windrows of coarse gravel, cobbles, and boulders—the waste from hydraulic mining; this material is inferred to represent the coarse fraction of the alluvium in that district.

In the interstream tracts or "islands" of the Delta country stream-borne sand and silt have in many places mingled with the silt of the tidal flats and with the disintegration products of tules to form extensive bodies of muck. Elsewhere but little alluvium has been mingled with the vegetal matter, and extensive deposits of peat have resulted. At present the natural regimen is altogether upset, because many of the stream channels have been confined by levees, so that the intervening "islands" are no longer overflowed and the tules have been cleared to permit cultivation. According to the agricultural classification of the soils, the Recent alluvium in this part of the Mokelumne area occupies tracts that range in altitude from sea level to a few feet above. However, on plate 1 the boundary between the alluvium and the abutting Victor formation has in most places been drawn somewhat arbitrarily along the zero or sea-level contour.

Stearns [29] reports that "near the axis of the Great Valley [California

[29] Stearns, H. T., Robinson, T. W., and Taylor, G. H., Geology and water resources of the Mokelumne area, California: U. S. Geol. Survey Water-Supply Paper 619, p. 32, 1930.

Trough], under some of the islands west of Lodi, where the land has been reclaimed from sea-level marshes, the peat attains a thickness of more than 50 feet." Such a condition indicates that the historic environment of sedimentation has prevailed for many centuries and that the tidal flats in the axis of the trough have subsided continuously in that period, for tules do not grow in water much more than 10 or 15 feet deep, and the accumulation of a foot of peat is conservatively estimated to require on the average about 75 years.

A minimum measure of the thickness of the Recent alluvium along the Mokelumne River is afforded by the records of test borings made on the flood plain by the East Bay Municipal Utility District. Thus, of 133 borings between Clements and Woodbridge, 29 were less than 10 feet deep but 104 ranged in depth between 10 and 23 feet. These deeper borings were widely scattered, and none reached material that could be discriminated from the known alluvium. At the Langley & Flockhart gravel pit the alluvium is at least 20 feet thick—that is, the maximum depth of excavation below the flood plain.

Several observation wells that have been drilled on the flood plain between Lodi and Lockeford—nos. 4636J1, 4725G3, 4725L1, 4731N6, and 4734G1 (see p. 122)—penetrate beds of gravel and coarse sand 25 to 45 feet beneath the surface. Even sediments so coarse can scarcely be interpreted as channel deposits at the base of the alluvium, because similar coarse deposits occur at all depths in the Victor formation and because in texture, degree of weathering, and mineral composition the alluvium closely resembles the underlying Victor formation. Thus, the sediments penetrated by wells 4724P1 and 4724N1 are very similar, even though well 4724P1 alone enters the alluvium; these wells are about 300 yards apart and are located on the flood plain and on the Victor plain, respectively. In fact, the sediments in these two wells are more nearly alike than in many pairs of adjacent wells drilled entirely in the Victor formation (pl. 7).

According to a recent detailed survey [30] much of the soil on the flood plains is a light-brown to faintly reddish-brown very fine sandy loam, whereas the subsoil commonly is lighter in color and at certain places has a definite textural stratification. Along the Mokelumne River these uppermost layers are grayer than usual and range from relatively coarse sand on some channel ridges to fine silt loam or even clay in oxbows. Irrespective of these variations, the soil is relatively porous and is reported to have an apparent specific gravity as low as 0.90 at certain places.

In connection with tests of specific yield, several samples of the Recent alluvium were collected at depths ranging from 1.7 to 13.8 feet below the flood plain along the Mokelumne River. Each sample

[30] Cosby, S. W., and Carpenter, E. J., Soil survey of the Lodi area, California: U. S. Dept. Agr., Bur. Soils (in preparation).

appears to be relatively uniform in texture, but among the several samples the dominant grade size ranges from coarse sand to silt.

The Recent alluvium is inferred to have a relatively large capacity to transmit water because (1) so far as known, it is completely unindurated; (2) although composed largely of sand and silt, commonly it is thoroughly assorted and contains relatively little clay; (3) its average porosity is high; and (4) it includes beds of coarse clean sand which form ground-water arteries.

PLEISTOCENE SERIES

VICTOR FORMATION

DEFINITION AND REPRESENTATIVE SECTIONS

The strata next older than the Recent alluvium are the sedimentary deposits of the epoch that culminated in the construction of the Victor alluvial plain (pp. 15–17). For them the name "Victor formation" is proposed in this report, after the type portion of the plain in whose topography they are so forcefully expressed. This name is also ascribed to the strata of the type district by Tolman [31] in a private report.

The type section of the Victor formation is disclosed in a drainage sump or pit dug in December 1931 in the town of Victor, although this section and the known natural outcrops in the vicinity expose only the uppermost part of the formation. This section, as observed by the senior writer (Gale) before the pit was cribbed, follows:

Type section of the Victor formation, Mokelumne area

[Pit in the SW¼NE¼ sec. 3, T. 3 N., R. 7 E., 190 feet north of the Southern Pacific Railroad at the east edge of Bruella Road]

	Feet
Top of section at level of the Victor plain, approximately 73 feet above sea level.	
1. Soil, blackish, street earth	0–1
2. Silt or clay, light gray	1–1¼
3. Sand, silty, reddish, locally called "loam"	1¼–8
4. Silt or clay, light gray, thin seam, not measured.	
5. Sand, medium to coarse, light gray, well sorted; composed almost wholly of well-rounded quartz grains; porous but not water-bearing because it is above the water table	8–12
6. Sand, silty, reddish; called "dirt" or "loam" locally; water-yielding capacity presumably small	12–14
7. Sand, well sorted; resembles no. 5	14–16
8. Sand, silty, reddish, similar to no. 6	16–26
Base of measured section about 47 feet above sea level; lowest 5 feet of section sampled with auger below bottom of pit.	

Other sections that are exposed in the central part of the Mokelumne area and are correlated with the Victor formation are described in the

[31] Tolman, C. F., typewritten report to the Pacific Gas & Electric Co. on the geology of the Mokelumne region, San Francisco, 1931.

following paragraphs. These sections are presented in natural sequence proceeding westward from the apex of the Victor alluvial fan near Clements.

Of the terrace deposits along the Mokelumne River, the easternmost that has been correlated tentatively with the Victor formation is at the site of the former town of Lancha Plana, about 2 miles downstream from the dissected Arroyo Seco pediment. As disclosed by gold-dredging operations, the deposit at that place was about 65 feet thick and included 50 feet of fine gravel and sand underlain by 10 to 15 feet of coarse gravel, cobbles, and boulders as much as 30 inches through. The base of the deposit was 250 to 300 feet below the projected altitude of the Arroyo Seco pediment at that place.

The most extensive of the terrace deposits occurs north of the river about 6 miles farther west, in secs. 4 and 5, T. 4 N., R. 9 E. This terrace, which is nearly a mile long and as much as half a mile wide, is in part of constructional origin, for 35 feet of unsorted and loosely consolidated sand is exposed in a gully in the NW¼SE¼ sec. 5. This sand encloses three or more beds of semiconsolidated fine-grained cross-bedded micaceous sandstone composed of well-sorted particles. These beds are 6 inches to 2 feet thick. In texture, composition, degree of sorting, and consolidation these sediments resemble those of the typical Victor formation farther west. In part, however, the terrace is cut on rock, because two low knobs of the underlying Mehrten and Valley Springs formations (pp. 61, 71) project through it, and for half its length it is separated from the present river channel by a ridge which is composed of the same rocks and which rises about 20 feet above the terrace.

The clearest exposures that have been correlated with the Victor formation occur in the north bank of the river at the Clements and Lockeford bridge heads. These and other sections are tabulated below:

Partial sections of the Victor formation

South bank of Mokelumne River at Clements gaging station, NE¼NW¼ sec. 15, T. 4 N., R. 8 E.

	Feet
Top of exposed section 104 feet above sea level.	
Silt, sandy, very light buff; encloses beds of medium sand, brown, 1 to 12 inches thick, and discontinuous pebbly seams	9
Gravel, ill-sorted, well-rounded pebbles generally less than 1 inch in diameter, coarse sand matrix; a discontinuous lentil	0–3
Base of section rests unconformably on disintegrated andesitic sandstone of the Mehrten formation, altitude 92 feet above sea level.	
Thickness of exposed section	**12**

Partial sections of the Victor formation—Continued

North bank of Mokelumne River at Clements bridge, NW¼NW¼ sec. 15, T. 4 N., R. 8 E.

	Feet
Top of measured section at level of Victor plain, about 135 feet above sea level.	
Concealed in large part but with a few exposures of thin-bedded compact very fine sand	20
Silt, gray; medium sand, brown, unsorted, in alternating beds 6 inches to 3 feet thick	10½
Coarse sand, brown, and very fine sand and silt, light gray, in alternating beds 1 inch to 2 feet thick	4¾
Light-gray silt	½
Coarse sand, brown, poorly sorted, and fine sand, micaceous, light gray, and cross-bedded, in alternating lenticular beds half an inch to 1 foot thick	3¾
Base of measured section about 5 feet above bridge head, about 95 feet above sea level.	
Thickness of measured section	39½

North bank of Mokelumne River at Lockeford bridge, SW¼SW¼ sec. 24, T. 4 N., R. 7 E.

	Feet
Top of measured section at level of Victor plain, about 101 feet above sea level.	
Soil and concealed	6
Very fine sand and silt, light gray; one 9-inch bed of brown medium sand near the middle	6½
Sand, unsorted, chiefly coarse to medium, gray to brown	1
Very fine sand and silt, thin-bedded, light gray	2½
Coarse sand, well sorted	3
Concealed	5
Silt, well sorted, white with brown streaks	2
Coarse sand, brown, with some pebbles as much as half an inch in diameter; matrix of fine sand to silt with some thin beds of fine sand, unsorted	6
Fine sand, well sorted, brown, with white to brown silt, in beds 1 to 6 inches thick	3
Sand, unsorted, light gray, probably chiefly fine sand but with some grains 5 millimeters in diameter; one discontinuous bed of coarse sand 6 inches in maximum thickness at top	5½
Very fine sand and silt, well sorted	3
Base of exposed section reads 2 feet on staff gage—that is, 57 feet above sea level.	
Thickness of measured section	43½

Partial sections of the Victor formation—Continued

West wall of test pit on Woods-Wilhoit ranch, NE¼NW¼ sec. 33, T. 4 N., R. 7 E.

[About 200 yards northeast of residence; section measured by A. M. Piper]

	Feet
Top of section at level of Victor plain, about 75 feet above sea level.	
1. Fine sand to silt, compact, brown to light drab, no visible lamination; lower contact undulating (relief 4 inches)	0–6
2. Sand, medium and fine, poorly sorted, coarser toward base; raw sienna color; no visible stratification; bottom contact irregular and indicates current scour	6–6¾
3. Silt, sandy, micaceous, moderately indurated, olive gray	6¾–7½
4. Sand, medium and coarse, brown, massive	7½–8½
5. Fine sand to silt, olive drab, laminated	8½–9¼
6. Sand, coarse at top, medium below, brown to gray, laminated at base	9¼–10
7. Sand, blue gray, fine at top, coarser toward base; rudely bedded; grades downward into bed below	10–11
8. Sand, coarse and very coarse, well sorted, rude cross-bedding but no pronounced stratification	11–12

In the east wall of the test pit, 5 feet from the section just given, beds 4, 5, and 6 were absent and their place was occupied by gray and brownish-gray cross-bedded coarse and very coarse sand, the lower 6 inches of which was especially well sorted.

Still farther west there are few exposures of the Victor formation. At the Victor bridge and at the Woodbridge Dam unsorted sand and silt crop out in the banks of the river; the proportion of silt and very fine sand is higher at Woodbridge. The east bank of the Mokelumne River in the southwest corner of sec. 9, T. 4 N., R. 6 E., 4 miles northwest of Woodbridge, is made up principally of coarse and medium sand in alternating beds 6 to 12 inches thick. At this place part of the sand is cross-bedded. This outcrop is within 5 miles of the western or downstream edge of the Victor plain.

GENERAL CHARACTER

Throughout the Mokelumne area the Victor formation is composed largely of poorly rounded grains of quartz, feldspar, and mica, with local concentrations of magnetite, hornblende, and pyroxene. Thus it is similar in mineral composition to the Arroyo Seco gravel and Laguna formation (pp. 49, 57), which underlie it.

In the central part of the Mokelumne area the exposed parts of the Victor formation are stream-laid, as is shown by the sections that have been described. At the Clements and Lockeford bridge heads and on the Woods-Wilhoit ranch a considerable portion of the coarser sand is cross-bedded; thin beds of coarse and fine material alternate in vertical succession and interfinger intricately with one another; the particles of some beds grade rather abruptly from fine to coarse either laterally or vertically; and the contacts between beds, though commonly distinct, are not plane and are not parallel. Some of the more irregular contacts between beds are presumed to represent scour. In each of these three sections light-colored micaceous sand and silt occur in thin discontinuous beds. All these features indicate repeated reversals between relatively strong and shifting currents and slack water—the stream environment. The Victor deposits are somewhat finer at the Woodbridge Dam than at the Victor bridge, and that difference in size of particles may reflect the normal decrease in the carrying power of the streams with increasing distance from the source of the detritus, the Sierra Nevada. On the other hand, the suggested graduation in grain size is by no means constant in direction or rate—for example, coarse sand occurs near Thornton, within 5 miles of the western edge of the Victor plain. This indicates that the competence of the streams to transport detritus (ordinarily measured in terms of the size of particles transported) fluctuated greatly in the Victor epoch. Confirmatory evidence as to the genesis of the Victor formation may be drawn from its outward form, a succession of coalescing flat cones whose apexes occupy the debouchures of the Mokelumne River and other major streams along the flank of the Sierra Nevada (pp. 16–17). Clearly the formation is alluvial.

The detailed soil survey of the Mokelumne area [32] has classified the uppermost part in the Victor formation into several soil series, of which the Hantord series is rudely coextensive with the flat alluvial cone of the Mokelumne River (p. 16), whose margins coincide approximately with Bear Creek on the south and Jahant Slough on the north. The Hanford series is described as comprising light-brown and brown friable sandy loam and loamy sand without definite stratification. Locally the soil contains much angular quartz sand as large as an eighth of an inch in diameter. These loose friable soils extend downward to a rather uniform depth of 6 to 8 feet in the Mokelumne area.

The texture and physical character of the uppermost part of the Victor formation are disclosed by numerous samples taken in 1-foot segments at 23 infiltration plats maintained on the Victor plain between 1929 and 1933. All these plats were on soils of the Hanford series. Histograms based upon data from five of these plats are given in figure 4.

These five plats fall in an area that is 4½ miles across from north to south and 6¾ miles from east to west and that is centered roughly about Lodi. Two of the plats (374Fa and 374Fb) [33] adjoin one another. Although the five plats are spaced so widely, the sediments have several characteristics in common. All 63 samples contain

[32] Cosby, S. W., and Carpenter, E. J., op. cit.

[33] The number of an infiltration plat indicates its location after the manner of the numbers ascribed to wells. (See p. 122.)

0.5 percent or more of each of the seven grade sizes that are commonly used to denote the mechanical composition of a sediment. Notwithstanding this relatively wide distribution in size of particle, medium sand is the most abundant fraction in 50 of the 63 samples;

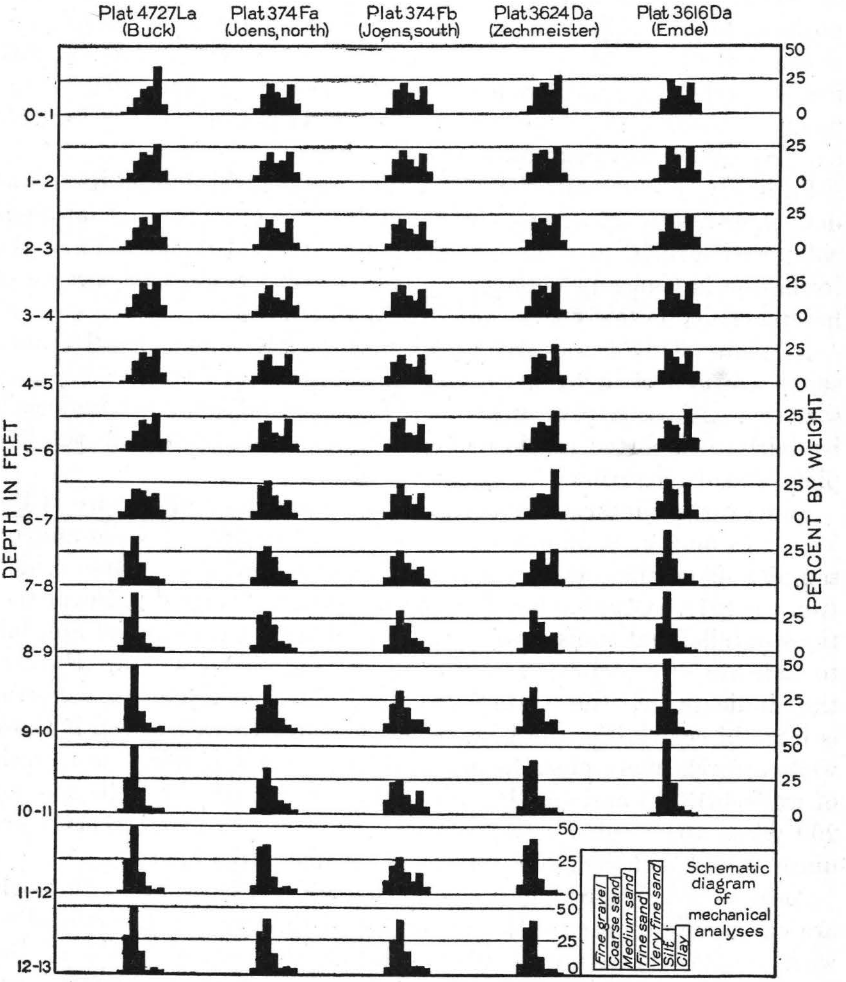


Figure 4.—Mechanical composition of sediments of the Victor formation at five localities in the Mokelumne area.

of these 50 samples, 23 are well sorted or moderately well sorted—that is, the medium sand fraction is 30 percent or more of the whole. In the remaining 13 samples the most abundant fraction is silt, and in only 4 of these is the silt fraction 30 percent or more of the whole.

In all five plats the sediments to a depth of 7 or 8 feet are poorly sorted and comprise medium and fine sand, with much silt. Below the depth of 7 feet at all the plats but one the sediments are coarser and relatively well sorted, the medium sand fraction is the most abundant, and commonly 75 percent or more of the material is composed of the several grades of sand. This characteristic applies down to the greatest depth sampled, 13 feet. At the one exceptional plat (379Fb) poorly sorted sand and silt recur from 10 to 12 feet below the surface. It is striking that the difference in mechanical composition of the sediments at the two Joens plats, which adjoin one another, is almost as great as in the entire group of five plats. Thus, it is suggested that the moderate changes in texture exhibited in any particular outcrop of the Victor formation do not necessarily indicate extreme differences in texture in larger areas.

Similarly, at all plats for which the mechanical composition was determined, the uppermost 6 to 9 feet of the Victor formation is composed largely of medium sand, fine sand, and silt. Thus the formation is typically heterogeneous as to texture, but the degree of heterogeneity is fairly constant over a wide area.

At plats 3716Na and 4727C the loose friable soils of the Hanford series are underlain by a compact and relatively impermeable substratum. At other plats the soils of the Hanford series are underlain by fairly well sorted medium sand, similar to that found in the five plats already described.

Some further information as to the composition and texture of the Victor formation is afforded by the drillers' records of wells and by samples of cuttings collected from wells as they were being drilled (pp. 91–101). Graphic logs of the wells, when arranged in linear sections parallel and transverse to the axis of the Victor alluvial fan, fail to indicate any useful correlation of the individual strata. Rather, they indicate that the strata are so lenticular that the chance of error is large in correlating the beds penetrated in two wells, even if those wells are relatively close to one another. For example, the records of wells 4613M3 and 4613R1 are dissimilar, though the wells are but 200 yards apart (pl. 7); the records of wells 3717F3 and 3717G3 are quite unlike, although the wells are only 800 yards apart.

As an alluvial deposit such as the Victor formation is built, channels are commonly scoured into the surface of the growing fan and filled with tongues of sediment whose texture differs from that of the banks and usually is coarser. Subsequently these tongues are buried and, if enclosed by less permeable material, may become functional ground-water arteries. Because coarse-textured tongues of the sort just described presumably are devious, they might not be delineated by linear sections. Accordingly a peg model was prepared to depict in three dimensions the records of 150 wells, most of which were located in the area of heavy pumping east of Lodi, in T. 3 N., R. 7 E. Elsewhere, the wells for which satisfactory records are available are too widely spaced to be useful for this purpose. This model, like the linear sections, fails to discriminate coarse-textured tongues in the Victor formation. Thus, it is indicated that if functional ground-water arteries exist, they are too narrow, too devious, and too closely braided to be discriminated with the well records available.

STRATIGRAPHIC RELATIONS AND THICKNESS

The top of the Victor formation, over the greater part of its outcrop area (pl. 1), is the initial surface of the Victor plain, but beneath the flood plains the formation underlies the Recent alluvium in unconformable contact. In turn, the base of the Victor formation presumably rests upon the concealed westward extension of the dissected Arroyo Seco pediment. Although the basal contact is generally an unconformity in the outcrop area, it is believed that beneath the district that is irrigated by ground water (pl. 10) the contact is in places conformable. Thus, near the apex of the Victor fan at Clements the Victor formation rests unconformably upon volcanic detritus of Miocene (?) age and veneers the floor of a trench which at that place had been cut at least 100 feet deep into the Arroyo Seco pediment. The minimum measure of the depth of trenching is afforded by the difference in altitude of the projected pediment and the exposed base of the Victor formation in the south bank of the Mokelumne River at the Clements gaging station, in the NE¼NW¼ sec. 15, T. 4 N., R. 8 E. This difference is about 110 feet. Although the few exposures of the base of the Victor formation in the vicinity may not disclose the lowest part of the trench, it seems unlikely that the depth was more than 150 feet. The fingerlike tongues of the Victor formation that extend eastward across the dissected pediment and that lap unconformably across the full sequence of Tertiary rocks (pl. 1) appear to cover the floors of corresponding trenches along other streams of the Mokelumne area. These trenches in the Arroyo Seco pediment must have initially extended westward beneath the present irrigated district and must have been completely filled by the Victor sediments. However, it is presumed that gradually they became shallower in that direction and eventually died out altogether, somewhat as the trenches of the present streams in the Mokelumne area become shallower toward the west and die out along the edge of the Delta plain. This presumption is based upon the facts that, first, the depth of the trench cut by the ancestral Mokelumne River decreases about 150 feet from Lancha Plana to Clements—that is, about 13 feet in each mile toward the west or downstream; second, if the pediment is projected westward (p. 54), it passes below the projected floor of the trench about at the longitude of Lodi. The floor of the trench can be projected westward only approximately, on the assumption that it is parallel to the surface of the Victor plain between those points; but this assumption is supported in a general way by the known approximate altitudes of the top and bottom of the Victor formation at Lancha Plana and at Clements. Admittedly these data are scanty, but they are believed to afford a rough indication of the extent to which the Arroyo Seco pediment was trenched before the Victor formation was laid down upon it.

In the interstream tracts the Victor formation was deposited over the maturely dissected pediment. There the formation laps unconformably over and feathers out against the Laguna formation, of Pliocene (?) age (p. 57), and possibly also against the Arroyo Seco gravel (p. 49).

On the stratigraphic relations that have been developed in the preceding paragraphs two postulates are based. First, beneath the district irrigated by ground water the Victor formation rests upon the westward extensions of the Arroyo Seco gravel and of the Laguna formation, correlatives of which are believed to have been deposited extensively in the California Trough (pp. 53, 60); second, beneath parts of the irrigated district the Victor formation rests conformably upon the Arroyo Seco gravel.

In the south bank of the Mokelumne River at the Clements gaging station about 30 feet of Victor sediments rest upon andesitic detritus of the Mehrten formation. The exposures at this place may not indicate the deepest part of the pre-Victor trench, however, and thus not the maximum thickness of the formation in the vicinity. Farther east, at Lancha Plana, the formation is at least 65 feet thick. Farther west the base of the formation passes below the present land surface, so that a direct measure of the thickness is not afforded.

A hypothetical maximum thickness of the Victor formation in the district irrigated by ground water might be obtained by projecting the Arroyo Seco pediment westward, deducting its projected altitude at any point from the present altitude of the Victor plain, and adding to this difference the estimated depth of the trenching that preceded the deposition of the Victor sediments. The hypothetical altitudes of the projected pediment are 30 feet above sea level at Victor, 50 feet below sea level at Lodi, and 85 feet below at Woodbridge. The corresponding hypothetical maximum depth of the projected pediment is 45 feet at Victor, 100 feet at Lodi, and 125 feet at Woodbridge; the actual depth is probably somewhat less (p. 54). The depth of trenching, as has been pointed out, is perhaps 100 or 150 feet at the Clements gaging station and is inferred to be progressively less toward the west.

The thickness of the Victor formation in the irrigated district cannot be determined from the mineral composition of the samples from wells (p. 44), but it is perhaps disclosed by the peg model. Thus, within a lobate area (fig. 5) that starts 1½ miles southeast of Victor and extends both northwestward and southwestward over 5 to 6 square miles, nearly every well for which a record is available indicates that sand and fine gravel predominate in the upper 50 to 75 feet of the section. Wells 3717N1 and 3612R3 are typical. The samples from wells in this area suggest that the sand and gravel are poorly sorted and inconstant in texture, as is usual in the post-Mehrten deposits. In a few wells the top of the coarse sand is very close to the land surface, but in most wells it occurs at a depth of 15 to 25 feet. The bottom of the coarse sediments, which is fixed by underlying silty beds

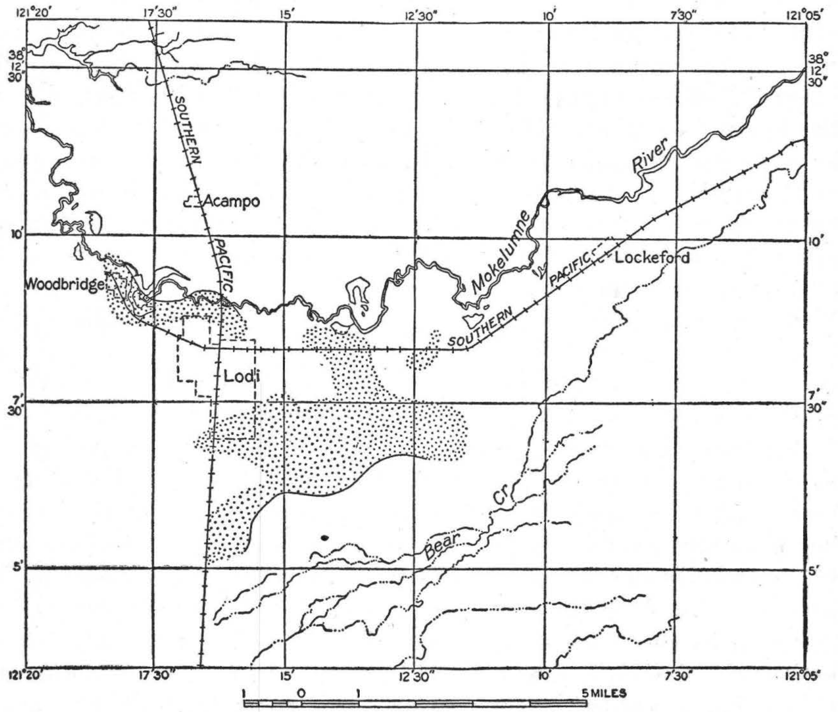


Figure 5.—Map of the Lodi-Victor district showing areas within which sand and gravel (stippled pattern) predominate in the upper 50 to 75 feet of most wells.

("clay" of the well driller), is somewhat variable in depth but averages about 50 feet below the land surface at Victor and 60 to 70 feet below at the longitude of Lodi. Along its southern edge the body of coarse sediments grades or fingers abruptly into material of finer texture, as is shown by several well records. To the east and north there are a few wells that penetrate a considerable thickness of coarse sediments within 100 feet of the land surface, but they are relatively far apart, and in places they are interspersed with wells that do not penetrate corresponding beds of sand and gravel. Thus the form and extent of the body in that direction are not known. South of Lodi and west of the Southern Pacific Railroad there are no well records to fix the westward extent of the body. Half a mile southeast of Victor there is a similar but ill-defined small body of sand and gravel. A third body, apparently elongate, underlies the Mokelumne River from the Southern Pacific Railroad crossing north of Lodi as far west as Woodbridge. Its southern boundary and its eastern and western ends are not fixed by well records. These two outlying bodies of sand and gravel may be arms of the major body that lies farther south, but the well records are too few to confirm the suggested relation.

The body of sand and gravel southeast of Lodi is rudely triangular in plan, has its acute apex approximately opposite the debouchure of the Mokelumne River from the Sierra Nevada, and underlies the axis of the Victor fan. It fills all or a major part of the vertical interval that has been postulated to define a hypothetical thickness of the Victor formation. Also, it is known to be bordered on the south by sediments of finer texture and is presumed to be likewise bordered on the north. It is inferred to comprise the coarsest detritus dropped by a stream—an ancestral Mokelumne River, perhaps—that was aggrading throughout much if not all of the Victor epoch. The axis of this aggradation apparently did not swing widely during the period. Furthermore, in most wells the body of sand and gravel is terminated below by relatively fine material that must be the product of an entirely different regimen of sedimentation. Both the Arroyo Seco gravel and the Laguna formation, either of which might underlie the Victor formation, were deposited from streams that planed widely as much as 10 miles east of the apex of the triangular body of sand and gravel (pl. 1). These streams planed at a profile of equilibrium that has been projected approximately to the base of the sand body. It seems unlikely that so narrow a body of coarse sediment would have been deposited by a stream of the Arroyo Seco or Laguna epoch so far down on its plane of equilibrium as the Lodi-Victor district. It is postulated, therefore, that the abrupt change in regimen of sedimentation that began the accumulation of the triangular body of coarse sediment represents the beginning of sedimentation in Victor time and that the total thickness of the Victor formation in the irrigated district is measured by that body. It is altogether possible that the apex of the body defines the position of the mouth of the trench cut in the Arroyo Seco plain by the ancestral Mokelumne River.

Other definitely limited bodies of coarse material in the sediments that underlie the Victor fan may perhaps be identified in the Mokelumne area as more well records become available. Well drillers have described portions of such bodies to the writers, and a typical example underlies the low ridge that extends northwestward across secs. 11 and 3, T. 4 N., R. 7 E. (See topographic map of Lockeford quadrangle.) According to E. A. Thayer, of Acampo, this ridge is underlain by gravel and coarse sand to a depth of 80 feet—that is, down to an altitude 20 to 30 feet above sea level—but there are no available logs of wells along this ridge.

The Victor formation is believed to be largely of late Pleistocene age, chiefly because it was deposited after the early Pleistocene tilting of the Sierra Nevada (p. 26) and after the Arroyo Seco pediment (pp. 20–22) had been cut along the flank of the tilted mountain block. Fragmentary fossils found at two localities in and near the Mokelumne area tend to confirm the Pleistocene age of the Victor formation, but do not indicate any particular stage of that epoch. One locality is 1½ miles north of Elk Grove, in the NE¼SW¼ sec. 30, T. 7 N., R. 6 E., where the land surface is a part of the Victor plain but not more than 1,000 feet from its east margin. There the left scapula of a horse was collected by H. T. Stearns 17½ feet below the land surface in a pit. Gilmore [35] determined this fossil as probably of the genus *Equus*, species undeterminable, and considered it to be Pleistocene. The other locality is near Sacramento, in sec. 32, T. 9 N., R. 5 E., about 1,000 feet north of the American River and 600 feet west of the Southern Pacific Railroad; it is about 6 miles beyond the north margin of the Mokelumne area (pl. 1), but the land surface (altitude 25 feet) is topographically continuous with the Victor plain. There a skull and several fragments of teeth of *Elephas* were uncovered 12½ feet below the land surface during the construction of a levee in January 1933. The enclosing sediments are lenticular beds of unconsolidated coarse sand and gravel, apparently stream deposits. The fossils were tentatively identified by Vickery [36] as pertaining to *Elephas columbi?*

ARROYO SECO GRAVEL

The extensive Arroyo Seco pediment, which is one of the conspicuous geomorphic features of the Mokelumne area (pp. 20–22), is covered with a characteristic brick-red soil that encloses much gravel, many cobbles, and scattered boulders. This soil is the surface expression of a stratigraphic unit for which the name "Arroyo Seco gravel" is proposed in this report, after the Arroyo Seco land grant, in which the formation is extensively preserved. This formation is next older than the Victor formation and lies stratigraphically below it.

The easternmost and clearest exposures of the formation occur in pits that have been excavated for placer gold on the upland northeast of Wallace; this locality lies on the projected axis of the Mokelumne River Canyon and about 5 miles southwest of its mouth. The section at this place follows:

[35] Gilmore, C. W., written communication.

[36] Vickery, F. P., oral communication.

Section of the Arroyo Seco gravel and underlying formations in pit a quarter of a mile northeast of Wallace, in the SE¼ sec. 15, T. 4 N., R. 9 E. (unsurveyed)

	Feet
Top of section at altitude of the Arroyo Seco pediment, about 425 feet above sea level.	
Arroyo Seco gravel:	
Soil, sandy and gravelly, iron-stained	2
Unsorted gravel and cobbles, with matrix of iron-stained sand and some silt; most particles less than 2 inches in diameter but some boulders as large as 8 inches in diameter; rudely shingled in places. Composed largely of quartzite and other crystalline rocks. Base of member is rough-scoured unconformity with relief of about 5 feet	15
Mehrten formation:	
Sandstone, coarse-grained, andesitic	6
Concealed	5
Valley Springs formation (?):	
Rhyolitic tuff, massive, base not exposed	1+
Base of section and bottom of pit.	

About 100 feet farther north the Arroyo Seco gravel is 11 feet thick and encloses a 3-foot lentil of coarse cross-bedded compact gray sand. Deposition from strong and shifting currents is indicated by the lenticular and discontinuous beds and by the coarse, poorly sorted material.

The two other clear exposures of the gravel in the Mokelumne area occur north of the Cosumnes River a mile southwest of Slough House, and west of the Elk Grove cemetery in sec. 31, T. 7 N., R. 6 E. Both are near the northern edge of the area represented on Plate 1. The sections at these places are as follows:

Section of the Arroyo Seco gravel and Laguna formation in road cut 1 mile S. 70° W. from Slough House, in the NE¼ sec. 4, T. 7 N., R. 7 E. (unsurveyed)

	Feet
Top of section is at level of the Arroyo Seco pediment, about 190 feet above sea level.	
Arroyo Seco gravel:	
Soil, gravelly	5
Gravel and sand, unsorted, particles commonly less than 2 inches in diameter but some cobbles as large as 5 inches. Base of member is wavy but horizontal	4
Laguna formation:	
Silt, gray, and brown sand, medium and fine, in alternating beds 6 to 18 inches thick	6
Sand, coarse, gray, cross-bedded, and compact	2
Base of exposed section.	

Section of the Arroyo Seco gravel in southwest wall of gravel pit west of the Elk Grove cemetery, in the SE¼ sec. 31, T. 7 N., R. 6 E.

	Feet
Top of section about 65 feet above sea level.	
Sand, unsorted, chiefly fine and medium, also unsorted gravel and sand in alternating beds 3 to 9 inches thick. Base of member is uneven, with a vertical range of 2 feet	3–5
Sand, unsorted, dominantly fine and medium, iron-stained	7–5
Gravel, commonly less than 1 inch in diameter but some cobbles 4 inches, with matrix of unsorted iron-stained silt and sand; encloses some coarse sand in discontinuous beds as much as 4 inches thick	8–9
Base of section is floor of pit, which uncovers light-gray sandy silt (Laguna formation?).	
Maximum thickness of measured section	19

The gravel pit at Elk Grove is in the south end of an outlying ridge that is some 4 miles long, is gravel-covered in part, and has a gently undulating surface. This ridge is surrounded by the Victor plain and lies 6 to 7 miles west of known remnants of the Arroyo Seco pediment. However, the restored pediment, if projected westward from the Cosumnes River with the gradient that prevails in that vicinity, coincides with the crest of the ridge. Accordingly, the top of the section exposed in the gravel pit is presumed to be only a few feet below the initial top of the Arroyo Seco gravel.

The Arroyo Seco gravel, like the younger Victor formation, comprises discontinuous beds and interfingering lentils of stream-borne detritus; but unlike the Victor formation it is composed largely of coarse sand and gravel and is generally, rather than locally, decomposed and deeply iron-stained beneath remnants of the initial land surface. The constituent cobbles and pebbles are usually well rounded and are derived from quartz and quartzite almost to the exclusion of other petrographic classes. Some of the pebbles and boulders are derived from the hardest and most resistant of the other crystalline rocks from the core of the Sierra Nevada, including some of volcanic origin. Locally, most of the pebbles and cobbles are composed of andesite such as is typical of the Mehrten formation (p. 61). Near several such localities the Arroyo Seco gravel truncates a cobble stratum that is interbedded in the Mehrten formation; presumably it has reworked the interbedded Mehrten cobbles without transporting them far. In a general way the Arroyo Seco gravel consists largely of coarse pebbles and cobbles near the Sierra Nevada and becomes finer down the slope of the pediment toward the west.

The greatest known thickness of the Arroyo Seco gravel is that exposed in the gravel pit at Elk Grove—19 feet. In spite of its present thinness, however, it is believed to have initially mantled the entire Arroyo Seco pediment, for it now seems to occur in place only as a relatively thin cap on nearly all the ridges and hills that rise to the altitude of the projected pediment. Thus, its inferred outcrop initially extended entirely across the Mokelumne area from north to south and was 8 to 15 miles wide. In the dissection of the pediment during the early part of the Victor epoch and subsequent time the cobbles of the Arroyo Seco gravel have been washed down and distributed widely over the lower slopes. Thus they have become mingled with others from the underlying Laguna formation, and in most places it is virtually impossible to delimit the Arroyo Seco gravel sharply and to determine its thickness. On plate 1 it has been mapped only where weathered gravel is known to occur at the altitude of the projected pediment. Thus most of its present outcrops are limited to a belt not more than 7 miles wide in the easternmost part of San Joaquin and Sacramento Counties. There are two extensive outliers. One caps the ridge north of Elk Grove, and the other caps the mesalike upland northeast of Wallace. Both of these are represented in the stratigraphic sections that have been tabulated. The outlier near Wallace lies opposite the canyon of the Mokelumne River; it is the easternmost outcrop that is ascribed with assurance to the Arroyo Seco gravel. Other small outliers are indicated on plate 1.

Within the outcrop area the top of the Arroyo Seco gravel was initially the constructed surface of the Arroyo Seco pediment; it now comprises the remnants of that pediment and the minor erosion forms superposed upon it (pp. 21–22). The base of the formation is essentially parallel to its top and is an unconformity composed of diminutive erosion forms with a relief of a few feet. This unconformable base truncates the tilted late Tertiary rocks, so that the Arroyo Seco gravel laps eastward across the Laguna, Mehrten, and Valley Springs formations in turn (pl. 1). The inclination of the formation is that of its restored upper surface—namely, 20 to 35 feet to the mile S. 70°–80° W. in the Clements-Wallace district, east of Lodi; and 10 to 20 feet to the mile S. 50°–65° W. in the Elk Grove-Slough House district, in the northern part of the Mokelumne area. The inclination of the underlying late Tertiary rocks is about 100 feet to the mile S. 80° W. in the vicinity of Clements. In that district, accordingly, the Arroyo Seco gravel has an angular discordance of about 75 feet to the mile with respect to the Tertiary rocks on which it rests.

The Arroyo Seco gravel is clearly the deposit of streams of large competence, for, although relatively coarse, it was distributed as a veneer of nearly constant thickness over an extensive piedmont erosion surface. Conversely, it was deposited at the profile of equilibrium of streams that planed widely while transporting their burden of coarse detritus. The present inclination of the surface of planation is little if any greater than the minimum slope at which material so coarse would be transported without aggradation. It is but one-sixth to one-third of the angular discordance with the underlying rocks and an equally small fraction of the tilt of the Sierra Nevada block in Pleistocene time (p. 26). Accordingly it is concluded that the Arroyo Seco gravel is a pediment gravel—that is, it comprises the residual products of long-continued sorting and fluvial transportation of rock waste across the Arroyo Seco pediment, which had been cut across the late Tertiary rocks on the west slope of the Sierra Nevada. It is concluded further that planation and deposition followed the Pleistocene tilting of the Sierra Nevada and that the initial inclination of the formation has been little if any steepened by subsequent tilting of the Sierran block. The large competence required of the planing streams suggests that the formation was deposited relatively soon after the Pleistocene tilting and that its age is middle or late Pleistocene. Though they planed widely across the pediment, the streams of the Arroyo Seco epoch flowed down the slope of the Sierra Nevada in courses essentially the same as those they now occupy. Thus the apexes of planation were essentially the mouths of the present canyons.

The Arroyo Seco epoch may be defined as the period of the erosion cycle that began when the Sierra Nevada block was tilted and that culminated when the piedmont planation was complete. It began, therefore, when the California Trough was newly deepened by that tilting and accordingly when the arm of the sea that occupied the trough presumably was deeper and more extensive than in any other part of Pleistocene and subsequent time. In the epoch the major part of the post-deformation dissection of the west slope of the Sierra Nevada was accomplished, so that a relatively large volume of detritus must have been transported westward across the present outcrop area of the Arroyo Seco gravel and toward the axis of the trough. It may be postulated that the detritus was deposited extensively in the axial part of the trough and that at the culmination of the epoch the pediment that is now preserved in the outcrop area merged westward into an even more extensive plain or surface of aggradation. This surface was perhaps submarine in part. Accordingly, the initial westward extension of the Arroyo Seco gravel was theoretically a wedge-shaped mass of fluvial and perhaps marine sediments whose base was the surface of the tilted Sierra Nevada block and whose top was the extended profile of equilibrium defined by the Arroyo Seco pediment. The angular discordance between the Arroyo Seco plain and the late Tertiary strata of the tilted block suggests that this wedge would have thickened westward about 75 feet in a mile.

If it is assumed, as seems permissible, that the initial top of the extended Arroyo Seco gravel has not been dislocated by faulting or differential warping, that top can be fixed hypothetically by projecting the known gradient of the Arroyo Seco pediment westward. Such projection might be made according to either of two methods. First, the gradient along the present western edge of the dissected pediment, 10 to 25 feet in a mile, might be projected in constant magnitude and in the direction of maximum slope to derive a hypothetical minimum altitude of the surface of the pediment. Thus, the top of the Arroyo Seco gravel would be 50 feet below sea level at Lodi, or about 100 feet below the land surface if the slope of the present surface were taken into account. This method of projection is the basis of the hypothetical maximum thickness of the Victor formation that has been derived on page 46. Second, the known gradient might be projected to decrease westward in a geometric progression fixed by the rate at which it is known to decrease westward among the present remnants of the pediment. In this way a hypothetical probable altitude of the top of the Arroyo Seco gravel would be fixed. According to this method, the top of the Arroyo Seco gravel would be at sea level at Lodi—that is, 50 feet beneath the land surface—and about 100 feet below sea level at the eastern edge of the present tidal flat or Delta plain. Conversely, the baselevel of the Arroyo Seco profile of equilibrium would be about 100 feet below present sea level if the ancestral San Francisco Bay of that epoch was as extensive as the area encompassed by the present sea-level contour. It is well established that in late geologic time the region about San Francisco Bay has subsided slightly and progressively with respect to sea level, perhaps as a result of compaction of the thick mass of detrital sediment that fills the axis of the California Trough.

It is postulated that the hypothetical wedge-shaped westward extension of the Arroyo Seco gravel is composed of ill-sorted sediments that include gravel, sand, and finer material—a typical alluvial or littoral deposit. Although such a wedge-shaped mass of sediments cannot be discriminated on the basis of mineral or mechanical composition of the samples from wells in the Mokelumne area, theoretical considerations indicate that its thin eastern edge must underlie the Victor formation at the approximate longitude of the district irrigated by ground water. If, as has been postulated on page 45, the trenches that were cut into the Arroyo Seco pediment in the first part of the Victor epoch extended westward only to the approximate longitude of Lodi, it would follow that a considerable number of the irrigation wells enter the westward extension of the Arroyo Seco gravel.[37]

[37] For a frequency distribution of the irrigation wells of the Mokelumne area according to the geologic formation in which they bottom see "Location and classification of observation wells" (p. 122).

No fossils have been found in outcrops of the Arroyo Seco gravel, and none have been reported from wells that reach the buried equivalents of the Arroyo Seco gravel in the Mokelumne area. A few miles south of the area, near Stockton, several fossils were encountered at a depth of 225 feet in a bored well. At this locality the projected Arroyo Seco pediment is probably not more than 100 feet below the land surface, but the top of the Mehrten formation (p. 61) is probably at least 800 feet below the surface. Thus it is inferred that these fossils occurred in the upper part of the undifferentiated sediments that represent the Arroyo Seco and Laguna epochs. The fossils, reported by Hay,[38] include the lower second milk molar and other bones of *Elephas columbi*, the hoof phalange and foot bones of an unidentified genus of Equidae, and the upper tooth of a camel. So far as these fossils could be identified, they suggested a Pleistocene age for the enclosing sediments.

GRAVEL DEPOSITS OF UNCERTAIN AGE

Surficial deposits of gravel and cobbles that cannot be ascribed with assurance to any of the stratigraphic units of the Mokelumne area occur at many places. All these deposits are above the Victor alluvial plain and are therefore older. Many of them are presumed to be the product of chance segregation of pebbles and cobbles that have rolled down the steeper erosion slopes from outcrops of gravel-bearing strata and come to rest on the more gentle slopes below. Such deposits are especially numerous in the dissected parts of the Arroyo Seco pediment and somewhat less numerous near outcrops of cobble beds that are interbedded in the andesitic Mehrten formation (p. 61) and the rhyolitic Valley Springs formation (p. 71). These deposits are thin and discontinuous.

There are some other deposits of gravel whose topographic form indicates that they are of constructional origin and accordingly represent temporary stages of rest in the development of the present streams or of channels now abandoned. Such deposits fall into two classes—(*a*) those that are near an outcrop of the Arroyo Seco gravel and can be shown to be younger by projecting the Arroyo Seco pediment above them; (*b*), those which are distant from known outcrops of the Arroyo Seco gravel and whose age with respect to that gravel is uncertain. Some of the larger of these gravel deposits are shown on plate 1. Those of the first class occur in the valleys of the Mokelumne and Cosumnes Rivers; those of the second class occur at moderately high altitudes in the Wallace-Ione basin.

The most conspicuous deposits in the Mokelumne River valley constitute a thin veneer that caps a dissected terrace in the north bank of the river and that extends from the mouth of Rabbit Creek upstream to Lancha Plana and southeast to Camanche. At Rabbit Creek this terrace is about 100 feet above the river, 30 feet above the

[38] Hay, O. P., The Pleistocene of the western region of North America and its vertebrated animals: Carnegie Inst. Washington Pub. 322B, pp. 27, 65, 86, 1927.

terrace remnants that have been correlated with the Victor plain, and 100 feet below the Arroyo Seco pediment; it rises upstream about 50 feet in a mile. It appears to be the product of an intermediate stage of rest, probably brief, in the downcutting of the Mokelumne River. Other deposits of gravel about the same distance above the river extend upstream as far as Campo Seco and are dispersed over the area to the south nearly as far as Valley Springs Peak. These are about 500 feet above sea level but do not constitute one distinct surface. Apparently, however, they were formed at about the same stage in the development of the river valley as the terrace west of Camanche. The deposits in the Cosumnes Valley occur in the west bank of the river at the Slough House and form a narrow, discontinuous, and indistinct terrace about 40 feet above the flood plain and 50 feet below the Arroyo Seco pediment. Where exposed in a cut along the Slough House Road they are steeply cross-bedded and consist of coarse sand and fine gravel, with some finer material.

Deposits at two places might be correlated tentatively as remnants of the Arroyo Seco gravel. One of these lies 1 mile east of Burson, in the S½ sec. 22, T. 4 N., R. 10 E., and forms a distinct terrace of small area at altitude 660 feet above sea level. The surface of the terrace is strewn with cobbles, which rest upon a thick stratum of conglomerate; this conglomerate is a member of the Valley Springs formation and is exposed in railroad cuts along the north edge of the terrace. The Arroyo Seco pediment, if projected eastward from its nearest outcrop at Wallace, would coincide approximately with the top of the terrace; thus correlation of the terrace with the pediment is suggested. About 8 miles northwest of this place and 2 miles west of Buena Vista Peak there are caps of gravel on two summits that also coincide approximately in altitude with the projected pediment. Admittedly, these correlations are weak, because the pediment must be projected several miles to small patches of gravel whose initial slope is indeterminate.

In the Wallace-Ione basin deposits of gravel occur at many places and vary rather widely in altitude (pl. 1). Some of them are perhaps not of constructional origin but rather may be composed of residual cobbles, concentrated locally from the Arroyo Seco gravel or from gravel-bearing strata in the Tertiary rocks.

In two districts there are beds of gravel and cobbles that are definitely higher than the Arroyo Seco pediment; these are in the vicinity of Valley Springs Peak and of Buena Vista Peak. The more extensive deposit caps the conspicuous ridge whose flat crest extends about 6 miles southwestward from Valley Springs Peak and declines S. 60° W. about 125 feet to the mile. The north end of the ridge is about 1,075 feet above sea level. The gravel mantle, of unknown thickness, consists of pebbles and cobbles 1 to 8 inches in diameter. These cobbles are derived chiefly from the pre-Tertiary crystalline rocks and display much greater petrographic variety than is usual in the Arroyo Seco gravel and other gravel deposits that are known to be of Pleistocene age. Cobbles of fresh, dense rhyolite are common, but cobbles of andesite are entirely wanting; the deposit appears to be derived entirely from rocks older than the andesitic Mehrten formation. About Valley Springs Peak there is a cobble collar which forms a narrow but distinct shoulder about 200 feet below the summit on the west, north, and east slopes and which has the same altitude as the gravel cap on the north end of the ridge. The cobbles in this collar are petrographically similar to those in the ridge cap. In places they are embedded in a fine-grained or medium-grained matrix of nonandesitic material, and the whole constitutes a moderately consolidated conglomerate. South and west of Buena Vista Peak there is a cobble-covered terrace whose gravel is also petrographically similar to that on the ridge southwest of Valley Springs Peak. These gravel deposits may be local and may have been derived from a conglomerate member of the Valley Springs formation, or they may be remnants of extensive surficial deposits of post-Miocene age that initially surrounded Buena Vista and Valley Springs Peaks and formed extensive constructional terraces farther west. That these gravel deposits are local accumulations of residual cobbles from a resistant conglomerate member of the Valley Springs formation is suggested by the presence in them of many rhyolite cobbles and the total absence of andesite cobbles, by the petrographic dissimilarity to gravel deposits known to be of post-Miocene age, and by the degree of consolidation in the matrix of the conglomeratic facies.

Gravel deposits that have been worked for placer gold occur at many places in the Jackson quadrangle, especially east of the longitude of Jackson. Most of these deposits are described by Lindgren.[39]

TERTIARY SYSTEM

LAGUNA FORMATION (PLIOCENE ?)

CHARACTER, DISTRIBUTION, AND THICKNESS

In the central part of the Mokelumne area—that is, over much of the area occupied by the Arroyo Seco dissected pediment—the stratigraphic interval between the Arroyo Seco gravel (Pleistocene) and the andesitic Mehrten formation (upper? Miocene) is occupied by nonandesitic detrital sediments. These are named the "Laguna formation" in this report, after the basin of Laguna Creek, in which they underlie an extensive area. Commonly the outcrop area of the formation, which comprises the lower slopes of the dissected pediment adjoining the Victor alluvial plain, is deeply covered with soil and vegetation, so that there are but few cut banks or other exposures to

[39] Lindgren, Waldemar, Tertiary gravels of the Sierra Nevada of California: U. S. Geol. Survey Prof. Paper 73, pp. 195–213, 1911.

reveal its character. The clearest exposure and type section occurs in the north bank of Hadselville Creek a short distance upstream from its junction with Laguna Creek and about a mile northeast of Clay post office. This section is described below.

Type section of the Laguna formation, 1 mile northeast of Clay post office, in the NE¼NE¼ sec. 25, T. 6 N., R. 7 E.

	Feet
Top of measured section is crest of hill, about 165 feet above sea level.	
1. Concealed, grass-covered slope	20
2. Silt or clay, dark earthy brown to red, iron-stained	6
3. Interval covered, probably sand	4
4. Sand, coarse and medium, cross-bedded	3
5. Gravel, lenticular bed (break or unconformity?)	0–6
6. Silt and very fine sand, reddish, iron-stained; some clay and some medium to coarse sand	14
7. Silt and clay, well sorted, gray	10
Base of section is creek bed, approximate altitude 107 feet.	
Thickness of measured section	57

Mechanical composition of sediments of the Laguna formation

[Analyses by V. C. Fishel, U. S. Geological Survey; quantities expressed in percent by weight]

	1	2	3	4	5
Gravel (more than 1.0 mm)	0.3	0.0	12.7	2.1	13.4
Coarse sand (1.0–0.50 mm)	.8	3.5	41.7	2.5	26.5
Medium sand (0.50–0.25 mm)	3.4	16.1	27.8	6.3	22.2
Fine sand (0.25–0.125 mm)	5.5	12.2	3.4	6.3	9.3
Very fine sand (0.125–0.062 mm)	20.9	24.1	2.1	6.6	10.6
Silt (0.062–0.005 mm)	42.4	33.8	6.4	60.5	14.6
Clay (less than 0.005 mm)	26.8	10.9	6.3	15.8	4.4

1. Upper part of bed 7 of the type section of the Laguna formation.
2. Lower part of bed 6 of the type section.
3. Bed 4 of the type section.
4. Exposure in road cut 3½ miles south of Clements, in the SW¼ sec. 2, T. 3 N., R. 8 E.; about 40 feet below the Arroyo Seco gravel.
5. Exposure in stream bed 6 miles south of Clements, in the SE¼ SE¼ sec. 11, T. 3 N., R. 8 E.; immediately overlying a bed of coarse conglomerate and about 150 feet above the top of the Mehrten formation.

The incomplete exposure of the Laguna formation in the Mokelumne area does not disclose the nature of its contacts with the overlying Arroyo Seco gravel or with the underlying Mehrten formation, but the pattern on plate 1 indicates that it is truncated by the Arroyo Seco gravel in quite the same way as the Mehrten and Valley Springs formations are truncated. Accordingly it is presumed that the Laguna formation is a single stratigraphic unit that is essentially parallel to and tilted equally with the Mehrten formation. If it is postulated on this basis that the Laguna formation dips 100 feet in a mile nearly due west, the width of its outcrop in the Clements-Linden district, east of Lodi, indicates its thickness to be about 400 feet. The formation presumably forms a wedge or large lens, perhaps beginning initially as a thin deposit on the slope of the tilted Mehrten formation and thickening westward toward the axis of the California Trough.

The character of the Laguna formation beneath the Victor plain in the area irrigated by ground water is believed to be represented by the strata penetrated in well 4712A1 between 16 and 475 feet beneath the land surface. This well is on the Victor plain about 4 miles north of Lockeford. As is shown by the driller's log (p. 97), this 459-foot section of the Laguna formation comprises beds that range from "shale" (compact silt and clay) to coarse gravel and "conglomerate" (unsorted gravel and coarse sand in a matrix of sand and silt), but more than two-thirds of its thickness is composed of fine-textured material such as might have only small capacity to transmit ground water. The thickness of this section is of the same order as the hypothetical thickness computed from the width of outcrop and the presumed dip. Of similar texture are the materials that underlie the triangular body of coarse sand and gravel that has been postulated to define the bottom of the Victor formation in the Lodi-Victor district (p. 48).

The sections penetrated in two other wells, however, contrast sharply with that just described. One of these, well 283E1 (p. 94), is on the flood plain of the Calaveras River half a mile west of the front of the dissected Arroyo Seco pediment. In this well the supposed Laguna formation is 145 feet thick and contains beds of sand and gravel that total 80 feet in thickness. Only the lowermost 53 feet of the section resembles the type section at Clay. The other well, 4827R1 (p. 99), is 2 miles south of Clements on the dissected pediment. In this well the presumed top of the underlying Mehrten formation is 127 feet below the land surface, and the Arroyo Seco gravel and Laguna formation combined comprise two members consisting of unsorted cobbles, gravel, and sand, with an aggregate thickness of 80 feet; also two members made up of sandy silt, with an aggregate thickness of 47 feet. Sections such as these, which are much coarser than the type section of the Laguna formation, might indicate proximity to a source of the Laguna detritus.

The records of the wells just described indicate that the Laguna formation is extremely heterogeneous and imply that lithologic characters will not serve to discriminate it from the overlying Pleistocene sediments. This implication is confirmed by the samples of well cuttings, whose mineral and mechanical composition seems not to afford any basis for discriminating the Laguna formation. Thus, the well records serve only to indicate total thickness of sediments above the recognizable andesitic sands of the Mehrten formation. Well 4718R2, 4 miles north of Lodi, is 470 feet deep and does not reach recognizable Mehrten formation. Well 4517J1, 1 mile south of Thornton, is 752 feet deep, and the driller's record does not mention black (andesitic) sand. The hypothetical maximum thickness of the Victor formation at Lodi has been estimated as 100 feet (p. 46), and the same type of estimate gives a maximum of 200 feet at Thornton. Subtraction gives minimum figures for the combined thickness of the Arroyo Seco gravel and Laguna formation of 370 feet near Lodi and 550 feet at Thornton. The hypothetical combined thickness based on the restored upper surfaces of the Arroyo Seco gravel and Mehrten formation (p. 52, pl. 4) is more than these minima; it is 400 feet at Victor, 650 feet near Lodi, and 1,000 feet at Thornton.

It seems probable that many of the irrigation wells of the Mokelumne area enter the Laguna formation, but relatively few are so deep that they can be presumed to pass through it into the underlying Mehrten formation. Of the latter group, satisfactory records or samples of only 16 wells were available.

CORRELATION AND AGE

Inasmuch as the Laguna formation in the Mokelumne area embraces the sediments that are younger than the Mehrten formation (upper? Miocene and Pliocene?) and older than the Arroyo Seco gravel (middle? Pleistocene), presumably it is the product of the Pliocene and possibly the early Pleistocene epochs. No fossils have been found in outcrops of the Laguna formation in the Mokelumne area. However, a horse tooth was collected in November 1934 by the junior writer (Thomas) from a well owned by E. Bottomore about 4 miles northeast of Galt, in the SE¼NE¼ sec. 18, T. 5 N., R. 7 E., about 800 feet west and 2,100 feet south from the northeast corner of the section. This tooth was found embedded in clayey silt 58 feet below the land surface. A log of the well is not available, but E. A. Thayer, the driller, reports 10 feet of coarse sand and gravel, suggestive of a stream deposit, immediately above the clayey silt. The Victor plain forms the land surface at the well and extends about 2 miles farther east. The uppermost layers encountered in the well—members of the Victor formation—are inferred to rest unconformably upon the Laguna formation, for the land surface at the well is lower than the projected Arroyo Seco pediment. Possibly the Victor formation extends to the base of the coarse sand and gravel in the well. Certainly it is not likely that the Arroyo Seco pediment in this area between minor streams such as Dry Creek and Laguna Creek has been trenched to a depth as great as that of the fossil horizon. Thus it is inferred that the clayey silt surrounding the horse tooth is part of the Laguna formation.

Stirton has identified this fossil as *Neohipparion* cf. *N. gidleyi* and remarks: [40]

> The Bottomore well specimen is one-fourth larger than *N. leptode* Merriam, from the Thousand Creek middle Pliocene of Nevada. It differs from *N. leptode* and agrees with a $\overline{M3}$ that was found at the type locality of *N. gidleyi* in the absence of an ectostylid. The Bottomore well specimen is, however, larger than the topotype $\overline{M3}$ from Lawlor ranch. As in other Neohipparions, the metaconid and metastylid are separate to the base of the tooth, and the intervening valley

[40] Stirton, R. A., A *Neohipparion* tooth from the Mokelumne area, Sacramento County, Calif. (personal communication, Nov. 6, 1934).

is widely U-shaped instead of somewhat V-shaped as in advanced species of *Calippus* and in *Equus*. The ectoconid and metastylid are separated by a narrow groove. The outer side of the tooth is flattened, with a shallow groove between the protoconid and the hypoconid.

An increase in size and height of crown as well as the extreme elongation of the protocone are recognized as progressive characters. The characters of *N. gidleyi* are sufficiently advanced over those of the middle Pliocene Neohipparions (*N. leptode* and *N. eurystyle*) to warrant the recognition of that species as belonging to an early upper Pliocene fauna * * * probably equivalent in age to the upper [part of the] Etchegoin [formation].

South and west of the Mokelumne area the Pliocene epoch is represented by thick and extensive deposits in the California Trough, particularly by sediments of marine, brackish-water, and fresh-water origin at the south end of San Joaquin Valley. In thickness these deposits reach at least 8,000 feet, for they have been penetrated to that depth in drilling at Semitropic Ridge. The marine Pliocene deposits extend northward on the east side of San Joaquin Valley about to the city of Fresno, but so far as known they do not extend north of that place. An extensive Pliocene section also exists in the Coast Ranges and about San Francisco Bay and includes marine, brackish-water, and fresh-water or land-laid deposits. The Laguna formation of the Mokelumne area may well be the land-laid extension of these sections.

MEHRTEN FORMATION (UPPER ? MIOCENE AND PLIOCENE ?)

DEFINITION AND TYPE SECTION

The strata that lie stratigraphically below the Laguna formation in the Mokelumne area are composed largely of volcanic detritus and are the products of two distinct volcanic epochs in the Sierra Nevada—an early epoch in which acidic (rhyolitic) materials were accumulated and a late epoch characterized by basic (andesitic) materials. The detrital sediments of these two epochs are widespread in the Mokelumne area, but those of the late epoch are the more extensive. These late andesitic rocks, which lie immediately below the Laguna formation, have been named the "Mehrten formation" by Tolman[41] in a private typewritten report, without a definition of their stratigraphic limits. The name is formally proposed and defined in this report, with the description of a type section.

The Mehrten formation is named after its exposures in the bluffs along the Mokelumne River near the Mehrten dam site, which is about 3½ miles upstream from the Clements bridge. The type section of the formation is along the Clements-Camanche road about 1¼ miles east of the dam site, in the NE¼SW¼ sec. 5, T. 4 N., R. 9 E. The lower 45 feet of this section is composed chiefly of light-buff siltstone that closely resembles the underlying Valley Springs forma-

[41] Tolman, C. F., typewritten report to the Pacific Gas & Electric Co. on the geology of the Mokelumne region, San Francisco, 1931.

tion. Above the siltstone well-sorted andesitic sandstone predominates, but there are also beds of laminated siltstone and conglomerate. Commonly the beds are not more than 5 feet thick. The top of the type section is a conspicuous ledge of resistant andesitic agglomerate. This is composed of unsorted angular fragments of hard gray porphyritic andesite as large as 8 inches in maximum dimension. The detailed section follows:

Type section of the Mehrten formation in the bluff north of the Mokelumne River, in and near the NE¼SW¼ sec. 5, T. 4 N., R. 9 E.

	Feet
Top of measured section is top of bluff, about 310 feet above sea level.	
Mehrten formation:	
Breccia, very compact and hard, andesitic fragments as much as 8 inches in diameter	14
Sandstone, coarse and angular; at the top cobbles 3 inches in maximum diameter, in a bed 1 foot thick	13
Concealed	7
Clay, white, laminated	2
Sandstone, chiefly coarse and medium, of angular andesitic grains; contains a hard siliceous median layer 6 inches thick, with fragments of pumice	25
Clay, white, laminated	1
Sandstone, coarse and medium, andesitic; discontinuous bed of cobbles at base	22
Silt, yellowish gray	4
Concealed	3
Sandstone, coarse and medium, cross-bedded, of angular andesitic fragments; also white to gray laminated silt, containing pumice fragments; in alternating beds 2 to 9 feet thick	48½
Silt, white, pumiceous (50 feet to the west this bed is 6 inches thick and is underlain by 3 feet of coarse andesitic sandstone)	5½
Silt and clay, white to buff, laminated at top; some pumice; (in places this is a breccia in which both fragments and matrix are now clay, perhaps derived by weathering of volcanic tuff or breccia). Similar to the Valley Springs formation	27½
Concealed	7
Fine sandstone, gray, cross-bedded, many thin clay laminae; quartz is dominant, but andesitic grains are present and cause the gray color	4
Thickness of Mehrten formation	183½
Valley Springs formation: Clay, white, dense, in laminae a quarter to half an inch thick; contains some quartz crystals barely visible to the naked eye	6
Thickness of exposed section	189½
Base of section is level with road and less than 10 feet above the flood plain of the Mokelumne River, about 120 feet above sea level.	

Along Murphy Creek, which is three-quarters of a mile west of the type section, the Mehrten formation is again well exposed, and its andesite breccia members crop out in ledges that are almost continuous around the drainage basin. In that basin the succession and character of the beds differ somewhat from the type, as is indicated by the following partial section:

Partial section of the Mehrten formation in the NE¼SE¼ sec. 6, T. 4 N., R. 9 E

[Average dip, based on plane-table traverse, S. 80° W. about 100 feet in a mile]

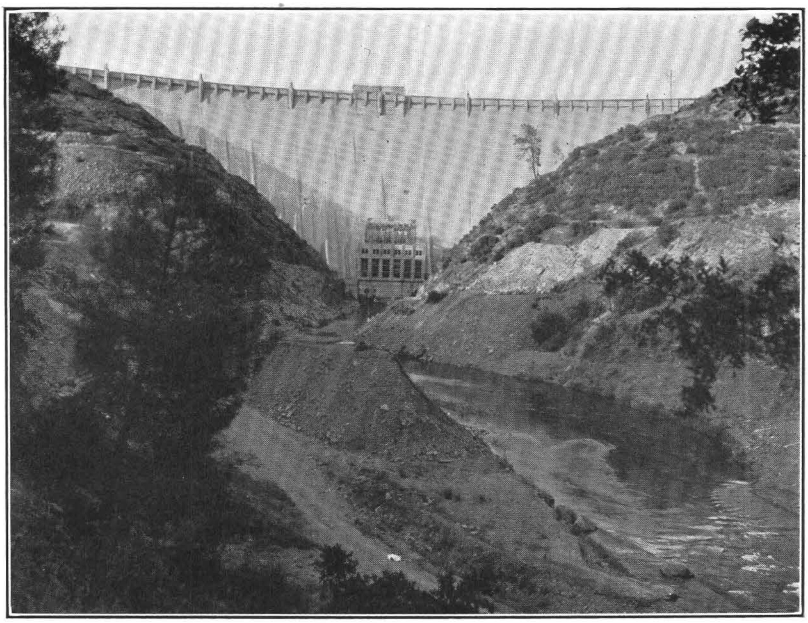
	Feet
Top of measured section is summit of ridge, 312 feet above sea level.	
Breccia, andesitic, containing angular blocks as large as 2 feet across	13
Fine-grained beds (sandstone, silt, and clay), poorly exposed	12
Breccia, andesitic, angular fragments as much as 1 foot in diameter (A channel filling (?) whose base locally dips as much as 400 feet to the mile and transgresses several underlying beds. This is probably the top member of the type section)	10–28
Fine-grained beds, poorly exposed	24–6
Tuff or fine breccia, andesitic fragments measuring 1 inch or less, discontinuous	0–2
Fine-grained beds, poorly exposed	54
Tuff, andesitic; at the top a discontinuous zone of cobbles attaining a maximum thickness of 3 feet	6
Fine-grained beds, poorly exposed	10
Tuff, andesitic, fragments less than half an inch in maximum dimension	2
Fine-grained beds, poorly exposed	10
Cobbles 1 to 4 inches in diameter	6
Thickness of measured section	149

LITHOLOGIC CHARACTER

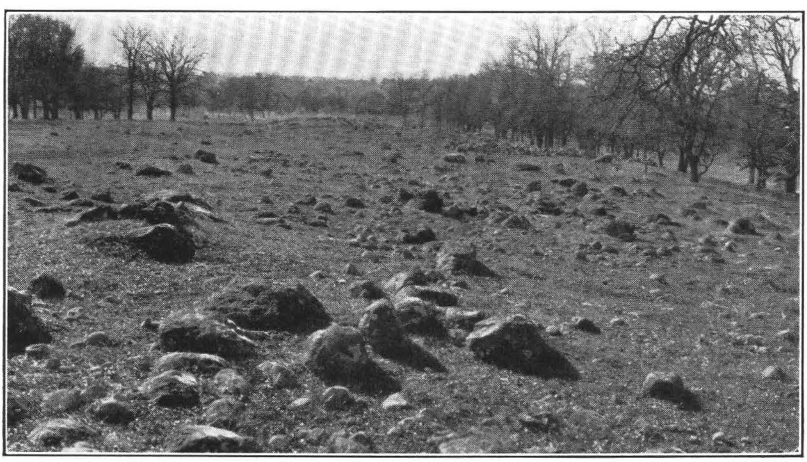
In the area represented on plate 1 the Mehrten formation consists of fluviatile deposits of the detritus brought down from the slopes of the Sierra Nevada while the andesitic eruptions of that district were going on. These deposits include sandstone, laminated siltstone, conglomerate, and andesitic breccia and tuff; layers of nonfragmental andesite are not known to occur. Though composed almost entirely of andesitic material, they contain also a small amount of detritus from the other rocks of the Sierra Nevada, both igneous and metamorphic. In places many of the beds near the base of the formation are made up chiefly of rhyolitic tuff and pumice that presumably were derived from the underlying Valley Springs formation. The sandstone and siltstone make up the major part of the Mehrten formation and include every gradation from massive cross-bedded coarse-grained sandstone to laminated siltstone, in beds generally only a few feet thick. These rocks commonly are well bedded and stratified and thus are the products of rather thorough sorting of the andesitic detritus by streams working at moderate grade; the finer of these deposits, however, appear to have accumulated in temporary pools or lakes. Any particular bed is usually composed of rather well sorted grains and commonly is distinctly more uniform in texture than any of the younger deposits of the Mokelumne area. The conglomerate beds are lenticular or of channel form, and some of them are interstratified with cross-bedded coarse sandstone. The coarser beds are made up of cobbles 3 to 6 inches in diameter with some boulders 1 foot or more across. The layers of breccia or agglomerate make up a minor part of the Mehrten formation, but they are disproportionately conspicuous because they resist erosion and commonly form persistent ledges on the steep slopes or caps on the flat-topped mesas. Excellent examples occur in the northeastern part of the Goose Creek quadrangle. The flat-topped hills of that area are capped by 30 to 50 feet of coarse fragmental andesite, either in loose blocks or consolidated in exceedingly craggy black ledges. Commonly the fragments are 6 inches to 2 feet across, and the lava that composes them is fresh and hard. In places these fragments weather out from the finer matrix and cover the surface of the mesas, so that they might be confused with residual boulders from a lava flow. The agglomerate beds are presumed to have originated as mud flows; they undoubtedly descended from the volcanic sources in the higher mountains as the outwash of torrential floods, for they are in many places interbedded with or underlain by lenses that are composed almost exclusively of water-rounded andesitic gravel and cobbles. The agglomerate layers or tongues occur at several horizons in the Mehrten formation, and each covers several square miles, but none is so widespread that it can be used as a stratigraphic marker over the whole area.

