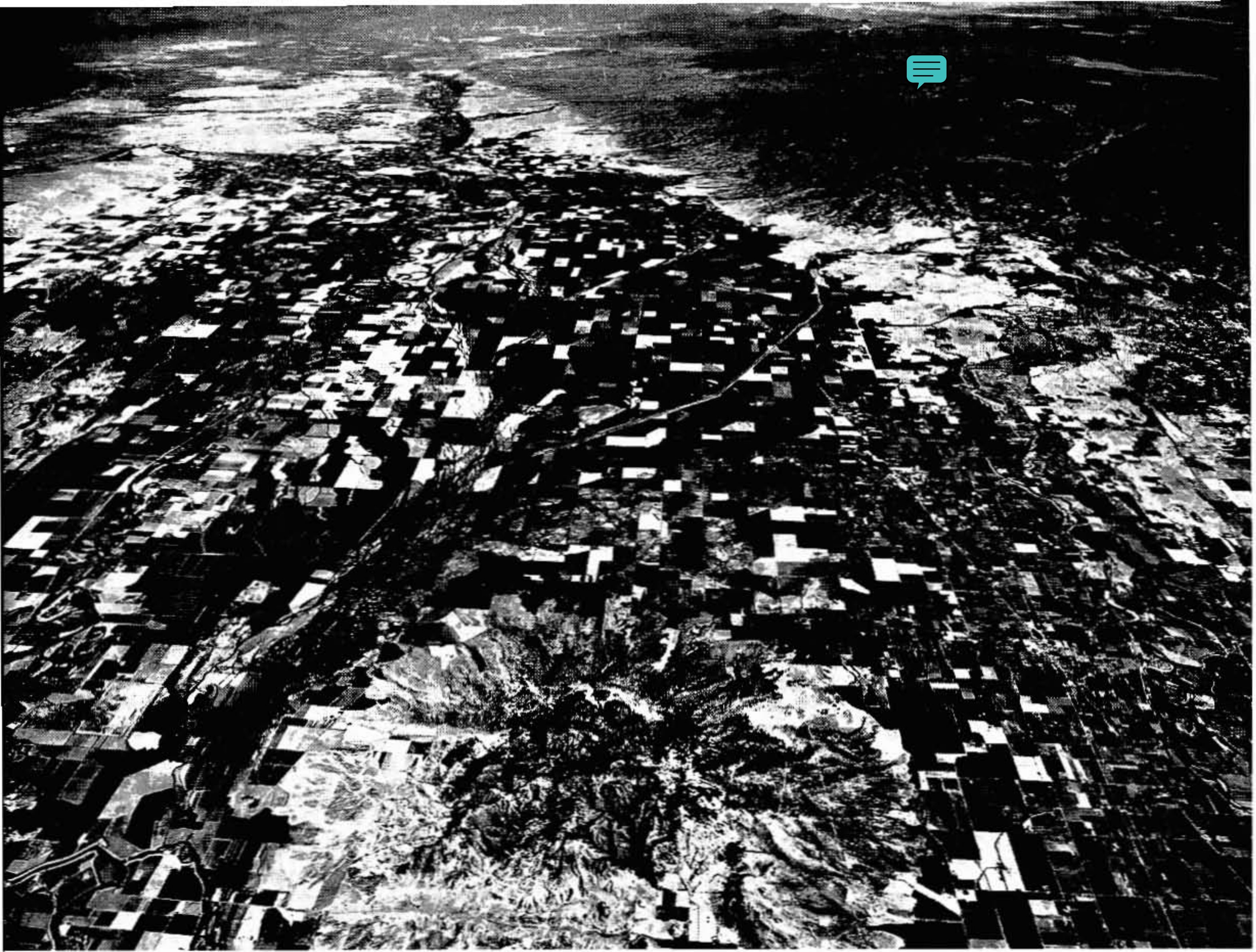

State of California
The Resources Agency

Department of
Water Resources

Evaluation of Ground Water Resources: Sacramento Valley

Department of Water Resources
in cooperation with the
U.S. Geological Survey

Bulletin 118-6
August 1978

Cover Photo: U.S. Air Force photograph shows northern Sacramento Valley with Sutter Buttes, a long-extinct volcano, in the foreground. The Cascade Range borders the northeast edge of the valley and extends in the photo to Mt. Shasta, barely visible at the horizon, center. The Feather River enters the valley on the right at Oroville. The Sacramento River, with its meanders and oxbow lakes, is visible on the left.

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August 1978

Huey D. Johnson
Secretary for Resources

The Resources Agency

Edmund G. Brown Jr.
Governor

State of California

Ronald B. Robie
Director

Department of Water Resources

A NOTE ABOUT UNITS OF MEASURE

This report was originally prepared using English units of measure—feet, acres, gallons, and so on. The rapid adoption of metric units in this country posed a dilemma. To most people the English system was still more familiar and easily grasped, but there was broad agreement that the Metric System is ultimately preferable. To accommodate both the old and new systems, an effort was made to present each measurement in the text in both English and metric units. The result was a scarcely-readable mass of figures. It was decided finally to use the Metric System entirely, with appropriate conversions for the convenience of readers unfamiliar with it. Except in a few places where it was not practicable to alter original data, measurements in this report are therefore expressed in metric units.

Appendix A, prepared by the U.S. Geological Survey, was reproduced as submitted, with English units. A list of conversion factors is included with that report.

FOREWORD

To a readily accessible depth of 60 metres, the immense ground water reservoir of the Sacramento Valley holds as much water as all the surface reservoirs in the State combined. In the period of study reported in this bulletin, 1961 to 1970, average annual recharge of the ground water basin exceeded the amount used, and the total quantity of water in storage increased. Surface runoff which could not be accommodated in the basin flowed to the sea. With the exception of isolated areas in the southern end of the valley, this basin is an underutilized resource.

This report presents reconnaissance-level information on the geologic and hydrologic conditions that influence occurrence, movement, storage, and utilization of Sacramento Valley ground water. Prepared in cooperation with the U. S. Geological Survey, it includes a hydrologic inventory for the ten-year study period.

It is anticipated that this information will prove useful in planning and managing the State's overall water resources and will provide a foundation for detailed studies of local water supply in cooperation with local water agencies.

Ronald B. Robie

Ronald B. Robie, Director
Department of Water Resources
The Resources Agency
State of California

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Department of Water Resources

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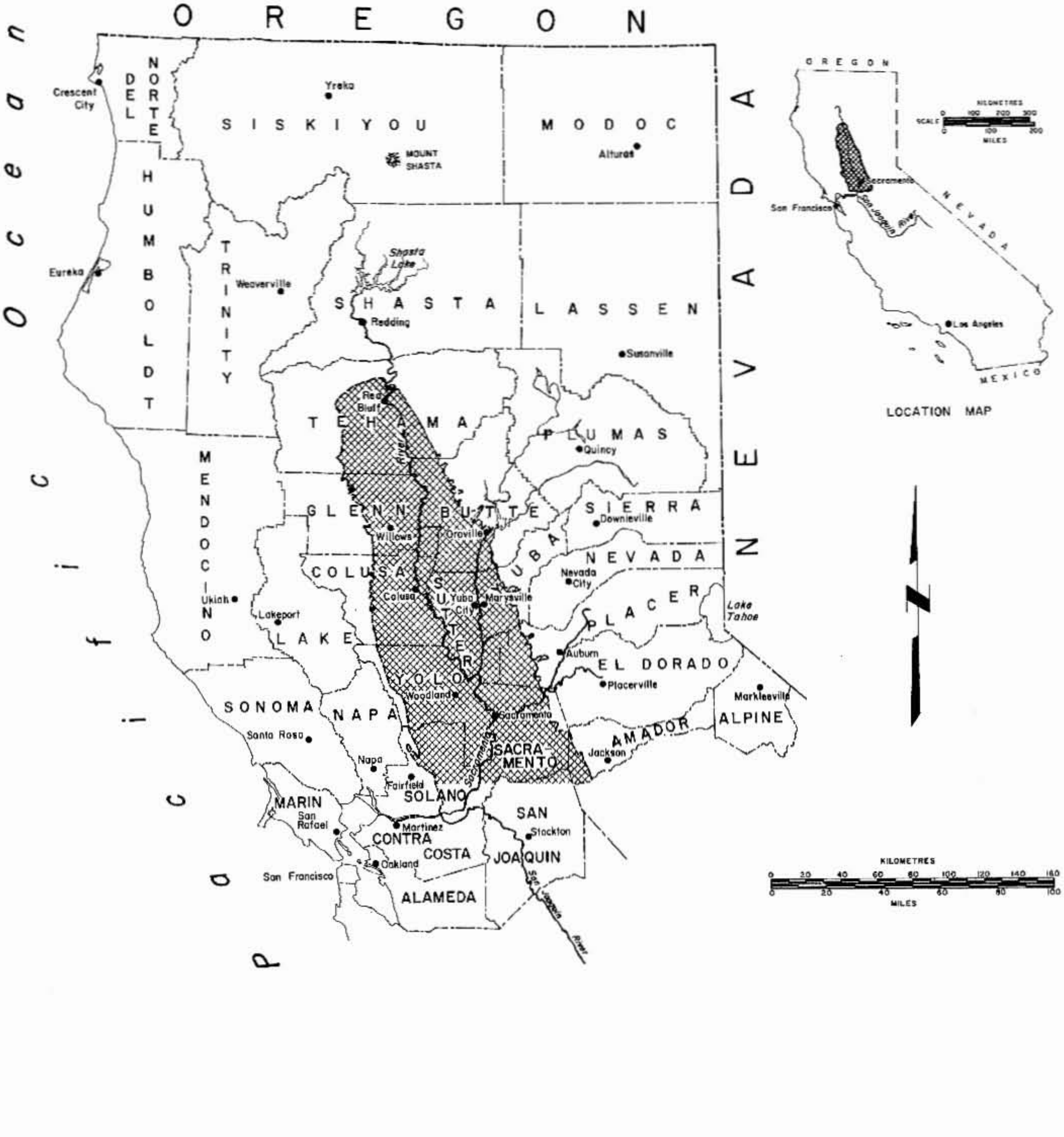


Figure 1. Area of Investigation

CHAPTER I. INTRODUCTION AND SUMMARY

Beneath the Sacramento Valley lies a vast ground water basin, second in California only to the San Joaquin Basin. Large quantities of water are stored in thick sedimentary deposits extending from the Sacramento–San Joaquin Delta to north of the city of Red Bluff. Ground water is used intensively in some areas and only slightly in others, where surface water supplies are abundant. However, overall consumption has been increasing steadily since the early 1900s. In 1970 ground water accounted for almost 30 percent of all agricultural water in the valley. The total amount of Sacramento Valley ground water pumped represents about 12 percent of the 18 500 cubic hectometres pumped annually from all basins in the State.

Description of Area

Located in north central California, the Sacramento Valley is bounded on the east by the Sierra Nevada and Cascade Ranges and on the west by the North Coast Range. The ground water basin extends from about 8 kilometres north of Red Bluff southward 240 kilometres to the Sacramento–San Joaquin Delta. With a surface area of about 15 500 square kilometres, the basin includes all of Sutter County and portions of Yuba, Tehama, Glenn, Butte, Colusa, Yolo, Solano, Placer, and Sacramento Counties (Figure 1).

The valley is relatively flat except at its margins; about half of the basin is at an elevation of 30 metres or less. Sutter Buttes, an isolated body of volcanic rocks, rise to 650 metres, the highest elevation in the basin, and the valley floor reaches approximately 240 metres in the northwest. Peripheral areas are dissected by tributary streams, draining to the Sacramento River.

Beneath the valley floor is a thick sequence of sedimentary materials deposited in both marine and nonmarine environments. The upper, nonmarine portion attains a maximum thickness of about 1 000 metres. Its materials consist of volcanics transported to the valley as mudflows and fragmental rock eroded from the surrounding mountains and transported by stream action. As these were deposited in the structural trough, it gradually downwarped or subsided. As a result, a large volume of material accumulated without significant changes in surface elevation. Fresh ground water occurs in the void spaces between these granular materials to a maximum depth of about 900 metres in the south valley. Throughout the basin, saline water underlies the fresh water.

Physiographic Provinces

As shown in Figure 2, there are 11 physiographic provinces, or units, within the basin. Features associated with the valley floor unit are the stream channels and flood plains of the Sacramento River, its main tributaries, the Feather and American Rivers, and their smaller tributaries. The youngest alluvial materials occur here.

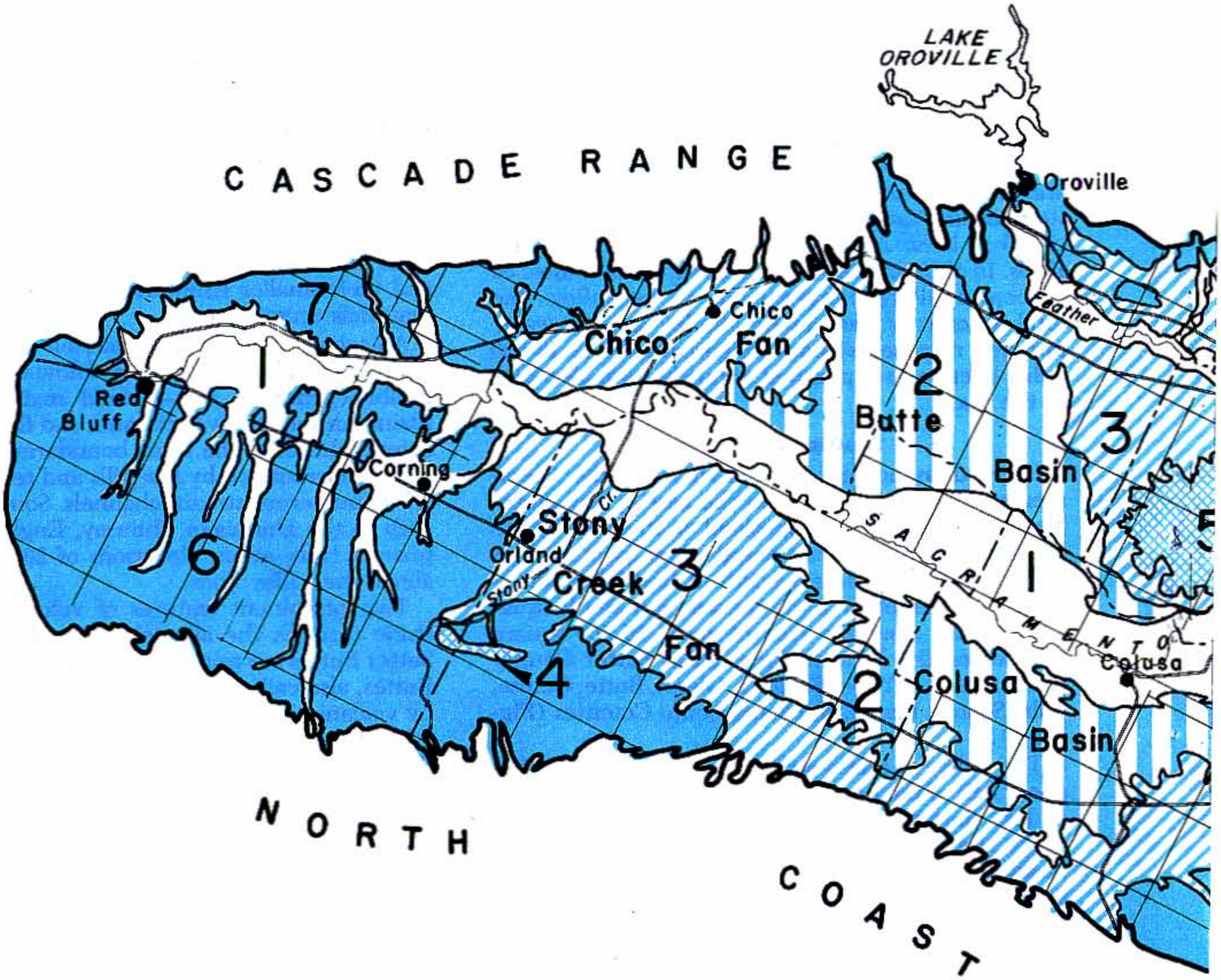
Adjacent to the stream channels and flood plains are five flood basins where overflow waters have deposited generally fine–grained materials. Alluvial plains border the river channel and flood basins and extend almost to the basin boundaries. The basin is largely surrounded by low hills and terraces dissected by numerous stream channels. Some of the hills, such as the Dunnigan, Rumsey, English, and Montezuma Hills, attain elevations of 20 to 500 metres above the valley floor.

Two prominent features of volcanic origin protrude through the alluvial materials of the valley. Sutter Buttes are remnants of an old volcano. Orland Buttes, also called Black Buttes, are a ridge capped by volcanic rock rising about 180 metres above the surrounding area and forming the eastern margin of Black Butte Reservoir. Some of these physiographic features are shown in Figure 2 and are visible in photos 1–3.

Valley Floor Features. The principal physiographic features are the river channels, flood basins, alluvial plains and fans, and river flood plains. The Sacramento River flood plain extends from Red Bluff to the Delta, dividing the valley longitudinally. Just north of Colusa, the plain attains its greatest width—about 13 kilometres. In the Red Bluff–to–Colusa reach, a distance of 120 kilometres, the average flood plain width is about 6 kilometres and its gradient is about 0.3 metres per kilometre. Also in this reach, much of the river's bedload of gravel and sand is deposited, and the suspended silt load is deposited on the broad flood plain. The river course is sinuous here, with many bends and meanders. Old meanders, now cut off and abandoned, form oxbow lakes.

Below Colusa, the river takes a more southeasterly course, and the flood plain narrows except where it is joined by the Feather and American Rivers.

English equivalents: 1 kilometre (km) = 0.62 mile (mi); 1 square kilometre (km^2) = 0.386 square mile (mi^2); 1 metre (m) = 3.28 feet (ft); 1 cubic hectometre (hm^3) = 810.7 acre–feet (ac–ft).



VALLEY FLOOR FEATURES

☐ 1 Stream channels, floodplains and natural levees of the Sacramento and Feather Rivers and their tributaries.

▥ 2 Flood Basins.

▨ 3 Alluvial Plains and Fans of the east and west sides.

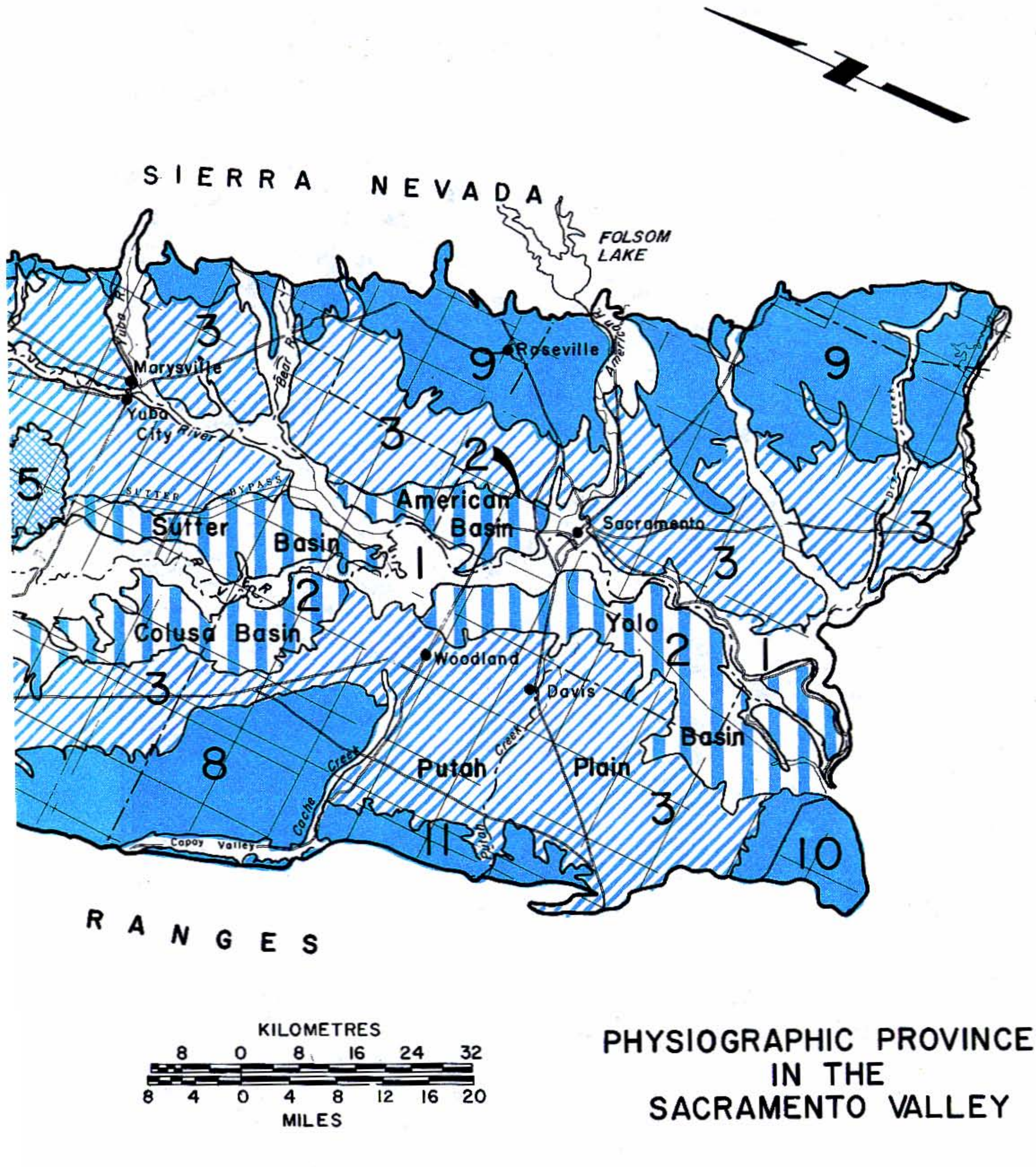
FEATURES OF VOLCANIC ORIGIN

▩ 4 Orland Buttes
5 Sutter Buttes

LOW HILLS, DISSECTED UPLANDS AND TERRACES

■ 6 Low hills and dissected uplands on the west side.
7 Dissected, low, alluvial terraces adjacent to the Cascade Range.
8 Dissected uplands of the Dunnigan-Rumsey Hills.
9 Dissected alluvial and volcanic uplands adjacent to the Sierra Nevada.
10 Dissected alluvial uplands of the Montezuma Hills.
11 Dissected alluvial uplands of the English Hills.