Plate 3, *B*, is a view taken 3½ miles east of Clements along the top of a ridge that is capped by residual andesite boulders. These boulders are derived from a tongue of agglomerate that initially filled a distributary stream channel in Mehrten time and that now forms a ridge because it resists erosion. This ridge is continued farther north, across Bear Creek, by a similar collinear feature in secs. 8 and 17, T. 4 N., R. 9 E. The bipartite ridge trends S. 35° W. from a point south of the present course of the Mokelumne River, and its direction is a clue to the course taken by some of the distributary channels of the Mehrten epoch. Other distributary channels are suggested by similar but less conspicuous features at several places.

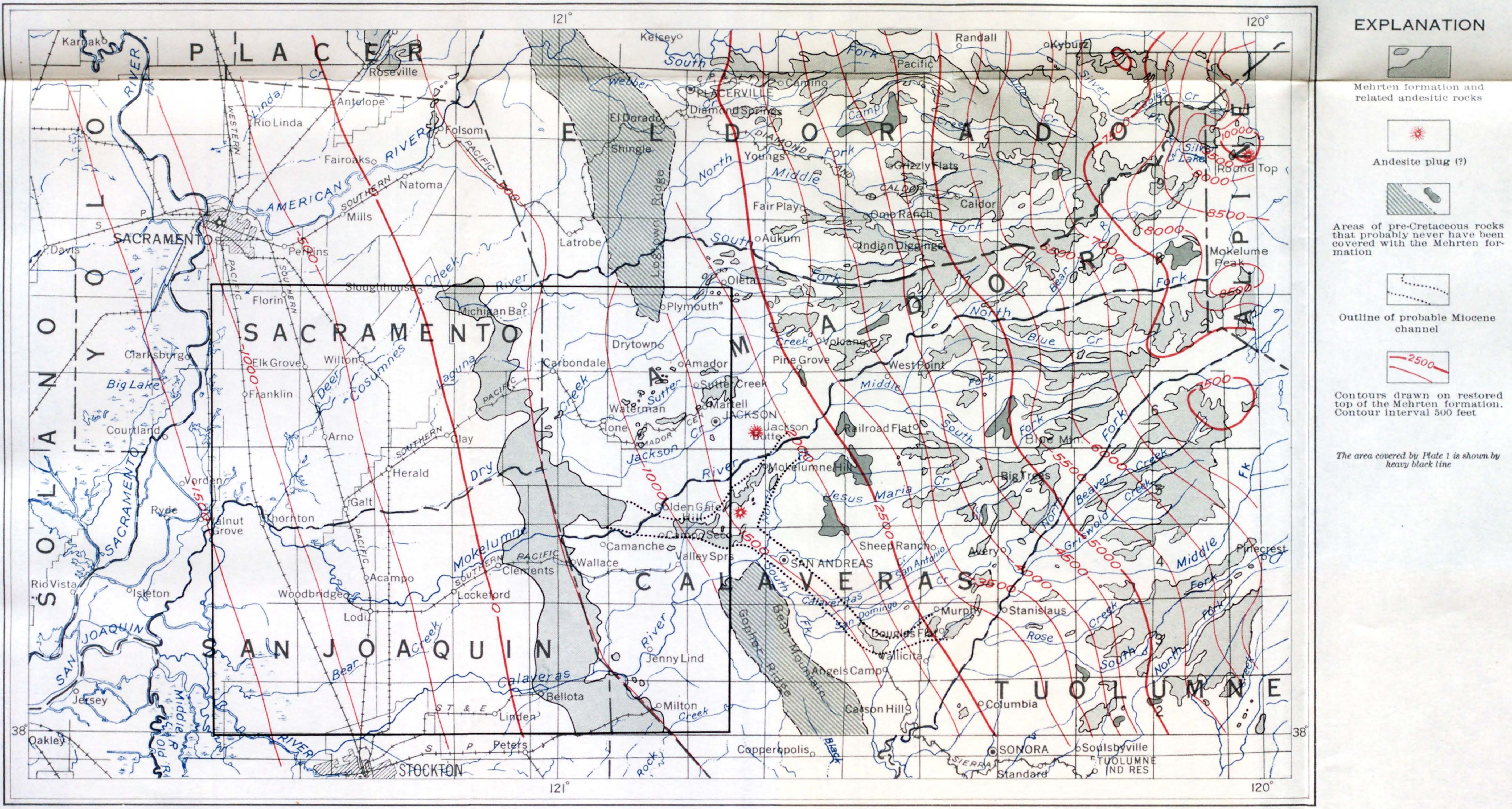
The outcrops of the Mehrten formation along the Mokelumne River and in the basins of Laguna and Dry Creeks (pl. 1) exhibit the entire range of texture but are commonly composed largely of coarse sand, conglomerate, and tuff or agglomerate. Farther north, however, where the formation is transected by the Cosumnes River, it



A. PARDEE DAM OF THE EAST BAY MUNICIPAL UTILITY DISTRICT, MOKELUMNE RIVER.



B. RESIDUAL BLOCKS FROM ANDESITIC AGGLOMERATE CAPPING A RIDGE OF THE MEHRTEN FORMATION 3½ MILES EAST OF CLEMENTS.



MAP OF THE MOKELUMNE REGION, CALIFORNIA, SHOWING THE DISTRIBUTION OF THE MEHRTEN FORMATION AND RELATED ANDESITIC ROCKS

10 0 10 20 30 Miles

1938

is made up dominantly of fine sand and silt, and its agglomerate members are composed of fragments that commonly do not exceed 1 inch in diameter. This character of the formation is shown by the following section:

Section of the Mehrten formation exposed on hill south of Stone House School, in the SW¼SE¼ sec. 33, T. 8 N., R. 8 E.

	Feet
Top of section is crest of hill, 276 feet above sea level.	
Sandstone, fine, thin-bedded, dark gray, andesitic	7
Silt or clay, dense, white, laminated	5
Sandstone, very fine, and silt, dark gray, well-sorted, massive; one very resistant ledge 3 feet thick at base	24
Sandstone, very fine, well-sorted, in beds ⅛ inch to 10 inches thick	10
Base of section rests upon siliceous clay of the Valley Springs formation.	
Thickness of measured section	46

Farther south the proportion of fine sand and silt is likewise greater. At Bald Mountain, in the NW¼SE¼ sec. 2, T. 3 N., R. 9 E., the only coarse material is a 2-foot bed of unsorted sand and gravel in which the largest cobbles are about 2 inches in diameter. This bed occurs about 100 feet below the top of a poorly exposed section that is 150 feet thick and that otherwise seems to be composed of fine sand and silt.

The uppermost bed in the type section of the Mehrten formation is a conspicuous layer of andesitic agglomerate, but where the formation is overlain by the Laguna formation, as in the basins of Dry and Laguna Creeks and along the Calaveras River, the uppermost agglomerate is commonly overlain by fine-grained andesitic sandstone and siltstone. These fine-grained beds also belong to the Mehrten formation. They attain a possible maximum thickness of more than 100 feet in the Bald Mountain section, of which they make the upper part. These beds are not resistant to erosion and have been removed almost entirely where the Arroyo Seco pediment gravel transects the Mehrten formation. Only along the Cosumnes River and locally in the southern part of the Carbondale quadrangle and the northern part of the Goose Creek quadrangle is the probable initial top of the Mehrten formation a bed of andesite breccia.

DISTRIBUTION AND SOURCE

As is shown by the detailed geologic map (pl. 1) and by the generalized map that constitutes plate 4, the principal outcrops of the Mehrten formation form a nearly continuous belt that trends about N. 20° W. entirely across the Mokelumne area from the vicinity of Bellota, on the Calaveras River, to the village of Cosumne, on the Cosumnes River. The width of this belt, except where the Mehrten formation is mantled by the Arroyo Seco gravel, ranges from 2 miles along the Cosumnes River to 8 miles between the Mokelumne River and Jackson Creek. This belt contains most of the higher ridges and uplands that form the immediate eastern border of the California Trough—a reflection of the fact that the Mehrten formation is the most resistant of the Tertiary system. Farther east outliers of the resistant andesite breccia cap many of the highest hills and ridges, even in the outcrop area of the pre-Tertiary rocks.

Initially, one broad tongue of the Mehrten formation evidently forked from the main outcrop belt in the highland south of Buena Vista Peak and trended southeastward to pass through Campo Seco and north of Valley Springs Peak, thence eastward and northeastward around the north ends of Gopher Ridge and Bear Mountain and through Cottage Spring and Mokelumne Hill.[42] This tongue is now defined by somewhat discontinuous outcrops that are arranged in a general linear pattern, the principal gap being where the tongue has been transected by the Mokelumne River between Campo Seco and Lancha Plana. The tongue is composed of coarse andesite cobbles and coarse andesitic breccia, particularly where it joins the main mass of the Mehrten formation south of Buena Vista Peak. The main body of the formation in general becomes progressively finer radially westward from this point of junction. Evidently the tongue represents the filling of one of the principal Tertiary channels by which the andesitic detritus was transported westward from the Sierra Nevada to an apex of radiating distributary channels in the vicinity of Burson. One such distributary channel east of Clements has been described. Others doubtless spread west and southwest from the present site of Valley Springs, but their fillings have been entirely stripped away by tributaries of the modern Calaveras and Mokelumne Rivers.

The position of the top of the Mehrten formation under the Victor plain is certain in only a very few wells. Of the wells for which samples were available (p. 89) 77 are west of the outcrop of the Mehrten formation, but only four (283E1, 473N1, 4712A1, and 5725R1) penetrated definitely into the Mehrten formation. In well 4712A1 andesitic sediments predominate between 475 and 991 feet below the land surface, whence the Mehrten formation is inferred to be about 515 feet thick. Several of the drillers' logs of the deeper wells in the Lockeford-Clements area recorded considerable thicknesses of andesitic sediments ("black sand"); evidently these wells passed through the Pleistocene and Pliocene (?) deposits and went down into the Mehrten formation. All wells that are known to reach the concealed top of the Mehrten formation are east of Victor. The top of the Mehrten formation has, however, been restored hypothetically on plate 4 by contours drawn on the basis of its known altitude in the

[42] Turner, H. W., U. S. Geol. Survey Geol. Atlas, Jackson folio (no. 11), 1894.

outcrop area and projected westward under the Victor plain through the few wells in which its altitude is known. This restored surface is the hypothetical initial volcanic plain of the Sierra Nevada section. Among 1,408 irrigation wells of known depth in the central part of the Mokelumne area (Tps. 3 and 4 N., Rs. 6 and 7 E.) only 55 are deep enough to reach that hypothetical surface.

In a few of the wells for which samples were available beds of black andesitic sand 1 to 15 feet thick are penetrated, but commonly these beds are underlain by many feet of nonandesitic sediments. In wells west of Victor, particularly, these beds of andesitic sand are so high above the hypothetical top of the Mehrten formation that they must be regarded as concentrations of andesitic detritus reworked from outcrops in the foothills in Pliocene or Pleistocene time, and thus as components of the Laguna or the Victor formation.

Several deep wells drilled in the central part of the California Trough in and near the Mokelumne area formerly (1880 to 1910) yielded material quantities of natural gas. Near Stockton and Lodi these wells are presumed to have obtained gas from the Mehrten formation and possibly from underlying formations. (See p. 226.)

The ultimate source of the abundant andesitic detritus that composes the Mehrten formation presumably lies in volcanic vents in the high Sierra. Two possible vents of this sort are Golden Gate Hill and Jackson Butte, which are just east of the Mokelumne area (pl. 4). Golden Gate Hill is 4 miles southwest of the town of Mokelumne Hill; Jackson Butte is 3 miles east of Jackson. Both are made up of dark-gray porphyritic andesite, with phenocrysts of hornblende and plagioclase in a microcrystalline to glassy groundmass. These hills project high above the general level of the andesitic plain. Turner[43] suggests that they may well be the cores of volcanoes that were active in Mehrten time.

STRATIGRAPHIC RELATIONS AND THICKNESS

The Mehrten formation is overlapped unconformably by both the Arroyo Seco gravel and the Victor formation of Pleistocene age (pp. 45, 52), but in normal stratigraphic succession is overlain by the nonandesitic Laguna formation, of Pliocene (?) age. Accordingly, its top would be at the base of the lowest nonandesitic beds. This contact is in many places intangible, both because it is poorly exposed and because there are beds of andesitic sandstone that are separated stratigraphically from the main mass of the Mehrten formation by nonandesitic beds. Thus, although the beds of the two formations seem to be essentially parallel, they evidently interfinger with one another at the contact. Such interfingering is to be expected, for both formations are essentially fluviatile, and the latest beds of the andesitic

[43] Idem, p. 4.

Mehrten epoch might well have been extensively reworked by the streams of the Laguna epoch and thus interlaminated or even commingled with the nonandesitic detritus. The areal distribution of the two formations (pl. 1) suggests that this zone of interfingering transgresses the upper 150 feet of the Mehrten section.

In the eastern part of its outcrop area the Mehrten formation truncates all the underlying Tertiary rocks, so that it rests in turn upon the Valley Springs and Ione formations (pp. 71 and 80) and upon the pre-Cretaceous crystalline rocks. In that district the sub-Mehrten surface of unconformity was composed of mature erosion forms and in places had a relief of at least 400 feet across relatively short distances. For example, three-quarters of a mile south of Buena Vista Peak—that is, about 6 miles south-southwest of Ione—the Mehrten formation rests on rhyolitic Valley Springs formation at an altitude of 500 feet, or about 350 feet below the summit of the peak, which is also composed of the Valley Springs formation. Half a mile farther east the Valley Springs formation is absent and the Mehrten formation rests directly upon the Ione formation. Likewise, a mile north of Valley Springs Peak—that is, 1½ miles northwest of the town of Valley Springs along the road to the Pardee Dam—the sub-Mehrten surface is at an altitude of 800 feet, or 425 feet below the rhyolitic tuff that forms the summit but a mile away. Such steep surfaces of unconformity are somewhat extreme for the Mokelumne area as a whole, though in many places the base of the Mehrten formation transgresses a considerable thickness of the underlying Valley Springs formation. The irregular base of many of the outliers of the formation in the eastern part of the Goose Creek quadrangle is conspicuous, for massive dark-gray ledges of andesite breccia rest upon the light-colored beds that constitute the underlying Valley Springs formation. The outlier in the NE¼ sec. 6, T. 5 N., R. 9 E. (unsurveyed), exposes the contact in the eastern bluff at an altitude of 380 feet, but 300 yards northwest the contact is 100 feet lower; there the contact slopes 10°.

Where the lower part of the Mehrten formation is composed of fine sandstone and siltstone, particularly in the western part of the outcrop zone, it commonly interfingers with the underlying rhyolitic tuff of the Valley Springs formation, so that the contact is not readily traced. Careful search, however, will disclose grains of the characteristic andesite at many places in the more abundant rhyolitic detritus. Under this circumstance the base of the Mehrten formation has been placed at the horizon of the lowest known andesite particles.

It is presumed that there is a slight angular discordance between the Mehrten formation and the underlying Valley Springs and Ione fromations, but it is too slight to be measured in the outcrops. East of the longitude of Valley Springs the Mehrten formation generally rests directly upon the pre-Cretaceous rocks in pronounced angular discordance.

The thickness of the Mehrten formation is not disclosed in any one section but must be calculated from the known width of its outcrop belt and its dip. Thus, the base of the formation at the type section is about 125 feet above sea level; its top is exposed at an altitude of 90 feet about 4½ miles downstream—that is, near the stream-gaging station a quarter of a mile east of the Clements bridge. By applying the dip measured in the adjacent Murphy Creek Basin—100 feet to the mile in the direction S. 80° W.—the thickness indicated by this section is found to be about 390 feet. Similarly the section exposed along Dry Creek indicates the thickness to be about 400 feet, though the greatest exposure in any one hill is but 230 feet thick. In well 4712A1, 4 miles north of Lockeford, dark-gray and black sedimentary rocks were penetrated between 475 and 1,000 feet below the land surface. If, as seems likely, these rocks constitute the Mehrten formation, the thickness at that place is about 525 feet. Farther north, along the boundary of the Mokelumne area, the thickness diminishes and was computed to be only 75 feet along the highway 2 miles west of Bridge House, in sec. 32, T. 8 N., R. 8 E.

ORIGIN AND AGE

As has been pointed out, the andesitic detritus that constitutes the Mehrten formation in the Mokelumne area was swept westward from the volcanic terrane of the Sierra Nevada as stream-borne sediment and as mud flows. East of the Mokelumne area (pl. 4) andesitic breccia and detritus that are equivalent to the Mehrten formation and that are similar to it in texture, bedding, and composition are widespread over the entire west slope of the Sierra Nevada and extend far to the north and south. These materials are described by Lindgren [44] and Turner.[45] In that area the andesitic rocks exceed 1,000 feet in thickness at many places and attain a maximum thickness of 2,000 feet on the northeast side of Silver Lake, 40 miles northeast of Jackson. All these are the products of one epoch of volcanism.

The earliest andesitic outwash apparently followed relatively shallow channels that existed in the surface of the underlying rocks. In the Mokelumne area the principal channel of this sort trended southwestward through Mokelumne Hill, passed around the north end of Bear Mountain and Gopher Ridge, swerved westward and northwestward at Campo Seco, and crossed the highland south of Buena Vista Peak. This channel and others have been described on page 66. As deposition continued the andesitic detritus was spread ever more widely. The coarse mud flows represented by the andesitic agglomerate were apparently distributed in the late part of the epoch, when the plain of volcanic waste was so extensive as to have on its upper surface

[44] Lindgren, Waldemar, U. S. Geol. Survey Geol. Atlas, Sacramento folio (no. 5), 1894; Pyramid Peak folio (no. 31), 1896.

[45] Turner, H. W., U. S. Geol. Survey Geol. Atlas, Big Trees folio (no. 51), 1898.

distributary channels radiating from the mouths of the major stream channels. Sandstone and siltstone of andesitic composition were deposited extensively and in places to a depth of at least 100 feet after the latest outwash of agglomerate that is known in the Mokelumne area. By the end of this epoch the andesitic detritus had covered all the lower western slope of the Sierra Nevada and extended westward into the California Trough as a great unbroken plain composed of volcanic detritus. All but a few of the highest peaks of the underlying rocks had been covered (pl. 4), and the drainage systems of earlier epochs probably were entirely obliterated. Thus was formed the volcanic plain of the Sierra Nevada, which has been described on pages 22 and 23. The initial westward slope of this constructional andesitic plain has been estimated on page 26 to have been 90 to 100 feet to the mile.

One fossil is recorded which probably came from the Mehrten formation in the Mokelumne area—namely, the symphysis of the lower jaw of a mammal resembling a horse.[46] This fossil presumably was embedded in andesitic beds about 4 miles northeast of Valley Springs. It is not diagnostic as to age.

Several localities outside the Mokelumne area have yielded fossils that help to determine the age of the Mehrten formation. Thus, at Table Mountain, Tuolumne County, 25 miles southeast of Valley Springs, andesitic sediments that are presumed to be equivalent to the lower part of the Mehrten formation have yielded 16 species of fossil leaves and a tooth of an extinct species of horse. These fossil remains are cited by Lindgren and Knowlton,[47] who ascribe the plant remains to the Miocene. The flora identified with certainty by Knowlton [48] is listed below:

Fagus antipofii Heer.	Cornus ovalis Lesquereux.
Quercus elaenoides Lesquereux.	Acer bolanderi Lesquereux.
Quercus convexa Lesquereux.	Ilex prunifolia Lesquereux.
Quercus olafseni Heer.	Rhus typhoides Lesquereux.
Salix californica Lesquereux.	Rhus metopioides Lesquereux.
Platanus dissecta Lesquereux.	Rhus dispersa Lesquereux.
Ficus microphylla Lesquereux.	Zanthoxylon densifolium Lesquereux.
Persea pseudocarolinensis Lesquereux.	Cercocarpus antiquus Lesquereux.

Lindgren considered the horse tooth to be indeterminable. As Matthes [49] has reported, the flora has been reclassified recently by R. W. Chaney and ascribed by him to the upper Miocene, thus confirming the more general correlation by Knowlton and Lindgren. Also, the horse tooth has been identified by Chester Stock and likewise ascribed to the upper Miocene.

[46] Hay, O. P., The Pleistocene of the western region of North America and its vertebrated animals: Carnegie Inst. Washington Pub. 322B, p. 63, 1927.

[47] Lindgren, Waldemar, The Tertiary gravels of the Sierra Nevada of California: U. S. Geol. Survey Prof. Paper 73, pp. 52, 56–64, 1911.

[48] Knowlton, F. H., idem, pp. 61–62.

[49] Matthes, F. E., Geologic history of the Yosemite Valley: U. S. Geol. Survey Prof. Paper 160, p. 28, 1930.

Vanderhoof[50] recently described fossil material found in a clay lens enclosed in andesitic sandstone about 4 miles east of Oakdale, in the NW¼ sec. 4, T. 2 S., R. 11 E., about 10 miles south of the Mokelumne area. Reconnaissance by one of the writers (Piper) tentatively correlates the fossiliferous zone with the uppermost part of the Mehrten formation of the Mokelumne area. Vanderhoof identified the fossiliferous beds as lowermost Pliocene and considered them approximately equivalent to the Ricardo formation of the Mojave Desert.

Andesitic detritus was deposited extensively in the Sierra-Cascade and Pacific Border provinces in late Tertiary time. It is presumed that this deposition was limited to one relatively short epoch and that the Mehrten formation is the representative of that epoch in the Mokelumne area. Thus, vertebrate fossils derived from andesitic sediments or from land-laid deposits overlying andesitic rocks at localities near the Mokelumne area indicate in a general way the age of the Mehrten formation. These fossils have been determined as upper Miocene or lower Pliocene. Probably the most direct tie of this sort is that which was suggested by Louderback[51] between the andesitic rocks of the Sierra Nevada and the San Pablo formation of the Coast Ranges. Thus, in those areas that lie west and southwest of the Mehrten formation in the Mokelumne area the San Pablo formation is made up largely of andesitic detritus, whereas older and younger formations in the same areas do not carry an appreciable quantity of such material. No source of this andesitic material is known in that part of the Coast Ranges, and the fine texture of the material suggests that it may well be the finer detritus from the andesitic eruptions in the Sierra Nevada. The San Pablo formation contains a rather abundant marine fauna that most paleontologists ascribe wholly to the upper Miocene, although some would not restrict its stratigraphic range so closely.

Thus, although the Mehrten formation is not known to be fossiliferous in the Mokelumne area, its geologic age is presumed to be Miocene, probably upper Miocene, on the basis of the meager information that can be derived from adjacent areas. In part it may be of lower Pliocene age.

VALLEY SPRINGS FORMATION (MIDDLE? MIOCENE)

DEFINITION AND TYPE SECTION

In the full stratigraphic sequence the Mehrten formation is underlain by beds that are composed almost wholly of the fragmental and glassy products of the Miocene rhyolitic epoch. The total absence of fresh andesitic detritus discriminates them from the overlying Mehrten formation; their volcanic origin discriminates them from

[50] Vanderhoof, V. L., A skull of *Pliohippus tantalus* from the later Tertiary of the Sierran foothills of California: California Univ., Dept. Geol. Sci., Bull., vol. 23, pp. 183–194, 1933.

[51] Louderback, G. D., Period of scarp production in the Great Basin: California Univ., Dept. Geol. Sci., Bull., vol. 15, pp. 16–18, 1924.

nonvolcanic sediments that underlie them. For the beds that are so discriminated the name "Valley Springs formation" is proposed in this report, after a type exposure in the west slope of Valley Springs Peak, a conspicuous butte 1½ miles northwest of the town of Valley Springs, near the center of sec. 11, T. 4 N., R. 10 E. They also constitute the Ione clay rock or tuff as originally discriminated by Turner[52] and included in the Ione formation. To the strata that constitute the Valley Springs formation Tolman,[53] in his typewritten report on the Mokelumne area, ascribed a name that is preempted in the geologic literature for a well-known stratigraphic unit of Mississippian age, the Buena Vista sandstone member of Ohio.

Valley Springs Peak is capped by dense vitreous rhyolitic tuff or tuff breccia that has withstood the erosion of the sub-Mehrten epoch and all subsequent time. Thus there has been preserved at this place a greater thickness of the rhyolitic materials than elsewhere in the Mokelumne area, except possibly at Buena Vista Peak. About 110 feet below the base of this member is another similar bed of tuff that forms a vertical bluff 50 feet high along the west slope of the peak. The absence of a similar bluff at this stratigraphic horizon on the slopes of the gravel-capped ridge that extends southwestward from Valley Springs Peak (p. 56) suggests that the conspicuous lower tuff of the type section was deposited only locally or that it is a product of local induration. Between the two layers of tuff and at the altitude of the gravel-capped ridge there appears to be a bed of coarse conglomerate 40 feet thick that is poorly but repeatedly exposed in the south and west slopes of the peak. This conglomerate has a matrix that is moderately indurated; it contains many cobbles of rhyolite (which are uncommon in gravel of known post-Mehrten age) and is entirely without cobbles of andesite. These features suggest that the conglomerate is an integral part of the Valley Springs formation (p. 57). The lower part of the formation is made up largely of greenish-gray siltstone and sandstone that contain some particles and shreds of pumice; these strata enclose other conglomerate members. The detailed section follows:

Type section of the Valley Springs formation in the west slope of Valley Springs Peak, in sec. 11, T. 4 N., R. 10 E.

Top of section is the edge of the tableland about 25 feet below the summit, altitude about 1,200 feet.

Valley Springs formation:

	Feet
1. Tuff, rhyolitic, vitreous, white; angular fragments of quartz, plagioclase, and pumice one-eighth to one-half inch in diameter embedded in microcrystalline groundmass; conspicuous columnar joints. The lower 20 feet is somewhat friable	70

[52] Turner, H. W., Geological notes on the Sierra Nevada: Am. Geologist, vol. 13, pp. 229-249, 1894.
[53] Tolman, C. F., op. cit.

Type section of the Valley Springs formation in the west slope of Valley Springs Peak, in sec. 11, T. 4 N., R. 10 E.—Continued

	Feet
Valley Springs formation—Continued.	
2. Concealed by talus	45
3. Conglomerate; a few cobbles 1 to 3 inches in diameter, pebbles, and coarse sand in a dense light-buff matrix of fine sand and silt. Locally the matrix is coarse sand, and a few of the included boulders are as much as 4 feet long. The cobbles and boulders are from granite, quartzite, porphyrite, and other pre-Cretaceous crystalline rocks	40
4. Concealed	25
5. Tuff, rhyolitic, vitreous, pink; similar to bed 1, but columnar joints more widely spaced, some as much as 15 feet apart. The lower 20 feet is friable; its fragments of pumice are half an inch to 2 inches in diameter	70
6. Sandstone and siltstone, pumice-bearing, light greenish gray; mostly concealed by talus	42
7. Sandstone and siltstone, greenish gray; contains much pumice	4
8. Coarse sandstone, anauxite-bearing, white to light buff	1
9. Sandstone and siltstone, greenish gray, some pumice	27
10. Largely concealed; a few exposures (talus blocks?) of sandstone and siltstone similar to underlying bed	43
11. Coarse massive sandstone, greenish gray, clayey, made up chiefly of angular quartz and biotite	2
12. Concealed	20
13. Conglomerate, pebbles and cobbles as much as 6 inches in diameter, matrix ranges from coarse anauxite-bearing sandstone to siltstone with a few fragments of pumice	8–4
14. Sandstone, clayey siltstone, and fine conglomerate in alternating beds 1 to 4 feet thick; a few shards of pumice; most of the pebbles in the conglomerate are now clay, but may well have been derived initially from pumice or tuff	0–27
Maximum thickness of Valley Springs formation	420
15. Concealed	10
Ione (?) formation:	
16. Conglomerate and clayey anauxite-bearing sandstone; pebbles are chiefly white quartz or from pre-Cretaceous rocks	1
17. Concealed	8
18. Conglomerate, compact, limonitic; quartz grains as much as a quarter of an inch in diameter	5
Base of section rests on white clayey schist and other pre-Cretaceous crystalline rocks. It is on a spur ridge 0.6 mile west of the summit; approximate altitude 730 feet.	

LITHOLOGIC CHARACTER

The section on the north slope of Buena Vista Peak, in the E½ sec. 19, T. 5 N., R. 10 E., is shown diagrammatically in figure 6. The uppermost member of this section is a massive bed which Turner[54] described as a rhyolite tuff and of which he quoted W. F. Hillebrand's chemical analysis. Turner found that the rock consisted of phenocrysts of plagioclase, sanidine, and accessory quartz and brown biotite in glass. In petrographic composition this member is

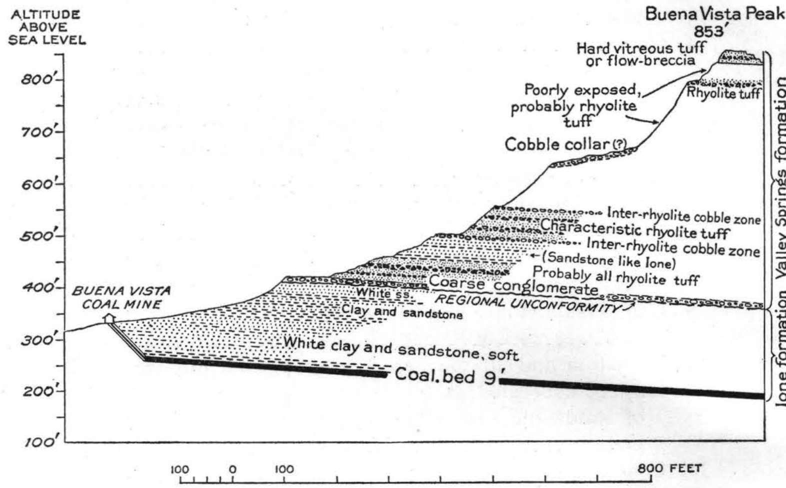


FIGURE 6.—Profile and stratigraphic section of Buena Vista Peak, in the E½ sec. 19, T. 5 N., R. 10 E. Section trends S. 10° W. from shaft of Buena Vista coal mine.

similar to beds 1 and 5 of the type section. Below the cap of vitreous tuff the section exposed in Buena Vista Peak is made up chiefly of tuffaceous clay that bears abundant shards of pumice one-eighth to half an inch in diameter. Thin beds of quartz sandstone and discontinuous lenticular beds of cobbles 1 to 3 inches in diameter also occur. In these beds of sandstone and conglomerate particles of rhyolitic composition are commonly sparse or absent. The basal member of the section is a stratum of indurated coarse sandstone and conglomerate that upholds a prominent tableland along the east base of the peak, at an altitude of 600 to 650 feet above sea level. To casual inspection this tableland appears to be a continuation of the cobble-strewn terrace that lies on the south and west sides of the peak. The rocky cliffs that edge the tableland expose 10 feet or more of this resistant conglomerate. At various places the top layer of the conglomerate stratum contains pebbles and shards of pumice in the matrix, and although no pumice has been found in the lower part of the stratum, it seems reasonable to assume that the entire

[54] Turner, H. W., Further contributions to the geology of the Sierra Nevada: U. S. Geol. Survey 17th Ann. Rept., pt. 1, p. 721, 1895.

conglomerate is the basal member of a new cycle of deposition and therefore belongs to the same epoch of erosion and deposition as the succeeding volcanic rocks and their interbedded conglomerates. This basal conglomerate overlies about 25 feet of sandstone, likewise indurated, which is classed with the underlying Ione formation. The extreme induration of the basal conglomerate and the associated sandstone is more or less local but is traceable from the plateau around Buena Vista Peak southward to the vicinity of Camanche in a relatively narrow discontinuous belt. It is thought to be due to silicification from waters associated with the rhyolitic eruptions. At some places rhyolitic pebbles become a more conspicuous part of the basal conglomerate stratum, as in exposures along the road on the north side of the Mokelumne River 1½ miles northeast of Camanche.

In still other parts of the Mokelumne area the Valley Springs formation differs materially from the type section. In general the most conspicuous constituents of the formation are the shards of pumice and the beds of rhyolitic tuff. Local beds that are composed almost entirely of pumice are as much as 20 feet thick. Even in the interbedded layers of clastic sandstone that are composed of grains from the pre-Cretaceous crystalline rocks, the shards of volcanic glass are often a diagnostic though sparse constituent. In some places the tuffaceous deposits are mixed with angular grains of white quartz sand; in other places the more massive tuffs contain clear quartz crystals clustered in cavities. Much of the formation in the Mokelumne area is well stratified and suggests deposition in quiet water, but none of it is known to be marine.

The basal conglomerate of the sections exposed at Valley Springs Peak and Buena Vista Peak is a local feature. Over most of the Mokelumne area the lower part of the formation consists of light-gray clay that weathers to a greenish-yellow color. These beds are brittle, have an irregular fracture, and enclose irregular aggregates of harder and perhaps more siliceous clay. These aggregates may be decomposed fragments of tuff or pumice. Such are the beds that led Turner [55] to term the formation "clay rock." Even in them diagnostic fragments of pumice are commonly found on close inspection. In many places the lowest part of the formation consists of quartz-anauxite sandstone that is interbedded with rhyolitic tuff and pumice-bearing clay. These sandstone beds are lithologically so similar to the white sands of the Ione formation that they must be assumed to be the products of erosion and redeposition of materials from that formation.

Still another facies of the Valley Springs formation comprises the local and very lenticular beds of coarse gravel and conglomerate that are believed to represent the deposits of inter-rhyolitic streams along whose channels boulders and cobbles accumulated. These gravel

[55] Turner, H. W., Geological notes on the Sierra Nevada: Am. Geologist, vol. 13, pp. 229-249, 1894.

beds include pebbles of white quartz, quartzite, and other resistant pre-Cretaceous crystalline rocks. Such deposits occur at approximate altitudes of 500 and 560 feet in the section exposed in Buena Vista Peak. A similar bed crops out near the base of the section south of Stone House School, given below. The coarse conglomerate near the top of Valley Springs Peak may be another example. These are evidences that at least a part of the formation was deposited by strong and active currents.

The entire formation is 75 feet thick on a hill south of Stone House School, along the northern border of the Mokelumne area, as shown in the following section:

Section of the Ione, Valley Springs, and Mehrten formations south of Stone House School, in the SW¼SE¼ sec. 33, T. 8 N., R. 8 E.

	Feet
Top of section is at top of hill, 276 feet above sea level.	
Mehrten formation: Fine andesitic sandstone, well sorted, parallel-bedded; some silt	46
Valley Springs formation:	
Silt and clay, siliceous, greenish gray; a thin discontinuous bed of conglomerate at top; encloses one bed of fine sandstone, gray, thin-bedded, well sorted, 1 foot thick	26
Conglomerate; pebbles of pre-Cretaceous crystalline rocks and shards of pumice embedded in a matrix of silt	6
Silt and clay, siliceous, greenish gray. Pumice is very sparse	11½
Gravel and coarse sand, chiefly of greenstone and quartz, but pumice is common; bed is local and entirely absent 100 feet to the south	8½
Silt and clay, siliceous, greenish yellow, with sparse pumice	2
Concealed	13
Sand, greenish, with thin beds of greenish-gray clay	8
Probable base of Valley Springs formation; contact with the underlying Ione formation has a vertical range of several feet.	
Ione formation: Sand, gray, quartzose, with some anauxite; exposed	25
Base of section is in creek bed north of road, altitude about 130 feet.	
Thickness of measured section	146

DISTRIBUTION, SOURCE, AND THICKNESS

The Valley Springs formation crops out in a belt 7 or 8 miles wide between the towns of Wallace and Valley Springs; toward the south it laps completely across the Ione formation as far as the southern limit of the Mokelumne area. Here the formation dips uniformly 1½°–2° W. To the north this belt is continuous but becomes narrower and at the Cosumnes River, 20 miles north of Valley Springs, is less than 2 miles wide. East of the longitude of Valley Springs there exist only small remnants of the rhyolitic deposits. Plate 5, which is compiled from the Jackson and Big Trees folios [56] and from the map that accompanies this report (pl. 1), shows approximately the initial extent of the rhyolite tuffs in the Mokelumne area—that is, confined to narrow tongues in the Sierra Nevada and covering a broad piedmont surface farther west along the edge of the California Trough. Thus the rhyolitic strata are much less extensive than the Mehrten formation.

The maximum stratigraphic thickness of the Valley Springs formation at the type section is about 420 feet. The corresponding section at Buena Vista Peak is 450 feet thick. These are the thickest known sections of the Valley Springs formation, but soft beds may once have existed above the tuff that forms the present summits, and the initial thickness may have been somewhat greater than the present. On many of the steep hills in the northeastern part of the Goose Creek quadrangle 250 to 275 feet of Valley Springs sedimentary beds are exposed below the caps of Mehrten breccia. Farther north the formation thins rapidly and in the section near the Cosumnes River is not over 75 feet thick.

Of the wells from which samples are available (p. 89) only one (4712A1) is deep enough to reach the Valley Springs formation. In this well the Valley Springs formation is believed to be represented by beds of tuffaceous sand and clay from 991 to 1,203 feet below the land surface, a thickness of about 210 feet. Another well drilled for oil (7828L1) is likewise believed to penetrate the Valley Springs formation; from the driller's log the formation is inferred to be at least 345 feet thick.

In four townships that comprise nearly all the district of intensive pumping for irrigation—Tps. 3 and 4 N., Rs. 6 and 7 E.—no irrigation well is known to be deep enough to reach the Valley Springs formation. Indeed, as shown by the record of well 4712A1, the top of the formation is 1,000 feet below the land surface at the eastern margin of this district, and because the formation has an appreciable westerly dip its depth below the land surface presumably would be even greater farther west.

STATIGRAPHIC RELATIONS AND ORIGIN

The Valley Springs formation was deposited upon an uneven surface. Usually it rests upon the Ione formation, but in some places it rests directly upon the pre-Cretaceous crystalline rocks, as shown in the road cut 1 mile southwest of Valley Springs. In many such places the Valley Springs formation contains sand so like that of the Ione formation that it must be assumed that the Ione surface was eroded and the

[56] Turner, H. W., U. S. Geol. Survey Geol. Atlas, Jackson folio (no. 11), geologic map, 1894; Big Trees folio (no. 51), geologic map, 1898.

detrital sands from it redeposited with the volcanic materials. Allen[57] gives other evidence of a disconformity between the Ione and Valley Springs formations and cites in particular at Buena Vista Peak a vertical range of 100 feet for this contact within a short horizontal distance. This particular evidence the senior writer (Gale) was not able to recover in the field, but Allen's description suggests that he may have found rhyolitic deposits filling a channel beneath the Valley Springs, stratigraphically below the massive basal conglomerate of the type section—a relation that is in harmony with those observed by the writers.

The uneven surface upon which the Valley Springs formation was deposited had moderate or low relief and was largely the product of a remote cycle of erosion. To a component of this surface as developed in the Yosemite region, about 95 miles east-southeast of the Mokelumne area, Matthes[58] has applied the term "broad valley." This feature of the Yosemite region was cut on the massive granitic rocks of the Sierra Nevada and comprises broad open valleys whose level floors sloped perhaps 12 feet in a mile and were separated by rolling hills 500 to 1,000 feet high. The character of this land surface in and near the Mokelumne area is not known from direct observation, but it is presumed to have been similar to that of the Yosemite region, for it was cut in part on the same granitic rocks by streams of comparable gradient. In the western part of the Mokelumne area the land surface was cut on the weaker rocks of the Ione formation, and there it might have been nearly a plain.

Apparently this erosion cycle was terminated in middle (?) Miocene time by deformation in the Sierra Nevada and adjacent regions. In the Mokelumne area the deformation seems only to have tilted or rotated the Sierra Nevada block toward the west, and the immediate result was to steepen the gradients of those parts of the streams that flowed westward or southwestward—down the slope of the tilted mountain block—and to increase their erosive power. The surface of the Eocene deposits, particularly near the outlets of the main channels, was extensively incised and eroded by the rejuvenated streams. The courses of the streams are the Tertiary channels described by Lindgren.[59] The land surface that comprised the extensive remnants of the middle (?) Miocene erosion surface and the channels or trenches of the rejuvenated streams was the surface upon which the rhyolitic Valley Springs formation was deposited unconformably.

Almost coincident with the deformation and the first stage of stream rejuvenation, volcanism broke forth in the Sierra Nevada on a grand

[57] Allen, V. T., The Ione formation of California: California Univ., Dept. Geol. Sci., Bull., vol. 18, p. 411, 1929.

[58] Matthes, F. E., Geologic history of the Yosemite Valley: U. S. Geol. Survey Prof. Paper 160, pp. 31–33 1930.

[59] Lindgren, Waldemar, The Tertiary gravels of the Sierra Nevada: U. S. Geol. Survey Prof. Paper 73, pp. 28–37, 1911.

scale, following a long period of quiescence. The rocks extruded were siliceous or rhyolitic. The flow rocks did not proceed far down the mountain slopes, but a great quantity of pumice and coarser fragmental material was thrown out. In the Sierra Nevada these ejectamenta were washed into the channels of the rejuvenated streams, and the finer detritus was thence transported and spread over the border of the California Trough, west of the mountains. The fluvial deposits thus formed constitute the Valley Springs formation. In the Mokelumne area the rhyolitic sediments were transported along a channel south of the present valley of the Mokelumne River, now defined by the tongue of Valley Springs formation that is outlined on plate 5. This channel now descends from an altitude of 1,500 feet above sea level at the town of Mokelumne Hill to about 700 feet at Valley Springs—that is, 800 feet in less than 10 miles. Ultimately it was filled to a present altitude of more than 1,200 feet at Valley Springs, and the upper 250 feet of the deposit included the layers of vitreous rhyolitic flow-breccia or tuff such as now cap Valley Springs Peak and Buena Vista Peak. The rhyolitic detritus eventually formed broad coalescing fans along the foot of the Sierra Nevada and spread far to the north and south in the California Trough. The lenses of coarse conglomerate interspersed in the rhyolitic section at Valley Springs Peak and Buena Vista Peak are presumed to indicate the courses of distributary channels of an ancestral Mokelumne River that existed during the rhyolitic epoch.

In the Mokelumne area there are no known vents for these rhyolitic materials, but 1 mile southwest of Jackson Butte, in the east half of the Jackson quadrangle, there is a small area covered by vitreous rhyolite, specifically mentioned by Turner [60] as a possible orifice of the rhyolitic material. This lies within the channel-like initial tongue of the formation (pl. 5). (Jackson Butte itself stands high above the rhyolite flow and is composed mainly or wholly of the later andesite.) Neither are there in the Mokelumne area any known remnants of original rhyolite flows, but the beds of flow-breccia or tuff are so hard and vitreous that they may well be considered part of the original ejectamenta, accumulated without much stream sorting.

GEOLOGIC AGE

The Valley Springs formation is not known to contain fossils in the Mokelumne area, but the senior writer (Gale) feels that it may be correlated tentatively with deposits of somewhat similar composition that extend across the California Trough into the Coast Ranges. Thus, although coincidence has not been proved, it seems likely that the well-known marine Salinas shale of the Monterey group in the Coast Ranges is not only derived from the siliceous rocks and products

[60] Turner, H. W., U. S. Geol. Survey Geol. Atlas, Jackson folio (no. 11), p. 4, 1894.

of this epoch but throughout a wide area in the Pacific Border province actually includes tuffs that represent the epoch of rhyolitic volcanism. Accordingly the Valley Springs formation and the Salinas shale would be products of the same epoch and would be of the same geologic age. The Salinas shale is generally conceded to be middle Miocene. Lindgren [61] has cited the large collections of fossil leaves taken from beds of gravel immediately below the lowest rhyolitic tuffs in two localities—at Chalk Bluffs, near You Bet, Nevada County, and at the Washington gravel mine in Independence Hill, near Iowa Hill, Placer County. These leaves were initially classified by Knowlton [62] as Miocene. Recently, however, Chaney [63] has cast doubt on this correlation by classifying flora from a new locality at Buckeye Flat, in Nevada County, "which may represent the original Chalk Bluffs locality of Lesquereux", as Eocene or possibly younger.

IONE FORMATION (EOCENE)

DEFINITION AND GENERAL FEATURES

In the full stratigraphic succession of the Mokelumne area the rhyolitic beds of the Valley Springs formation are underlain by nonvolcanic strata that constitute the Ione formation as now defined. These strata are well exposed in quarries, pits, and mines near the town of Ione, Amador County, whence the formation name was originally derived by Lindgren [64] and Turner.[65] In this report, however, the name is applied in the restricted sense introduced by Allen.[66] Thus it becomes equivalent to the Ione sandstone and the white clay and sand beds containing coal seams, as those members are defined by Turner, by excluding the overlying Ione clay rock or tuff (Valley Springs formation of this report).

In its more nearly complete sections the Ione formation comprises three members that are moderately well defined. These are an upper member of massive white sandstone; an intermediate member that includes alternating lentils of white or light-colored clay and beds of sand similar to the upper member; and a lower member that consists of gray or bluish shale and clay, lignite or coal, and other carbonaceous beds. The complete section is not everywhere present, as may be observed in many places along the outcrop zone. The formation yields or has yielded commercial deposits of clay, sand, coal, and limonitic iron ore or ocher.

[61] Lindgren, Waldemar, Tertiary gravels of the Sierra Nevada of California: U. S. Geol. Survey Prof. Paper 73, pp. 56–64, 148, 1911.

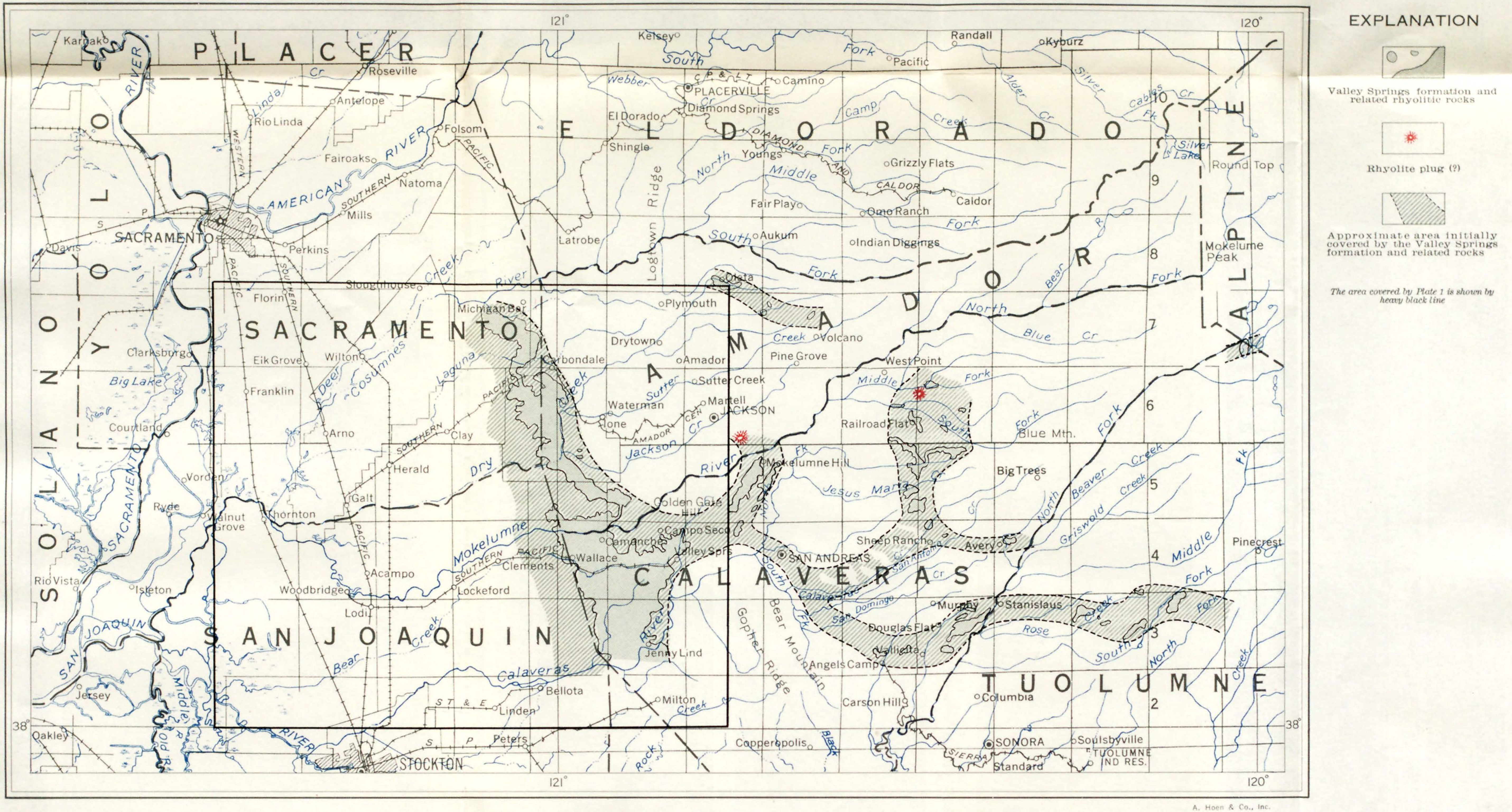
[62] Knowlton, F. H., in Lindgren, Waldemar, idem.

[63] Chaney, R. W., Age of the auriferous gravels [abstract]: Geol. Soc. America Bull., vol. 43, pp. 226–227, 1932.

[64] Lindgren, Waldemar, U. S. Geol. Survey Geol. Atlas, Sacramento folio (no. 5), 1894.

[65] Turner, H. W., Geological notes on the Sierra Nevada: Am. Geologist, vol. 13, pp. 228–249, 1894.

[66] Allen, V. T., The Ione formation of California: California Univ., Dept. Geol. Sci., Bull., vol. 18, no. 14, p. 353, 1929.



MAP OF THE MOKELUMNE REGION, CALIFORNIA, SHOWING APPROXIMATELY THE INITIAL EXTENT OF THE VALLEY SPRINGS FORMATION AND RELATED RHYOLITIC ROCKS

10 0 10 20 30 Miles

1938

The Ione formation is distributed extensively in central California and crops out in a belt west of the pre-Cretaceous crystalline rocks at the western foot of the Sierra Nevada. The part of this belt that lies in the Mokelumne area extends from Valley Springs on the south to and beyond the Cosumnes River on the north (pl. 1). The formation is a useful stratigraphic horizon marker throughout this region.

LITHOLOGIC CHARACTER

The predominant constituent of the Ione formation is probably sand. Commonly uniform and medium to coarse in texture, this sand is distinguished by its clear angular grains of quartz, which are commonly embedded in a scant matrix of white chalky clay, and usually interspersed with flakes of pearly-white anauxite. These beds, which are used for making pottery and fire brick, present a striking appearance in the quarries, being a dazzling white in the bright sunlight. Heavy minerals are associated with the sand in minor proportions and are reported by Allen [67] to be distinctive of the pre-Cretaceous crystalline rocks of the Sierra Nevada, indicating origin in the granodiorite, basic igneous rocks, and metamorphic schists. Particles of feldspar are generally absent. Locally the sand includes lentils of gravel, in which the predominant constituent is milky-white vein quartz, usually in pebbles or cobbles that are smoothly water-worn. These have the aspect of channel deposits and occur chiefly in the uppermost part of the formation, where it laps over the underlying crystalline rocks.

In the area that extends from the Mokelumne River northward to the tableland around Buena Vista Peak the massive sandstone in the upper part of the Ione formation is unusually hard. At one locality on the east end of the tableland, in sec. 27, T. 5 N., R. 10 E., massive red and white sandstone from these beds was quarried more than 40 years ago, and the red facies was used extensively in construction of buildings such as the California National Bank at Sacramento and the old Chronicle Building in San Francisco.[68]

The "clay", which is the conspicuous component of the intermediate member of the Ione formation, is an even-textured siltlike material that is chalky white in the pure deposits and generally white or very light-colored. These beds are extensively used in the ceramic industry. In a few places the clay is more highly colored—red, yellow, and even purplish. This clay occurs in massive deposits that are indistinctly bedded and apparently of lenticular form. Commonly it is interbedded or even commingled with sand such as characterizes the upper member of the formation. The clay is generally brittle when dry, usually breaks with a hackly or conchoidal

[67] Allen, V. T., op. cit., pp. 375–376.

[68] California State Mineralogist Rept., vol. 23, no. 2, p. 201, California State Min. Bur., 1927.

fracture, but becomes plastic when wet and slakes readily in water. The mineral composition of the clay is described in some detail by Allen,[69] who states that it is composed chiefly of particles large enough to be visible under the microscope and so cannot rightfully be regarded as colloidal. It may be noticed at the pit that the clay is slippery when wet but that it does not stay long in suspension in water nor appear to have the consistency of a gel. The dominant constituent is the mineral anauxite—like the flakes of "pearly mica" in the sandstone—which is apparently the product of weathering of biotite derived from the granodiorite of the Sierra.[70] Most of this mineral is exceedingly fine-grained, as if it had settled from suspension in quiet water. Anauxite is described by Allen as one of the minerals of the kaolin group, $Al_2O_3.3SiO_2.2 \pm H_2O$, closely related to kaolinite.

In some places where the clay of the Ione formation rests directly on the pre-Cretaceous crystalline rocks it is stained bright yellow or red by deposits of iron oxide, presumably limonite. Some of these deposits constitute ocher, and others are so pure as to be classed as iron ore, of the bog-iron type. Commonly in these places the crystalline rocks that underlie the clay are obviously deeply weathered; these features suggest that the limonitic deposits originated by precipitation of iron from mineralized ground water in the swamps of an area that had long been exposed to weathering.

The lower member of the Ione formation is composed largely of gray or bluish clay and silt that enclose lentils of brownish carbonaceous matter and beds of coal or lignite at several places in the Mokelumne area. The thickest coal beds are found in basins that are bounded on the east by the pre-Cretaceous crystalline rocks in the Sierra Nevada foothills and on the west by outlying parallel ridges of the same rocks. The coal contains much volatile carbon and moisture, is very dark brown to black, and commonly shows the texture of wood, much compressed. These features suggest its classification as lignite. Lumps or flattened patches of yellowish pitch are common in the coal.

These beds of coal or lignite have been explored and mined over an area that extends from the gravel pits north of Lancha Plana to Carbondale, a distance of 13 miles. Only the Buena Vista mine, at the northern base of Buena Vista Peak, in the NE¼ sec. 19, T. 5 N., R. 10 E., is now operating. This mine is worked through an inclined shaft that descends 70 feet to the base of the main bed of coal. The coal is divided into three beds, of which the upper two—each about 2 feet thick—are separated by a discontinuous clay parting; below these are a persistent clay parting 4 inches thick and the main bed of coal, which is 5 feet thick. The coal is overlain in turn by shale 11

[69] Allen, V. T., op. cit., pp. 379–382.
[70] Idem, p. 377.

feet thick and by coarse white sand that is indistinctly bedded, contains a clay matrix, and extends upward to the land surface; it is underlain by shale that is exposed to a depth of 3 feet in the sump of the shaft.

In well 4712A1 the 576-foot section between 1,203 and 1,779 feet below the surface contains much pure white or glassy quartz sand commingled with biotite and its alteration product anauxite and interbedded with shale; this mineral composition is of characteristic Ione aspect. A 6-foot bed of lignite between 1,601 and 1,607 feet strongly suggests the lower part of the typical Ione section, as does also the "green clay containing carbonaceous matter" at 1,675 feet. A conglomerate of well-rounded quartz pebbles cemented by limonite, between 1,765 and 1,790 feet, is taken as the base of the Ione formation. Minute marine fossils from a depth just above 1,600 feet are reported in the driller's log, but no record of their identity has been found.

The presence of typical Ione sandstone is shown by cores from well 7828L1, which was drilled in 1929 by the Allied Petroleum Corporation on the Meiss ranch, in the SE¼ sec. 28, T. 7 N., R. 8 E., about 5½ miles west of Carbondale School. In this well the Ione formation appears to be 430 feet thick—that is, it lies between 668 and 1,098 feet below the land surface; it rests on fresh dense granodiorite that belongs to the pre-Cretaceous crystalline rocks. Cores of typical Ione sandstone representing at least 45 feet of beds were preserved at the well when it was visited by the senior writer (Gale) in 1931, but the depth at which they were obtained is unknown. All these cores were of white clayey anauxite-bearing sandstone that ranged from coarse- to fine-grained; some of the core material seemed to have been soft and plastic when first recovered and similar in physical character to the typical Ione clay. The driller's record reports fossils from beds between 584 and 668 feet deep. These might have provided a useful clue to the age of the beds, but no record of their identity has been found.

The Ione formation is in unconformable contact with the overlying Valley Springs formation and in pronounced angular discordance with the underlying crystalline rocks of pre-Cretaceous age. Both the unconformities are uneven surfaces of erosion. The lower unconformity is a rugged mature surface which has a relief of several hundred feet and which accounts for some of the basinlike areas in which the lower member of the Ione formation was deposited along the western flank of the Sierra Nevada. The upper unconformity explains the absence of outcrops of the Ione formation from Valley Springs to and beyond the southern edge of the Mokelumne area (pl. 1), for in that district the Valley Springs formation laps entirely across the Ione formation.

The maximum thickness of the Ione formation was originally given by Turner [71] as apparently more than 1,000 feet, but this estimate includes the thickness of the "Ione clay rock or tuff", which in this report is separated as the Valley Springs formation. It is also based in part on the reported record of a boring made many years ago, said to have penetrated 800 feet of sandy clay below the coal at the former coal mine 3, about 3½ miles northwest of Ione. The validity of this record is questioned by the senior writer (Gale). Other exposures observed during the present work appear to indicate a maximum thickness of 450 feet, and in most places the total thickness of the Ione formation, as indicated by the width of its outcrop, is even less. The formation may be assumed to thicken westward toward the axis of the California Trough.

ORIGIN AND AGE

The Ione formation is largely fluviatile, as indicated by its lenticular beds of water-worn white quartz gravel, by its cross-bedding, and by indications of scour and fill. It is thought by Allen [72] that the Ione formation was deposited contemporaneously with the earlier auriferous gravel and by the same streams. The deposits of clay and coal indicate lagunal or estuarine conditions and suggest a shore line far up toward the present foothills, probably not far from the area in which the pre-Cretaceous rocks now crop out. At one locality in the Mokelumne area marine fossils are preserved as casts in the upper part of the sandstone that has been quarried at the east end of the Buena Vista tableland, 3 miles southeast of Buena Vista. Apparently the fossiliferous layer is thin, but initially it may have been thicker, for it is truncated by the present erosion surface. The beds immediately below the fossiliferous strata are cross-bedded and in part are clearly the product of scour and fill; these features indicate that they were deposited in flowing water. Apparently this place was reached only temporarily by the farthest advance of the sea, and the fossiliferous zone marks the shore line of Ione time. The fossils of the locality have been collected and identified by several geologists. Clark [73] considers them diagnostic of Eocene age and correlates them with the fauna of the Meganos formation (middle Eocene). Dickerson [74] lists the following fauna:

Venericardia planicosta merriami Dickerson.
Meretrix hornii Gabb.
Psammobia cf. P. hornii Gabb.
Crassatellites sp.
Turritella merriami Dickerson.
Natica sp.
Clavella sp.

[71] Turner, H. W., U. S. Geol. Survey Geol. Atlas, Jackson folio (no. 11), p. 2, 1894.

[72] Allen, V. T., The Ione formation of California: California Univ., Dept. Geol. Sci., Bull., vol. 18, no. 14, pp. 395–402, 1929.

[73] Clark, B. L., personal communication reported in Allen, V. T., op. cit., p. 358.

[74] Dickerson, R. E., Stratigraphy and fauna of the Tejon Eocene of California: California Univ., Dept. Geology, Bull., vol. 9, p. 397, 1916.

UNNAMED GRAY SHALE AND SAND (EOCENE)

Wherever the Ione formation crops out in the Mokelumne area it rests directly upon the pre-Cretaceous crystalline rocks. In a few deep wells, however, and in outcrops at several districts in central California it appears to be underlain by gray micaceous shale and sand that constitute a distinct stratigraphic unit. Allen [75] refers to these underlying strata and mentions exposures of corresponding sections at Table Mountain (near Oroville), at Marysville Buttes, at Lincoln, and in the deep well near Elliott, in the Mokelumne area (well 4712A1 of this report and the Clements well of Allen).

According to the driller's record the last 200 feet penetrated in well 4712A1—that is, from 1,779 to 1,975 feet in depth—consisted chiefly of dark-gray and brown shale and gray sand, mostly fine, contained many fossils, and included carbonaceous streaks or flakes. These beds appear to be a distinct stratigraphic unit that does not crop out in the Mokelumne area. The samples of cuttings from these beds were examined by the senior writer (Gale) and found to show the lithology characteristic of known Eocene strata in other wells farther south in San Joaquin Valley, for example, near Fresno.

These beds of shale and sand are reported to contain fossils from depths of 1,919 to 1,922 feet, which have been identified by Julia Gardner, of the United States Geological Survey, to include marine pelecypods, a tubular fragment that might possibly be *Dentalium*, and a gastropod tip that is probably a species of *Cancellaria*. This faunal list does not fix the age of the deposits, for all the genera represented have been common throughout the Tertiary and Quaternary periods. Other fossils are reported from sand throughout the remainder of the section to the bottom of the hole. Fossiliferous beds between depths of 1,971 and 1,975 feet are said by Allen [76] to have yielded an Eocene form of *Exilia*, collected by him and identified by B. L. Clark as diagnostic of the Meganos epoch (middle Eocene).

The unnamed Eocene strata are also suggested in the accompanying graphic classification (pl. 6) of the log of the Oakdale Oil Corporation well, Gilbert No. 1, about 1 mile north of Oakdale, 35 miles southeast of Lodi, in the SE¼ sec. 3, T. 2 S., R. 10 E. Some of the cores from the presumed Eocene strata in this well were of dark-gray micaceous shale and soft fine sandstone. These included a soft dark-gray sandstone, with carbonized wood and a "marine clam", at 2,000 to 2,007 feet, and a similar sandstone "with several well-preserved *Acila*" at 2,011 to 2,012 feet. Some of the fossils derived from the cores of these beds are complete marine molluscan shells. Unfortunately not much of this fossil material remained in the well samples when they were examined by the senior writer (Gale), but he recovered one almost complete specimen of *Macoma* sp. and several specimens

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[75] Allen, V. T., op. cit., pp. 402–403.
[76] Allen, V. T., op. cit., pp. 402–403; also written communication.

of *Mytilus* sp. about 1 centimeter in length. None of these are diagnostic, and all might be of almost any age from Tertiary to Recent. One other fairly complete specimen that showed hinge characters was extracted from the core material and described by H. R. Gale [77] as follows:

This specimen has a hinge like the various Oligocene and Eocene species of the group called "*Meretrix*", "*Macrocallista*", "*Antigona*", etc., which names are not correct. It is like the hinge of "*Meretrix hornii* Gabb" figured by Dickerson,[78] but the surface looks more like that of "*Marcia*" (?) *conradi*.[79] It also resembles some species in the Martinez [80] formation.

It happens that "*Meretrix*" *hornii* Gabb occurs in the fauna from red Ione sandstone at the quarry on Buena Vista Peak (p. 84), but apparently this species is not considered diagnostic as to age. These fossils therefore suggest but do not prove the age of the presumed Eocene beds in the well at Oakdale. The lithologic character of these presumed Eocene beds also suggests that they are properly classed as a part of the unnamed gray micaceous Eocene shale and sandstone that have been penetrated by several wells in San Joaquin Valley from the vicinity of Fresno to well 4712A1 in the Mokelumne area.

The presumed Eocene beds in the well near Oakdale also include dull-gray micaceous shale and sand with many specks or patches of carbon, and in that respect they are similar to the underlying beds of known Cretaceous age. As a whole, however, they are softer and more friable than the Cretaceous beds, a slight distinction that has been noted elsewhere between known Eocene and Cretaceous sections. Only one core is reported to have been taken in the Oakdale well from the upper part of the section of presumed Eocene age, and this core was not preserved when the senior writer (Gale) examined the cuttings and record. The division indicated at the base of the Eocene is hypothetical. A hard-drilling conglomerate between 2,385 and 2,620 feet in depth was made up of boulders and cobbles of granite and hard well-rounded quartz, quartzite, and basic igneous rocks from the pre-Cretaceous strata of the Sierra Nevada. This conglomerate may be of Cretaceous age, but it has been indicated as Eocene because such conglomerates occur at the base of the Eocene in the Coast Ranges.

CRETACEOUS SYSTEM

Strata of Cretaceous age do not crop out in the Mokelumne area but in all probability underlie at least part of the area covered by the Tertiary and later deposits, and might be encountered by deep wells in the area, particularly in the western part. Strata of Upper Cre-

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[77] Written communication.

[78] Dickerson, R. E., Stratigraphy and fauna of the Tejon Eocene of California: California Univ., Dept. Geology, Bull., vol. 9, pl. 39, fig. 1-b, 1916.

[79] Idem, pl. 39.

[80] Dickerson, R. E., Note on the faunal zones of the Tejon group: California Univ., Dept. Geology, Bull., vol. 8, pl. 11, figs. 1a, 2a, 5, 1914.

taceous (Chico) age crop out along the Sierran foothills at one locality near Folsom, about 40 miles north of the Mokelumne area, and are at least 2,000 feet thick in the well near Oakdale. The Cretaceous system is also represented by thick sections of sedimentary rocks in the Coast Ranges west of the California Trough. Accordingly, if the Sierran crustal block has always acted as a rigid mass when deformed (p. 26), a corresponding Cretaceous section may be expected at the base of the Tertiary system throughout much of central California, and very likely without great disconformity to the overlying strata.

The most extensive exposures of Cretaceous rocks in the region about the Mokelumne area occur in the northern part of the Diablo Range, on the west side of San Joaquin Valley. Here the Chico group, of Upper Cretaceous age, described by Anderson and Pack,[81] has been subdivided into two units, the Moreno formation above, and the Panoche formation below. West of the Mokelumne area the Moreno formation is an argillaceous shale that locally resembles the shaly parts of the underlying Panoche formation, but farther south, in the Diablo Range, the Moreno formation is composed of fine dark clay shale that is quite distinct. The Panoche formation of the Diablo Range is principally arenaceous shale and thin-bedded sandstone, with hard concretionary beds, especially in its upper part. Locally lenses of conglomerate form a large portion of the total thickness. The Panoche formation is 2,000 feet thick at the type district in the Panoche Hills but apparently thins by overlap toward the north, so that only its upper part is represented in the northern Diablo Range and on the west side of San Joaquin Valley opposite the Mokelumne area.

Sections that represent the Cretaceous system of the Coast Range are exposed in the southwestern part of Stanislaus County, as, for example, on Hospital Creek,[82] which drains the east front of the Diablo Range opposite Oakdale. Here the Moreno formation is 1,950 feet thick and is mainly shale but includes some conglomerates and in certain zones much fossiliferous sandstone.

The deep well at Oakdale discloses an informative stratigraphic section on the east side of San Joaquin Valley, at a locality about 25 miles from the outcrops of the Diablo Range section. The lower part of this section (pl. 6, p. 88), which comprises the 2,130 feet of beds from the depth of 2,620 feet to the bottom at 4,750 feet, is undoubtedly of Cretaceous age. This age is indicated by fragments of *Inoceramus* and ammonites, including *Baculites*, some of which are reported to have been so complete as to be diagnostic of the geologic age. However, most of the fossil material reported to have

[81] Anderson, Robert, and Pack, R. W., Geology and oil resources of the west border of the San Joaquin Valley north of Coalinga, Calif.: U. S. Geol. Survey Bull. 603, pp. 36–58, 1915.

[82] Anderson, Robert, and Pack, R. W., op. cit., p. 55.

been obtained during the drilling of this well has been scattered or lost, so that close correlation with the Coast Range section is not possible. Many beds in this section contained pearly iridescent shell fragments that suggest these fossil genera. This Cretaceous section is composed of dark-gray micaceous shale and sandstone, with some limy beds, and in places includes much carbonized plant residue.

PRE-CRETACEOUS CRYSTALLINE ROCKS

The pre-Cretaceous rocks that make up the mass of the Sierra Nevada east of the Mokelumne area comprise strata of Carboniferous and Jurassic age that were closely folded and metamorphosed in the late part of the Jurassic period. These older rocks form the higher catchment area in which most of the larger streams gather their water and from which the run-off is delivered by stream channels that commonly are deeply entrenched in the rugged surface. This run-off is effected without appreciable diversion or loss to the body of ground water, because these metamorphosed rocks are sensibly impermeable.

The strata of the Tertiary system lap over the pre-Cretaceous rocks along the western slope of the Sierra Nevada and thus limit the distribution of those rocks in the present land surface. Because material parts of the Tertiary rocks were formed by sediments derived from the disintegration and decomposition of the pre-Cretaceous rocks, it is necessary to recognize the various petrographic types and the major structural units of those older rocks as a foundation for geologic study of the overlapping Tertiary system. These features of the pre-Cretaceous rocks are reviewed briefly in following pages.

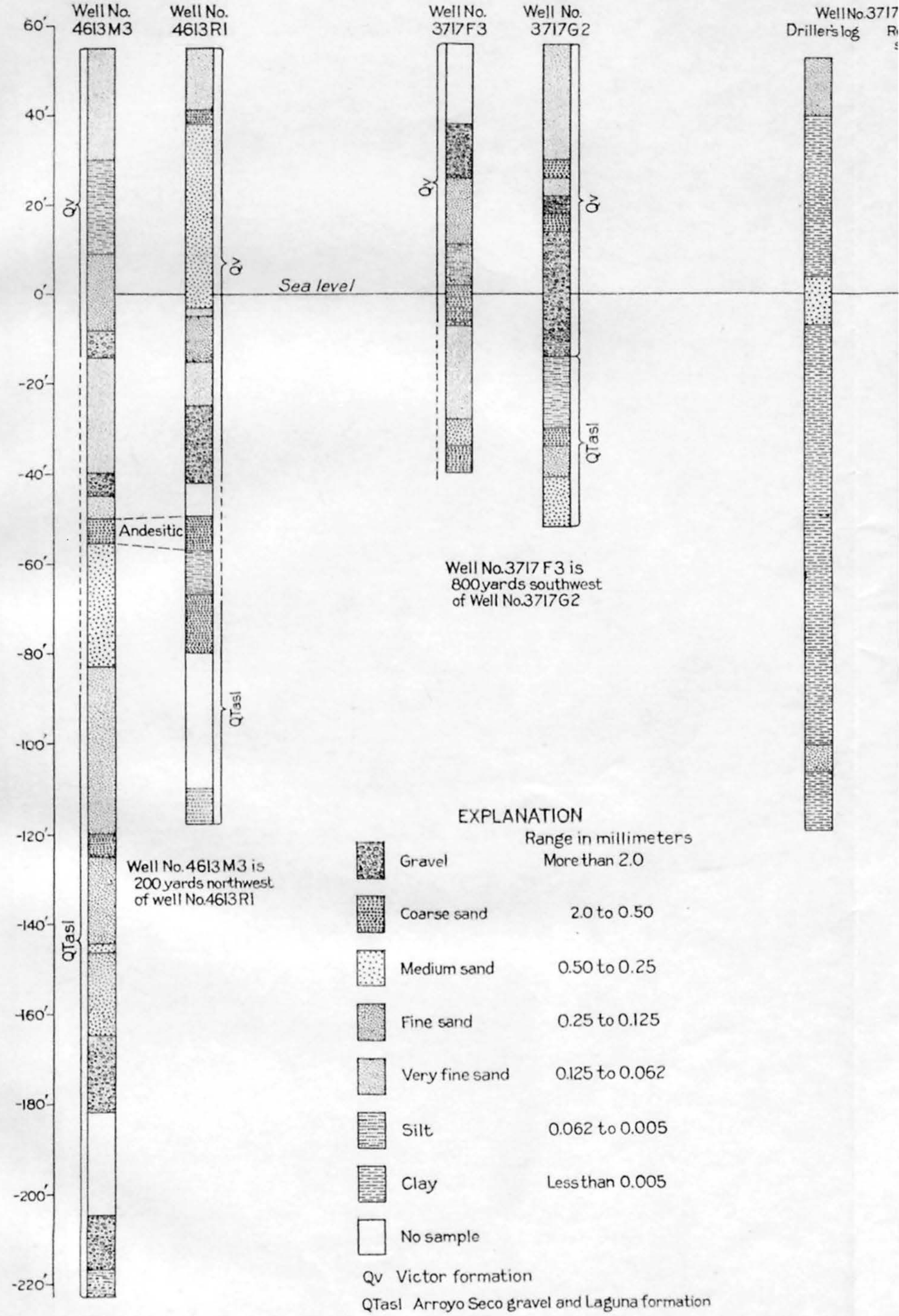
Along the western front of the Sierra Nevada block the pre-Cretaceous rocks comprise metamorphosed sedimentary beds and associated igneous rocks that are generally divided into two formations, the Calaveras formation and the Mariposa slate. The Calaveras formation is composed of metamorphosed shale, conglomerate, sandstone, limestone, and chert and is usually regarded as of Carboniferous age. The Mariposa slate is composed chiefly of slate but includes sandstone and conglomerate and is late Jurassic. The most distinctive and common feature of these two formations is their almost universal steep dip, for they have been generally compressed into isoclinal folds or faulted into nearly vertical positions. In the westernmost part of the Sierran block, where the Tertiary system laps against it, the Mariposa slate is the more extensively exposed, and its steeply dipping beds form long and essentially continuous belts that trend approximately N. 30° W. entirely across the Mokelumne area parallel to the mountain front. More than half the thickness of the formation is composed of metamorphosed volcanic rocks that are described by Turner[83] as diabase but are now popularly known as greenstone.

[83] Turner, H. W., U. S. Geol. Survey Geol. Atlas, Jackson folio (no. 11), 1894.

Stratigraphic correlation	Depth (feet)	Section	Driller's record	
Pleistocene.			Sandy gray shale, gravel in streaks.	
?			Black water sand at 241-263 feet.	A local horizon marker.
Pliocene? to Miocene (undifferentiated).			Brown sandy shale.	
			Coarse gravel. Sand, blue shale, and gravel.	
			Hard blue shale; boulders.	
	1,000			
?			Hard shells.	Lithology suggests Ione form
			Sandy shale, blue to gray.	Argillaceous sandstone at 1,3 Fine-grained well-assorted sa
			Sticky blue shale; tools stuck at 1,600 feet and circulated with oil.	
Eocene?			Black shale streaked with thin hard shells.	Soft gray shaly sandstone; ca
	2,000			Dark-gray micaceous sandsto sp., *Mytilus* sp., "*Meretrix*'
			Thin hard shells. Hard sharp conglomerate at 2,152 feet.	From 2,144 to 2,500 + feet, in
			Sand mixed with blue shale, soft but sharp.	
			2,385	
			Conglomerate.	Hard round cobbles or bould
?			2,620	
			Shale; some hard streaks.	From 2,715 to 2,732 feet, dark- carbonized plants and som From 2,792 to 2,800 feet, dark At 2,842 feet, fine dark-gray m
	3,000		2,997	
Cretaceous.			Shale streaked with lime shells (acid test).	At 3,160 feet, light-gray shale From 3,310 to 3,325 feet, coar nearly horizontal. From 3,336 to 3,357 feet, light At 3,400 feet, a well-preserve At 3,820 feet, shell fragments
			3,900	
	4,000			
			Dark-grayish sandstone, hard and soft streaks, but no shale; tools stuck at 4,060 feet and circulated with oil a second time.	From 3,890 to 4,000 feet, foran At 4,534 feet, fine gray sand f One core shows dip of about
			Hard shell at 4,577 feet.	Very dense calcareous sandst
			Hard shell at 4,678 feet	
			Bottom of hole at 4,751 feet.	
	5,000			

RECORD OF THE GILBERT NO. 1 (BARNHART NO. 1) WELL OF THE OAKDALE C

In the SE¼ sec. 3, T. 2 S., R. 10 E.; altitude of land surface 210 feet; spudded Aug.



WELL SECTIONS SHOWING THE HETEROGENEITY OF THE SEDIMENTS UNDERLYING THE VIC
PLAIN.

The greenstone masses, by reason of their superior hardness and resistance to weathering and erosion, form the most prominent exposures of the pre-Cretaceous rocks along the mountain front. Gopher Ridge and Bear Mountain are conspicuous examples of masses that have withstood baseleveling throughout the Tertiary period.

The core of the Sierra Nevada block, on the other hand, consists chiefly of plutonic rocks—granite, granodiorite, and related types. These plutonic masses were intruded into the sedimentary rocks of the Calaveras and Mariposa formations probably in late Jurassic time; their intrusion presumably marked in a general way the culmination of the Jurassic epoch of major diastrophism and the beginning of a new major cycle of erosion and deposition.

The disintegration products of the granite, greenstone, and other petrographic types of the pre-Cretaceous rocks have constituted a large part of the detritus that built up certain of the Tertiary formations. It is to that extent important for the study of the sedimentary deposits of the Mokelumne area that the general nature of these pre-Cretaceous formations should be known, but beyond that application and the fact that these rocks form the foundation on which all the Tertiary sedimentary rocks rest, the geology of the crystalline rocks need not be discussed.

GENERAL DATA FROM WELLS

SOURCES AND CLASSES OF DATA

Most of the information about the nature and composition of the post-Mehrten deposits in the California Trough section of the Mokelumne area is obtained from the records of wells drilled for water. In connection with the present investigation, driller's samples taken from 81 wells drilled in 1930 were available for study and classification. Cady [84] has described the manner of collecting these samples and has presented graphic well sections based on them, with conclusions as to the origin and character of the sediments. These samples have been reexamined by the junior writer (Thomas), and some others from the same wells have also been studied.

In addition to these samples, more than 250 well logs were furnished by the drillers. In these logs gravel, sand ("caving" and "standing"), and clay are commonly distinguished, and the more complete logs mention the color of the cuttings as they were taken from the well. In attempting correlations based on the textures distinguished in these logs, allowance must be made for incompleteness of the driller's record and for the different senses in which any particular term is used among several drillers. This is particularly necessary in reference to the poorly sorted sediments that are most common in the wells. The

[84] Cady, R. C., typewritten report supplemental to U. S. Geol. Survey Water-Supply Paper 619, pp. 109-209, 1931.

term "clay" as applied by the driller is likely to include many beds that are silty, sandy, or even gravelly, if they contain much material so fine that it remains in suspension in the drilling sludge. Comparative columnar sections of well 3717N6 based on inspection of samples by the junior writer (Thomas) and on the driller's log are presented in plate 7 to show this difference in terminology.

METHODS OF INVESTIGATION

Specimens of the granular samples were examined under the binocular microscope to discriminate any characteristics that might be used with confidence in correlating strata between wells. The characteristics that were considered are mechanical composition, assortment, roundness of grains, initial consolidation, color, and mineral composition. The standards of classification adopted for each of these six characteristics are described in subsequent paragraphs.

The size of the largest and smallest grains and of the most abundant grade in each of the granular samples was measured under the microscope by comparison with a micrometer eyepiece and the known apparent diameter of the microscope field. At the magnification used, 38 diameters, the smallest particles of the silt fraction could just be resolved as individuals. For these finer grades the size was more readily estimated by silhouetting the grains in transmitted light.

The samples of cuttings were classified in textural grades according to the standard grades discriminated by the United States Bureau of Soils. These grade terms are defined by the following table:

Standard of classification by mechanical composition

Size of particle (millimeters)	Grade term	Size of particle (millimeters)	Grade term
Greater than 5	Coarse gravel.	0.25–0.125	Fine sand.
5.0–2.0	Gravel.	0.125–0.062	Very fine sand.
2.0–1.0	Fine gravel.	0.062–0.005	Silt.
1.0–0.5	Coarse sand.	Less than 0.005	Clay.
0.5–0.25	Medium sand.		

The materials were discriminated as "well sorted", "poorly sorted", and "unsorted." "Well-sorted" material consists almost entirely of particles of one standard grade size and of the grades next larger and next smaller. "Poorly sorted" material might include particles belonging to more than five grades but with a definite maximum size of particle. "Unsorted" sediments might not show any wider range in size of particle than "poorly sorted" material, but the distribution among the several grades would be more nearly uniform.

The mineral composition was determined by visual inspection of such physical characteristics as color, cleavage, fracture, luster, hardness, and magnetic properties. For determining many of the smaller grains the binocular microscope magnifying 80 diameters was used. By transmitted light the characteristic color of such minerals as hornblende became recognizable, though grains of this mineral appear black under reflected light. More precise estimates of the percentage of the various minerals such as might afford a correlation of strata, would involve segregation of the heavy minerals and classifying them under the polarizing microscope and with immersion fluids. It was deemed impracticable to apply these criteria of classification.

CHARACTER OF THE SEDIMENTS

The samples show that the sediments penetrated in any particular well have a wide range in mechanical composition, also that individual beds are lenticular and discontinuous and generally cannot be traced more than a few hundred yards. The samples from the deepest wells show no well-marked systematic changes in texture according to increased depth below the land surface. Sand and silt are the dominant grades in all samples. On the whole the sediments become finer toward the west, but even in the Delta country most of the sediments represented are silt, and true clay is not common.

In general, the samples indicate that the sediments are poorly sorted. It is true that drillers' samples would not differentiate thick beds of unsorted sediments from alternating thin beds of different textural grades, but lumps of undisturbed sediment in the samples and exposures of the sediments in natural outcrops and in the walls of certain dug wells all indicate that poor sorting is a common feature.

Well-rounded grains are very uncommon in all the drillers' samples. Grains finer than coarse sand are almost invariably angular and subangular, though most are somewhat water-worn; many of the coarse grains of quartz, feldspar, and volcanic sand are very angular. On the other hand, the coarse andesitic sand grains are commonly rather well rounded. The pebbles and cobbles are generally well rounded and usually water-worn. Because of this relation to size of grains, roundness is not a distinctive characteristic apart from general mechanical composition.

The beds that are appreciably consolidated are for the most part those that contain a large proportion of silt and clay. Other cements are uncommon. The initial degree of consolidation is commonly not clear, but it seems to be definitely linked with an abundance of the finer particles and therefore dependent upon general mechanical composition. The clean, well-sorted sands are usually loose; such are the "caving" sands that make well construction costly because casing is required.

Most of the samples are of a nondescript gray to brown color, not so distinctive as to serve as a criterion in correlation of particular beds from well to well. There is a general gradation from reddish-brown sediments adjacent to the foothills to greenish-gray sediments beneath the tidal flats, but the few beds of medium and coarse sand in the Delta country are yellow to brown, and silt in the Clements area is commonly gray; this difference in color may be due largely to the increasing proportion of fine sediments toward the west.

Certain beds are distinctive in color. Thick sections of dark-gray sand are penetrated by wells 283E1, 473N1, 4712A1, 4822B2, 4822B3, 4827H1, and 5725R1, in the district east of Lodi. The color of these beds is due to an abundance of andesitic grains. Many beds of gravel are dark, owing to numerous pebbles of greenstone and basic igneous members of the pre-Cretaceous rocks. In the western part of the area many of the beds of silt and clay are dark gray, owing largely to organic matter.

Quartz is the most abundant mineral in the post-Mehrten sediments; commonly feldspar, very little decomposed, is second in abundance. These two are plentiful in all the samples and together compose the greater part of most. Mica, specially biotite, appears in nearly all the samples and is so abundant in a few samples as to be conspicuous. Fragments of the igneous and metamorphosed members of the pre-Cretaceous rocks, usually water-worn, are plentiful in most beds of gravel and coarse sand. The abundance of feldspar, mica, and particles of the easily decomposed basic rocks indicates that the sediments originated by mechanical disintegration with little chemical decomposition.

Hornblende, magnetite, and andesite are common accessory minerals and in some samples are so abundant that they color the whole perceptibly. In the samples from a few wells these dark minerals are more abundant than the quartz and feldspar, particularly in the seven wells that penetrate thick sections of andesitic grains. The beds of coarse and medium sand in the Mehrten formation comprise the constituent minerals of the parent andesite, which is largely disintegrated. Most of the dark grains in these beds are hornblende, either in angular cleavage fragments or in water-worn particles. There are, however, some grains to which enough of the fine-grained andesitic matrix clings to confirm the suggested origin of the hornblende.

Calcium carbonate seems not to occur in the sediments, either as grains or as a secondary cement. Its absence was confirmed by chemical tests.

Columnar sections based upon such classification of the samples permit few satisfactory correlations of the beds, even across relatively short distances. For example, plate 7 compares the columnar sections of two wells (4613M3 and 4613R1) only 200 yards apart. These wells are exceptional in the fact that one positive correlation is possible. Two other wells (3717F3 and 3717G2) 800 yards apart seem not to have a single common bed.

Several wells penetrate the hypothetical maximum thickness of the Victor formation, and many continue several hundred feet into the underlying post-Mehrten formations. The sediments encountered at these greater depths are very similar in both mechanical and mineral composition and in all other characteristics to those at shallow depths, and they furnish no suitable basis for delimiting the several formations encountered—the Victor, Arroyo Seco, and Laguna formations. Great variations in mechanical composition occur throughout these well sections and are far too numerous to be used as bases for stratigraphic boundaries. Neither does the degree of weathering, as shown by the color of the sediments, seem to offer any rational basis for such limits.

On the other hand, the Mehrten formation and the formations that underlie it have distinctive lithologic characters that can be recognized in the samples of cuttings from wells.

The beds of the Mehrten formation may be identified readily by the predominance of grains derived from andesite. However, beds that are altogether like those of the Mehrten formation in mineral composition also occur in the overlying formations, as is indicated by samples so shallow that they must have been taken high above the projected top of the Mehrten formation (pl. 4). Thus, in well 4719B4, andesitic sand is encountered between the depths of 320 and 357 feet below the land surface, whereas the top of the Mehrten formation, on the assumption that the Sierra Nevada block has been tilted westward at least 80 feet in a mile since the Miocene epoch (p. 26), can scarcely be less than 650 feet below the surface. In well 4722Q5 beds of andesitic sand and gravel that extend from 224 to 249 feet beneath the land surface are at least 250 feet above the projected top of the Mehrten formation.

Two wells drilled for oil (4712A1 and 7828L1) penetrate both the Mehrten formation and the underlying formations. In the samples from these wells the presence of pumice and the absence of andesitic material indicate the Valley Springs formation; the occurrence of anauxite is diagnostic of the Ione formation, and the presence of nonvolcanic quartz sand and of carbonaceous beds is suggestive of that formation.

SELECTED RECORDS OF WELLS IN THE MOKELUMNE AREA

From the 81 wells that afforded drillers' samples, the records of 18 wells have been selected to represent the central part of the Mokelumne area. With the exception of 7828L1, these records are based on the classification of the samples by the junior writer (Thomas). All the wells are on the Victor plain unless otherwise indicated. Drillers' records for other typical wells have been presented by Stearns.[85]

[85] Stearns, H. T., Robinson, T. W., and Taylor, G. H., Geology and water resources of the Mokelumne area, California: U. S. Geol. Survey Water-Supply Paper 619, pp. 276–288, 1930.

Records of wells in central part of Mokelumne area

279Q1. 1½ miles west of Waterloo. D. Podesto, owner. Approximate altitude, 45 feet.

	Thickness (feet)	Depth (feet)
Victor formation: Fine sand, black	3	3
Unclassified:		
Silt, light gray; some sand	97	100
Coarse sand and gravel	20	120
Sand, yellow, unsorted; some silt and pebbles	20	140
Gravel and sand, medium and coarse	10	150
Arroyo Seco and Laguna formations:		
Silt, light gray; some sand	50	200
Sand, medium and fine, yellowish red	8	208
Silt, very light gray	12	220
Coarse sand, dark gray	5	225

283E1. 2 miles north of Linden, at edge of Victor Plain. G. Messick, owner. Approximate altitude 105 feet.

	Thickness (feet)	Depth (feet)
No sample	35	35
Laguna formation:		
Coarse gravel, matrix of fine sand	15	50
Sand, coarse to very fine, red brown	3	53
Coarse sand, gray	1	54
Clay, gray; some silt and fine sand	12	66
Sand, medium and fine, brown with some silt	10	76
Coarse sand and gravel, dark gray	25	101
Coarse gravel and sand	14	115
Fine sand, light gray, well sorted	12	127
Clay and silt, gray	3	130
Silt, dark gray, with few pebbles	50	180
Mehrten formation:		
Coarse sand and gravel, dark gray (much of sand derived from andesite)	16	196

3612R3. 1½ miles south of Lodi. Lodi Academy, owner. Approximate altitude 49 feet.

	Thickness (feet)	Depth (feet)
Victor formation:		
Fine sand, dark gray	8	8
Very fine sand, buff	16	24
Coarse sand, gray	10	34
Silt, white	3	37
Coarse sand, yellow	17	54
Sand, coarse to fine, poorly sorted	5	59
Sand, fine to coarse, reddish, and silt	11	70
Fine sand, yellow	1	71
Silt, well sorted, white	4	75
Fine sand with some larger grains, yellow	12	87
Unclassified:		
Silt, well-sorted, white	3	90
Sand, fine to coarse, brown	6	96
Fine sand, well-sorted	9	105
Coarse sand, some gravel, and fine sand	5	110
Medium sand, yellow-brown	4	114
Sand, fine to coarse, and silt, buff	5	119
Arroyo Seco and Laguna formations:		
Clay, light gray	6	125
Very fine sand and silt, gray	2	127
Fine sand, yellow	11	138
Coarse sand, yellow	12	150
Gravel and coarse sand	5	155
Very fine sand, light gray	5	160
Fine sand, yellow	20	180
Gravel and coarse sand	5	185
Coarse gravel	2	187
Very fine sand and silt	3	190
Fine sand, poorly sorted, orange	15	205
Sand, fine to coarse, poorly sorted, dark brown	5	210
Silt, light cream-colored	22	232
Medium sand, poorly sorted	16	248
Coarse sand, yellow	6	254

Records of wells in central part of Mokelumne area—Continued

3635Q1. 3½ miles south of Lodi. L. McLung, owner. Approximate altitude 31 feet.

	Thickness (feet)	Depth (feet)
Victor formation:		
Silt, sandy, black	2	2
No sample	13	15
Fine sand, poorly sorted, gray	20	35
Clay, white	6	41
Very fine sand, gray; much silt	19	60
Sand, fine to very fine, buff	10	70
Sand, medium to fine, buff	4	74
Unclassified:		
Very fine sand and silt, light gray	26	100
Very fine sand, buff; many larger grains	15	115
Silt, sandy, brown	15	130
Sand, coarse to fine, gray	4	134
Clay, light gray	2	136
Sand, coarse to fine, gray	14	150
Coarse sand, buff	5	155

379B3. 3 miles east of Lodi. Schiebelhut, owner. Approximate altitude 67 feet.

	Thickness (feet)	Depth (feet)
Victor formation:		
Soil, dark gray	2	2
Coarse sand, fairly well-sorted	13	15
Sand, silt, and gravel, unsorted	28	43
Very fine sand	5	48
Medium sand, poorly sorted	8	56
Silt, yellow	2	58
Silt, sandy	5	63
Coarse sand; some gravel	12	75
Arroyo Seco and Laguna formations:		
Silt, with few sand grains	9	84
Fine gravel	28	112
Fine sand to silt, red	11	123
Very fine sand and silt	12	135
Medium sand, poorly sorted	10	145
No sample	5	150
Very fine sand and silt, orange	75	225
Fine sand; much silt and very fine sand	10	235
Silt, well-sorted	10	245
Gravel; some sand	10	255

3710K4. 4 miles east of Lodi, 6.5 feet west of well 3710K3. E. Pressler, owner. Observation well drilled by U. S. Geological Survey. Altitude 72.3 feet.

	Thickness (feet)	Depth (feet)
Victor formation:		
Sand, coarse to very fine, and silt, buff	8	8
Silt and very fine sand, brown to gray	3	11
Very fine sand, poorly sorted	4	15
Sand, coarse to fine, orange	3	18
Sand, coarse to very fine, grayish brown	4	22
Sand, coarse to very fine, and silt, with some pebbles	13	35
Coarse sand, with unsorted matrix of sand and silt	2	37
Arroyo Seco and Laguna formations:		
Very fine sand and silt, white to buff	9	46
Silt and very fine sand, light buff	11	57
Fine sand, light buff	7	64
Sand, fine and very fine, white	2	66
Sand, unsorted, gray	8	74
Very fine sand, light brown, with some larger grains	9	83
Sand, coarse to fine, light brown	3	86
Gravel to medium sand, light buff	11	97
Coarse gravel and sand	8	105
Coarse sand and fine gravel, buff	12	117
Coarse gravel, sand, and silt, reddish brown	9	126

453E4. Thornton. J. Thornton, owner. Approximate altitude 10 feet.

	Thickness (feet)	Depth (feet)
Victor formation:		
Soil, silty, dark gray	2	2
Very fine sand	4	6
Coarse sand, not well sorted	64	70
Gravel, with sand	7	77
Silt, greenish gray, with some pebbles and sand grains	43	120
Unclassified:		
Silt, sandy, greenish gray	91	211
No sample	17	228
Medium sand, greenish gray	6	234

Records of wells in central part of Mokelumne area—Continued

4613M3. 1½ miles northeast of Acampo. Van Valkenburg, owner. Approximate altitude 56 feet.

	Thickness (feet)	Depth (feet)
Victor formation:		
Very fine sand, brown	25	25
Silt, well sorted, light buff	10	35
Silt, well sorted, white	11	46
Fine sand, light brown	17	63
Gravel, silt, and sand, light brown	6	69
Unclassified:		
Very fine sand, well sorted	26	95
Coarse gravel, sand, and silt	5	100
Very fine sand, very light gray	5	105
Coarse sand, well sorted, chiefly derived from andesite	5	110
Arroyo Seco and Laguna formations:		
Fine sand, light buff	28	138
Very fine sand, well sorted, gray	37	175
Coarse sand, light gray	5	180
Very fine sand, light gray, well sorted	40	220
Gravel, silt, and sand	17	237
No sample	23	260
Gravel, silt, and sand	12	272
Silt, light gray, with few pebbles	6	278

4626J2. 1 mile northeast of Woodbridge. C. Rutledge, owner. Approximate altitude 44 feet.

	Thickness (feet)	Depth (feet)
No sample	103	103
Unclassified:		
Coarse sand, well sorted	24	127
Very fine sand, poorly sorted	23	150
Arroyo Seco and Laguna formations:		
Coarse gravel and cobbles; some sand	13	163
Fine sand, greenish gray; some silt	33	196
Medium sand, light gray, well sorted	2	198
Very fine sand, poorly sorted, gray	44	242
Fine sand, greenish gray; some coarse sand	62	304
Gravel, sand, and silt	3	307
Very fine sand, greenish gray; some coarse sand	10	317
Sand and gravel; some silt	7	324
Very fine sand, poorly sorted	3	327
Fine sand, greenish gray; some silt	16	343
Sand, coarse and medium, greenish gray	8	351
Silt, light gray; some sand	19	370
Sand, coarse to fine, light-colored	5	375
Very fine sand and silt; some coarse sand	7	382
Coarse sand; some fine sand and silt	6	388
Very fine sand; some pebbles	13	401
Silt, sandy	18	419
Coarse sand, clay matrix; some of sand derived from andesite	16	435
Fine sand, greenish gray; some pumice	57	492
Coarse sand, greenish gray.		

473N1. 5 miles northwest of Lockeford. H. Hokinsingh, owner. Approximate altitude 82 feet.

	Thickness (feet)	Depth (feet)
Victor formation:		
Very fine sand, poorly sorted, yellow	7	7
Silt, well sorted, light yellow	10	17
Fine sand, yellow	24	41
Unclassified:		
Coarse sand, well sorted, light-colored	25	66
Coarse gravel and cobbles, very fine sand matrix	2	68
Arroyo Seco and Laguna formations:		
Silt, white	30	98
Silt, yellow, poorly sorted	6	104
Fine sand, silty, light gray	6	110
Fine sand, silty and pebbly	48	158
No sample	12	170
Sand, unsorted, chiefly very fine, with some silt and pebbles	44	214
Clay and silt, gray	38	252
No sample	25	277
Medium sand, with some silt and pebbles	38	315
Medium sand poorly sorted; some of sand possibly derived from andesite	14	339
Silt; some sand and gravel	4	343
Very fine sand and some coarse sand; in part from andesite	4	347
Silt, white, well sorted	15	362
Silt, sandy, very light gray	2	364
Sand, unsorted, with some pumice; minor part of sand from andesite	1	365
Very fine sand, gray; some coarser sand; minor part of sand from andesite	6	371
Coarse sand, unsorted, matrix of silt and fine sand	38	409
Medium sand, matrix of silt and fine sand	3	412

Records of wells in central part of Mokelumne area—Continued

473N1. 5 miles northwest of Lockeford. H. Hokinsingh, owner. Approximate altitude 82 feet.—Con.

	Thickness (feet)	Depth (feet)
Unclassified:		
Coarse sand, clay matrix; much of sand from andesite	5	417
Coarse sand and gravel; in part from andesite	16	433
Very fine sand, yellow	17	450
Coarse sand and gravel, mostly from andesite	3	453
Very fine sand, well sorted, gray	11	464
Very fine sand, reddish; some pumice	7	471
Mehrten formation:		
Cobbles and gravel, mostly from andesite	4	475
Coarse sand and gravel, mostly from andesite	2	477
Fine sand, poorly sorted, mostly from andesite	23	500
Silt, with some pumice	6	506
Very fine sand, reddish brown	4	510
Coarse sand or fine breccia, almost entirely from andesite	5	515
Fine sand, in part rhyolitic	10	525
Very fine sand, yellow	30	555
Medium sand, largely from andesite; some pebbles	10	565
Silt and very fine sand, largely rhyolitic	5	570
Very fine sand; some pumice; part of sand from andesite	5	575

4712A1 (Elliott oil well). 4 miles north of Lockeford. Pacific Petroleum Producers, owner. Approximate altitude 103 feet. The driller's record, with some comments on the character of the samples, is reported by Stearns,[85a] but the record given below is based in part on samples of the cuttings and differs somewhat from that of Stearns. However, the samples furnish a very incomplete record, which has been completed by addition of notes from the driller's record, in quotation marks.

Victor formation:		
Silt and very fine to medium sand	3	3
"Sandy brown shale"	6	9
"Brown sandstone"	7	16
Unclassified:		
Silt; some sand grains as much as 2 millimeters in diameter	29	45
"Water sand"	8	53
Silt and clay, gray	12	65
"Sand and gravel"	10	75
Laguna formation:		
"Light-brown clay"	25	100
"Dark-brown shale"	15	115
"Brown conglomerate"	65	180
Silt; some very fine to medium sand	45	225
"Gray shale"	20	245
Clay and silt; some sand	25	270
"Coarse gravel"	5	275
"Gray clay"	55	330
"Brown clay; some zones of sandy clay"	145	475
Mehrten formation:		
Coarse sand, black, andesitic; some pebbles as much as 1 inch in diameter	10	485
"Gray clay"	32	517
"Water sand"	18	535
"Brown sandy clay"	6	541
Sand, poorly sorted, chiefly medium and coarse; fragments of rhyolite and andesite	12	553
"Dark-brown clay"; silt in lower 5 feet	32	585
Coarse sand and fine gravel; chiefly pumice	11	596
Silt and clay, light brown	18	614
Sand, poorly sorted, chiefly coarse, andesitic	6	620
Silt and clay, light brown	6	626
Coarse sand, andesitic	14	640
"Light-brown shale"	16	656
Coarse sand and fine gravel, poorly sorted, andesitic	7	663
Coarse gravel, andesitic; some pumice; some silt	12	675
"Light tan-colored sandy shale"	15	690
Silt, possibly a rhyolitic tuff	18	708
Sand, poorly sorted, chiefly coarse; rhyolite dominant	12	720
"Light-gray clay"	20	740
Sand, poorly sorted, andesitic, in matrix of clay	5	745
Alternating fine and coarse sand with some gravel and breccia, andesitic, in beds 5 to 20 feet thick	45	790
"Gray shale"	2	792
Coarse sand and fine gravel, andesitic	18	810
Dense rhyolitic tuff; some grains derived from andesite	12	822
Sand, poorly sorted, coarser at base, chiefly andesitic, but many rhyolite fragments	36	858
Dense rhyolitic tuff, silicified at top, pink, numerous dark grains 0.5 millimeter or less in diameter	12	870
Sand, poorly sorted, chiefly fine and medium, andesitic; some pumice	25	895

[85a] Stearns, H. T., Robinson, T. W., and Taylor, G. H., The geology and water resources of the Mokelumne area, California: U. S. Geol. Survey Water-Supply Paper 619, pp. 278–280, 1930.

Records of wells in central part of Mokelumne area—Continued

4712A1. 4 miles north of Lockeford. Pacific Petroleum Producers, owner. Approximate altitude 103 feet—Continued

	Thickness (feet)	Depth (feet)
Mehrten formatiom—Continued.		
Dense rhyolitic tuff; some andesite	5	900
Sand, fine and medium; some silt; andesitic	26	926
Clay, gray, with some sand	6	932
Sand, medium to very coarse, andesitic	33	965
Fine sand, andesitic, with large fragments of pumice	6	971
"Gray clay"	7	978
Very coarse sand, andesitic; also much rhyolite	13	991
Valley Springs formation:		
Sand, grading from fine to coarse; silicified at top, and with a 1-foot "gray clay" parting	27	1,018
"Gray sandy clay"	17	1,035
Coarse sand, andesitic; many large fragments of rhyolite tuff	2	1,037
Rhyolitic tuff, numerous angular fragments of andesite as much as 2 millimeters in diameter	63	1,100
Coarse sand and fine gravel, andesitic	1	1,101
Rhyolitic tuff with much andesite as much as 2 millimeters in diameter	18	1,119
Rhyolitic tuff; many large fragments of acid pumice	24	1,143
Rhyolitic tuff; much coarse sand, andesitic	2	1,145
"White sticky clay"	25	1,170
Rhyolitic tuff, with some andesitic fragments as much as 2 millimeters in diameter	28	1,198
"Soft sticky clay"	5	1,203
one formation:		
Sand, poorly sorted, chiefly medium, light gray; dominantly angular quartz and feldspar	7	1,210
"Sticky white clay"	9	1,219
Sand, poorly sorted, same as sample at 1,203–1,210 feet	1	1,220
Clay, light gray	11	1,231
"Sticky blue shale"	15	1,246
Coarse sand, light buff, of angular quartz and feldspar	7	1,253
Silt and clay, greenish gray	7	1,260
Coarse sand, same as sample at 1,246–1,253 feet	5	1,265
"Blue sticky shale"	35	1,300
"Gray sand"	1	1,301
"Blue shale"	11	1,312
"Sand"	26	1,338
Sand, medium and fine; chiefly quartz, with much mica and hornblende at top	3	1,341
Coarse sand, of quartz and fragments of granite and metamorphic rocks	11	1,352
Silt, pale green, with angular rock fragments as much as 1 millimeter in diameter	5	1,357
Sand, fine to coarse, of angular quartz	2	1,359
"Blue shale"	29	1,388
Sandstone, buff	6	1,394
"Blue shale"	9	1,403
Sand, fine and medium	27	1,430
Clay and silt	10	1,440
Coarse sand, well sorted, chiefly quartz	5	1,445
"Sticky pale-green shale"	25	1,470
"Blue shale, with some sandy beds"	57	1,527
Medium sand, well sorted, or angular quartz	12	1,539
"Blue shale"	1	1,540
"Water sand"	10	1,550
"Light-blue shale"	5	1,555
"Dark sandy blue shale"	35	1,590
Clay and silt; many large rock fragments	11	1,601
Coal and dark-gray carbonaceous shale with crystals of gypsum	6	1,607
Silt and clay, gray to green	31	1,638
"Black shale"	2	1,640
"Sticky black shale" and green clay containing carbonaceous matter at 1,654–1,658 feet	35	1,675
Silt, with much sand; some grains as much as 2 millimeters in diameter	7	1,682
"Blue sandy shale"	2	1,684
"Hard lime shell", gray fine sandstone at 1,690–1,691 feet	9	1,693
"Light-gray sandy shale"	55	1,748
Medium sand, well sorted, white; of clear quartz	17	1,765
"Blue shale"	3	1,768
Gravel and sand, coarse and medium	11	1,779
Strata of middle Eocene age, not named:		
"Dark shale", greenish-gray clay rock	51	1,830
"Dark shale, sandy in part"	32	1,862
Silt, dark gray, with some quartz gains as much as 0.4 millimeter in diameter	22	1,884
"Black lime shell"	1	1,885
Silt, dark gray, with some flakes of carbonaceous matter	34	1,919
Sand, poorly sorted chiefly medium, gray; of angular quartz (sample contains a fragment of a ribbed pelecypod)	8	1,927
"Black shale"	35	1,962
Sand, poorly sorted, chiefly medium; of angular quartz; sample contains many fragments of pelecypods	13	1,975

Records of wells in central part of Mokelumne area—Continued

4719B4. 1½ miles northeast of Acampo, 500 yards southeast of well 4718N3. S. Sanguinetti, owner. Approximate altitude 60 feet.

	Thickness (feet)	Depth (feet)
No sample	260	260
Arroyo Seco and Laguna formations:		
Sand, unsorted but chiefly very fine, and silt, yellow	25	285
Gravel and sand, poorly sorted, dark gray	13	298
Clay and silt, brownish gray	2	300
Sand, unsorted, chiefly fine; silt, brown	12	312
Coarse sand; some gravel and fine sand and silt; derived in part from andesite	4	316
No sample	4	320
Medium and fine sand, dark gray; derived in part from andesite	15	335
Coarse sand, well sorted; much of sand derived from andesite	22	357

4722Q4. 2¾ miles west of Lockeford. A. Eddlemon, owner. Observation well drilled by U. S. Geological Survey. Altitude 83.6 feet.

	Thickness (feet)	Depth (feet)
Victor formation:		
Very fine sand, brownish gray	3	3
Fine sand to silt, yellowish gray	4	7
Silt, sandy, yellowish gray	2	9
Medium sand, yellow, some silt and fine sand	7	16
Very fine sand, buff-colored, some coarser sand	3	19
Fine sand, well sorted	6	25
Silt, sandy	3	28
Unclassified:		
Coarse sand and gravel	22	50
Gravel and sand	1	51

4722Q5. 2¾ miles west of Lockeford, 4 feet south of well 4722Q4. A. Eddlemon, owner. Observation well drilled by U. S. Geological Survey. Altitude 84.2 feet.

	Thickness (feet)	Depth (feet)
No sample	51	51
Unclassified:		
Coarse sand and gravel	6	57
Arroyo Seco and Laguna formations:		
Silt, yellow	3	60
Fine sand, well sorted	3	63
Sand, medium and coarse, well sorted	12	75
Coarse sand and gravel	4	79
Silt, yellow; some pebbles	5	84
Silt, sandy, yellow; some sand	12	96
Very fine sand and silt, orange	3	99
Gravel and coarse sand	9	108
Coarse sand, matrix of silt to fine sand	6	114
Very fine sand and silt; some pebbles	19	133
Medium sand; some fine sand to silt	14	147
Sand, fine and medium, and silt	13	160
Medium sand, well sorted	1	161
Silt, fairly well sorted	8	169
Medium sand, yellow; some silt to fine sand	24	193
Silt and very fine sand	4	197
Medium sand, not well sorted	3	200
Silt, fairly well sorted	24	224
Coarse sand and gravel; derived in part from andesite	25	249
Medium sand, poorly sorted; some pumice	11	260
Silt, light-colored; some pumice	6	266

4827R1. 1.8 miles south of Clements, on remnant of Arroyo Seco pediment. F. Ather, owner. Approximate altitude 197 feet.

	Thickness (feet)	Depth (feet)
Arroyo Seco gravel and Laguna formation:		
Coarse gravel, matrix of sand and silt	75	75
Silt to very fine sand, pebbly	25	100
Unclassified:		
Coarse sand and gravel, derived chiefly from andesite	5	105
Silt to very fine sand, well sorted	15	120
Silt, somewhat sandy	7	127
Mehrten formation:		
Coarse angular sand, matrix of silt; derived chiefly from andesite and also contains pumice	38	165
Very fine sand to silt, derived in part from andesite and pumice	------------	---------

Records of wells in central part of Mokelumne area—Continued

5725R1. 6 miles north of Lockeford, on dissected Arroyo Seco pediment. M. Vargas, owner. Altitude 106.1 feet.

	Thickness (feet)	Depth (feet)
Laguna formation:		
Sand, coarse to fine, and silt, reddish brown	4	4
No sample	13	17
Sand, coarse to fine, and fine gravel	15	32
Gravel and sand, coarse to fine	11	43
Silt to very fine sand, gray, with some pebbles	26	69
Silt, brown, well sorted	15	84
Coarse sand and gravel	6	90
Silt, with some pebbles	19	109
Silt, sandy	6	115
No sample	10	125
Silt, sandy	13	138
Sand, coarse to fine, and silt	4	142
No sample	6	148
Silt, light gray, with some pebbles	9	157
Fine sand, with some gravel; some pumice	18	175
No sample	10	185
Gravel, matrix of fine sand to silt	9	194
Fine sand to silt	11	205
Unclassified:		
Gravel and sand, unsorted, derived in part from andesite; matrix of silt, yellow	15	220
No sample	20	240
Fine sand, yellow; few larger grains	5	245
Coarse sand, largely derived from andesite; also magnetite in part	5	250
Silt; some sand and larger fragments	25	275
No sample	4	279
Mehrten formation:		
Fine gravel, largely derived from andesite; matrix of silt and sand	6	285
Sand, coarse to fine, largely derived from andesite	8	293
Silt, some sand and gravel, derived in part from andesite	11	304
Coarse sand and fine gravel; some sand and silt, gray; chiefly derived from andesite	18	322
Sand, coarse and medium, largely derived from andesite, dark gray	3	325
Gravel and sand, coarse and medium, chiefly derived from andesite, dark gray	5	330
Clay, white, and sand, yellow; many fragments of andesite	5	335
Sand, medium and fine, well sorted, gray, derived in part from andesite	5	340
Fine sand to silt, yellow	5	345
Sand, medium and coarse, well sorted, largely derived from andesite	5	350
Sand, fine and medium, poorly sorted, in part derived from andesite; some silt and clay	19	369
Sand, fine to coarse; some silt; light buff	61	430
Silt and sand, very fine to medium; some fragments of pumice and a very few of andesite	3	433
Sand, medium and coarse; many large fragments of pumice and some grains of andesite	2	435
No sample	5	440
Silt and sand, reddish brown	7	447

5728A2. 4½ miles east of Galt, G. Bechthold, owner. Altitude 78.0 feet.

	Thickness (feet)	Depth (feet)
No sample	205	205
Laguna formation:		
Silt, gray, with some pebbles	8	213
Silt, well sorted	7	220
Gravel, matrix of fine sand to silt	20	240
Silt, gritty	12	252
Very fine sand; some coarser grains	6	258
Silt; some pebbles	4	262
Very fine sand, with some coarse sand and gravel	8	270
Fine sand, with some silt	8	278
Medium sand; some gravel	3	281
Silt and sand, fine to coarse, dark gray	4	285
Coarse sand, greenish gray	7	292
Silt, gray, with some sand and pebbles	3	295
Very fine sand, some coarse sand, and pebbles	21	316
Sand, coarse to very fine	4	320
Very fine sand; some pebbles	11	331
Medium sand, some silt, and pebbles	17	348
Silt, with some coarser sand	2	350
Coarse sand, with some silt	18	368
Silt, with some sand grains	29	397
Very fine sand and silt	13	410
Gravel; some sand and silt	---------	---------

Records of wells in central part of Mokelumne area—Continued

7828L1 (driller's record). 5 miles west of Carbondale, on dissected Arroyo Seco pediment. Allied Petroleum Corporation, owner (Meiss No. 1). Approximate altitude 175 feet.

	Thickness (feet)	Depth (feet)
Mehrten formation:		
Sand and boulders	200	200
Unclassified:		
Sand and shale	70	270
Sand and blue shale	53	323
Valley Springs formation:		
Shale, blue; streak of hard sand	261	584
Shale; streak of hard sand, with sea shells (fragments of pumice?)	84	668
Ione formation:		
Shell (a hard-drilling layer) and hard sand	4	672
Sand, shale, shell	16	688
Clay, red	42	830
Shale, blue	40	870
Sand	9	879
Shell	2	881
Clay, gray	4	885
Shale, blue	15	900
Clay, gray	40	940
Sand and clay, gray	20	960
Sand and shale	55	1,015
Shell	1	1,016
Sand, hard	9	1,025
Shale, hard sand (quartz-anauxite)	73	1,098
Pre-Cretaceous rocks:		
Granite (granodiorite, fresh, hard)	116	1,214

GROUND-WATER HYDROLOGY OF THE MOKELUMNE AREA

By A. M. Piper, H. E. Thomas, and T. W. Robinson

SPECIFIC YIELD AND SPECIFIC RETENTION OF WATER-BEARING MATERIALS [86]

METHODS OF DETERMINATION

Two methods have been used to determine the specific yield of typical water-bearing materials of the Mokelumne area—(1) measuring the volume of material saturated and unwatered by alternate addition and withdrawal of measured volumes of water from columns of undisturbed soil; and (2) determining the difference between the porosity and the specific retention of samples of undisturbed material after drainage for periods as long as 390 days. These are hereinafter termed, respectively, the volumetric method and the drainage method.

Determinations of specific yield by the volumetric method were made from 1927 to 1932, and early results were reported by Stearns, Robinson, and Taylor.[87] The general technique is that developed and

[86] The specific yield of a pervious material is the ratio of (1) the volume of water which, after being saturated, it will yield by gravity to (2) its own volume; the specific retention is the ratio of (1) the complementary volume of water that it will retain against the pull of gravity to (2) its own volume. (See Meinzer, O. E., Outline of ground-water hydrology: U. S. Geol. Survey Water-Supply Paper 494, pp. 28–29, 1923.) Obviously, the sum of specific yield and specific retention for a particular material is equal to its porosity, provided the pore spaces are continuous.

[87] Stearns, H. T., Robinson, T. W., and Taylor, G. H., Geology and water resources of the Mokelumne area, California: U. S. Geol. Survey Water-Supply Paper 619, pp. 151–172, 1930; typoscript report supplemental to Water-Supply Paper 619, pp. 149–164, Dec. 10, 1930.

described by White.[88] In brief, (1) a pit was dug at the location selected for sampling (see p. 104); (2) a cylinder 18 inches in diameter and 36 to 42 inches long, of 16-gage galvanized steel, was driven vertically into the pervious material below the bottom of the pit; (3) the cylinder was exposed by deepening the pit; (4) a base plate was jacked beneath the cylinder and sealed to it in order to confine the undisturbed cylindrical column; (5) an artificial water table was established at a high stage in the column; and (6) measured volumes of water were withdrawn and added alternately, the stage of the artificial water table being observed after each addition or withdrawal until and after equilibrium appeared to have been reached. This report summarizes the experimental data from all tests except those made in 1927 on two cylinders; for those, the intervals between additions and withdrawals of water (15 minutes to 53 hours) were too short to allow the artificial water table to reach equilibrium.

Several noteworthy modifications in technique have been made or have suggested themselves for future tests by this method. (1) The 42-inch cylinders were introduced in 1928 to provide greater space to accommodate the capillary fringe, although even that length may not have been adequate for the materials of finer texture. (2) In the later work, once the cylinder had been driven, the sample was confined temporarily between a top plate and a base plate, which were bolted together with tie rods; then the whole was inverted, the base plate was removed, the exposed end of the sample was allowed to dry, the permanent base plate was soldered in place, and, finally, the sample was returned to its normal position for the tests. This procedure obviated leakage such as developed in a few cylinders whose base plates were soldered while the sample was still moist and upright. (3) Early tests were made without removing the cylinders from their pits, but that practice proved unsatisfactory because a rather wide range in temperature induced correspondingly large water-level fluctuations in the cylinders, also because unmeasured additions of water resulted occasionally from rain. Later all cylinders were transported to Lodi and stored in a single room; also each was insulated by surrounding it with a layer of straw about 7 inches thick. Finally, in 1931, the cylinders were removed to a covered observation pit on the outskirts of Lodi. As the roof of the pit was covered with a layer of earth about 10 inches thick, the natural range in temperature was suppressed to about 2° F. a day and to about 30° F. during the year. Even so, the water levels in the test cylinders responded appreciably to changes in temperature; to achieve a moderately narrow limit of precision by this method, the cylinders would need be stored in a room

[88] White, W. N., Recent work on the discharge method of estimating ground-water supplies [abstract]: Washington Acad. Sci. Jour., vol. 17, pp. 238–240, 1927; A method of estimating ground-water supplies based on discharge by plants and evaporation from soil: U. S. Geol. Survey Water-Supply Paper 659, pp. 74–76. 1932.

where the temperature could be kept constant. (4) Temperatures in the cylinders were measured approximately by a pocket thermometer lowered into the central observation well and withdrawn for reading, or by a water-tank thermometer tapped permanently through the wall of the test cylinder. Probably neither procedure indicated the mean temperature of the whole soil column. (5) Evaporation from the cylinders was minimized by sealing the top of each with tar paper and tar, the seal being perforated with a few holes about 0.1 inch in diameter so that air could pass in and out as water was withdrawn or added. Also, the atmosphere in the observation pit was kept approximately saturated with water vapor by maintaining two open vessels filled with water. (6) At first, two 1½-inch holes were bored the full length of each confined soil column about 4 inches from the enclosing cylinder and at diametrically opposite points. These holes were then cased with nickel-plated brass tubes, of which one was perforated its full length except the uppermost 6 inches and the other was perforated only for 6 inches at its lower end. The latter tube formed the well through which water was added to the soil column or withdrawn from it; the former was intended primarily as an observation well. To determine the water-table stage within the soil column, the depth to water in both tubes was measured with a steel tape from the lower edge of a spirit level that spanned the cylinder, the duplicate measurements indicating whether the water table was level. Later, only one hole was bored in each cylinder, and the casing of that hole was perforated only for the lowermost 6 inches; also, depths to water were measured with a micro-hydro-gage, an electrical device having a precision of a thousandth of a foot.[89] Instead of the second hole, a plumber's water-gage fitting was tapped through the wall of the cylinder at its bottom and a glass piezometer tube was attached. Water was added through the piezometer and withdrawn through the petcock of the gage fitting; further, the water-table stage was observed in the piezometer with reference to a suitable scale. All the foregoing devices have appreciable entrance head; thus, if the water-bearing material is fine-grained the water table approaches equilibrium slowly after water is added or withdrawn. Material improvement in this respect would result if a layer of screened sand were placed at the bottom of the soil column while it was inverted for attachment of the permanent base plate, and if water were added or withdrawn through a perforated tube extending entirely across the cylinder within that sand layer. (7) Some of the early tests allotted relatively little time for the water table to reach a constant stage after water had been added or withdrawn; accordingly, those particular determinations of specific yield are weak. Beginning in 1929, no test has allowed less than 21 days for the water level to attain equilibrium, and some tests have continued as long as

[89] Stearns, H. T., Robinson, T. W., and Taylor, G. H., op. cit., pp. 158–159.

220 days. Additional tests over terms so long or even longer would have been desirable but are believed to be impracticable without rigorous control of temperature.

Determinations of specific yield by the drainage method—that is, by the difference between porosity and specific retention—were made in 1932 and 1933, and the technique and preliminary results have been reported elsewhere.[90] In brief, cylindrical samples 6 inches in diameter and 12 inches long were taken in duplicate by driving and excavating steel cylinders in the manner already described for the larger samples of the first method. Transported to Lodi, these samples were set up on benches in the wall of another covered pit, so that each pair was in contact with a repacked 6-inch layer of the same material, and that repacked layer in turn was in contact with the sandy subsoil in which the pit was dug. Thus, essential continuity of the capillary openings was maintained between the samples and the water table, which was about 20 feet below them. The samples were then thoroughly wetted in two stages—namely, (1) to the top of each cylinder was added water equivalent to about 25 percent of the volume of the sample; (2) after draining 10 days, each sample was placed in a pan filled to a shallow depth with water until it no longer would absorb water by capillary rise as indicated by weighing. From 24 to 96 hours was required by the several samples to complete this second stage. Then the cylinders were returned to their places and allowed to drain, the top of each being sealed with waxed paper pierced by one perforation made with a sharp pencil. Thus, atmospheric pressure was maintained at the top of the sample, and evaporation was minimized. (The atmosphere of the pit also was saturated.) The rate of drainage was determined by periodic weighing, one or more times the first few days, then at progressively longer intervals. After 96 to 111 days, the distribution of moisture was tested by taking three subsamples from the axis of one of each pair of samples, using a sampling tube about 0.9 inch in diameter and removing the top, middle, and bottom thirds separately. Retained moisture and moisture equivalent were then determined for the three axial subsamples and for the remainder of the gross sample; the natural porosity of the gross sample was also determined from its apparent specific gravity and the specific gravity of its component particles. Finally, the second sample of each pair was broken down similarly after the lapse of about a year (322 to 390 days).

EXPERIMENTAL RESULTS

VOLUMETRIC METHOD

Determinations of specific yield by the volumetric method have been made on soil columns from 13 localities in the Mokelumne area. Six of these columns were taken from alluvium along the flood plain of the

[90] Piper, A. M., Notes on the relation between the moisture-equivalent and specific retention of water-bearing materials: Am. Geophys. Union Trans. 14th Ann. Meeting, pp. 481–487, 1933.

Mokelumne River and within the zone of recent water-table fluctuations. The remaining seven columns were taken from the Victor formation, all above the zone of recent water-table fluctuations; five were from the zone unwatered since 1907 (pp. 118, 197), but two were taken a few feet above the water-table stage for 1907. The following table lists the 13 localities and summarizes the physical properties of subsamples taken opposite the large specific yield cylinders in several of the pits. Figure 7 shows the general character of the materials that constitute the respective columns.

In all tests by the volumetric method the water levels were influenced by temperature and barometric pressure. For example, take the column from the Emde ranch (3616Db) in 1931. For nearly a month after water was withdrawn from the column late in February, also after water was added late in April, the fluctuations were not dominated by changes in temperature and barometric pressure; thus, the water level rose more rapidly in early March than in April, and it receded steadily through most of May, although the temperature rose quite as steadily and the barometric pressure tended to fall slightly. After approximate equilibrium had been reached, however, the minor fluctuations from day to day corresponded rather closely with the changes in temperature and barometric pressure, rising temperature causing the water level to rise in the small well or piezometer tube, because surface tension diminished and some water was rejected from the capillary fringe, but increasing barometric pressure causing the water level to fall.

Approximate mean coefficients for adjusting the observed water levels to a standard temperature (60° F.) have been derived by plotting water level against temperature for observations made when the barometric pressure was within the range 29.9 ± 0.04 inches of mercury. For the range in which experiments were conducted (about 50° to 80° F.) the data for the several cylinders defined rude curves, of which none were straight and some were sigmoidal or S-shaped. For example, the temperature coefficient for the tests on column 3616Db in 1931 ranged from 0.0035 to 0.007 foot for each degree Fahrenheit. Among the five columns tested during 1931 the range was from 0.002 to 0.008 foot for each degree Fahrenheit. On the basis of these curves, the water levels were adjusted to 60° F. and plotted against barometric pressure, whence mean coefficients were derived for a further adjustment to standard pressure (30 inches of mercury). For the columns tested in 1931 the coefficients were sensibly constant within the range of the data; the smallest was 0.0003 and the largest 0.0006 foot for each 0.01 inch change in pressure—that is, the columns were only 3 to 6 percent efficient as barometers.

4612—39——8

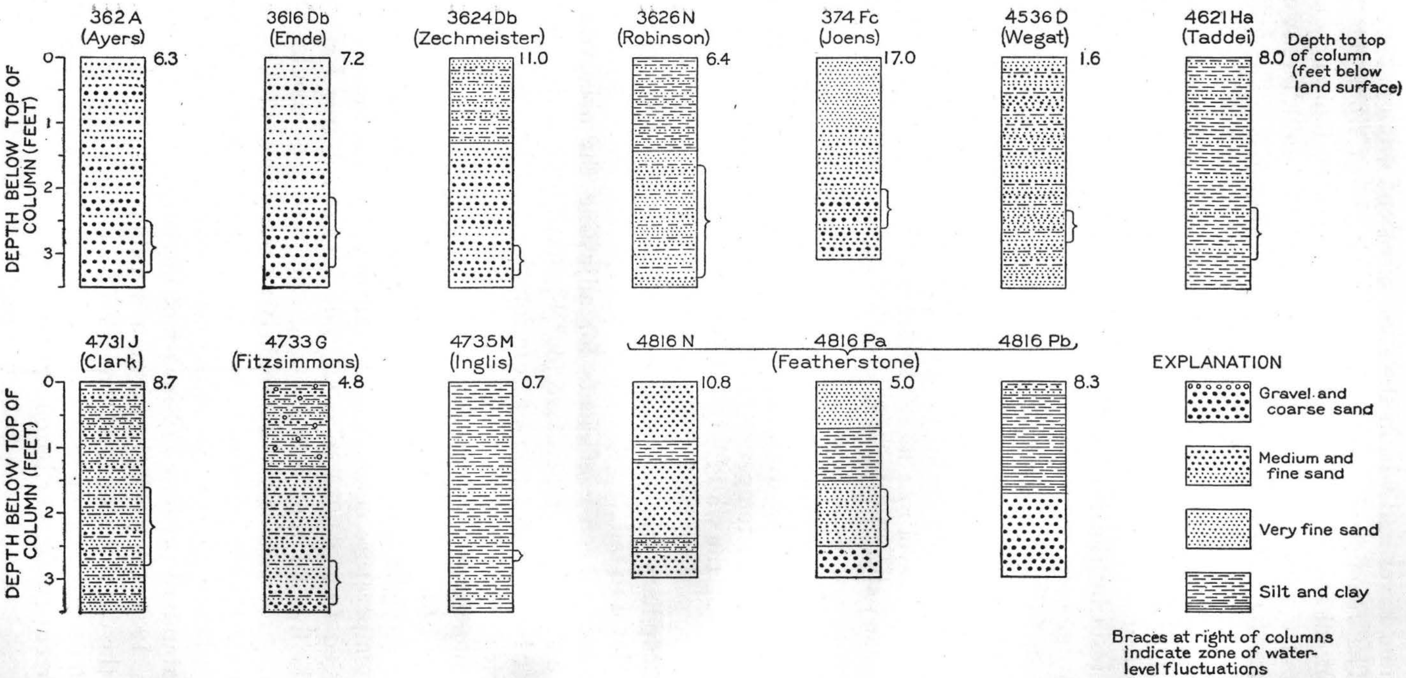


FIGURE 7.—Materials composing columns whose specific yield was tested by the volumetric method.

Physical properties of subsamples adjacent to specific yield columns

[Analyses by V. C. Fishel, Geological Survey]

No.[1]	Owner	Stratigraphic horizon [2]	Year of collection	Depth of subsample below top of column (feet)	Mechanical composition (percent of dry weight)							Apparent specific gravity	Porosity (percent of gross volume)	Moisture equivalent (percent of dry weight)	Coefficient of permeability [3]
					More than 1.00 mm (fine gravel)	1.00 to 0.50 mm (coarse sand)	0.50 to 0.25 mm (medium sand)	0.25 to 0.125 mm (fine sand)	0.125 to 0.062 mm (very fine sand)	0.062 to 0.005 mm (silt)	Less than 0.005 mm (clay)				
362A	Ayers	Qv	1929	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
3616Db	Emde	Qv	1929	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
3624Db	Zechmeister	Qv	1929	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
3626N	Robinson	Qv	1928	1.0–2.0	--------	1.4	3.4	14.9	18.8	49.4	11.6	1.32	52.3	18.6	1.5
				2.5–3.5	--------	4.9	17.3	32.8	25.5	16.9	2.8	1.35	50.3	4.6	180.0
374Fc	Joens	Qv	1931	2.0–2.5	4.3	31.0	44.4	12.6	3.9	1.2	.8	1.48	45.3	1.8	1,850
4536D	Wegat	Qv	1928	1.0–2.0	.9	8.8	22.8	22.1	13.7	24.3	6.9	1.61	41.2	7.0	1.0–0.5
				2.5–3.5	1.3	8.0	23.4	22.8	13.5	22.6	7.5	1.61	40.6	7.9	1.0–0.5
4621Ha	Taddei	Qal	1928	1.0–2.0	--------	.7	2.2	13.9	16.6	48.2	17.2	1.53	44.0	22.8	Less than 0.5
				2.5–3.5	--------	1.5	3.8	7.3	9.1	56.0	20.2	1.24	53.7	27.4	Less than 0.5
4731J	Clark	Qal	1928	.7–1.7	2.8	10.7	18.9	15.7	13.1	29.1	8.9	1.57	41.2	10.2	3.0
				1.7–2.2	3.2	9.3	18.8	17.2	15.4	27.3	7.0	1.63	38.6	13.5	--------
				2.4–3.4	2.8	9.3	18.8	18.0	15.5	27.7	7.4	1.69	36.7	8.5	3.5
4733G	Fitzsimmons	Qv	1929	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------
4735M	Inglis	Qal	1928	1.0–2.0	--------	1.8	3.7	3.3	2.4	64.2	22.9	1.25	54.2	34.1	1.0–0.5
				2.4–3.4	2.6	5.4	7.8	4.6	2.8	56.0	23.7	1.53	43.3	25.3	Less than 0.5
4816N	Featherstone	Qal	1927	.2–1.2±	--------	6.3	56.7	24.1	5.5	6.4	2.1	1.33	51.7	5.0	900
				2.0–2.8	--------	5.7	52.0	24.8	8.8	7.5	2.9	1.34	51.0	4.6	720
4816Pa	do	Qal	1928	.5–1.5	--------	.5	.9	4.5	12.4	66.4	13.8	1.11	59.7	22.0	3.0
				1.6–2.6	4.8	26.5	9.9	21.1	19.5	14.2	4.4	1.44	47.6	4.1	210.0
4816Pb	do	Qal	1927	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------	--------

[1] The number ascribed to a specific-yield column indicates its location according to the method for numbering wells (see p. 122) except that lower-case letters are used to discriminate the several columns if two or more are from one 40-acre tract (or if there is also a rainfall-infiltration plat in the tract).

[2] Qal, alluvium; Qv, Victor formation.

[3] The coefficient of permeability of a material is the rate of gravity flow, in gallons a day, through a square foot of its cross section, under a hydraulic gradient of 100 percent, at a temperature of 60° F. (Stearns, N. D., Laboratory tests on physical properties of water-bearing materials: U. S. Geol. Survey Water-Supply Paper 596, p. 148, 1928.)

Adjustments of the sort described above are possible only for the tests made in 1930 and 1931. As is shown by tabulated data to follow, they increase the consistency between separate determinations of specific yield but do not change materially the average for all determinations on a particular column. In the tests made prior to 1930 the temperature of the water in the columns was not determined. During the latest tests, which were made in 1932, after the piezometer tubes had been installed, the effects of changing temperature and barometric pressure were decidedly less but proved not to be evaluated satisfactorily by the experimental data.

Rigorous analysis of the effects of changes in temperature and in barometric pressure seems not to be warranted by the data from the tests of specific yield herein described, for the following reasons: (1) The observed temperatures probably deviated materially from the mean tempertaure within the capillary fringe and had a wider range, for presumably they anticipated changes in the mean temperature; (2) the lapse of time required to establish equilibrium between the quantity of water retained in the fringe and any particular temperature or barometric pressure is unknown; (3) as the columns were composed of heterogeneous natural sediments, the quantity of water potentially retained by the capillary fringe and the influence of temperature and pressure upon that quantity depended upon the stage of the artificial water table; (4) as the columns were too short to contain the full capillary fringe in the finer material, the actual storage in the fringe tended to diminish as the water table was raised, and thus the effects of change in temperature and pressure may have been offset or increased.

The following tables summarize the experimental data for tests by the volumetric method. They show mean water level, temperature, and barometric pressure during selected periods after each withdrawal or addition of water, the period beginning as soon as the water level appeared to have reached equilibrium and continuing while the trend of water level, temperature, and pressure was steady. Most of those periods were between 6 and 20 days, although one spanned 90 days. For the tests made during 1930 and 1931, the net rise or fall of the mean water level is adjusted to standard temperature and pressure by the approximate method just described. Finally, the specific yield is derived from the net volumes of water and of material involved.

Summary of specific-yield determinations by the volumetric method, 1928 and 1929

Date or period	Volume of water added or withdrawn (cubic feet)[1]	Observations				Mean elapsed time (days)	Net rise or fall of water level (feet)	Volume of material saturated or unwatered (cubic feet)	Specific yield (percent by volume)
		Number included in mean	Mean temperature (° F.)	Mean barometric pressure (inches of mercury)	Mean water level (feet below top of column)				
3626N. W. J. Robinson, owner									
1928–29									
Nov. 26–Dec. 7		7	48.4	30.10	1.648	26			
Dec. 7–8	−0.0403						−1.639	2.842	0.3
Dec. 26–Jan. 7		5	45.4	30.12	3.287	26			
Jan. 10	+.0316						+1.286	2.230	.7
Feb. 8–16		7	43.2	30.06	2.001	33			
Feb. 16	−.0340						−1.383	2.398	.2
Apr. 13–25		8	59.3	29.94	3.384	62			
Apr. 30	+.0258						+1.050	1.820	.9
June 7–19		6	65.4		2.334	46			
Mean of 2 determinations by unwatering									.25
Mean of 2 determinations by saturation									.8
Average for 4 determinations									.5
4536D. G. W. and A. F. Wegat, owners									
1929									
Feb. 11–16		5	45.1	30.08	2.815	10			
Feb. 16–18	+0.103						+0.485	0.841	[2] 12.2
Mar. 11–29		4	55.2	30.08	2.330	36			
4621Ha. Angela Taddei, owner									
1929									
Feb. 8–16		7	42.9	30.09	2.378	55+			
Feb. 16–18	−0.0248						−.730	1.266	2.0
Apr. 13–30		9	59.0	29.95	3.108	61			
Apr. 30	+.0220						+.803	1.392	1.6
June 13–22		6	71.9		2.305	51			
Average for 2 determinations									1.8
4731J. Perry O. Clark, owner									
1928									
Nov. 30–Dec. 7		5	45.4	30.08	1.599	15+			
Dec. 7–10	−0.184						−1.208	2.094	8.8
1929									
Jan. 2–10		7	42.2	30.15	2.807	28			
Jan. 10	+.184						+1.207	2.093	8.8
Feb. 4–14		8	42.9	30.01	1.600	30			
Feb. 14–16	−.190						−1.175	2.037	9.3
Mar. 29–Apr. 30		10	50.8	29.98	2.775	63			
Average for 3 determinations									8.9
4735M. Henry Inglis, owner									
1929									
Apr. 19–25		5	58.9	29.95	2.576	27			
Apr. 30	−0.0149						−0.159	0.276	[2] 5.4
June 13–26		9	73.3		2.735	51			
4816Pa. R. S. Featherstone, owner									
1929									
Feb. 8–16		7	43.1	30.09	1.635	18+			
Feb. 16–18	−0.0846						−.890	1.543	[3] 5.5
Apr. 18–30		7	59.6	29.94	2.525	63			
Apr. 30	+.0935						+.271	.470	[3] 19.9
June 13–26		9	73.4		2.254	50			

[1] Corrected for change in storage within observation wells.
[2] Determination not checked but compatible with results for other columns of similar texture.
[3] Wide divergence of determinations not explained; neither accepted as satisfactory.

Summary of specific-yield determinations by the volumetric method, 1930 to 1932

362A. M. F. Ayers, owner

Date or period	Volume of water added or withdrawn (cubic feet)[1]	Observations				Mean elapsed time (days)	Net rise or fall of water level (feet)	Corrections		Corrected rise or fall of water level (feet)	Volume of material saturated or unwatered (cubic feet)	Specific yield (percent by volume)
		Number included in mean	Mean temperature (°F.)	Mean barometric pressure (inches of mercury)	Mean water level (feet below top of column or gage)			To constant temperature (feet)	To standard pressure (feet)			
1930												
Mar. 21–Apr. 7		11	60.9	29.96	2.513	33						
Apr. 7–10	−0.406						−0.707	−0.011	−0.001	−0.719	1.259	32.2
Apr. 28–May 28		19	62.9	29.88	3.220	29						
May 28	+.346						+.575	−.032	−.001	+.542	.949	36.5
June 17–July 2		12	72.6	29.84	2.645	27						
July 3–7	−.436						−.579	−.004	+.001	−.582	1.019	34.0
July 23–Aug. 4		11	73.6	29.91	3.224	19	−.655	+.086	+.000	−.569	.996	[2] 34.7
1931												
Feb. 5–16		6	54.3	29.83	3.300	215						
Feb. 16–17	+.346						+.631	−.038	+.003	+.596	1.043	33.1
Mar. 6–Apr. 25		49	60.0	29.99	2.669	41						
Apr. 25	−.328						−.553	−.038	−.003	−.594	1.040	31.6
May 18–June 11		25	69.5	29.85	3.222	30						
June 13	+.329						+.558	−.032	−.001	+.525	.919	35.8
July 8–Aug. 3		14	77.1	29.81	2.664	32						
Mean of 3 determinations by unwatering												32.6
Mean of 3 determinations by saturation												35.1
1932												
Jan. 16–Apr. 8		22		29.98	[3] .296	33+						
Apr. 8	−.183						−.253				.443	41.3
July 29–Sept. 8		37		29.80	[3] .043	131						
Average for 7 determinations												34.9

3616Db. J. W. Emde estate, owner

1930												
Jan. 3–Feb. 17		12	53.8	29.95	2.631							
Feb. 26–27	−0.233						−0.393	−0.036	+0.001	−0.428	0.749	31.1
Mar. 21–Apr. 7		11	60.9	29.96	3.024	32						
Apr. 7	+.234						+.388	−.011	−.005	+.372	.651	35.9
Apr. 28–May 28		19	63.4	29.88	2.636	32						
May 28	−.279						−.479	−.036	−.002	−.517	.905	30.8
June 16–July 2		13	72.8	29.84	3.115	26						
July 3	+.280						+.419	−.003	+.004	+.420	.735	38.1
July 23–Aug. 4		11	74.0	29.91	2.696	23	+.341	+.080	−.002	+.419	.733	[2] 38.2
1931												
Feb. 5–17		7	54.4	29.80	2.774	220						
Feb. 17–20	−.261						−.434	−.027	+.010	−.451	.789	33.0
Mar. 6–Apr. 25		49	59.6	29.99	3.208	38						
Apr. 25	+.346						+.615	−.049	−.008	+.558	.977	35.4
May 5–Aug. 3		65	71.7	29.84	2.593	42						
Mean of 3 determinations by unwatering												31.6
Mean of 3 determinations by saturation												36.5
1932												
Jan. 16–Apr. 8		22	50.1	29.98	[3].522	33+						
Apr 8	−.227						−.347				.607	37.3
July 29–Sept. 8		37	78.1	29.80	[3].175	131						
Average for 7 determinations												34.1

[1] Corrected for change in storage within observation wells or piezometer tube.
[2] Not included in mean or average.
[3] Feet above zero of gage.

Summary of specific-yield determinations by the volumetric method, 1930 to 1932—Continued

3624Db. J. J. Zechmeister, owner

Date or period	Volume of water added or withdrawn (cubic feet)	Observations: Number included in mean	Observations: Mean temperature (°F.)	Observations: Mean barometric pressure (inches of mercury)	Observations: Mean water level (feet below top of column or gage)	Mean elapsed time (days)	Net rise or fall of water level (feet)	Corrections: To constant temperature (feet)	Corrections: To standard pressure (feet)	Corrected rise or fall of water level (feet)	Volume of material saturated or unwatered (cubic feet)	Specific yield (per cent by volume)
1930												
Apr. 1–7		6	60.5	30.05	2.979	20						
Apr. 7–10	−0.192						−0.363	−0.016	−0.007	−0.386	0.676	28.4
May 2–28		16	63.3	29.90	3.342	32						
May 28	+.224						+.467	−.029	−.003	+.435	.762	29.4
June 17–July 2		12	73.0	29.84	2.875	26						
July 3–7	−.157						−.370	−.002	+.004	−.368	.644	24.4
July 23–Aug. 4		11	73.7	29.91	3.245	23	−.441	+.083	.000	−.358	.626	[2] 25.2
1931												
Feb. 5–16		6	54.4	29.83	3.316	215						
Feb. 16	+.172						+.378	−.029	+.008	+.357	.625	27.5
Mar. 6–Apr. 25		49	59.5	30.00	2.938	48						
Apr. 25–27	−.189						−.351	−.046	−.007	−.404	.707	26.8
May 18–June 11		25	69.3	29.85	3.289	33						
June 11	+.190						+.365	−.016	−.002	+.347	.607	31.3
July 8–Aug. 3		14	76.9	29.81	2.924	33						
Mean of 3 determinations by unwatering												26.5
Mean of 3 determinations by saturation												29.4
1932												
Jan. 16–Apr. 8		22	50.2	29.98	[3].315	33+						
Apr. 8–9	−.0525						−.113				.198	26.5
July 29 to Sept 8		37	78.8	29.80	[3].202	130						
Average for 7 determinations												27.8

374Fc. Peter Joens, owner

1931												
Apr. 19–May 6		18	62.7	29.81	[3].763	20+						
May 6	−0.234						−0.542	−0.047	0.000	−0.589	1.041	22.9
May 23–June 11		20	68.7	29.85	[3].221	27						
June 13	+.209						+.422	−.055	−.001	+.366	.647	32.7
July 9–Aug. 3		18	76.0	29.78	[3].643	35						
Aug. 3	−.209						−.464	−.029		−.435	.769	24.5
Aug. 26–28		3	79.7		[3].179	24						
Average for 3 determinations												26.7

4733G. V. F. Fitzsimmons, owner

1930												
Mar. 21–Apr. 7		11	62.0	29.96	2.856	35						
Apr. 7–8	−0.178						−0.550	−0.004	−0.005	−0.559	0.988	18.1
Apr. 28–May 28		19	64.0	29.88	3.406	31						
May 28	+.182						+.500	−.015	−.003	+.482	.855	21.3
June 17–July 2		12	69.8	29.84	2.906	27						
July 3	−.156						−.505	−.011	+.005	−.511	.903	17.3
July 23–Aug. 4		11	72.6	29.91	3.411	23						
1931												
Feb. 5–16		6	54.8	29.83	3.526							
Feb. 16–17	+.156						+.494	−.006	+.010	+.498	.880	17.7
Mar. 6–Apr. 25		49	58.5	29.99	3.032	41						
Apr. 25	−.121						−.370	−.026	−.009	−.405	.716	16.9
May 18–June 11		25	69.7	29.85	3.402	30						
June 11	+.122						+.395	−.053	−.003	+.339	.599	20.3
July 8–Aug. 3		14	77.2	29.79	3.007	34						
Mean of 3 determinations by unwatering												17.4
Mean of 3 determinations by saturation												19.8
Average for 6 determinations												18.6

[2] Not included in mean or average.
[3] Feet above zero of gage.