Figure 2



PHYSIOGRAPHIC PROVINCES IN THE SACRAMENTO VALLEY

Photo 1. Sacramento Valley looking north -- Mount Shasta in the distance.

Photo 2. Sacramento Valley looking south from Sutter Buttes area – Sacramento-San Joaquin Delta in the distance.

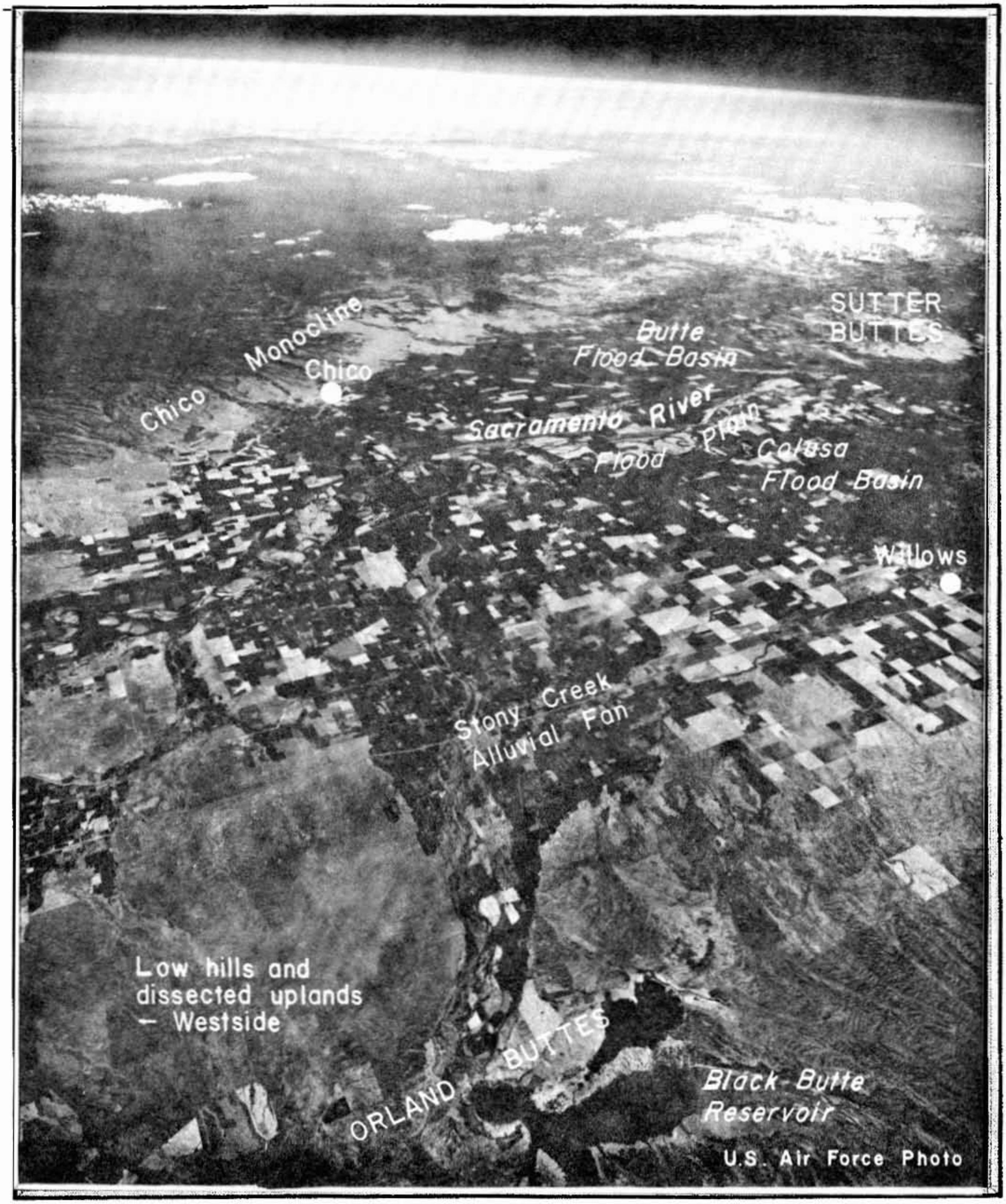


Photo 3. Northern Sacramento Valley looking toward the southeast -- Sierra Nevada in the distance.

The Feather River, one of the Sacramento's principal tributaries, originates in the Sierra Nevada and enters the basin at Oroville. It follows a southwesterly course for 10 kilometres and then turns south, flowing east of Sutter Buttes to join the Sacramento River. At Marysville, it is joined by its main tributary, the Yuba River, and farther south by the Bear River. These tributaries have carried considerable hydraulic mining debris to the channel of the Feather and changed its original character. Where it once flowed in a narrow channel, it now has a wide sand–choked channel which is raised above the adjoining alluvial plains in its lower reach.

Five distinct flood basins, identified in Figure 2, occupy lands adjacent to the Sacramento and Feather River flood plains. They are the Colusa, Butte, Sutter, American, and Yolo basins—broad, shallow troughs lying between the natural levees and the low alluvial plains and fans on both sides of the valley. They are flat, poorly drained lands which have received flood waters as the natural levees were overtopped. Sediments deposited in these basins are the fine–grained portion of the suspended load; the soils are heavy–textured clay and adobe types. Shallow water tables are common to all of these basins, but because of the availability of diverted surface water, very little ground water is used. Water and soil conditions are excellent for growing rice.

On the sides of the valley, situated between the flood basins and the hills and dissected uplands, are alluvial plains and alluvial fans. Underlying sediments and soils in these areas are generally older than those of the flood basins.

The eastside alluvial plain extends from Butte Basin south through Sacramento County. It is often called the "Victor Plain" because of the Victor Formation which underlies it. Nearly flat, it is dissected by many westward–flowing streams draining the Sierra. No deposition of sediment occurs on the plain now. Instead, the area exists in equilibrium without deposition or substantial erosion. This plain has reached a state of maturity, as evidenced by extensive hardpan in the subsoil horizon.

The westside alluvial plain differs from its eastern counterpart. It consists of a belt of coalescing, low–sloping alluvial fans reaching south 160 kilometres from Stony Creek near Orland in the northern portion of the study area to the Montezuma Hills at the southwestern extremity of the area. Two predominant agricultural areas are the Stony Creek alluvial fan and the Putah Plain. The Stony Creek fan is the largest single fan in the valley. Putah Plain is actually two coalesced fans of Putah and Cache Creeks. Between Stony Creek and Putah Plain the alluvial plain narrows to an average width of about 8 kilometres and is as narrow as 3 kilometres near Dunnigan. Unlike the eastside plain, the alluvial fans in this area are under active formation by numerous intermittent streams draining from the Coast Ranges. Materials deposited in the Putah Plain are mostly fine–grained, while those of the Stony Creek fan are coarse.

Features of Volcanic Origin. Sutter Buttes and Orland Buttes are the two most prominent features in the valley, although they are not water–bearing. Sutter Buttes are the remains of a plug–type volcano of Late Pliocene age which pushed through the previously deposited Tertiary and Cretaceous sediments. These sediments are now upturned around the eroded core of the volcano. Surrounding them are volcanic mudflows which are in turn surrounded by an alluvial apron.

Less prominent are the Orland Buttes, formed by a tilted fault block which is capped by a resistant Tertiary age lava flow.

Low Hills, Dissected Uplands, and Terraces. These areas lie along the east and west margins of the basin. Rocks exposed at the surface are the same types which extend toward the center of the valley beneath the more recent alluvial deposits. Six general areas are identified in Figure 2. On the extreme east side of the valley, numerous low hills extend south from Oroville to the end of the study area (Area 9, Figure 2). In Yuba, Placer, and Sacramento Counties, the hills represent outcrop areas of rocks which extend westward beneath alluvial fill. The rocks are mostly volcanic types which originated in the Sierra Nevada. Near Oroville, the hills are capped by gravelly deposits of more limited distribution.

North of Chico is a dissected terrace underlain by sediments which are geologically related to volcanic rock of the Cascade Range. The area is somewhat barren, with limited agricultural development. The terrace is crossed by a number of streams flowing in shallow gorges.

On the west side of the valley, dissected uplands can be divided into four areas—unnamed hills west of Red Bluff and Corning (Area 6, Figure 2), the Dunnigan–Rumsey Hills (Area 8), the Montezuma Hills (Area 10), and the English Hills (Area 11). All of these are underlain by semi–consolidated rocks of Pliocene to Pleistocene age. From the outcrop area in the hills, these sediments extend eastward beneath the surface toward the center of the valley, where they merge with sediments extending in like manner from the eastern side of the valley. Since agriculture is limited in these upland areas, few wells have been drilled and relatively little is known of their water–bearing character.

English equivalents: 1 metre (m) = 3.28 feet (ft); 1 kilometre (km) = 0.62 mile (mi); metre per kilometre (m/km) = 5.28 feet per mile (ft/mi).

Objectives and Scope

The objective of this study is to provide reliable data on the geology and hydrology of the Sacramento Valley and their effect on the ground water resource. The study presents a broad description of the valley–wide ground water resource rather than extensive details on any single area or problem. Occurrence and quantity of water are emphasized more than is quality. Also, considerable emphasis is placed on the basin's hydrologic operation under natural conditions and its operation under present–day use.

Gross hydrologic properties of water–bearing materials were determined, including storage capacity, specific yields, and transmissivity. Other hydrologic conditions in the basin, such as specific capacities and yields of existing wells, ground water movement, long–term changes in water levels, sources and amounts of recharge and discharge, were also evaluated. Quantities of applied irrigation water from both ground and surface sources were determined from land use surveys for the 10–year period 1961–1970. These sums were calculated with changes in storage values to develop an inventory of ground water supply and disposal.

Detailed information on aquifer location, depth, thickness, and continuity from area to area are beyond the scope of this study. No new efforts were made to develop information on surface geology, as the subject has been thoroughly covered in previous publications.

Methods of Study

Seven thousand well logs, prepared by well drillers while drilling irrigation, domestic, and industrial wells, were studied for information on materials encountered at various recorded depths. This provided a broad data–base for determining the gross character of aquifer systems. A computer program was designed to convert these log descriptions to numerical designations. In conjunction with other information, this produced data on extent and depth of water–bearing materials in terms of specific yield. The depth for which information is available is therefore limited to the depths of drillings as recorded in well logs. Since wells do not exist or are very scarce in some areas, knowledge of aquifers in those areas is partial or non–existent.

Methods of study also included use of available basic data on ground water levels, water quality, precipitation, and land use. Available information on surface geology was adequate for reconnaissance–level resource evaluation.

Water–level measurements obtained from the Department's basic data program were used extensively to prepare depth–to–water and ground water elevation contour maps. Changes in storage values for each township were determined from annual spring measurements. Mineral analyses, also from the basic data program, were used to describe the general chemical characteristics of ground water.

Pump efficiency tests made by Pacific Gas and Electric Company and Sacramento Municipal Utility District were collected and utilized to develop information on well yields and specific capacity by township. This information was supplemented by pump tests reported by well drillers.

Development of a hydrologic inventory for the period 1961–70 was an important part of the study. Land use surveys made in all counties in 1961 and again in the late 1960s and early 1970s provided the basic knowledge needed to measure pumpage and applied water. Most of the information on aquifers, wells yields, specific capacity of wells, ground water storage and pumpage has been developed and is presented for single township and four–township areas.

Cooperative Studies by the U. S. Geological Survey

In July 1970, the Department entered into a cooperative agreement with the U. S. Geological Survey (USGS) to make ground water studies in the Sacramento Valley. The work program as formulated in 1971–72 included preparation of a hydrologic simulation model and a series of data maps, some of which were required as input data for the model. This model provided a digital simulation of the hydrologic system's response to stress and yielded information on transmissivity, recharge, and discharge. The USGS report on these studies, with explanation of models and how they work, is presented in this bulletin as Appendix A.

Data maps, prepared as part of the cooperative effort, were published separately as USGS Open File Reports. They include the following:

1. "Base of Fresh Water in the Sacramento Valley and Sacramento–San Joaquin Delta, California"

2. "Base and Thickness of Post Eocene Continental Deposits in the Sacramento Valley"

3. "Estimated Permeabilities for the Soils in the Sacramento Valley".

Complete listings of these publications are found in Appendix B, "Selected References".

Previous Investigations

The earliest comprehensive ground water investigation of the valley was made by Kirk Bryan of the USGS from 1912 to 1914. The results were published as USGS Water Supply Paper 495 in 1923. Field studies included the measurement of 2,500 wells and the sampling of 68 wells for water quality. Measurements provided data for the first ground water contour map ever prepared for the valley. Bryan's report remains an important source of information on the geology and hydrology of the basin.

The second basin-wide study was made in 1929–1931 by Hyde Forbes of the State Division of Water Resources as part of a comprehensive Sacramento River Basin study. In his 1931 report, Forbes described the surface geology of five physiographic units and, to a limited extent, the types of water-bearing materials underlying the surface. Storage capacity for three of the physiographic areas, totalling 371 500 hectares was determined for a shallow zone where ground water levels fluctuated from 4 to 9 metres. The total capacity of these areas was reported to be 3 724 cubic hectometres, using a drainage factor (specific yield) from 12.5 to 20 percent. The report also records depths to water in 196 wells in the fall seasons of 1929, 1930, and 1931. Many of these wells are still being measured today as part of the Department's basic data program.

A third basin-wide study was begun in 1948 by the USGS and reported in USGS Water Supply Paper 1497 in 1961. The paper documents the results of a thorough geologic study of the valley and includes the first modern geologic map. It remains the best basic reference on geology in regards to ground water resources in the valley. The investigation did not include evaluations of ground or surface water hydrology, but ground water storage capacity determinations were an important component. Storage capacity for a depth zone between 6 and 60 metres was determined to be 41 000 cubic hectometres beneath an area of approximately one million hectares.

Many other studies, published and unpublished, have been made on local areas by public and private agencies. The U. S. Bureau of Reclamation has made comprehensive studies of existing and proposed service areas for surface water development projects on the west side of the Sacramento Valley in portions of Tehama, Glenn, Colusa, Yolo, and Solano Counties and on the east side in Butte County. These were undertaken to determine potential ground water supply for overlying lands and supplemental water needs. The Tehama–Colusa Canal, to extend ultimately from Tehama County to northern Yolo County, and the Putah–South Canal, extending south from Putah Creek through the western valley portion of Solano County resulted from such studies.

Surface and ground water supplies of various counties have been the subject of several investigations made by the Department of Water Resources and its predecessors since the early 1950's. Sutter–Yuba and Placer County reports were issued by the State Water Resources Board in 1952 and 1955, respectively. A report to the California State Legislature on Putah Creek Cone, issued by the Division of Water Resources in 1955, covered portions of Yolo and Solano Counties.

Data on ground water storage capacity and yield of lower Cache Creek and Capay Valley in Yolo County were included in the Clear Lake–Cache Creek Investigation, published by the Department in 1961. In 1974 the Department published the results of a cooperative study on the geology and ground water resources of Sacramento County. Yolo County was again the subject of a ground water report published in 1976 by a private engineering firm (Clendenen, 1976).

During the period 1948–52, the USGS made studies on geology, ground water resources, and storage capacity for a portion of Solano County in cooperation with the U. S. Bureau of Reclamation. This report was published in 1961 as USGS Water Supply Paper 1464.

These and other reports describing geology, hydrology, and water quality are listed in Appendix B, "Selected References". Reports by the U. S. Bureau of Reclamation are not available in most libraries and therefore are not included.

History of Irrigation and Ground Water Development

The first irrigation in California was practiced by the Spanish Fathers as they established missions throughout Southern California in the late 18th century. Teaching the Indians to grow small gardens, irrigated by diverting water from nearby streams, was an important part of their work. It was not until the 1840s however, that any irrigation took place in the Sacramento Valley. At this time, it was reported that John Sutter was irrigating his large gardens with water hand–carried by Indian workers.

James Moore, a planter in the valley, built a canal near Woodland in 1856 to irrigate his wheat fields. It was the first large irrigation effort. After the decline of gold–rush activity, around 1860, farming began in earnest. Interest in irrigation grew slowly, as most growers considered the costs prohibitive and preferred dry farming and cattle ranching. But by the turn of the century some growers were raising two or three crops a year on irrigated land. There was little danger of crop failure, and high–value, water–intensive plantings were possible. Land value appreciated heavily where irrigation water was available.

The Conservation Commission report of 1913 to the State of California remarked that development of irrigation in the Sacramento Valley was behind that of other parts of the State; however, the advent of the first world war brought a period of major growth, with rice a leading wartime product of the valley. By 1930, thirteen irrigation districts had been formed.

English equivalents: 1 hectare (ha) = 2.47 acres (ac); 1 cubic hectometre (hm^3) = 810.7 acre–feet (ac–ft); 1 metre (m) = 3.28 feet (ft).

The use of ground water as a source for irrigation has lagged behind that of surface water in the valley. Early settlements used ground water for domestic and stock supplies, but it was not until 1879 that the first well for irrigation was constructed on the Blowers Ranch near Woodland. This 7-metre-deep well was so successful that more drilling followed, but development continued to be slow. Costs for drilling equipment were high, and in most cases surface water supplies were plentiful.

Eventually, however, twentieth century innovations and improvements, such as development of tools capable of drilling deep, large-diameter wells, use of electricity, and availability of more efficient motors and pumps, promoted the use of ground water. Pumping costs decreased, and the division of large farms into 4 to 8 hectare plots, unreachable by existing surface canals, made the use of ground water economically preferable.

The first reliable information on ground water development in the Sacramento Basin appeared in a USGS report (Bryan, 1923), which showed that in 1913 nearly 16 600 hectares were irrigated by water from 1,664 wells. No figures were reported for surface water use that year, but by 1919, 191 400 hectares were being irrigated from all sources. In 1929, the California Division of Water Resources reported that over 202 300 hectares were irrigated in the Sacramento Valley, including 82 150 hectares from wells.

Little additional land was irrigated during the Depression years, but World War II stimulated renewed ground water development. By 1950, almost 303 500 hectares were under irrigation, and of this about 141 600 hectares were irrigated by ground water.

Investigation for this report determined that 7 780 cubic hectometres (hm^3) of applied water were used by farms and cities in the Sacramento Valley north of the Rio Vista area during 1970. Of this, approximately 29 percent, or 2 242 hm^3, came from wells, and the remainder, 5 538 hm^3, from surface sources. Crops irrigated by ground water used an average of 0.01 cubic hectometres/hectare (by English measure, 3.2 acre-feet per acre), as compared to 0.013 hm^3/ha (4.2 acre-feet per acre) for those using surface sources. The lower use is attributed to a tendency for ground water irrigators to apply water more efficiently and to grow crops with a higher economic return and smaller water requirement.

Figure 3 shows the increase in all irrigated lands and those dependent solely on ground water from the early 1900s to 1970. Irrigated areas, by water source, are shown in Plate 1 (in pocket).