In the tests summarized above the mean elapsed time ordinarily ranged between 19 and 63 days. The shorter term was perhaps inadequate for equilibrium to be fully attained, but in contrast, the three columns for which the elapsed time was least (362A, 3616Db, and 3624Db; withdrawal of July 3 to 7, 1930) also afford results for specific yield after the lapse of 215 to 220 days and without further withdrawal or addition of water. The longer term increased the specific yield between 1 and 3 percent of the result derived from the shorter term. However, these three columns were coarse in texture; the increase in yield with longer term might well have been greater had the material been finer. Also, the increase was determinable only roughly, owing to uncertainties in the adjustment to standard temperature and pressure.

Obviously, the lapse of time required for the water level to reach true equilibrium at any particular temperature depends largely upon the lag in replenishing the capillary fringe as water is added and in draining the fringe as water is withdrawn. In either case, the volume of material saturated or unwatered tends to diminish as the term of the test is lengthened—that is, the result for specific yield tends to increase. All the columns of material tested in the Mokelumne area have tended to give larger results for specific yield by saturation than by unwatering, whence it is inferred that the lag following withdrawal is the greater. For example, among four columns tested in 1930 and 1931, the respective mean results for determinations by saturation are between 108 and 115 percent of the mean results for alternate determinations by unwatering, the particular materials being relatively coarse. That the range might have been much greater for fine materials is suggested by the determinations for column 3626N in 1928–29. For that column, two results for specific yield by saturation were about three times as large as two results by unwatering, although all were small. The experimental errors due to lag seem not to compensate in short-term tests which withdraw and add equal volumes of water alternately. Further, if the columns are too short to contain the full capillary fringe, the results for specific yield tend to be too small, and the error becomes progressively greater as the stage of the water table is raised in the column. All the foregoing considerations suggest that the respective average specific yields determined by the volumetric method are likely to be less than the true specific yields of similar materials in the field.

DRAINAGE METHOD

Determinations of specific yield by the drainage method were made on 13 duplicate samples from one pit in the Victor formation; also on three pairs of samples from as many localities in the alluvium that constitutes the flood plain of the Mokelumne River. Together, the samples covered a rather full range of textures between coarse sand and silt. The tests on one set of the samples (series 2) were terminated after drainage for 96 to 111 days. The accompanying tables indicate the physical composition of those samples and summarizes the experimental results.

Physical properties of materials tested for specific yield by the drainage method (series 2) [1]

Number of plat	Owner	Stratigraphic horizon [2]	Depth below land surface (feet)	Mechanical composition (percent of dry weight): More than 1.00 mm (fine gravel)	1.00 to 0.50 mm (coarse sand)	0.50 to 0.25 mm (medium sand)	0.25 to 0.125 mm (fine sand)	0.125 to 0.062 mm (very fine sand)	0.062 to 0.005 mm (silt)	Less than 0.005 mm (clay)	Apparent specific gravity	Porosity (percent of gross volume)	Moisture equivalent (percent of dry weight)	Coefficient of permeability [3]
4733Bb	Woods & Wilhoit	Qv	0- 1	----------	4.6	11.7	12.1	18.6	42.3	10.7	1.71	36.4	11.2	4
			1- 2	----------	4.2	11.4	11.1	19.6	41.0	12.7	1.50	44.6	11.5	3
			2- 3	----------	3.7	10.3	10.0	20.3	42.0	13.4	1.49	44.8	11.8	3
			3- 4	0.4	2.9	9.3	10.1	20.9	45.0	11.2	1.53	40.0	12.0	5
			4- 5	.6	2.3	7.5	6.3	23.6	47.0	12.1	1.69	32.9	13.6	5
			5- 6	2.9	3.6	6.0	5.8	8.3	45.3	27.4	1.51	39.8	26.2	4
			6- 7	2.9	5.0	10.7	8.1	24.5	40.1	7.3	1.47	43.0	16.4	6
			7- 8	1.9	9.5	16.5	8.0	14.1	40.4	7.7	1.34	47.9	19.0	7
			8- 9	1.3	14.6	28.2	11.1	22.5	19.3	1.9	1.65	36.8	5.1	45
			9-10	1.4	20.3	40.6	7.7	12.2	12.8	4.4	1.60	38.9	7.4	30
			10-11	1.3	7.4	7.1	6.2	22.5	52.2	2.9	1.51	43.7	9.5	15
			11-12	.9	20.3	25.2	7.5	23.3	21.2	1.2	1.46	45.7	4.1	40
			12-13	3.0	21.4	30.2	15.8	18.8	9.3	1.0	1.54	42.1	3.4	130
4725G	Bain	Qal	12-13	----------	.1	.4	.5	.8	64.8	31.6	1.37	47.5	34.0	1
4725E	do	do	6.6-7.6	.6	.7	14.1	6.3	39.0	32.9	5.9	1.59	41.8	8.7	20
4735G	Inglis	do	8-9±	----------	.2	.7	.6	2.7	60.8	34.5	1.36	48.9	34.8	1

[1] Mechanical composition, apparent specific gravity, porosity, and coefficient of permeability by V. C. Fishel, Geological Survey; moisture equivalent by A. D. Rizzi, College of Agriculture, Davis, Calif.; specific retention by C. A. McClelland, Geological Survey.

[2] Qal, alluvium; Qv, Victor formation.

[3] For definition see corresponding table for materials tested by the volumetric method.

Specific yield of materials tested by the drainage method (series 2)

Number of plat	Depth below land surface (feet)	Specific retention after draining 96 to 111 days		Specific yield (percent of gross volume)	Number of plat	Depth below land surface (feet)	Specific retention after draining 96 to 111 days		Specific yield (percent of gross volume)
		Percent of dry weight	Percent of gross volume				Percent of dry weight	Percent of gross volume	
4733Bb	0-1	14.4	24.6	11.8	4733Bb—Con.	8-9	9.7	16.0	20.8
	1-2	13.4	20.1	24.5		9-10	8.6	13.8	25.1
	2-3	13.7	20.4	24.4		10-11	19.2	29.0	14.7
	3-4	15.2	23.3	16.7		11-12	11.1	16.2	29.5
	4-5	14.7	24.8	8.1		12-13	6.2	9.5	32.6
	5-6	25.1	37.9	1.9	4725G	12-13	34.1	46.7	.8
	6-7	20.9	30.7	12.3	4725E	6.6-7.6	12.5	19.9	21.9
	7-8	21.0	28.1	19.8	4735G	8-9±	33.8	46.0	2.9

The moisture retained by each of the gross samples after 96 to 111 days exceeded the average retained by the corresponding three axial subsamples, though the excess was less than 5 percent of the retention in four samples, was less than 10 percent in six other samples, and averaged 12 percent in all samples. These relations imply that the retained moisture was not distributed uniformly and was appreciably less in the axial portion of the cylinders, perhaps in part owing to differences in mechanical composition from place to place in the samples. However, because none of the gross samples retained less water than its axial subsamples, it is inferred that much of the excess retention was due to slower drainage adjacent to the steel cylinder that contained each sample. The results for specific yield shown by the preceding table are taken to be comparable to those determined by the volumetric method, at least to the extent that the terms of drainage are of the same order of magnitude.

Figure 8 shows the relation between the results for specific yield as determined by the drainage method and the mean size of the particles composing the respective samples.[91] On that diagram the abscissas allot equal space to successive grades or classes whose limiting particle sizes are in the constant ratio 2:1; thus the silt fraction of the conventional nomenclature spans 3.6 classes, and the clay fraction is extended indefinitely. With three exceptions, the plotted points fall within a moderately narrow zone with parallel straight-line limits as indicated, the width of that zone being equivalent to one class interval. Without exception, the points that represent materials with small dispersion of particle sizes (standard size-ratio deviation[92] is small) fall to the right on the diagram; likewise, the points that represent the materials of higher porosity for any particular mean size and size-ratio deviation fall to the right. These relations suggest that the specific yield of these particular water-bearing materials is a systematic

[91] Wentworth, C. K., Method of computing mechanical composition types in sediments: Geol. Soc. America Bull., vol. 40, pp. 776-777, 1929.

[92] Idem, pp. 777-779.

function of mechanical composition and texture, although obviously the 16 tests just described afford too few data for statistical treatment of that suggestion.

The drainage tests on the second set of samples (series 1) were terminated after about a year (322 to 390 days). In all the samples the quantity of retained water decreased steadily, though at a dimin-

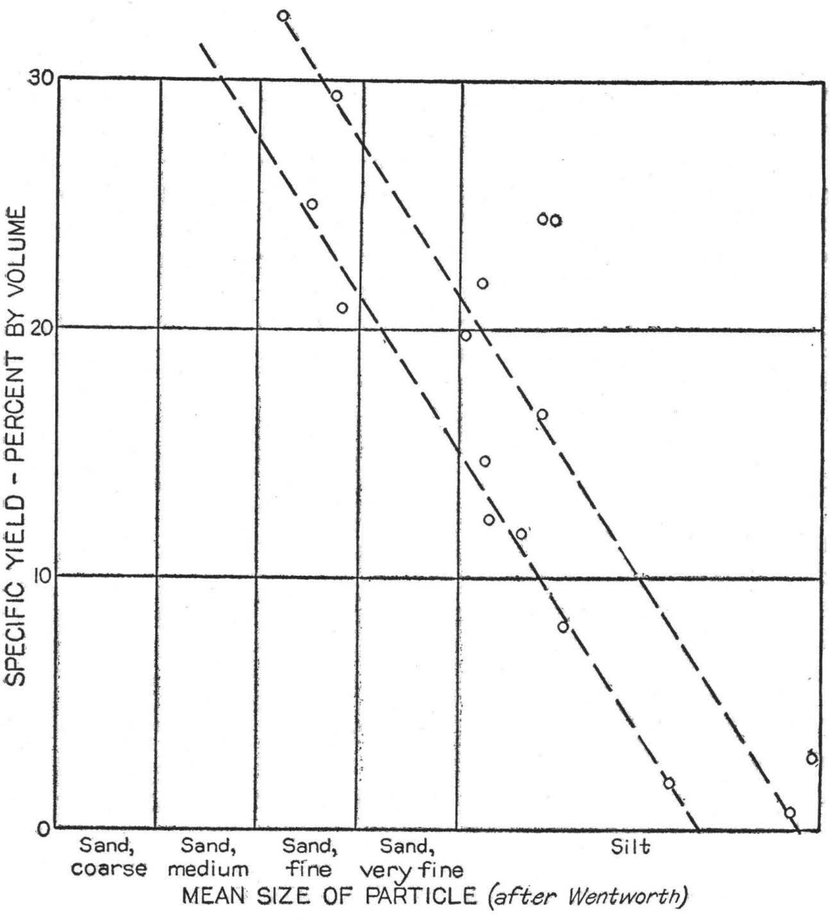


FIGURE 8.—Relation between texture and specific yield of materials after draining approximately 100 days.

ishing rate. Thus, the retention at the end of the tests ranged between 61 and 97 percent of the respective quantities retained after the lapse of 96 to 111 days; also, in general, the greater additional drainage came from the coarser-grained samples. In part the additional drainage may have been caused by the higher temperature that prevailed during the middle part of the term. Further, the additional drainage appears to have been less at the axes of the samples than next to the enclosing steel cylinders, for after the lapse of 322 to 390 days the retention in the gross samples averaged 105 percent of the retention in the axial subsamples, whereas after the lapse of 96 to 111 days it had averaged 112 percent. The specific yields derived from the longer term of drainage ranged between 106 and 167 percent of the respective results derived from the shorter term and averaged 127 percent. In general, the percentage increase was least for the materials of large specific yield and greatest for the materials of moderate specific yield.

The percentage increase in the results for specific yield derived from the longer term of drainage is greater than the increase in the few long-term tests by the volumetric method. However, it has been inferred that the volumetric method tends to yield results that are too small, whether the test is made by saturation or by unwatering, although the tests by saturation have consistently afforded results somewhat greater than those by unwatering. Accordingly, the increased yield indicated by the long-term drainage tests may measure the actual behavior of water-bearing materials under field conditions, whereas tests by the volumetric method as conducted in the Mokelumne area may not evaluate the final small increments of specific yield.

The graphs that constitute figure 9 show the mean specific retention of the materials tested by the drainage method in relation to their moisture equivalent, a property that has been used commonly as an approximate measure of the quantity of water that a material would retain against the pull of gravity. The graphs are based upon the two sets of axial subsamples taken from the respective gross samples after the two terms of drainage. They are analogous to the graph that has been published to summarize the preliminary results from this method.[93]

MEAN SPECIFIC YIELD FOR ZONES OF WATER-TABLE FLUCTUATION

Ground-water inventories for the area that receives percolate from the Mokelumne River above the gaging station at Woodbridge [94] involve changes in ground-water storage, which are perforce evaluated from the volumes of granular material that are saturated and unwatered. Accordingly, appropriate mean figures for the specific yield of the material are required. These means are derived for two distinct zones—namely, (1) an upper zone that is limited by the respective water-table stages for January 1907 and for January 1933, and (2) a contiguous lower zone whose bottom is the lowest known pumping level attained between 1926 and 1933.[95] Within the area that receives percolate from the river the mean altitude of the imaginary surface that separates the two zones—that is, the water-table

[93] Piper, A. M., Notes on the relation between the moisture equivalent and the specific retention of water-bearing materials: Am. Geophys. Union Trans. 14th Ann. Meeting, p. 485, 1933.

[94] The boundaries of the area that receives percolate are given on pages 204 to 206.

[95] Piper, A. M., Pumpage of ground water for irrigation in the Mokelumne area, California, 1927–35: U. S. Geol. Survey typoscript report, pp. 39–46, pl. 3, April 9, 1934.

stage of January 1933—is 38.2 feet above sea level. The following sections that describe the form and depth of the water table and the fluctuations of ground-water levels in wells show that in recent years the greater part of the upper zone has been continuously unwatered, owing to progressive recession of the water table, whereas the lower

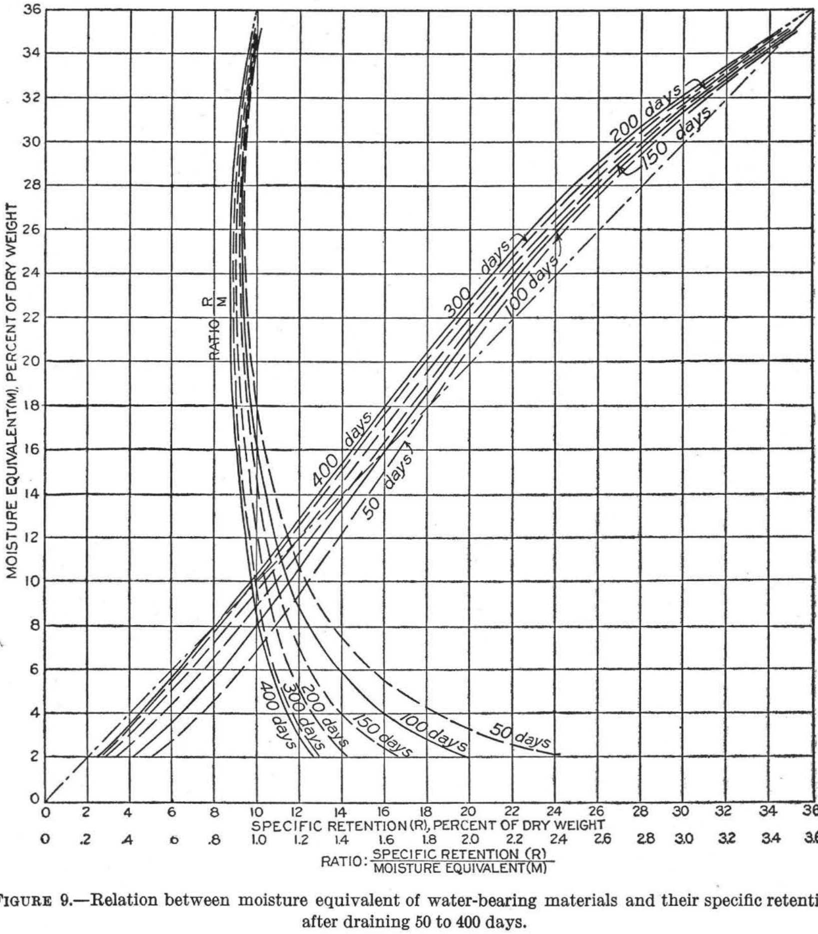


FIGURE 9.—Relation between moisture equivalent of water-bearing materials and their specific retention after draining 50 to 400 days.

zone has been alternately unwatered and resaturated each year. Further, they indicate the depth of the two zones below the land surface.

Although the water table has receded progressively through the upper zone, the suspended water in that zone has been replenished continually by infiltration of rain and of water applied on the land for irrigation. The material at the top of the lower zone is resaturated transiently each year and subsequently drains for most of the succeeding 12 months. On the other hand, the material at the bottom of the lower zone drains only transiently each year. Thus, it is inferred that on the average each of the two zones drains about 6 months of the year without replenishment of its suspended water from extraneous sources, and that the mean figures for the specific yield can with propriety be taken from the foregoing experimental data without weighting for the term of drainage. The specific yield of the upper zone is inferred to have been somewhat less than it would have been if drainage had continued from 1907 to 1933 without any replenishment from above.

Records for 231 irrigation wells within the area that receives percolate are available in sufficient detail to show the physical character of the material in the two zones. Of these, 185 wells have driller's records, which commonly discriminate three general classes of material—"gravel" and "coarse sand", "sand" or "standing sand", and "silt" or "clay." The remaining 46 wells have yielded samples that have been classified according to the standard grades or classes of granular material. (See pp. 89–90.) By comparing the two sorts of records for several wells within selected small areas approximate correlations have been derived as follows: (1) By "gravel" and "coarse sand" the driller designates material whose dominant grade falls under one or the other of those same terms in the standard classification—that is, material in which most particles are larger than 0.5 millimeter in diameter; (2) "sand" and "standing sand" span the medium-sand and fine-sand grades of the standard classification—that is, they include material in which the dominant fraction is 0.5 to 0.125 millimeter in diameter; (3) "silt" and "clay" include the very fine sand, the silt, and the clay fractions of the standard classification—that is, material composed largely of particles smaller than 0.125 millimeter in diameter. The percentage volume of these three classes of material in each of the two zones has been determined by summing up the respective footage for the three classes of material, subtotals having been taken by quarters of a township and weighted according to the number of items in each. The following table summarizes the results:

Mechanical composition of zones of water-table fluctuation in the area receiving percolate from the Mokelumne River above the gaging station at Woodbridge

Class	Approximate range in size (millimeters)	Percentage of total volume	
		Zone between water-table stages for January 1907 and January 1933	Zone between water-table stage for January 1933 and lowest pumping level from 1926 to 1933
Gravel and coarse sand	Greater than 0.5	11.0	17.6
Medium and fine sand	0.5–0.125	17.6	24.4
Very fine sand, silt, and clay	Less than 0.125	71.4	58.0

In accord with the mechanical composition of the respective columns, the average results for specific yield determined by the volumetric method are allocated to the foregoing three classes of material, as follows:

	Average specific yield (percent)
Gravel and coarse sand:	
362A, Ayers	34.9
3616Db, Emde	34.1
Mean	34.5
Medium and fine sand:	
3624Db, Zechmeister	27.8
374Fc, Joens	26.7
4536D, Wegat	[1] 12.2
4733G, Fitzsimmons	18.6
Mean	22.6
Very fine sand, silt, and clay:	
3626N, Robinson	.5
4536D, Wegat	[1] 12.2
4621Ha, Taddei	1.8
4731J, Clark	8.9
4735M, Inglis	5.4
Mean	5.0

[1] Weighted one-half in each of 2 classes owing to intermediate texture of the material.

In turn, corresponding mean results for specific yield determined by the drainage method are interpolated from figure 8 as follows: Gravel and coarse sand, 35 percent; medium and fine sand, 26 percent; very fine sand, silt, and clay, 3.5 percent. The foregoing approximate results give due consideration to the fact that the mean size of particle was found to average about one class interval smaller than the size of the dominant particle in the materials tested. For the three classes of material, the averages from the two methods are, respectively, 34.8, 24.2, and 4.2 percent. In general, these averages agree with findings by Eckis and Gross [97] as to the specific yield of valley fill in the South Coastal Basin, California, although their intensive studies dealt chiefly with coarser materials. Finally, mean results for the specific yield of the two zones are derived by summing up the partial products of the preceding averages and the respective percentage volumes already shown; these are 11.1 percent for the zone between the water-table stages of January 1907 and January 1933 and 14.5 percent for the zone between the water-table stage of January 1933 and the lowest pumping level from 1926 to 1933.

Obviously, the foregoing means are approximations. To the extent that they are based upon relatively short experimental terms they tend to be somewhat small, although the long-term drainage tests

[97] Eckis, Rollin, and Gross, P. L. K., South Coastal Basin investigation—geology and ground-water storage capacity of valley fill: California Div. Water Resources Bull. 45, pp. 91–95, 1934.

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suggest that the error from that cause is less serious than the uncertainty due to the fact that only a few samples were tested by each method.

LOCATION AND CLASSIFICATION OF OBSERVATION WELLS

In recent years measurements of depth to water have been made by at least eight agencies in about 1,800 observation wells within the Mokelumne area. The agencies and the periods of their activity are (1) the United States Geological Survey, in 1906–7, 1913–14, and 1926–33; (2) C. H. Widdows, acting for a group of landowners in the central part of the area, in October 1925; (3) Cyril Williams, for the East Bay Municipal Utility District, from October to December 1925; (4) the Division of Water Resources, California Department of Public Works, in March and April 1926; (5) the city of Stockton, in September 1926; (6) the city of Lodi, from January 1930 to May 1933; (7) the East Bay Municipal Utility District, beginning in May 1930; and (8) the Pacific Gas & Electric Co., beginning in May 1930. Records by all these agencies have been drawn upon for the basic data of this chapter. Prior to 1930 measurements were made monthly or quarterly in some 450 wells, largely by the United States Geological Survey. From 1930 to 1933, however, many new observation wells were established by the several agencies, and measurements were made daily or weekly in about 450 wells by one agency or another. The records for practically all these wells have been released to the public.[98] Plate 1 shows the location of 1,394 observation wells in which measurements have been made periodically over the greater part of 1 year or longer.

In the tables and descriptions these wells are designated by numbers that indicate the respective locations according to the official rectangular land survey.[99] For well 4722Q5, for example, the first digit

[98] Stearns, H. T., Robinson, T. W., and Taylor, G. H., Geology and water resources of the Mokelumne area, California: U. S. Geol. Survey Water-Supply Paper 619, pp. 139–142, 292–398, 1930.

Table of well measurements, Mokelumne area, California [in the period July 1, 1929, to June 30, 1931]: U. S. Geol. Survey typoscript report, 246 pp., Oct. 23, 1930, to Oct. 15, 1931.

Measurements of depth to water in observation wells of the Mokelumne area, California [in the period July 1, 1931, to July 4, 1933]: U. S. Geol. Survey typoscript reports dated Dec. 24, 1931; Mar. 21, 1932; Apr. 30, 1932; July 29, 1932; Oct. 22, 1932; Feb. 1, 1933; Apr. 20, 1933; July 15, 1933.

Corrections to tables of measurements of depth to water in observation wells of the Mokelumne area, California, in the period prior to Feb. 1, 1933: U. S. Geol. Survey typoscript report, 12 pp., Mar. 18, 1933.

Well measurements in the vicinity of Lodi [in the period January 15, 1930, to Sept. 5, 1932]; record of San Joaquin County Court, case No. 22415, plaintiff's exhibit 6, 652 pp., September 1932.

Depth to water and altitude of water surface in observation wells in T. 3 N., R. 7 E., Mokelumne area, California: U. S. Geol. Survey typoscript report, 288 pp., June 15, 1934.

Depth to water and altitude of water surface in observation wells in T. 3 N., R. 6 E., Mokelumne area, California: U. S. Geol. Survey typoscript report, 224 pp., Feb. 15, 1935.

Depth to water and altitude of water surface in observation wells in T. 4 N., R. 6 E., Mokelumne area, California: U. S. Geol. Survey typoscript report, 204 pp., Apr. 27, 1935.

Depth to water and altitude of water surface in observation wells in T. 4 N., R. 7 E., Mokelumne area, California: U. S. Geol. Survey typoscript report June 10, 1935.

Depth to water and altitude of water surface in observation wells in T. 4 N., R. 8 E., Mokelumne area, California: U. S. Geol. Survey typoscript report June 22, 1935.

[99] Stearns, H. T., Robinson, T. W., and Taylor, G. H., Geology and water resources of the Mokelumne area, California: U. S. Geol. Survey Water-Supply Paper 619, p. 209, 1930.

indicates the township (T. 4 N.), the second digit indicates the range (R. 7 E.), the next two digits indicate the section (sec. 22), and the letter indicates the 40-acre subdivision of the section as shown on the accompanying diagram.

A	B	C	D
E	F	G	H
J	K	L	M
N	P	Q	R

Within each 40-acre tract the wells are numbered serially as indicated by the final digit or digits of the number. Thus, well 4722Q5 is in the SW¼SE¼ sec. 22, T. 4 N., R. 7 E., and is the fifth well in that tract to be listed. The system of numbers has been adopted by each agency now active in the Mokelumne area. With the exception of the district within 2 miles of Lodi, practically all observation wells whose serial number does not exceed 10 (pl. 1) were established by the Geological Survey, although water-level measurements may have been made in them by several agencies under the same number.

In the district about Lodi, however, there are 81 observation wells that were established and have been used solely by the city. The serial numbers of these wells also do not exceed 10, neither are they duplicated among the observation wells of any other agency. To the observation wells that it has established the East Bay Municipal Utility District has commonly assigned serial numbers beginning with 11, although certain of these wells have also been given smaller serial numbers by the Geological Survey in its lists of irrigation pumping plants [1] and although several of the higher serial numbers have been set by the Geological Survey where it has listed more than 10 wells in a 40-acre tract. A few test wells bored by the Pacific Gas & Electric Co. on the flood plain of the Mokelumne River carry serial numbers beginning with 21.

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[1] Stearns, H. T., op. cit., pp. 210–239.

Sherwood, G. M., Changes in area irrigated from ground water in the Mokelumne area, California, as indicated by records of irrigation wells and pumping plants: U. S. Geol. Survey typoscript report, 26 pp., May 5, 1932.

Additions and corrections to records of pumping plants on wells in the Mokelumne area, California: U. S. Geol. Survey typoscript report, 10 pp., Oct. 3, 1933.

Additions and corrections to records of pumping plants on wells in the Mokelumne area, California: U. S. Geol. Survey typoscript report, 19 pp., Mar. 6, 1934.

The most intensive observations of ground-water levels are (1) those from 37 wells on which water-stage recorders have been operated by the Geological Survey for periods of 3 months to 6 years, the charts having been released for consultation by the public;[2] and (2) those from wells along four critical profiles. Plate 1 and figure 10 show the sites of recorders and profiles; tables that follow describe these particular wells. A water-stage recorder has been operated on one additional well (3617A1) by the East Bay Municipal Utility District.

Observation wells in the Mokelumne area on which water-stage recorders have been operated by the Geological Survey

Number of well	Depth (feet)	Diameter (inches)	Geologic classification [1]		Period of operation of water-stage recorder
			Land surface	Bottom of well	
3612A2	76.0	6	Qv	Qv<75	Feb. 3, 1930–June 26, 1933.
3616C1	11.5	10	Qv	Qv	Nov. 14, 1927–July 27, 1928.
3616D2	13.0	12	Qv	Qv	Nov. 22, 1929–Sept. 2, 1931.
3625R3	107.0	10	Qv	Qv<75	Mar. 2, 1932–July 26, 1933.
3625R4	40.0	12	Qv	Qv	Do.
373B1	48.0	8	Qv	Qv	Dec. 12, 1930–Nov. 22, 1932.
373G1	[2] 200	12	Qv	QTasl	Jan. 20, 1927–Jan. 17, 1929.
373G3	37.0	10	Qv	Qv	Dec. 19, 1927–June 22, 1928.
373K2	52.0	10	Qv	Qv<75	May 27, 1930–Nov. 22, 1932.
375L3	169.0	10	Qv	QTasl	Jan. 28–Dec. 9, 1927.
3710B4	50.0	8	Qv	Qv<75	Dec. 12, 1930–Mar. 5, 1931.
3710K3	57.0	10	Qv	Qv<75	June 14, 1930–June 26, 1933.
3710K4	190.0	12	Qv	QTasl	Do.
3715P2	55.0	10	Qv	Qv	May 27, 1930–June 1, 1932.
383D1	108.0	48	Tl	Tl	Sept. 18, 1929–Mar. 11, 1930.
386C1	69.0 [2] 500	10	Qv	Tl Tm	July 30, 1929–Mar. 25, 1930.
4616N1	111.8	12	Qv	Qv<75	July 23, 1928–Apr. 20, 1929.
4715Q2	55.0	10	Qv	Qv<75	May 27–Dec. 9, 1930.
4722Q4	51.0	10	Qv	Qv<75	May 26, 1930–June 26, 1933.
4722Q5	266.0	10	Qv	QTasl	Do.
4725E1	12.4	12	Qal	Qal	Sept. 3–Nov. 20, 1931.
4725E2	10.9	48	Qal	Qal	Aug. 28–Dec. 8, 1931; Mar. 16–Nov. 9, 1932.
4725G4	14.2	36	Qv	Qal	Aug. 28–Dec. 1, 1931; Apr. 25–Nov. 16, 1932.
4726K1	67.0	12	Qv	Qv<75	July 15, 1927–Feb. 4, 1928.
4727A1	46.0	12	Qv	Qv<75	Jan. 14, 1927–Nov. 14, 1928.
4727A4	36.0	10	Qv	Qv<75	Dec. 9, 1927–June 22, 1928.
4727F2	64.0	6	Qv	Qv<75	Dec. 17, 1930–Mar. 5, 1931.
4727L1	51.0	8	Qv	Qv<75	Dec. 10, 1930–Sept. 29, 1931.
4727P1	49.0	10	Qv	Qv<75	May 26, 1930–Nov. 22, 1932.
4734K3	51.8	10	Qv	Qv<75	Mar. 11, 1927–June 26, 1933.
4735G2	10.2		Qal	Qal	Aug. 21–Dec. 8, 1931; Apr. 18–May 2 and Aug. 3–Nov. 3, 1932.
4816N1	17.0	15	Qal	Qal	Jan. 7, 1927–Dec. 21, 1928; July 7, 1929–Feb. 18, 1930.
4821H1	20.5	60	Qal	Qal	Jan. 6–Dec. 3, 1927.
495Q1	19.0	24	Qal	Qal	June 25, 1927–Apr. 30, 1928.
5635F1	50.0	8	Qv	Qv<75	Dec. 16, 1927–Dec. 7, 1928.
5734A2	52.7	8	Qv	Qv<75	Dec. 7, 1927–Nov. 23, 1928.
5830D1	42.5	8	Tl	Tl	Do.

[1] The geologic classification conforms to the stratigraphic column for the Mokelumne area: Qal, alluvium; Qv, Victor formation (<75, less than 75 feet below the projected Arroyo Seco pediment, by interpolation); QTasl, Arroyo Seco gravel or Laguna formation (more than 75 feet below the projected pediment); Tl Laguna formation; Tm, Mehrten formation.
[2] Reported by owner or driller.

[2] List of observation wells in the Mokelumne area in which water-stage recorders have been operated [in the period Jan. 6, 1927, to Oct. 14, 1930]: U. S. Geol. Survey typoscript report, Oct. 14, 1930. Charts from water-stage recorders on observation wells in the Mokelumne area [in the period Oct. 14, 1930, to June 26, 1933]: U. S. Geol. Survey typoscript reports dated Oct. 15, 1931; Feb. 10, 1932; Apr. 30, 1932; July 15, 1932; Oct. 20, 1932; Jan. 18, 1933; Apr. 12, 1933; July 15, 1933.

Observation wells composing critical profiles in the Mokelumne area [1]

Lockeford profile

Well no.	Depth (feet)	Diameter (inches)	Depth of casing (feet below land surface)	Depth of perforations (feet below land surface)	Geologic classification (bottom of well)	Agencies [2]	Term of record [3]
4715C3 [4]	64.1	8	41	27–41	Qv<75	P, U, E	Apr. 22, 1930.
4714P1	234	6			QTasl	P, U, E	May 17, 1926.[5]
4714P3	75.9	10			QTasl	P, U, E	May 16, 1930.
4723M2 [4]	58.0	4	60	50–60	Qv<75	P, U, E	Apr. 22, 1930.
4724N1 [4]	60.0	4	60	50–60	Qv<75	P, U, E	Do.
4724P1 [4]	25.0	4	25	15–25	Qal	P, U, E	Do.
4725B2 [4]	37.0	4	39	29–39	Qv<75	P, U, E	Do.
4725B1	465				Tm	U, E	Oct. 31, 1929.
4725G1	545	14	50+		Tm	P, U, E	Apr. 22, 1926.
4725G3 [4]	23.0	4	26	16–26	Qv<75	P, U	Apr. 22, 1930.
4725M1 [4]	54.0				Qv<75	P	Dec. 22, 1931.
4725R3 [4]	27.0	4	29	19–29	Qv<75	P, U, E	Apr. 22, 1930.
4830N1	61.5	48	None		Qv<75	P, U	Sept. 10, 1926.[5]
4831L1	54.5	10			QTasl	P, U, E	Oct. 21, 1925.

Victor profile

Well no.	Depth (feet)	Diameter (inches)	Depth of casing (feet below land surface)	Depth of perforations (feet below land surface)	Geologic classification (bottom of well)	Agencies [2]	Term of record [3]
472N2	59.8	12			Qv<75	P, U, E	Sept. 2, 1930.
4715C3 [4]	64.0	8	41	27–41	Qv<75	P, U, E	Apr. 22, 1930.
4715Q2 [4 6]	55.0	10	55	45–55	Qv<75	U, P, E	May 16, 1930.
4722K2 [4]	53.0	8	53	41–51	Qv<75	P, U, E	Do.
4722Q4 [4 6]	51.0	10	51	39–49	Qv<75	U, P, E	Do.
4722Q5 [4 6]	266	10	79, 129–149		QTasl	U, P, E	Do.
4727F2 [6]	63.4	6			Qv<75	U, P, E	Do.
4727L1 [4 6]	51.0	8	51	41–51	Qv<75	U, P, E	Do.
4727P1 [4 6]	49.0	10	49	39–49	Qv<75	U, P, E	Do.
4734G1 [4]	30.0	8	30	20–30	Qal	P, U, E	Do.
4734K2	63.0	14	62		Qv<75	U	June 28, 1926–Apr. 2, 1930.
4734K3 [4 6]	54.0	10	48		Qv<75	U, E	Mar. 11, 1927.
373B1 [4 6]	48.0	8	48	38–48	Qv<75	U, P, E	May 16, 1930.
373G1 [6]	200	12			QTasl	U, E	Dec. 7, 1925–Jan. 17, 1929.[5]
373G3 [4 6]	37.0	10	26		Qv<75	U	Dec. 19, 1927–June 16, 1928.
373K2 [4 6]	52.0	10	52	42–52	Qv<75	U, P, E	May 16, 1930.
3710B4 [4 6]	50.0	8	50	40–50	Qv<75	U, P, E	May 17, 1930.
3710K3 [4 6]	57.0	10	57	47–57	Qv<75	U, P, E	June 7, 1930.
3710K4 [4 6]	190.0	12, 10	160		QTasl	U, P, E	Do.
3710Q1	65.2	6			Qv<75	P, U, E	Apr. 27, 1926.
3715C5 [4]	52.0	8	52	42–52	Qv<75	P, U, E	May 22, 1930.
3715P2 [4 6]	55.0	10	55	45–55	Qv<75	U, P, E	Do.
3722B1	217.0	14	95+		QTasl	P, U, E	Oct. 9, 1925.[5]
3727F1	60.0	6			Qv<75	P, U, E	July 18, 1929.
3727F3 [4]	46.0	8	46	36–46	Qv<75	P, U, E	May 25, 1930.

Cherokee Lane profile

Well no.	Depth (feet)	Diameter (inches)	Depth of casing (feet below land surface)	Depth of perforations (feet below land surface)	Geologic classification (bottom of well)	Agencies [2]	Term of record [3]
476A1	45.0	6			Qv<75	P, U, E	Oct. 22, 1925.[5]
477E2	49.0	12	21–27		Qv<75	P, U, E	Apr. 12, 1926.
4612R1	84.0	6	17		Qv<75	P, U, E	May 25, 1930.
4718N3 [4]	45.0	4	45	35–45	Qv<75	P, U, E	Apr. 12, 1930.
4719A1	91.3				Qv<75	P, U, E	Apr. 12, 1926.
4625D1	55.8	6	42		Qv<75	P, U, E	Do.
4730E4	75.5	6			Qv<75	P, U, E	Jan. 4, 1928.
4730J2	48	4			Qv	P, U, E	Do.
4731A1	60.5	4			Qv<75	P, U, E	Apr. 12, 1926.
4636H6	83.0	3			Qv<75	P, U, E	Jan. 20, 1930.
4636M2	54.0	8			Qv	U, E	Oct. 21, 1931–June 26, 1933.
4731J3	49.9	6			Qv	P, U, E	Oct. 19, 1929.
4731J9 [4]	27.0	4	27	17–27	Qv	P, U, E	Mar. 31, 1930.
4731N5 [4]	25.0	4	25	15–25	Qal	P, U, E	Do.
4731N1	34.9	8			Qv	L, P, U	Apr. 12, 1926.
361H1	51.1	10	40		Qv	L, U, E	Oct. 16, 1929.
376J8 [4]	40.0	4	40	30–40	Qv	P, U, E	Mar. 31, 1930.
376J6	76.8	6			Qv<75	P, U, E	Oct. 16, 1929.
377A1	38.9	6			Qv	P, L, U, E	Mar. 8, 1928.

See footnotes at end of table.

Observation wells composing critical profiles in the Mokelumne area—Continued

Cherokee Lane profile—Continued

Well no.	Depth (feet)	Diameter (inches)	Depth of casing (feet below land surface)	Depth of perforations (feet below land surface)	Geologic classification (bottom of well)	Agencies	Term of record
3612H1	40.5	6	--------	--------	Qv	U, E	Oct. 21, 1931–Dec. 19, 1932.
377J1	49.2	10	--------	--------	Qv	P, U, E	Oct. 16, 1929.
3612M3	165.0	10	--------	--------	QTasl	U, E, L	Jan. 22, 1930–June 27, 1933.
3718A1	63.1	6	--------	--------	Qv<75	P, U, E	Apr. 16, 1926–Apr. 12, 1933.
3718A10	37.5	6	--------	--------	Qv	U, P, E	Oct. 21, 1931.
3613R2	87.0	8	--------	--------	Qv<75	L	Jan. 23, 1930–May 19, 1933.
3719A2 [4]	40.0	4	40	30–40	Qv	P, U, E	Mar. 31, 1930.
3625D2	88.0	10	--------	--------	Qv<75	U, E	Oct. 21, 1931–June 9, 1933.
3730A5	55.0	7	--------	--------	Qv	U, E	Oct. 21, 1931.
3730E2	59.0	6	--------	--------	Qv	P, U, E	Apr. 17, 1926.[5]
3625R3 [6]	107.0	10	--------	--------	Qv<75	U, E	Oct. 15, 1929–June 26, 1933.
3625R4 [4, 6]	40.0	12	40	20–40	Qv	U, E	Feb. 17, 1932–June 26, 1933.
3731A1	59.0	6	10	--------	Qv<75	P, U, E	Apr. 19, 1926.
3636M2	64.0	10	--------	--------	Qv	U, E	Oct. 21, 1931–June 26, 1933.
3636R2	78.0	10	--------	--------	Qv<75	P, U, E	July 21, 1926.
276A1	77.6	8	--------	--------	Qv<75	U, E	Mar. 23, 1926.

Woodbridge profile

Well no.	Depth (feet)	Diameter (inches)	Depth of casing (feet below land surface)	Depth of perforations (feet below land surface)	Geologic classification (bottom of well)	Agencies	Term of record
368P1	44.9	8	--------	--------	Qv	P, U, E	Apr. 10, 1926.
368D2	36.3	4	--------	--------	Qv	P, U	July 14, 1926–Jan. 29, 1932.
364P3	43.7	8	--------	--------	Qv	E	Dec. 3, 1930.
369C1	93	8	25	--------	Qv<75	P, U, E	Apr. 10, 1926.
364H11 [4]	15.0	1.5	15	--------	Qv	E	Sept. 22, 1930.
363F1	116.8	12	80	--------	Qv<75	P, U	Apr. 26, 1929.
4634R1	34.0	10	--------	--------	Qv<75	P, U, E	Apr. 8, 1926.
4635L1	37.8	6	--------	--------	Qv	L	Jan. 22, 1930–May 19, 1933.
4636A1	35.0	6	--------	--------	Qv	P, U, E	Aug. 14, 1926.
4730E4	75.5	6	--------	--------	Qv<75	P, U, E	Apr. 12, 1926.

[1] Profiles listed in order downstream along the Mokelumne River; wells in order beginning at the north or west.
[2] U, Geological Survey; E, East Bay Municipal Utility District; L, city of Lodi; P, Pacific Gas & Electric Co. Sequence indicates decreasing frequency of measurements.
[3] If terminal date is not indicated, record has been maintained after July 5, 1933, by one or more of the agencies collaborating with the Geological Survey.
[4] Drilled and cased particularly for observation of ground-water levels.
[5] Also in 1906–7 or in 1913–14 by the Geological Survey.
[6] Water-stage recorder operated on the well; see preceding table for its term.

The observation wells just cited vary rather widely in depth and in submergence (the distance that the well extends below the ground-water level). Accordingly, it has been inferred that their water levels represent several distinct water-bearing zones and possibly separate bodies of ground water, owing to (1) the diverse physical character of the sediments penetrated and (2) a rude discrimination of water-bearing zones that is shown by the depths of irrigation wells in the intensively cultivated district—specifically in T. 3 N., Rs. 6 and 7 E., and T. 4 N., Rs. 6 to 8 E.

Depth is known for 1,437 irrigation wells in the district—that is, for about three-fourths of all. These depths range from 20 feet (well

3610K1, in the Woodbridge Irrigation District) to 910 feet (well 4728M1, in the pumping district north of the Mokelumne River). As the accompanying summary table shows, there is a wide range of depths in all parts of the district but also a progressive increase in average depth from west to east.

Depth of irrigation wells in the central district of the Mokelumne area

[Quantities in percentage of wells of known depth]

Depth range (feet)	T. 3 N., R. 6 E.		T. 4 N., R. 6 E.		T. 3 N., R. 7 E.		T. 4 N., R. 7 E.		T. 4 N., R. 8 E.
	West half	East half	West half	East half	West half	East half	West half	East half	
Less than 50	41	40	28	7.4	9.2	--------	3.2	--------	--------
50–99	44	40	57	53	30	21	40	18	3.4
100–199	14	18	10	32	43	43	35	33	--------
200–299	--------	1.4	3.4	5.4	16	15	8.4	15	24
300–399	--------	.3	1.2	1.3	1.2	9.7	5.8	11	38
400–499	--------	--------	--------	.7	.6	3.5	2.6	8.4	21
500–599	--------	--------	--------	.7	.3	3.5	2.6	7.6	6.9
600–699	--------	--------	--------	--------	--------	1.8	.5	5.9	6.9
700+	--------	--------	--------	--------	--------	1.8	1.0	--------	--------
Number of wells of known depth	134	289	88	150	324	114	190	119	29

If the stratigraphic horizon for the bottom of each well is expressed in distance above or below the projected Arroyo Seco pediment (see pp. 20–54), a frequency distribution of those distances has the following characteristics: (1) It is decidedly skewed, with the mode or average horizon about 20 feet below the projected pediment—that is, relatively

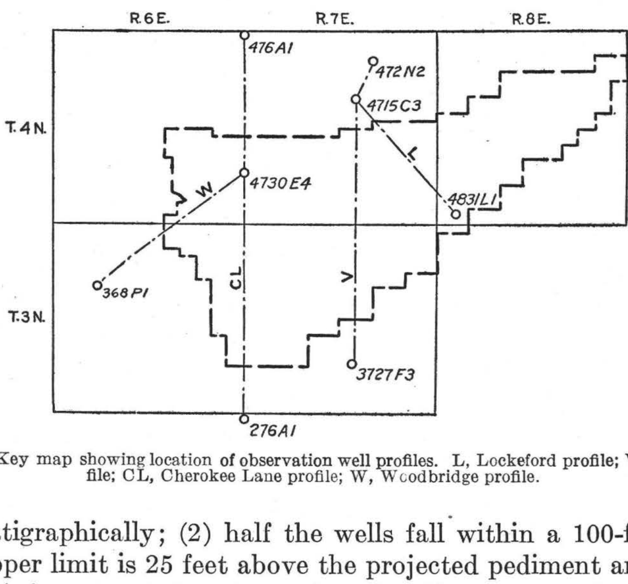

FIGURE 10.—Key map showing location of observation well profiles. L, Lockeford profile; V, Victor profile; CL, Cherokee Lane profile; W, Woodbridge profile.

high stratigraphically; (2) half the wells fall within a 100-foot zone whose upper limit is 25 feet above the projected pediment and whose lower limit is 75 feet below the projected pediment; (3) only 6 percent of the wells fall into the next lower 25-foot zone, but the percentage increases sharply for the classes that are still lower. In a district so intensively developed as the Mokelumne area, drillers would tend to shun thick impervious zones and would tend to bottom their wells in or slightly below the known water-bearing strata. Accordingly, it is inferred that impervious strata are relatively persistent between 75 and 100 feet below the projected Arroyo Seco pediment in the five townships involved in the foregoing statistical analysis. In the central part of the same district the base of the Victor formation has been fixed tentatively on lithologic grounds at a horizon about 25 feet higher than the relatively impervious zone just delimited. (See pp. 46–48.) Thus, the 100-foot zone in which half the irrigation wells bottom is approximately correlative with the part of the Victor formation that lies below the water table; also, the underlying zone of low perviousness is in the uppermost part of the Arroyo Seco gravel or the Laguna formation. Of the 1,437 irrigation wells of known depth, 77 bottom in the Mehrten formation and only 6 are so deep that they probably enter the Valley Springs formation; three-fourths of these 83 wells are north of the Mokelumne River and in the eastern half of the pumping district.

The following table shows the frequency distribution of irrigation wells among the stratigraphic zones just described:

Distribution of 1,437 irrigation wells of known depth in the central district, Mokelumne area, according to the stratigraphic zone in which they bottom

District	Geologic horizon [1]				
	Qv	Qv<75	QTasl	Tm	Tv
T. 3 N., R. 6 E., west half	116	17	1		
east half	158	108	23		
T. 4 N., R. 6 E., west half	56	26	6		
east half	15	113	22		
T. 3 N., R. 7 E., west half	23	136	164	1	
east half		14	88	12	
T. 4 N., R. 7 E., west half	2	97	83	8	
east half		10	75	34	
T. 4 N., R. 8 E.			1	22	6
The 5 townships	370	521	463	77	6

[1] Qv, definite Victor formation; Qv<75, probable Victor formation, a 75-foot zone lying immediately below the projected Arroyo Seco pediment; QTasl, Arroyo Seco gravel or Laguna formation; Tm, Mehrten formation; Tv, Valley Springs formation. There are no irrigation wells tapping the alluvium.

A corresponding segregation of the observation wells in the five central townships has led to a significant discrimination of ground-water levels. Thus, eastward about to Lockeford and the east boundary of R. 7 E., practically all wells that do not reach more than 75 feet below the projected Arroyo Seco pediment seem to tap a common body of unconfined water and seem competent to define the form of the regional water table (pp. 199–204), although the submergence of some wells exceeds 100 feet. Specifically, of 580 observation wells known to bottom in that zone (which is essentially equivalent to the

Victor formation and overlying alluvium), only 8 are known to have water levels that stand persistently as much as 0.5 foot above a piezometric surface passing through the water levels in the adjacent wells whose submergence does not exceed 50 feet. This classification disregards temporary recession of water levels in the deeper wells caused by the pressure effects of pumping (pp. 186–188). On the other hand, nearly all wells so deep that they reach more than 75 feet below the projected pediment—that is, essentially the wells that reach the Arroyo Seco gravel or some underlying formation—do not indicate water-table stage. Near the Mokelumne River the water levels in these deep wells stand below the water table, which is semiperched. In most deep wells remote from the river the water level stands above the water table except during the pumping season; thus, there is subartesian head (p. 218). Only 20 observation wells that bottom more than 75 feet below the projected pediment fail to show a persistent differential head of 0.5 foot or more in the nonpumping season, in spite of the fact that wells in the area commonly have their casings perforated opposite all coarse strata below the water table or else are uncased at depth. Owing to that construction practice, the many irrigation wells in the district may allow some of the artesian head to be dissipated by leakage; nevertheless the aggregate cross section of all wells is an insignificant fraction of the district's area, so that the loss of head is presumed to be small at most places.

Farther east, in R. 8 E., the water table passes successively into the Laguna and Mehrten formations, so that the preceding classification fails. However, with the exception of those that tap perched water (pp. 216–218), the wells whose submergence is less than 50 feet are accepted as defining the regional water table. Certain wells with greater submergence show artesian head.

The next table shows the frequency distribution of observation wells according to the geologic horizon in which they bottom.

Distribution of 825 observation wells of known depth in the central district, Mokelumne area, according to the stratigraphic horizon in which they bottom

District	Geologic horizon [1]					
	Qal	Qv	Qv<75	QTasl	Tm	Tv
T. 3 N., R. 6 E., west half		47				
east half		94	35	4		
T. 4. N., R. 6 E., west half		58	5	2		
east half	3	34	33	6		
T. 3 N., R. 7 E., west half	1	24	57	17		
east half			24	19	1	
T. 4 N., R. 7 E., west half	18	9	46	11	4	
east half	58		34	27	10	
T. 4. N., R. 8 E.	71		3	31	37	2
The 5 townships	151	266	237	117	52	2

[1] Qal, alluvium; other symbols as in corresponding table showing distribution of irrigation wells.

FLUCTUATIONS OF GROUND-WATER LEVEL

CAUSES OF FLUCTUATIONS

The level at which ground water stands in wells of the Mokelumne area—the so-called static level—is constantly rising or falling in response to changes in the hydrostatic pressure or pressure head of the ground water. The changes in pressure head, so far as they have been discriminated, are ascribed to (1) moving or changing load on the land surface (for example, railroad trains or trucks); (2) seismic disturbances or earthquakes; (3) variation of barometric pressure; (4) ground-water draft by vegetation; (5) infiltration of rain and certain indirect effects of rainfall; (6) infiltration of water applied to the land for irrigation; (7) variation in the discharge of streams; and (8) pumping from wells. Of these, the first three are extraneous forces that cause the ground-water level to fluctuate momentarily or through periods of a few hours or days. On the other hand, each remaining force or agency may cause cyclic fluctuations whose periods range from hours to years but at the same time may tend to depress or to raise the ground-water level steadily over a relatively long term. Evaporation appears not to affect the ground-water level over most of the Mokelumne area, although commonly it causes relatively large fluctuations in other areas where the water table is shallow. Fluctuations whose cycles cover a term of years are common; usually they are the net result of several forces whose individual effects cannot be discriminated.

FLUCTUATIONS CAUSED BY MOVING OR CHANGING LOAD ON THE LAND SURFACE

Stearns [3] has shown that in two wells near Victor (373G1 and 375L3, 4 miles and 2 miles east of Lodi, respectively) the water level rose momentarily about 0.01 to 0.03 foot whenever a train passed on the railroad close at hand but did not recede below its normal level. Both wells extended several tens of feet below the water table and tapped confined water. On the other hand, the water level did not fluctuate in one companion well (373G3), which was drilled just to the water table. Stearns concludes that the weight of the passing train compresses the underlying strata, so that the confined ground water assumes a share of the additional load, which it offsets by an increase in hydrostatic head. That increased head is transmitted to a distance in the confined water but does not influence the static level of the unconfined water at shallow depth, because the physical conditions necessary for the transmission of pressure are absent.

In another well (3617A1, 4 miles west and 1½ miles south from Lodi), which is only 20 feet south of the Kettleman-Terminous road,

[3] Stearns, H. T., Robinson, T. W., and Taylor, G. H., Geology and water resources of the Mokelumne area, California: U. S. Geol. Survey Water-Supply Paper 619, pp. 148–150, figs. 20, 21, 1930.

the ground-water level likewise rises abruptly at irregular frequency and then subsides quickly, the range amounting to less than 0.01 foot. Presumably these fluctuations are due to the passage of heavily loaded trucks on the road close at hand.

In two shallow water-table wells on the flood plain of the Mokelumne River near Lockeford certain sharp fluctuations of the ground-water level have been observed early in the rainy season. These fluctuations, 0.04 foot or less in amplitude, are presumed to have been an effect of the pressure of air entrapped in the soil during intense rainfall, the pressure causing the level in the well to rise suddenly and then recede gradually as the entrapped air escaped.

FLUCTUATIONS RELATED TO EARTHQUAKES

Fluctuations of the ground-water level due to earthquakes have been shown repeatedly by water-stage recorders on several wells in the Mokelumne area, typical instances having been described and figured by Stearns[4] and by Piper.[5] The fluctuations of greatest amplitude yet observed were caused by the earthquake of December 20, 1932, at Cedar Mountain, Nev.[6] The following table shows the magnitude of the water-level fluctuation in the eight wells of the Mokelumne area on which water-stage recorders were being operated by the Geological Survey during the earthquake. (See p. 124.)

Wells in the Mokelumne area equipped with water-stage recorders during the earthquake of Dec. 20, 1932

Well no.	Altitude of land surface (feet above sea level)	Mean altitude of water surface in well, Dec. 20–21, 1932 (feet above sea level)	Mean submergence of well, Dec. 20–21, 1932 (feet)	Amplitude of water surface fluctuation during earthquake (feet)	
				Rise	Fall
3612A2	46.9	23.78	52.9	0.490	0.255
3625R3	41.4	16.15	81.8	[1] .20	[1] .03
3625R4	41.2	16.16	15.0	None	None
3710K3	72.4	33.88	18.5	None	None
3710K4	72.2	33.92	151.7	.065	.185
4722Q4	83.6	43.10	10.5	None	None
4722Q5	83.8	44.02	226.2	.240	.205
4734K3	82.2	47.52	17.1	None	None

[1] Approximate.

[4] Stearns, H. T., op. cit. (Water-Supply Paper 619), pp. 145-151; Record of earthquake made by automatic recorders on wells in California: Seismol. Soc. America Bull., vol. 18, pp. 9–15, 1928.

[5] Piper, A. M., Fluctuations of water surface in observation wells and at stream-gaging stations in the Mokelumne area, California, during the earthquake of December 20, 1932; Am. Geophys. Union Trans. 14th Ann. Meeting, pp. 471–475, 1933. Morris, S. B., Fluctuations of water levels in wells during the Nevada earthquake of December 20, 1932 (paper before Seismol. Soc. America, Apr. 8, 1933).

[6] Gianella, V. P., and Callaghan, Eugene, The Cedar Mountain, Nevada, earthquake of December 20, 1932: Am. Geophys. Union Trans. 14th Ann. Meeting, pp. 257–260, 1933.

All the wells penetrate the unconsolidated Victor formation, but, as the table shows, those that disclosed water-level fluctuations during the earthquake extend 50 feet or more below the water table and tap confined water. Companion wells extending less than 20 feet below the water table disclosed no fluctuations at the time. Six of the wells are arranged in pairs of one shallow and one deep well a few feet apart (3625R3 and R4, 3710K3 and K4, 4722Q4 and Q5). All the water-stage recorders were of the same type; also, at the time, the planes of their float wheels lay in different quadrants of the compass, but at each pair of wells the float wheels were parallel to one another. Thus, mechanical features of the recorders and the orientation of the recorders with respect to the maximum amplitude of the earth vibrations are not competent causes for the observed difference in the behavior of the ground-water levels in the shallow and deep wells.

Seemingly the fluctuations resulted from a single momentary pressure wave. On the original charts from wells 3612A2 and 4722Q5 the vertical trace produced during the earthquake is somewhat wider where it crosses the normal trace, as if the oscillation of the water surface had continued for several minutes with diminishing amplitude, but this is not conclusively indicated. Furthermore, on the chart from well 3710K4, the trace of the water surface after the earthquake was displaced downward an amount equivalent to 0.165 foot with respect to the trace immediately before the earthquake. However, when the recorder was inspected on December 27 the measured altitude of the water surface agreed with that indicated by the trace. Evidently the downward displacement reflected an actual subsidence of the water surface, suggesting that the earthquake produced in the water-bearing bed a condition of elastic strain which was dissipated so gradually in the ensuing 6 days that it did not deflect the trace noticeably.

The subjoined table lists the earthquakes whose effects have just been described and all others that are known to have caused fluctuations in wells of the Mokelumne area from July 1, 1930, to July 1, 1933. Most of these had epicenters along the western coast of North America. None of the others caused fluctuations of the ground-water level even approaching the amplitude of those just described, but the effect of the disastrous earthquake in northern Japan on March 2, 1933, is noteworthy owing to the great distance of the Mokelumne area from its epicenter.

Earthquakes known to have caused fluctuations of ground-water levels in wells of the Mokelumne area, July 1, 1930–July 1, 1933

Date	Time at epicenter (Pacific standard)	Location of epicenter (latitude and longitude)	Character of shock	Fluctuations of ground-water level				
				Approximate time (Pacific standard)	Amplitude (feet)			
					Well 3612A2	Well 3625R3	Well 3710K4	Well 4722Q5
1931								
Jan. 14	5:50:20 p. m.	16° N., 96° W. (Mexico)	Strong	6:00 p. m.	0.09			0.08
Jan. 16	11:19:26 a. m.	14.5° N., 96° W. (Mexico)	Moderately strong	11:20 a. m.	.04			
1932								
June 3	2:36:36 a. m.	17° N., 104° W. (Mexico)	Strong	3:00 a. m.	.09	0.03+		.06
June 6	12:44:12 a. m.	42° N., 123° W. (Eureka, Calif.)	do	12:45 a. m.	.06	.02		.02?
Dec. 20	10:10:04 p. m.	38.5° N., 118° W. (Cedar Mountain, Nev.)	do	10:40 to 11:30 p. m.	.74	.23	0.25	.44
1933								
Mar. 2	9:31:00 a. m.	39.5° N., 143.5° E. (northern Japan)	do	10:45 to 11:30 a. m.	.02	.02?		.06
Mar. 10	5:54:12 p. m.	33°40′ N., 118°02′ W. (Long Beach, Calif.)	do	6:10 p. m.	.19	.07		.12
Mar. 16		37.5° N., 122° W. (Niles, Calif.)	do	3:50 a. m.	.08			.03

NOTE.—Data as to the time, location, and character of earthquakes from preliminary determinations of epicenter by the U. S. Coast and Geodetic Survey and from records of the seismograph station of the University of California at Berkeley.

Recently F. B. Blanchard, of the East Bay Municipal Utility District, and Perry Byerly,[7] of the seismographic station of the University of California at Berkeley, have collaborated in assembling a water-stage recorder with an extended time scale. Having been installed on well 3612A2 in the Mokelumne area, it has recorded minute fluctuations of the ground-water level during earthquakes and offers a method for sorting out the dilatational components of the earth motion.

Fluctuations of the ground-water level of the sort just described indicate work done through the earth motion but not the magnitude of the force involved. In the Ogden Valley of Utah the magnitude of the pressure wave set up by an earthquake has been measured by Leggette and Taylor [8] in a confined artesian well and compared with the corresponding change in hydrostatic head as traced by a water-stage recorder in a companion well.

FLUCTUATIONS DUE TO VARIATION IN BAROMETRIC PRESSURE

The effect of variation in barometric pressure upon ground-water levels is suggested by the accompanying diagram (fig. 11), which compares graphic records for three wells of the Mokelumne area (3710K3, 3710K4, and 4715Q2) and for the barograph at the station of the United States Weather Bureau in Sacramento, about 40 miles to the northwest. On the diagram the scale of barometric pressure is taken equivalent to feet of water; also, the graph of barometric pressure is plotted in inverted position, because an increase in barometric pressure would tend to depress the water level in wells. Thus, the fluctuations in water level and in barometric pressure are comparable directly; their close correlation is obvious. Throughout the 11-day period represented by the diagram practically the only fluctuations of the ground-water level were those traceable to fluctuations of barometric pressure, although the graphs tend to diverge because both ground-water levels and barometric pressure tended to rise. It is evident that if the pressure had remained constant, the ground-water level would not have oscillated but would have risen steadily. The oscillations are the effects of a succession of major barometric "highs" and "lows" associated with cyclonic storms; they are common only during the winter—that is, from October to March—because cyclonic storms do not prevail in central California in the other seasons. Throughout the year, however, the solar heating of the atmosphere commonly induces a diurnal barometric cycle. Owing to that cycle the water level tends to rise in wells from about 10 a. m. to 6 p. m. and then to decline. Usually the fluctuation is less than 0.1 foot. On figure 11 the hydrographs for the three wells repeatedly include small

[7] Byerly, Perry, and Blanchard, F. B., Well gauges as seismographs: Nature, vol. 135, no. 3408, pp. 303-304, 1935. Blanchard, F. B., and Byerly, Perry, Well-gauge seismometer: Seismol. Soc. America abstract 98, p. 61, April 1935.

[8] Leggette, R. M., and Taylor, G. H., Earthquakes instrumentally recorded in artesian wells: Seismol. Soc. America Bull., vol. 25, no. 2, pp. 169-175, April 1935.

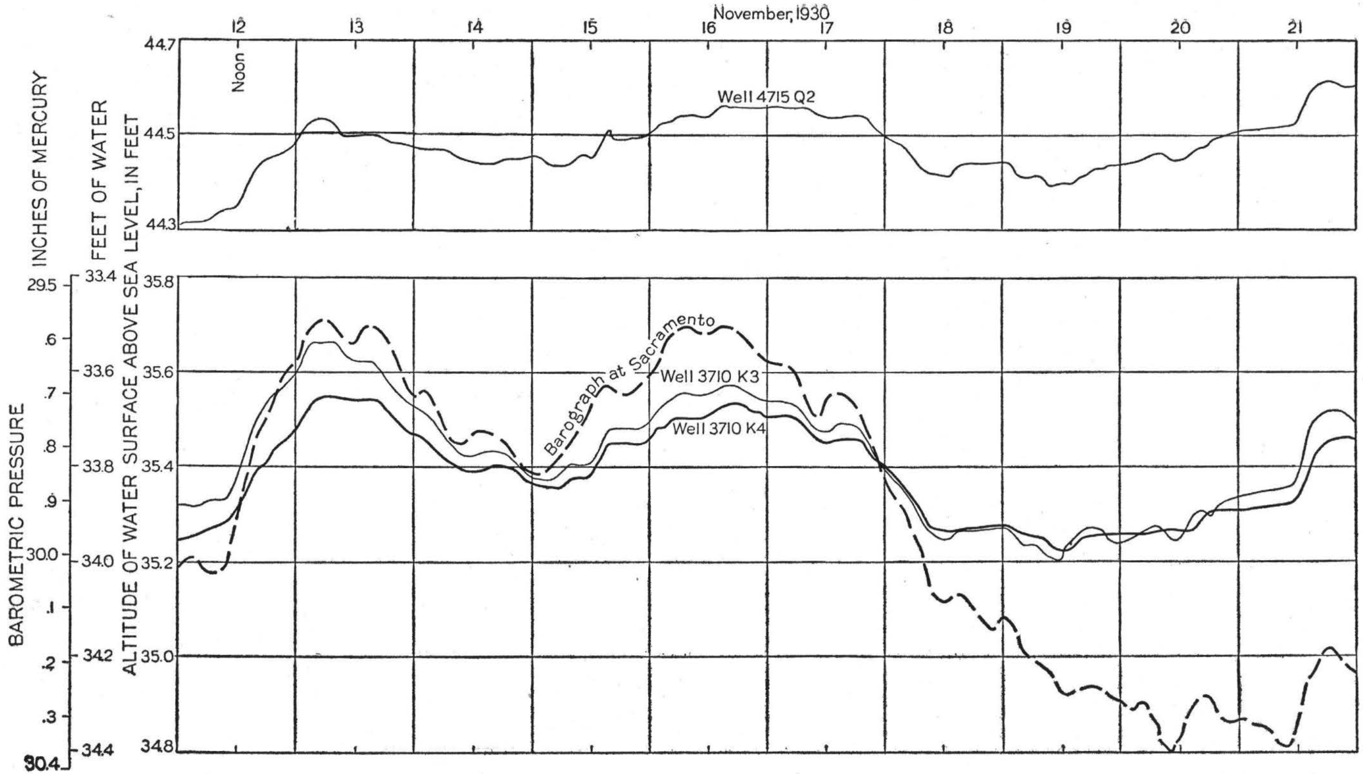

Figure 11.—Fluctuations of ground-water level in three wells of the Mokelumne area in relation to barometric pressure at Sacramento, Calif.

dimples about midday; these are effects of the diurnal barometric cycle superposed on the greater fluctuations due to the cyclonic storms.

In some wells the fluctuations related to cyclonic storms are virtually the only short-term fluctuations of the ground-water level during the winter, as is shown by plate 8, which comprises condensed hydrographs for the wells along the Victor profile and the graph of daily mean barometric pressure at Lodi from October 1930 through January 1931. Obviously the hydrographs for wells 3710B4, 3710K3, and 3710K4, correspond rather closely with the graph of barometric pressure; in those wells the amplitude of the short-term fluctuations in ground-water level was as great as 0.5 foot and as much as 65 percent of the corresponding changes in barometric pressure. In all those wells the short-term fluctuations due to barometric cycles were superposed upon a steady rise of the ground-water level. In certain other wells (373K2, 3715C5, 3715P2, 4727P1, and 4722Q5) the short-term fluctuations due to barometric change did not exceed 0.2 foot, and in yet other wells (373B1, 4722Q4, and 47427L1) the ground-water levels seem not to have been affected. Although the levels in these three shallow wells did not respond to barometric fluctuations during this period, it should not be inferred that this condition exists at all times. Rather, in well 373B1, certainly, and in 4722Q4, possibly, the ground-water level responds to diurnal barometric fluctuations under certain conditions of submergence. (See pp. 185–186.) Similarly, in wells 3625R3 and 3625R4 of the Cherokee Lane profile (pl. 9) the short-term fluctuations of water level from November 1932 through March 1933 correspond closely with fluctuations in barometric pressure.

In the corresponding season of the following year (1931–32) minor fluctuations of water level occurred simultaneously in wells 3710K3, 3710K4, and 3715P2 and suggest barometric control, although the daily barometric pressures at Lodi are not available. Similar fluctuations occurred in well 4722Q5 during the nonpumping season. The hydrograph for well 3710B4 in this same year is drawn from only 6 to 10 measurements of depth to water a month, yet it indicates the magnitude of the effect of barometric cycles upon the water level nearly as well as the hydrograph for the preceding year, which was based upon daily measurements or upon the continuous graphic record from a water-stage recorder.

Because fluctuations of water level due to barometric cycles have been recognized in most of the wells equipped with water-stage recorders, it is inferred that they are equally common in the other wells of the Mokelumne area. They seem not to be restricted to wells of any certain depth nor to wells that reach any particular geologic horizon. Response of water levels to barometric fluctuations appears to be no indication of a regional artesian condition in the Mokelumne area, for the well that has the greatest known percentage response (3710K3) extends less than 20 feet below the water table. However, all the wells whose static levels do not respond to barometric cycles are shallow. It has been shown that in the Mokelumne area the range in the water level due to barometric cycles may be as great as 0.5 foot. From that cause alone any single measurement of depth to water may deviate several tenths of a foot from the mean depth of that week or month; indeed, for some wells, the deviation is believed to be a large fraction of the yearly range in ground-water level—especially wells on the dissected Arroyo Seco pediment, where ordinarily the yearly range is small. Thus, for the outlying parts of the Mokelumne area such deviations might introduce an appreciable percentage error into an estimate of the net yearly change in ground-water storage. For the central part of the area, however, they are completely masked by the much larger fluctuations caused by other forces.

FLUCTUATIONS DUE TO DRAFT BY VEGETATION

During the growing season considerable water is absorbed through the roots and transpired from the leaves of plants. The rate of transpiration is greatest during the day and small or even zero during the night, because it is induced largely by solar energy. To meet that water requirement, many native plants and crop plants must rely on moisture stored in the soil above the water table, but certain species habitually send their roots down to the water table or to the capillary fringe that lies immediately above it and thus draw water from the zone of saturation.[9] Owing to that draft by vegetation, the ground-water level commonly declines during the day and recovers during the night, so that it fluctuates diurnally.[10] From his intensive investigation in the Escalante Valley of Utah White [11] says:

> There is a marked daily fluctuation of the water table nearly everywhere in fields of ground-water plants. The water table generally goes down during the daytime, when transpiration is rapid. Usually the water starts down at 9 to 11 a. m. and reaches its lowest stage at 6 to 7 p. m. At 7 to 9 p. m. the water begins to rise, and it continues to rise until 7 to 9 the next morning. As a rule the daily draw-down is somewhat greater than the nightly recovery, the deficiency in recovery indicating the rate of seasonal decline of the water table. In general the daily fluctuations begin in the spring with the appearance of foliage and cease in the fall after killing frosts. They do not occur in plowed fields, cleared lands, tracts of sagebrush, and areas where the water table is far below the surface. Generally the daily fluctuations vary directly with the temperature, wind movement, and intensity of sunlight and inversely with the humidity, and they follow more or less closely the daily fluctuations in evaporation from a free water sur-

[9] Meinzer, O. E., Plants as indicators of ground water: U. S. Geol. Survey Water-Supply Paper 577, 95 pp., 1927.

[10] White, W. N., A method of estimating ground-water supplies based on discharge by plants and evaporation from soil—results of investigations in Escalante Valley, Utah: U. S. Geol. Survey Water-Supply Paper 659, pp. 23–54, 1932.

[11] Idem, pp. 23–24.

face. They are also affected somewhat by changes in barometric pressure. Usually the greatest draw-down occurs on hot windy days. The water table remains constant or rises on cloudy days accompanied by rain and falls on cloudy days with no rain but not so much as on sunny days. The amount of the daily fluctuation varies with the stage and vigor of plant growth.

In the Mokelumne area it is only along the flood plain of the river and in certain parts of the Woodbridge Irrigation District west of Lodi that the water table is so close to the land surface that the common ground-water plants, chiefly alfalfa, willows, and native brush, may draw directly from ground water. Three wells which were dug by the Geological Survey on the flood plain near Lockeford disclose the relative magnitude of the fluctuations induced by several types of vegetation, as follows: 4735G2, willows and other species of native brush; 4725G4, irrigated alfalfa; and 4725E2, nonirrigated alfalfa. A fourth well on fallow land, 4725E1, and a gage-height station on the Mokelumne River below Lockeford Bridge, both close at hand, afford standards of comparison. The locations of these wells are shown on plate 14. The greatest depth to water measured in any of the four during 1931 or 1932 was about 14 feet; accordingly the water table or the capillary fringe was generally within reach of the plant roots.

At the four wells and the river station water-stage recorders were operated discontinuously in 1931 and 1932. Typical water-level fluctuations occurred from October 28 to November 1, 1931. In that period the stage of the river varied as much as 0.05 foot a day, owing largely to regulation at the Pardee Dam, upstream, whereas the ground-water stage was steady at the well on fallow land (4725E1) and thus was not influenced by river stage or by soil-water evaporation. In contrast, at each of the three wells that were surrounded by ground-water plants the ground-water level fluctuated diurnally; usually it was highest about noon, declined rapidly during the afternoon, and rose less rapidly during the early morning. In order of decreasing amplitude, the fluctuations in the three wells were as follows: 4735G2, in native brush, daily range 0.07 foot, afternoon decline lasting about 11 hours, or until about midnight; 4725E2, in nonirrigated alfalfa, daily range 0.03 foot, term of decline about 7 hours, or until about 6 p. m.; 4725G4, in irrigated alfalfa, daily range about 0.01 foot. The small daily range in well 4725G4 is believed to have indicated the relative magnitude of the ground-water draft, the adjacent alfalfa having drawn heavily from moisture stored in the soil by previous irrigation and only lightly from ground water. The two wells in alfalfa were along the borders of their respective tracts, but their fluctuations are believed to have been typical, because the amplitude and time phase of those fluctuations were verified near the centers of the tracts in supplemental observation wells (4725E3 and 4725G5). These diurnal fluctuations in ground-water stage were independent of the range in river stage and were of the type that White [12] has ascribed to ground-water draft by plants.

As would be expected the ground-water draft by vegetation appears to be greater in midsummer than in late autumn, for the daily range in ground-water stage is then greater. For example, at well 4725E2 the diurnal range during the first 10 days of September 1931 was about 0.06 foot, whereas in the first 10 days of November it was only about 0.03 foot. Moreover, during September the decline in ground-water stage owing to transpiration draft generally began about 9 a. m., whereas in November it began about noon.

During most of the growing season of 1932 the discharge of the river was so regulated at the Pardee Dam that its stage fluctuated considerably each day in the lower reaches of the stream (pl. 12); beneath parts of the flood plain the ground-water stage fluctuated in response and nearly coincided in time with the fluctuation due to transpiration. Thus, hydrographs for wells 4735G2 and 4725E2 indicate that in 1932 the diurnal range in ground-water stage was materially greater than in 1931; however, the effect of transpiration alone was indeterminate.

In another well (4816N1), which is on the flood plain of the Mokelumne River about 1½ miles west of Clements, the ground-water level has fluctuated diurnally, presumably owing to ground-water draft by trees about 25 feet from the well. In that well the water table is commonly 10 to 15 feet below the land surface. The diurnal recession continues for about 12 hours during daylight but generally is less than 0.02 foot. Stearns [13] reproduces a hydrograph for still another well (4821H1) depicting similar diurnal fluctuations of the ground-water level; those fluctuations he ascribes to transpiration from trees close at hand. In that well the ground-water level began to decline about 5 p. m.—that is, several hours later than in the several wells just described—and remained nearly stationary at night. According to White,[14] fluctuations of that type are usual where the water table is in a stratum of pervious sand or gravel.

FLUCTUATIONS RELATED TO RAINFALL

In the Mokelumne area fluctuations of ground-water level related to rainfall are common and include two types—(1) fluctuations that result from rain penetrating to the water table and that measure the increase in ground-water storage, and (2) certain fluctuations that are related indirectly to rainfall although induced primarily by variations in the rate of pumping from wells.

The fluctuations due to deep infiltration of rainfall are the more obvious, though perhaps the less frequent. Where the water table is

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[12] White, W. N., op. cit., pp. 23–54.
[13] Stearns, H. T., op. cit. (Water-Supply Paper 619), p. 136, fig. 17.
[14] White, W. N., op. cit., p. 24.

less than 20 feet below the land surface—that is, chiefly along the western margin of the Victor alluvial plain, on the Delta plain farther west, and along the flood plain of the Mokelumne River—the effect of certain single storms is evident in most wells, but usually no such effect can be detected where the water table is more than 30 feet deep. For an example of the influence of rainfall on the stage of a shallow water table, figure 12 comprises a graph showing accumulated rainfall at Lodi in 1931–32 and hydrographs showing ground-water stage in four wells near the west margin of the Victor alluvial plain (3615C1, 3619B1, 3625R3, and 4630N1). In each of the four wells the rise of the water table was accelerated after the storms of December 21–31, 1931, and February 5–10, 1932. That area is served by the gravity canals of the Woodbridge Irrigation District (p. 148), but in 1932 gravity irrigation did not commence until March 5; therefore, the rise of the water table in these wells was not caused by seepage from the canals or their distributary ditches (pp. 150–152). Also, each well is far from the Mokelumne River and from any intermittent stream that might flow during storms; accordingly, the rise of the water table cannot be attributed to stream run-off. The graph that shows rainfall is plotted with its vertical scale six times as great as the scale of the hydrographs for the wells, so that it indicates hypothetical fluctuations of ground-water stage in a material which has a specific yield of 16⅔ percent by volume and which transmits all the rainfall to the water table immediately. The influence of single storms on the stage of the water table is shown best by the hydrograph for well 3619B1. Rain prior to mid-December amounted to 3.43 inches but failed to accelerate the moderate and steady rise of the water table that had continued throughout the autumn; apparently that quantity of rain was dissipated in replenishing the initial soil-water deficiency. However, before the end of the storm period of December 21–31, during which 6.29 inches of rain fell, the water table began to rise much more rapidly, presumably as soon as the soil had been wetted in excess of its specific retention. That rapid rise continued unchecked for at least 3 weeks and less rapidly for 2 weeks longer; altogether, the ground-water level rose from 10.7 to 7.6 feet below the land surface, a total rise of 3.1 feet. After the storm of February 5–10, during which 2.78 inches of rain fell, the water table rose even more sharply than in December; the infiltration lagged very little after the storm and was completed by February 16, probably owing to the facts that the depth to the water table was only about two-thirds as great as in December and that the moisture capacity of the soil had been thoroughly satisfied theretofore. A minor storm of 0.96 inch on March 15 appears to have checked a downward trend of the ground-water level and to have caused a further and final rise amounting to 0.2 foot, although its rainfall was less than during one storm in October and

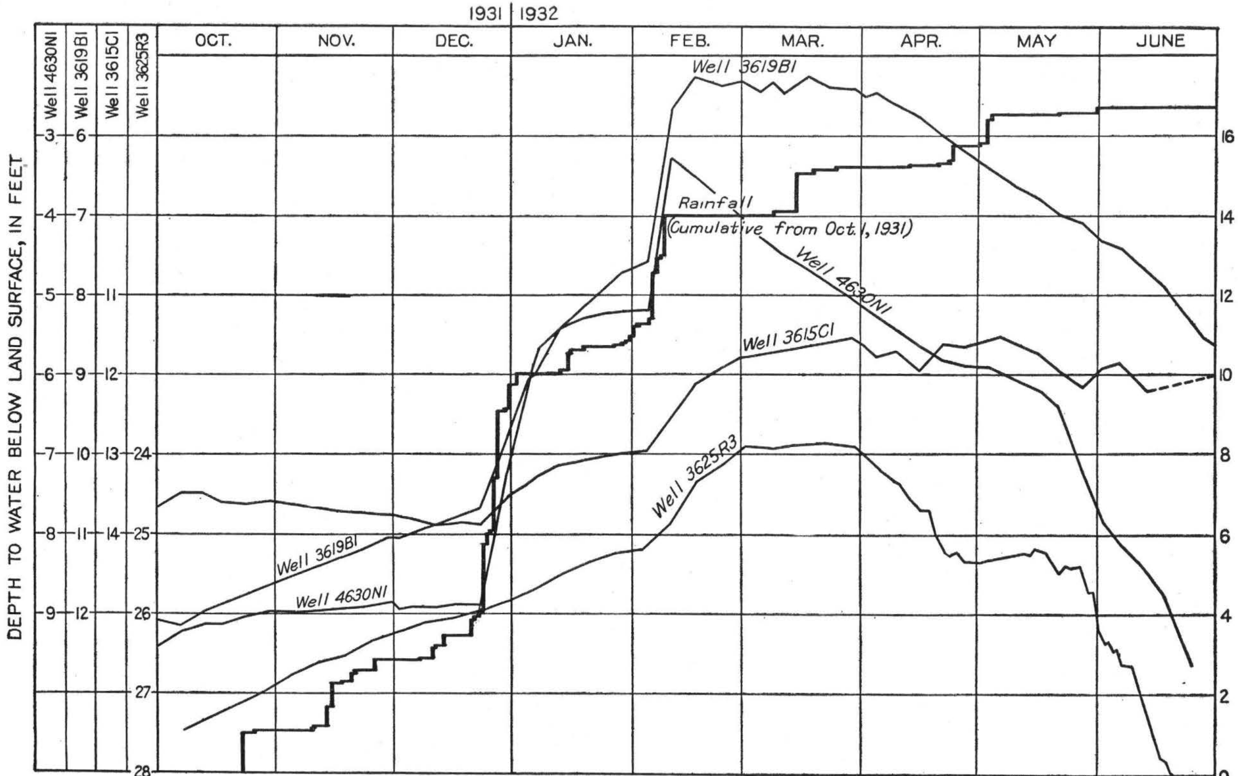

FIGURE 12.—Hydrographs for four wells near the west margin of the Victor alluvial plain and graph showing accumulated rainfall at Lodi, 1931–32.

during another in November which had been inadequate to replenish the soil-moisture deficiency. After March 17 none of the rain appears to have penetrated to the water table, probably because it was inadequate to offset the growing soil-moisture deficiency. Each of the foregoing effects of rainfall is reflected in the hydrograph for well 4630N1; at that well the depth to water was generally less than in well 3619B1, and the term of infiltration following each storm was correspondingly shorter. In well 3615C1 the effect of the rainfall on the ground-water stage was similar except that the rise was only about half as great, although it continued until late March, or about 6 weeks longer, possibly owing to slight infiltration after the storm of March 15 or to infiltration from irrigation in the Woodbridge Irrigation District. Those differences may have been due largely to differences in the specific retention of the soil and in the specific yield of the material saturated by the rise.

In well 3625R3 the steady autumn rise of the ground-water level was accelerated but slightly after the storm period of December 21–31, and this acceleration continued about a week longer than in wells 3619B1 and 4630N1. Presumably the smaller rise and greater lag resulted in part from the greater depth to the water table, which was 26 feet below the land surface when the storm began. Owing to that relatively great depth, the wavelike advance of infiltration from the single storm so early in the season would have been largely damped before any water penetrated to the water table. After the storm of February 5–10, however, the ground-water stage in this well rose about as sharply as in well 3615C1 and with about the same time lag, presumably because the soil-moisture deficiency had been fully replenished by that time. The rise was not sustained so long, for some recession took place after March 2 and was checked only briefly after the storm of March 15. Again, the ground-water stage was probably not influenced directly by the storms in late April and early May, the terrace on the hydrograph for that period having been an effect of pumping (p. 192).

The close correlation between rainfall and fluctuations of the ground-water stage in 1931–32 was repeated in most observation wells within the Woodbridge irrigation district and on the Delta plain farther west, at least in those wells whose ground-water stage was determined with competent frequency. (See also the hydrographs for the southerly three wells of the Cherokee Lane profile, pl. 9; also those of pl. 11.) In none of those wells did the rise of ground-water stage fall outside the range already shown on figure 12. With the exception of well 3615F3, those wells are shallow, and their static levels ordinarily indicate the stage of the regional water table. Accordingly, it seems obvious that ground-water storage was increased generally by deep infiltration of rainfall in that particular district and year. Competent records are not now available to show whether deep infiltration of rainfall would have induced fluctuations of the ground-water level in tightly cased deep wells in the particular district.

Along the flood plain of the Mokelumne River the water table commonly is within 5 to 15 feet of the land surface, and presumably its stage tends to respond to individual storms in the fashion already described. However, a regional storm generally produces ephemeral run-off and thereby causes the river stage to rise briefly; this rise of itself induces a response in ground-water stage close to the river (p. 166) and repeatedly has masked the rise that would have been expected from rainfall infiltration alone. Nevertheless, in one observation well on the flood plain (4725G5) for which there is a competent record of fluctuations during 1931–32 the ground-water stage rose in unmistakable response to infiltration after the storms of December and February. That well is about 2,500 feet from the river and near the outer margin of the flood plain (see pl. 14); it is the single observation well on the flood plain that has a competent record covering the particular period and that is known to lie beyond the reach of the fluctuations of ground-water stage induced by range in the river's discharge. In wells on the flood plain of Dry Creek the ground-water level is generally within 25 feet of the land surface, but here also storm run-off causes the ground-water level to rise and makes it difficult to evaluate rainfall infiltration alone.

Storms in certain other years, too, have affected the ground-water levels appreciably. Thus, at certain wells in the Woodbridge Irrigation District the ground-water stage rose after storms in February and March 1927; at that time the irrigation canals were drained. The major fluctuations in well 265R1 during the same year have been ascribed by Lee[15] to rainfall infiltration, although he was unable to correlate ground-water stage with single storms, because in that well the stage had been determined only once a month. That well is about 4 miles southeast of well 3619B1 (fig. 12); in 1926–27 its static level was less than 11 feet below the land surface. Some miles to the northeast the same storms caused the ground-water stage to rise in well 4821H1, which is close to the south or outer margin of the flood plain of the Mokelumne River near Clements. Certain minor fluctuations of the ground-water stage in 1930 might be ascribed, though not with assurance, to deep infiltration following moderately intense rainfall in late February and March.

Three years have been cited during which the ground-water stage along the west margin of the Victor alluvial plain and along the flood plain of the Mokelumne River is known to have risen in response to recharge from rainfall—namely, 1926–27, 1929–30 (possibly), and,

15 Lee, C. H., The interpretation of water levels in wells and test holes: Am. Geophys. Union Trans. 15th Ann. Meeting, pt. 2, p. 545, 1934.

most obviously of the three, 1931–32. In other years during the investigation by the Geological Survey no rise of ground-water stage from rainfall infiltration has been recognized at any observation well. In those other years not only has the rainfall been less than the long-term average but the individual storms have been neither unusually long nor heavy. Furthermore, although the water table has been relatively shallow, nevertheless it has ordinarily been deep enough over most of this particular district for the capillary fringe to lie below the reach of evaporation and transpiration. Given those conditions, it is scarcely to be expected that the rainfall would have been adequate to replenish the initial soil-water deficiency, satisfy the draft by evaporation from the soil, and yet induce recharge in a quantity so great that the ground-water stage would have been heightened obviously. In general substantiation of this conclusion, soil-moisture inventories have indicated that the quantity of deep infiltration from rainfall at bare-land plats on the Victor plain was small or negligible in 1929–30 but was material in 1931–32; also that in 1930–31 and 1932–33 the initial soil-water deficiency was never fully replenished.

The foregoing demonstrations imply that in one year or another the infiltration of rain has tended to raise the ground-water stage beneath the higher parts of the Victor plain—in particular, within the district of intensive ground-water pumping (p. 184). There the water table is relatively deep, commonly as much as 40 feet beneath the land surface, yet the initial soil-water deficiency is probably not materially greater than farther west. That deficiency should have been satisfied as early in the rainy season, and about the same quantity of soil water should have become available for deep infiltration although the greater depth of the water table would tend to damp thoroughly the wave-like infiltration from a single storm. The storms of late December 1931 and early February 1932 are those most likely to have effected ground-water recharge in recent years. In the pumping district the ground-water stage was rising steadily through December and January, owing largely to recovery from the pumping of the preceding season; accordingly the presumptive gradual recharge from rain would easily have been overlooked. By February pumping had begun again at some places (see pl. 8) and had depressed the ground-water levels so much by pressure effects and by unwatering that recharge from rain could not possibly have been discriminated. Thus the implication that such recharge has taken place generally over the pumping district remains valid. Its effect may be measurable indirectly in the net recession of the ground-water levels from one year to another, and perhaps directly in an unseasonable addition to ground-water storage early in 1932 (p. 211).

In a number of outlying wells to the north, east, and south of the district of intensive pumping, the net annual fall or rise of ground-water stage appears to depend upon the yearly rainfall, although the short-term fluctuations seem not to be correlative with single storms. However, because the discharge of streams [17] and the quantity of water pumped from wells for irrigation [18] both depend also upon the yearly rainfall, fluctuations of the ground-water level that are caused by those two variables (pp. 159–196) might falsely be correlated directly with rainfall. A true correlation is undertaken on figure 13, which comprises long-term hydrographs for five wells that are outside the areas of influence of either the Mokelumne River or Dry Creek and are 0.75 mile to 3 miles from the nearest irrigated land. During the 7-year period represented by the hydrographs the ground-water level declined progressively in each of the wells, the aggregate fall having ranged between 2.1 feet in well 5826H1 and 7.2 feet in well 389Q1. The short-term fluctuations of the ground-water level in these wells have been of small amplitude, in sharp contrast to the large fluctuations in wells that are influenced by streams and by pumping plants. On the diagram the greatest deviation of stage in each year above the average trend of the ground-water levels is indicated by small circles. The net yearly recession in stage, measured between the successive maximum deviations, differs among the several wells in any particular year, also from one year to another. In each well, however, the recession has usually been greater after a season of little rainfall and less after a season of abundant rainfall. For instance, the ground-water level declined at a slower rate in 1930 and 1932, after winters with moderately abundant rainfall, than it did in 1929 and 1931, which followed seasons with deficient rainfall. Figure 14 compares the net yearly recessions for the several wells with the weighted mean yearly rainfall for the Mokelumne area. The relatively close correlation is obvious.

In these five wells the ground-water level ranges from about 70 feet below the land surface in well 572D1 to about 185 feet in well 4931J1. Accordingly, the absence of recognizable short-term fluctuations of the level in response to individual storms may very well have been due to the damping and gradual merging of the successive infiltration waves as they advanced downward to the water table; the tendency toward merging of that sort, even where the water table is within 25 feet of the land surface, has already been mentioned. On the other hand, the correlation between the net yearly recession and the yearly rainfall suggests that infiltration may go on during much of the year, but that the quantity of infiltration is greater during periods of abundant rainfall.

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[17] Pritchett, H. C., Bue, C. D., and Piper, A. M., Seepage loss and gain of the Mokelumne River, California: U. S. Geol. Survey typoscript report, figs. 32 and 33, p. 33, June 5, 1934.

[18] Piper, A. M., Pumpage of ground water for irrigation in the Mokelumne area, California, 1933, and revised estimates of pumpage, 1927 to 1932: U. S. Geol. Survey typoscript report, pp. 68–69A, fig. 3, Apr. 9, 1934.

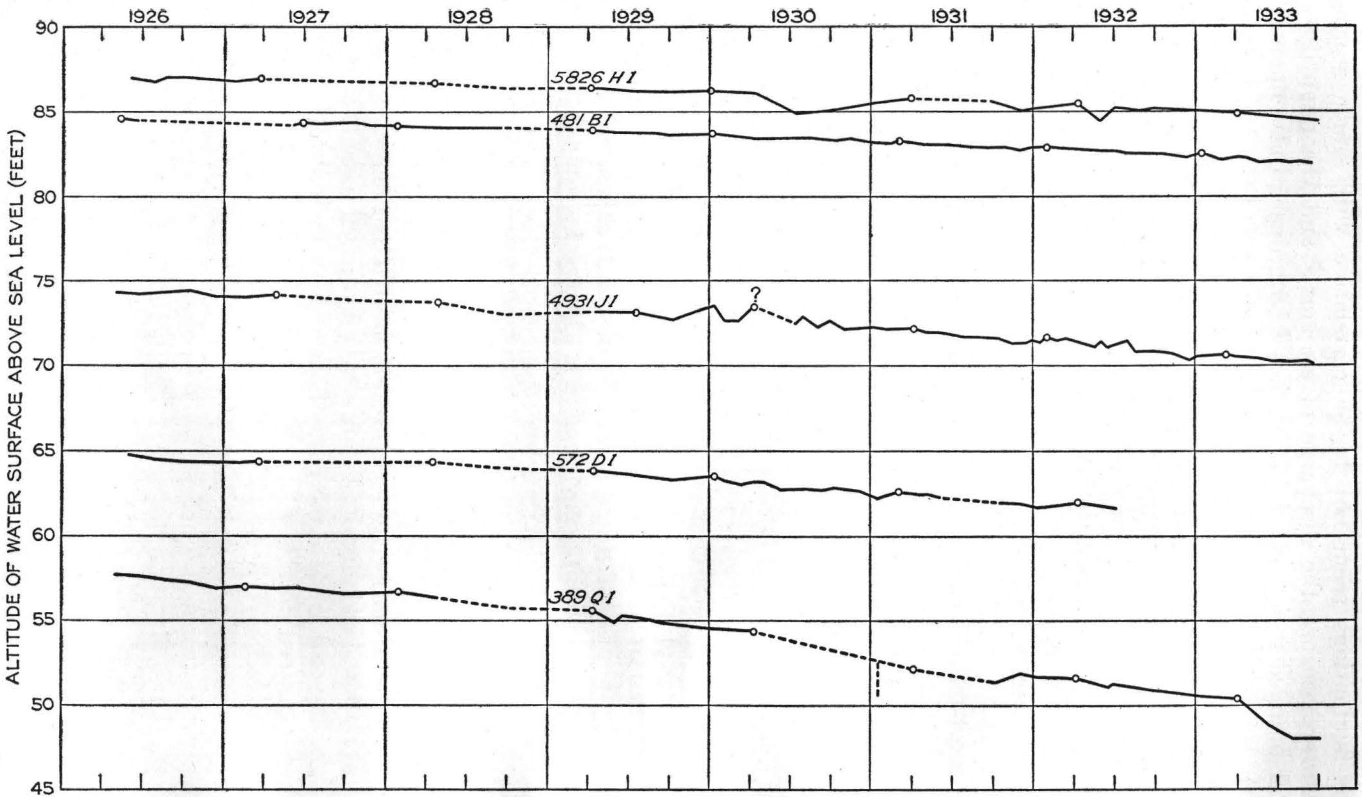


FIGURE 13.—Hydrographs for five wells in which the net yearly recession of the ground-water level from 1926 to 1932 appears to have been related to yearly rainfall.

The most obvious indirect effect of rainfall upon ground-water levels is the sharp recovery that takes place within the district of ground-water pumping if numerous pumps are stopped during a long storm.

An analogous indirect effect of rainfall has taken place in several water-table wells that are outside the area of intensive ground-water pumping and outside the areas influenced by the Mokelumne River

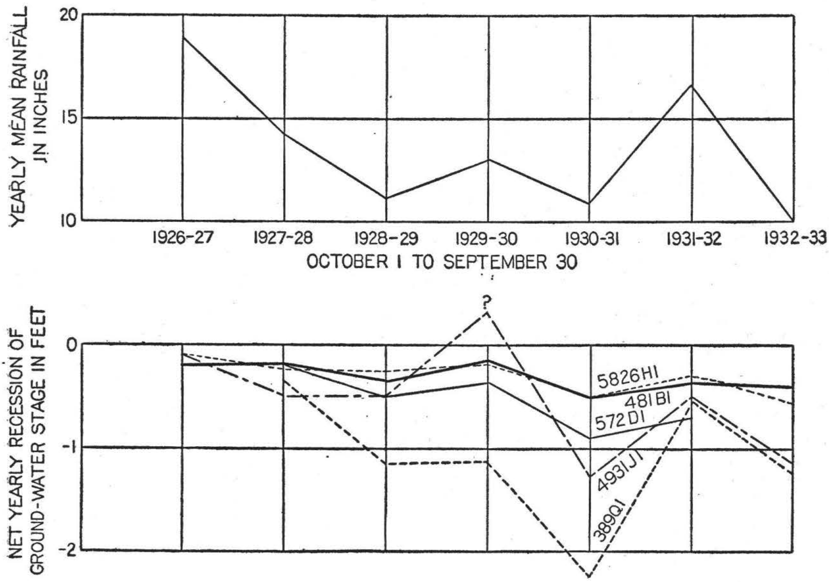


FIGURE 14.—Mean yearly rainfall and corresponding net yearly recession of ground-water level in the five wells whose hydrographs constitute figure 13.

and Dry Creek but are less remote than the marginal wells already described. These wells are in T. 5 N., Rs. 6 and 7 E., and T. 3 N., Rs. 7 and 8 E. In them also the yearly recession in ground-water level corresponds closely with the yearly rainfall. However, the seasonal range in ground-water stage is much greater than in the marginal wells—commonly as much as 4 feet—and the fluctuations are contemporaneous with those of wells within the pumping district. It seems likely, therefore, that these fluctuations are to be ascribed in part, probably in greater part, to pumping (p. 193).

In a few wells the water level has risen inordinately soon after certain storms, so that it seems to have stood for a time above the regional ground-water stage. In well 373K2, for example, the water surface rose 0.8 foot from December 29 to January 1, 1931–32 (see pl. 8), after 6.29 inches of rain in the 10 days preceding. Prior to the rise the water level had stood 37 feet below the land surface. The well is 52 feet deep and is cased to its bottom with 14-gage stovepipe casing, of which the lower 10 feet is perforated; it was drilled for the particular purpose of observing fluctuations of ground-water level and appears to have been in adequate condition to yield trustworthy records. A month later the water level in the same well rose 10.3 feet on February 6 to 9, during a rain of 2.78 inches; within 5 days the water level had receded 5 feet, but it did not regain its normal stage until 3 weeks had passed. During that extraordinary rise the land adjacent to the well was not being irrigated, as it was later, when the water level rose 9.9 feet beginning April 24. Similarly, in well 3811J1 several measurements of depth to water which appear to be erratic—notably those of February 27, 1928, January 21, 1929, and January 7, 1932—were taken 1 to 5 days after heavy rain. Two tenable explanations suggest themselves for fluctuations so odd—namely, (1) water drains into the well from the land surface or from saturated soil at shallow depth and produces a seeming water level, which recedes more or less slowly, depending upon casing conditions and the permeability of the adjacent sediments; and (2) owing to infiltration of rain, a perched zone of saturation is created intermittently above a stratum of low permeability, the stage of the perched water table being indicated accurately by the well. The latter condition is known to exist at certain places after infiltration of water applied to the land for irrigation (pp. 157–159). Under that particular condition the perched water table would recede to the regional level only as rapidly as the perched water drained downward through wells and laterally to the edge of the restraining stratum.

FLUCTUATIONS INDUCED BY IRRIGATION IN THE WOODBRIDGE IRRIGATION DISTRICT

Certain fluctuations of ground-water level in wells of the Mokelumne area are obviously related to the operation of irrigation works or result from the deep infiltration of water applied to the land for irrigation. Such fluctuations are especially conspicuous within the Woodbridge Irrigation District, which diverts water from the Mokelumne River and which, by gravity canals, serves numerous discontinuous tracts in the western part of the area, mostly in Tps. 3 and 4 N., Rs. 5 and 6 E. Plate 10 shows that those tracts are scattered over a district which is 20 miles long (from north to south) by 6 miles wide and which is bounded on the east by the area of intensive pumping from wells, on the south by the natural channel of the Calaveras River, on the west by the zero or sea-level contour on the land surface, and on the north by the Mokelumne River. In the 7 years from 1926 to 1933 the total area so irrigated by gravity has ranged from 4,089 acres in 1928 to 10,630 acres in 1931. The yearly diversion from the river has ranged from 25,600 acre-feet in 1927 to 87,000 acre-feet in 1932; the time has ranged from 175 days in 1927 to 334 days in 1931, having begun usually in March or April and ended in November or December.[20]

Diversion is effected at Woodbridge by an open-weir dam with removable flashboards. The sill of the dam is 26.6 feet above mean sea level, and its crest is at 40.6 feet when all flashboards are in place.[21] During diversions in recent years the water-surface altitude just above the dam has been regulated through a maximum range of 6.4 feet and up to a maximum altitude of 41.6 feet, as the following table shows. Under those conditions the Woodbridge Reservoir has attained an ordinary maximum water-surface area of about 600 acres and its backwater effect has extended upstream as much as 11 miles—that is, about to the bridge north of Victor.[22] On the other hand, ordinarily all flashboards except a few have been removed during the nonirrigating season, so that the water level above the dam has varied about 15 feet each year.

Water-surface altitudes above mean sea level in the Woodbridge Reservoir at the dam during periods of diversion, 1927–33

[Based on measurements from crest of west wing wall of dam in the period ending Dec. 17, 1930; thereafter from water-stage recorder in the forebay of the Woodbridge Canal]

Term of diversion [1]	Water-surface altitude (feet)		
	Highest stage	Lowest stage	Range
May 4–Oct. 26, 1927	41.6	37.8	3.8
Mar. 23–Nov. 14, 1928	41.2	37.6	3.6
Mar. 1–Nov. 27, 1929	41.1	36.1	5.0
Apr. 4–Dec. 17, 1930	41.4	37.5	3.9
Jan. 15–Dec. 31, 1931	40.8	36.3	4.5
Mar. 4, 1932–Jan. 7, 1933	41.2	35.8	5.4
Mar. 9, 1933–Jan. 9, 1934	41.6	35.2	6.4

[1] Includes intervening short periods when the reservoir was drained, partly or wholly.

Until 1935 Smith Lake, a southern arm of the Woodbridge Reservoir, was separated from the main body by levees at its upstream and downstream ends. The downstream levee was overtopped at an altitude of 39.2 feet, and the ridge that separates the lake from the inner channel of the river was overtopped at several places at 40 to 41 feet. Thus, when the flashboards were above these critical altitudes the reservoir and lake were connected. Furthermore, the downstream levee was pierced by a 24-inch pipe and gate valve, which provided the only outlet for the lake when its altitude was less than 39.2 feet. The bottom of the pipe stood at 30.8 feet. The floor of the channel that joins the lake and outlet rises to 33.6 feet at a high section midway of its length. Thus, between altitudes of 39.2 and 33.6 feet the level of

[20] Pritchett, H. C., Bue, C. D., and Piper, A. M., Seepage loss and gain of the Mokelumne River, California: U. S. Geol. Survey typoscript report, p. 171, June 5, 1934.

[21] Idem, p. 44.

[22] Idem, pp. 45, 86.

the lake might have been controlled so that it stood above or below the level of the main reservoir, although regulation of that sort was not ordinarily practiced. Below 33.6 feet the lake became landlocked. Water stored in the lake below that level, after all movable flashboards had been taken from the dam, was withdrawn permanently from the river channel and is presumed to have been dissipated by seepage chiefly, for during the nonirrigation season evaporation is generally less than rainfall. The foregoing relations are brought out by comparative hydrographs on plate 11. The hydrograph for Smith Lake records a minor sharp rise of the water level beginning December 24, 1931, and another on February 7, 1932; those were obvious products of intense rainfall (see fig. 12) coupled with local run-off from the lake shores. With those exceptions, the fluctuations in stage of the two surface-water bodies were mainly the direct and indirect effects of regulation. Obviously, they were reflected closely in fluctuations of the ground-water level in shallow wells close at hand—for example, in wells 4635L1 and 4634R1 of the Woodbridge profile—although certain minor fluctuations in the wells were not due solely to changes of surface-water stage. They appear to have been reflected in part and with considerable lag in a deep well (363F1) 0.8 mile from Smith Lake. No instance is known of direct response to filling and draining of the reservoir in any well more remote.

Early in 1935 extensive changes were made in the levees and other works about Smith Lake, and a new practice in water-level regulation was begun.

Farther east, about the head of the Woodbridge Reservoir, notable recessions of ground-water stage take place in water-table wells soon after the reservoir is drained and its backwater effect is dissipated. For example, in the period December 31, 1931, to January 5, 1932, the river stage fell 2.9 feet at the Cherokee Lane bridge; in the same 6 days the ground-water level declined as much as 0.7 foot in the closest five wells of the Cherokee Lane profile (pl. 9). Those wells are within 0.3 mile of the river. Recession continued at a slower rate the remainder of the month and terminated when the reservoir was again filled in early February. In 1932, ground-water recession due to reservoir manipulation began as early as mid-August in certain wells of that profile, and it continued into March 1933.

The foregoing are by no means the only types of water-level fluctuations caused by operation of the Woodbridge Irrigation District. Indeed, in all parts of the district the ground-water stage fluctuates almost universally with the filling and draining of canals and laterals and with the application of water to the land. For example, plate 11 includes hydrographs for four representative wells (364H11, 364P3, 368D2, and 3616D2) within the gravity-irrigation district. All four are shallow water-table wells, ranging in depth between 13 and 44 feet.

Plates 1 and 10 show the positions of these wells with respect to the south branch canal, to lateral ditches, and to irrigated lands.

During 1931 the south branch canal was first filled on January 17, was drained on February 24, and then was refilled for the remainder of the irrigation season on March 12. Distribution of water through laterals in sec. 4, T. 3 N., R. 6 E., probably began somewhat later in March. As plate 11 shows, the ground-water stage in well 364H11, nearest the canal, failed to rise materially during the preliminary diversion in January and February but rose 4.1 feet between March 26 and April 15; in analogous fashion, the ground-water stage in well 364P3 rose 5.2 feet between March 27 and April 20, whereas in well 368D2 it rose gradually and reached a peak on April 28. Thus the peaks in the latter two wells lagged about 5 days and 13 days, respectively, behind the corresponding peak in well 364H11. Thereafter, until the irrigation season waned in early October, the ground-water stage in the three wells seems to have fluctuated in rude proportion to the flow through the branch canal. From October to December the average diversion by the irrigation district was only 25 second-feet—that is, about 15 percent of the diversion during July. In response, the ground-water stage at well 364H11 fell rapidly in September and early October, then remained nearly steady throughout November; at the other wells it declined gradually and lagged noticeably behind well 364H11. It is characteristic that the ground-water stage at these representative wells stood higher throughout the irrigation season than at any other time of year.

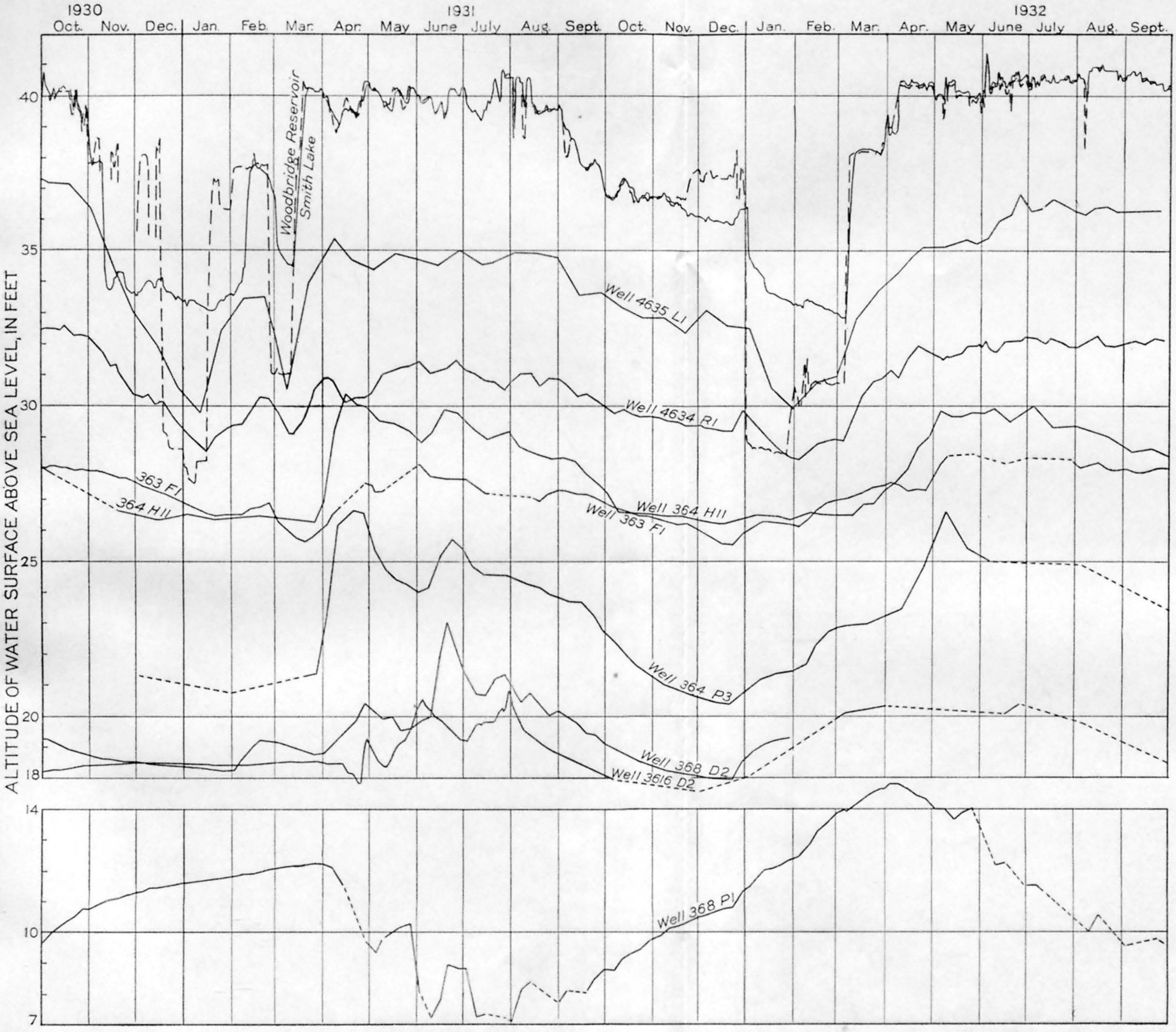
The fluctuations of ground-water stage in well 3616D2 are not correlative in time with those just described, though their trace on the hydrograph is of similar form. They are especially instructive because (1) they were determined by means of a water-stage recorder, so that their form is known in detail, and (2) the sharp rises to the peaks of April 29, June 4, and July 30, 1931, are known to have followed closely after irrigation water was applied on land adjacent to the well and to have terminated with the irrigation. Because the well is relatively remote from the permanent canals and laterals, it seems obvious that the particular rises just cited were due to deep penetration of some of the water applied on the land.

The four hydrographs just discussed (364H11, 364P3, 368D2, 3616D2; pl. 11) typify a condition that is believed to prevail in the Woodbridge Irrigation District—namely, that the conspicuous rises of ground-water stage are induced in part by seepage from canals and laterals and in part by deep penetration of water applied to the irrigated land. Possibly the first of these causes is the less effective, as is suggested by the failure of well 364H11 to respond to the initial filling of the south branch canal in January 1931, although that canal is but 50 feet away. Conversely, it is concluded that the conspicuous recessions of ground-water stage indicate lateral percolation away from the area of ground-water recharge after the obvious source has failed.

In contrast, the remaining hydrograph on plate 11 shows the characteristic fluctuations of ground-water stage in another water-table well (368P1) which is a short distance west of the land served by the south branch canal but on land irrigated entirely by pumping from wells. In that well the stage is usually lower during the irrigation season than at any other time and is highest just before pumping begins—that is, about as the reservoir is being filled.

Three of the hydrographs that constitute figure 15 show fluctuations of the ground-water stage that are typical for the Woodbridge Irrigation District. They represent (1) well 4619R1, which is in the central-northern part of the district and about 400 feet north of its northwest branch canal; (2) well 4634R1, which is about 50 feet southwest of Smith Lake (see pl. 11); and (3) well 3615C1, which is in the central-southern part of the district, 1,400 feet southwest of an angle in the south branch canal and 500 feet from the nearest land served by that canal. All these wells are shallow; in them, the least depth to the water table has been 4 feet below the land surface and the greatest depth 17 feet. In all, the major water-level fluctuations have been synchronous with the filling and draining of the canals throughout the 8-year term; also the yearly range has been relatively small for wells in the intensively cultivated part of the Mokelumne area. (See pls. 8, 9.) These features of the fluctuations are largely peculiar to wells in the Woodbridge Irrigation District. However, certain minor fluctuations have been due to infiltration of rain after exceptional storms (p. 142).

Several features of the hydrograph for well 4619R1 are somewhat peculiar to wells in the northern part of the irrigation district: (1) the low ground-water stage of the year has risen steadily, the total rise from 1927 to 1933 having been about 2.5 feet, or about 0.4 foot a year; (2) except in 1932, when the ground-water stage in the district was heightened generally by infiltration of rain, the yearly range in stage has tended to decrease—specifically, from 5.2 feet in 1926–27 to 2.6 feet in 1933, although it was least (2.4 feet) in 1930–31; and (3) the high stage of the year fell steadily from 1927 through 1930 but subsequently rose until in 1933 it was approximately equal to the high stage of 1926. Those features are related to progressive changes in the regimen of the diversions through the Woodbridge Canal—namely (1) diversion in quantity has tended to begin earlier and to end later each year, so that the canals (especially the northwest branch canal) have been drained for a shorter and shorter term; (2) the maximum diversion has tended to occur somewhat later and to be longer, especially since 1930; and (3) the gross yearly diversion has tended to increase, par-



HYDROGRAPHS FOR THE WOODBRIDGE RESERVOIR, FOR SMITH LAKE, AND FOR CERTAIN WELLS ALONG THE WOODBRIDGE PROFILE IN 1930–31 AND 1931–32

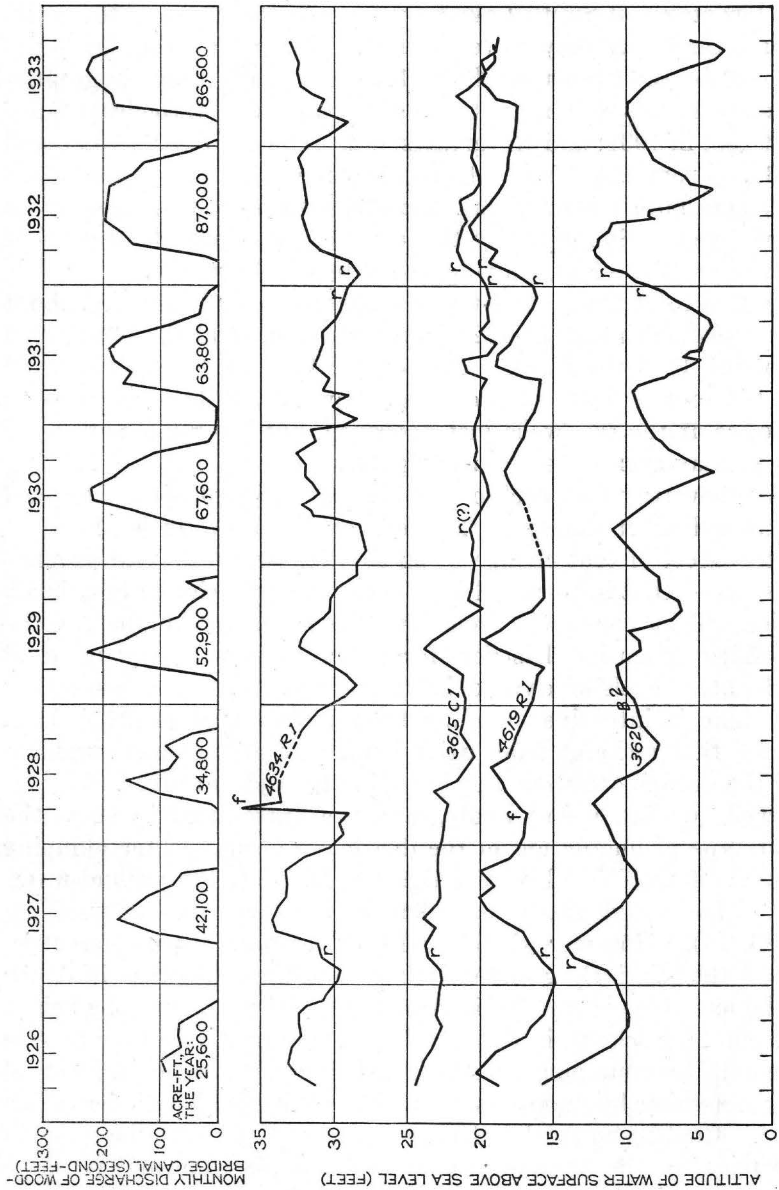


FIGURE 15.—Typical fluctuations of ground-water level in the Woodbridge Irrigation District in relation to the discharge of the Woodbridge Canal and to fluctuations in an area of ground-water pumping farther west, 1926–33. f, Rise induced by the record freshet of March 1928; r, rise due to infiltration of rain.

ticularly in the 4 years beginning with 1930 in comparison with the 4 years preceding.

The hydrograph for well 4634R1 shows the effect of Smith Lake upon the ground-water stage in wells close at hand; it extends the term of a corresponding record shown by plate 11. After each irrigation season the decline of ground-water level in well 4634R1 has lagged somewhat after that in wells 4619R1 and 3615C1, very much as the low stages of Smith Lake have lagged after those of the reservoir and canals as they were drained. Except for the brief rise occasioned by the freshet of March 1928, the yearly range in ground-water stage at this well has not changed progressively; the least range was 2.9 feet in 1931, and the greatest was 4.6 feet in 1927, 1928, and 1930–31. From 1926 until about 1930 the high and low ground-water stages both tended to fall, the average rate having been about 0.6 foot a year. Subsequently the low stage has risen about 0.4 foot a year, whereas the high stage has been relatively steady.

At well 3615C1 the ground-water stage ordinarily has varied about 2 feet a year, although in 1929 it varied about 4 feet. From 1926 until about 1930 the mean ground-water level at the well receded about 0.8 foot a year; subsequently, however, it has not trended upward, as at the two wells just described, but has remained nearly steady or may even have receded slightly.

It is noteworthy that each of the three hydrographs just discussed indicates a distinct change in the trend of ground-water levels about 1930, the effect of that change being to heighten subsequent ground-water stages—that is, to retard or to check any recession or to quicken any rise. That change in trend is believed to be unique for the Woodbridge Irrigation District, for it contrasts with the trend of ground-water levels elsewhere in the Mokelumne area, especially where there is intensive pumping from wells. (See pl. 22.) It is presumed that recharge from irrigation in the district has served to retard the decline occasioned by pumping in adjacent areas.

At well 3620B2, whose hydrograph was introduced to show the distinct type of fluctuation in the district of ground-water pumping southwest of the Woodbridge Irrigation District, the ground-water level has fluctuated nearly as widely as in other areas of pumping (figs. 25, 26). However, the annual hydrograph is more symmetric, owing to the relatively gradual decline from the high stage in April; thus the low stage is reached in September rather than at the height of the pumping season, in June or July. The relatively slow decline throughout the pumping season is attributed to replenishment of the ground-water by underflow from the area served by the irrigation district. Replenishment by that means would of course be greatest in the midst of the pumping season, when infiltration and recharge from the gravity-irrigation district would be greatest. In certain years, notably 1929, the ground-water stage rose somewhat in the midst of the pumping season; possibly a rise of that sort may also be ascribed to recharge by underflow. Between 1926 and 1930 the ground-water level in the well declined about 1.5 feet a year, but subsequently that decline appears to have been entirely abated. Presumably the abatement was due to increased underflow from the Woodbridge Irrigation District, for doubtless the water-table gradient toward the well had been steepened steadily by increased pumping to the west and by increased use of gravity water to the east.

FLUCTUATIONS INDUCED BY IRRIGATION IN THE PUMPING DISTRICT

In certain wells on the flood plain of the Mokelumne River the ground-water level is raised at times by recharge from water that is pumped from the river and applied to the plain for irrigation. For example, in July and August 1927, 1928, and 1931, the ground-water level in well 4816N1 rose sharply after irrigation on the flood plain and then subsided gradually to its normal stage, as is shown by prominences on its hydrograph (fig. 16). The land within one-eighth mile of this well is watered from river pumps 35 and 37,[23] whose monthly discharge is shown by the following table:

Monthly draft, in acre-feet, from the Mokelumne River by pumps 35 and 37, 1927–31

Year	Pump no.	April	May	June	July	August	September
1927	35	0	0	0	18.0	3.7	0
	37	0	12.7	34.2	48.3	38.6	0
1928	35	0	0	0	13.5	11.8	0
	37	0	19.4	9.4	50.2	62.3	0
1929	35	3.8	3.2	.6	0	20.2	2.7
	37	6.3	9.2	63.8	8.7	99.0	26.9
1930	35	12.1	.6	0	23.4	11.7	0
	37	0	24.0	48.5	44.6	51.8	33.6
1931	35	6.5	2.6	0	13.7	0	0
	37	59.7	60.2	31.6	92.3	49.1	3.0

Each prominence on the hydrograph rises abruptly, has a rounded crest, and declines gradually; its form is entirely dissimilar to those due to recovery from pumping. Moreover, at the time there were no fluctuations of river stage so pronounced as to be a competent cause for the fluctuations of ground-water level. The obvious cause seems to have been deep penetration from irrigation. Recharge from irrigation in 1929 and 1930 is also suggested by the hydrographs, although in those years the fluctuations of the ground-water level were largely masked by pronounced fluctuations induced by the river.

Certain fluctuations of the ground-water level in some wells within the area of intensive pumping are probably caused by recharge from irrigation on the adjacent land. For instance, in well 373B1 of the Victor profile the water level rose 1.5 feet during the 13-day period from February 25 to March 9, 1931 (see pl. 8), maintained that higher altitude until March 25, and then declined 1.2 feet in the next 18 days. A similar fluctuation occurred in well 4734K3 nearly a month later. In the same two wells, similar but even greater rises occurred in April 1932, also between March and July 1933. Quite evidently none of these particular fluctuations were caused by a variation in

[23] Pritchett, H. C., Bue, C. D., and Piper, A. M., Seepage loss and gain of the Mokelumne River, California: U. S. Geol. Survey typoscript report, pp. 139–162, June 5, 1934.

stage of the Mokelumne River. Rather, each of them coincided in time with the operation of river pump 21 and of the pumping plants on certain wells that jointly serve the land adjacent to the two wells. Accordingly, the particular fluctuations are ascribed with fair assur-

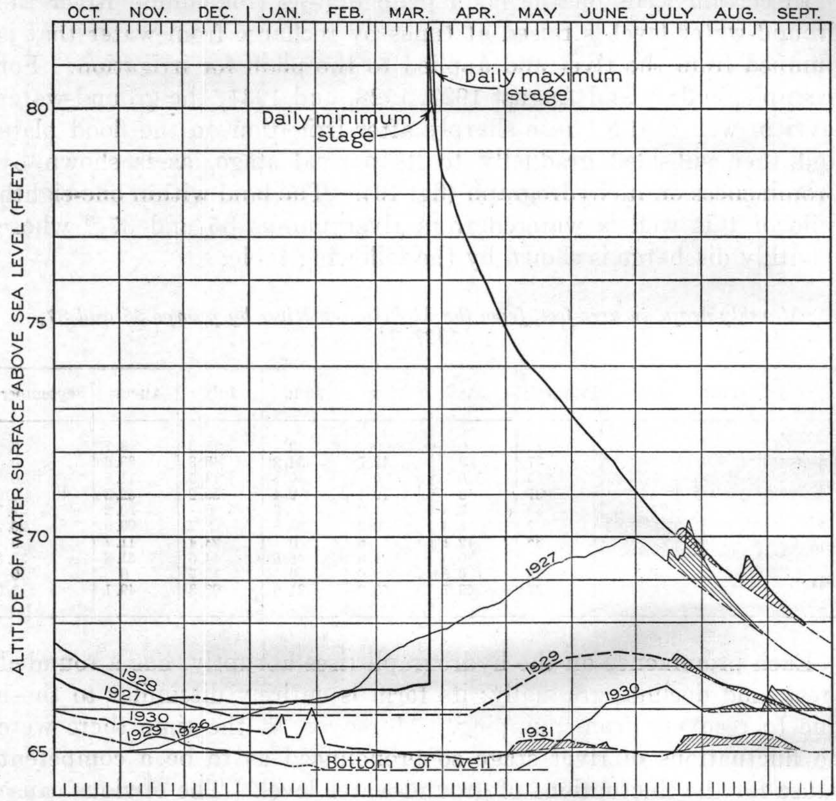


FIGURE 16.—Hydrograph for well 4816N1 showing fluctuations of the ground-water level due to recharge from irrigation (shaded areas), 1927–31.

ance to intermittent local recharge from irrigation. They are taken to indicate accurately the local rise of the water table as deep penetration ensues from irrigation, also the decline which ensues when irrigation ceases and the stored water is dispersed by lateral percolation.

From the foregoing statements it might be inferred that recharge from irrigation occurs commonly in the intensively cultivated central district, which is watered by pumping from wells. That such may be the case is indicated by the intermittent existence of a perched zone of saturation beneath certain irrigated tracts. Because commonly the water table is relatively deep, however, and because the draft by pumps causes the ground-water levels to fluctuate through a rather wide range throughout the irrigation season (pp. 185–196), few fluctuations due chiefly to recharge from irrigation have been discriminated in the individual records from wells in the heart of the pumping district. Nevertheless, certain pronounced additions to ground-water storage in the later part of the pumping season are believed to indicate recharge from irrigation in considerable volume. (See pp. 208–211.)

Like those associated with deep penetration by rain (p. 147), certain brief fluctuations of the water level in some wells are presumed not to indicate the stage of the regional water table. These may be caused by irrigation water running into the well from the land surface or from the soil zone, or by irrigation water becoming perched above a slightly permeable stratum until it drains downward through wells or laterally by percolation to the edge of the restraining stratum. As a suggestive example of the first type, the water level in well 373K2 of the Victor profile (pl. 8) stood at an altitude of 36.27 feet at noon on April 25, 1932, but within 16 hours had risen 9.82 feet, apparently owing to irrigation near the well. However, no water had run into the well from the land surface, and the rise was inordinately large for an addition to ground-water storage over any extensive area. Thereafter the water level declined constantly for 31 days, but not until 15 days had passed did the rate of recession suggest that the water level in the well indicated the ground-water stage outside. On May 27, when all but 1.6 feet of the initial rise had been dispersed, the recession was terminated by a minor rise which amounted to 0.8 foot within 4 days; in the next 14 days the water level in the well receded 1.0 foot. The form of the hydrograph for this fluctuation contrasts sharply with that for the gross rise late in April; it is inferred that the graph indicated the ground-water stage rather closely throughout and that the fluctuation was caused by recharge from irrigation. From similarity it is inferred further that a fraction of the rise from April 24 to 26 may also have represented actual ground-water recharge, although probably only a minor fraction. At any rate, some recharge is suggested very strongly by the fact that the water table at the well stood 1.4 feet higher as a net effect of the two fluctuations.

Analogous fluctuations related to irrigation in the pumping district occurred in the same well in April 1931 and in April and May 1933. A similar fluctuation induced by exceptional rain in February 1932 is described on page 148. These three extraordinary rises in the well are presumed to have exceeded greatly the rise in ground-water stage outside the well, although some ground-water recharge may have occurred at the time.

The two hydrographs that constitute figure 17 afford the strongest available example of water-level fluctuations in a shallow well being controlled by intermittent perched ground water. One of the hydrographs represents an idle irrigation well 200 feet deep (373G1), whose water-level fluctuations show chiefly the effects of pumping. The other bydrograph represents a companion well (373G3) 2 feet from the 200-foot well and bored only deep enough (37 feet) to reach the water

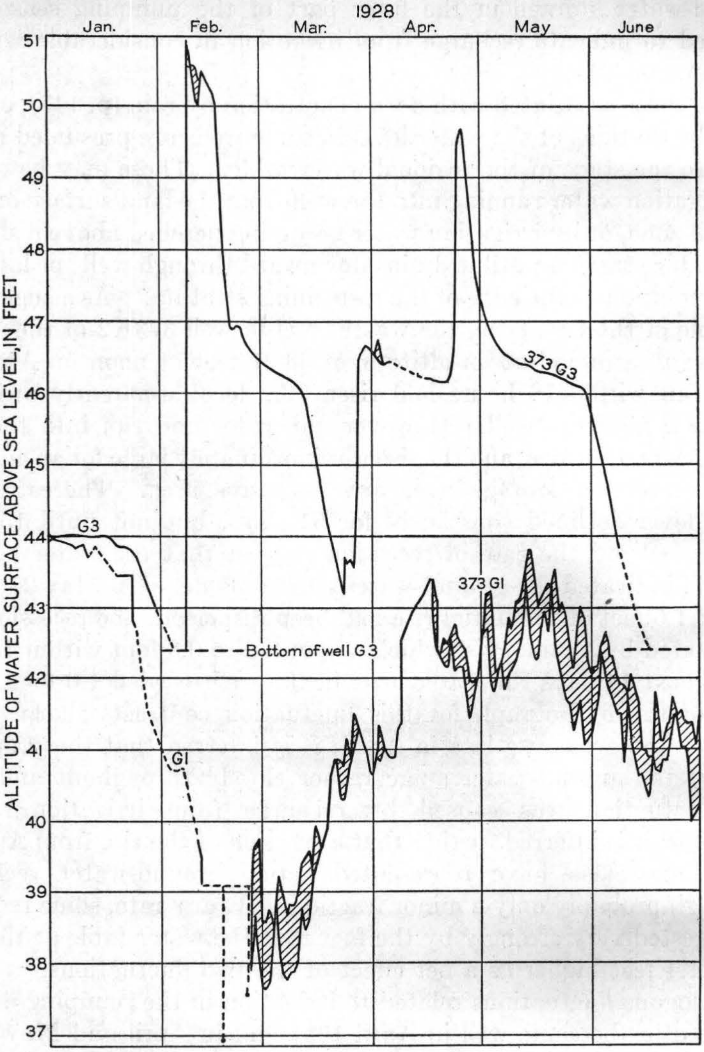


FIGURE 17.—Hydrographs for wells 373G1 and 373G3, January to June 1928.

table.[24] Water-stage recorders were operated on both wells from December 19, 1927, until June 16, 1928. As the comparative hydrographs suggest, the static water levels in the two wells were approximately the same early in January 1928, although that in the shallow well lagged somewhat behind the earliest pumping recession in the deep well. On February 8, March 27 and 28, and April 23 and 24,

[24] Stearns, H. T., Robinson, T. W., and Taylor, G. H., Geology and water resources of the Mokelumne area, California: U. S. Geol. Survey Water-Supply Paper 619, p. 149, 1930.

however, the water level in the shallow well rose notably higher than the regional level. The highest stages in the well during February and April may have been above the ground-water stage because irrigation water ran into the well by way of an open pit. However, that condition is immaterial to the present discussion. On the other hand, although the rise on March 27 and 28 accompanied the record freshet in the Mokelumne River, the backwater of the freshet did not come closer than about a third of a mile from the well. Accordingly, the water level in the well at the time is presumed to have indicated ground-water level accurately. Three segments of the hydrograph are of peculiar interest—from February 25 to March 10, from March 29 to April 21, and from May 5 to 29. In form, each of these segments suggests a typical draw-down curve approaching an altitude of 46 feet as a stage of equilibrium. Nevertheless, that stage seems to have been at least 3 feet above the true water table, because the water level in the well descended sharply for about 3 feet beginning March 12 and again beginning May 30. A tentative explanation is that water was perched intermittently above a restraining stratum at an altitude of about 46 feet but was dissipated by mid-March and late May, so that subsequently its level receded sharply toward the regional ground-water stage.

FLUCTUATIONS RELATED TO THE STAGE OF THE MOKELUMNE RIVER

GENERAL CONSIDERATIONS

Along the reach of the Mokelumne River that traverses the intensively cultivated district about Lodi ground-water levels fluctuate in response to changes in river stage. During the early part of the investigation these changes in stage were caused largely by the natural seasonal cycle of run-off. However, from March 1929 through 1933, they have been determined by regulation at the Pardee Dam [25] except on June 12 and 13, 1932, when some water passed over the spillway, and except for the intermittent storm run-off carried by the small streams that enter the river below the dam.[26] The regulation has caused fluctuations in stage that are quite distinct from those which characterize the natural regimen of the river; they have included daily fluctuations of moderate range caused by operation of hydroelectric turbines, constant stages maintained for periods ranging from 2 to 47 days, and seasonal fluctuations within a fairly small range. It has proved feasible to discriminate the effects on the ground-water levels caused by each of these distinctive fluctuations and thus to trace the more complex effects of the natural regimen.

Ordinarily the hydroelectric turbines at the Pardee Dam have been operated 12 to 16 hours each day under a discharge of about 600 second-

[25] Pritchett, H. C., Bue, C. D., and Piper, A. M., Seepage loss and gain of the Mokelumne River, California: U. S. Geol. Survey typoscript report, pp. 30–43, June 5, 1934.

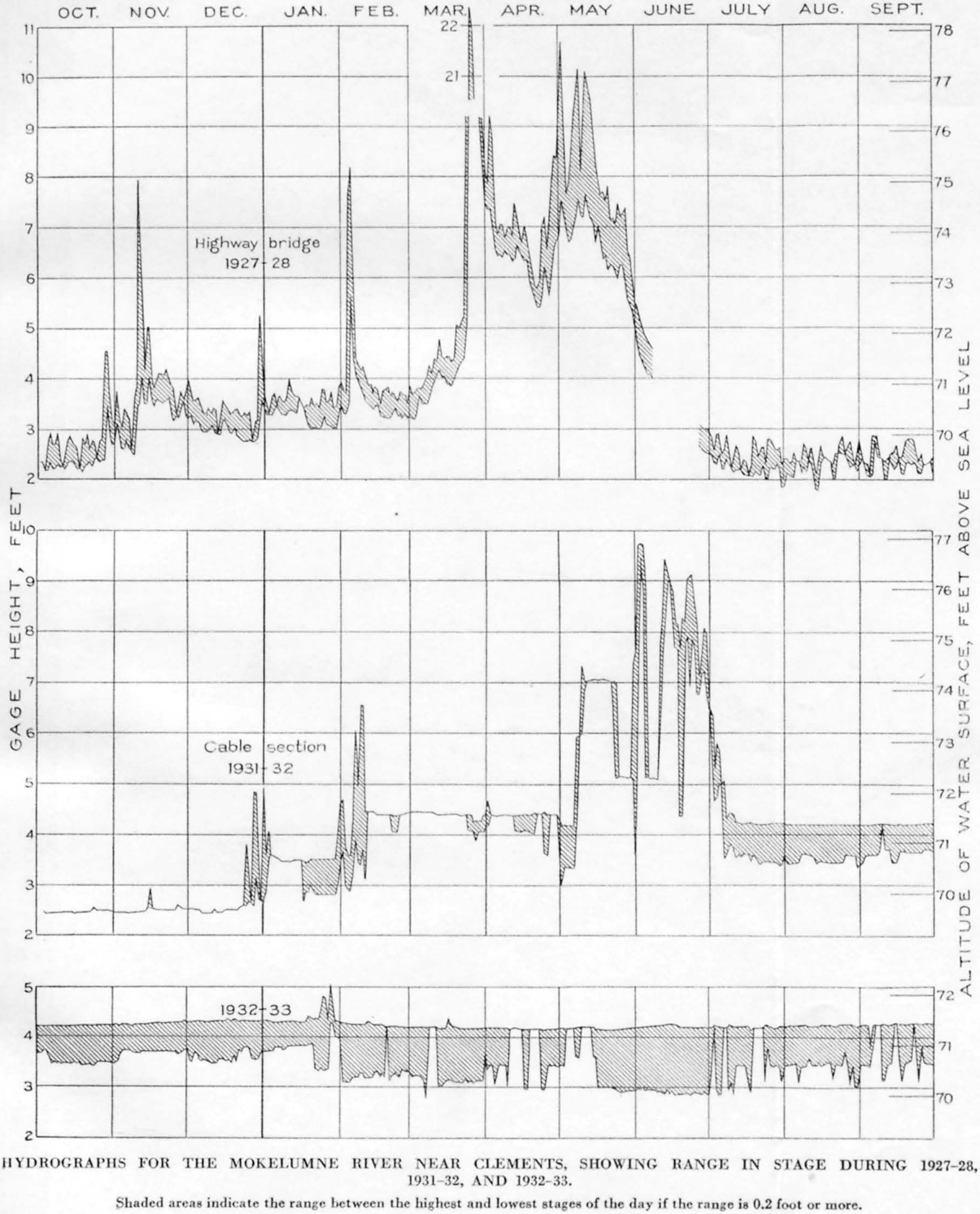
[26] Idem, pp. 37–43, 96–125.

feet, but during the remaining 8 to 12 hours the discharge has been between 150 and 300 second-feet. The corresponding daily range in river stage has been from 0.75 foot to 1.5 feet at the gaging stations at Lancha Plana and near Clements and as much as 2.5 feet at the gage-height station near Victor. At times the turbines have been idle on Sunday, and the discharge on that day has been steady. These characteristics of the regulated stream stage are shown by the hydrographs for 1931–32 and 1932–33 on plate 12. The constant river stages have corresponded to steady discharges ranging from 55 to 4,000 second-feet; thus, those stages have varied about 7 feet at the gaging station near Clements and as much as 13 feet along the reach between Clements and Woodbridge.[27] The least yearly range in river stage under regulation has occurred in the year ending September 30, 1933. In that year the monthly run-off at the gaging station near Clements ranged between 26,700 acre-feet in June and 36,600 acre-feet in January;[28] that range in monthly run-off was less than one-sixth the minimum range recorded under the natural regimen. The greatest daily range in stage was 1.5 feet; the yearly range, 3.3 feet.

Before regulation at the Pardee Dam began, in March 1929, the stage of the river was influenced by daily operation of the hydroelectric plant at Electra, 6 miles below the junction of the North Fork and the South Fork of the Mokelumne River.[29] Operation of that plant caused daily fluctuations of river stage analogous to those already described, but smaller in height, and the peak in the reach below Lancha Plana occurred 12 to 14 hours later. For instance, in October 1927 the daily variation in stage at the gaging station near Clements was ordinarily between 0.4 and 0.7 foot (pl. 12), and the highest stage occurred between noon and 3 p. m. However, the storage capacity of the regulative works operating above Electra at the time was too small for effectively regulating the discharge in the lower reaches of the stream except during the periods of low flow in late summer.[30] Thus the natural discharge was very little modified during a large part of each year.

Under the natural regimen, an annual freshet in the Mokelumne River resulted from the melting of snow in the headwater area.[31] While the snow run-off was at its height, the discharge has varied as much as 3,000 second-feet during a day, and the corresponding range of stage has been considerably greater than that caused by operation of the hydroelectric plant at Electra or at the Pardee Dam. Thus, in late April and May 1928 the daily range in stage due to snow run-off was as much as 3.2 feet at the gaging station near Clements (pl. 12)—that is, about three times as great as the ordinary range due to the

27 Idem, pp. 53–58, pl. 34.
28 Idem, pp. 41–42.
29 Idem, pl. 1.
30 Idem, p. 36.
31 Pritchett, H. C., and others, op. cit., p. 30.



HYDROGRAPHS FOR THE MOKELUMNE RIVER NEAR CLEMENTS, SHOWING RANGE IN STAGE DURING 1927-28, 1931-32, AND 1932-33.

Shaded areas indicate the range between the highest and lowest stages of the day if the range is 0.2 foot or more.

hydroelectric plant at Electra and twice that due to the plant at the Pardee Dam. On May 17, 1927, the range in stage at Clements was even greater—3.8 feet. Between the peak of the spring freshet and the scant flow of late summer and autumn the monthly run-off has varied widely, the least range having been 60,600 acre-feet in 1923–24 and the greatest 353,000 acre-feet in 1905–6. Owing to that relatively great range in discharge, the stage has also varied greatly. The maximum occurred during the record freshet of March 1928. At that time the river overflowed all its flood plain as far downstream as the electric-railroad bridge a mile east of Lodi; still farther downstream it spread even more widely, so that the cities of Lodi and Woodbridge were endangered, and much land on the Delta plain to the west was flooded. At the peak of the freshet the stage near Clements was about 18 feet higher than it had been a week earlier and was 20.6 feet higher than the minimum of the following August.

On the basis of its relation to the water table (pp. 199–200), the reach of the Mokelumne River between the Pardee Dam and tidewater may be divided into three segments—(1) from the Pardee Dam downstream about to the Mehrten dam site, which is in the SW¼ sec. 6, T. 4 N., R. 9 E., about 3½ miles northeast of Clements; (2) from the Mehrten dam site to the Woodbridge Dam; and (3) from the Woodbridge Dam to Thornton. In the upstream segment the river traverses the dissected Arroyo Seco pediment; in the lower two segments it traverses the Victor alluvial plain. The upper two segments correspond roughly to the two reaches of the stream for which seepage loss and gain have been determined—that is, (1) between the gaging stations at Lancha Plana and near Clements and (2) between the Clements station and the one at Woodbridge.

In the segment or reach between the Pardee Dam and the Mehrten dam site the Mokelumne River is a gaining stream—that is, the river occupies a valley of the water table. According to the meager data available, the gradient of the water table toward the river is relatively steep and comparable to the steep slopes of the land surface. In the few observation wells along that particular reach the ground-water level commonly has not responded to fluctuations of river stage. For example, Stearns [32] compared the ground-water level in well 495Q1, which is 1.5 miles east of the Mehrten dam site and 700 feet south of the river, with the stage of the river at the Lucas gage and found that the ground-water level rose 3 feet in response to the freshet of March 1928 but otherwise had not fluctuated with the river stage. Except during the freshet, however, the ground-water level was higher than the river. Owing to that difference in altitude, it is believed that ordinarily the fluctuations in river stage do not affect the static level in water-table wells along that reach of the river, except as they may cause minor backwater effects.

[32] Stearns, H. T., op. cit. (Water-Supply Paper 619), fig. 9, pp. 122, 288.

Along the downstream reach—that is, from Woodbridge to tidewater at Thornton—the river has commonly, though not constantly, coursed obliquely across the water-table contours; also, in places it seems to be insulated from the ground water by beds of slight permeability. On both scores the ground-water levels close to the river have tended at times not to respond to river stage except for backwater effects.

On the other hand, along the intermediate reach—that is, between the Mehrten dam site and Woodbridge—the Mokelumne River is ordinarily a losing stream, for there it occupies the crest of a ridge on the water table. That reach traverses the intensively cultivated lands of the Lodi district; hence, its relation to the ground-water supply is of prime importance. Along it the ground-water levels have fluctuated commonly in response to changes in river stage, the relative magnitude of the response having been limited chiefly by the distance of the well from the river.

Along the intermediate reach more than 90 percent of the observation wells near the river (pl. 1) are shallow water-table wells (pp. 128–129) that bottom in the alluvium, the Victor formation, the Arroyo Seco gravel (possibly), the Laguna formation, or the Mehrten formation. In this class belong the wells of the Victor and Cherokee Lane profiles near the river, also the numerous test wells put down by the East Bay Municipal Utility District on the flood plain. However, a few observation wells near the river are relatively deep and extend more than 75 feet below the projected Arroyo Seco pediment. Those wells bottom in the Laguna formation, the Mehrten formation, or the Valley Springs formation; in some of them fluctuations of the ground-water level are entirely dissimilar to those in adjacent shallow wells, which respond to river stage (pp. 177–179).

The most informative data on the response of ground-water levels in shallow wells along the intermediate reach of the river come from four critical groups of wells; in order downstream these are (1) the "K line" of test wells observed by the East Bay Municipal Utility District, trending southward across the flood plain along the western margin of secs. 16 and 21, T. 4 N., R. 8 E., about midway between Lockeford and Clements; (2) the wells along the Lockeford profile and numerous observation wells and test borings in secs. 24 and 25, T. 4 N., R. 7 E.; (3) the wells along the Victor profile, which follows a north-south line through the gage-height station near Victor; and (4) the wells along the Cherokee Lane profile, which follows the boundary common to Rs. 6 and 7 E. (See pp. 125–127 and pl. 1.)