Investigation Results

This section summarizes findings for the present report by both the U. S. Geological Survey and the Department of Water Resources. The information is presented in greater detail in following chapters and in Appendix A, *Ground Water Conditions in the Sacramento Valley, California, 1912, 1961, and 1971.*

Geology

The Sacramento Valley is a large northwest-trending structural trough extending about 240 kilometres north from the Sacramento-San Joaquin Delta and occupying an area of about 15 500 square kilometres. It is bounded on the east by the Sierra Nevada and Cascade Ranges and by the Coast Range on the west. Rocks underlying the basin and the bordering mountains include Paleozoic and Mesozoic granitic, metamorphic and marine sediments. They are found at considerable depths at the center of the valley and shallow depths near the margins. They are overlain by Eocene marine and continental sedimentary rocks which contain saline or brackish water. All of these rocks are impermeable and form the bottom of the basin. Fresh water is not present beneath them.

Overlying the older sequence of Eocene and pre-Eocene rocks is a series of continental deposits (non-marine origin) of post-Eocene age, which yield fresh water except in the deeper portions of the valley. These post-Eocene continental deposits were laid in place by streams flowing from the surrounding mountains into the subsiding trough. This assemblege of predominately sedimentary rocks also includes volcanic mudflows, lava flows, and volcanic ash deposits, all associated with the volcanic action which occurred in the middle to late Tertiary period. Sutter Buttes are prominent volcanic features on the valley floor which originated during the late Tertiary period. For purposes of study, these rocks are identified and categorized by distinctively named geologic formations (Plate 2 in pocket).

Several formations of post-Eocene age are present in the valley and are important as sources of ground water. They include the Tuscan, Mehrten, Tehama, Laguna, and Victor Formations and several unnamed alluvial units, principally alluvial fans and flood plain deposits.

The Tuscan Formation in the northeastern portion of the valley contains fresh water to depths of 460 metres in moderately permeable sand aquifers. Also present are beds of volcanic tuff breccia of low permeability which act as confining beds and restrict the upward movement of water from the underlying aquifers. Wells drilled through these beds may encounter water under sufficient pressure to force it to the surface.

English equivalents: 1 hectare (ha) = 2.47 acres (ac); 1 cubic hectometre (hm^3) = 810.7 acre-feet (ac-ft); 1 cubic hectometre per hectare (hm^3/ha) = 328 acre-feet per acre (ac-ft/ac).

English equivalents: 1 kilometre (km) = 0.62 miles (mi); 1 square kilometre (km^2) = 0.386 square mile (mi^2).

South of Oroville, along the east side of the valley, the Mehrten Formation is particularly important, especially in Sacramento County. Permeability of this formation is quite variable due to the presence of permeable sediments and impermeable tuff breccia. The upper part of the formation may have a higher percentage of clay and fine-grained sediments than the middle or lower portions, tending to confine ground water in the more permeable underlying sand and creating the pressure conditions found throughout much of the formation. The sand and gravel strata are generally moderately to highly permeable and yield large quantities of good-quality water to irrigation and industrial wells.

The Tehama Formation is a source of ground water for irrigation in most areas along the west side of the valley. Although this formation is mostly fine-grained, it contains sufficient sand and/or gravel zones in many areas to provide large quantities of ground water. In certain areas along the west side of the valley it is predominantly clayey, particularly in the area between Willows and Williams. Wells in these areas generally will not yield large quantities of water, and those which penetrate the entire thickness of the formation may yield water of poor quality because some of the basal sands contain connate water derived from underlying marine sediments.

Along the east side of the valley, the Laguna Formation is a wedge-shaped deposit that thins toward the foothills and thickens to more than 300 metres along the valley axis. Fine-grained materials seem to predominate in the Laguna, with lenticular sands and gravels occurring sporadically. Gravels are more common toward the east but they may be clayey or cemented. This formation is tapped by domestic, irrigation and industrial wells throughout much of the east valley area. Most wells in this area do not draw all their water from the Laguna Formation, but are perforated or gravel-packed so that they may also receive part of their yield from underlying and overlying formations.

The Victor Formation is an assemblage of old alluvial deposits which include lenticular bodies of silt, sand, and gravel. The formation occupies the low alluvial plain on the east side of the valley. Together with the underlying Laguna Formation, the Victor constitutes the most important source of ground water on the east side of the valley south from the vicinity of Gridley.

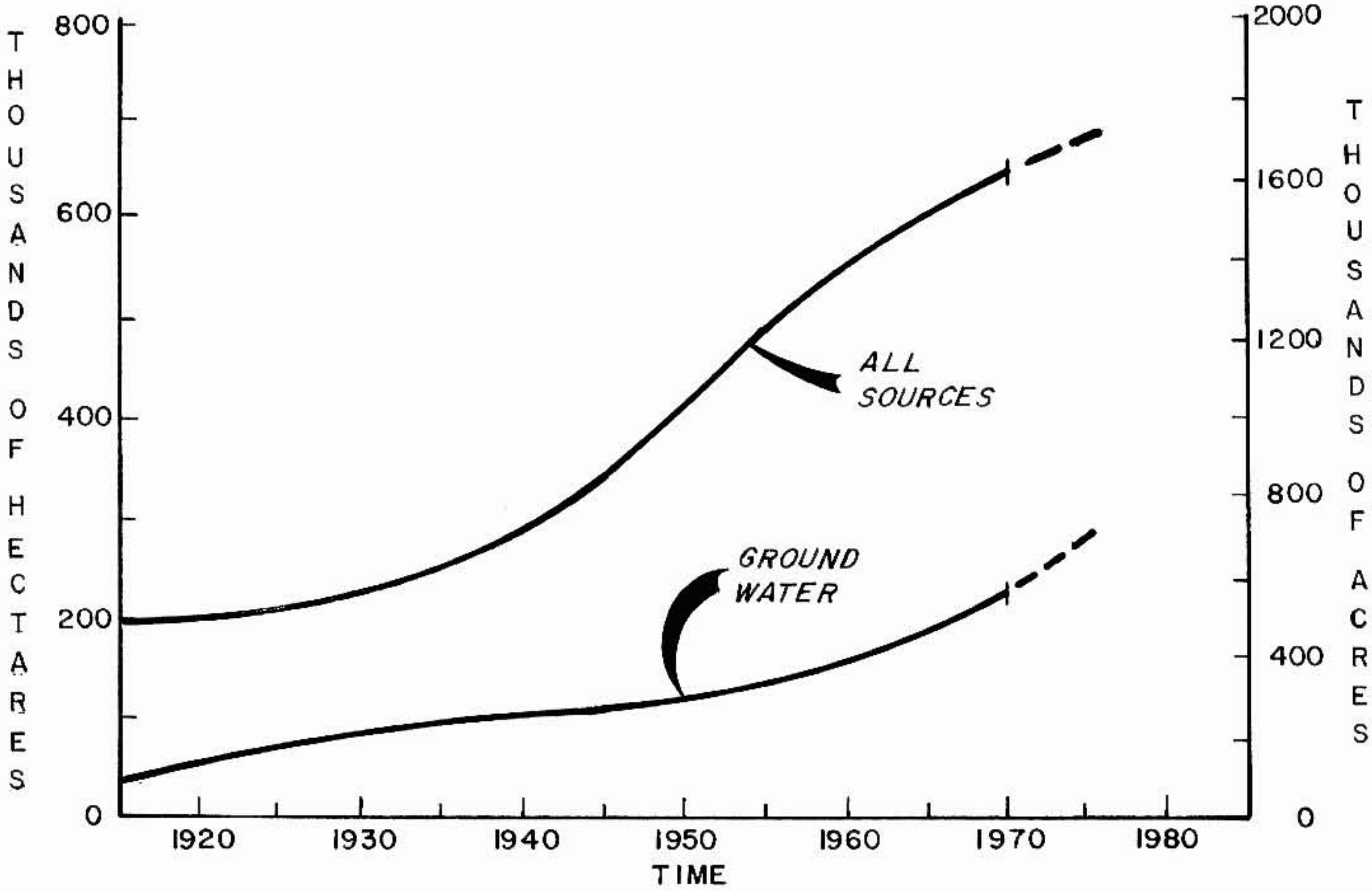


Figure 3. Development of Irrigated Land in the Sacramento Valley, 1913-1970

The fanglomerate unit (not given a formation name), is an assemblage of partially cemented layers of sand and gravel with thick layers of clay and silt. The sediments were derived from large areas of Tuscan rock in the Cascades and now overlie the Tuscan Formation in the northeast margin of the valley. It is similar to the Tuscan Formation from which it was derived except that it does not contain tuff breccia (volcanic mudflows). It supplies moderate quantities of water to moderately deep wells on the east side of the valley north of Chico.

Along the east margin, near Oroville and in small isolated areas south to Sacramento County and west of Red Bluff, Corning, and Orland, are gravelly deposits belonging to the Red Bluff Formation. In Sacramento County similar deposits are known as the Arroyo Seco and South Fork gravels. These are all surficial deposits that occur mostly above the zone of saturation and have little importance as sources of ground water. Collectively they are known as the Pleistocene gravels.

Alluvial fans, stream channel deposits, flood plain and flood basin deposits—these are the most recently deposited materials and represent important water sources. Alluvial fans occur mostly on the west side adjacent to the Coast Range, around Sutter Buttes, and at Chico. They are relatively thin, but most contain highly permeable materials. Stream channel and flood plain deposits consist of well–sorted sand, gravel, and silt adjacent to the major streams. The deposits are up to 13 kilometres wide and 60 metres thick in the north valley area. Flood basin deposits are the finest–grained materials, consisting mostly of clay and silt. Five major flood basins occupy large areas adjacent to the Sacramento River (Figure 2). Their deposits are thin and poorly permeable and therefore unimportant for ground water development, but the older alluvium underlying the basin sediments often contain highly productive aquifers, particularly in the north valley.

Seven major structural features, shown in Plate 2, influence the occurrence and movement of ground water in the Sacramento Valley:

1. *Chico monocline,* extending from the vicinity of Red Bluff southeast to Chico, tends to facilitate ground water inflow to the valley from areas outside the basin.

2. *Red Bluff arch,* forming the northern boundary of the basin is a series of paralleling faults and gentle folds which tend to restrict movement of water between the Redding ground water basin and the Sacramento Valley ground water basin.

3. *Corning anticline* impedes the eastward movement of ground water between Red Bluff and Corning.

4. *Sutter Buttes,* northwest of Yuba City, are the surface expression of coalescing domes that were thrust from below, tilting, faulting, folding, and exposing at the surface the intruded Cretaceous–to–Pliocene sediments. The Buttes divert ground water around their flanks. Marine sediments surrounding them have been flushed of their saline water by meteroic water to great depths. This flushing action may be related to the shallow connate water found in the Sutter Basin to the south.

5. *Dunnigan anticline,* which has folded the Tehama and Red Bluff Formations, diverts ground water southeast into Hungry Hollow.

6. *Plainfield Ridge,* possibly a southern continuation of the Dunnigan anticline, impedes the flow of ground water toward the east, causing it to flow through notches in the anticline and southeast toward Putah Creek.

7. *Willows Arch,* located just west of Artois and extending northward toward Orland, is probably the northern extension of an anticlinal structure which occurs in the Beehive Bend gas field to the southeast. It appears to be a partial barrier to southwesterly movement of ground water from Stony Creek.

Geohydrology

Ground water is termed *confined* when it is separated from the surface by some impermeable barrier. In this condition it is under greater than atmospheric pressure. *Unconfined* water is found in materials sufficiently porous to permit contact with the atmosphere and forms a water table. Ground water occurs in both conditions through most of the Sacramento Valley Basin. Generally unconfined in the relatively shallow alluvial fan, flood plain and stream channel deposits, it appears partially confined in and under the flood basin deposits. In the older Pleistocene and Pliocene formations, especially at deeper levels, water is confined beneath impervious thick clay and mudflow strata.

In the low–lying central portion of the basin, from the Delta north to Glenn and Butte Counties, depth to water in wells is 3 metres or less. Depth to water increases to 25 to 30 metres and more toward the basin margins.

Elevation contours of the upper surface of the ground water body in the north valley indicate that the general direction of movement is toward the Sacramento River. In the valley floor south of Sutter Buttes the upper surface of the zone of saturation is virtually flat, so there is no marked movement toward the river under present conditions. Under natural conditions ground water moved from the

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English equivalents: 1 metre (m) = 3.28 feet (ft); 1 kilometre (km) = 0.62 mile (mi).

margins of the valley to its floor with a nearly flat gradient, sloping toward the lower Sacramento River or the Delta, but intensive development of ground water since 1914 has created three pumping depressions along the east side from Marysville to Sacramento County and one on the west side in Solano County. By 1971, these depressions were modified in size and depth, increasing or decreasing according to changes in withdrawal rates. In 1971, they were located in Sacramento County south of the state capitol, in southwestern Placer County, in Yuba County at Marysville, and in Solano County south of Davis. Ground water moves toward these areas of heavy pumping rather than toward the central part of the valley or the Delta as it did in 1912–13.

Ground water levels fluctuate according to supply and demand on daily, seasonal, annual, and even longer bases. Short–term and long–term water level changes have been recorded for wells since the first documented measurements in 1929. In the north valley, there have been no consistent downward trends, but at the southern end, representative wells show long–term declines in nearly all counties since early measurements were made.

As mentioned in "Methods of Study" approximately 7,000 drillers' well logs were tabulated in a computer program designed to study subsurface geology. Different underground materials encountered by drillers were classified according to specific yield[1] and assigned numerical values. Average specific yield was calculated by 10–foot layers (converted to 3–metre layers for this report). Through the use of such data, it was possible to delineate areas of predominantly coarse–grained material, constituting major aquifer systems, and predominantly fine–grained materials, which may be minor aquifers or contain no recoverable water. The relative amounts of coarse and fine–grained materials are shown in terms of specific yield in six 3–dimensional, sectional views of the valley. (Plates 3 and 4 in pocket.)

Well yields and specific capacities of wells generally increase toward the center of the valley. Areas of high yield and capacity correspond to areas of coarse–grained alluvial fans and floodplain deposits. Along the margins of the valley where older, more compact formations occur, yields and capacities are low. The greatest incidence of wells with high specific capacity and potentially high yields occur in the north–central portion of the valley, where there is a concentration of coarse materials deposited by the Sacramento River and its main tributaries.

Distribution of transmissivity[2] and storage coefficients[3] of water-bearing materials throughout the entire depth of post–Eocene continental deposits was determined by the U. S. Geological Survey through model studies. Transmissivity values range from 400 to 6,000 square metres per day[4]. The area of highest values extends north of Sutter Buttes along the Sacramento River and west into the Stony Creek alluvial fan area. They are slightly lower toward the east basin boundary. Except for small areas along the Sacramento River, the lowest values are found in the south Sacramento Valley.

Storage coefficient was found to vary from 0.04 to 0.12, when averaged over specific areas. In an unconfined system, assumed to exist for the model study, these values are related to specific yields of 4 to 12 percent. Areas of highest specific yield, 8 to 12 percent, occur where streams have deposited coarse alluvial materials on flood plains and alluvial fans. Examples are found along the Feather River near Oroville, at Cache and Putah Creeks near the edge of the valley, the lower portion of the Stony Creek alluvial fan, Yuba River, American River, and Sacramento River between Stony Creek and Sutter Buttes. Gravels carried downstream along the Sacramento River from Stony and Chico Creeks have resulted in high specific yields in the flood plain north of Sutter Buttes. Most other areas in the valley have specific yields in the 4 to 8 percent range.

Replenishment of ground water occurs through deep percolation of streamflow, precipitation, and applied irrigation water. Estimated values were determined in a ground water inventory which showed that stream percolation and deep percolation of rainfall combine to provide a greater amount of recharge than does applied irrigation water. Recharge by subsurface inflow is considered negligible compared to other sources.

The U. S. Geological Survey determined percentage of total recharge under natural conditions for various areas in the valley. Approximately two–thirds of the basin's total recharge under natural conditions occurs north of the Sutter Buttes, with the remainder in the south valley.

Average annual ground water pumpage, the principal method of discharge, was estimated to vary from 2 228 hm^3 to 2 242 hm^3 for the years 1961 and 1970, respectively. (These estimates include township 4 north, not included in inventory figures cited in Chapter IV). Approximately two–thirds of this pumpage is in the south valley; one–third is in the north valley.

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[1] Specific yield is the ratio of the volume of water a given mass of rock or soil will yield by gravity to the volume of that mass. The ratio is stated as a percentage.

[2] Transmissivity is defined as the rate of flow of water through a vertical strip of the aquifer of a unit width extending the full saturated height of the aquifer under a hydraulic gradient of 100 percent.

[3] Storage coefficient of an aquifer is defined as the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in ground water level. When expressed as a percentage, it is usually referred to as "specific yield."

[4] Square metres per day is equivalent to cubic metres per day per metre width of aquifer ($m^3/d/m$). Likewise the USGS formulation of cubic feet per day per foot width of aquifer (ft^3/day/ft) reduces to square foot per day (ft^2/day).

Storage of ground water has been determined for the year 1965 for each of six depth zones—6 to 30 metres and each 30–metre increment to a depth of approximately 180 metres. The total in storage for all depth zones was determined to be 140 200 hm^3.

Quality of ground water is generally excellent throughout the valley and is suitable for most uses. Concentration of total dissolved solids is normally less than 300 milligrams per litre (mg/l) although water in some areas may contain solids to 500 mg/l. Ground water beneath the eastern basin is commonly a magnesium–calcium or calcium–magnesium bicarbonate water. In portions of the area, calcium, magnesium, and sodium are present in equal amounts as the dominant cations, while bicarbonate is nearly always the dominant anion. High concentrations of sodium chloride waters are found at Robbins, Clarksburg, and several areas near the edge of the basin where Cretaceous–age rocks are nearby. There are also some areas where iron, manganese, and boron are present in undesirable amounts, but the water remains suitable for most purposes.

In terms of mineral content, ground water in the west half of the valley is significantly poorer than that in the east half. This is a reflection of the rock types in the Coast Range, which contain more soluble minerals and saline connate waters than do the igneous and metamorphic rocks in the Cascade Range and Sierra Nevada. Calcium–magnesium and magnesium–calcium bicarbonate types are common here as well, but there are areas near Maxwell, Williams, and Arbuckle where high concentrations of sodium, chloride, and sulfate waters occur with total dissolved concentrations of 500 mg/l or more. Some of these waters are unsuitable for irrigation and drinking.

At a considerable depth beneath the valley, nearly all ground water contains sodium chloride. Depth to base of fresh water is about 350 metres beneath most of the north valley and commonly over 480 metres in the south valley. Two exceptions are in the Robbins area south of Sutter Buttes and the Colusa area, where saline water occurs at shallow depths. Depth of saline water may be similarly shallow at the valley margins on both sides.

Hydrologic Inventory

A reconnaissance–level ground water inventory (an accounting of inflow, outflow, and storage change in the basin) was made on a township area basis for the 10–year period 1961 through 1970. Average annual recharge from applied water and the combination of stream percolation and precipitation were calculated for each of 45 township areas. Average annual recharge from deep percolation of applied irrigation water was estimated at 726 hm^3, and from streams and precipitation at 1 436 hm^3—a total of 2 162 hm^3 annually. During this 10–year period, accumulated water in storage increased about 390 hm^3, or an average of 39 hm^3 annually, indicating a greater amount of recharge than discharge. Most of this increase occurred in the north valley.

On a township basis, discharge exceeded recharge in three areas over the study period. These were Sacramento County, a portion of Yolo County, and a portion of Glenn County near the west basin boundary. In three areas recharge approximately equalled discharge and in the remaining areas, recharge exceeded discharge.

English equivalents: 1 cubic hectometre (hm^3) = 810.7 acre–feet (ac–ft); 1 metre (m) = 3.28 feet (ft).

CHAPTER II. GEOLOGY OF THE BASIN

Rocks underlying the Sacramento Valley, and the low bordering foothills and mountains, vary in type and age from crystalline and metamorphic rocks of Paleozoic and Mesozoic age to the very youngest alluvial materials still being deposited. Plate 2 shows the distribution of 14 geologic units divided into three categories: igneous and metamorphic rocks, nonfreshwater–bearing formations, and freshwater–bearing formations.

A common characteristic of rocks in the first two categories is that they yield little or no water to wells, although igneous and metamorphic types may yield small quantities of potable water where the rock contains open fractures. Nonfreshwater–bearing formations may yield small quantities of water, which is either brackish or saline. The surface exposures of all these rocks, except the volcanic rocks at Sutter Buttes, lie outside the valley in the Sierra Nevada and Coast Ranges. From their areas of surface exposure, these rocks extend beneath the valley to a considerable depth beneath younger sedimentary rocks.

Rocks of the freshwater–bearing category include all of the nonmarine sediments that have filled the valley since the end of Eocene epoch approximately 38 million years ago. The category also includes a middle–Eocene age formation which outcrops along the eastern margin of the valley. Known as the Ione Formation, this unit contains both fresh and brackish water. Ten rock units, including the Ione Formation, are included in the third category. Each unit may include one or more designated geologic formations. The general character, location, thickness, and water –bearing properties of each formation are presented in Tables 1 and 2 for the northern and southern portions of the valley.