DIURNAL FLUCTUATIONS IN WATER-TABLE WELLS

Diurnal or daily fluctuations of ground-water levels induced by a diurnal range in river stage have been discriminated only in water-table wells within about 700 feet of the river. For example, the hydrographs in figure 18 show fluctuations of stage in the Mokelumne

River at the bridge near Lockeford from July to December 1930 and contemporaneous fluctuations in four wells of the Lockeford profile, which passes through the bridge. At that time the flow of the river was fully regulated through the hydroelectric turbines at the

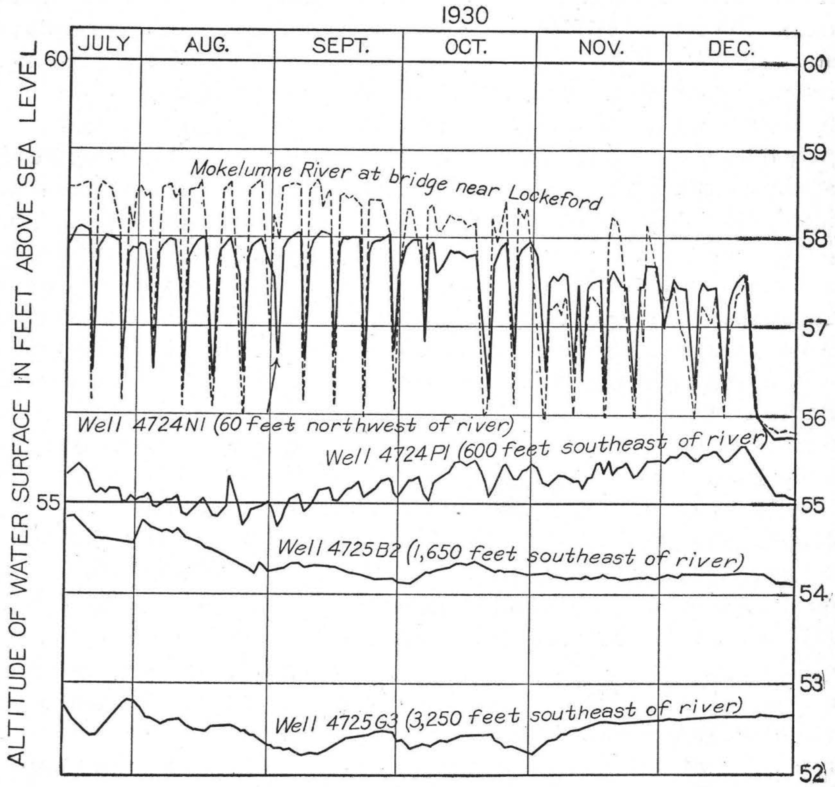


FIGURE 18.—Hydrographs for the Mokelumne River at the bridge near Lockeford and for four wells of the Lockeford profile, 1930.

Pardee Dam, and the discharge varied so widely on week days that the stage commonly fluctuated from 1.1 to 1.3 feet at the gaging station near Clements and presumably somewhat more at the bridge near Lockeford. Each week end, however, the river stage was maintained constant for about 24 hours and about equal to the daily low stage of the mid-week period. The hydrographs are based upon observations of the several water levels made at about the same hour each day and in quick succession, the staff gage at the bridge having been read about at the height of its daily range and within a few minutes of well 4724N1. That well is at the edge of the Victor plain, 60 feet northwest of the river, and is considerably closer to the river channel than any other observation well having a comparable record of ground-water levels. Its collar is 95.5 feet above sea level, or about 42 feet above the stream bed, and its bottom is about 18 feet below the stream bed; throughout its depth of 60 feet it penetrates the sandy sediments of the Victor formation. Whenever the discharge of the river has been steady for several days or longer, the ground-water level in that well commonly has been 0.2 to 0.4 foot lower than the river level. However, during the period of stream regulation represented by the hydrographs the range of ground-water stage in the well was generally about 80 percent of the corresponding range in river stage; also, differences in ground-water level of 1 to 2 feet on successive days have been common. During each mid-week period the river level was somewhat the higher, but, on the other hand, at times during the low stage of the week end the river level was commonly the lower. Thus, owing to lag of the ground-water fluctuations behind those of the river the ground-water gradient was intermittently reversed by each weekly recession, so that it sloped downward toward the river. At those times, presumably, water drained into the river from storage in the sedimentary beds about the well. This result of the diurnal fluctuation of ground-water levels—that is, a diurnal return seepage to the river—has not been discriminated in the record for any other well, but it is probably characteristic of a narrow zone adjacent to the river channel.

Figure 19 comprises hydrographs from water-stage recorders on the Mokelumne River at the gage-height station below the Lockeford bridge, 2,700 feet downstream from the locality just described, and on two water-table wells on the flood plain close at hand. Those wells (4725E1 and 4725E2) are 510 and 650 feet from the river, respectively; each was dug in the alluvium and each bottoms at about the same level as the bed of the river. Both show a pronounced diurnal fluctuation of ground-water level on September 21 and 22, 1931, when the river rose 0.8 foot within 7½ hours, and then fell 1.2 feet in the next 16 hours. In well 4725E1 the peak ground-water stage lagged about 5½ hours after the peak in the river. Thus the rise of river stage set up a ground-water wave whose crest traveled toward the well with an average velocity of about 90 feet an hour. On the other hand, the trough that follows immediately after the peak in the river was not reflected in the well; presumably it was wholly damped by the lag.

After the major fluctuation just described, the river stage oscillated through a range of about 0.1 foot from September 23 to 25. Such minor fluctuations, which are probably caused by intermittent diversion from the river by pumps below Clements, were also reflected very faintly in well 4725E1, although the cumulative effects of lag seem to have caused a gradual recession in the well as the mean daily stage of the river rose gradually. In contrast, the ground-water level at well 4725E2 behaved much the same on September 20 and 21 as from September 23 to 25 and was largely independent of river stage. On those days it varied about 0.06 foot, owing to ground-water draft

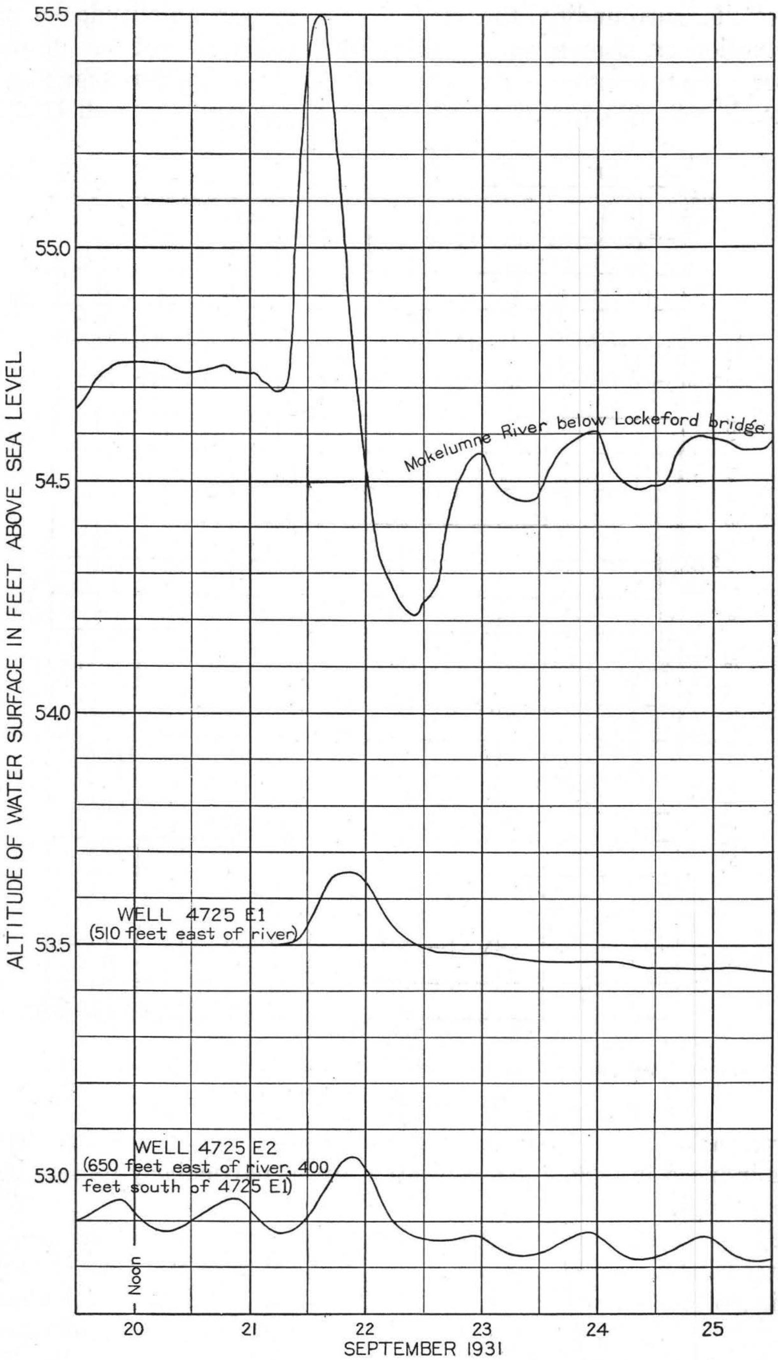


FIGURE 19.—Hydrographs for the Mokelumne River below the Lockeford Bridge and for wells 4725E1 and 4725E2, September 20–25, 1931.

by alfalfa surrounding the well. The greater amplitude of the fluctuation on September 22 (0.18 foot) indicates that the ground-water wave propagated by the pronounced range in river stage passed through well 4725E2 with about the same time lag as for well 4725E1.

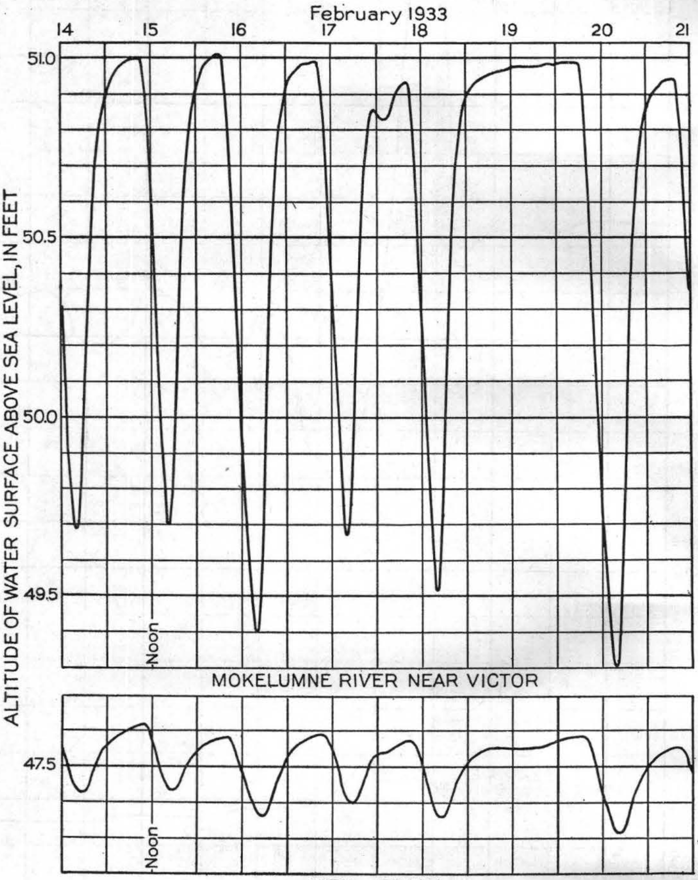


FIGURE 20.—Hydrographs for the Mokelumne River near Victor and for well 4734K3, February 14–21, 1933.

Nevertheless, even that large fluctuation in well 4725E2 probably was induced in part by transpiration draft, particularly its relatively sharp crest.

Figure 20 is a third and final example of fluctuations of the ground-water level induced by diurnal fluctuations of river stage, due to regulation of the river through the hydroelectric turbines at the Pardee Dam. The well is 100 feet from the south bank of the river and about 250 feet south of the gage-height station near Victor. Its collar is on the Victor plain about 38 feet above the river bed; its bottom is about 14 feet lower than the river bed. At the time represented by the hydrograph the daily fluctuation in river stage was from 1.3 to 1.7 feet except on Sunday, February 19. The corresponding diurnal fluctuation in the well was about 0.2 foot—that is, from 12 to 15 percent of that for the river; also, the well lagged from 1 to 1½ hours after the river, the ground-water waves traversing the intervening space with a velocity of about 65 to 100 feet an hour. Before the river was completely regulated at the Pardee Dam—that is, prior to 1929—the ground-water level in well 4734K3 fluctuated in similar fashion, owing to diurnal changes in river stage, but not in the same amount. For example, the diurnal variation in run-off from melting snow during May 1928 caused the river stage to fluctuate as much as 3.2 feet a day near Clements; presumably the fluctuation in river stage was not less than 4 feet near Victor, although the gaging station there was not in operation at the time. In the well the ground-water level varied only 0.1 to 0.2 foot a day, although it rose and fell progressively over a term of weeks in accord with the river. Commonly under those conditions, the water level in the well rose or fell throughout the 24 hours in accord with the trend of the river stage. Regulation of discharge by the power plant at Electra also caused small fluctuations of the water level in the well prior to 1929; for example, fluctuations from that cause during October 1927 were common but amounted to less than 0.05 foot.

Diurnal fluctuations of ground-water level induced by changes in river stage have not been recognized in wells more than 700 feet from the river channel. Thus, diurnal fluctuations having an amplitude less than 20 percent of the corresponding fluctuations in the river are shown by the hydrograph for well 4724P1 (fig. 18), which is on the Lockeford profile at the outer edge of the flood plain about 500 feet south of the river. In well 4725B1 of the same profile, however, 1,300 feet south of the river, there is no indication of a daily fluctuation of the water level. Similarly, along the Victor profile (pl. 8) the ground-water level fluctuates in about the same manner in well 4734G1 as in well 4734K3 in response to daily and weekly changes in river stage. Well 4734G1 is about 500 feet from the river, at the outer edge of the flood plain. On the other hand, in well 4727P1 of the same profile, 1,100 feet north of the river, diurnal fluctuations in the river again appear not to have influenced the ground-water level. Accordingly, it is inferred that diurnal fluctuations of the ground-water level ordinarily die out within about 1,000 feet of the river.

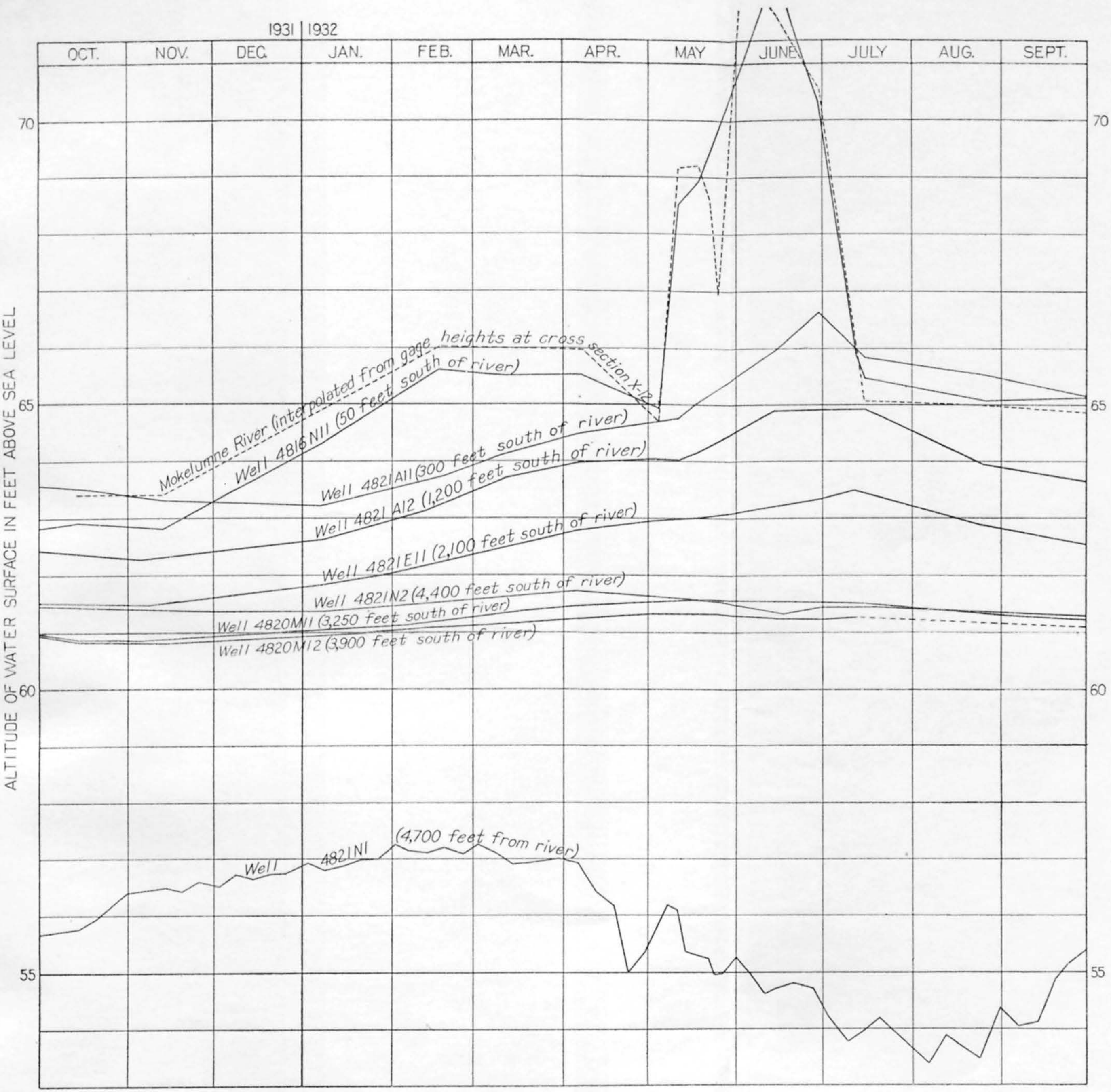
At the typical localities that have been described ground-water waves actuated by daily fluctuations of river stage have traveled as much as 650 feet from the river at average velocities of the order of 65 to 100 feet an hour. Also, the height of the ground-water wave at well 4724N1 has been 80 percent of the range in river stage 60 feet away; at wells 4724P1, 4725E1, and 4725E2 it has been as much as 20 percent at a distance of 500 to 600 feet; but at well 4734K3 it has been from 5 to 15 percent at a distance of only 100 feet. In the alluvium that forms the flood plain the ground-water waves have traveled farther with less percentage of damping than in the sediments that underlie the outlying Victor plain, but even there they have traveled with relative freedom. These features suggest that the alluvium and to a less degree the sedimentary beds of the outlying plain are readily permeable and offer free percolation to and from the river. Thus it is inferred that seepage loss and gain of the river may well be sensitive to all changes of ground-water level. Some substantiative evidence is derived from the response of ground-water levels to the longer-term fluctuations of river stage; other substantiative evidence is assembled on pages 212–216. However, it is shown on pages 169–173 that in certain localities the sedimentary beds of the outlying Victor plain are much less permeable than the alluvium of the flood plain.

SEASONAL FLUCTUATIONS IN WATER-TABLE WELLS

With respect to the influence of seasonal fluctuations of river stage upon ground-water levels, two reaches of the losing segment of the Mokelumne River may be discriminated—(1) an upstream reach from the Mehrten dam site, about 3½ miles northeast of Clements, downstream to the sharp constriction of the flood plain 1½ miles west of Lockeford, and (2) a succeeding downstream reach that extends to and beyond the far margin of the intensively cultivated district about Lodi. Along the upstream reach the flood plain is much wider than in other parts of the Mokelumne area and, except for about 1½ miles immediately downstream from the Mehrten dam site, is bordered by the higher Victor alluvial plain. Nevertheless, the tongue of alluvium that forms the flood plain passes off the Mehrten formation, crosses the Laguna formation and possibly a concealed correlative of the Arroyo Seco gravel, and then passes onto the Victor formation near the downstream end of the reach. Thus the water table in the alluvium passes laterally into those formations in succession downstream. Throughout the downstream reach the alluvium rests on and abuts against the Victor formation.

Stearns [33] has compared the fluctuations of river stage at the gaging station near Clements, near the head of the upstream reach, in 1926 and 1927 with corresponding fluctuations of ground-water stage in well 4815F1, which is at the Clements cemetery, 1,500 feet southeast of the gaging station. The well (subsequently abandoned) was on a peninsula of the Victor plain. It was about 70 feet deep, although barely deep enough to reach the water table; it probably entered the consolidated Mehrten formation which crops out a quarter of a mile to the north in the lower part of the bluff at the margin of the flood

[33] Stearns, H. T., Robinson, T. W., and Taylor, G. H., Geology and water resources of the Mokelumne area, California: U. S. Geol. Survey Water-Supply Paper 619, pp. 120–122, fig. 8, 1930.



HYDROGRAPHS FOR THE MOKELUMNE RIVER AND FOR WELLS ALONG AND NEAR THE "K-LINE," 1931-32.

plain. From November 1926 to May 1927 the river stage showed a range of about 10 feet, whereas the ground-water stage varied about 1 foot and lagged about 2 months behind the river. Stearns concludes that this is "probably due to the relatively impermeable rock between the well and the river."

Farther downstream, where the flood plain is wide, the seasonal fluctuations of river stage have affected the ground-water levels in wells half a mile away, in spite of considerable lag, as in 1931–32, during which the discharge of the river was regulated between about 50 second-feet and 4,000 second-feet by successive increases that were long sustained (pl. 12). By way of illustration, plate 13 comprises hydrographs for the six test wells of the "K line" and for two additional wells close at hand. The accompanying table describes these wells.

Test wells of the K line on the flood plain of the Mokelumne River and 2 wells close at hand on the Victor plain

Well no.	Geomorphic district	Distance south of river (feet) [1]	Altitude of land surface (feet above sea level)	Depth of well (feet) [1]	Geologic horizon of bottom of well	Lowest ground-water stage observed in 1931–32 (feet above sea level) [2]	Range in static level 1931–32 (feet)
4816N11 (K1)	Flood plain	50	79.6	18.7	Alluvium	62.8	8.7
4821A11 (K2)	do	300	80.2	19.0	do	63.2	3.4
4821A12 (K3)	do	1,200	77.7	19.6	do	62.2	2.7
4821E11 (K4)	do	2,100	71.5	12.4	do	61.5	2.0
4820M11 (K5)	do	3,250	78.5	18.4	do	60.8	.7
4820M12 (K6)	do	3,900	75.4	15.9	do. (?)	60.8	.5
4821N2	Victor plain (25 feet from edge).	[3] 4,400	117.0	78.0	Victor formation or Laguna formation.	61.3	.4
4821N1	Victor plain (500 feet from edge).	[4] 4,700	125.5	105.8	Laguna (Mehrten?) formation.	53.4	3.8+

[1] By East Bay Municipal Utility District.
[2] Altitude of river bed about 62 feet above sea level.
[3] About 900 feet east of the K line and 200 feet south of the flood plain's outer margin.
[4] About 150 feet east of the K line and 650 feet south of the flood plain's outer margin.

In the well 50 feet from the river (4816N11) the ground-water level fluctuated 8.7 feet in the year—that is, about as widely as the river stage at cross section X–12, which is 1,500 feet upstream (the basis for the interpolated hydrograph for the river). On the other hand, in the most remote flood-plain well (4820M12), which is 3,900 feet from the river, the ground-water level fluctuated only about 0.5 foot, although seemingly in response to river stage. Whenever the discharge of the river is steady, the water surface ordinarily is higher in the river than in any well of the K line; thus the ground-water gradient declines southward entirely across the flood plain, although it flattens progressively. Again, ground-water waves are set up by each fluctuation in river stage but commonly die out before the distant wells are reached, so great is the lag. For example, in well

4612—39——12

4821E11, which is 2,100 feet from the river, the highest ground-water stage lagged fully a month behind the major rise of the river in early June 1932; and in the more distant wells the effect of that rise could not be discriminated from the gentle seasonal fluctuation of the ground-water level. Owing to lag, the ground-water gradient close to the river was steepened sharply for a time after the rises in river stage in May and June, but on the other hand it was reversed for a time after the sharp recessions on May 5 and in early July. Thus, from mid-July to and after the end of September the river was lower than the ground-water level close at hand, and a ground-water divide persisted in the vicinity of wells 4821A11 and 4821A12, several hundred feet from the river. When the river stage is low and recedes only moderately, the recession of ground-water levels lags even more, owing to the flatter hydraulic gradients. For example, for several months late in 1930 the regulation at the Pardee Dam had been such that the mean daily river stage near Clements was nearly constant, although each day the stage had varied about 1.2 feet; beginning December 21, 1930, however, the stage was steady for about 3 months, there being little or no diurnal fluctuation and the stage being equal to the daily minima of the earlier period. Owing to that recession in river stage, a ground-water divide formed in the vicinity of well 4821A11 and persisted for about 4 months, until it was wiped out by rising river stage in mid-April, 1931. An analogous history accounts for the ground-water divide at the same place in October 1931. It is obvious that along the K line weeks or even months will elapse after a pronounced change in river stage before ground-water levels reach a steady stage beneath the flood plain, even within a few hundred feet of the river.

In the two wells on the Victor plain close at hand (4821N2 and 4821N1) the grour d-water levels have behaved somewhat differently. Well 4821N2 is only 200 feet from the outer margin of the flood plain but about 900 feet southeast of well 4820M12. In 1931–32 its static level varied only a few tenths of a foot, as in the nearest two test wells on the flood plain, and apparently was controlled chiefly by the river. However, its stage was highest in April rather than in June, as if it receded somewhat in response to ground-water levels in the pumping district to the south. The other of the two wells (4821N1) is only about 150 feet east of the K line but is about 650 feet beyond the outer margin of the flood plain. In 1931–32 its static level ranged from 4 to 8 feet lower than that in the companion well and fluctuated in much the same manner as the ground-water level along the edge of the area of intensive pumping (pp. 193–194). Thus, the highest ground-water stage occurred in February and the lowest in July or August; the measured range for the year was many times greater than in the companion well. The bottom of this second well is 34 feet below the lowest ground-water stage of 1931–32. Accordingly, it may be so deep that its water level responds to the pressure effects of pumping to the south, although there is no reason to believe that its water level ordinarily stands either higher or lower than the water table. (See pp. 186–192.) Locally, the response of the ground-water level to short-term and even to yearly fluctuations in river stage thus ceased rather abruptly at the outer edge of the flood plain.

In contrast to the moderate range of 1931–32, the discharge of the Mokelumne River was regulated within narrow limits in 1932–33, so that the stage varied only 2.5 feet at the gage-height station near Victor. Along the K line the measured range in ground-water stage was only 0.5 foot in the flood-plain well nearest the river (4816N11), whereas in the most distant flood-plain well (4820M12) it was 0.8 foot. Furthermore, in the distant well the highest ground-water stage occurred in April and was 0.2 foot above the highest stage of the year before.

Near Lockeford, about 3 miles downstream from the K line, the flood plain of the Mokelumne River is about a mile wide but surrounds two flat-topped outliers of the Victor plain that are south of the river and are traversed by the highway that leads northwest from Lockeford. The larger outlier is about 3,400 by 1,600 feet and lies athwart the flood plain. The two outliers are separated from one another and from the cuspate edge of the Victor plain by tongues of alluvium about 100 and 350 feet wide, respectively; along these tongues course shallow sinuous drains that head on the flood plain farther east and trend southwestward, toward the river.

Both outliers are composed of the Victor formation, although the Laguna formation underlies them, perhaps only slightly below the level of the flood plain. The locality affords further information as to the manner and rate of movement of ground-water waves set up by the seasonal range in river stage.

Plate 14 comprises two maps of the Mokelumne River flood plain near Lockeford, which show (1) the net change in ground-water stage from mid-June to mid-July 1932, while the river was regulated from a temporary high stage of about 12.4 feet on the staff gage at the Lockeford bridge to a steady mean daily stage of about 3.0 feet; also (2) the form of the water table at the end of that period. The form of the water table during the high stage of early June is readily visualized. The water-surface altitudes corresponding to the gage heights mentioned are 67.4 feet and 58.0 feet above sea level, respectively; the daily discharges are about 3,500 and 520 second-feet.

Here, as at the K line, farther upstream, by mid-June the high river stage had raised the ground-water level sharply within 500 to 1,500 feet of the river, but the ensuing 9-foot recession in river stage dissipated much of that ground-water rise by mid-July. Nevertheless, the ground-water level lagged so much that again a ground-water divide existed temporarily a few hundred feet from the river, as is shown on plate 14, B, by the contour lines for the range between 55 and 60 feet above sea level on July 13–16. That divide was dissipated before mid-August. Also, the ground-water wave set up by the high river stage continued to advance so that ultimately it reached the outer margin of the flood plain at the eastern edge of the area represented by the maps and reached nearly to the outer margin of the flood plain in the NW¼ sec. 36, T. 4 N., R. 7 E. The ground-water wave appears to have halted soon after mid-July and nowhere to have advanced much more than half a mile from the river; thus it never reached the alcove of the flood plain immediaely north of Lockeford and perhaps did not enter the alcove immediately west of Lockeford. Apparently it was the principal cause for the ground-water level rising slightly in the L-shaped area shown on plate 14, A, with an apex beneath the larger outlier of the Victor plain and with lobes extending eastward and southward; however, some of that rise may have been due to recharge from irrigation on the flood plain.

In most of the wells close to the southern margin of the flood plain in this district near Lockeford, both in the wells that bottom in the alluvium and in those that bottom in the Victor (Laguna?) formation, the ground-water level varied relatively little during 1931–32, reached its highest stage about March, and responded but little, if at all, to the high river stage of June. Thus the seasonal cycle of ground-water stage along that margin was altogether different from the seasonal cycle in the central part of the flood plain. Also, a relatively steep hydraulic gradient is inferred to have persisted between the outer margin of the flood plain and outlying wells on the Victor plain, to the south and west of the area represented by plate 14. These features were repeated in the wells of the so-called A line, which trends eastward through the center of sec. 25, T. 4 N., R. 7 E., the high stage of the year occurring about March in all wells east of the outliers of the Victor plain, whereas in all wells west of the outliers the ground-water stage was highest in June or July, following the high river stage. Relatively steep hydraulic gradients persisted between the eastern and western segments of the A line, also across the peninsula of the Victor plain that extends northwestward from Lockeford and across the smaller of the two outliers (pl. 14, B). These features suggest that the peninsula and outlier were impeding the percolation of ground water and that percolation was impeded in similar fashion at the margin of the flood plain along the southern and western edges of the district.

The fluctuations of ground-water level at the Clements cemetery, along the K line, and in the area north of Lockeford are believed to be typical for the reach of the Mokelumne River between the Mehrten dam site and the constriction of the flood plain west of Lockeford. From the foregoing data on the behavior of ground-water levels several critical generalizations are inferred for the reach: (1) The river and the ground water in the alluvium of the flood plain are not insulated from the ground water in the sedimentary beds that form the adjacent Victor plains; (2) locally if not generally, however, there are discontinuities in pervious strata along the outer margin of the flood plain where the water table passes from the alluvium into the enclosing sedimentary beds, so that percolation of ground water is impeded materially at that margin; (3) rising river stages set up ground-water waves that store relatively large volumes of water in the alluvium close to the river, whereas falling stages cause much of that storage to percolate back into the river, weeks and even months lapsing before the ground-water stage becomes steady within the flood plain; (4) seepage loss from the river into the alluvium tends to be intermittent and to alternate with seepage gain, the rate of loss or gain lagging weeks or months behind the fluctuations of river stage and lagging more for moderate changes at low stage.

In the downstream reach of the losing segment of the Mokelumne River several of the hydrographs for wells along the Victor profile (pl. 8), all within half a mile of the river, show response of ground-water level to the fluctuations of river stage in 1931–32. Well 4734K3 reflected as much as 80 percent of the longer-term changes in river stage, whereas commonly it has reflected only about 15 percent of the diurnal changes (p. 166). During May and June 1932 the ground-water level in the well began to rise or to fall, with little lag behind the corresponding changes in river stage; nevertheless, 2 months elapsed before the ground-water level became steady after the major drop in river stage early in July, although the well is only 100 feet from the south bank of the river and at the edge of the Victor plain. Although well 4727P1 is on the Victor plain about 750 feet north of the edge of the flood plain and 1,100 feet from the river, its ground-water level ordinarily was about the same as in the well just described but did not rise as much in response to a major rise of river stage. In well 4734G1, which is between the two wells just described but about 500 feet from the river, the ground-water level is commonly higher than in all other wells along the profile. Thus, when the river stage is steady the ground-water gradients tend to become symmetrical with respect to the flood plain but not with respect to the river channel, which is sinuous and which swings from one side of the flood plain to the other. Ordinarily the river stage has not fallen below the ground-water stage in any well except briefly, as after the major recession of early July 1932. Thus a ground-water divide has not occurred commonly beneath the flood plain at the Victor profile.

Of the wells along the Victor profile that responded to the major rise of river stage in May and June 1932, the one farthest north and the one farthest south are 4727L1 and 373B1, respectively; these are

2,700 feet and 1,500 feet from the nearest points on the river. Otherwise, their water levels have not been influenced appreciably by river stage, the discharge under the regulated regimen having been less than 1,000 second-feet; also, their water levels have commonly declined steadily throughout each pumping season and have recovered gradually to a high stage about March. In all wells of the profile remote from the river, the seasonal cycle of water-level fluctuations since 1930 appears to have been caused largely by pumping (p. 192), although it is possible that the ground-water waves set up by changes of river stage have reached some of the remote wells and have tended to offset or minimize the pumping effects. In the 25 years before the Pardee Dam began to impound water the mean discharge in the lower reach of the Mokelumne River exceeded 4,000 second-feet in one or more months of 8 years; exceeded 2,000 second-feet in 15 other years, and failed to reach 2,000 second-feet in 2 years only. Presumably the corresponding changes of stage would have set up ground-water waves higher than any yet described, and presumably those high waves could have been traced farther from the river, in spite of the recession caused by pumping.

Hydrographs for the Cherokee Lane profile (pl. 9) indicate that the ground-water waves ascribed to changes of river stage have reached five wells—4731N1 and 4731N5, south of the river, and 4731J3, 4731J9, and 4636M2, north of the river. All these are within 700 feet of the river. In other wells along the profile the ground-water levels have fluctuated so much from pumping that the waves ascribed to river stage cannot be discriminated with assurance. However, the hydrograph for well 376J8 from March through July 1932 suggests that waves from the river may have offset partly the effects of pumping in that well, if not in those more remote. Even the sharp recession of early July 1932 did not carry the river stage at the Cherokee Lane profile below the ground-water stage in any well.

If the fluctuations of ground-water level near the river at the Victor and Cherokee Lane profiles are typical for the downstream reach of the losing segment, it may be inferred (1) that percolation of ground water is not impeded generally along the outer margin of the flood plain, implying that the Victor formation is quite as pervious as the alluvium; and (2) that the river tends to lose by seepage into the alluvium almost continuously rather than intermittently, although the rate of loss varies somewhat in response to changing river stage. These inferences are opposite to the corresponding generalizations already drawn for the succeeding reach upstream (p. 173).

During the record freshet of late March 1928 the Mokelumne River attained a maximum discharge of 25,600 second-feet near Clements (stage 22.45 feet on gage, or 89.6 feet above sea level).

In the week that preceded the freshet the stage of the river had been as low as 4.1 feet, and during the 2 months that followed the freshet the stage ranged between 5.0 feet and 10.7 feet (daily discharge 1,300 to 4,060 second-feet). (See pl. 12.) At no other time during the intensive investigation in the Mokelumne area has the river stage fluctuated so widely. Thus 1928 affords the most useful data from which to estimate the maximum effect of changing river stage upon ground-water levels before the river was first impounded above the Pardee Dam.

In nearly all wells a mile or less from the river the ground-water level rose inordinately during or after the high-water period, although the rise began earlier and was greater in the shallow wells. The subjoined table lists the wells that experienced the inordinate rise, but it excludes all wells on the Delta plain and in the area served by the Woodbridge Irrigation District, for there the rise caused by the river could not be discriminated from the rise characteristic of the irrigation season (p. 152), and it also excludes the wells in which ground-water levels were obviously influenced by contemporary freshets in Dry Creek and the Cosumnes River. However, a part of the inordinate rise in these wells may have resulted from (1) infiltration of the 5-inch rain that fell from March 23 to April 4 (p. 143); (2) cessation of pumping during that rain (p. 188); (3) ordinary seasonal rise of the water table from October to April; or (4) contemporary freshets in Dry Creek. The measurements of depth to water were not made with sufficient frequency or regularity to determine the rate of advance for the ground-water wave set up by the freshet, but wave motion is indicated, nevertheless. Thus, in the wells nearest the river the highest ground-water stage occurred within a week after the freshet, in most wells within a mile of the river the highest stage occurred within 2 weeks, but in wells somewhat more than a mile away the stage continued to rise until 1 or 2 months had elapsed. The height of the ground-water wave was clearly greatest in wells near the river.

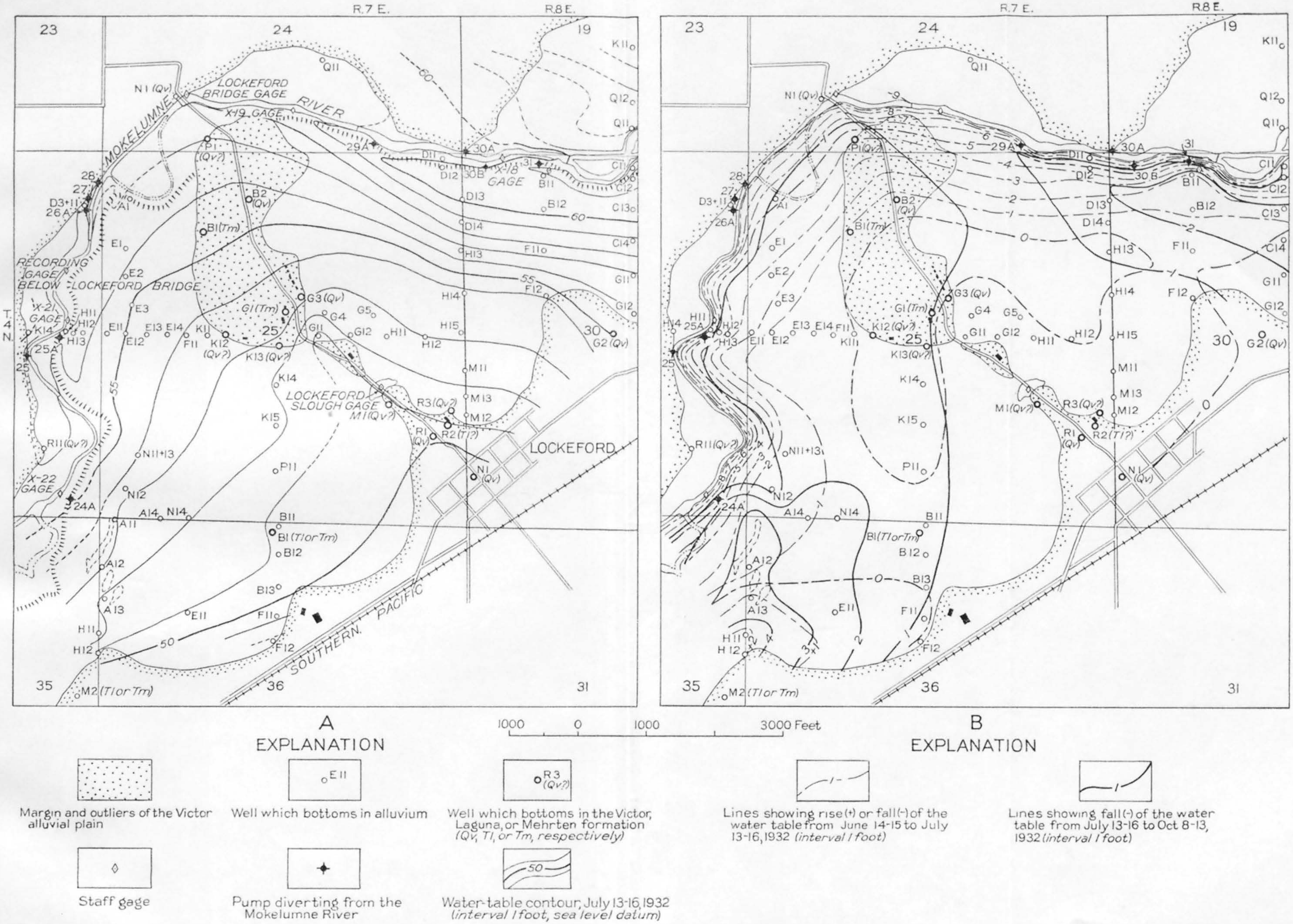
The ground-water wave actuated by the freshet of 1928 and sustained by the snow run-off that followed was perceptible over a greater area than any other fluctuation set up by the river during the term of the investigation. However, even this wave was not traced to the limits of the area that receives percolate from the Mokelumne River (p. 204). The high-water run-off of 1928 was exceeded in 13 of the 24 years during which the discharge of the Mokelumne River had been measured near Clements before regulation began at the Pardee Dam. Commonly, during these 13 years the high-water run-off was sustained longer than in 1928. Those sustained high stages may have heightened the ground-water level even more than the freshet of 1928.

Wells of the Mokelumne area in which the ground-water stage rose inordinately after the record freshet in the Mokelumne River, Mar. 25–28, 1928

No. on pl. 1	Distance (miles) and direction from river	Altitude of ground-water level (feet above sea level)						Rise in ground-water level after Mar. 17–26 (feet)
		Feb. 16–28	Mar. 17–26	Mar. 27–30	Apr. 3–6	Apr. 17–27	May	
361A1 [1]	0.3 S	31.53	[2] 28.13	35.23	37.43	36.33	35.63	-------
361J2	1.0 S	-------	26.25	26.60	27.80	27.75	26.05	1.6
361Q2	1.1 S	28.05	25.90	26.55	-------	27.50	23.80	1.6
362P2	1.2 S	27.30	26.20	26.35	26.95	27.65	27.15	1.4
373D1	0.4 S	46.35	46.00	50.90	50.90	50.45	51.65	4.9
373G1 [3]	0.7 S	39.75	40.85	41.25	40.90	43.40	41.93	2.6
373G3	0.7 S	46.66	43.18	46.66	46.42	46.17	46.15	3.5
374A1	0.02 S	41.95	43.10	-------	-------	45.55	48.65	5.6
374F1 [3]	0.4 SE	34.55	35.60	36.15	37.55	-------	-------	2.0
374H4	1.0 SW	-------	-------	39.20	37.90	40.60	42.00	-------
375L3 [3]	0.6 SW	33.57	[2] 28.57	[2] 29.47	31.82	34.82	36.62	-------
376G3	0.6 S	30.65	29.75	30.45	31.00	31.85	31.15	2.1
465R1	1.0 N	14.40	14.75	-------	15.90	16.90	17.40	2.7
469P1	0.3 E	15.26	15.36	-------	20.46	20.26	20.31	5.1
4610N1 [3]	1.0 NE	19.20	19.20	-------	20.55	21.00	21.05	1.8
4614P2	1.5 E	[4] 21.59	21.04	-------	22.94	23.49	23.59	2.6
4616L1	0.1 NE	16.70	17.05	-------	23.50	22.35	22.00	6.4
4616N1	0.2 W	14.80	14.60	21.60	22.75	21.35	20.25	8.2
4617D2	0.02 W	12.90	14.90	-------	-------	20.25	19.50	5.4
4621D1	0.02 E	18.00	18.95	-------	27.20	24.75	23.95	7.2
4622F1	0.6 E	20.75	20.35	-------	26.65	25.55	24.70	6.3
4623J2	1.3 NE	24.15	22.60	-------	25.90	26.55	26.50	4.0
4626D1	1.1 N	26.50	26.30	-------	27.40	27.95	26.35	1.6
4626E1	0.6 N	26.00	23.70	-------	34.05	33.35	31.15	10.4
4627A1	0.3 N	20.40	21.10	-------	33.95	30.50	28.80	12.8
4627B1	0.5 NE	22.10	21.35	-------	34.20	32.80	30.25	12.8
4634R1 [1]	0.1 SW	29.60	28.95	-------	36.30	33.65	33.75	7.4
4635A2	0.2 NW	29.30	27.70	-------	38.20	36.10	34.65	10.5
4635E2 [1]	0.1 NE	31.15	29.35	-------	37.65	35.20	36.20	8.3
4636A1	0.4 NE	28.90	29.30	31.60	33.40	33.35	32.95	4.1
4723R1 [3]	0.2 W	53.37	51.62	56.62	56.07	54.82	54.47	5.0
4725G1 [3]	0.5 SE	53.65	53.50	-------	61.65	60.30	59.70	8.2
4727N1	0.1 NE	46.85	47.90	52.65	52.85	51.85	53.55	5.0
4731A1	0.7 N	31.55	29.50	-------	30.30	32.05	33.15	2.6
4731N1 [1]	0.1 S	34.47	33.97	37.17	39.22	38.17	39.82	5.2
4731Q1	0.3 S	35.50	36.15	53.45	40.80	40.80	42.25	17.3
4732K1	0.2 NW	40.25	40.50	53.50	47.80	45.55	47.10	13.0
4733F1	0.2 NW	43.00	44.15	50.40	48.45	46.95	47.60	6.2
4734D2 [3]	0.5 NW	47.20	[4] 47.70	49.10	48.15	-------	-------	-------
4734J1 [3]	0.4 S	44.00	42.80	44.05	45.35	47.55	49.40	6.6
4734K2	0.02 S	48.17	48.90	57.30	54.70	53.81	54.94	8.4
4734K3	0.02 S	48.57	49.48	60.48	55.52	54.16	55.80	11.0
4735G1 [1] [3]	0.03 S	51.11	49.81	-------	-------	51.21	50.41	1.4
4735M2 [1] [3]	0.3 S	49.48	46.98	-------	-------	[5] 57.43	[5] 58.98	([5])
4735Q1	0.6 SE	49.00	48.45	49.40	50.55	51.15	51.90	3.4
4736B1 [1] [3]	0.6 SE	51.70	-------	-------	-------	55.30	56.90	-------
4811E1	0.4 N	76.31	76.11	-------	-------	77.61	77.66	1.5
4812D1	0.1 S	86.47	86.42	-------	-------	87.42	87.62	1.2
4815F1	0.3 S	-------	70.45	70.60	70.90	71.90	72.65	2.2
4816N1 [1]	0.1 N	66.46	66.58	81.91	77.78	75.20	73.23	15.3
4817M1	0.3 NW	62.85	[2] [6] 58.65	63.65	63.90	63.90	[6] 61.90	-------
4819C2 [3]	0.4 NW	57.91	60.01	58.36	58.56	58.66	56.11	-------
4821B1 [1] [3]	0.2 S	65.70	65.45	-------	-------	75.60	73.35	10.2
4821J2 [1]	0.5 S	-------	64.30	-------	-------	72.40	-------	8.1
4821N1	0.7 SE	61.10	60.25	60.00	61.50	60.05	59.15	1.2
4822B1 [3]	0.9 SE	64.90	[4] 64.55	64.95	66.40	66.00	66.15	-------
4829E1 [3]	0.6 SE	57.35	56.65	58.05	58.20	58.15	-------	1.6
4830G2	0.4 S	56.70	56.95	60.25	60.60	60.40	61.55	3.6
4830N1	0.8 S	53.35	53.30	54.60	54.30	55.55	56.25	3.0

[1] Within area overflowed Mar. 24–27, 1928.
[2] Pump operating in adjacent well.
[3] Deep well, bottom more than 75 feet below the projected Arroyo Seco pediment.
[4] Power-driven pump operating in well.
[5] Well used as sump for draining flood plain.
[6] Windmill operating.

Hydrographs spanning the 8 years from 1926 to 1933 for water-table wells near the river suggest that commonly the long-term fluctuations of the ground-water level are relatively small, even in



MAPS OF THE MOKELUMNE RIVER FLOOD PLAIN NEAR LOCKEFORD, SHOWING FORM (A) AND FLUCTUATIONS (B) OF THE WATER TABLE FROM JUNE TO OCTOBER 1932.

comparison with those in wells in outlying parts of the Mokelumne area. Moreover, the regional downward trend of ground-water levels during recent years is shown only faintly, presumably because minimum river stages obviously are limited. Even in the deeper irrigation wells moderately close to the river the net recession of the ground-water level has been considerably less than in the heart of the pumping district, again owing to the presumptive influence of river stage, which has been highest about when the depression of ground water by pumps was greatest.

FLUCTUATIONS IN DEEP WELLS

To the east of the district of intensive pumping, between the Mehrten dam site and Lockeford, there are several observation wells so deep that they enter the Mehrten formation. In those that are near the Mokelumne River and that are adequately cased the ground-water level commonly is lower than in shallow wells close at hand and fluctuates in a different manner. For example, figure 21 compares hydrographs for two wells on the flood plain of the Mokelumne River half a mile west of Lockeford. (See pl. 14.) One of these is an irrigation well 319 feet deep, which penetrates into the Mehrten formation; the other is a test well only 16.5 feet deep, which has been bored in the alluvium 50 feet to the east. In the shallow well the static level rose after each increase of the river stage in the first half of 1932 and continued to rise until June. This behavior is characteristic of all water-table wells whose static level is controlled primarily by river stage. In contrast, the water level in the deep well declined steadily from early March until June or July, the measured recession having been 4.8 feet in 1932 and 5.5 feet in 1933; thus the yearly range of ground-water stage was distinctly greater than that in the shallow well and largely opposite in direction. In brief, the fluctuation in the deep well was of the type caused by pumping from wells (pp. 192–196), rather than by changing river stage, although certain slight rises in 1932 contemporaneous with increasing river stage may have been an effect of loading by the river. So far as the hydrographs show, the differential head between the two wells was never less than about 1 foot. Wells 4725B1 and 4735M2 likewise reach the Mehrten formation, and their water levels fluctuate in the fashion just described and stand always below the water table.

Over a period of several years, the highest ground-water stage in the deep wells has occurred commonly while the river stage and the water table were low, whereas the lowest ground-water stage has occurred repeatedly during the freshets. This condition made it possible to drain part of the flood plain west of Lockeford into well 4735M2 after the freshet of March 1928. The height of the water table near the Mokelumne River above the static level of the water in the Mehrten formation is known for few wells and for infrequent

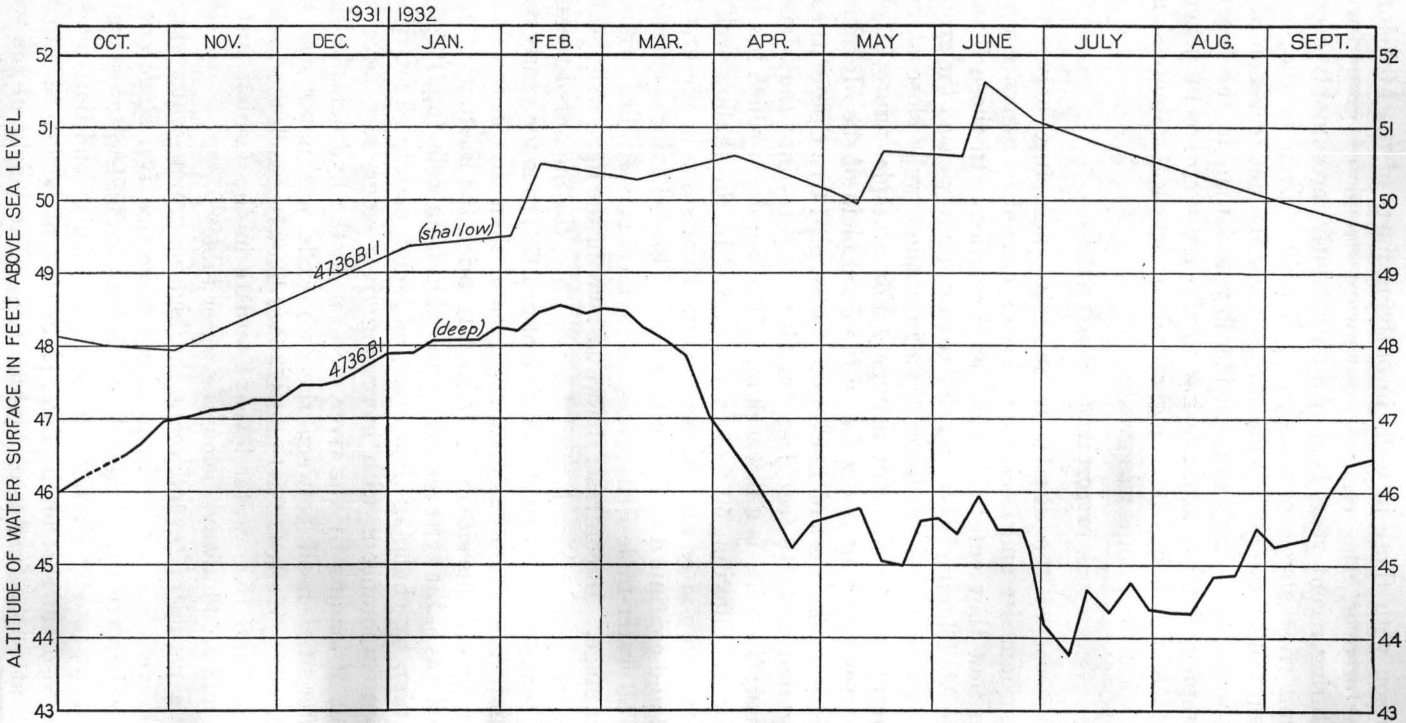


FIGURE 21.—Hydrographs for a deep well (4736B1) and for a companion shallow well (4736B11) on the flood plain of the Mokelumne River near Lockeford, 1931–32.

intervals; according to those fragmentary data the difference in hydrostatic head has been as much as 15 feet (pp. 218–223).

FLUCTUATIONS RELATED TO THE STAGE OF INTERMITTENT STREAMS

DRY CREEK

With respect to the behavior of ground-water levels beneath adjacent land, three segments of Dry Creek may be discriminated in the Mokelumne area—(1) an upstream segment from the mouth of Jackson Creek downstream about to the center of R. 8 E.; (2) an intermediate segment that extends about to Elliott, or about 3 miles into R. 7 E.; and (3) a downstream segment that extends to and beyond Galt. These segments correspond approximately to the outcrop belts of the Valley Springs and Mehrten formations, the Laguna formation, and the Victor formation, respectively.

Along the upstream segment there are only five observation wells within a mile of Dry Creek, four of them on the flood plain. In three of these four (5810N1, 5814J1, and 5815P1) the ground-water level stands constantly 20 to 40 feet below the creek bed, commonly fluctuates less than a foot a year, has declined progressively from 1926 to 1933, and ordinarily has risen to its highest yearly stage in late spring. Well 5815P1 is typical; it is 0.7 mile south of the main channel of the creek, is 59 feet deep, and has a minimum submergence of 4 feet (the least of the three wells). At the opposite extreme, well 5810N1 is 0.2 mile north of the main channel, is 108 feet deep, and has a minimum submergence of 56 feet. In each the water-level fluctuations are similar in type and amplitude to those in well 5826H1 (fig. 13). Well 5826H1 is almost 2 miles from Dry Creek, in a small gully tributary to Goose Creek; its submergence has not exceeded 6 feet from 1926 to 1933, although its depth is 121 feet. All these wells are believed to indicate the stage of the regional water table, which is inferred not to fluctuate in response to flow in Dry Creek, at least in their vicinity. So far as known, all these wells penetrate into the Mehrten formation and are thus comparable to shallow wells along the flood plain of the Mokelumne River east of Clements. The fourth flood-plain well along the upstream segment (5812E2) is a dug well 34 feet deep. Its water level has fluctuated rather widely in response to the stage of the creek and has stood 17 to 28 feet higher than that in a companion well (5812E1) about 200 feet away, which is about 100 feet beyond the margin of the flood plain and whose water level has followed the regional water table. Clearly, well 5812E2 taps perched water.

Along the downstream reach of Dry Creek the ground-water level fluctuates in response to flow in the creek much as it does along the Mokelumne River west of Clements. Thus, in wells near the channel the water level rises when the creek starts to flow, begins to decline as the creek ceases to flow, and varies rather widely during the year.

The influence of the creek extends over a wider area during periods of exceptionally large discharge than at other times.

Along the intermediate segment of Dry Creek the geologic and hydrologic conditions are in some respects unique for the Mokelumne area. There the tongue of alluvium that forms the flood plain traverses the Laguna formation for about 5 miles, whereas along the Mokelumne River, to the south, the flood plain abuts against that formation at a few places only. (However, see pp. 168–173.) Also, there the fluctuations of water levels in shallow wells on and near the flood plain of the creek are distinct in magnitude and in time from fluctuations in deep wells. In general, the shallow wells bottom either in the alluvium or in the Laguna formation, whereas the deep wells penetrate into the Mehrten formation. The hydrographs in figure 22 contrast typical fluctuations in four shallow wells with those in four deep companion wells and in a fifth shallow well remote from the creek. The accompanying table lists and describes the wells.

Typical observation wells on and near the flood plain of Dry Creek in T. 5 N., Rs. 7 and 8 E.

No. of well	Distance between companion wells	Distance from Dry Creek	Distance from Goose Creek	Distance from Dry Creek flood plain	Depth [1]	Land-surface altitude	Geologic formations penetrated [2]	Minimum known submergence
	Feet	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*		*Feet*
5725R2	90	2,400	1,800	600	54	106	Tl	11
5725R1		2,500	1,800	600	435	106	Tl, Tm	388
5725D1 [3]	800	2,000	300	(4)	404	100	Qal, Tm	381
5830E2		2,800	500	300	[5] 240	108	Tl, Tm	194
5830D1	950	2,600	500	200	42	112	Tl	5
5830D11		2,300	500	(4)	[6] 101	109	Tl	58
5821E1	13	1,500		40	44	126	Tl	4
5821E2		1,500		50	249	126	Tm	194
5832R1		14,000	7,000	11,000	145	162	Tl, Tm (?)	44

[1] Depths measured by the East Bay Municipal Utility District or by the United States Geological Survey except as indicated.
[2] Zones where casing is perforated or lacking: Qal, alluvium; Tl, Laguna formation; Tm, Mehrten formation.
[3] In the SE¼NE¼ sec. 25 (subdivision H), rather than in the NE¼NE¼ sec. 25 as indicated by the number of the well; casing perforated opposite the alluvium, so that in effect the well is shallow.
[4] On flood plain.
[5] Reported.
[6] Also reported to be 619 feet deep, thus implying that the well may reach the Mehrten formation.

In three of these typical shallow wells (5725D1, 5830D1, and 5821E1) the ground-water level declined steadily between July and late December 1934, then rose steadily until April or May 1935, in obvious response to storm run-off in Dry Creek and Goose Creek. In well 5725D1, which is on the flood plain, the seasonal range was greatest (18.2 feet) and the water level lagged only a few days behind the stage of the creeks; in the two remaining wells, which lie a short distance beyond the flood plain, the range was about half as great and the lag as much as 3 weeks (5830D1). Two features of the hydrographs are worthy of special note. First, in well 5821E1 the water level rose at a steady rate from January 6 to April 7, 1935—that is, so long as Dry Creek was confined to its main channel. However, during the major storm run-off of April 8–10 the creek discharged in part through a channel that passes only 100 feet north of the well;

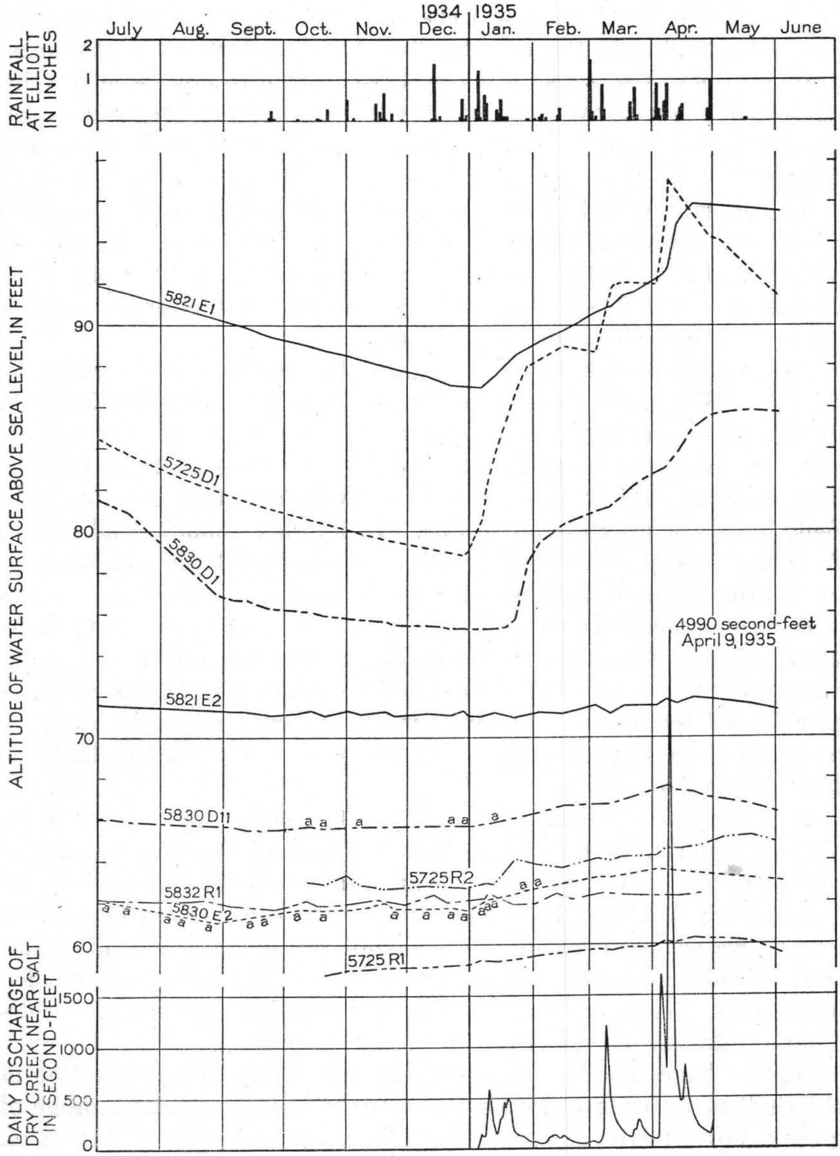


FIGURE 22.—Fluctuations of the ground-water level in four pairs of companion wells along Dry Creek in relation to rainfall, to run-off, and to fluctuations in a shallow well remote from the creek, in the year beginning July 1, 1934. (Hydrographs for shallow wells ruled with light lines, for deep wells with heavy lines. a, Water entering well from strata above static level. Discharge of Dry Creek by the East Bay Municipal Utility District.)

the ensuing ground-water rise was decidedly more rapid. Second, in well 5830D11 between July 15 and August 28 the water level fell with relative rapidity from 81 to 77 feet above sea level; in the following

January the water level rose rapidly through the same range. Similar fluctuations in well 373G3 (fig. 17) have been inferred to indicate the draining of an intermittent body of perched water (p. 157). Characteristically in these shallow wells the ground-water level has never been steady during the investigation but has declined continuously through the dry seasons until Dry Creek began to flow, whether that time was November or January; the ensuing rise has been more rapid than the decline, so that each yearly hydrograph is decidedly asymmetric.[34]

The fourth typical shallow well (5725R2) is half a mile from Dry Creek and 200 yards beyond its flood plain. In that well the ground-water level varied only 2.5 feet during the season, but the sharp rise of January 12 to 22, 1935, and the gradual rise thereafter are ascribed tentatively to infiltration from the creek.

As a standard of comparison, figure 22 includes a hydrograph for well 5832R1, which also is shallow and which is 2.6 miles from the creek. Its water level varied about 0.9 foot during the year and did not respond to the intermittent run-off in Dry Creek. From October 1925 to June 1933 its observed water levels have fluctuated only 5.0 feet, largely a progressive decline. In another shallow well remote from the flood plain (5724P1, 85 feet deep, about 1,600 feet from the creek) the ground-water level has varied only 2.7 feet during the 2½-year term of measurements of depth to water—that is, from September 1927 to May 1930. There are too few observation wells to determine the most remote point reached by the shallow ground-water waves propagated by the intermittent run-off in Dry Creek, although the available data suggest that it is little more than a few hundred feet beyond the flood plain.

It is altogether unlikely that the yearly decline in the level of the shallow water along the intermediate segment of Dry Creek is due to pumping, for in that district there are only two irrigation wells on the flood plain; both are deep and seem not to draw from the shallow ground water. Furthermore, the shallow water level is so far below the land surface that appreciable draft by transpiration or evaporation is unlikely. Thus, in wells 5821E1 and 5830D1 the water level declines steadily, even though at times the static level has been as much as 40 feet below the land surface. Rather, the yearly fluctuation of the shallow water level seems due entirely to intermittent storage of ground water in the alluvium along the creek and gradual dispersion of that water into the enclosing Laguna formation.

In contrast, the water levels in three of the typical deep wells (5830E2, 5830D11, and 5821E2) stood from 9.4 to 33.5 feet below the water level in the respective shallow companion wells during the year beginning July 1, 1934. These differences in hydrostatic head are

[34] See also Stearns, H. T., Robinson, T. W., and Taylor, G. H., Geology and water resources of the Mokelumne area, California: U. S. Geol. Survey Water-Supply Paper 619, pl. 10, 1930.

considerably greater than those found between water-table wells and deep wells along the Mokelumne River and in other parts of the Mokelumne area. Further, the seasonal range of water levels was much less than in the shallow wells—from 0.9 foot in well 5821E2 to 2.1 feet in well 5830D11. Only in the latter well, which is on the flood plain, did the water level seem to respond definitely to the fluctuation in creek stage. However, there is reason to distrust the tightness of the casing, so that the apparent response may be due to shallow water leaking into the well and heightening its normal water level temporarily. Also, those particular fluctuations may have been due in part to the additional load imposed on underlying beds by the storage of water in the alluvium. In the other deep wells the water levels attained a low stage for the season in August or September—that is, at least 3 months before the shallow water levels ceased to decline. Further, although they rose steadily from January to May, the rate for two of the deep wells (5725R1 and 5830E2) was no greater than that which had prevailed for 2 months or more before the first run-off in Dry Creek.

In general, the water levels in the deep wells just described fluctuate at the same time as the regional water table in adjacent districts and show about as wide a range during the year. Moreover, they conform approximately to the water table in altitude. Hence, water-level fluctuations in deep wells along the intermediate segment of Dry Creek are taken to represent fluctuations in the regional water table, although many of these wells are so deep that they may have a slight artesian head. On the other hand, the fluctuations in the shallow wells are inferred tentatively to represent fluctuations in a local body of perched water, which gains storage intermittently whenever Dry Creek or its tributaries flow and which is dispersed by lateral percolation to the edge of the restraining stratum or by downward percolation through uncased wells. (See p. 217.) The wells are too few to permit a rigorous test of the validity of this inference.

BEAR CREEK

Bear Creek appears to have very little influence upon the water level in wells close at hand, as Stearns [35] concluded after comparing the discharge of Bear Creek near Lockeford with the water-level fluctuations in five wells near the creek. That conclusion is substantiated by the more detailed subsequent records of ground-water levels. Thus, in no observation well within 1,000 feet of Bear Creek (with the possible exception of well 3636R2) does the water table rise in response to the intermittent storm run-off; even in wells within 25 feet of the creek (3728K1 and 386C1) the water levels seem to be entirely independent of creek stage. It is presumed, therefore, that seepage into

[35] Stearns, H. T., op. cit. (Water-Supply Paper 619), pp. 191–194, fig. 33.

the bed of the creek does not reach the water table but is dissipated in soil moisture. This presumption gains support from the statement by Stearns that "field inspection of the channel shows that the creek flows on either hardpan, compact sandstone, or conglomerate, all of which are nearly impermeable; hence appreciable losses by deep percolation do not appear probable. Water has been observed to stand in pools in the stream bed for 2 or 3 weeks after the stream has stopped flowing." Thus, Bear Creek east of the Woodbridge Irrigation District is essentially a perched stream, for its bed is relatively impermeable, and it is relatively far above the regional water table. In January 1932 the creek bed was about 54 feet above the water table near Clements, 40 feet above at the Lockeford profile, 29 feet above at the Victor profile, and 24 feet above at the Cherokee Lane profile.

The one well that may respond to flow in Bear Creek (3636R2) is close to the eastern margin of the Woodbridge Irrigation District. In this well several rises of the water level, which is about 24 feet below the land surface, have been synchronous with periods of flow in the creek, but they may have been induced by direct infiltration of the rain that caused the creek to flow. For instance, the water level rose sharply between December 24, 1931, and January 4, 1932, and again from February 5 to 11, 1932. Heavy rain during both these periods is known to have heightened the water level in numerous wells of the vicinity; its effect upon the water level in well 3625R3, a mile to the north, has been described on page 140. The hydrograph for well 276A1 (pl. 9), 0.3 mile to the southeast, likewise shows the infiltration of rain in these two periods. It seems likely, therefore, that a good share of the rise in well 3636R2 was due to infiltration of rain, although it is possible that seepage from Bear Creek augmented the rise somewhat.

Farther west Bear Creek traverses the area served by the Woodbridge Irrigation District. There its bed is inferred commonly to be less than 20 feet above the water table, although there are no observation wells so close to the creek as to measure the effect of storm run-off upon the water table.

FLUCTUATIONS RELATED TO PUMPING FROM WELLS

PUMPING PRACTICE

In recent years about 50,000 acres of land in the Mokelumne area has been irrigated by pumping from wells. Of that area about 60 percent lies in a district of intensive pumping bounded on the north by Jahant Road and its projection westward, on the east by the section line passing a mile west of Lockeford, on the south by Bear Creek, and on the west by the lands served by the Woodbridge Irrigation District. The district of intensive pumping constitutes the central and larger part of the land covered in the inventory of electric energy expended in pumping from wells.[36] The yearly pumpage for irrigation has been as much as 114,600 acre-feet (1928–29),[37] and there have been as many as 2,500 wells equipped with irrigation pumping plants (1931).[38] The frequency distribution of the wells according to depth and according to the geologic horizon in which they bottom has been described on pages 126 to 128.

In the Mokelumne area the irrigation wells are commonly pumped only in daylight and are idle over week ends and holidays; many also are idle during and after long rainstorms in the early part of the pumping season. The pumping season does not begin simultaneously over the whole area. In a district that covers a few square miles south and west of Victor, pumping in recent years has begun in January or February, has reached its height in March, and largely has ceased by April. In outlying localities general pumping has begun as late as May, reached its height in June or July, and waned by September, the lateness of pumping having increased progressively with increasing distance from the heart of the pumping district. At any particular locality, however, the pumping season begins for nearly all the pumping plants at the same time. Owing to these pumping practices and to the fact that the wells tap water-bearing beds at many stratigraphic horizons, virtually all parts of the body or bodies of ground water beneath the central part of the Mokelumne area are set in motion during the pumping season. The rate of draft by pumps and the velocity of the ground water fluctuate through distinct ranges for the day, the week, and the season. Thus, the static ground-water level in observation wells commonly fluctuates in characteristic daily, weekly, and seasonal cycles. Certain of those fluctuations indicate commensurate saturation and unwatering of pervious strata by rise and fall of the water table; but others indicate merely changes in the pressure head of confined water.

DAILY AND WEEKLY FLUCTUATIONS

Water-stage recorder charts from well 373K2 serve to discriminate daily water-level fluctuations due to pumping from those due to variations in barometric pressure. This well is one of those along the Victor profile, which traverses the district of intensive pumping about a mile from its eastern margin (pl. 8, also p. 125). The nearest irrigation well (373K1) is 600 feet to the southeast. From January 7 to 12, 1931, the submergence of the well—that is, the height of the ground-water level above the bottom of the well—was 17 feet;[39]

[36] Piper, A. M., Pumpage of ground water for irrigation in the Mokelumne area, California, 1933, and revised estimates of pumpage, 1927–32: U. S. Geol. Survey typoscript report, pl. 1, Apr. 9, 1934.

[37] Idem, p. 26 A.

[38] Sherwood, G. M., Changes in area irrigated from ground water in the Mokelumne area, California, as indicated by records of irrigation wells and pumping plants: U. S. Geol. Survey typoscript report, p. 5, May 5, 1932.

[39] For a discussion of the influence of submergence on certain types of water-level fluctuations in wells, see p. 189.

also, adjacent irrigation wells were idle. The recorder chart for that period comprises two components—(1) a fairly smooth curve whose period spans more than the particular week and (2) sharp dimples that occur about 10 or 11 o'clock each morning and are due to the ordinary diurnal range in barometric pressure (pp. 134–136). No effects of pumping are recognized. A second period, February 18–23, is within the early part of the pumping season; its chart contains the daily barometric dimples, although they are less pronounced. It also includes a new daily component, which is ascribed to pumping from one or several wells in the vicinity, although the adjacent irrigation well (373K1) was not operating. Thus, if the barometric dimple is disregarded, the hydrograph indicates a daily recession of the water level beginning about 6 p. m. and ending about 2 a. m., at a rate more rapid than during the rest of the day. This recession is revealed for each day of the period, although it was distinctly smaller on Sunday, probably because many irrigation wells were idle. A third and final typical period, April 1–6, comes in the late half of the pumping season; at that time the adjacent irrigation well (373K1) was operating and the ground-water level had receded so that submergence had decreased to 13 feet. Also, the daily barometric dimples had become very shallow but nevertheless persisted throughout the period. The daily pumping fluctuation, ostensibly caused by the adjacent irrigation well, had become a sharp recession of about 0.03 foot between 5 p. m. and 10 p. m., the intervening space having damped a 15-foot drawdown with a lag of 8 to 10 hours. Thus, the average rate of propagation of the ground-water wave set up by the daily pumping was 60 to 75 feet an hour—that is, about the same as for the diurnal fluctuations set up by changes in river stage.

These daily fluctuations ascribed to pumping are believed to measure changes in ground-water storage at the observation well and not to represent changes in pressure head of the ground water. Thus, they are true water-table fluctuations. Analogous fluctuations have been recorded in four additional wells of the Victor profile (373B1, 4722Q4, 4727L1, and 4727P1), whose submergence ranged from 7.6 to 19.8 feet.

Shallow wells mainly record changes in ground-water storage, but even wells with submergence as little as those just described do not always indicate changes in storage when water is being pumped. For example, figure 23 represents another well of the Victor profile and shows daily water-level fluctuations set up by pumping from four wells within 1,500 feet. The mean submergence of the observation well was about 13 feet at the time. The 1.9-foot range of water level on July 29, 1931, was caused by pumping in an irrigation well 200 feet to the south (3722B1); the fluctuations lagged very little behind the pumping and were typical responses to loss in pressure head. In contrast, the sharp fluctuations of 0.02 to 0.10 foot (such as the one marked "a") were caused by an automatic domestic pump in a well 25 feet to the southeast. Further, the fluctuations of

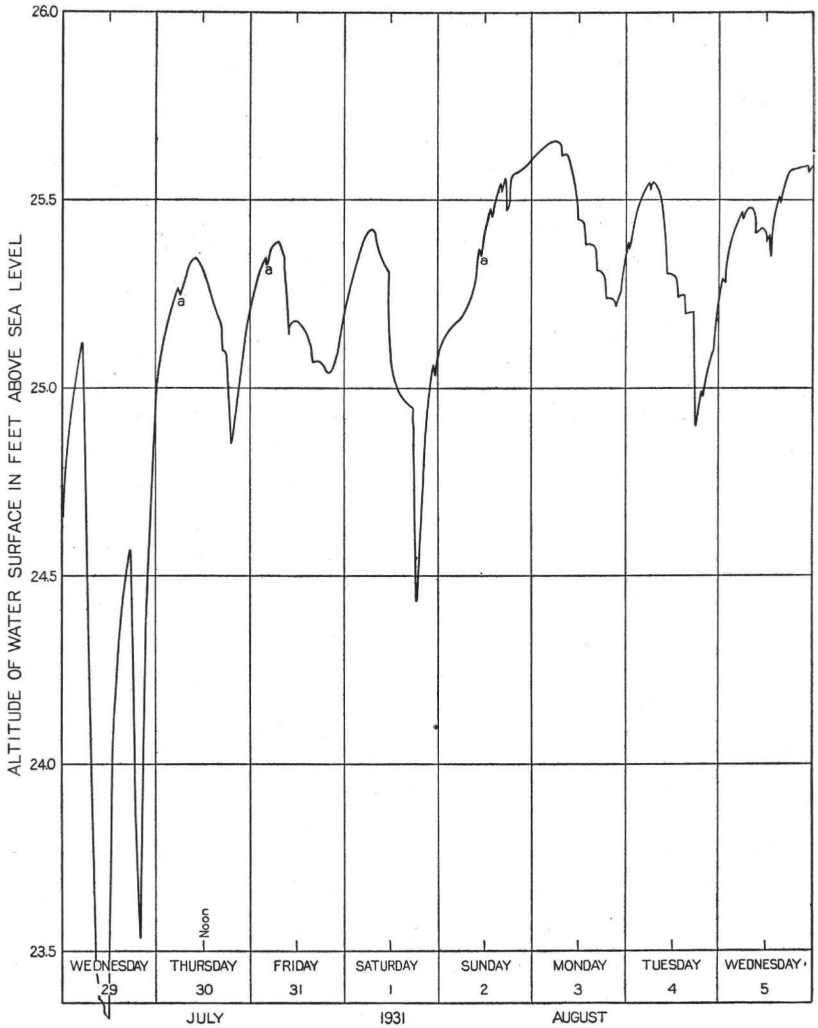


FIGURE 23.—Hydrograph for well 3715P2, showing water-level fluctuations set up by pumping from adjacent irrigation wells. a, Typical fluctuations caused by automatic domestic pumping plant on adjacent well.

July 30 and 31 and August 3 and 4 were probably caused chiefly by pumping from two irrigation wells about 1,200 and 1,500 feet to the north (3715Q1 and 3715K1, respectively). In spite of the distance, the water level in the observation well started to decline within an hour or so after pumping began; also, the daily fluctuation of 0.3 to 0.6 foot was many times greater than in well 373K2 and was much too large to be ascribed wholly to saturation and unwatering. Rather, the fluctuations are believed to have been due largely to changes in head on water confined beneath restraining beds within the 13-foot zone of submergence. Thus, the water level in the well is presumed to have stood below the water table commonly during the pumping season.

A pair of wells on the Cherokee Lane profile, on the opposite side of the pumping district, confirms the preceding conclusion. The wells are (1) 3625R4, whose submergence in 1931–32 and 1932–33 was as little as 10 feet in the pumping season but as much as 16 feet in the nonpumping season; and (2) 3625R3, which is 36 feet southwest of R4, is cased tightly through shallow pervious strata, and has a submergence of 77 to 83 feet. (See pl. 9, also p. 126.) The deeper well taps the water-bearing strata that serve adjacent irrigation wells and are between 95 and 120 feet below the land surface; in the nonpumping season its water level is a few hundredths of a foot above that in the shallower observation well. During the pumping season of 1932 the water level in the deeper well commonly varied about 0.4 foot a day; its hydrographs indicate the cause to have been fluctuations in head of the confined water. In the shallower well the water level varied only about half as much, neither rising so high nor falling so low, also lagging very little at one time and not more than 2 hours at any time. Nevertheless, the hydrographs are similar in form to those of the deeper well. Thus, a large part of the daily fluctuation in the shallow well seems to measure changes in head and not unwatering.

In the heart of the pumping district the closely spaced wells interfere with one another so that the water-level fluctuations in the deep observation wells show the mass effect of pumping, which commonly is a steady tidelike surge with one cycle a day. For example, Stearns [40] reproduces a hydrograph for well 375L3, in which the week-day water level was highest about 5 a. m., fell off sharply as pumping started, receded steadily about 0.15 foot an hour for about 4 hours, and then continued to fall at constantly decreasing rate until about 6 p. m. The ensuing rise began rapidly, then slowed progressively. The whole daily surge was from 1.0 to 1.3 feet. Similar fluctuations in other wells have ranged between about 0.3 foot and 1.5 feet. In each well, the high stage occurs in the early morning and the low stage in the early evening; thus, within moderate limits, the daily surge seems to be synchronous over much of the district of intensive pumping.

Daily fluctuations of the sort described do not occur when the pumps are idle over week ends and holidays; then the water levels rise steadily, and the range commonly is as much as 2.5 feet for the longer term of recovery. Also ground-water levels may rise sharply with long rains, because at such times most irrigation wells stop pump-

[40] Stearns, H. T., Robinson, T. W., and Taylor, G. H., op. cit. (Water-Supply Paper 619), pp. 129-132, fig. 11.

ing; ordinarily that does not occur later than April. Ofttimes the water level begins to rise before the rain has ceased and before the soil-water deficiency has been replenished, so that the rise cannot be ascribed to deep penetration of rainfall. A notable example is the period March 22–24, 1928, in which 2.6 inches of rain fell after the pumping season had begun and just before the record freshet in the Mokelumne River. In well 4727A1, which is a mile north of the river, the water level rose steadily during the rain and as rapidly as during the daily period of recovery from pumping, the aggregate rise having been about 2 feet in the 2 days before the freshet passed to the south. Thus, a considerable part of the contemporaneous rise in other wells may have resulted from shut-down of pumps and not from percolation set up by the freshet.

Two localities along the Victor profile afford critical comparisons of water-level fluctuations in a shallow observation well and in a companion well so deep that in the nonpumping season it shows slight artesian head (p. 219). One pair is about 2 miles south of the Mokelumne River; it comprises well 3710K3, whose submergence has been as little as 4½ feet (April 1933) and as much as 20 feet (January 1931), and well 3710K4, 6 feet to the west, whose submergence has ranged from 138 to 164 feet. Drillers' records show that near these two wells the water table occurs in poorly permeable silt and fine sand, whereas deep well 3710K4 penetrates water-bearng sand and gravel from 83 to 126 feet below the land surface and again from 132 to 161 feet. Within a radius of half a mile there is only one irrigation well (3715A1) so shallow that it may pump entirely from the strata penetrated by the shallower observation well. On the other hand, 13 irrigation wells reach one or both the aquifers of the deeper well; the nearest three are well 3710K1, 140 feet to the southwest; well 3710L1, 750 feet to the northeast; and well 3710F1, 1,300 feet to the north. Plate 15 comprises three pairs of hydrographs for the companion wells. All three hydrographs for the deep well (3710K4) show pressure effects caused by pumping from the deep aquifers, the midweek daily range having been commonly about 1 foot and the week-end range as much as 2½ feet. The three graphs for the shallow well (3710K3) are not alike. Graph A, for the very early part of the pumping season in 1931, indicates that the water level varied half as much as that in the deep well; also, that it lagged about 2 hours after the start of the pumping recession in the deep well and 4 to 6 hours after the start of recovery. The relation of water levels is much the same as at wells 3625R3 and 3625R4 (p. 188). Graph B, nearly a month later, indicates a steady midweek recession in the shallow well, with faint reflections of the daily range in the deep well, but for each week end an extraordinary rise of 2.8 feet beginning nearly 12 hours later than in the deep well and proceeding as a typical pressure effect. Analogous rises have occurred at other times. Thus, adjacent irrigation pumping plants were idle for about 60 hours from January 30 to February 2, 1931. In the deep well the water level rose 2.3 feet, whereas in the shallow well it rose 4.5 feet (pl. 8). Graph C, however, shows virtually no daily surge in the shallow well, in spite of characteristic pumping effects in the deep well; at that time the submergence of the shallow well had decreased to about 6 feet. It is believed that graph C alone traces fluctuations in ground-water storage. On the other hand, shallow-well graphs A and B are believed largely to measure changes in head for confined water, even though submergence was never more than 19 feet. Again, it is inferred that at times during the pumping season the water level in the shallow well has stood below the water table. In the nonpumping season, however, the water surfaces in the two wells have fluctuated together, although their levels have differed by one- or two-tenths of a foot (pl. 8).

The other pair of wells is 1¼ miles north of the Mokelumne River and comprises well 4722Q4, whose submergence ranged from 12 feet in February 1931 to 6 feet in August 1933, and well 4722Q5, 4 feet to the south, whose submergence ranged from 215 to 227 feet. These wells penetrate five beds of sand or gravel at 28 to 57 feet, 63 to 79 feet, 99 to 114 feet, 160 to 161 feet, and 224 to 249 feet below the land surface; intervening beds are chiefly silt and very fine sand. There are ten pumped wells within half a mile; the nearest three are well 4727B1, 200 feet to the south, 350 feet deep; well 4722Q2, 800 feet to the northeast, 380 feet deep; and well 4722Q3, a domestic well with automatic pump, 800 feet to the east, 170 feet deep. The remaining seven are 1,100 to 2,100 feet away and range from 87 to 340 feet in depth. Five of the ten wells are cased so deeply that they would not draw from the aquifers of the shallow observation well (4722Q4). The hydrographs in figure 24 compare water-level fluctuations in the two observation wells. Obviously, the fluctuations in the deep well were pressure effects caused by interference between the several pumped wells in the vicinity, the highest stage of the period having been reached on Monday, June 22, after some wells had been idle for a day. The daily range, 0.6 foot to 3.2 feet, continued throughout the pumping season. (See pl. 8, which shows the range between the highest and lowest water levels of the day if that range exceeded 0.2 foot.)

On the other hand, the water level in the shallow well varied only 0.1 foot during the period and from 0.01 to 0.04 foot a day, the fluctuations presumably having indicated saturation and unwatering for the most part. Interchange of water between the shallow and deep water-bearing beds is effectively restrained, for throughout the pumping season the static level in the shallow well has been the higher, the maximum difference having been about 7.5 feet. In the nonpumping season, however, the static level in the deep well is commonly the higher by about 1 foot. (See pp. 218–223.) The upper casing in the deep well extends only 34 feet below the lowest observed stage of the water table; thus, the restraining beds may be relatively shallow.

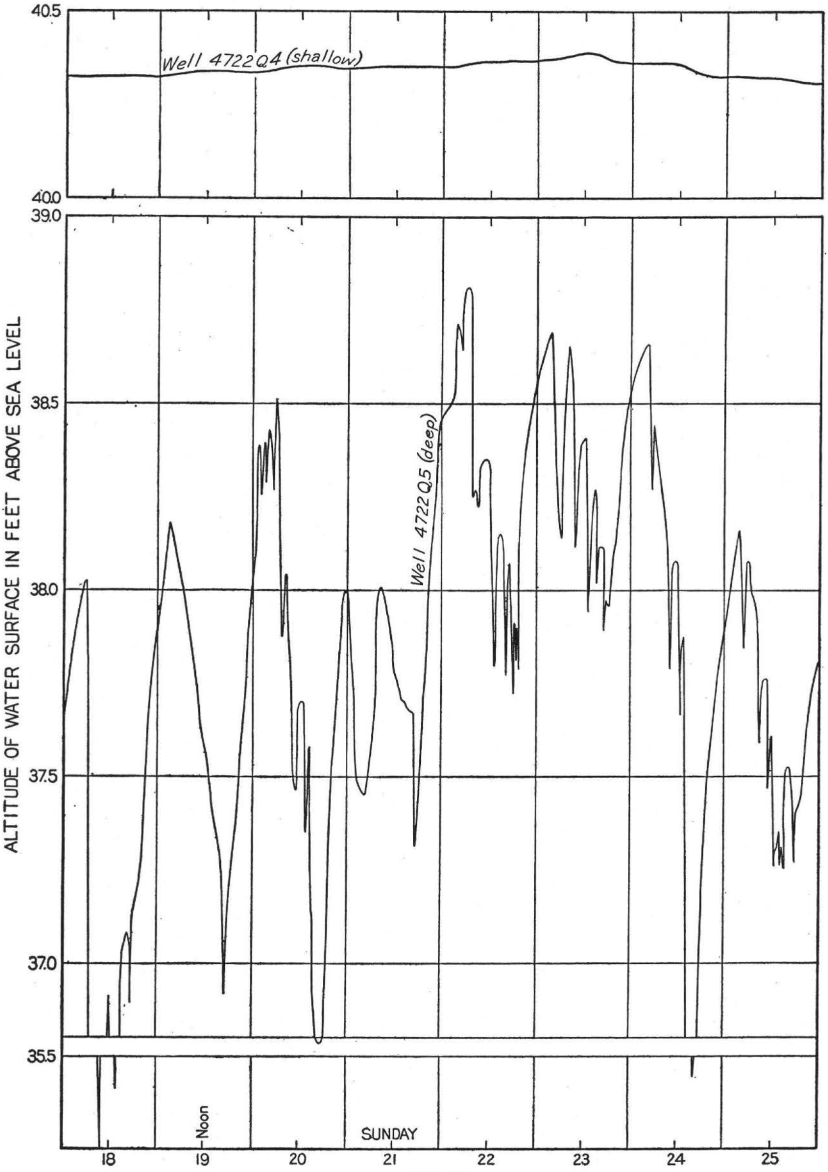


FIGURE 24.—Hydrographs for wells 4722Q4 (shallow) and 4722Q5 (deep), comparing daily water-level fluctuations caused by pumping.

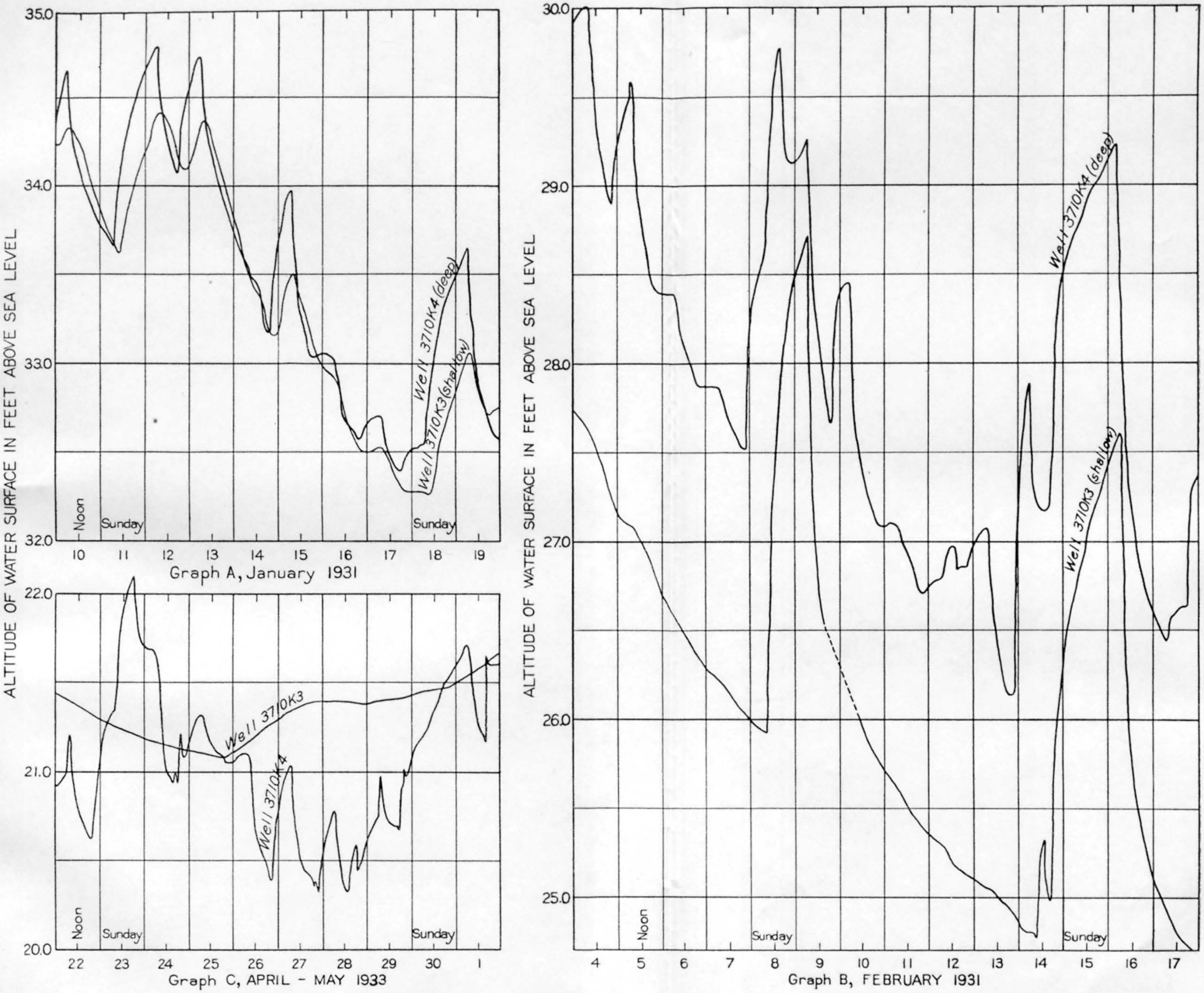
Nevertheless, the small daily range of water level in the shallow well must be a pressure effect in part, for it reflects faintly the major changes in pressure level in the deep well.

In some wells near the edge of the intensively pumped district the water level seems to respond slightly to daily pumping draft in the heart of the district by loss of pressure head after a lapse of several hours. For example, the water level in well 3612A2, in the southwestern part of Lodi, within a mile of a canal of the Woodbridge Irrigation District, usually declines between 10 a. m. and 8 p. m. each day in the pumping season, the range being as much as 0.5 foot. This well also shows the effects of earthquakes and of barometric changes. Its submergence has ranged between 46 and 54 feet. Further, in well 386C1, which is 2 miles east of the district of intensive pumping and 0.4 mile east of the nearest irrigation well, the water level varies as much as 0.4 foot a day but lags about 12 hours behind fluctuations in the heart of the district; thus, the daily recession begins about 7 p. m. and ends about 8 a. m. This well is reported to be 500 feet deep. The daily recession of pressure level is inferred not to indicate unwatering about either of these two wells.

The foregoing data on pressure effects place three critical limits on the validity of measurements of depth to water made during the pumping season. First, the mean water level of the day may deviate by several tenths of a foot from a single measurement in wells whose submergence is less than 20 feet and by as much as 2 feet in deep wells. Thus, the records by two agencies for a single well may seem incompatible. For instance, in well 361A1, near the northern boundary of Lodi, the depth to water was measured by the city of Lodi between 5 and 7 a. m. each day and by the Pacific Gas & Electric Co. in midafternoon about five times a month between January 1930 and April 1933. During the pumping season the measured depth to water commonly was 0.2 foot to 2.0 feet more in midafternoon than in the morning, whereas during the winter the difference was negligible. Second, in some shallow wells even the highest water level of the day may be lower than the water table by tenths of a foot, although the submergence may be as little as 10 feet. Third, in deep wells the highest level of the day may be several feet lower than the water table.

SEASONAL AND LONG-TERM FLUCTUATIONS

Seasonal fluctuations of ground-water level in the district of intensive pumping are shown in detail by the hydrographs for the Victor and Cherokee Lane profiles (pls. 8 and 9). The Victor profile traverses the locality where pumping begins earliest; there, south of the Mokelumne River, the recession caused by pumping has begun soon after January 1 and has ended by April or May—that is, within a month after pumping has slackened from its midseason peak (wells 3710B4, 3710K3, 3710K4, 3715C5). Farther south (wells 3715P2 and 3727F3) the recession has begun as late as early April and the lowest stage has been reached as late as early September. North of the river the recession has begun and ended quite as late, but there the low stage in the



HYDROGRAPHS FOR WELLS 3710K3 (SHALLOW) AND 3710K4 (DEEP), SHOWING FLUCTUATIONS OF THE WATER LEVEL CAUSED BY PUMPING.

shallow wells has lagged behind that in the deep wells and has occurred 2 or 3 months after the pumping draft has slackened. Ordinarily the range has been greater in the deep wells (4722Q5), although not exclusively (3710K3); it has been as much as 13 feet. Along the Cherokee Lane profile pumping ordinarily starts later, so that the recession of water level has not begun until February in the heart of the district (3612M3 and 377J1) and as late as May toward its northern and southern limits (4612R1 and 276A1, respectively). A notable feature is the water-level terrace that persisted along the southern margin of the district in May 1932; presumably it was produced by lapse of the early pumping near Victor followed by heavy pumping in outlying parts of the district.

The pressure effects seem to be dissipated within a few days or weeks after pumping slackens from its midseason peak, and thereafter the water level rises steadily in shallow wells as the unwatered strata are resaturated; also, the level rises commensurately in many deep wells. Commonly, however, the water level does not reach a steady stage in either shallow or deep wells before the ensuing pumping season begins. Where there are no effective restraining beds, as at wells 3710K3 and 3710K4, resaturation may be effected largely by upward percolation from deep pervious beds; elsewhere some water may be transmitted directly upward through uncased wells, but more may percolate from deep beds by devious paths that follow discontinuities in the restraining beds.

In many wells outside the district of intensive pumping the static level fluctuates a foot or more a year, presumably owing to pumping within the district, because (1) the wells are commonly beyond the influence of any stream, (2) the fluctuations occur where the water table is too far below the land surface to be reached by penetration from individual storms or to be affected by transpiration, (3) they are too large to be ascribed to changes in barometric pressure, (4) they occur as much as a mile from any irrigation well, and (5) they are approximately synchronous with fluctuations in the heart of the pumping district. For example, the hydrographs in figure 25 represent seven relatively shallow wells alined eastward through the heart of the pumping district south of the Mokelumne River. Three of these wells (3718A1, 3717D2, and 3710Q1) are within the district of intensive pumping; in them the high ground-water stage occurs simultaneously each year, presumably just before pumping begins in the vicinity. In the second succeeding well (3712R1) which is about a mile beyond the eastern edge of the district of intensive pumping, the high stage lags about 1½ months after that in the wells in the heart of the district; also, the yearly range has been only one-half to one-third as great. Wells 3817C1 and 389Q1 are still farther east; their water levels have not varied widely and appear to be unaffected by pumping. The primary cause for eastward lapse of the yearly water-level fluctuations is believed to be feathering out of the zone of unwatering, although the easterly three wells of this line penetrate the Laguna formation, whose

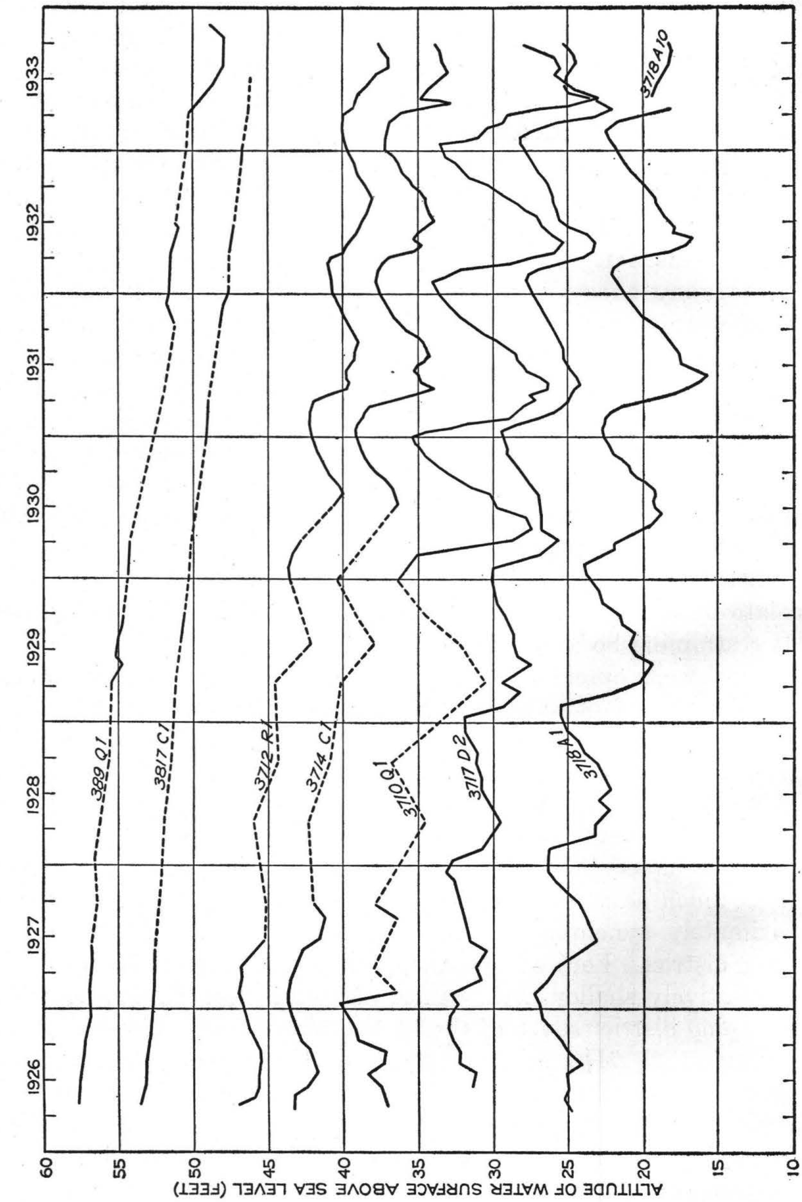


FIGURE 25.—Hydrographs for seven shallow wells along the Kettleman-Terminous Road, 1926–33.

mean perviousness is less than that of the Victor formation in the heart of the pumping district.

In contrast, figure 26 shows corresponding hydrographs for seven deep wells alined parallel to those just described but a mile to the south. In wells 3720A2 and 3716N1, which are in the heart of the pumping district, the measured range in static level has been as much as 10 feet and 14 feet a year, respectively. Toward the east the yearly

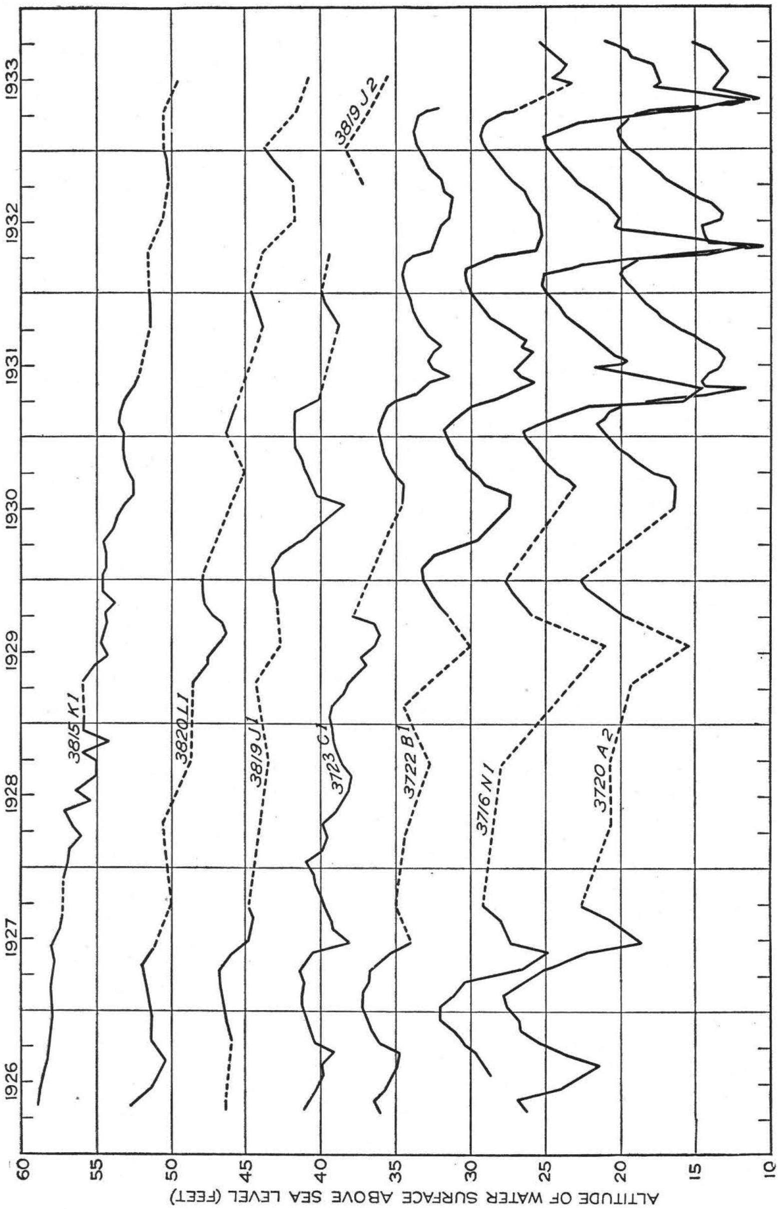


FIGURE 26.—Hydrographs for seven deep wells along Harney Lane, 1926–33.

range has diminished progressively, but even in the most remote well (3815K1), which is 5 miles beyond the pumping district, the range has been nearly 2 feet. Also, the highest stage of the year has been reached almost simultaneously in all seven wells—a coincidence that would scarcely have occurred unless the fluctuations were pressure effects of pumping.

REGIONAL WATER TABLE

RELATION TO SURFACE-WATER BODIES

It has been shown that the water levels in shallow wells within a few hundred feet of the Mokelumne River are influenced by minor changes in river stage, such as the diurnal range due to operation of hydroelectric turbines at the Pardee Dam; also, that the major changes in river stage set up ground-water waves which have been tentatively traced as much as half a mile from the river (p. 168). Thus it is inferred that the regional water table is constantly a prolongation of the river's surface. At the outer margin of the flood plain the zone of saturation in the alluvium is believed to be continuous with that in the sediments underlying the Victor plain and the dissected Arroyo Seco pediment, although locally, as in the reach between the Mehrten dam site and Lockeford, percolation is impeded materially, with consequent steepening of the water-table gradient (p. 172). Accordingly, in the absence of other control, the standard water-surface profiles of the river [41] have been taken to fix river crossings for water-table contours. (See pls. 18–21.)

Numerous undrained depressions on the flood plain of the Mokelumne River above the Woodbridge Dam commonly contain overflow storage. In the largest of these, Smith Lake, the water surface has been shown to be continuous with the water table (p. 150). Farther east, Soucie, Woods-Wilhoit, and Carey Ponds [42] receive inflow from the river whenever its discharge exceeds about 650 second-feet, 1,200 second-feet, and 2,000 second-feet, respectively, but they do not drain completely as the discharge declines. These particular landlocked ponds are presumed also to be continuous with the water table. On the other hand, the small pond in the SE¼SE¼ sec. 25, T. 4 N., R. 7 E., which is known locally as Locke's pond and which is maintained by periodic pumping to water livestock is insulated from the zone of saturation, for ordinarily its water surface is several feet above the water table.

Downstream from the Woodbridge Dam there are also several natural intermittent ponds, of which the largest, Tracy Lake, is mainly in secs. 8 and 9, T. 4 N., R. 6 E. Originally the lower reach of the sinuous channel of Jahant Slough, an intermittent stream, its former outlet has been closed by the levee that forms the north bank of the Mokelumne River, so that storm run-off during the rainy season is impounded. The lake may also be enlarged by overflow from Dry Creek during high stages. Under natural conditions the water in

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[41] Pritchett, H. C., and others, op. cit., pp. 53–56, pl. 34.

[42] Idem, pp. 74–78.

Tracy Lake would probably be dissipated slowly by seepage and evaporation, but a small volume might persist throughout the year. At present, however, the entire lake bed is unwatered by a drainage canal and pump and is cultivated during the spring and summer. Data are not at hand to show clearly the relation of Tracy Lake to the water table. Owing to its low position on the relatively pervious Victor plain, however, it is inferred also to prolong the water table.

The regional water table is likewise believed to be continuous with the water surface of Dry Creek along its downstream reach—that is, from about the eastern margin of sec. 26, T. 5 N., R. 7 E., to and beyond Galt—once the alluvial flood plain has been saturated during the year's first run-off. With the exception of that particular reach, however, the intermittent streams of the Mokelumne area are wholly or in large measure perched above the regional water table or insulated from it. Thus, upstream from Elliott, Dry Creek is continuous with a local body of perched ground water that appears to extend only a few hundred feet beyond the flood plain into the adjacent Laguna formation or Mehrten formation. (See pp. 180–183.)

The largest two tributaries of Dry Creek, Coyote and Goose Creeks, seem nowhere and at no time to be continuous with the regional water table. For instance, near well 483L1, Coyote Creek is perched about 75 feet above the water table, and near well 486M11 it is 55 feet above the water table. Furthermore, in water-table wells within 1,000 feet of Coyote Creek (see fig. 13, well 481B1) the static level declines steadily during the winter and does not fluctuate in such a way as to suggest percolation from Coyote Creek. For the most part, the beds of both creeks are in the Laguna formation and are thoroughly insulated from the regional water table. Likewise, Bear Creek has been shown to be rather completely insulated and to be 20 to 55 feet above the water table. (See p. 183.)

Numerous small depressions on the Arroyo Seco dissected pediment are filled with water during the rainy season. These small ponds are of course far above the regional water table; each year they are dissipated, chiefly by evaporation.

FORM, DEPTH, AND RECESSION OF THE WATER TABLE, 1907–27

Data concerning the form and depth of the water table in the Mokelumne area prior to 1927 have been drawn by Stearns [43] from measurements of depth to water by W. N. White [44] in the district south of the Mokelumne River in 1906–7, and to the north by Bryan [45] in 1913–15; also from reports of well owners and from evidences that pump pits

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[43] Stearns, H. T., Robinson, T. W., and Taylor, G. H., Geology and water resources of the Mokelumne area, Calif.: U. S. Geol. Survey Water-Supply Paper 619, pp. 136–142, 1930.

[44] Mendenhall, W. C., Dole, R. B., and Stabler, Herman, Ground water in San Joaquin Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 398, pp. 183–187, 1916; also unpublished official records.

[45] Bryan, Kirk, Geology and ground-water resources of the Sacramento Valley, Calif.: U. S. Geol. Survey Water-Supply Paper 495, p. 152, 1923; also published official records.

have been deepened once, twice, or even three times. As suggested by contours drawn by Stearns,[46] the water table in those years appears to have been similar in form to that of 1927, although it was appreciably higher than in 1927, according to measurements in numerous wells south of the Mokelumne River. In the 20 years from 1907 to 1927 the water table declined least in the area served by the Woodbridge Irrigation District. There, in four wells that were measured in January 1907 and again in January 1927, the average decline was only 3 feet, or 0.15 foot a year. However, among 18 shallow wells in the district of most intensive pumping for irrigation, in T. 3 N., R. 7 E., the average recession of the water table between January 1907 and January 1927 amounted to 11 feet, or 0.55 foot a year. The greatest of those recessions, 15 feet, or 0.75 foot a year, occurred in well 3728L1, in the very locality where the water table declined most in the 6 years from 1927 to 1933 (p. 200).

In May 1907 the depth to water was measured in about 25 wells, most of which were less than 2½ miles south of the Mokelumne River; in these wells the water table had receded 11½ feet on the average by January 1927. However, the recession in these wells is not strictly comparable to that in the wells measured in January 1907, because many of the wells were so close to the Mokelumne River that their water levels probably rose abnormally high in response to the major freshet of 1906–7. It would be misleading to compare ground-water levels for May 1907 and May 1927, because few irrigation pumping plants existed at the beginning of that 20-year term, whereas many were active by the end of the term and would have depressed the water table considerably.

In December 1913 measurements of depth to water were made in several wells in T. 4 N., Rs. 7, 8, and 9 E.—that is, in the eastern and northern parts of the Mokelumne area; in each of these wells the water table had declined by January 1927. For nine wells in T. 4 N., R. 8 E., the mean decline between 1913 and 1927 was 0.27 foot a year, whereas between 1927 and 1933 it was 0.52 foot a year, or about twice as great.

Still farther north, in the district beyond Dry Creek, in T. 5 N., Rs. 5 and 6 E., the water table appears to have risen somewhat between December 1914 and January 1927.

Sections along the Cherokee Lane and Lockeford profiles (pls. 16 and 17, respectively) show the form of the water table and its depth below the land surface in 1906–7, in 1913–14, and at several times during the present investigation. Along these profiles the general form of the water tables appears to have changed little during the 20 years prior to 1927, except that its relief has increased decidedly between the districts of intensive pumping and the Mokelumne River.

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[46] Stearns, H. T., op. cit. (Water-Supply Paper 619), pl. 13.

In general, the water table appears to have declined since 1907 throughout the part of the Mokelumne area that lies south of Dry Creek; also, the mean rate of recession has been persistently greater in certain districts, doubtless owing to the persistent dominance of the ground-water level by pumping, irrigation, or some such force. It is likely that in certain years the decline of the water table has deviated materially from the long-term average for the area. Thus J. G. Woodson reported that there was 0.2 foot of water in the pit for well 477E2 when it was dug in 1906 and that by 1916 (after 3 years in which the rainfall exceeded the normal) the water level was 4 feet above the pit floor, but that by April 1926 the water level had receded until it was 2 feet below the floor of the pit. In well 4830N1 the decline appears to have been somewhat more uniform. (See pl. 17.) There, the mean annual rate of decline was 0.44 foot from 1907 to 1914, 0.50 foot from 1914 to 1927, and 0.42 foot from 1927 to 1933.

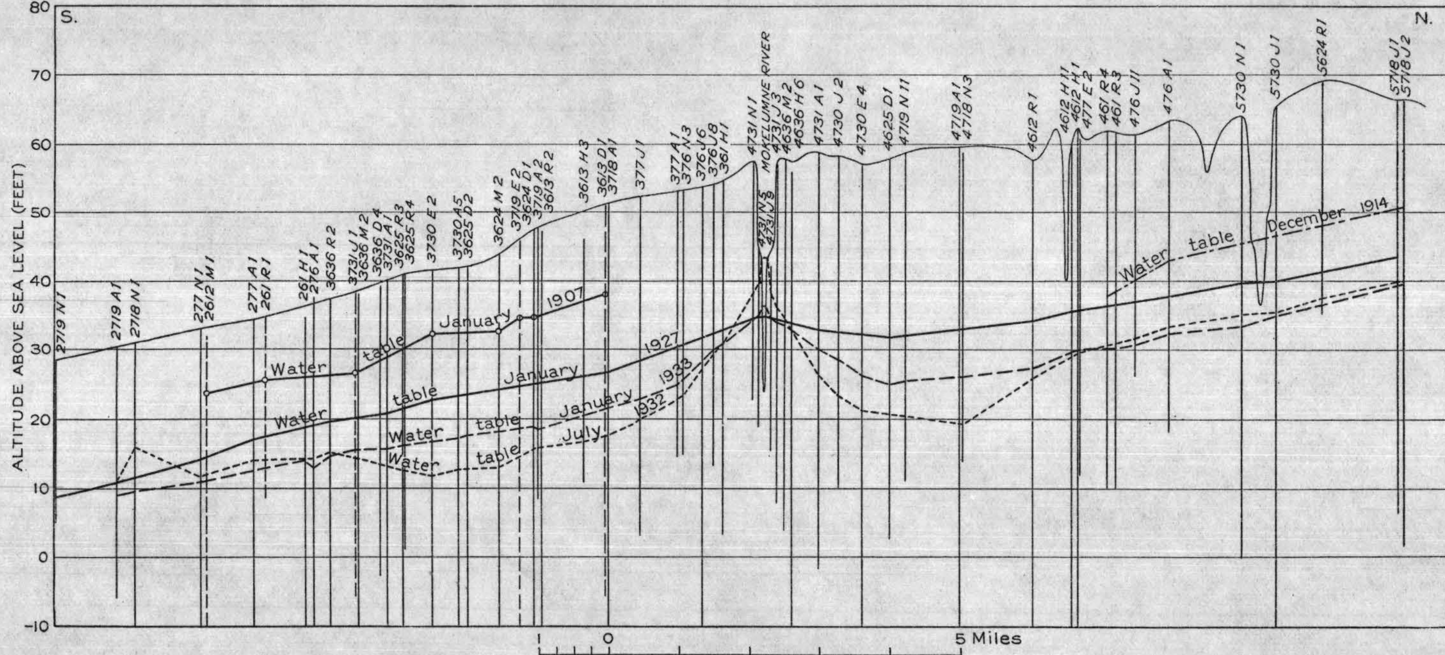
FORM AND DEPTH OF THE WATER TABLE, 1927–33

NET CHANGE IN THE 6-YEAR TERM

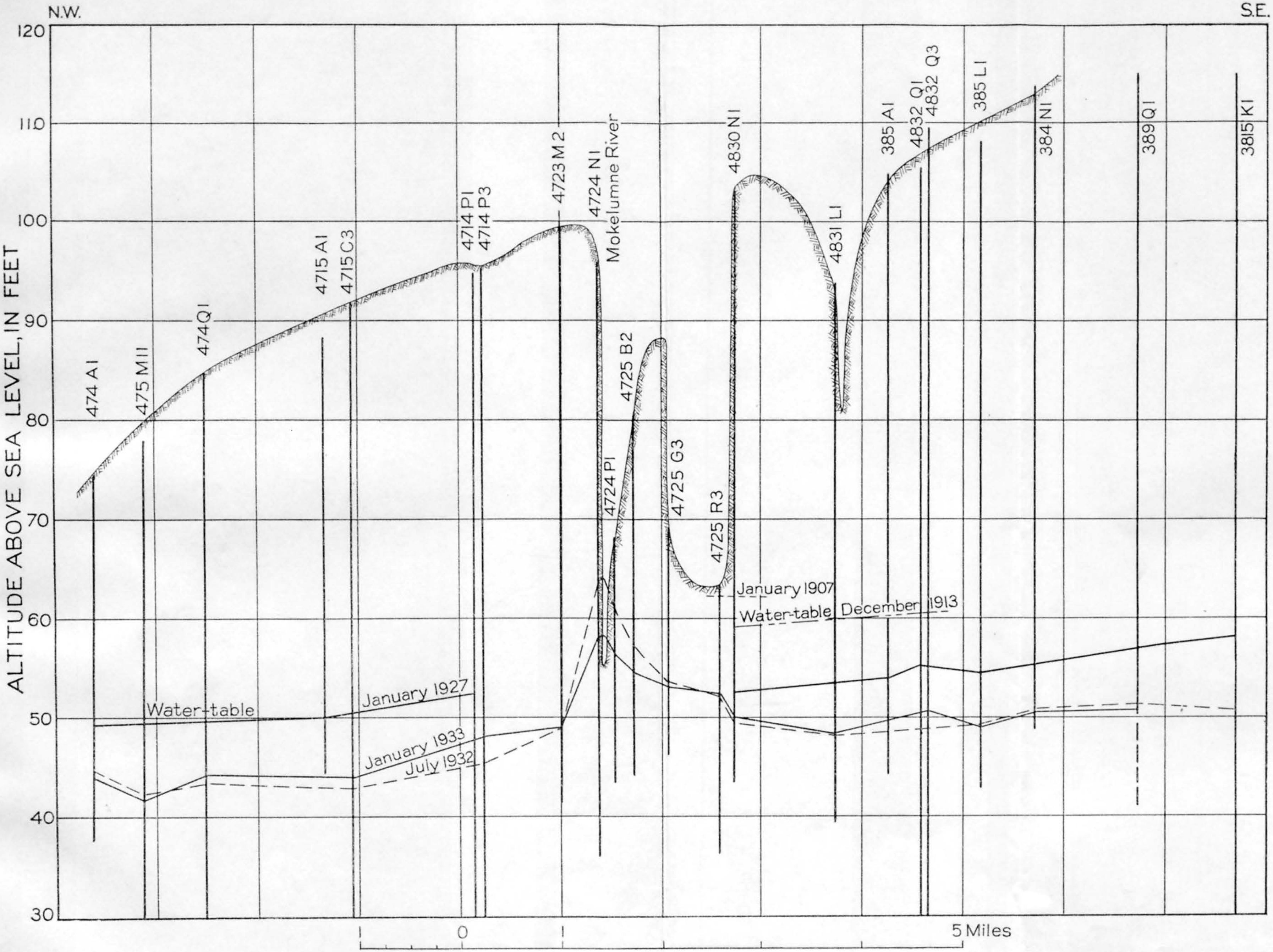
Plates 18 and 19 are contour maps that show the form of the regional water table in January 1927 and January 1933, respectively—that is, during the seasons of minimum pumping near the beginning and near the end of the cooperative investigation. Several elements in the form of the water table are common to the periods represented by these two contour maps and in part are common to all other periods during the investigation. (1) The water table slopes in the same general direction as the land surface, about S. 70° W., but commonly has less relief. (2) The gradient of the water table is flatter than the land surface, so that the depth of the water table below the land surface ranges from a fraction of a foot at some places on the Delta plain—which, under natural conditions, was tidal marsh in large part—to more than 200 feet beneath parts of the Arroyo Seco dissected pediment along the eastern margin of the area represented by the maps. (3) In the eastern part of the area the Mokelumne River is located in a water-table valley as far downstream as the Mehrten dam site, which is in the SW¼ sec. 6, T. 4 N., R. 9 E., about 3 miles east of Clements; along that upstream segment the river is inferred to gain by ground-water seepage. (4) Along the 33-mile segment between the Mehrten dam site and the Woodbridge Dam—that is, across the intensively cultivated district in the central part of the area—the Mokelumne River flows along the crest of a water-table ridge which is as much as 25 feet high and 7 miles wide across the base; it is inferred that the river loses by ground-water seepage all along that ridge and that the percolate ultimately reaches its base. (See pp. 204–206.) (5) Still farther west there is a relatively extensive water-table terrace beneath the Woodbridge Irrigation District, south of the river; there, as far downstream as Thornton, the river appears not to influence the form of the water table.

There are several noteworthy details in the form of the water-table ridge that intervenes between the Mehrten dam site and the Woodbridge Dam. (See pls. 16–19.) Thus, at the Lockeford profile, the water table descends sharply from the river but passes into a relatively flat terrace which underlies much of the flood plain and which extends southward about to the far edge of the flood plain, at least to well 4725R3. There the water table steepens decidedly, for commonly it stands about 3 feet lower beneath the margin of the Victor plain 700 feet away (well 4830N1). A gradient comparably steep exists along the edge of the flood plain farther upstream at the K line (pl. 13) and is indicated by data from wells as far west as well 4734K3, where the water table is commonly 2 to 4 feet lower than the river surface at the Victor gage-height station, 150 feet to the north. Hence that increased hydraulic gradient is inferred to be common between Clements and Victor; presumably it is required to overcome greater resistance to percolation in the outlying district. (See p. 172.) Still farther from the river the water-table gradient becomes relatively uniform beneath the Victor plain. Farther downstream, however, between Victor and Woodbridge, the water table appears to descend rather smoothly from the river without changing gradient at the outer margin of the flood plain. Thus, percolation from the alluvium into the Victor formation appears not to be impeded.

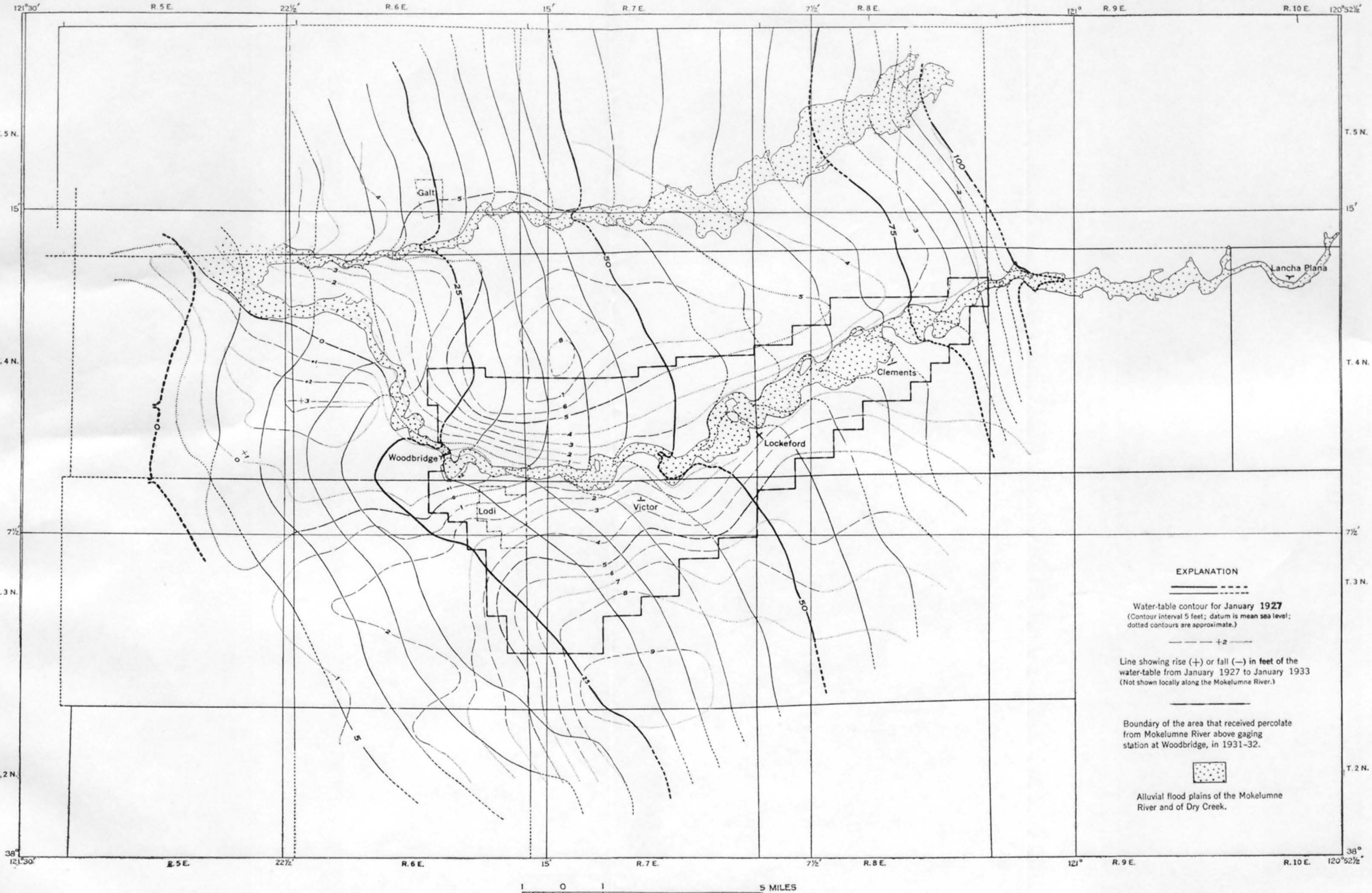
Plate 18 also shows the rise or fall of the regional water table from January 1927 to January 1933—that is, in the seasons of minimum pumping. Because ground-water levels were determined in few wells on and near the flood plain of the Mokelumne River throughout this 6-year period, also because the river stage fluctuated as much as 4 feet in a single day in January 1927, the net change in water-table stage under the flood plain is known only approximately, and no attempt has been made to represent it on the map. It is evident that the water table declined generally in the districts of ground-water irrigation north and south of the river in Tps. 3 and 4 N., R. 7 E., although the districts where the decline was greatest are somewhat farther from the Mokelumne River than the centers of most intensive pumping. The extreme decline—9 feet in the 6-year period—was in an area of about 6 square miles along the southern margin of T. 3 N., R. 7 E. The 6-year decline exceeded 5 feet over most of the central pumping district except within 2 miles of the Mokelumne River, also for 4 to 7 miles farther east; thus, on the map the line showing a 5-foot recession embraces a small part of T. 4 N., R. 8 E., and nearly all of T. 3 N., R. 8 E., where little ground water is pumped. A considerable part of this eastward extension of the area of decline is considered to indicate gradual draft on remote ground-water storage by the intensive pump-



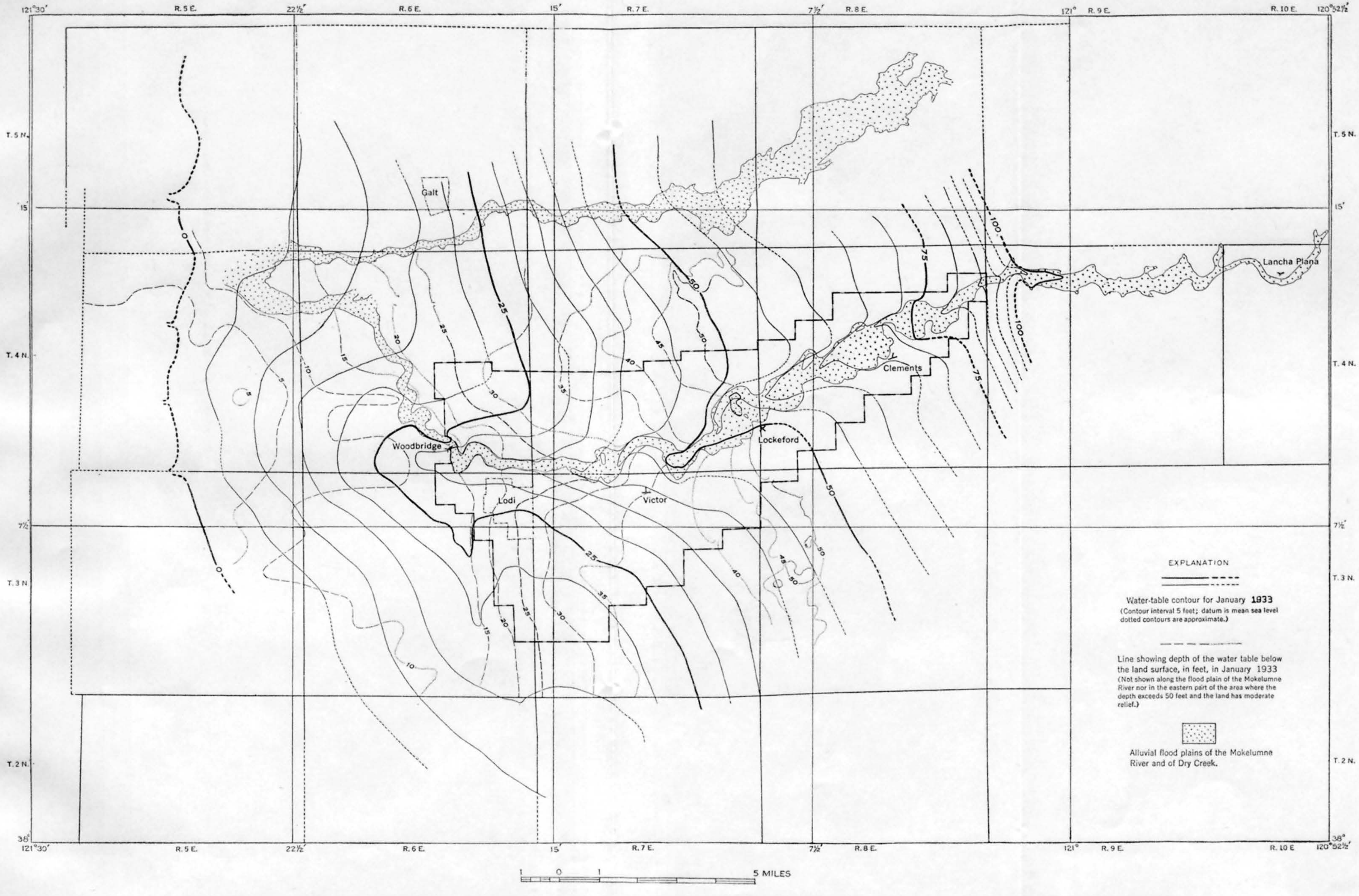
SECTION ALONG THE CHEROKEE LANE PROFILE SHOWING FORM AND DEPTH OF THE WATER TABLE, 1907-33.



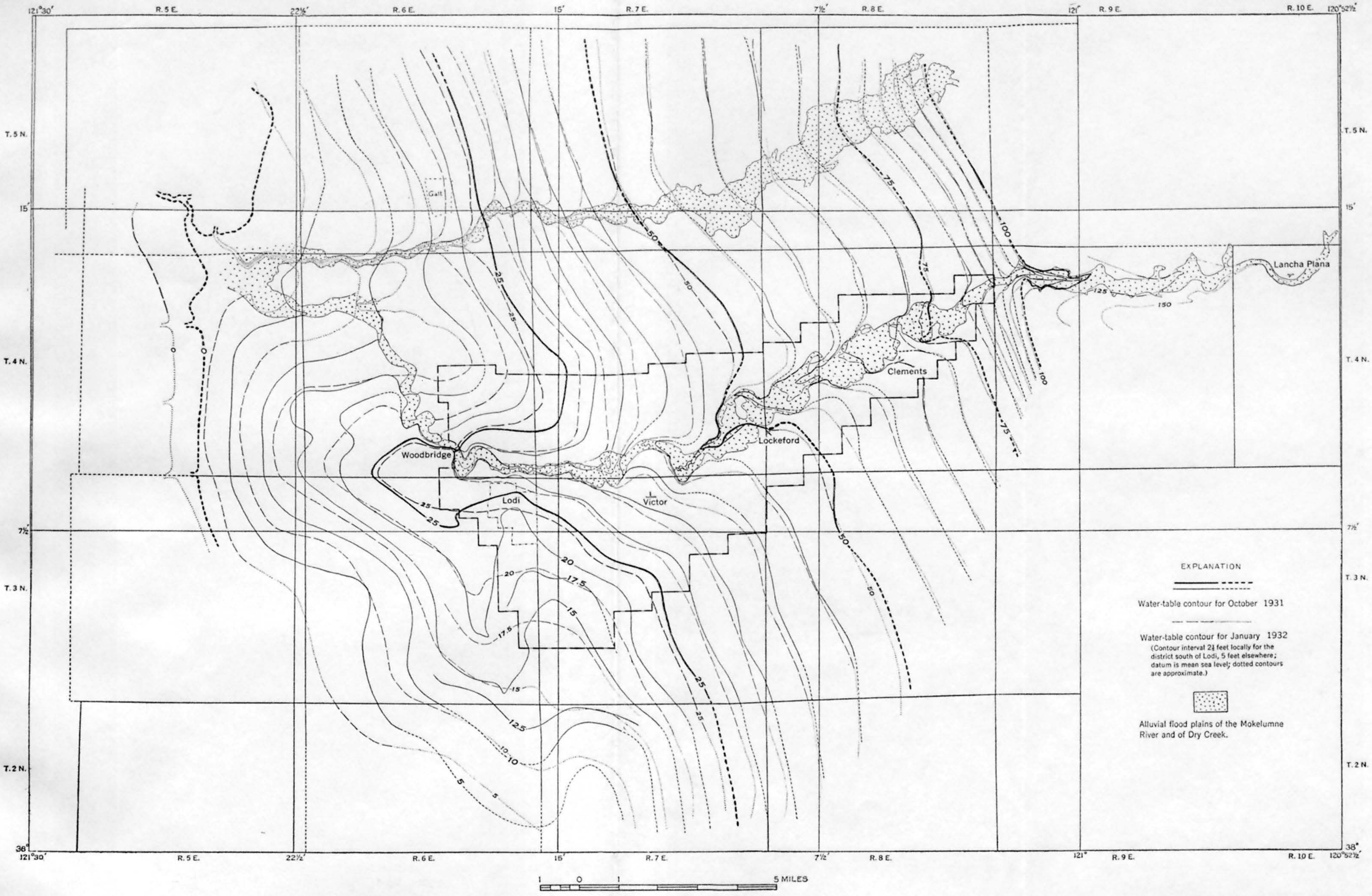
SECTION ALONG THE LOCKEFORD PROFILE SHOWING FORM AND DEPTH OF THE WATER TABLE, 1907–33.



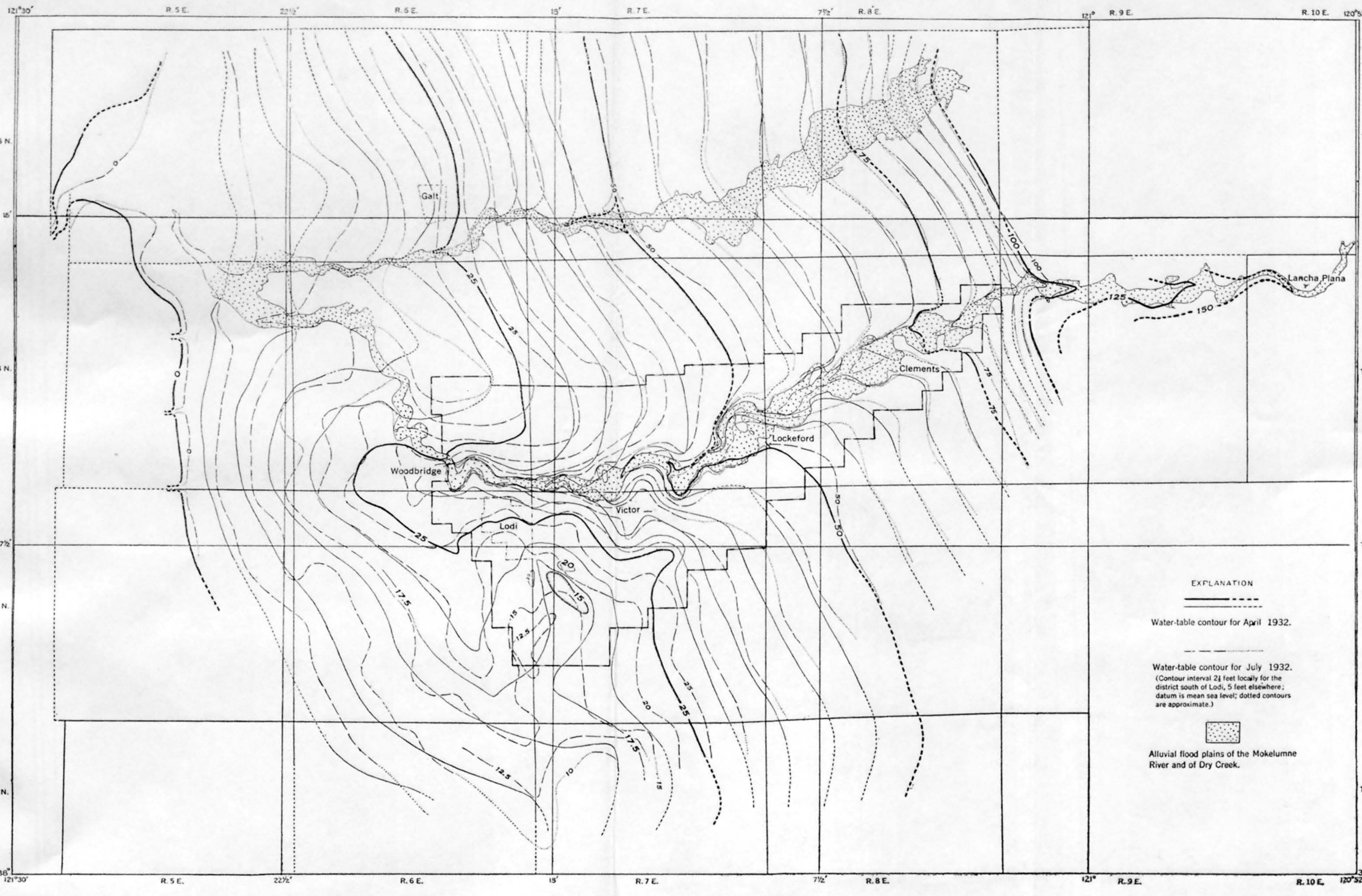
MAP OF THE MOKELUMNE AREA SHOWING WATER-TABLE CONTOURS FOR JANUARY 1927 AND RISE OR FALL OF THE WATER TABLE FROM JANUARY 1927 TO JANUARY 1933.



MAP OF THE MOKELUMNE AREA SHOWING WATER-TABLE CONTOURS AND DEPTH OF THE WATER TABLE BELOW THE LAND SURFACE IN JANUARY 1933.



MAP OF THE MOKELUMNE AREA SHOWING WATER-TABLE CONTOURS FOR OCTOBER 1931 AND JANUARY 1932.



MAP OF THE MOKELUMNE AREA SHOWING WATER-TABLE CONTOURS FOR APRIL AND JULY 1932.

ing farther west, where the recession has been even greater. Thus, the effect of pumping extends farther eastward—that is, up the hydraulic gradient—than in any other direction. Comparable westward expansion of the area of decline has been prevented by recharge from gravity irrigation in the area served by the Woodbridge Irrigation District, where the stage of the water table changed relatively little between 1927 and 1933. Thus, in T. 3 N., R. 6 E., the water table declined not exceeding 3 feet; the westward bulges of the lines on the map showing 1- and 2-foot recessions in this township are probably caused by pumping from wells west of the district. In the northern part of the gravity-irrigation district (in T. 4 N., Rs. 5 and 6 E.) the water table rose as much as 2 feet over a moderately extensive tract during the 6 years. The map indicates an extreme rise of 3 feet locally along the northwest branch canal; however, that feature is probably in large part fortuitous, for (1) in 1933 that canal was not drained until January 3, whereas the south branch and west branch canals were drained on December 9 and 14, 1932, respectively; and (2) there had been no flow through the canals for 2 months prior to January 1927.

SEASONAL CHANGES DURING 1931–32

Obviously, the water table in the Mokelumne area is changing constantly in form, owing to the interplay of fluctuations which have been described above, insofar as those fluctuations pertain to the water table and represent saturation and unwatering rather than pressure effects. Indeed, the gross seasonal changes commonly have exceeded the net change during the 6 years 1927–33. The seasonal changes in form during the year beginning October 1, 1931, are typical and are represented by plates 20 and 21, which show quarterly water-table contours and thus discriminate the effects caused by pumping from wells, by stream discharge, and by gravity irrigation in the Woodbridge Irrigation District.

Plate 20, the map showing water-table contours for October 1931 and January 1932, represents two stages in the recovery from pumping during 1931—specifically, as the pumping of 1931 had largely waned and just before the ensuing pumping season began, respectively. For both periods the water-table contours are spaced fairly uniformly, especially in January, because the pressure effects of pumping were largely dissipated. By January the form of the water table had become more stable for the whole Mokelumne area than in any other season of the year, because the material previously unwatered by pumping had been largely resaturated, diversion by the Woodbridge Irrigation District was small (fig. 15), and the stage in the Mokelumne River had been low and relatively steady for months (pl. 12). Even so, the embayments or valleys in the water table caused by pumping and the prominences caused by irrigation in the Woodbridge district were not effaced completely. From this map and from all foregoing data on fluctuations of the water table it is inferred that the water table generally has been most stable in form about January, under both the so-called natural regimen and the regulated regimen of the Mokelumne River. Thus, the calendar year appears to be the most practicable term for ground-water inventories, at least for the central part of the Mokelumne area.