Igneous and Metamorphic Rocks

Surface exposures of these rocks are confined almost entirely to the eastern border of the valley in the Sierra foothills. They extend westward beneath the valley and may be encountered in deep wells along the east side of the basin. They include such types as granite, metamorphic rocks, shallow intrusive rocks at Sutter Buttes, and an extensive basalt lava flow known as the Lovejoy Formation (Van Den Berge, 1968). At the surface, this basalt formation appears within the study area at Table Mountain near Oroville and at Orland Buttes. The subsurface basalt in the northern part of the valley would yield little or no water and is too deep to be feasible for drilling. It is significant because in places it forms a barrier separating the saline water–bearing Eocene and Cretaceous rocks from the fresh–water bearing continental deposits.

Sutter Buttes are important because their intrusion pushed up saline water–bearing marine sediments that now surround the igneous core (Williams, 1977). The complex is a hydrologic barrier and a source of saline water.

South of Oroville, igneous and metamorphic rocks of the Sierra Nevada form the eastern boundary of the basin. Runoff from these relatively impermeable rocks contributes large quantities of water to the valley, but the rocks themselves yield little or no water to wells. Being relatively insoluble, they contribute only small quantities of dissolved minerals to the surface water, some of which enters the ground water basin.

Nonfreshwater–Bearing Formations

The sedimentary rocks which compose the formations in this category were deposited under marine conditions during the Cretaceous and early Tertiary periods (Eocene epoch). Geologic formations included are the Chico Formation of upper Cretaceous age and several Eocene–age formations. All contain remnants of the original sea water in which they were deposited. Such indigenous waters are called connate waters and are highly saline except where diluted by fresh water.

The Chico Formation is exposed in the Coast Ranges where it attains a thickness of about 4 500 metres (Kirby, 1943). These well–stratified layers of sandstone and shale dip eastward beneath the Sacramento Valley and rise again on the east side where they are exposed discontinuously from Red Bluff to Folsom near the edge of the valley. Wells drilled for gas throughout the valley indicate that they underlie most of the valley, usually at considerable depths. The gas well data also indicate an eastward thinning of the formation to about a thousand metres. These rocks surround the igneous core of the Sutter Buttes, where they have been pushed upward by the intrusion. The once–horizontal beds are now tilted to an almost vertical position.

The Eocene series is composed of marine sedimentary rocks beneath the central and western parts of the valley. On the east side of the valley, mostly in Placer and Sacramento Counties, they were deposited in a swamp–like environment and contain largely fresh water with brackish water in places. These middle–Eocene age sediments are included in the Ione Formation and are further discussed as part of the freshwater–bearing category.

English equivalents: 1 metre (m) = 3.28 feet (ft).

TABLE 1

DESCRIPTION OF GEOLOGIC UNITS
NORTH SACRAMENTO VALLEY

Geologic Unit Plate 2	*Map Symbol*	*General Character Location and Thickness*	*Water-Bearing Properties*
Alluvium	Qal	Unconsolidated sand, gravel, and silt with minor amounts of clay deposited along the Sacramento River, Feather River and their tributaries. Includes natural levee and floodplain deposits. Deposits attain a maximum thickness of 40 metres north of Colusa on the Sacramento River, about 30 metres at Gridley near the Feather River. Thickness on tributaries generally less than 15 metres.	Gravelly portions are highly permeable and yield large quantities of water to wells of shallow depth. Deposits along Stony, Chico, and Thomes Creeks are important recharge areas.
Flood Basin Deposits	Qfb	Silt and clay deposited by flood flows in Colusa and Butte Basins. Deposits in Butte Basin are thin and overlie coarser materials. Thickness exceeds 15 metres in Colusa Basin west of Princeton.	Generally of low permeability and saturated to near the ground surface. Yields small quantities of water to domestic wells.
Alluvial Fan Deposits	Qaf	Includes a wide variety of materials ranging from clay to coarse gravel. Stony Creek fan contains mostly coarse material in the upper 30 metres. Alluvial fans along the west side are predominantly fine-grained. Chico fan contains about 15 metres of coarse-grained material.	Materials are highly permeable in the Stony Creek fan where 60 metre wells yield 7 500 to 11 000 litres/min. Alluvial fans on west side south of Stony Creek are poorly permeable and yield smaller quantities to wells.
Victor Formation	Qv	Occupies the east side valley floor area south of Oroville. Deposited by streams draining from the Sierra Nevada during the late Pleistocene. Consists of silt, sand, and buried channels of gravel. Soil development includes hardpan layers. Directly overlies the Laguna Formation. Approximately 30 metres thick.	Moderately permeable throughout and highly permeable where old stream channels are tapped. Yield of wells generally low due to the limited saturated thickness.
Pleistocene Gravels: Red Bluff Formation	Qg	Includes only the Red Bluff Formation in north valley. Poorly sorted, gravelly deposits with a red silty clay matrix. Rests on the eroded surface of the Tehama Formation but in places is gradational into the formation. Main deposits lie west of the Sacramento River where they are not over 15 metres thick. Deposits near Oroville are similar but overlie the Laguna Formation.	Unimportant as a source of ground water. Poorly permeable and generally above zone of saturation. May contain shallow, perched water.
Fanglomerate	Qfg	Exposed only in northeast valley area. Composed of volcanic detritus eroded from the Tuscan Formation and laid down as alluvial fans. Consists of layers of sand, gravel, and silt, much of which is cemented. Known to be 120 metres thick at Chico, but may be thicker to the west. Directly overlies the Tuscan Formation.	Moderately permeable and provides a source of irrigation water to many wells on the east side of the valley.
Tertiary-Quaternary Continental Deposits: Laguna Formation	TQc	Underlies the Victor and Red Bluff Formations on the east side, south of Oroville. Limited exposures not shown on Plate 2. Consists of debris derived from the erosion of the Sierra Nevada and deposited as silt, clay and sand with minor amounts of gravel. Contemporaneous with the Tehama Formation and interfingers with it beneath the center of the valley. Thickness is about 150 metres on the east side but may be much thicker beneath the valley trough.	Poorly-to-moderately permeable. Deep wells obtain moderate yields from sandy layers. High yielding wells attainable if overlying Victor Formation is also tapped.

English equivalents: 1 metre (m) = 3.28 feet (ft) . . .
1 litre per minute (l/m) = 0.264 gallons per minute (gal/min).

Table 1—Continued

DESCRIPTION OF GEOLOGIC UNITS NORTH SACRAMENTO VALLEY

Geologic Unit Plate 2	*Map Symbol*	*General Character Location and Thickness*	*Water-Bearing Properties*
Tertiary-Quaternary Continental Deposits: Tehama Formation	TQc	Largest area of exposure west of Red Bluff but formation underlies entire west side of valley beneath alluvial fans and flood basin deposits. Consists of various mixtures of clay, silt, sand and gravel derived from the Coast Ranges. Sediments are locally cemented and semi-consolidated throughout. Thickness is about 750 metres.	Sand and gravel deposits are locally absent or thin. Because of thickness and widespread distribution, this is an important source of ground water on the west side of the valley. Permeability ranges from low to moderate, but locally high. It is less permeable than overlying alluvial fan deposits of Stony Creek and Sacramento River alluvium. Deep wells obtain moderate yields. Well yields west of Red Bluff generally lower.
Pliocene Volcanic Rocks: Tuscan Formation	Pv	Mostly a consolidated tuff breccia (mud flow) in the principal area of exposure east of the valley floor in the Cascade Range foothills. From there tuff breccias grade westerly into volcanic sands, gravels, and clay. These volcanic sediments extend west of the Sacramento River where they interfinger with the Tehama Formation. Total thickness is about 450 metres east of the valley and about 300 metres beneath the valley.	Volcanic sediments are moderately to highly permeable. Tuff breccias and clay are confining beds. Deep wells in the Chico area obtain high yields from black sands. Formation is generally too deep west of Chico to be tapped except by deepest wells.
Tertiary Volcanic Rocks	Tv	Unit includes andesite and rhyolite volcanic rock forming high peaks at Sutter Buttes and basalt lava flow north of Oroville at Table Mountain and at Orland Buttes west of Orland.	Largely nonwater bearing.
Cretaceous Marine Rocks	Km	Sandstone and shale of marine origin. Forms basin boundary on the entire west side. Also exposed in small isolated areas along the entire east side.	Largely nonwater bearing or contains saline water.
Granitic and Metamorphic Rocks	gm	Fractured meta-sedimentary and metaigneous rocks and granitic rocks in the Sierra Nevada. Forms basin boundary along east side south of Oroville.	Contains fresh ground water in fractures and joints.

English equivalents: 1 metre (m) = 3.28 feet (ft).

Central Sacramento Valley with Coast Ranges in the foreground and Sierra Nevada in the distance.

TABLE 2

DESCRIPTION OF GEOLOGIC UNITS
SOUTH SACRAMENTO VALLEY

Geologic Unit Plate 2	*Map Symbol*	*General Character Location and Thickness*	*Water-Bearing Properties*
Alluvium	Qal	Consolidated sand and gravel with lesser amounts of silt and clay. Large gravelly deposits occur on streams draining the Sierra Nevada. Thickness up to 30 metres at Feather River near Marysville and 15 metres on tributaries to the Feather and Sacramento Rivers.	Highly permeable deposits on Yuba, Bear, American and Feather River. These areas provide recharge to their respective areas in the basin.
Flood Basin Deposits	Qfb	Unconsolidated beds of clay in Sutter, American, Yolo and lower Colusa Basins. Thickness up to 30 metres.	Poorly permeable deposits saturated to near the ground surface. Overlies more permeable material.
Alluvial Fan Deposits	Qaf	Heterogenous assemblage of clay, sand and gravel. Sand and gravel occur in buried channels deposited by migrating Putah and Cache Creeks. Deposits overlie Tehama Formation in thickness of up to 45 metres.	Moderately to highly permeable. Surface infiltration rates generally high in upper portion of fans. Well yields are high.
Victor Formation	Qv	Occupies the east side of the valley floor. Consists of sand, silt, and clay with a hardpan layer in the surface soil. Sand and gravel occurs in buried stream channel. Thickness approximately 30 metres.	Moderately permeable throughout and highly permeable where old stream channels are tapped. Generally yields little water except where old stream channels are present.
Pleistocene Gravels: Arroyo Seco Gravels, and South Fork gravels	Qg	Occur only in Sacramento County. Consists of well rounded pebbles and cobbles in a matrix of iron cemented sand and clay. Hardpan in surface soils.	Poorly permeable and yields only a small quantity of water to wells. Unimportant as a source of water.
Tertiary-Quaternary Continental Deposits: Laguna and Fair Oaks Formations	TQc	Principal area of surface exposure in Sacramento County and south Placer County. Laguna type sediments in north Sacramento County locally known as Fair Oaks Formation. Consists of compacted layers of silt, sand and clay with hardpan in surface soils. Overlain by Arroyo Seco gravels south of the American River. Thickness approximately 100 metres and possibly up to 300 metres along valley axis.	Sand layers yield moderate amounts of water to wells. Deep wells required for large yields. A locally important source of water for southeast Sacramento Valley.
Tertiary-Quaternary Continental Deposits: Tehama Formation	TQc	Occupies west side of valley and extends eastward beneath alluvial cover. Merges and interfingers with Laguna Formation. Sediments derived from the Coast Range are predominantly fine-grained. Thickness may be greater than 750 metres.	Principal water-bearing formation on the west side of the valley due to widespread distribution and thickness. Less permeable than overlying alluvium. Deep wells obtain moderate yields.
Pliocene Volcanic Rocks: Mehrten Formation	Pv	Similar to Tuscan Formation. Includes beds of black sand, brown clay and brown sand with layers of volcanic tuff breccia (mudflow deposits). Principal area of occurrence in eastern Sacramento and Placer Counties. Formation is largely overlain by younger sediments and only eastern edge is exposed. Thickness varies from 60 to 360 metres.	Volcanic sands yield large quantities of water to wells. Brown sands yield lesser amounts while clays and tuff breccias yield little water. An important source of water in southeast valley it provides large quantities of water to wells. Generally too deep in middle of valley to be tapped by most wells.
Miocene Volcanic Rocks: Valley Springs Formation	Mv	Occurs only in southeast valley. Consists of beds of volcanic sand and ash with little gravel. Thickness varies from 25 to 40 metres. Immediately underlies the Mehrten Formation.	Deposits are of low permeability and yield only small quantities of water to wells.

English equivalents: 1 metre (m) = 3.28 feet (ft).

TABLE 2—Continued

DESCRIPTION OF GEOLOGIC UNITS SOUTH SACRAMENTO VALLEY

Geologic Unit Plate 2	*Map Symbol*	*General Character Location and Thickness*	*Water-Bearing Properties*
Eocene Continental Deposits: Ione Formation	Ec	Occurs beneath the east side of the valley south of Marysville, generally at considerable depth. Exposed only along east margin of the basin in Placer and Sacramento Counties. Consists of quartz sandstone and clay beds. Thickness varies from 30 to 120 metres.	Deposits are of low permeability and yield only small quantities of water to domestic wells. May contain brackish water.
Eocene Marine Rocks	Em	Sandstone and shale beds exposed on west side near Vacaville and Capay Valley.	Largely nonwater-bearing.
Cretaceous Marine Rocks	Km	Sandstone and shale of marine origin. Forms basin boundary on west side. Extends to great depth beneath valley.	Largely nonwater bearing or contains saline water.
Granitic and Metamorphic Rocks	gm	Fractured meta-sedimentary, meta-igneous rocks, and granitic rocks in Sierra Nevada. Forms basin boundary on east side.	Contains fresh ground water in fractures and joints.

Freshwater–Bearing Formations

Formations comprising the freshwater–bearing sequence range in composition from semiconsolidated sands, gravels, and clay to completely unconsolidated equivalents and mixtures of these detrital materials. Materials of volcanic origin, such as mudflows and volcanic ash deposits, are present in the older formations. Although all these formations contain fresh water in highly variable amounts, the lower portions may contain brackish to saline water. The base of fresh water generally lies above the base of the post–Eocene deposits except in places along the margins of the valley where fresh water lies below the base of these deposits. Saline water has apparently been flushed from the marine sediments toward the valley trough and into the continental deposits, which at one time contained only fresh water.

Those water–bearing sediments that constitute the principal ground water reservoir are included in the post–Eocene age group. The thickness of this sequence is shown in Figure 2A, Appendix A. The greatest thickness of all the post–Eocene continental deposits, about 975 metres, is in the southwestern portion of the Sacramento Valley. There the sequence thins rapidly to the west and gradually to the east. At the north end of the valley its maximum thickness is slightly over 600 metres (Page, 1974).

The freshwater–bearing formation in the valley comprises a group of sedimentary and volcanic rocks that have the ability to absorb, transmit, and yield significant quantities of fresh water to wells. In its publication on base of fresh water (Berkstresser, 1973), the USGS defines fresh water as that which has a specific conductance of less than 3 000 micromhos per centimetre at 25°C. This is about 2 000 mg/l dissolved solids.

A knowledge of the physical and water–bearing properties of the principal geologic formations is necessary to an understanding of how ground water occurs and moves and to what extent it is available in the basin. Brief descriptions of the formations are presented in Tables 1 and 2. Plate 2 shows surface distribution of these formations. In some cases, two or more geologic formations are grouped together because it is not possible on a small–scale map to show each. Following are brief descriptions of the principal freshwater–bearing formations found in the Sacramento Valley.

Eocene Continental Deposits: Ione Formation

The Ione Formation, of middle Eocene age, is exposed in eastern Sacramento and Placer Counties along the edge of the basin as shown in Plate 2. (Infrequent exposures, as far north as Oroville, are not shown.) In this area the formation is present as low rounded hills, presenting a subdued topography. It overlies the older metamorphic and marine sedimentary rocks to the east. To the west it is overlain by younger sediments.

In Sacramento and Placer Counties, the Ione Formation is divisible into three distinct members, only the upper two of which are exposed. The uppermost member of the formation is composed principally of a uniformly graded, medium–to–coarse–grained quartz sandstone. The second member, below the sandstone, is a thick bed of white clay of ceramic quality, which in some areas has been stained red or yellow. The lower member is a blue–to–gray clay with occasional seams of brown coal and lignite. The base of the formation is frequently a zone of gravel composed of quartz and metamorphic fragments.

In outcrop, the Ione Formation appears to have a stratigraphic thickness of about 120 metres. As the

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English equivalents: 1 metre (m) = 3.28 feet (ft).

exposed surface is eroded, it can be assumed that the original thickness of the formation was much greater. The Ione has a dip of about 5 degrees to the west. In the subsurface it persists at least as far as the Sacramento River, where it apparently merges with contemporaneous marine sediments.

In most area of the valley, the Ione Formation is considered to be nonwater–bearing because much of the formation was deposited in a marine environment. Deep wells entering the marine portions of this formation yield water with high chloride concentrations.

In the eastern part of the valley in Sacramento and Placer Counties, where the Ione was deposited under near–shore or on–shore conditions such as in a delta environment, the formation yields fresh–to–brackish water to wells. In these areas yields are low because of the low permeability of the Ione sediments. In some areas north of Sacramento County, wells drawing entirely from the Ione yield only 180 litres per minute (l/m) and have specific capacities of less than 0.6 litre per minute per metre of drawdown (l/min/m).

Miocene Volcanic Rocks: Valley Springs Formation

This formation is exposed mainly along the eastern side of Sacramento County from the southeastern corner of the study area northward to the Cosumnes River. It is generally exposed over an area 1.5 to 6 kilometres wide (Plate 2) and consists largely of white, stream–laid rhyolite tuff, quartz sand, and beds of ashy clay. The tuff was probably deposited as volcanic ejecta in the Sierran foothills and carried to its present location by streams choked with volcanic debris.

The Valley Springs Formation lies unconformably over the older Ione Formation and metamorphic rocks. It dips west at a generally uniform slope of 1.5 to 2 degrees. In the area of outcrop it has a stratigraphic thickness of at least 20 metres and in other areas it attains a thickness of about 40 metres. However, some well data have indicated a total thickness of about 60 metres, largely of greenish gray, sandy clay.

In and near its areas of outcrop, the Valley Springs Formation is considered to be a producer of good–quality ground water. Yields are generally low due to the presence of clay and volcanic ash which tend to lower the overall permeability. Much of the formation lies below the present depth of water wells and little is known about its lower portion. The formation is unimportant as a source of ground water except for local domestic use.

Pliocene Volcanic Rocks

This unit includes the Mehrten Formation in the southeastern Sacramento Valley and the Tuscan Formation in the northeastern Sacramento Valley, both important ground water sources. Similar volcanic deposits also surround Sutter Buttes and are locally important sources of water in the areas from Pennington south to the town of Sutter. The water–bearing characteristics of these volcanic deposits are similar to the Mehrten and Tuscan and are not discussed further here.

Mehrten Formation. The Mehrten Formation is exposed discontinuously along a broad belt from the southeast portion of the study area, where it is over 6 kilometres wide, to the town of Lincoln in Placer County (Plate 2). In the subsurface, the Mehrten Formation extends westward from the area of outcrop at least as far as the Sacramento River.

The Mehrten is divisible into two strikingly different units. One is sedimentary, composed of gray–to–black andesitic sands reported by well drillers as "black sand", and interbedded blue to brown clay. The other is a hard, gray tuff–breccia reported by well drillers as "lava".

The black sands generally are fairly soft and well sorted. They were formed as fluvial deposits, having been derived from andestic ditritus washed down the slopes of the Sierra Nevada. Beds of black sand are commonly about 2 metres thick, although beds up to 6 metres or more have been reported. Where exposed in road cuts, these beds exhibit crossbedding, indicating a stream–laid mode of origin. Associated with the black sands are lenticular beds of stream gravel containing andesitic cobbles and boulders up to a metre or more in diameter. Also associated with the sands are beds of brown to blue clay and silt.

The second major unit of the Mehrten Formation is the tuff–breccia. This rock is very dense and hard. It is composed of angular pieces and blocks of black to gray andesite which range from less than 2 centimetres to nearly one metre in diameter. The fragments are contained in a highly cemented ground mass of andesite lapilli and tan to gray ash. The tuff–breccia was derived from andesitic eruptions to the east in the Sierra Nevada.In the area of outcrop, the Mehrten Formation is about 60 metres thick. It dips westward on a slope of 1 to 2 degrees. It also thickens to the west so that along the axis of the valley, where it is essentially horizontal, it is from 120 to 150 metres thick.

This formation provides copious quantities of ground water to many wells in Sacramento County. Water yielded is generally of good–to–excellent quality. It has been found that many wells derive their supply from the "black sands" as reported on the drillers' logs. The underlying tuff–breccias yield little

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English equivalents: 1 metre (m) = 3.28 feet (ft); litres per minute (l/m) = 0.264 gallons per minute (gal/min); litres per minute per metre (l/m/m) = 0.08 gallons per minute per foot (gal/min/ft).

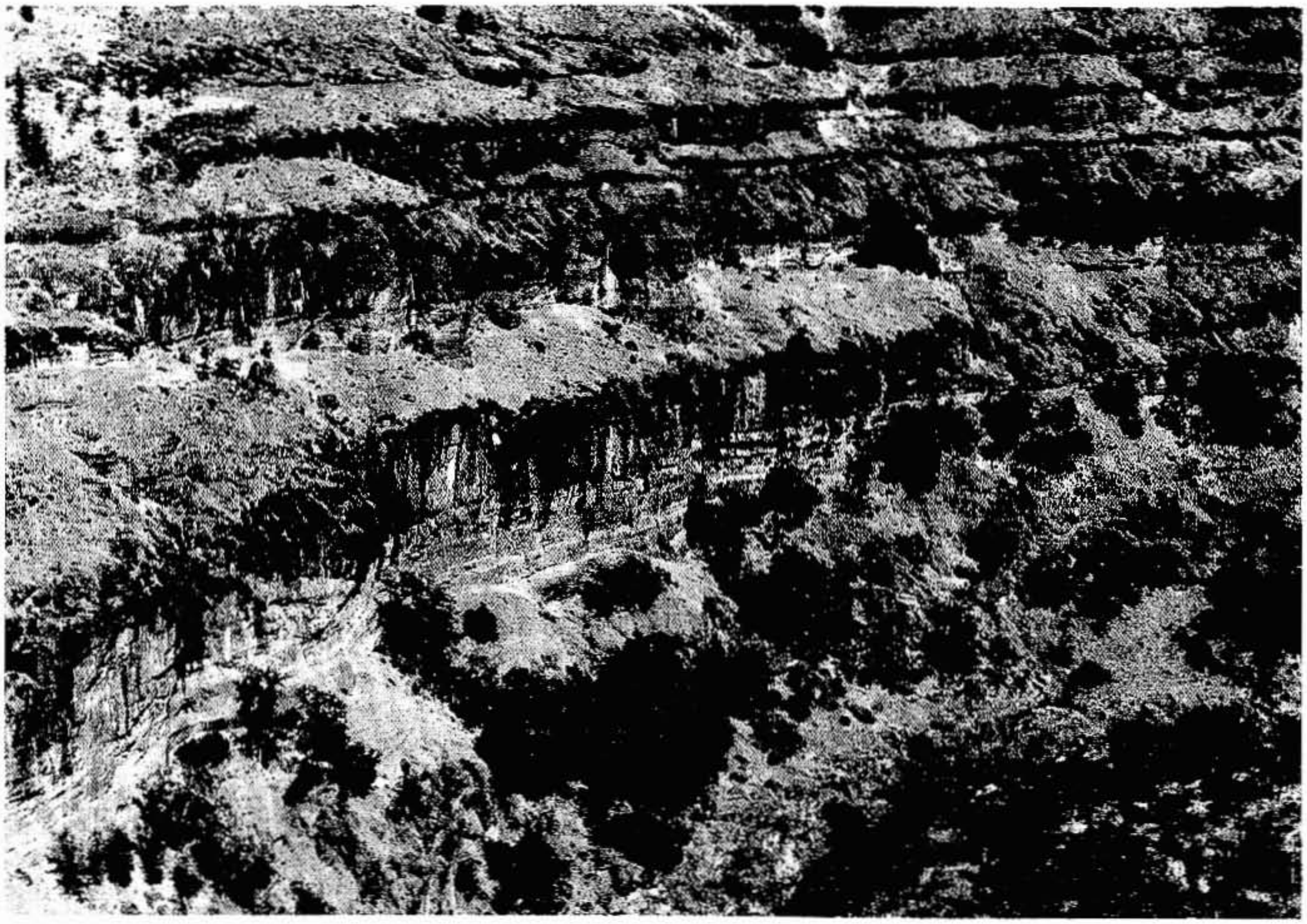
water, but wells that are drilled through them reportedly have entered highly permeable volcanic materials and some obtained large yields. Because of the impermeable nature of the tuff–breccia, much of the water in the underlying volcanic sands is in a state of partial confinement.

Tuscan Formation. This formation is an important water–bearing unit in the northeast portion of the study area. Its major surface exposure lies outside the basin boundary in the Cascade Range as shown on Plate 2. From the northeast margin of the basin, it extends westward beneath the valley floor into Glenn County past the Sacramento River. In this valley floor area it underlies approximately 2 300 square kilometres of land as shown on Figure 4. Along the east margin of the valley north of Oroville, it is the principal water–producing formation.

In the northern portion of the outcrop area (Figure 4), the formation consists chiefly of layers of tuff–breccia, volcanic conglomerate, and lesser amounts of sandstone and siltstone (Anderson, 1933). Toward the south in the area east of Chico, the exposed Tuscan is predominantly volcanic sediment with few tuff–breccia beds. Some of the tuff–breccia beds extend from their outcrop areas westward for a distance of 8 to 16 kilometres as shown on Figure 4, but for the most part the formation beneath the valley floor consists of black volcanic sands and tuffaceous clays. These volcanic sediments represent a reworking of the tuff–breccias by streams during periods of nondeposition. The sands and gravels were carried only a short distance from their source, whereas the finer–grained materials, such as clay and silt, were deposited further west toward the valley trough.

The Tuscan Formation forms a wedge–shaped mass with a southwesterly tilt. From a maximum thickness of 500 metres in the Cascade Range (Lyndon, 1969), it thins southwesterly to approximately a hundred metres, where it interfingers with the Tehama Formation beneath the valley. The largest structural feature is the Chico monocline along the edge of the valley as shown in Figure 4.

Fresh ground water can be found in the Tuscan sands to depths of 450 metres along the east side of the Sacramento Valley. The formation acts as a conduit for ground water movement into the valley



Tuscan Formation sedimentary rocks in Butte Creek Canyon east of Chico. These rocks extend westward beneath the Sacramento Valley

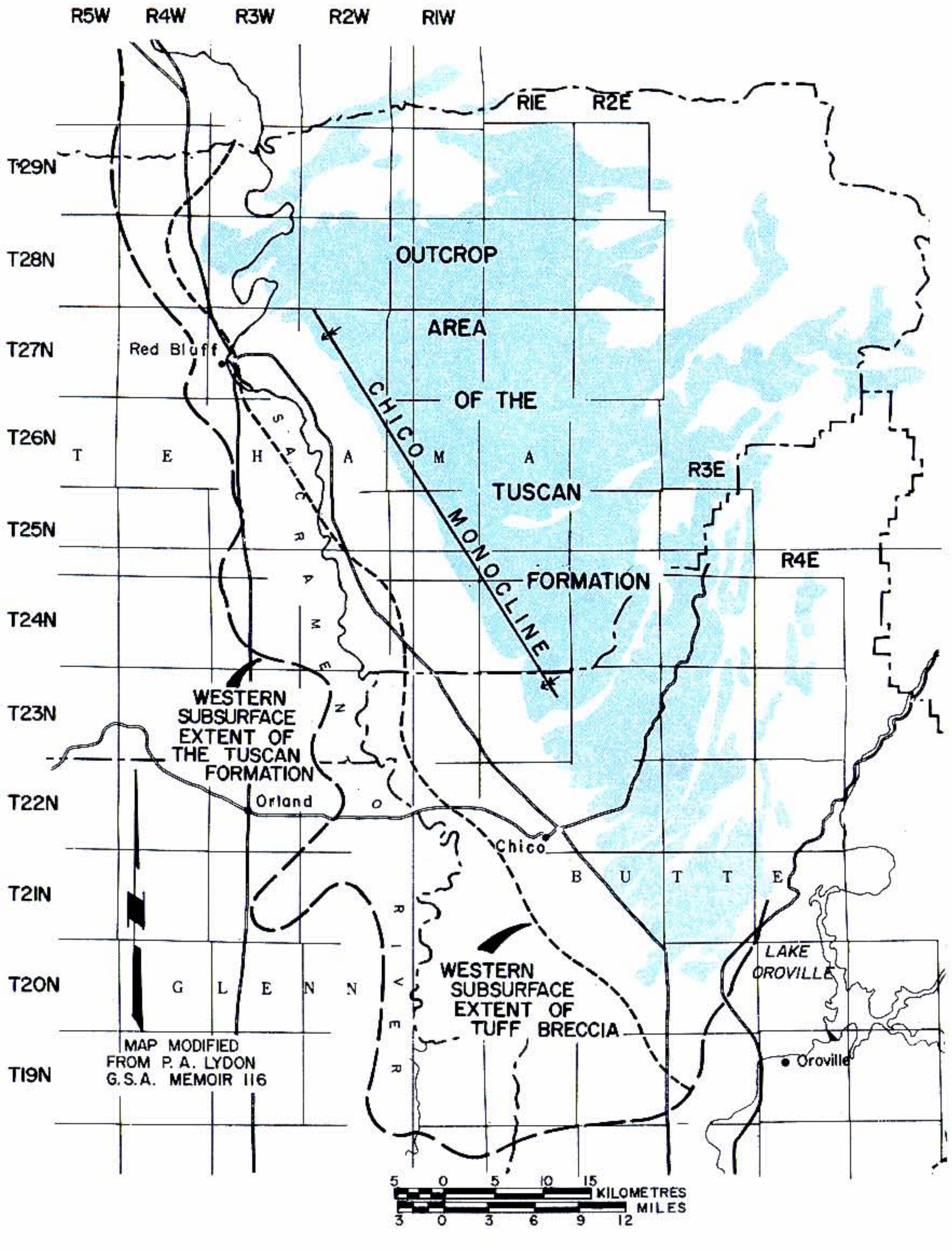
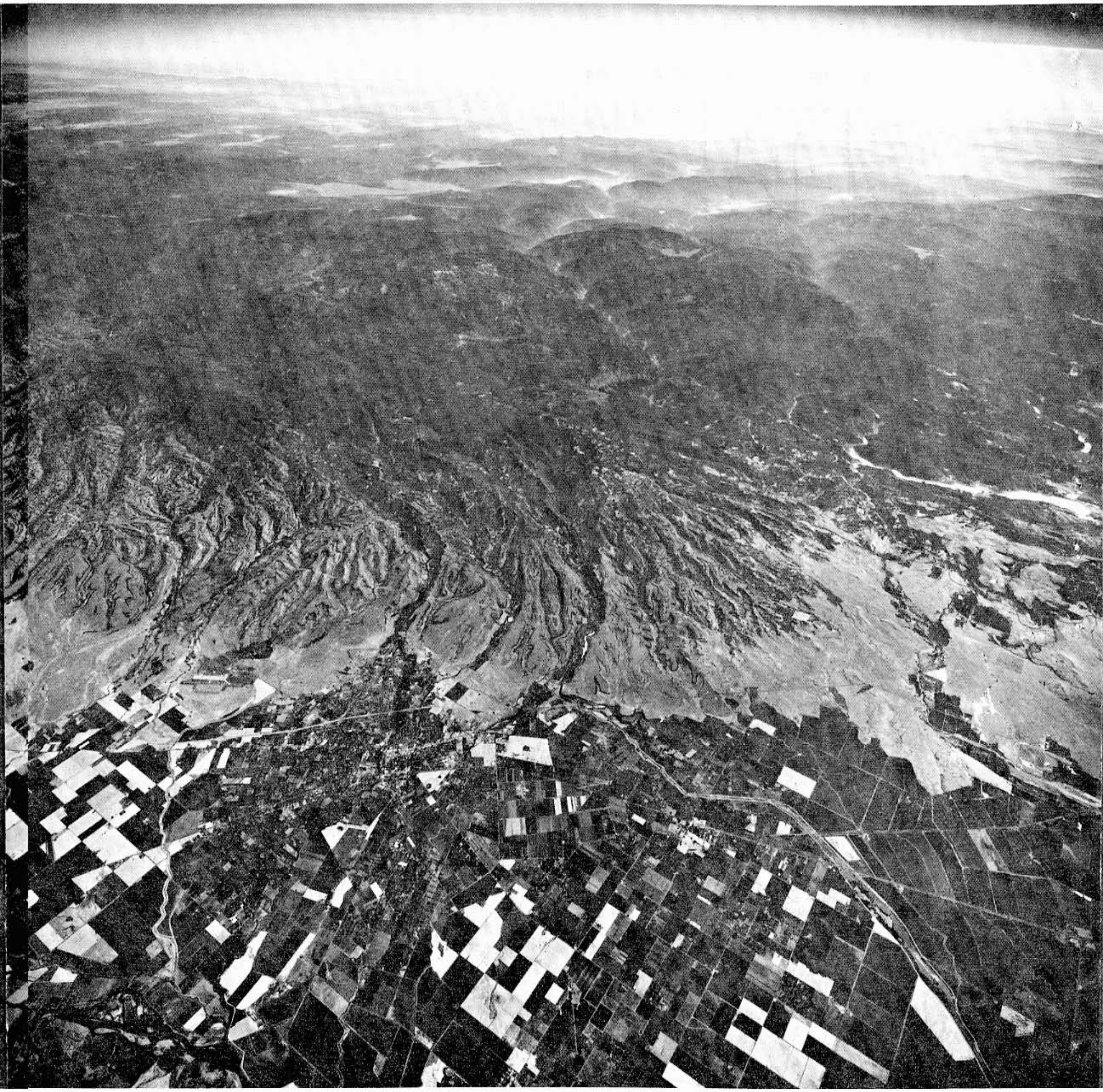


Figure 4. Surface and Subsurface Distribution of the Tuscan Formation



East side of Sacramento Valley at Chico. Tuscan Formation sedimentary rocks visible in foothills and Lake Almanor in the distance.

from the recharge areas in the Cascade Range foothills to the east.

Except for wells along the very edge of the valley near the monocline, drilling must be deep to tap this ground water source. At Chico, the depth to its upper surface is about 140 metres, becoming shallower to the east and deeper to the west. Southeast of Red Bluff, near Los Molinos, depth to its upper surface is slightly over 120 metres. Wells deep enough to tap this formation obtain water from black sands in amounts up to 11 500 l/min. Specific capacities for wells that tap only the Tuscan Formation sands average 600 litres per minute per metre of drawdown (l/min/m). Most wells on the east side obtain water from both the Tuscan sands and the old alluvium overlying it; therefore, data specific to the water-bearing character of the Tuscan Formation are limited. Most ground water in the formation is confined under pressure by layers of impermeable clay and tuff–breccia.

Tertiary–Quaternary Continental Deposits

This unit includes a description of two contemporaneous formations, the Tehama and the Laguna Formations.

Tehama Formation. The Tehama Formation is well exposed in a large area in the northwest portion of the basin in Tehama and northern Glenn Counties (Plate 2). Between the community of Willows and Highway 20 it is discontinuously exposed in small areas adjacent to the Coast Range. Most of the formation here is covered by gentle–sloping alluvial fans. It is also extensively exposed in the Rumsey–Dunnigan Hills between Highway 20 and Cache Creek. South of Cache Creek to Vacaville, it is exposed in the English Hills.

The Tehama extends easterly from the west margin of the basin toward the trough of the valley, where it interfingers with the Tuscan Formation in the north valley and the Laguna Formation in the south. Except in the areas of exposure, it is overlain by the Red Bluff Formation, alluvial fans, and stream and floodplain deposits. North to south it occupies the entire west half of the basin either at or beneath the surface. Its maximum thickness is 760 to 900 metres, but over most of the west side it averages about 600 metres. Based on fossil evidence, it ranges in age from upper Pliocene to middle Pleistocene. It is, in part, equivalent in age to the Tuscan and Laguna Formations, which occur in the northeast and southeast portions of the basin, respectively.

In areas where the formation is exposed, it consists of poorly sorted sediments comprising thick–bedded, sandy silt and clay. Gravel and sand deposits are usually thin and discontinuous. Mineral composition of the sediments indicates that they were derived by erosion of the Coast Ranges and Klamath Mountains to the west and northwest. They were deposited under floodplain conditions on the west side of a broad valley of low relief (Russell, 1931).

Proportions of coarse material vary considerably. In places on the west side, very little gravel is present, resulting in low–yielding wells. In other places, such as near El Camino in Tehama County, there are highly productive gravel beds 15 metres thick. Possibly these coarser layers were deposited by the ancestral Sacramento River rather than by streams draining from the west.

The Tehama is the principal water–bearing formation in the valley. Generally, wells drilled to a depth of 45 to 60 metres through the overlying alluvial material will penetrate it. On the extreme west side, wells less than 15 metres deep may penetrate. Well yields reflect the highly variable proportions of gravel in the formation. There are few areas along the west side of the basin where wells extract water solely from the Tehama Formation. In the valley floor along the west side they are drilled through the overlying alluvium and Red Bluff Formation, and well logs do not clearly distinguish the overlying materials from those of the Tehama Formation.

The following are examples of the Tehama Formation's water–bearing characteristics along the west side:

In the western upland area, west of Red Bluff and Corning, wells to depths of 150 metres yield 1 800 to 3 600 l/min., while wells near the west basin boundary have maximum yields of 1 800 l/min. Some specific capacities of most wells are generally less than 420 l/min/m.

Davis and Olmsted (1961) report that 20 wells in the El Camino Irrigation District in south Tehama County, which range in depth from 80 to 300 metres, discharge 2 000 to 8 400 l/min. Specific capacities for the same wells range from 420 to 2 000 l/min/m.

In the area west of Artois, numerous deep irrigation wells extract water solely from the Tehama Formation. Wells in this area, to 180 metres in depth, range in yield from 3 600 to 7 200 l/min.

Many irrigation wells near Arbuckle have been drilled to depths greater than 300 metres and yield 7 200 to 15 000 l/min. These wells penetrate many thick beds of yellow clay and thin gravel layers. Shallower materials are probably alluvial fan materials rather than parts of the Tehama Formation. The deeper materials are undoubtedly Tehama.

Dunnigan Hills represent an anticline in the Tehama Formation, but the formation here appears to lack coarse material. Kirk Byron (1923) reports that a 220–metre well drilled in 1912 failed to encounter large amounts of gravel.

Laguna Formation. The Laguna Formation is well exposed in the southeastern part of Sacramento County, where it comprises much of the low, rolling

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English equivalents: 1 metre (m) = 3.28 feet (ft); 1 litre per minute (l/m) = 0.264 gallons per minute (gal/min); 1 litre per minute per metre = 0.08 gallons per minute per foot (gal/min/ft).

foothills. Its outcrop area extends northward from Dry Creek to its northernmost exposure near Highway 50 (Plate 2). The Laguna has not been identified as such north of the American River, but beds equivalent to the upper portion of the Laguna extend from the American River to south Placer County, and other equivalent materials previously mapped as "old alluvium" extend north along the edge of the valley to Yuba County. The Laguna or its companion formations probably extend north as far as Gridley, but are largely concealed by the Victor Formation. It is similar in age, at least in part, to the Tehama Formation on the west side of the valley.

The Laguna Formation (and its companions) was deposited as a westward–thickening wedge by streams draining the Sierra Nevada. It rests conformably over the older Mehrten Formation and underlies the Victor Formation. In its area of outcrop, it is estimated to be not more than 60 metres thick. It dips westward toward the valley trough at an average gradient of about 17 metres per kilometre, a slope of slightly less than 1 degree. In the subsurface, the Laguna thickens to not more than 120 metres. It apparently interfingers with the Tehama Formation near the axis of the valley.

The Laguna is strikingly different from the underlying Mehrten Formation. Where the Mehrten Formation is andesitic in character and generally dark–colored, the Laguna is nonvolcanic and generally tan to brown. Mineralogy of its particles is decidedly granitic. Flakes of mica are locally abundant and serve as a distinguishing characteristic of much of the formation. The gravels are mostly from granitic and metamorphic rocks; little or no volcanic material is present.

The formation is composed of a heterogeneous assemblage of beds of silt, clay, and sand with lenticles of gravel deposited on westward–sloping floodplains by meandering, sluggish streams. Some of the sands are clean and well sorted while some of the gravels are extremely silty and poorly sorted. Sediments of the Laguna are variable; for example, in one area the formation consists of compact silt, clay with lenses of poorly sorted gravel, sand, and silt, and in others it contains sand with only a few interbeds of clay and silt.

Where fine–grained, the Laguna Formation will yield only moderate quantities of water to wells. In areas where soft, well–sorted granitic sand predominate, yields will be high. Olmsted and Davis (1961) reported the yield of a well in south Sacramento County, 140 metres deep, as 6 600 l/min with a drawdown of 11 metres. The well produced almost entirely from the Laguna and had a specific capacity of 600 l/min/m.

Fanglomerate

An unnamed geologic formation underlies the margin of the valley north from Chico to the northeast corner (Plate 2). This unit is composed of alluvial fans that have merged to form a continuous plain of sands, gravels, silts, and clays. Much of the material has been cemented to form sandstone and conglomerate and is thus called fanglomerate. The ground surface is generally very gravelly and unsuitable for agriculture and, except north of Chico and east of Red Bluff, very few wells have been drilled for irrigation.