Pumping from wells depresses the water table and deflects the water-table contours eastward. Where the pumping is most intensive, a basinlike depression may be formed in the water table by the coalescence of the cones of influence of individual wells; thus, the map for April and July 1932 (pl. 21) includes closed depression contours in the western part of T. 3 N., R. 7 E. Owing to pressure effects, the areas enclosed by these contours may be somewhat more extensive than the zone actually unwatered, although all the maps have been based wholly on the shallow wells (p. 128), in which pressure effects are minimum. For the most part, however, pumping merely steepens the water table along the eastern edge of the central district and flattens the water table in the western part of the district. The elements of form thus developed are shown most strikingly by the water-table contours for July 1932. At that time there were embayments beneath the districts of intensive pumping both north and south of the Mokelumne River in Tps. 3 and 4 N., R. 7 E.; also in the southern part of T. 5 N., R. 6 E., in T. 2 N., R. 7 E., and in the southwestern part of T. 3 N., R. 6 E., owing to pumping in outlying districts. Several of the minor irregularities of the contours are explained by known inequalities of pumping draft. Thus, the embayments defined by the 30-, 35-, and 40-foot contours in T. 4 N., R. 7 E., extend northward only to the far edge of the district of most intensive pumping; also, the ridgelike prominence delineated by the 35-foot contour in sec. 4, T. 3 N., R. 7 E., probably results from relatively light ground-water draft in the northern part of the section, where the land is irrigated in part by pumping from the Mokelumne River. In detail the water table is doubtless still more uneven than is indicated by the map, for moderate generalization results invariably when form is interpolated from observations in representative wells.

In April 1932 there were pronounced irregularities in the water-table contours in T. 3 N., R. 7 E. In that district pumping ordinarily has begun in January or February (p. 192), whereas elsewhere in the Mokelumne area pumping has not begun ordinarily until April. Thus, in certain outlying parts of the Mokelumne area the water-table stage for April represents the maximum recovery from the preceding pumping season. For the area as a whole the water table is smoother in April than in July.

Because its crest rises and falls faithfully with the stage of the Mokelumne River, the relief of the water-table ridge between the Mehrten dam site and the Woodbridge Dam was increased by the high river stage in April 1932, and even more so in July. (See pl. 12.) Its relief was accentuated further by the contemporary lowering of the water table in the pumping districts to the north and to the south, so that the gradient of the water table away from the river was much steeper than in October or January. Plate 21 suggests the maximum relief of the water table that might have existed before the river was regulated at the Pardee Dam. At most places and times the crest of this water-table ridge is formed by the river, but locally the crest cuts across meanders or sinuosities, so that temporarily or permanently it is some distance from the river. Thus, the 70-foot contour in April 1932 defines the water-table divide as about 1,500 feet northwest of the river. Occasionally, when the river stage declines sharply, an intermittent and relatively shallow valley may occupy the axis of the water-table ridge, with a divide a few hundred feet to one side or to both sides of the river; thus, ground water drains back into the river from storage in the alluvium close at hand. (See pp. 164,169.) For example, in October 1931 the water table at the south edge of the flood plain near Clements was higher than the river (pl. 20); the mean discharge in the river had declined from 525 second-feet for August to 108 second-feet for September and 58 second-feet for October.

Seasonal diversion from the Mokelumne River by the Woodbridge Irrigation District has pronounced effects upon the form of the water table, especially in Tps. 3 and 4 N., R. 6 E. Filling the reservoir heightens the water-table ridge; also, application of water to the land served by the district builds up the water table into water-table ridges alined roughly along the three branches of the main canal. These features are shown by the 15-, 20-, and 25-foot contours during October 1931 and in April and July 1932. At the latter time the ridge along the south branch canal was accentuated, because the water table had been depressed to the east and to the west by pumping. In January 1932, a few days after gravity diversion had ceased, the water table within the Woodbridge Irrigation District still stood higher than in adjacent areas to the north or south, but the ridges along the several canals had subsided greatly.

Throughout 1931–32 the water table sloped northward from the Woodbridge Irrigation District to and even beyond the Mokelumne River. Thus, there appears to have been ample opportunity for ground water to percolate from the Woodbridge district into the district of ground-water pumping north of the river, especially during the irrigation season. Further, although discharge measurements have shown the river to be a gaining stream between Woodbridge and Thornton at low stages, the land adjacent to the north is comparable in every respect with that adjacent to the losing segment of the river upstream from the Mehrten dam site, for it receives seepage from the direction of the river. It is conceivable that the seepage loss from the river to this area to the north at times exceeds the seepage gain from the irrigation district to the south—that is, the river may be intermittently a losing stream below Woodbridge. That condition would be most likely to occur when the river stage was high, especially if irrigation were also at a minimum. As the records of discharge for the gaging station near Thornton cover only the periods of low water from 1926 to 1931,[47] comparisons of the run-off at Woodbridge and near Thornton do not include periods when the river might be expected to lose by seepage.

AREA RECEIVING PERCOLATE FROM THE MOKELUMNE RIVER

BOUNDARIES

The inference has been drawn that the seepage loss from the Mokelumne River above the gaging station at Woodbridge ordinarily takes place downstream from the Mehrten dam site. Justification for that inference lies in the fundamental principle that ground water moves directly down the slopes of the water table or other piezometric surface—that is, normal to contour lines of that surface. Accordingly, the water lost from the Mokelumne River must percolate down the flanks of the water-table ridge that has been described. Furthermore, it must percolate ultimately to the base of that ridge but no farther. On the north the area that receives percolate is bounded by the lowest thread of the broad water-table valley that heads about at the Mehrten dam site and thence trends nearly due west. (See pls. 18–21.) On the south the area is bounded by another broad water-table valley that trends about S. 60° W. from the Mehrten dam site. To the west, the sector between those diverging boundaries is closed during most of the year by the foot of the water-table terrace or low ridge that underlies the Woodbridge Irrigation District.

If these boundaries for the area that receives percolate from the river are traced on the quarterly water-table maps for 1931–32 it becomes apparent that west of Lockeford they migrated to and fro as much as 2 miles during the year, but that east of Lockeford they remained fairly stable in position. In general, they were most remote from the river when the water table was highest and the pumpage was least. Thus, during 1931–32, in the area of most intensive pumping (Tps. 3 and 4 N., R. 7 E.) the area receiving percolate from the river was most extensive in January. At that time the area was about 3 miles wide between Clements and Lockeford and thus extended about a mile beyond the outer margin of the flood plain on each side of the river. Farther west, between Victor and Lodi, the area was about 6 miles wide. On the other hand, the area was least

[47] Stearns, H. T., Robinson, T. W., and Taylor, G. H., op. cit. (Water-Supply Paper 619), pp. 65–66.

extensive in April throughout the area of intensive pumping, but there was little change east of Lockeford. In general, the boundaries of the area at other times of the year were intermediate between the positions of January and April.

The seasonal migration of the northern and southern boundaries of the area that receives percolate appears to be the direct result of pumping. Deep valleys and even closed depressions are characteristic of the water table under areas of most intensive pumping, especially south of the river. If developed in proximity to the river, such features would effectively limit the area of the river's influence, for movement of ground water away from the river must be down slope, and the reverse slopes on the uneven water table would constitute barriers to percolation. Although the area receiving percolate was least extensive in April, the effect of pumping is also fairly well shown in July, especially south of the river. This effect of pumping is not to restrict the rate of seepage but to limit the distance which the percolate may reach ultimately.

On plates 1 and 18–21 the most remote position for the boundary of the area that received percolate from the river during 1931–32 is conventionalized by quarter-mile steps within the rectangular net of the official land surveys. As drawn, that boundary encloses (1) about 5,200 acres of the flood plain of the river, that area involving an assumption that the mean area of the river and connected water bodies is 510 acres; (2) outlying districts to the north and to the south which together cover about 36,500 acres. Those outlying districts are almost wholly on the Victor Plain, but their most easterly parts transgress the Arroyo Seco dissected pediment.

In January 1933 the area receiving percolate from the river was somewhat less extensive than the conventionalized area for 1931–32. (See pl. 19.) In January 1927 the northern and southern boundaries of the area receiving percolate from the river also lay closer to the river. Thus, east of Lockeford the area in 1927 commonly extended only about half a mile beyond the edges of the flood plain, and west of Lockeford it extended only about 2 miles north of the flood plain. Moreover, the western limit of the area receiving percolate in January 1927 cannot be traced definitely, for south of the river the water table at that time sloped gently to the southwest entirely across the Woodbridge Irrigation District. Thus, percolate from the river might have continued to the Delta. However, percolation westward for an indefinite distance is not likely to occur except after several months of inactivity by the Woodbridge Irrigation District, when the low ground-water barrier built up by gravity irrigation has been dissipated. Ordinarily that condition has not prevailed for long during any year of the investigation. Accordingly, it is believed that the conventionalized boundary for 1931–32 can be taken as marking without material error the area whose ground-water supply has been replenished in part by seepage loss from the Mokelumne River from 1926 to 1933.

MEAN WATER-TABLE FLUCTUATIONS WITHIN THE AREA RECEIVING PERCOLATE

GENERAL FEATURES

The accompanying table and the lower graph of plate 22 indicate fluctuations in the monthly mean altitude of the water table within the conventionalized boundary of the area that has received percolate from the Mokelumne River above the gaging station at Woodbridge, excluding the flood plain of the river. These data span the period from 1926 through 1933, although they are incomplete for the years ending September 30, 1928 and 1929. They consider the influence of the Woodbridge Reservoir and of Smith Lake on the stage of the water table but not the influence of the canals and other distribution works of the Woodbridge Irrigation District.

Monthly mean altitude, in feet above sea level, of the water table beneath the segment of the Victor Plain that receives percolate from the Mokelumne River, 1926–34

Month	1926–27	1927–28	1928–29	1929–30	1930–31	1931–32	1932–33	1933–34
October	41.68			38.82	38.33	36.26	36.95	35.73
November	41.84			39.39	38.69	36.79	37.48	[1] 36.27
December	42.37			39.55	39.01	37.22	37.90	36.82
January	42.54	42.21	41.23	39.70	38.89	37.69	38.21	37.33
February	42.60			39.44	38.59	37.99	38.20	
March	42.67			38.87	37.84	37.61	37.69	
April	42.89	42.22	39.40	37.67	36.40	36.40	36.34	
May	42.45			36.90	35.43	36.19	35.53	
June	41.81			36.77	35.37	36.25	35.33	
July	41.22		38.34	36.45	35.10	35.88	34.80	
August	40.99			36.74	35.34	35.98	34.69	
September	41.26	40.43		37.61	35.80	36.38	35.22	
Average	42.02			38.16	37.07	36.72	36.53	

[1] Interpolated.

The computation of mean water-table altitudes has involved four steps. (1) Records were segregated to show ground-water levels in most of those observation wells that were within or near the particular area, that were competent to define the stage of the regional water table (except for the transient pressure effects of pumping; see pp. 128–129), and that had been observed with relative frequency during much of the term of the investigation. Of necessity, the list includes a moderate proportion of wells whose submergence during the pumping season is so great that at times the static level is lowered somewhat by the pressure effects of pumping. (See pp. 189–192.) However, the few measurements that showed large pressure effects were rejected in computing the mean water-table altitudes. In the main, the list comprised the wells that had been observed by the United States Geological Survey from 1926 to 1930 and jointly by the Survey and the Pacific Gas & Electric Co. from 1930 to 1933; also, selected records of shorter term from other agencies insofar as they were necessary to afford representative data. However, some competent records were excluded for districts in which the observation wells were disproportionately numerous. For the years ending September 30, 1927 to 1930, the lists included 60 or 61 wells—that is, one well to 600 acres on the average; for the next 4 years, the lists included 96 to 104 wells—that is, one well to each 380 to 350 acres, respectively. (2) The area represented by each of the segregated records was established as follows: (*a*) On a map adjacent wells were joined by lines dividing the area into quadrilaterals or into triangles that were, respectively, as nearly rectangular or equilateral as possible; (*b*) the quadrilaterals were subdivided by joining the mid-point of each side with the intersection of the two diagonals; (*c*) the triangles, which were relatively few, were subdivided by projecting lines from the mid-points of the sides toward the opposite vertices; (*d*), the area represented by each well was taken to comprise the subdivisions that surrounded it. (3) From hydrographs, monthly mean altitudes of the water table were interpolated for each of the segregated wells. (4) Finally, the monthly mean water-table altitudes were computed as weighted averages, the altitudes interpolated for the several wells having been weighted in proportion to the respective areas that were represented.

By trial for typical quadrilaterals, the weights derived by the method above described were found to agree closely with those determined by locating the centroid and joining it to the mid-points of the sides; and those for triangles were found to agree with weights determined by the common Thiessen method [48] (by erecting perpendiculars at the mid-points of the sides). Further, the construction was less laborious than for either of the foregoing alternatives. For the particular pattern of wells involved, the weights are believed to be as trustworthy as if the Thiessen method had been used throughout.

As plate 22 shows, the mean water-table altitude has fluctuated moderately each year; by inference, the fluctuations have been due primarily to draft by pumping from wells and to recovery from that draft, although obviously they seek to maintain a dynamic balance between all items of recharge and discharge. From 1927 to 1931 the yearly fluctuation increased progressively from 1.9 to 3.9 feet—that is, it doubled within 4 years; however, in 1932 it diminished by nearly half (2.1 feet), but in 1933 it was again relatively large (3.5 feet). From 1930 to 1933, the period for which the record of water-level fluctuations is strongest, the high water-table stage of the year ranged between December and February, whereas the low stage occurred in June or July. Further, from 1927 through 1931, the successive high stages declined about 1.0 foot each year; in the same

[48] Thiessen, A. H., Precipitation averages for large areas: Monthly Weather Review, vol. 39, pp. 1082–1084, 1911. Horton, R. E., Rational study of rainfall data makes possible better estimates of water yield: Eng. News-Record, vol. 79, pp. 211–213, 1917.

period the low stages declined even more, about 1.5 feet a year. In 1932 and early 1933 the downward trend was checked but the low stage of 1933 again fell off about 1 foot.

RELATION TO SOURCE AND DISPOSAL OF GROUND WATER

The fluctuations in mean water-table altitude verify the presumption that simple storage methods [49] will afford sound ground-water inventories for the conventionalized segment of the Victor plain that has received percolate from the Mokelumne River. Also they indicate the periodicity and relative volume of the ground-water replenishment or draft that has not been measured by direct methods. Thus, the following table indicates the monthly mean rise or fall of the water table beneath the particular area. The same data are shown by one of the four graphs that constitute the upper diagram on plate 22 after they have been transformed into monthly change in ground-water storage by involving the extent of the area (36,500 acres) and the mean specific yield of the two zones of water-table fluctuation (11.1 percent above mean altitude 38.2 feet, 14.5 percent below that altitude; see discussion of specific yield of water-bearing materials). All the graphs on plate 22 are drawn with equivalent scales for water-table stage and for ground-water storage.

Monthly mean rise or fall, in feet, of the water table beneath the segment of the Victor plain that receives percolate from the Mokelumne River, 1926–34

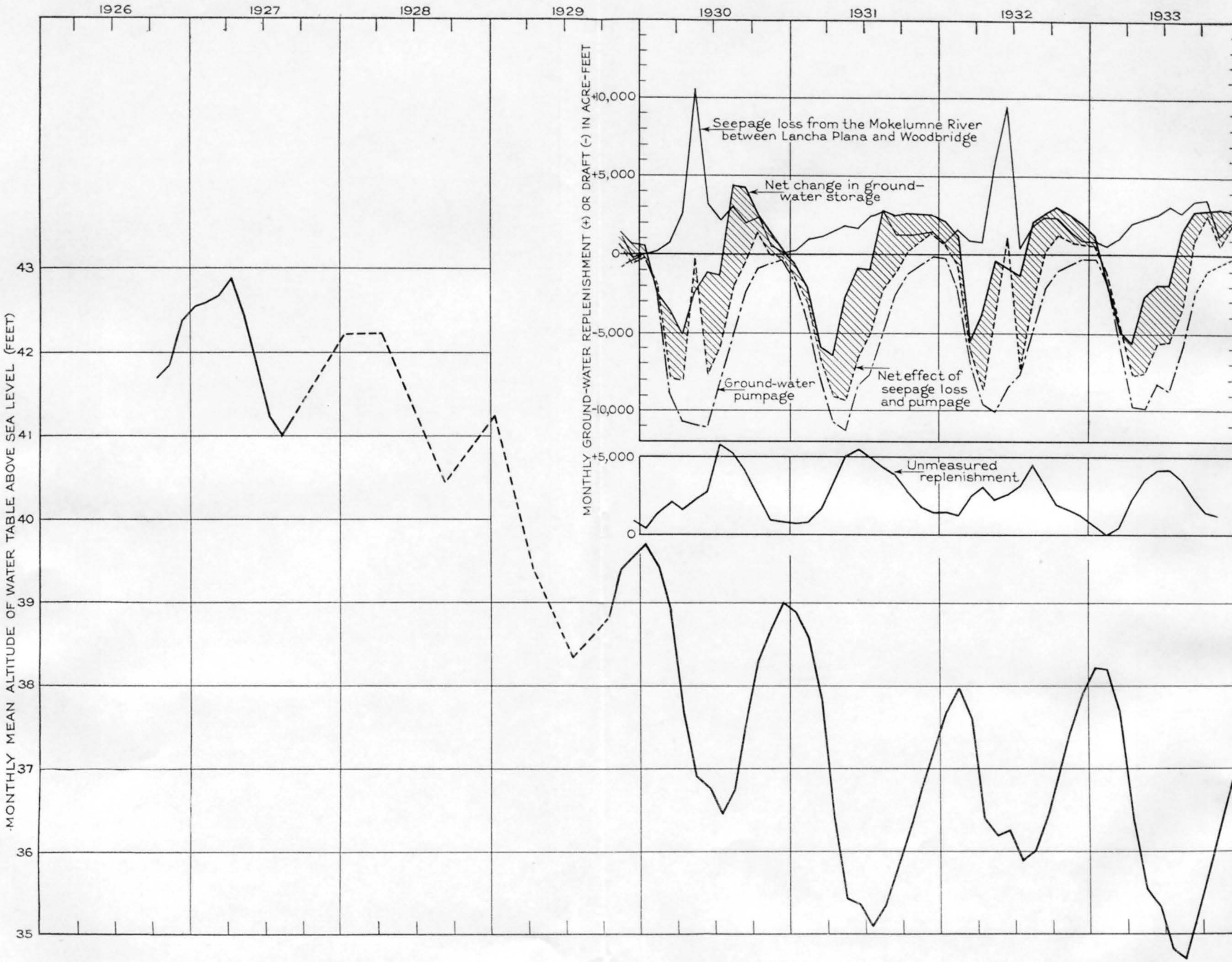
[Interpolated from monthly mean altitudes of the water table]

Month	1926–27	1929–30	1930–31	1931–32	1932–33	1933–34
October	----------	----------	+0.54	+0.49	+0.56	+0.52
November	+0.34	+0.37	+.34	+.48	+.47	+.54
December	+.36	+.15	+.04	+.46	+.37	+.56
January	+.11	+.13	−.15	+.38	+.24	----------
February	+.07	−.60	−.52	+.21	−.35	----------
March	+.14	−.88	−1.10	−1.05	−.93	----------
April	−.11	−.99	−1.20	−.70	−1.08	----------
May	−.54	−.44	−.52	−.08	−.51	----------
June	−.61	−.23	−.16	−.16	−.37	----------
July	−.40	−.26	−.19	−.26	−.36	----------
August	.00	+.83	+.52	+.38	+.26	----------
September	----------	+.79	+.46	+.48	+.51	----------

The upper diagram on plate 22 comprises three additional graphs which show (1) monthly seepage loss or gain of the Mokelumne River between Lancha Plana and Woodbridge,[50] (2) monthly ground-water pumpage for all purposes within the conventionalized segment of the Victor plain that receives percolate from the river above Woodbridge, and (3) the algebraic summation of monthly seepage loss and monthly pumpage. The upstream third of the reach for which seepage loss is shown (the 9.6-mile segment between Lancha Plana and the

[49] Meinzer, O. E., Outline of methods for estimating ground-water supplies: U. S. Geol. Survey Water-Supply Paper 638, pp. 110–113, 1932.

[50] Pritchett, H. C., Bue, C. D., and Piper, A. M., Seepage loss and gain of the Mokelumne River, California: U. S. Geol. Survey typoscript report, pp. 199, 202, June 5, 1934.



MONTHLY MEAN ALTITUDE OF THE WATER TABLE IN RELATION TO CHANGES IN GROUND-WATER STORAGE IN THE SEGMENT OF THE VICTOR PLAIN THAT RECEIVED PERCOLATE FROM THE MOKELUMNE RIVER, 1926–33.

Mehrten dam site) has been inferred to gain by ground-water seepage ordinarily. However, along most of that gaining segment the regional water table is not well defined and bodies of perched ground water appear to be numerous, whence it is inferred that percolation to the river is relatively slow and relatively small in amount. Further, the seepage to the river is not so large that it offsets seepage from the river along the 3.3-mile segment between the Mehrten dam site and Clements, for generally there is a net loss along the two segments, which together constitute the section between the gaging stations at Lancha Plana and near Clements. Accordingly, it is inferred that the net loss or gain between Lancha Plana and Woodbridge can be taken as approximately correlative with changes in ground-water storage between the Mehrten dam site and Woodbridge. Essentially the algebraic summation of seepage loss and pumpage assumes that all seepage loss from the river can be credited immediately to ground-water storage beneath the particular segment of the Victor plain. Thus it disregards the lapse of time necessary for the percolate to traverse the intervening flood plain, although a material volume of percolate is retained beneath the flood plain to be returned ultimately to the river. (See pp. 172, 203.) However, these errors are transient and are compensated in the cumulative figures for seepage loss.

In plate 22 unmeasured ground-water replenishment or draft is indicated by the height of the shaded zone between the graphs for net monthly change in storage and for summation of monthly pumpage and monthly seepage loss, also by a distinct supplemental graph. The ordinates of the supplemental graph correspond to the height of the shaded zone, but they were plotted after the two graphs that bound the zone had been smoothed by moving averages of 3-month span. Thus the ordinate of the smoothed graph for any particular month is the average of ordinates taken from the unsmoothed graph for that month and for the months preceding and following. In effect, this smoothing accentuates periodicity through slight suppression of short-term deviations. For about the first 3 months of each pumping season the unmeasured replenishment appears to be negligible, whence it is inferred (1) that ground-water pumpage was drawn almost if not quite entirely from storage within the area, although nearly half the pumped wells reach deep aquifers that confine water under slight subartesian head (pp. 126, 218), and (2) that the mean results for specific yield are fairly trustworthy. Before the height of each pumping season, however, the rate of water-table recession became disproportionately small with respect to pumpage; moreover, in the late part of each season the water table began to rise, although the pumpage draft was still half as great as at the height of the season. In other words, from 1930 to 1933 ground-water storage diminished less during the later two-thirds of each pumping season than can be accounted for by pumpage and seepage. Thus, two alternatives arise: (1) a considerable fraction of the pumpage was drawn from outside the area, presumably through deep aquifers, or (2) there was considerable ground-water replenishment within the area from a source or sources not yet considered. The first of these alternatives is opposed by the close correlation between pumpage and decrease in storage during the early part of the pumping season, and it is not strongly supported by the form and differential head of the piezometric surface for the water in the deep aquifers. (See pp. 218–225.) Thus it is inferred that draft from outside the area is relatively small and that replenishment occurs within the area. The unsmoothed graphs indicate unmeasured ground-water draft for May 1930 and June 1932, months in which the seepage loss was relatively great for a brief term. However, that indicated draft is largely fictitious and is due wholly to the fact that seepage is credited as replenishment beneath the Victor plain as soon as it is lost from the river and while it still remains beneath the flood plain. Subsequently, the fictitious draft is compensated by fictitious replenishment.

The foregoing correlations are inferred to be valid in spite of the pressure effects of pumping upon ground-water levels. Among the reasons for that inference are the following: (1) The derivation of mean water-table altitudes excludes data on water levels in deep wells, in which the large pressure effects generally occur; (2) if the mean pressure effect depresses the water level equally throughout the pumping season, the net monthly change in ground-water storage is measured precisely except for the first and last months of the season; and (3) to the extent that the mean pressure effect is likely to depress the water level more and more as the pumping season advances, the indicated replenishment is too small rather than too large.

The data on unmeasured replenishment span two years during which the seepage loss rose to a pronounced seasonal peak (1930 and 1932) and two alternate years during which the seepage loss was comparatively steady (1931 and 1933). The two seepage peaks cause synchronous secondary troughs on the smoothed graph for replenishment. With the exception of those secondary features, the graph indicates fairly regular periodicity, because replenishment first becomes pronounced about 3 months after the pumping season begins, is greatest somewhat after the season reaches its height, diminishes steadily as the season wanes, and finally becomes small and rudely constant for 3 or 4 months before the ensuing pumping season. The most likely competent source for replenishment in so large volume is infiltration of water applied for irrigation within the district of ground-water pumping, because (1) the presumptive replenishment reflects the periodicity of pumping draft with moderate lag, (2) ground-water pumpage in the area is done largely for irrigation, and (3) the conventionalized area excludes the Woodbridge Irrigation District, which is served by gravity diversion from the Mokelumne River.

The mean fluctuations of the water table in 1932 suggest material replenishment of ground-water storage by deep penetration of rain in the district of intensive pumping, as has been demonstrated for the margin of the Victor plain farther west. (See pp. 139–144.) Thus,

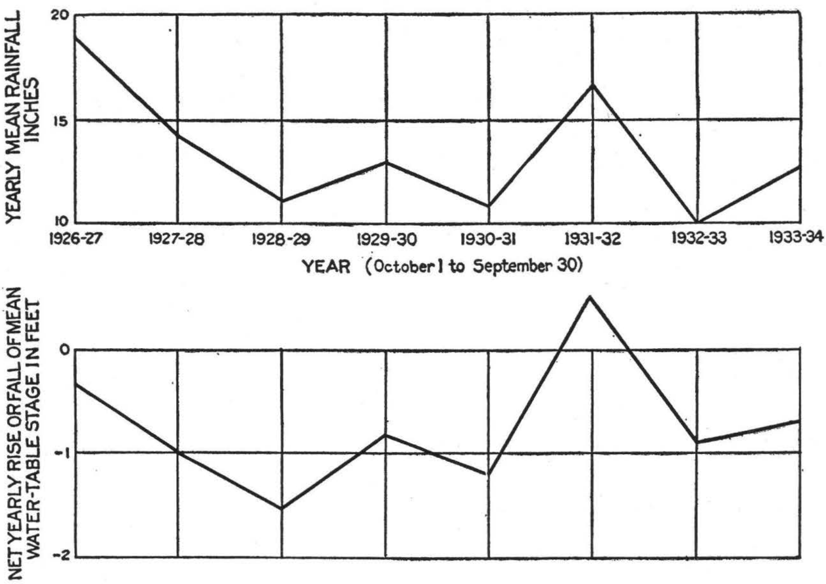


FIGURE 27.—Relation between yearly mean rainfall and corresponding net yearly rise or fall of the water table beneath the segment of the Victor plain that received percolate from the Mokelumne River, 1926–27 to 1933–34.

although pumping began nearly a month later than usual in 1932, replenishment of ground-water storage began a month earlier than in any other year from 1930 to 1933. On the smoothed graph of unmeasured replenishment the effect is shown by the sharp upturn toward the secondary peak in the early part of the year. In this particular year, unseasonable replenishment is ascribed tentatively to infiltration of rain.

The graphs in figure 27 indicate an obvious correlation between yearly mean rainfall and the change in mean water-table stage from one January to the next. It is analogous to the correlation that has been made for outlying districts on figure 14, and ascribed to variable ground-water replenishment by infiltration of rain. However obvious it may seem, the relation between rainfall and net change in water-table stage beneath the central district does not necessarily indicate any replenishment whatsoever. Rather, the seeming correlation may be due chiefly to differences in the net volume of material unwatered by pumping during the several years, because pumpage for irrigation has been rudely complementary to rainfall.[52]

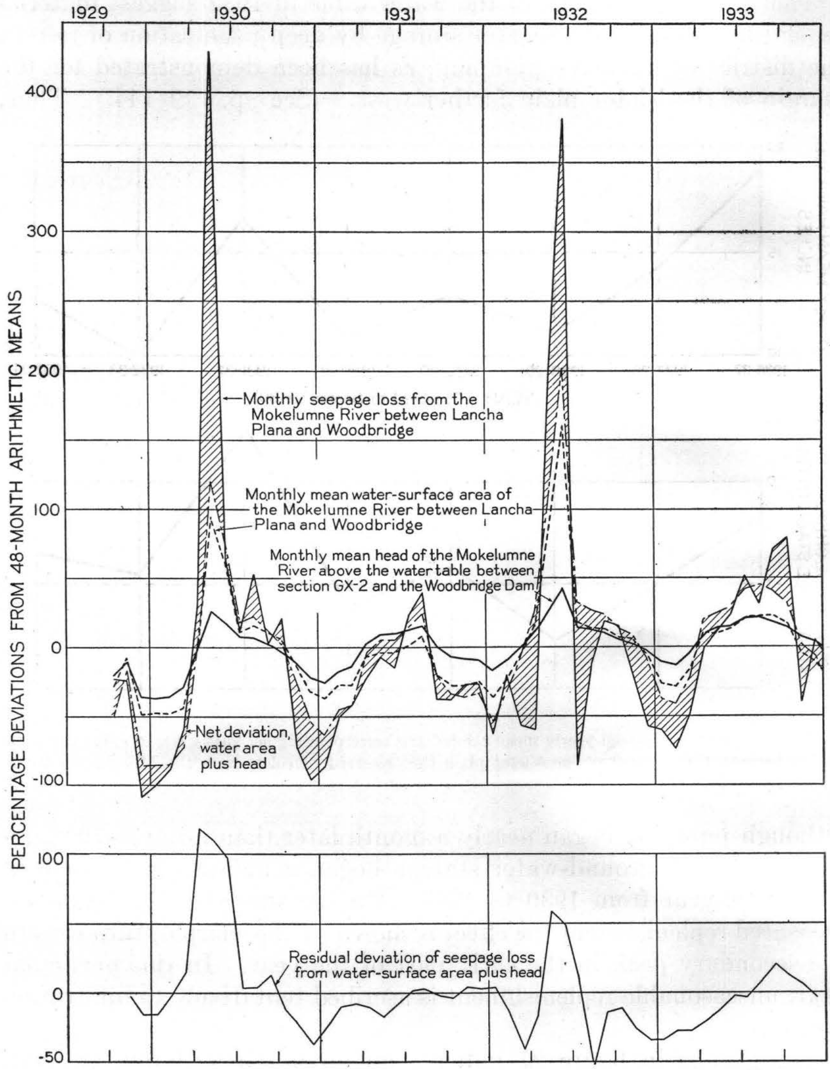


FIGURE 28.—Relation between monthly mean head of the Mokelumne River above the water table, monthly mean water-surface area of the river, and monthly seepage loss from the river, 1930–33.

RELATION TO SEEPAGE LOSS OF THE MOKELUMNE RIVER

Several tables that follow show (1) monthly mean water-surface altitude of the Mokelumne River between cross section GX–2 and the Woodbridge Dam—that is, for the reach that is inferred to lose by seepage; (2) monthly mean head or difference in altitude between the

[52] Piper, A. M., Pumpage of ground water for irrigation in the Mokelumne area, Calif., 1927–33: U. S. Geol. Survey typoscript report, pp. 68–69, fig. 3, Nov. 13, 1933, and Apr. 9, 1934.

river and the water table beneath the conventionalized segment of the Victor plain receiving percolate from the river, in feet and in percentage of the average head for the years ending September 30, 1930 to 1933 (16.3 feet); (3) monthly water-surface area and monthly seepage loss or gain of the river between Lancha Plana and Woodbridge,[53] in percentages of their respective 48-month averages (668 acres and 2,003 acre-feet, respectively). The graphs in figure 28 compare differential head, wetted area, and seepage loss in terms of percentage deviations from their respective 48-month averages and, after the manner of plate 22, evaluate the residual deviation in seepage loss from the algebraic sum of the deviations in head and in wetted area. Again, the available data span 2 years during which seepage loss varied rather widely (1929–30 and 1931–32) and two alternate years during which seepage loss was relatively steady (1930–31 and 1932–33).

Monthly mean water-surface altitude, in feet above sea level, of the Mokelumne River between cross section GX–2 and the Woodbridge Dam, 1926–34

Month	1926–27	1927–28	1928–29	1929–30	1930–31	1931–32	1932–33	1933–34
October	51.79	--------	--------	51.69	54.08	51.71	54.20	54.51
November	52.22	--------	--------	54.03	53.17	51.70	54.22	53.98
December	52.42	--------	--------	49.97	51.80	52.07	53.79	53.86
January	52.92	51.69	50.64	49.97	51.06	51.33	52.85	52.88
February	56.98	--------	--------	49.97	51.99	52.84	52.42	--------
March	55.12	--------	--------	50.43	51.89	53.90	53.34	--------
April	58.72	58.87	54.26	53.59	53.19	54.52	54.27	--------
May	60.38	--------	--------	57.46	53.23	56.97	54.22	--------
June	60.27	--------	--------	56.01	53.31	59.50	54.24	--------
July	54.11	--------	52.61	54.07	53.63	54.60	54.53	--------
August	52.88	--------	--------	54.23	54.21	54.32	54.56	--------
September	52.48	52.57	--------	54.18	52.23	54.35	54.61	--------
Average	55.02	--------	--------	52.97	52.82	53.98	53.94	--------

Monthly mean head of the Mokelumne River between cross-section GX–2 and the Woodbridge Dam above the water table beneath the segment of the Victor plain that received percolate from the Mokelumne River, 1926–34

In feet

Month	1926–27	1927–28	1928–29	1929–30	1930–31	1931–32	1932–33	1933–34
October	10.11	--------	--------	12.87	15.75	15.45	17.25	18.78
November	10.38	--------	--------	14.64	14.48	14.91	16.74	17.61
December	10.05	--------	--------	10.42	12.79	14.85	15.89	17.04
January	10.38	9.48	9.41	10.27	12.17	13.64	14.64	15.55
February	14.38	--------	--------	10.53	13.40	14.85	14.22	--------
March	12.45	--------	--------	11.56	14.05	16.29	15.65	--------
April	15.83	16.65	14.86	15.92	16.79	18.12	17.93	--------
May	17.93	--------	--------	20.56	17.80	20.78	18.69	--------
June	18.46	--------	--------	19.24	17.94	23.25	18.91	--------
July	12.89	--------	14.27	17.62	18.53	18.72	19.73	--------
August	11.89	--------	--------	17.49	18.87	18.34	19.87	--------
September	11.22	12.14	--------	16.57	16.43	17.97	19.39	--------
Average	13.00	--------	--------	14.81	15.75	17.26	17.41	--------

[53] Pritchett, H. C., Bue, C. D., and Piper, A. M., op. cit., pp. 176–177, 199, 202.

Monthly mean head of the Mokelumne River between cross-section GX–2 and the Woodbridge Dam above the water table beneath the segment of the Victor plain that received percolate from the Mokelumne River, 1926–34—Continued

In percentage of average monthly head, 1929–33

Month	1926–27	1927–28	1928–29	1929–30	1930–31	1931–32	1932–33	1933–34
October	62.0	--------	--------	78.9	96.6	94.7	106	115
November	63.6	--------	--------	89.8	88.8	91.4	103	108
December	61.6	--------	--------	63.9	78.4	91.0	97.4	104
January	63.6	58.1	57.7	63.0	74.6	83.6	89.8	95.3
February	88.2	--------	--------	64.6	82.2	91.0	87.2	--------
March	76.3	--------	--------	70.9	86.1	99.9	96.0	--------
April	97.0	102	91.1	97.6	103	111	110	--------
May	110	--------	--------	126	109	127	115	--------
June	113	--------	--------	118	110	142	116	--------
July	79.0	--------	87.5	108	114	115	121	--------
August	72.9	--------	--------	107	116	112	122	--------
September	68.8	74.4	--------	102	101	110	119	--------

Monthly water-surface area of the Mokelumne River between the gaging stations at Lancha Plana and at Woodbridge, 1929–34

[In percentage of average monthly area, 1929–33]

Month	1929–30	1930–31	1931–32	1932–33	1933–34
October	70.4	106	72.6	108	118
November	92.8	85.3	71.9	106	95.1
December	50.9	68.1	75.6	93.6	89.8
January	52.4	62.9	64.4	74.1	76.3
February	51.6	73.4	77.1	71.9	----------
March	56.1	71.9	94.3	83.1	----------
April	99.6	93.6	116	112	----------
May	195	96.6	181	110	----------
June	157	96.6	260	114	----------
July	111	100	118	121	----------
August	115	108	114	123	----------
September	110	78.6	112	123	----------

Monthly net seepage loss or gain of the Mokelumne River between the gaging stations at Lancha Plana and at Woodbridge, 1929–34

[In percentage of average monthly loss, 1929–33]

Month	1929–30	1930–31	1931–32	1932–33	1933–34
October	−77.4	−121	−62.4	−115	−179
November	−75.9	−27.7	−72.9	−78.4	−59.4
December	+11.0	−4.7	−73.9	−43.4	−106
January	−1.0	−14.9	−38.2	−40.3	−90.9
February	−12.2	−49.6	−80.4	−27.1	----------
March	−42.2	−58.9	−43.9	−50.9	----------
April	−131	−78.4	−40.4	−99.4	----------
May	−529	−93.4	−297	−113	----------
June	−164	−85.4	−477	−125	----------
July	−110	−123	−14.8	−152	----------
August	−153	−139	−87.9	−130	----------
September	−102	−63.4	−119	−171	----------

From the graphs of figure 28, it appears that seepage loss has varied in rude proportion to the wetted area and to the differential head between river and ground water—that is, in accord with Darcy's law for the flow of water through porous media. Thus, it is inferred that the rate of seepage loss depends jointly upon (1) river discharge; (2) regulation of stage in the Woodbridge Reservoir, which influences mean river altitude moderately and wetted area decidedly; and (3) ground-water pumpage, which is the chief control for water-table altitude.

As has been demonstrated empirically in another report,[54] it does not depend upon discharge alone. It is inferred that when discharge and reservoir stage have not fluctuated widely, as during much of 1933, the seepage loss has been influenced as much by ground-water pumping in the area receiving percolate from the river as it has by stream discharge. Even when discharge varied widely—as during 1930, 1932, and commonly under the so-called natural regimen (see pl. 12 and fig. 28)—the influence of pumping would persist, although it would be masked by the wide range in wetted area.

The graphs for the periods of large discharge in 1930 and 1932 are peculiarly instructive. Thus, so long as river stage was inordinately high the percentage increase in measured seepage loss was about twice as great as the percentage increase in wetted area and in differential head. However, excessive loss is to be expected at high stages, because the water-table gradient along the edge of the wetted area is temporarily oversteepened (p. 172) and ground-water storage increases greatly in a relatively narrow zone along the river. However, if the high stage had continued indefinitely the rate of seepage loss would necessarily have diminished as the wave of ground-water replenishment passed outward from the river. On the other hand, for 2 months after the high river stage of 1932 had subsided the percentage decrease in measured seepage loss was much greater than the percentage decrease in wetted area and in head; presumably the loss fell off inordinately owing to local return of bank storage to the river channel. Again, the measured seepage loss fell off decidedly after the high stage in May 1929 (not shown on fig. 28). Moreover, the measured seepage loss appears to have remained less than the potential loss for a year or longer after the peak discharge had passed in 1930 and again in 1932, for on figure 28 the smoothed residual deviations are small or negative for that term. Thus, it appears that a year or more may elapse after a major fluctuation in river stage before the ground-water gradient and the seepage loss become steady.

The foregoing inferences lead to several conclusions with respect to ground-water replenishment by seepage loss from the river in the intensively cultivated district about Lodi. (1) The annual replenishment has tended to increase for at least 20 years owing to the gradual increase in head between surface water and ground water as ground-water levels have been lowered progressively by pumping; (2) annual replenishment has tended to increase, especially in recent years, owing to gradually prolonged use of the Woodbridge Reservoir, for thereby a relatively large wetted area and great differential head have been maintained for an increasing term; (3) the rate of replenishment tends to be greater under regulation than under the so-called natural regimen to the extent that regulation has maintained a moderately large wetted

[54] Pritchett, H. C., Bue, C. D,. and Piper, A. M., op. cit., pp. 206–211.

area and stage in the river through the latter part of each pumping season while the ground-water levels have been lowest. (See pl. 12.) Moreover, for any particular yearly run-off below the Mehrten dam site, the replenishment by seepage would tend to be greater under the regulated regimen to the extent that fluctuations in discharge were suppressed, for the greatest yearly mean stage and mean wetted area would be afforded by constant discharge. Thus, diverting water out of the Mokelumne River Basin at the Pardee Dam does not necessarily entail a diminution in ground-water replenishment by seepage loss along the lower reach of the stream, at least in the replenishment beneath the Victor plain above the gaging station at Woodgridge. Rather, the Pardee Dam affords a means for so regulating the discharge as to effect a maximum ground-water replenishment with a given run-off in the natural channel.

PERCHED WATER TABLES IN THE LAGUNA FORMATION

Bodies of ground water perched above the regional water table are common in the Laguna formation, especially in its lower part. In this zone the sediments comprise chiefly poorly sorted fine sand and silt in irregular and commonly discontinuous beds (pp. 58, 65) and as a whole are relatively impervious. The following table lists 34 observation wells in the Mokelumne area that are inferred to tap perched water. Most of these wells bottom in the lower part of the Laguna formation or about at the interpolated contact of the Laguna and Mehrten formations. The most conspicuous examples of perched ground water are encountered in well 5818A1, one of a pair of companion wells about 3 miles south of Clay; in a district between 1 mile and 5 miles south of Clements, chiefly in Tps. 3 and 4 N., R. 8 E.; and along the flood plain of Dry Creek east of Elliott, in T. 5 N., Rs. 7 and 8 E.

The locality near Clay is about 3 miles west of the outcrop of the Mehrten formation. The deeper of the two companion wells at that place, well 3818A2, is 133 feet deep and has a minimum submergence of about 43 feet; its water level has agreed with the regional water table as defined by other shallow wells in the vicinity. On the other hand, well 5818A1, about 30 feet to the west, is only 21.6 feet deep, and its bottom is about 65 feet above the highest water level observed in well 3818A2. The water in well 5818A1 is thus obviously perched.

In the area south of Clements eight wells tap one or more bodies of perched water in the lowest part of the Laguna formation or close above the interpolated contact between the Laguna and Mehrten formations. In this area the ground-water levels in the deeper wells prolong the regional water table of adjacent districts, but the plane of this projected water table passes beneath the bottoms of the eight perched wells. In four of these wells (383D1, 383R1, 3810D1, and 3811J1) the perched water table is consistently 12 to 14 feet above the projected regional water table, whence it is inferred that all may tap a single body of perched water having a maximum extent of nearly 2 miles. The water level in one of these wells (383D1) is known to fluctuate in response to changes in barometric pressure. (See p. 134.)

Observation wells in the Mokelumne area that are inferred to tap perched water

Well no.	Depth (feet)	Altitude of land surface (feet above sea level)	Minimum observed submergence (feet)	Geologic classification [1] (bottom of well)	Estimated mean height of perched water table above regional water table (feet)
382C1	96	186	21	Tl	45
383D1	108	178	4	Tl	14
383R1	72	141	0	Tl	12
3810D1	63	128	5	Tl	14
3811J1	65	138	0	Tl	14
395A1	64	293	8	Tm	160
4826H1	34	165	1	Tl	70
4834G1	113	173	5	Tl	4
4834Q1	100	162	2	Tl	5
497L1	45	177	1	Tm	35
4912F1	24	202	0	Qu?	25
4917M1	70	186	13	Tv	20
4918E2		156			50
4918Q1	24	152	0	Tm?	45
4922M1	53	206	19	Tv?	20
4924P1	35	281	11	Tv	110
4926E1	31	217	2	Tv	60
4935P1	52	335	18	Tv	130
4106E1	57	214	18	Ti	30
4106E2	31	211	4	Ti	30
41030H1	39	291	0	Tv	200
5725B1	40	106	4	Tl	(2)
5725D1	[3] 404	100	381	Qal, Tm	(2)
5725N11	39	95	15	Tl	(2)
5726G1	[3] 127	102	97	Tl	(2)
5726N1	52	93	20	Tl	(2)
5812E2	34	153	8	Tm	(2)
5818A1	22	154	0	Tl	66
5820J1	34	116	11	Tl	(2)
5821E1	44	126	4	Tl	(2)
5829A1	47	114	1	Tl	(2)
5830D1	42	112	5	Tl	(2)
5830E1	34	108	0	Tl	(2)
5830F1	33	110	0	Tl	(2)

[1] Qal, alluvium; Qu, gravel deposits of uncertain age; Tl, Laguna formation; Tm, Mehrten formation; Tv, Valley Springs formation; Ti, Ione formation.
[2] Perched water table fluctuates through wide range owing to flowing in Dry Creek. (See pp. 179–183.)
[3] Deep well with casing perforated opposite perched water table.

The great differences in the static levels in companion deep and shallow wells along Dry Creek where it traverses the Laguna formation have been ascribed tentatively to the presence of a perched water table in the alluvium (pp. 179–183). The existence of perched water in this area is confirmed by the downward movement of this shallow water if given opportunity. Thus, shallow ground water flows continuously into several deep wells that have defective or inadequate casings. E. A. Thayer noted that while he was drilling well 5725D1 its water level receded 5 feet, a decline which is thought

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to have resulted from unwatering of shallow strata adjacent to the well by draining into unsaturated material at a lower level. It is inferred that this perched water is retained chiefly in the pervious beds of the alluvium along Dry Creek, but evidently the restraining strata are members of the Laguna formation.

The known perched water bodies in the Laguna formation range from about 5 feet to 70 feet above the regional water table. Others probably exist, but the wells are not sufficiently numerous to discriminate and bound them.

Generally the Mehrten formation is permeable and has a simple water table. However, small bodies of perched water are tapped by a few wells that bottom in this formation. Thus, well 395A1 taps a body of perched water that is 155 to 160 feet above the regional water table as defined by well 4932J1, 2,000 feet to the north.

Small bodies of perched water are inferred to be relatively common likewise in the Valley Springs and Ione formations, for they are tapped by numerous wells in the eastern part of the area, including nine observation wells in Rs. 9 and 10 E. The minimum submergence does not exceed 25 feet, yet the bodies of perched water are as much as 200 feet above the regional water table.

PIEZOMETRIC SURFACE FOR CONFINED WATER IN THE DEEP AQUIFERS

DIFFERENTIAL HEAD OF THE PIEZOMETRIC SURFACE WITH RESPECT TO THE WATER TABLE

In the Mokelumne area the piezometric surface for confined water in deep aquifers is commonly materially higher or lower than the regional water table, as is shown by the water levels in the relatively deep observation wells whose submergence exceeds 50 feet and which penetrate the Arroyo Seco gravel or the Tertiary rocks. The differential head is shown most clearly by companion deep and shallow wells, and the following table summarizes the observed extremes of differential head for the 15 pairs of companion wells that are available. For wells 4814K1, 4826K1, and 4828J1 the data are derived from comparative measurements of depth to water in an outer dug well that reaches very little below the water table and in a concentric drilled well whose casing shuts off the shallow water-bearing beds; for well 489N1 the measure of the differential head is taken from the change in depth to water before and after the well was deepened in November 1930; in the 11 pairs of wells remaining the differential head is determined by comparison of water levels with adjacent shallow wells. Two of these pairs—3710K3 and 3710K4, 4722Q4 and 4722Q5—were drilled and cased for observing ground-water levels. The differential head is inconstant in all 15 deep wells but varies most widely in wells near the Mokelumne River (4732H12 and 4816F12) and in wells in the area that is intensively irrigated from ground water (379B3 and 4722Q5). The table lists a single well (4719B4) in which subartesian head is inferred to have persisted throughout the period of record. In several wells, however, the static level has been continuously lower than the water table, which is semiperched. This condition prevails especially in the Laguna formation, as is inferred from the records of deep wells 489N1, 4814K1, 4826K1, and 4828J1 and from the irregularity of the water-table contours at certain localities. For example, the water levels in wells in and near secs. 7 and 18, T. 4 N., R. 8 E., disclose minor inconsistencies when an attempt is made to draw water-table contours (pls. 18–21), thus suggesting the possibility of differential head that the available data on water levels do not discriminate with assurance.

Pairs of companion wells in the Mokelumne area showing differential head of the piezometric surface above or below the regional water table

No. of well	Depth (feet)	Altitude of land surface (feet above sea level)	Minimum observed submergence (feet)	Geologic classification [1] (bottom of well)	Distance between wells (feet)	Observed extremes of differential head			
						Feet	Date	Feet	Date
379B3	255	70	206	QTasl	6	−0.35	Dec. 22, 1932	−7.92	Aug. 3, 1933.
379B11	49	70	8	Qv<75					
3710K4	190	72	138	QTasl	6	+4.10	Feb. 23, 1931	−2.05	June 22, 1930.
3710K3	57	72	4	Qv<75					
3722B1	217	67	172	QTasl	200	+3.70	Apr. 16, 1932	−.07	Apr. 4, 1933.
3715P2	55	67	10	Qv<75					
4715D1	140	96	83	QTasl	10	+1.40	June 14–15, 1932	−.30	Oct. 10–11, 1932.
4715D11	66	96	11	QV<75					
4719B4	356	60	319	QTasl	4	+1.12	Sept. 9, 1932	+.43	Dec. 7, 1932.
4719B11	77	60	39	Qv<75					
4722Q5	266	84	215	QTasl	5	+1.30	Dec. 28, 1931	−6.90	May 29, 1931.
4722Q4	51	84	6	Qv<75					
4732H12	250	67	215	QTasl	200	+2.40	Oct. 17, 1931	−10.4+	July 25, 1932.
4732H11	12	44	0	Qal					
4736B1	319	60	301	Tm	40	−.47	Nov. 17, 1930	−6.68	June 8, 1933.
4736B11	16	60	2	Qal					
489N1	220	129	148	Tm	----	−1.04	Nov. 7–12, 1930		
	68		2	Tl					
4814K1	177	134	110	Tm	----	−1.84	Mar. 8, 1934	−3.10	Oct. 12–16, 1933.
	65		1	Tm					
4816F12	100+	84	75+	Tm?	50	−6.67	Oct. 12, 1933	−15.34	June 15, 1932.
4816F11	18	82	1	Qal					
4826K1	193	172	86	Tm	----	−.93	Oct. 11, 1933		
	108		2	Tl					
4828J1	140	113	78	Tl	----	−.11	Jan. 6, 1933	−1.08	July 5, 1932.
	65		3	Tl					
5725R1	435	106	388	Tm	90	−3.75	Dec. 30, 1934	−5.14	May 19, 1935.
5725R2	54	106	11	Tl					
5733A1	500	67	479	Tm	5	−2.72	Dec. 10, 1932	−5.52	June 13, 1933.
5733A11	20?	67	3	Qal?					

[1] Qal, alluvium; Qv<75, Victor formation, less than 75 feet below the projected Arroyo Seco pediment, by interpolation; QTasl, Arroyo Seco gravel or Laguna formation, more than 75 feet below the projected pediment; Tl, Laguna formation; Tm, Mehrten formation.

Other deep wells that are scattered throughout the Mokelumne area afford estimates of differential head by comparison of their static levels with the position of the water table as interpolated from plates 18 to 21. These interpolations may not represent the differential head of the deepest beds reached by the wells, because certain wells are not cased throughout or their casings are perforated opposite all water-bearing strata. In certain outlying districts, such as T. 2 N., R. 7 E.; T. 3 N., R. 8 E.; and T. 5 N., R. 8 E., the observation wells are relatively few and do not define the form of the water table in detail; for those districts no interpolation of differential head was attempted. With the exception of wells in those districts and of six deep wells in the central part of the Mokelumne area, all deep observation wells appear to have shown some differential head during one or more of the periods represented by plates 18 to 21. In 14 of the wells the differential head was less than 0.5 foot in the nonpumping season, but in 76 wells the interpolated differential head was 0.5 foot or more in January, when the pressure effects of pumping would be least (p. 192). The next table presents critical data for these 76 deep wells, which include 10 wells from the pairs listed in the preceding table.

Estimated differential head of the piezometric surface in the Mokelumne area above or below the regional water table, 1927–33

[Comprising deep wells in which the interpolated differential head has been 0.5 foot or more in the nonpumping season]

Wells in which the differential head has been positive in the nonpumping season

Well no.	Depth (feet)	Altitude of land surface (feet above sea level)	Minimum observed submergence (feet)	Geologic classification (bottom of well)[1]	Distance from flood plain of the Mokelumne River (miles)	Interpolated differential head (feet)					
						Jan. 1927	Oct. 1931	Jan. 1932	Apr. 1932	July 1932	Jan. 1933
2613L1	152	30	130	QTasl	8.5	+0.5	+1.5	+1.5	------	+0.4	+0.4
271R1	96	73	55	QTasl	7.1	------	+2	+1.5	+3	+1	------
2713D1	212	67	173	QTasl	8.2	+1	+2	+3	+1	------	------
289C1	107	89	64	Tl	8.4	------	+.4	+1	+2	------	------
3615F3	277	32	263	QTasl	2.4	------	+.7	+.5	0	−.5	0
371N1	160	85	111	QTasl	1.4	------	0	------	−.5	−2.5	+.6
372Q1	289	82	244	QTasl	1.2	------	+.7	+1	------	------	+.5
375J5	160	64	120	QTasl	.6	------	+.7	+1.5	0	+2	+.5
376H1	190	60	157	QTasl	.5	------	+.5	+.7	+1.5	−2.5	+.4
378K3	253	59	209	QTasl	1.4	------	+.8	+1	−5.5	0	+1
3710K4	190	72	138	QTasl	1.6	------	+.2	+.2	+2.6	−.1	0
3715C1	334	71	290	QTasl	2.0	------	------	------	------	+2.5	+2
3715F2	243	70	196	QTasl	2.3	------	+.5	+.3	−1.5	------	+.9
3716C1	259	65	211	QTasl	1.9	+1.0	+.7	+1.5	------	−1.5	+1.5
3716N1	142	60	93	QTasl	2.6	+1.5	+3	+2	−5	+.4	+3
3720A2	160	53	120	QTasl	2.9	+.3	+.5	+.5	+2	−1	+.2
3722B1	217	67	172	QTasl	2.9	+1.5	+1.5	+1.5	−.7	−.9	+.5
3819J1	90	76	51	Tl	4.1	+1.5	------	+.5	+.7	−.3	+1
3820L1	114	93	61	Tl	4.9	+1.0	0	------	−.3	−1	0
3831E1	145	76	105	Tl	5.6	+.8	+.3	+.5	------	------	+.4
453L1	254	13	234	QTasl	.5	------	+1.0	+.7	−.3	0	+.4
4610N1	229	37	202	QTasl	1.0	+.3	+1	------	+.5	+.7	+.5
4612M1	204	63	169	QTasl	3.7	------	------	------	+.7	+1.0	+.8
4621K3	222	36	203	QTasl	.2	------	0	+.7	+2	+3.5	+.9
4623H1	461	51	419	QTasl	1.9	------	−.5	+.5	−1.0	------	------
473N1	575	89	530	Tm	3.7	------	------	+.8	0	------	+.3
475J1	159	75	121	QTasl	4.6	------	------	+.4	0	−.5	+.5
476R3	194	70	158	QTasl	4.6	------	------	+.3	−.2	−2.5	+.6

[1] QTasl, Arroyo Seco gravel or Laguna formation; Tl, Laguna formation; Tm, Mehrten formation; Tv, Valley Springs formation.

Estimated differential head of the piezometric surface in the Mokelumne area above or below the regional water table, 1927–33—Continued

Wells in which the differential head has been positive in the nonpumping season—Continued

Well no.	Depth (feet)	Altitude of land surface (feet above sea level)	Minimum observed submergence (feet)	Geologic classification (bottom of well)	Distance from flood plain of the Mokelumne River (miles)	Interpolated differential head (feet)					
						Jan. 1927	Oct. 1931	Jan. 1932	Apr. 1932	July 1932	Jan. 1933
479J1	144	76	105	QTasl	3.4	------	------	+.2	0	−.5	+.5
4710E2	379	87	335	QTasl	3.2	------	------	+1.5	+.9	------	+1
4711D1	520	105	465	Tm	2.7	------	------	+.5	+.3	------	+.7
4714L1	504	98	448	Tm	1.3	------	+.3	+.7	−.9	−2	+1.0
4714P1	234	94	178	QTasl	1.2	+.4	+.2	+.5	0	−4.5	+.9
4715D1	140	96	83	QTasl	2.1	+.2	+.6	+1.5	0	------	+1
4715D2	217	94	162	QTasl	2.2	------	+.6	+3	−.8	------	+1
4719B4	356	60	319	QTasl	2.5	------	------	+1.0	+.9	+1.0	+.9
4917D11	231	68	188	QTasl	2.3	------	+2	+1.5	+.9	------	------
4720L1	686	73	639	Tm	1.7	------	+2	+1.5	−.7	−3	+1
4721B1	614	81	564	Tm	1.9	------	+1.5	+1	−1.0	------	+.9
4721D1	170	84	118	QTasl	1.9	------	+1.0	+.6	−1.0	−.2	+.7
4722Q5	266	84	215	QTasl	1.1	------	+.6	+1	−3	−8	+.8
4723F1	388	96	333	Tm	.9	------	0	+.5	−2	------	+.9
4726A1	203	90	150	QTasl	.9	------	+.5	+.8	−3.5	−5	+.3
4729M1	783	70	742	Tm	.7	------	+.9	+1	−2	------	+.6
4732J1	120	66	89	QTas.	.1	------	+.4	+1.5	0	+2	+.6
576P1	102	67	80	QTasl	[2] 3.5	+1.0	+.6	+1.5	+1	+3	------
578J1	126	72	101	QTasl	[2] 3.0	+3	+.6	+1	+1	+2	------

Wells in which the differential head ordinarily has been negative in the nonpumping season

Well no.	Depth (feet)	Altitude of land surface (feet above sea level)	Minimum observed submergence (feet)	Geologic classification (bottom of well)	Distance from flood plain of the Mokelumne River (miles)	Jan. 1927	Oct. 1931	Jan. 1932	Apr. 1932	July 1932	Jan. 1933
374F1	107	70	66	QTasl	0.3	0	0	−.9	−8	−1.5	−1.0
376F2	319	58	288	QTasl	.4	------	−.2	−1.0	−1.5	−2	−1
379B3	254	70	206	QTasl	1.0	------	+.2	+.4	−8	−6	−1.0
3717R4	137	58	93	QTasl	2.7	------	−.3	−.7	0	−1.5	−.5
4719D1	150	68	109	QTasl	2.2	------	+.2	−1.0	−.9	------	------
4723R1	300+	97	247+	QTasl	.1	------	−2.5	−1.5	0	−1.0	−2.5
4725B1	465	83	430	Tm	------	------	−2.5	−1.5	−2.5	−4	−2
4726K1	366	93	313	QTasl	.4	------	−.6	−1	−.8	−5	−2.5
4726N1	378	92	328	QTasl	.3	−1.5	−.6	−1.0	−2.5	−2.5	−1
4728M1	910	80	860	Tm	.5	------	0	0	−.4	------	−.7
4732H12	250	67	215	QTasl	.1	------	+.2	+1.5	−3	−11	−1
4735F1	144	67	120	QTasl	------	−4.5	−2	−1	−3	------	−.8
4735G1	173	62	153	QTasl	------	−3	−5	−3	−5	−10	−2.5
4735M1	400	88	352	Tm	.1	------	−3	−1.5	−2.5	−4	−2
4735M2	337	60	317	QTasl	------	−1.5	−1.5	−2.5	−4	−6	−2
4736B1	319	61	301	Tm	------	−.8	−2	−1.5	−3.5	−7	−2
488K2	260	132	185	Tm	1.3	------	−2	−.2	−3	−1	−.8
488R11	170	136	91	Tm	.6	------	.6	------	−.7	------	−.7
489N1	220	129	148	Tm	.4	------	−.1	−1.5	−2	−1.5	−.9
4816F12	100+	84	75+	Tm?	------	------	------	------	------	−10	−6
4818A1	440	116	373	Tm	1.4	−2	−1	−.7	0	−4	−.4
4819C2	383	111	320	Tm	−.2	------	------	−1.5	−1	−6	------
4821B1	118	82	98	Tm	------	−.8	−1.5	−1.5	−1.5	−2.5	−1.5
4821F1	582	81	557	Tv?	------	------	------	------	------	−7	−3.5
4821P11	350	130	274	Tm	.3	------	------	------	------	------	−1.5
4822B1	172	146	85	Tm	.1	−4.5	−3	−2	−2	−4.5	−2.5
4824M2	169	166	75	Tm	1.5	−2.5	−2.5	−2.5	−3	−2.5	−2
4829E1	506	108	448	Tm	.1	−1	−1.5	−1.5	−1.5	------	−2
5725R1	435	106	388	Tm	[2] .2	------	−4.5	−4.5	------	−3	−4

[2] Distance from flood plain of Dry Creek.

The preceding table lists 47 wells that have had positive differential head in the nonpumping season. Among these, 13 wells have had positive head in all periods for which comparisons are available—that is, they have had persistent subartesian head; all 13 wells are outside the district of most intensive pumping for irrigation (p. 184). In the remaining 34 wells, most of which are within the area of intensive pumping for irrigation, subartesian head has existed for part of the year, ordinarily during the nonpumping season, but during the pumping season the piezometric surface is depressed to or below the level of the water table owing to the pressure effects. Only two of the 47 wells (375J5 and 4732J1) are within half a mile of the flood plain of the Mokelumne River; 28 are outside the area that receives percolate from the river. (See pp. 204–206, also pl. 1.)

The table also lists 29 wells in which the differential head in January ordinarily has been negative. Of these wells, 21 are within half a mile of the flood plain of the Mokelumne River. The negative differential head in these wells is commonly greatest during the pumping season, whence it is inferred that at these wells pumping lowers the piezometric surface with respect to the water table much as pumping dissipates the subartesian head in areas more remote from the river. In the remaining 8 wells the differential head is prevailingly negative, even though the wells are remote from the river. Several of these wells (488R11, 488K2, and 4818A1) are drilled in the Laguna formation in an area where the water table is considered to be semiperched locally. In two others (379B3 and 4719D1) the piezometric surface has stood above the water table during the nonpumping season of certain years. Its failure to rise above the water table in other years may be due merely to incomplete recovery.

Most of the deep observation wells that have afforded interpolations of differential head were drilled for irrigation; also, some are not cased throughout or their casings are perforated opposite all water-bearing strata. Thus, some of the difference in head between the deep and shallow aquifers may be dissipated by leakage through the wells. However, it is inferred from the behavior of water levels that this loss of head within the wells is small, if, indeed, it is appreciable.

From these relations between the piezometric surface and the water table, it is evident that the area receiving percolate from the Mokelumne River may be divided roughly into (1) a central area extending not more than half a mile beyond the flood plain, in which the piezometric surface is inferred to have stood below the water table throughout the term of the investigation and hence in which the difference in head has favored the percolation of water from shallow beds into deep beds in all seasons; and (2) an outlying area in which the difference in head likewise favors downward percolation into deep beds during the pumping season but favors upward percolation during the nonpumping season. This outlying area includes about 75 percent of the segment of the Victor plain that receives percolate from the river.

From 1927 to 1933 the subartesian head that existed during the nonpumping season in the districts remote from the river tended to increase; thus, it is inferred that the relative opportunity for seasonal recharge of the shallow water-bearing beds by underfeeding has likewise tended to increase. On the other hand, the negative differential head in wells near the river has also tended to increase; thus, in this central area the opportunity for discharge of water from shallow beds by downward percolation probably has tended to increase.

FORM OF THE PIEZOMETRIC SURFACE

Data concerning the piezometric surface of the confined water in deep aquifers are not adequate for the construction of contour maps showing the form of that surface over the whole Mokelumne area. However, several clues to its general form are afforded in Tps. 3 and 4 N., Rs. 7 and 8 E. Thus, east of Lockeford, in R. 8 E., isopiestic lines for the deep aquifers of the Mehrten formation appear to be approximately straight and suggest that the water in these aquifers moves roughly parallel to the Mokelumne River. The absence of any definite bulge in these contours where they cross the river indicates that the loading effect of the shallow ground water is small, and hence that the deep aquifers are thoroughly insulated. Partly because of this insulation, but also because the draft upon these aquifers for irrigation is comparatively slight (p. 128), the form of the piezometric surface appears to change very little in this district throughout the year.

Under the Victor plain just west of Lockeford, in R. 7 E., isopiestic lines for the deep aquifers are defined chiefly by the water levels in wells that bottom in the Arroyo Seco gravel or the Laguna formation. There the form of the piezometric surface north of the Mokelumne River differs markedly from that south of the river, both in its response to pumping and in its relation to the form of the water table.

Along the river and to the south the piezometric surface and the water table are similar in form in that each bulges downstream, although the bulge or ridgelike form of the piezometric surface appears to be much flatter than that of the water table. The similarity in form persists throughout the pumping season, and both water table and piezometric surface develop valleys and closed depressions under the area of most intensive pumping. These similarities imply that the confining beds above the deep aquifers are somewhat permeable within the pumping district south of the river (T. 3 N., R. 7 E.) and allow interchange of water between deep and shallow beds with relatively little lag. This implication is substantiated by the behavior of the water levels in companion deep and shallow wells. (See pl. 8, wells 3710K3 and 3710K4; also pp. 189–190.)

North of the river, on the other hand, the isopiestic lines for the deep aquifers are nearly straight and parallel to those farther east, where the deep aquifers are in the Mehrten formation. There the isopiestic lines appear to deflect slightly downstream, but only within a mile of the river and much less than the water-table contours deflect downstream in the same area. During the pumping season the piezometric surface declines markedly in the heart of the pumping district north of the river, especially in secs. 20 to 23, T. 4 N., R. 7 E.;

this decline is of greater magnitude than the contemporaneous recession of the water table. (See pl. 21.) Evidently comparatively little of the pumpage from the deep aquifers is replenished immediately by downward percolation from shallow beds. The fluctuations of water levels in pairs of companion deep and shallow wells north of the river (pp. 190–191) suggest that interchange of water between the deep and shallow beds is restrained rather effectively and lags materially behind the pumpage. Evidently the opportunity for such interchange is relatively small throughout T. 4 N., R. 7 E.; it is certainly less there than in the district of heavy pumping south of the river.

By way of summary, the foregoing data afford several critical inferences concerning the facilities for interchange of water between the deep aquifers and the shallow aquifers just beneath the water table—that is, concerning the relation between pumpage from the deep aquifers, percolate from the Mokelumne River, and concurrent groundwater storage. These inferences follow.

1. In the easternmost part of the area that receives percolate from the river there appears to be very little interchange between the shallow aquifers and the deep aquifers of the Mehrten formation. Little interchange would be expected, because of the known restraining beds in the overlying Laguna formation (pp. 216–218).

2. Beneath the flood plain of the river, also for about half a mile to the north and to the south in Tps. 3 and 4 N., R. 7 E., the differential head would permit downward percolation from the shallow aquifers to the deep aquifers throughout the year. That condition prevails especially south of the river. To the extent that deep uncased wells and pervious zones afford channels, then, an unmeasured quantity of the percolate from the river might pass downward into the deeper strata within this district and ultimately might pass westward beyond the area that receives percolate above the gaging station at Woodbridge. However, there are few deep wells on the flood plain; impervious zones are inferred to be common in the Laguna formation, which underlies the flood plain at moderate depth just west of Clements; and water-table fluctuations are not reflected faithfully by changes of static level in the few deep wells. Hence it is believed that ground-water storage within this particular area is not decreased materially by discharge westward through deep pervious beds.

3. Beneath the outlying parts of the segment of the Victor plain that receives shallow percolate from the river, subartesian head favors upward percolation from the deep aquifers during the nonpumping season. The water in these deep aquifers comes in part from a remote easterly source and moves parallel to the river across a broad front, whereas the area that receives percolate from the river is shaped like a wedge, lies with its apex upstream, and at its base spans a 7-mile front across the deep aquifers. Thus, water from the remote source

transgresses the boundary of the area that receives percolate from the river and, so far as differential head is involved, may increase ground-water storage in the outlying parts of that area by percolating upward into the shallow aquifers during the nonpumping season. However, the outlying districts in which there is subartesian head are only about twice as extensive as the area along the river in which negative differential head prevails; the subartesian head in the outlying districts is always small and on the average is a minor fraction of the negative differential head along the river; and the subartesian head exists only during the nonpumping season, which covers somewhat less than half the year. Thus, it is inferred that the yearly addition to ground-water storage by percolation from a remote easterly source is scant and that for all practical purposes it is offset by the withdrawal that results from downward percolation along the river.

4. Somewhat less than half the irrigation wells in the Mokelumne area reach the deep aquifers, but few of those wells are tightly cased through the upper water-bearing strata. Accordingly, some of the pumpage from wells within the area that receives percolate from the river may not be drawn from ground-water storage within that particular area but may have come instead from the remote easterly sources, moving down the slope of deep aquifers and thence entering the area of pumping influence. This unmeasured quantity of water would be included in inventories of pumpage but would not be accounted for by the change in ground-water storage, nor would it be supplied by seepage loss from the river. In principle, therefore, ground-water inventories based on simple storage methods would be in error by this unmeasured quantity of water from remote sources. However, the preceding discussion that deals with mean water-table fluctuations in relation to source and disposal of ground water (pp. 208–212) has led to the inference that this unmeasured quantity is small and that the resulting error is nominal.

FLOWING WELLS

Three deep wells in the western part of the Mokelumne area are known to have flowed for a time when first drilled. These wells are 2610M1, 1,165 feet deep; 4636N1, 1,950 feet deep; and 5532R2, 688 feet deep. In each well the flow was accompanied by release of natural gas, so that the wells are considered to have been gas-lift flowing wells.

Mendenhall [55] reports 29 flowing wells in San Joaquin County, and remarks: "By far the greater number of the flowing wells have been drilled for the gas they yield, but as the water with the gas is saline and therefore not usable for drinking or for irrigation it is allowed to waste." In ten such gas-lift flowing wells in the city of Stockton for

[55] Mendenhall, W. C., Dole, R. B., and Stabler, Herman, Ground water of the San Joaquin Valley, California: U. S. Geol. Survey Water-Supply Paper 398, pp. 177–196, 1916.

which drillers' logs are available,[56] the depth ranged from 1,003 to 2,230 feet, the temperature of the flowing water ranged from 77° to 101° F., and the gas yield was as much as 30,000 cubic feet a day. It is reported that water first flowed when the wells had penetrated 740 to 900 feet below the land surface, also that both the flow and the gas pressure increased with depth. It is inferred from the logs that the wells reached the top of the Mehrten formation between 800 and 1,100 feet below the land surface. Accordingly, the aquifers that yielded the flowing water were presumably in the Mehrten formation or underlying strata.

No wells are known to have flowed by simple hydrostatic pressure in the Mokelumne area. Even in well 4712A1, 1,975 feet deep, no aquifers were encountered capable of producing artesian flow. Concerning flowing wells in San Joaquin County, Mendenhall [57] says: "Only six * * * supply water suitable for irrigation, and the yield of these is small * * * Those of which records are available are from 975 to 1,200 feet deep. Wells of lesser depth do not yield flows, and those of greater depth, at least in the Stockton neighborhood, yield saline water and gas." Plausibly, even these six wells may have been gas-lift flowing wells in which the flow has declined as the gas pressure dwindled.

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[56] White, W. N., unpublished data.

[57] Mendenhall, W. C., op. cit. (Water-Supply Paper 398), p. 178.

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