The fanglomerate directly overlies the Tuscan Formation, from which its sediments have been derived. It was deposited subsequent to or concurrently with uplift of the Tuscan Formation in the Cascade Range foothills and formation of the Chico Monocline. No fossils have been discovered, but its relationship to adjacent geologic units of known age suggests that it is of Pleistocene age.

These old alluvial fan deposits consist of firmly cemented sand and gravel with considerable amounts of clay. Exposed sections stand in nearly vertical banks, generally along stream courses. The exposures are scarcely distinguishable from the volcanic sediments in the Tuscan except that they are more cemented. The fanglomerate unit underlies younger alluvium in the Chico alluvial fan at a depth of about 15 metres and extends to a depth of nearly 140 metres, where it is in contact with the Tuscan Formation. A core hole drilled at Chico by the U. S. Bureau of Reclamation showed that the formation is composed of 12 percent clay and clayey silt, 26 percent cemented silty sand, 31 percent sandy silt, 22 percent cemented gravel and 9 percent uncemented sand, gravel or gravelly sand.

Exposed stratified layers of the fanglomerate are nearly horizontal or have low dips to the west. In cross–section, the entire unit is wedge–shaped, thickening to the west where it probably interfingers with alluvial sediments deposited by the ancestral Sacramento River. The underlying Tuscan Formation may have been folded into a broad syncline with an axis approximately parallel to Highway 99 and to the Chico monocline. To what extent the fanglomerate has been affected is unknown, but it appears that most of the sediments have been deposited since the major folding took place.

Most deep wells for which production data are available derive water from underlying Tuscan sediments and permeable units in the fanglomerate. Pump tests of large capacity wells believed to obtain all their water from the fanglomerate indicate low to moderate yields. Overall, the formation is not highly permeable, and with poorly permeable surface soils it is not readily recharged. It is possible that most of the permeable material lies adjacent to the Chico monocline along the edge of the valley and that re-

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charge takes place there by subsurface inflow from the east.

Pleistocene Gravels

Gravel deposits are scattered along the east and west sides of the valley in the low hills and dissected uplands. They are usually found capping the hills and ridges ranging in thickness from a few metres to 15 metres. They are commonly cemented or contain cemented layers and hardpan in their surface soils. The gravels are all of similar age, probably middle to late Pleistocene and related to glaciation in the Sierra Nevada and Coast Ranges. At one time the deposits were much more extensive, covering most of the valley floor as it existed in Pleistocene time. Included in this unit are the Red Bluff Formation, Arroyo Seco Gravels, and South Fork Gravels.

The Red Bluff Formation occurs in the northern portion of the valley, where it overlies the Tehama Formation. Its largest area is in the vicinity of Red Bluff, where it attains an exposed thickness of about 15 metres. The formation also occurs west of the Feather River near Oroville, where it reportedly attains a thickness of 40 metres. It consists largely of gravels with minor amounts of interbedded sands. Gravels are of small cobble and pebble size in a reddish silty to sandy matrix. The upper surface usually consists of a hardpan soil. In the Red Bluff area, rock fragments are metamorphic and igneous types, indicating that the sediments were transported from the North Coast Ranges and Klamath Mountains. Apparently the formation was deposited during a period when glaciers were active in these mountain areas. Streams draining glacial areas were heavily choked with coarse debris and suspended fine–grained material. The suspended particles, clay and silt, filled the voids after deposition of the gravel, so that most of the Red Bluff gravels are not very permeable.

The Arroyo Seco gravels occur as a thin veneer, capping hills in the east–central part of Sacramento County and overlying sediments of the Laguna Formation. At a few locations, sediments of the Mehrten, Valley Springs, and Ione Formations can be seen to underlie the Arroyo Seco gravels. These gravels are composed of discontinuous beds and lentils of stream–laid detritus, deposited by rivers and streams of great load–carrying competence that drained the Sierra Nevada. The Arroyo Seco is easily distinguished from the underlying materials by both the coarseness of the particles and the red color of the iron oxide cement. It is characterized by well–rounded pebbles and cobbles of dark–colored metamorphic rocks and weathered Mehrten andesite.

A discontinuous belt of partially cemented channel gravels extends southwesterly from Mormon Island Dam at Folsom Reservoir to near Elk Grove in Sacramento County. Referred to here as the South Fork Gravels, these occur as a sinuous deposit about 1.5 kilometres in width. They are composed of rounded pebbles and cobbles in a medium–to–coarse–grained granitic sand matrix. Surface soils on this unit are mostly in the Corning series, which is identified by a dark reddish–brown color and absence of a hardpan layer. Some sandy micaceous clays are present as a binder to the larger fragments.

Pleistocene Gravels generally rest in a horizontal position on the erosion surface of the underlying formations. In most areas the deposits are not deformed by folding and faulting, but Davis and Olmsted (1961) report that the Red Bluff Formation is gently folded in the Rumsey–Dunnigan Hills and in the Corning anticline in Tehama County.

These gravels are relatively unimportant as sources of ground water. Since they usually occupy elevated areas, such as ridges and terraces, they are above zones of saturation. In areas where they are within saturation zones, they are expected to yield little water to wells because of their low permeability. From Red Bluff to Orland, the Red Bluff Formation may contain perched water tables, which can supply small quantities of water to shallow wells. In the Oroville area the formation is tapped by shallow wells, but yields are low and undependable. Hardpan soils, which are commonly present in all the Pleistocene gravels, have low infiltration rates and therefore restrict the recharge of ground water.

Victor Formation

The Victor Formation underlies a broad, slightly dissected alluvial plain in the east–central portion of the valley from Dry Creek in southern Sacramento County north to Gridley in Butte County. The term "Victor plain", used for a similar part of the Mokelumne area (Piper, 1939), is also used here. The plain is about 16 kilometres wide from west to east and attains a maximum width at Marysville. To the east the Victor Formation laps onto older materials composed of the Laguna Formation and the Arroyo Seco gravels. To the west it is overlain by younger alluvial materials laid down by the Sacramento River.

The Victor was deposited on a plain of aggradation, now partly dissected. Streams flowing across have cut deep trenches in which floodplains and stream channel sediments of Holocene age have been deposited. Age of the Victor Formation ranges from middle to late Pleistocene as determined by fossil evidence.

The formation is composed of a heterogeneous assemblage of fluvial deposits laid down by constantly shifting streams that drained the Sierra Nevada in Pleistocene time. These streams left sand and gravel in channel–like structures that grade laterally and vertically into silt and clay in a manner that provides little correlation of materials from well to well. This

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English equivalents: 1 kilometre (km) = 0.62 mile (mi).
1 metre (m) = 3.28 feet (ft).

Eastern Sacramento Valley south of Sutter Buttes. Feather River and Sutter Bypass in center, Sacramento River in foreground.

Southeastern Sacramento Valley and City of Sacramento. American and Feather Rivers are in foreground.

is characteristic of floodplain or low–sloping alluvial fan deposits. Well log data indicate a decrease in grain size toward the west, as would be expected with an eastern source, although some gravel channels apparently reach the center of the valley. Olmsted and Davis (1961) report that to a depth of 15 metres, the proportion of sand and gravel decreases markedly from 80 to 90 percent in the eastern portion of the formation to less than 10 in the western portion near the valley's center. Also, the percentage of blue clay increases to the west, suggesting a lacustrine or flood–basin type of depositional environment.

Soils developed on the surface of the Victor Formation contain a hardpan layer, and some well logs indicate buried hardpan in old soil horizons. Extensive hardpan development throughout the surface of the Victor Formation indicates a degree of maturity consistent with its Pleistocene age and an absence of recent sedimentation. This is in contrast to the west side of the valley, where alluvial fans have been forming in recent times.

The Victor Formation has a gentle homoclinal dip toward the west along its uppermost surface. This is assumed to represent the top of the formation. In Sacramento County the top of the formation slopes about 1 metre per kilometre (m/km) and the base dips westward at about 2 m/km, indicating a gradual thickening to the west. Throughout most of the east side area, the Victor Formation is as much as 30 metres thick and to the west, where it dips beneath a cover of younger materials, it probably attains a thickness of about 45 metres.

The Victor Formation is the most important water–bearing formation for domestic and shallow irrigation wells on the southeast side of the basin. It has moderate permeability throughout most of its area of occurrence. It is considerably more permeable than the underlying Laguna Formation, but because of its limited saturated thickness, high–capacity irrigation wells must be deep enough to tap aquifers in the Laguna Formation also.

There are insufficient data on wells drilled solely in the Victor Formation to evaluate its water–producing potential. Yields are not generally expected to exceed 3 600 l/min, but some wells located in more permeable portions where sand and gravel channels are present may have yields of up to 7 200 l/min. Davis and Olmstead (1961) refer to a 31–metre well near Sacramento, completed only in a Victor aquifer, as having a yield of 6 000 l/min and a specific capacity of 420 l/min/m.

Alluvial Fan Deposits

Alluvial fan deposits are distributed largely along the west side of the valley from Stony Creek south to the Montezuma Hills. On the east side of the valley alluvial fan deposits occur only in the Chico area between Pine and Butte Creeks. Alluvial fans also surround the Sutter Buttes. Age of all alluvial fan deposits range from Late Pleistocene through Holocene to the present. Except where flood–flows are controlled by dams, the alluvial fans on the west side are continuing to build.

On the west side of the valley is a continuous apron of coalesced fans from Putah Creek to Stony Creek. The deposits at Stony Creek form the most typical alluvial fan. South of Stony Creek, deposits left by streams draining the Coast Ranges have not formed the characteristic fan shape nor do they contain the characteristic coarse–grained material as along Stony Creek. This apron becomes 32 kilometres wide along Putah Creek and 24 kilometres wide at Stony Creek. At its narrowest, west of the Colusa flood basin, it is a few kilometres wide.

The Stony Creek fan is the most complex and contains more coarse–grained material than any other in the basin. Distinct abandoned channels south of the present channel are apparent at the surface, and several other buried channels are probably present. Although isolated fine–grained materials occur at the surface, some gravel deposits extend to depths of 60 metres in immediately adjacent areas. Wells in the Stony Creek fan average 75 to 90 metres in depth and may yield 11 000 to 15 000 l/min, although the average of many wells is 7 500 l/min. Specific capacities may exceed 1 250 l/min/m for wells drilled on the gravel channels, and the average for all wells is about 900 l/min/m. Olmsted and Davis (1961) report that to a depth of 60 metres, half the material in the fan is sand and gravel.

The deposits of Stony Creek fan directly overlie the Tehama Formation, but the buried surface of the formation is not easily distinguished in well logs. It appears that it is not uniform but was deeply dissected by erosion in Pleistocene time, and the channels were back–filled with both coarse and fine–grained alluvium. At the surface the fan merges southward with fine–grained Colusa flood basin deposits. Some coarse–grained channel gravels probably extend further south beneath the flood basin.

From Williams to Willows the fan deposits occupy a narrow zone adjacent to the Coast Ranges. No large streams occur in this reach, so fans are small and made up of fine–grained deposits. For wells to obtain significant yields, they must be drilled through the alluvial fan and tap the underlying Tehama Formation.

Fans in the Arbuckle area were constructed by deposition from several small intermittent streams draining from the Rumsey Hills and carrying considerable amounts of highly pervious sands and some sandy gravels. Overall composition appears to be much more fine–grained than the Stony Creek fan.

English equivalents: 1 metre (m) = 3.28 feet (ft); 1 metre per kilometre (m/km) = 5.28 feet per mile (ft/mi); 1 litre per minute (l/m) = 0.264 gallons per minute (gal/min); 1 litre per minute per metre (l/min/m) = 0.08 gallons per minute per foot (gal/min/ft).

Western Sacramento Valley between Orland and Williams. Willows is in the center of the photo with Coastal Ranges in the distance.

In the Putah Plain area, materials deposited by Cache and Putah Creeks have been divided into younger and older alluvium. Younger alluvium covers all of the Putah Plain except near the Coast Ranges where older alluvium is exposed along with the Tehama Formation. (Plate 2 in this report does not differentiate alluvial fan materials in Putah Plain.) The younger alluvium, about 10 metres thick, and the older alluvium, up to 45 metres thick, comprise the total thickness of 55 metres. The younger alluvium consists mostly of silt and fine sand, but includes some coarse sand and gravel. The older alluvium is more heterogenous. More clay deposits are present but so are more channelized deposits of gravel.

Fan deposits of the Putah Plain are moderately permeable overall. Cache Creek has deposited large amounts of gravel between Dunnigan Hills and Woodland. Large gravel deposits also occur south of Woodland near Putah Creek. Olmsted and Davis (1961) report that 25 to 30 percent of the depth interval from 6 to 60 metres is sand and gravel for both the Putah and Cache Creek areas. This depth interval approximates the thickness of the fan materials.

In the Chico area, deposition from Pine, Big Chico, Little Chico, and Butte Creeks have built up coalescing fans which attain a thickness of about 15 metres. There, underlying cemented alluvial materials are part of the fanglomerate unit.

Alluvial fans surrounding Sutter Buttes range up to 3 kilometres wide and up to 30 metres thick. In this area they directly overlie the tuff-breccia rocks which also surround the Buttes.

The most common characteristic of all the deposits is the great variability of materials. Alluvial fans are constructed by deposition of sediments from constantly shifting and meandering streams. As new channels form and old ones are abandoned, a complex system of buried channels is created. Common to alluvial fan deposits are young surface soils where deposition is continuing or mature soils with development of clay in subsoil layers. None of the soils contain hardpan.

Flood Basin Deposits

Along the Sacramento River there are five distinct flood basins where fine-grained sediments have been laid down by floodwaters. Prior to the construction of artificial levees, floodwaters frequently overtopped the natural levees and carried suspended silt and clay into the low-lying land on either side of the river. Over periods of thousands of years this sediment slowly accumulated in the lowlands. Figure 2 shows the locations of these basins, which correspond to the Holocene-age flood basin deposits shown on Plate 2.

The flood basins are broad, shallow troughs lying between the natural levees of the river and the low alluvial plains on both sides of the valley. They have probably existed throughout Holocene time, approximately 10,000 years. With frequent flooding, their fine-grained sediments have accumulated to thicknesses of over 30 metres. The valley's southern basins were probably flooded more frequently and deposits are thickest there. The greatest thickness known is in the Yolo Basin, where 50 metres of fine-grained material may be found. North of Sutter Buttes in Butte and northern Colusa Basin, the deposits appear to be much thinner, probably less than 15 metres.

Silt and clay are predominant basin materials, but it can be expected that fine sands occur near the natural levees. Colusa and Yolo basin deposits grade westerly and interfinger with coarse-grained, alluvial fan deposits. The Butte, Sutter, and American basin deposits probably overlie the Victor Formation in sharp contact without gradation. Along the eastern margin of these basins, the heavy-textured "adobe" type soils are underlain at shallow depths by hardpan, which is the upper buried surface of the Victor Formation. In the American Basin, soil types identified with the Victor Formation occur on low mounds, indicating that the basin deposits are thin.

Few water wells have been drilled in the flood basin deposits and water-bearing character, as determined from yield rates and specific capacities, is unknown. It can be expected that well yields would be low. High-yielding wells might be possible only if drilled deeply enough to tap coarse-grained materials beneath the flood basin deposits.

Alluvium

All alluvial deposits not classified as alluvial fan or flood basin deposits are undifferentiated and included as alluvium on Plate 2. This map unit includes stream channel, natural levee, and floodplain deposits, all of Holocene age. As shown in Plate 2, major areas of occurrence are along the Sacramento and Feather rivers and a few of their tributaries, including Stony Creek, and the Yuba, Bear, American, and Cosumnes rivers. The areal extent of these types of materials is defined by soil types and topography. Soils with little or no profile[1] development are young soils correlated with floodplain and natural levee deposits. The areal distribution of such types has been used to delineate the boundaries of floodplain deposits in areas where topographic evidence is lacking.

Stream channel deposits occur along the active channels several feet below the bordering floodplain or natural levee. These materials are shown on soil maps as "river wash" but are not differentiated in Plate 2. Relatively coarse-grained material is continually moving downstream as the stream's bedload.

English equivalents: 1 metre (m) = 3.28 feet (ft); 1 kilometre (km) = 0.62 mile (mi).

[1] "Soil Profile" is a vertical section of soil showing the nature and sequence of its various zones.

Except where human activity has altered the natural conditions, sand and gravel are constantly replenished.

The floodplain is the area adjacent to the active channel which is subject to flooding. Generally, finer-grained materials—sand and silt—have been deposited in these areas. Whereas channel deposits may range in width from a few metres to 30 metres, floodplains may be several kilometres wide. Along the west side of the Sacramento River, floodplain deposits merge and grade into flood basin or alluvial fan deposits. Only in two areas are they in direct contact with alluvial fans: Stony Creek and Cache Creek have both produced fans large enough to extend to the river.

Floodplains of the east–side streams lie in trenches and cut into the Victor Formation. The trenches were cut into the Pleistocene age Victor Formation during the last glacial stage and are now being backfilled with alluvium.

Natural levees occur mainly along the Sacramento River, formed where floodwaters, overtopping streambanks, decrease suddenly in velocity and deposit sand and silt. Finer particles, held longer in suspension, are carried out into the flood basins.

Thickness of these Holocene deposits is not well defined because they are difficult to distinguish from older underlying materials. It is possible that maximum thickness of alluvium occurs along the Sacramento River north of Colusa. Here, coarse sand and gravel deposits extend to depths of 25 to 35 metres. Along the Feather River and its tributaries, thickness of alluvium is more clearly defined in well logs. At Gridley, coarse–grained deposits beneath the Feather River floodplain extend to depths of 30 metres and along the Yuba and Bear rivers to 20 metres. Thickness of gravels beneath the American River are probably about 15 metres.

Alluvial deposits along the major streams comprise the most permeable materials in the basin. They are unconsolidated and range in size from boulders to sand and silt with minor amounts of clay. With little or no soil profile development, they have moderate to high infiltration rates.

Soils

Ability of a soil to transmit surface water to the ground water reservoirs is an important consideration in estimating relative amounts of recharge from deep percolation of precipitation and applied irrigation water. Mature soils with well–developed profiles containing hardpan and claypan in their substrata will allow only small quantities of water to percolate. In areas underlain by these types, water tends to run off as surface flow to other areas where it may infiltrate. Soils with weakly developed profiles or the youngest soils with no profile development are much less restrictive and allow more recharge from the surface.

English equivalents: 1 metre (m) = 3.28 feet (ft).

Sacramento River north of Colusa. Coast Range in distance.

The USGS prepared a soil permeability map (Bertoldi, 1974) using 15 soil reports prepared by the U. S. Department of Agriculture and the University of California. Estimates of permeability for each horizon and entire profiles were made for each soil series. Differing types were then divided into four permeability groups. Group 1 soils have the lowest permeability, (0 to 0.6 metres) per day. These have quantitative rates described as "very slow; slow; moderately slow". Soils of this group are the most widespread and occupy about 50 percent of the valley. They occur principally in areas underlain by smaller alluvial fans—on the west side between the Stony Creek Fan and Cache Creek, most of the Putah Plain, nearly all of the east-side alluvial plain (Victor Plain), the low dissected hills on the east and west sides of the valley, and the area of fanglomerate north of Chico. The remaining areas have soils in permeability groups 2 to 4 and have a permeability range of from (0.6 to 6 metres) per day. These are found in areas occupied by floodplain and stream channels of the main drainages and in the alluvial fans of Stony, Cache, and Putah creeks.

Data obtained to prepare the permeability map were also used by the USGS for a map which grouped soils according to the type of substratum and its effect on vertical infiltration. Figure 5 is a generalized reproduction of that information. "Soils containing hardpan or other consolidated horizons that restrict the vertical flow of water including soils over bedrock" (Figure 5) occupy about one-third of the basin. The largest hardpan-type area is in the low alluvial plain on the east side and extends to the low dissected hills at the east basin boundary. Other areas are in the Rumsey-Dunnigan Hills, the Montezuma Hills, and the area of fanglomerate north of Chico. In most of the remaining area of the basin, soils contain clay in sufficient quantities to impede vertical flow of water. Those with few barriers to vertical water flow occur only along the river floodplains and portions of alluvial fans. These areas are located mostly along the Sacramento River north of Colusa, Stony Creek, the Chico alluvial fan, Feather River, American River, and Putah and Cache creeks.

Geologic Structure

The Sacramento Valley is an elongated, asymmetric structural basin or trough formed by the westward tilting of the Sierra Nevada block against the eastern flank of the Coast Ranges. The basement rock complex of the Sierra extends westward, beneath the valley, on a gentle slope reaching near the Coast Range. Cretaceous age marine sedimentary rocks in the Coast Range plunge steeply eastward in the west limb of the Sacramento Valley syncline and then extend eastward, becoming thinner and overlapping the Sierran basement rocks. In the deepest part of the valley trough, located near the west basin boundary, the Cretaceous marine sedimentary rocks may be 3 kilometres thick, but they thin eastward to a thousand metres or less along the east basin boundary.

Within an ancestral Sacramento Valley trough, which was still partially under a marine environment during the early Eocene, more sediments were deposited. These Eocene marine deposits are thin and do not extend northward much beyond Orland or Chico. Their average thickness beneath the valley is about 900 metres, and in the north valley less than 300 metres.

The synclinal trough formed by the Eocene and Cretaceous marine formations has been filled in post-Eocene time with nonmarine sedimentary and volcanic rocks. However, most of these sediments are of Pliocene, Pleistocene, and Holocene ages. Figure 6 shows a maximum of about 900 metres of post-Eocene continental deposits in the south valley and 600 metres in the north valley (Page, 1974). The geologic formations include the Mehrten and pre-Mehrten sediments, Laguna, and Victor Formations on the east side of the southern portion of the valley. Most of these interfinger with the Tehama Formation on the west.

In the north valley the Tuscan Formation and fanglomerate unit are present on the east side, but only the Tuscan interfingers with the Tehama Formation beneath the valley floor. All of these formations have been tilted so that they are now inclined at low angles toward the center of the valley. Overlying them are the more recent stream-laid deposits in the alluvial fans, floodplains, and flood basins which have not been structurally deformed.

Except for these more recent deposits, the post-Eocene continental deposits have been locally folded and faulted, primarily along the west side of the valley. These structures are important because they dislocated water-bearing strata and uplifted rocks of older, more consolidated character to shallow zones, thus affecting the occurrence and movement of ground water. Some are apparent at the surface, but often they are concealed by alluvial materials and their presence can be inferred from ground water level measurements or other subsurface data.

Between Corning and the Sacramento River is a series of low hills which are surface expressions of the north-south trending Corning anticline (Plate 2). Along the same structural trend to the north, near Red Bluff, the Tuscan Formation appears to have been uplifted along this same anticline, since Tuscan rocks are known to occur at shallow depth beneath the Red Bluff Diversion Dam. To the east, they are believed to be much deeper, possibly along a paralleling syncline.

At Orland Buttes, Cretaceous rocks have been uplifted along a fault flanking the west side of the Buttes. This may be the northwest extension of the

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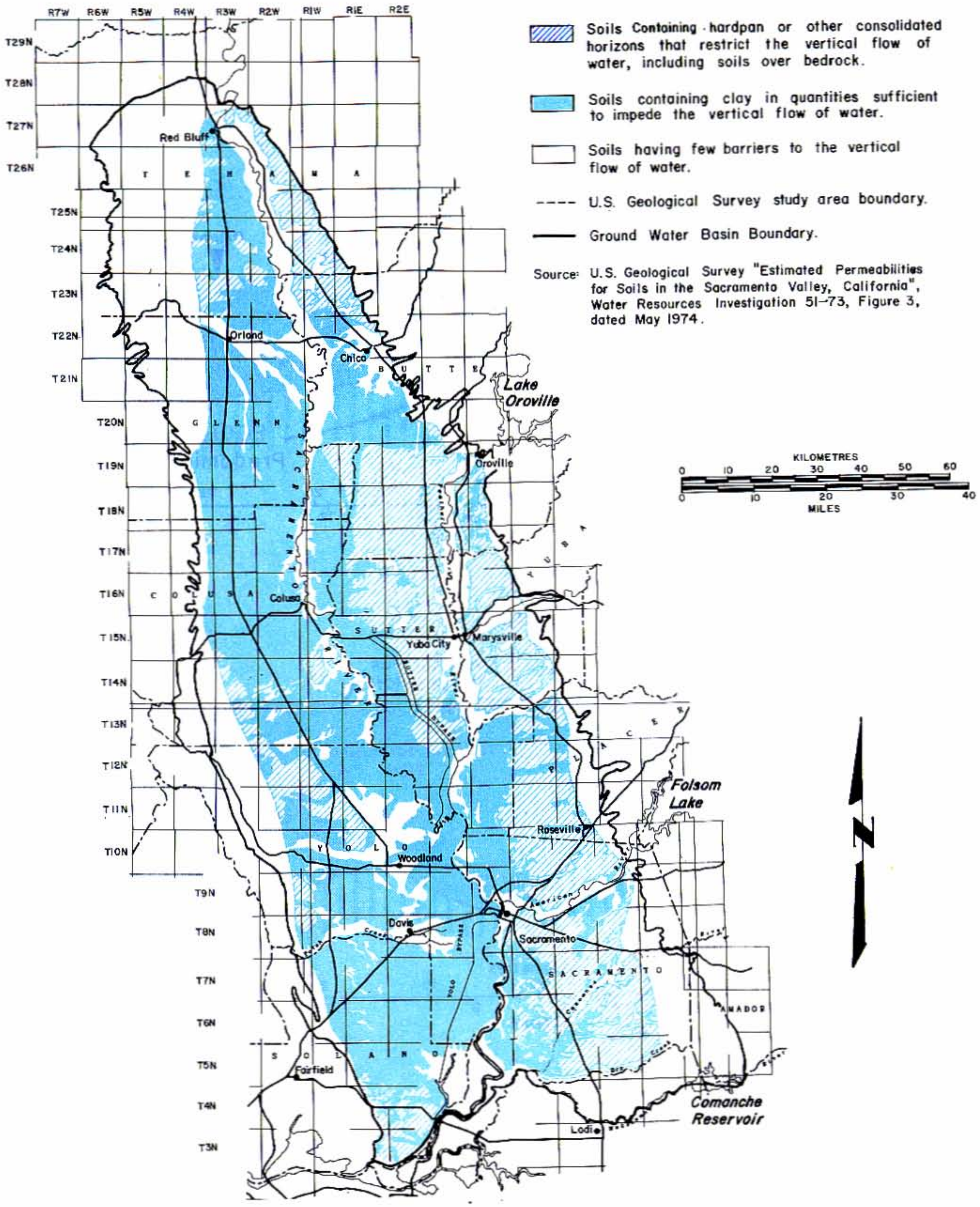
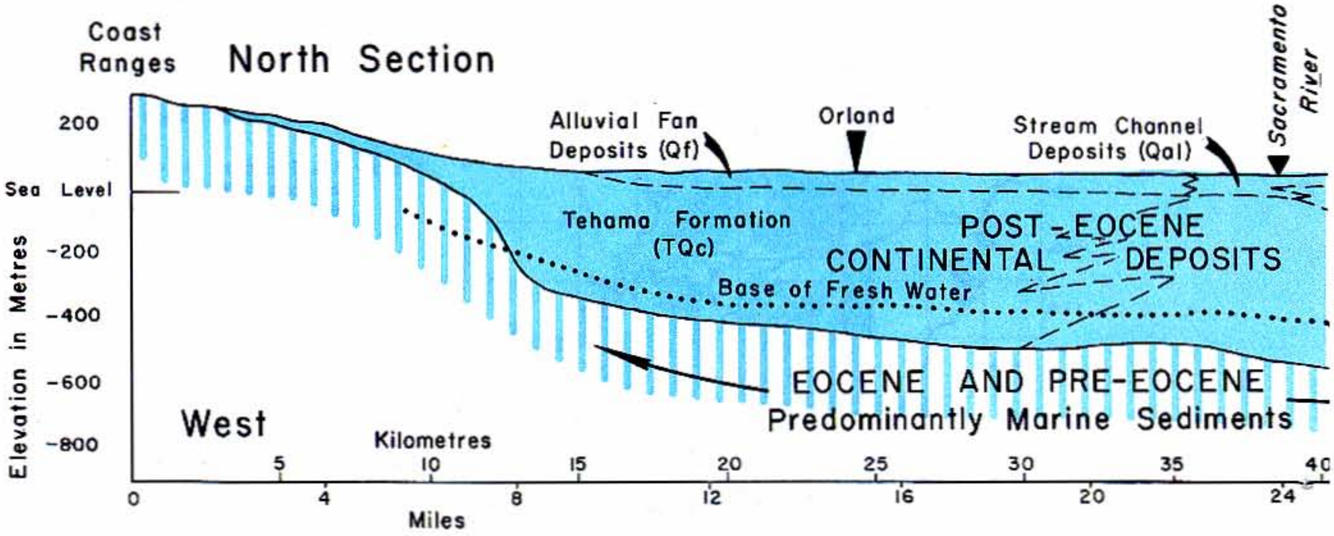
English equivalents: 1 metre (m) = 3.28 feet (ft); 1 kilometre (km) = 0.62 mile (mi).



Source: U.S. Geological Survey "Estimated Permeabilities for Soils in the Sacramento Valley, California", Water Resources Investigation 51–73, Figure 3, dated May 1974.

Figure 5. Barriers to Vertical Flow of Water in Soils


Coast Ranges
North Section
Alluvial Fan Deposits (Qf)
Orland
Stream Channel Deposits (Qal)
Sacramento River
200
Sea Level
-200
-400
-600
-800
Elevation in Metres
Tehama Formation (TQc)
POST-EOCENE CONTINENTAL DEPOSITS
Base of Fresh Water
EOCENE AND PRE-EOCENE Predominantly Marine Sediments
West
Kilometres
5
10
15
20
25
30
35
40
0
4
8
12
16
20
24
Miles

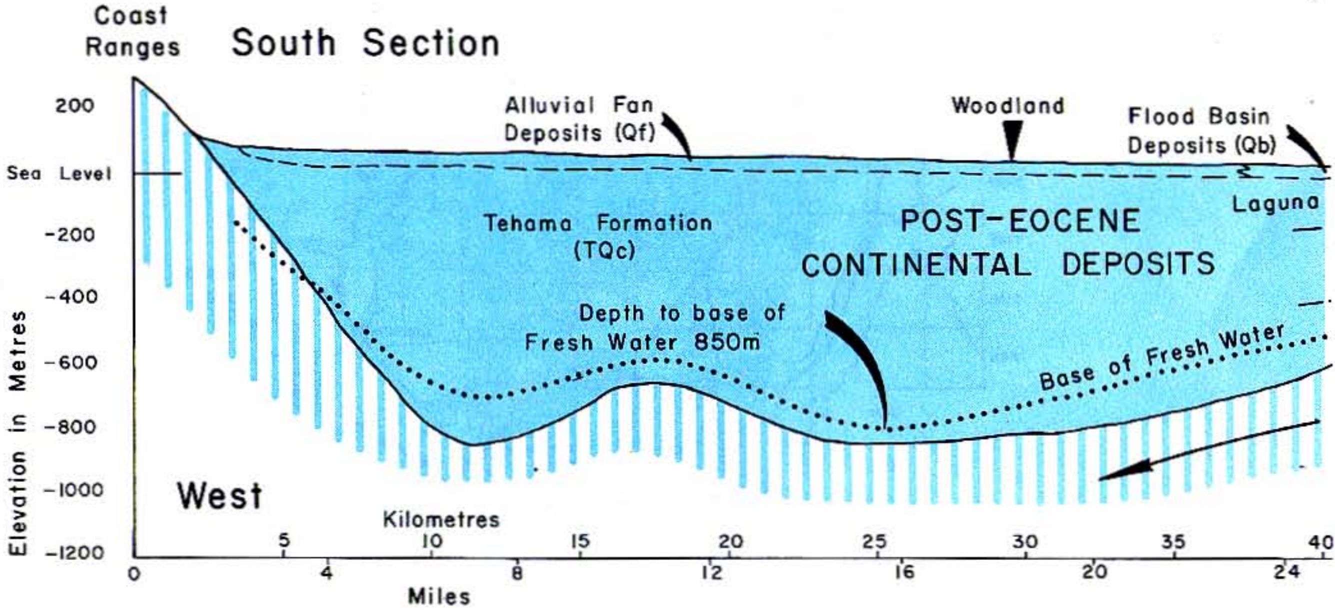
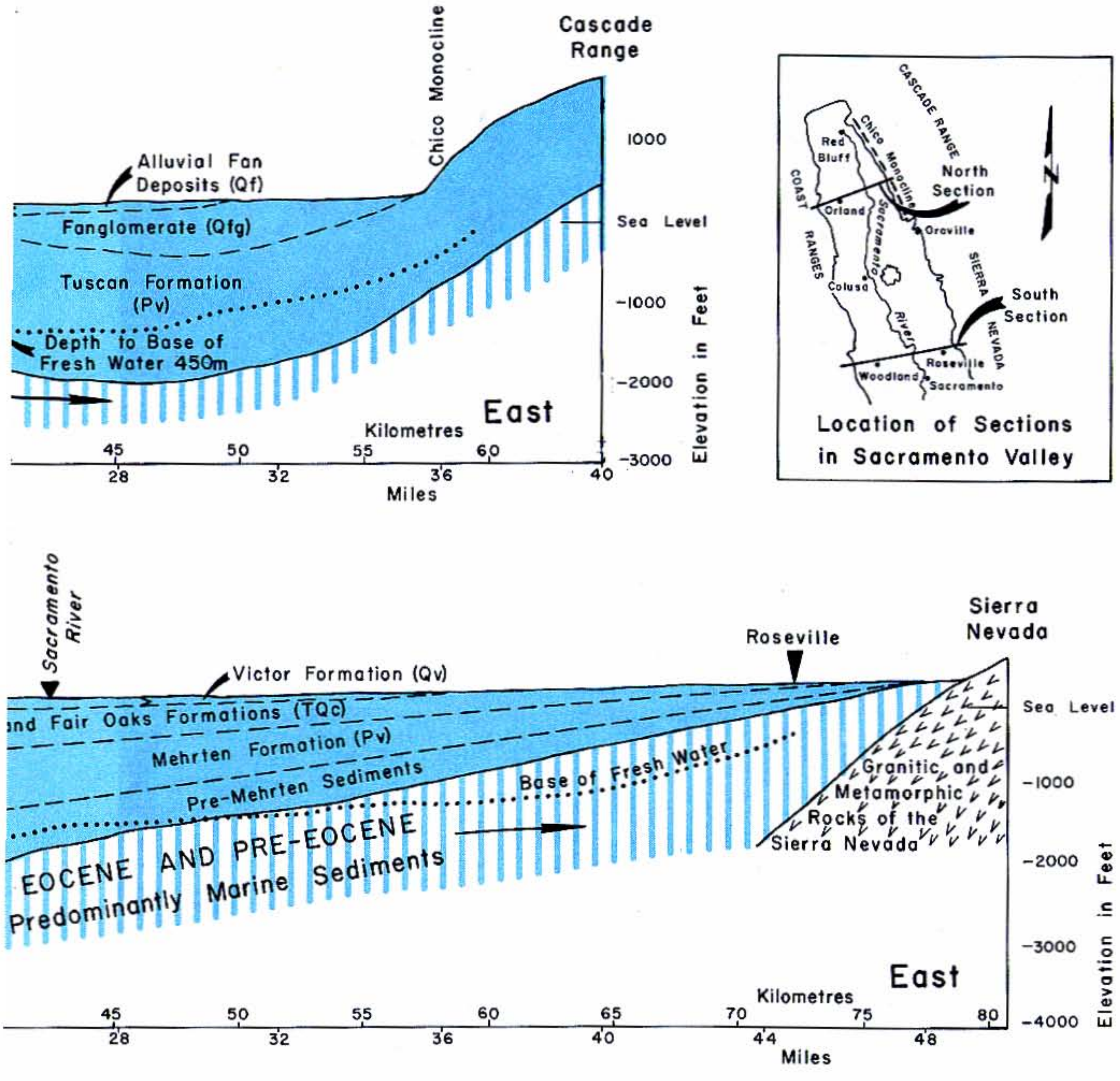
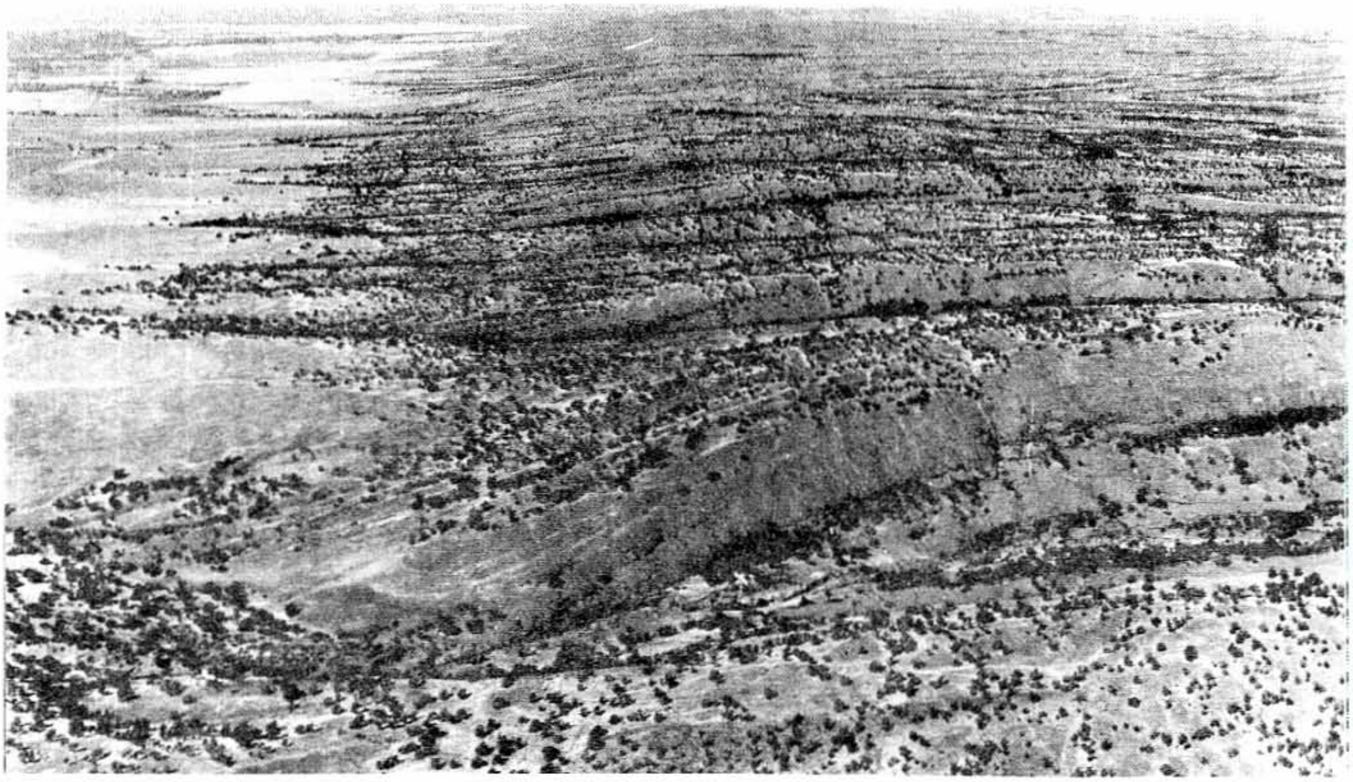

Coast Ranges
South Section
Alluvial Fan Deposits (Qf)
Woodland
Flood Basin Deposits (Qb)
200
Sea Level
-200
-400
-600
-800
-1000
-1200
Elevation in Metres
Tehama Formation (TQc)
POST-EOCENE CONTINENTAL DEPOSITS
Laguna
Depth to base of Fresh Water 850m
Base of Fresh Water
West
Kilometres
5
10
15
20
25
30
35
40
0
4
8
12
16
20
24
Miles

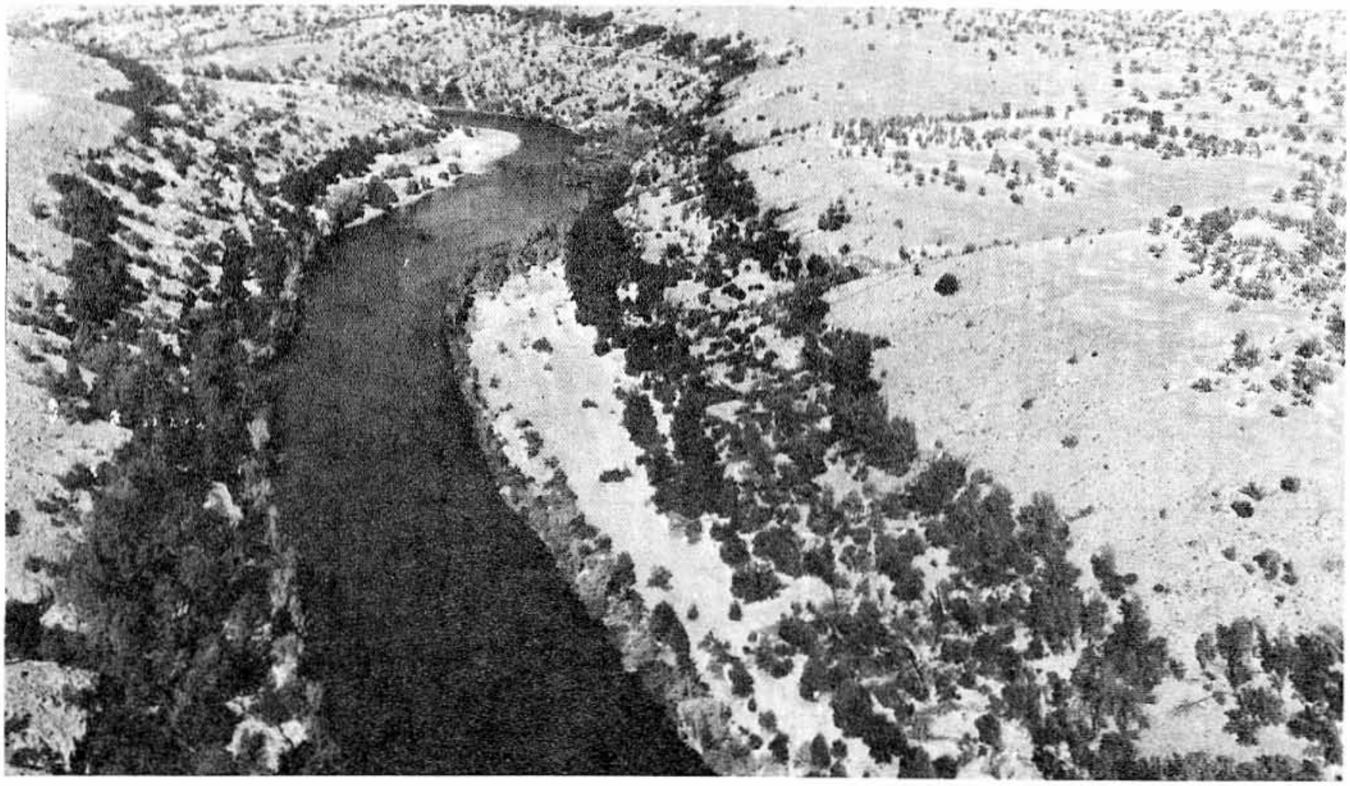
Figure 6



Generalized Geologic Sections



Chico monocline. Tuscan Formation beds are bent downward along the edge of the valley and extend west beneath younger sediments. View is to the north.



Sacramento River in Iron Canyon north of Red Bluff.

Willows fault, (Redwine, 1972) known to have dislocated the deeper strata in the Tehama Formation south of Orland (Plate 2). The Willows fault is not known to have affected the shallow water-bearing strata.

Extending south-southeast from Orland is the Willows arch, a probable anticlinal structure believed to be the northwest extension of an anticline in the Willows-Beehive Bend Gas Field in eastern Glenn County. Although there is no surface expression of this structure, its presence can be inferred from changes in ground water levels across the structure.

The Tehama Formation in the Dunnigan Hills of Colusa and Yolo counties is folded into a broad anticline for a surface distance of 30 kilometres northwest from Cache Creek. It is possible that a fault occurs along the east limb of the anticline, as first suggested by Bryan (1923). Gas exploration well data indicate the presence of a fault known as the Cook fault beneath the Dunnigan Hills. Projection of this reverse-type fault to ground surface could place it along the front of the Dunnigan Hills. If it is present there, it is probably concealed by alluvium. Both the fault and the anticline extend northwest but are concealed by alluvial fans. In this area, just west of Arbuckle, one or both of these structures appear to be barriers to the movement of ground water. The Dunnigan Hills anticline is probably accompanied by a paralleling syncline on its west side. It is probable that the axis of this structure would extend northwest through Hungry Hollow west of Dunnigan Hills.

Plainfield Ridge, a series of low hills west of Davis and north of Putah Creek, is the surface expression of an anticlinal structure, either paralleling the Dunnigan Hills anticline or its southern extension. This structure is a barrier to the eastward movement of ground water.

Between Chico and Red Bluff, along the east edge of the basin, the Tuscan Formation displays an abrupt downward fold along the Chico monocline. This structure accounts for the nearly straight basin boundary north from Pine Creek. Between Pine Creek and Antelope Creek the monocline dips from 20 to 35 degrees, whereas farther south toward Chico, the beds are inclined 2 to 3 degrees and evidence of the monocline almost disappears (Plate 2).

East of Red Bluff, in the northeast corner of the valley, the Chico monocline is terminated by the Red Bluff arch. This compound structure is a series of northeast-trending anticlines and synclines that cross the Sacramento River between Iron Canyon and Battle Creek. The Tehama and Tuscan Formations are both uplifted here, resulting in a structural barrier to ground water movement between the Redding Basin and the Sacramento Basin.

Sutter Buttes, the most visually prominent geologic structure, are the eroded remains of a Plio-Pleistocene age volcano. The Buttes are circular, with a diameter at the valley floor of 16 kilometres, and rise about 600 metres above the valley. They consist of a central core of andesite and rhyolite surrounded by a ring of volcanic tuff-breccia (mudflows). The igneous plug was pushed through the marine and continental sediments so that these rocks now encircle the igneous core and dip radially away from it. As noted in the preceding chapter, the Buttes' impervious rocks divert ground water around the east and west sides, and their upturned marine sedimentary rocks furnish saline connate water to the ground water basin through flushing action, particularly on the south side where shallow saline waters occur in Sutter County.

English equivalents: 1 metre (m) = 3.28 feet (ft); 1 kilometre (km) = 0.62 mile (mi).

CHAPTER III. GEOHYDROLOGY

This chapter discusses in general terms occurrence, movement, and fluctuations of ground water levels, and the hydrologic and physical properties of the aquifers throughout the Sacramento Basin. It describes how ground water is replenished and discharged, how much is pumped, and the amount in storage. Finally, it presents information concerning chemical quality of ground water.

Occurrence of Ground Water

Ground water occurs in spaces between particles of granular material within the zone of saturation, the upper surface of which defines the water table. In layers of predominantly coarse-grained material, open spaces are larger than in those of clay or silt and are in greater contact with each other, which facilitates ground water movement. Conversely, movement through layers having high percentages of clay is impeded because pore spaces are smaller and poorly connected. Therefore, clay and silt deposits do not readily yield water and retard its movement, while sand and gravel or sand alone freely transmit and yield ground water.

Fresh ground water occurs in a wide variety of geologic materials in the post-Eocene continental deposits beneath the Sacramento Valley. Most of the readily available ground water is stored and moves through sand or combinations of sand and gravel laid down by streams which flowed into and through the valley. Over millions of years, these streams have transferred the fragmental products of weathering and erosion from surrounding mountains to the valley. Materials carried by the streams include visible rock particles and dissolved minerals.

Coarser materials, sand and gravel, are initially deposited near the base of the foothills, where the streams enter the valley and reduce their gradients. Finer particles are carried in suspension farther into the valley where they settle out as stream velocity slackens more. Given sufficient time and periodic flood-flows, coarser materials may travel by bedload movement still farther, where they may be buried by subsequent deposition of fine-grained material. A complex system of alternating layers of sand and gravel can evolve this way. The layers are not of uniform thickness and usually not extensive. Typically, sand and gravel layers occur in elongated channels or tongue-like shapes having little lateral extent. The relative amount of coarse-grained to fine-grained material varies enormously, both vertically and horizontally, but clay and silt deposits far exceed those of coarse-grained materials. Sand and gravel beds may reach considerable depths in places where they are now being deposited. Some layers of predominantly sand and gravel extend downward 30 metres or more, terminating as dictated by changes in depositional environment.

Alluvial materials may undergo a cementation or consolidation process after being laid down. This occurs when they have been deposited and buried at considerable depth; thus while cemented sediments are generally deeply-buried older materials, they may occur at the surface after erosion of overlying layers. With cementation and consolidation, pore spaces are reduced, diminishing the capacity of materials to hold and transmit water.

In addition to the predominant alluvial deposits, post-Eocene continental deposits include small amounts of volcanic material, such as mudflows (tuff-breccias), in the Tuscan and Mehrten Formations and around Sutter Buttes. Mudflows are of no importance as sources of ground water as they are nearly impermeable. They act as confining layers to water and may prevent downward percolation.

Where ground water is unconfined, the water table is the upper surface of the zone of saturation. Where confined, it is overlain by sufficiently impermeable material to preclude free hydraulic connection with the surface. Water may also occur in a zone above the main body of ground water, being separated from it by an unsaturated layer. This is called "perched" ground water.

In the Sacramento Valley, ground water occurs in all three conditions. Water in the Holocene age deposits, including the floodplains and alluvial fans, is generally unconfined, but it is confined when these materials are overlain by flood basin deposits. In Pleistocene age materials, it may be unconfined in the shallow layers and completely confined in deeper zones such as in the Victor Formation and the fanglomerate unit. Ground water is mostly confined in the Tuscan, Tehama, Laguna, Mehrten, and other older formations. In a few areas, it is under sufficient pressure in deep aquifers to rise to the surface when the confining layers are penetrated by drilling. In the early 1900s, several wells drilled into the Tehama Formation at Artois were reported by Bryan (1923) as flowing. A few flowing wells are known in the Tuscan Formation, but these often flow only in the spring season, when water pressures are greatest. Perched water bodies are most common in the Pleistocene gravels where impervious layers, present within the formation, prevent downward movement of water to the main aquifer. This is common in the Red Bluff Formation.

Depth to water varies from a few metres in the central portion of the valley to over 30 metres in areas along the east and west margins. Water depths are determined through measurement of some 1,600 wells in the valley by the Department of Water Resources, the U. S. Bureau of Reclamation, and local agencies. In an area comprising about 25 percent of the valley lands, depth to water is 3 metres or less, as shown by Figure 7.[1] This figure shows areas where depth ranges from 10 to 40 feet (3 to 12 metres), 40 to 80 feet (12 to 24 metres), and areas of over 80 feet (24 metres). These represent depths for 1965, a year that approached the lowest levels for the 10-year study period 1961–70. Levels for those areas, which had been steadily rising or declining, were about average. The greatest depth to water in the valley floor area is in the Yolo–Solano and Sacramento County areas, where large extractions since World War II have lowered levels slightly more than 100 feet (30 metres) in Sacramento County and as much as 80 feet (24 metres) in Solano County.

Movement of Ground Water

Direction and relative rate of ground water movement may be determined by measuring water levels in wells and calculating variation in elevation from point to point. Ground water elevation maps are prepared from such data. Since ground water movement is influenced by gravity, direction of movement is at right angles to elevation contours, from higher to lower elevation. Where contour lines are closer together, the gradient is steeper and flow is faster, although the total quantity of flow for the same cross-sectional area may not be greater.

The earliest known ground water elevation contour map of the Sacramento Valley was prepared by Bryan of the U. S. Geological Survey (1923). This map is reproduced as Figure 5A in Appendix A. Contours are based on water level measurements of 2,500 wells for the years 1912 and 1913, prior to the time of intensive ground water pumpage. The contours therefore represent nearly–natural conditions and are used as base level conditions for the U. S. Geological Survey's hydrologic studies described in Appendix A. The generalized contours shown on the 1912–13 map indicate a movement from the sides of the valley to the Sacramento River. Under this condition, the Sacramento River was a gaining stream for its entire length; that is, it received ground water from adjacent areas.

Elevation contours depicted in Figure 8 are based on levels measured throughout the valley in 1971. (Figure 8 is in English units as originally prepared.) The contours show that ground water flows from the margins of the valley toward the river in the north valley. In the south valley, ground water is at a higher elevation along the lower Sacramento River and lower Feather River. Thus ground water flows from these higher elevations toward the pumping depressions adjacent to the river. Steep gradients occur when materials of low permeability present partial barriers to ground water movement. As mentioned earlier in this report, several major geological structures that break the horizontal continuity of aquifers by faulting or folding occur in the valley:

The Corning anticline at the north end of the valley causes ground water moving from the west to flow with a steeper gradient in order to cross its structure.

Willows Arch, the faulted anticline near Artois, presents a barrier to the movement of the water to the southwest. It appears that ground water moving south to southwest from Stony Creek cannot move west of the arch, where water levels are considerably lower in the west half of Range 3W, Townships 21 and 22 north. Apparently there is insufficient recharge from the west to support the amount of pumping in this area.

At Dunnigan Hills, an anticline in the Tehama Formation is shown in Plate 2. Although no well or water level data are available for this feature, it appears that little or no ground water moves across it eastward into the valley. Plainfield Ridge, the surface expression of the southern extension of the Dunnigan anticline, is a barrier to eastward movement from Cache Creek. The Dunnigan anticline, also extending northward beneath the alluvial fans west of Arbuckle, appears to restrict deep movement of ground water to the valley. In addition, the possible fault along the front of the Dunnigan Hills is believed to extend northward in conjunction with the anticline to restrict the movement of water eastward to the Sacramento Valley floor.

Ground water depressions occur where pumpage in excess of recharge has lowered levels so that closed depressions occur. These are the conditions at Marysville in Yuba County, north of the city of Sacramento in Sacramento, Placer and Sutter Counties, a large depression south of Sacramento in Sacramento County, and at Dixon in Solano County. These depressions have developed since World War II, due to intensified agriculture. Changes in their sizes in later years will be discussed in the following section.

Fluctuations of Ground Water Levels

Chapter One noted that ground water levels fluctuate annually in response to pumpage and to recharge from stream percolation, infiltration or rainfall, and applied irrigation water. Levels are usually highest in spring and lowest in fall. Long-term fluctuations occur when recharge either exceeds dis-

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English equivalents: 1 metre (m) = 3.28 feet (ft).

[1] Figure 7 appears as it was originally prepared, with English units of measure, but with the addition of equivalent metric units. For easy reference to the figure, English units precede metric units in this paragraph.

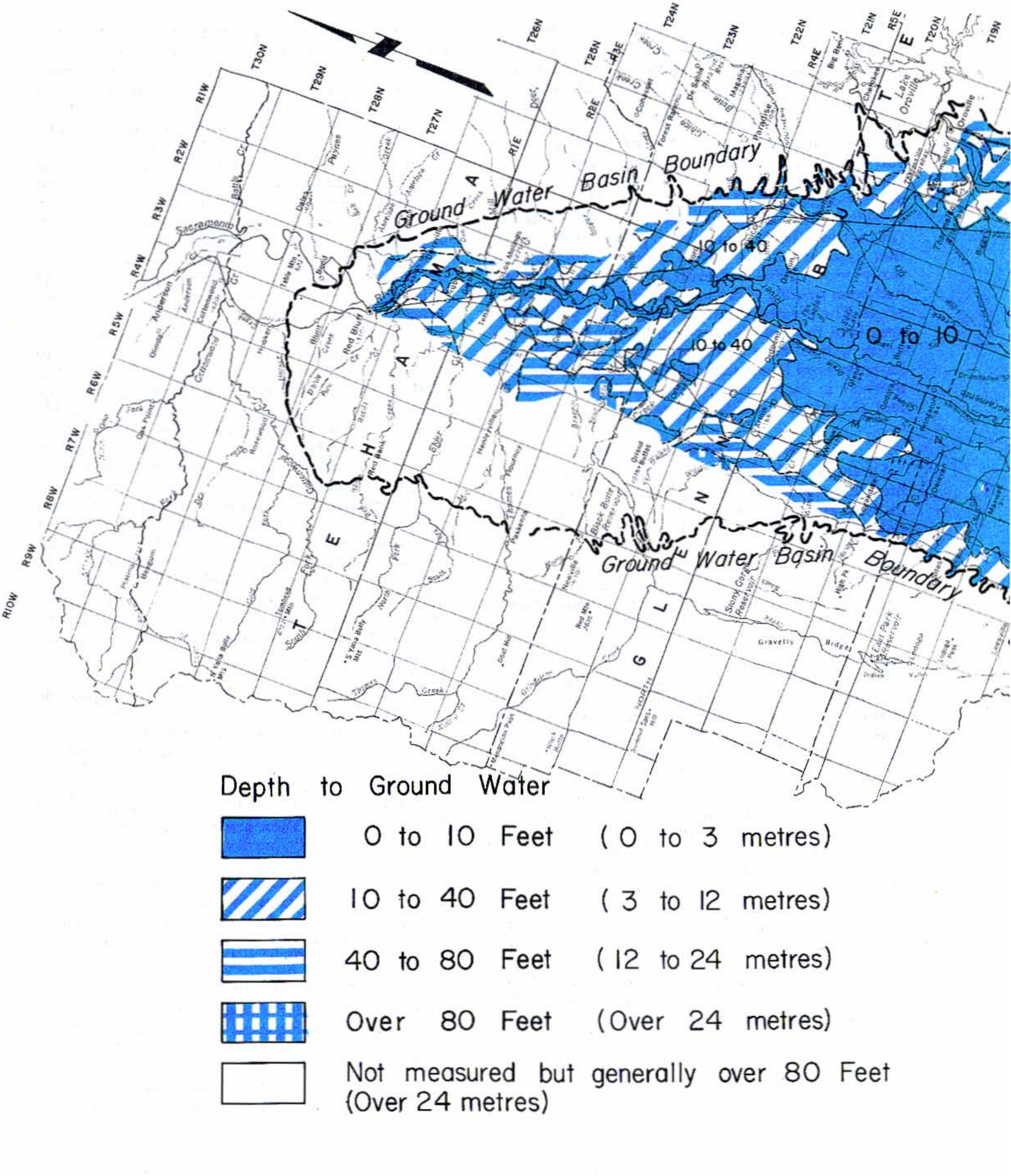
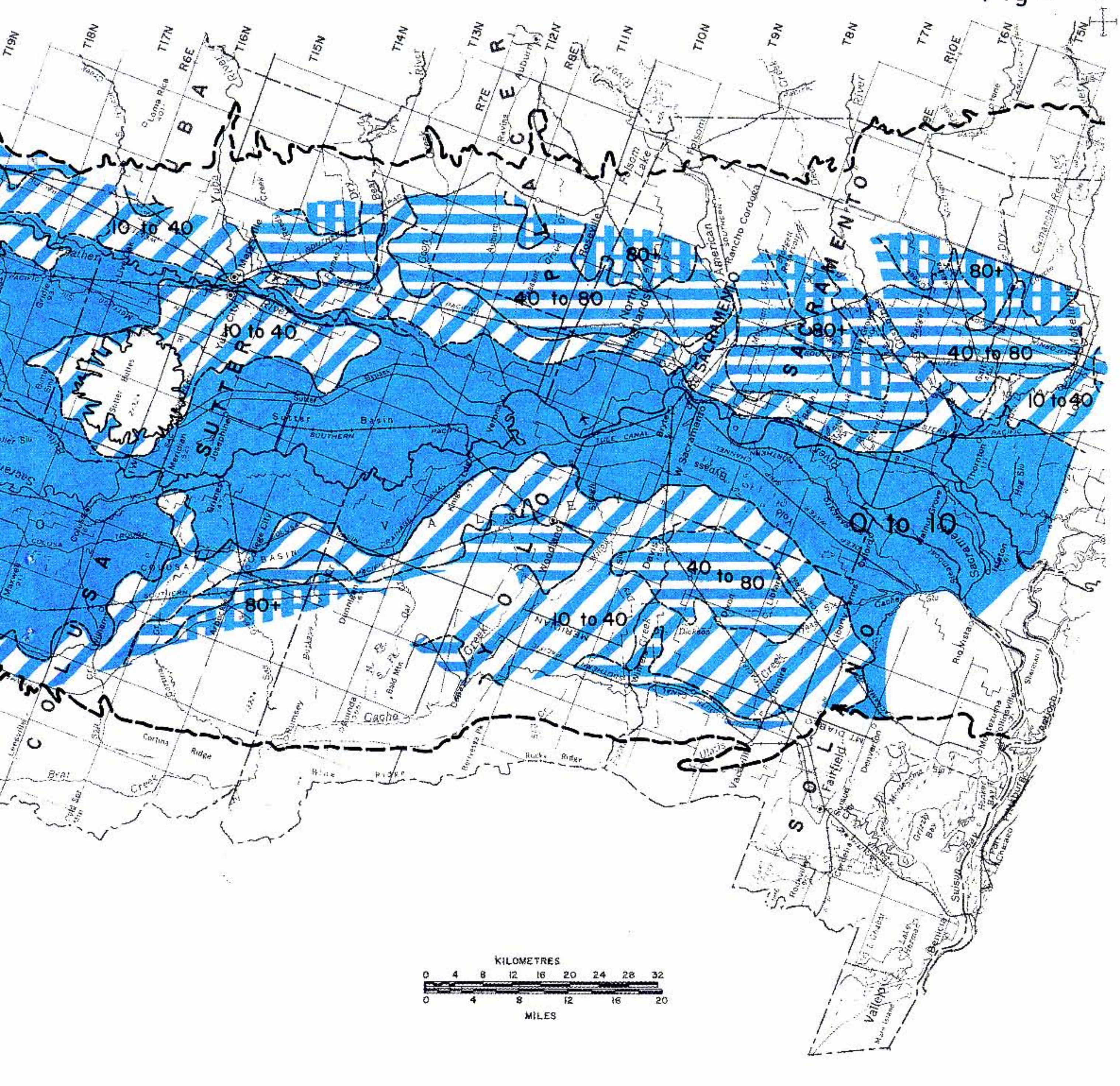
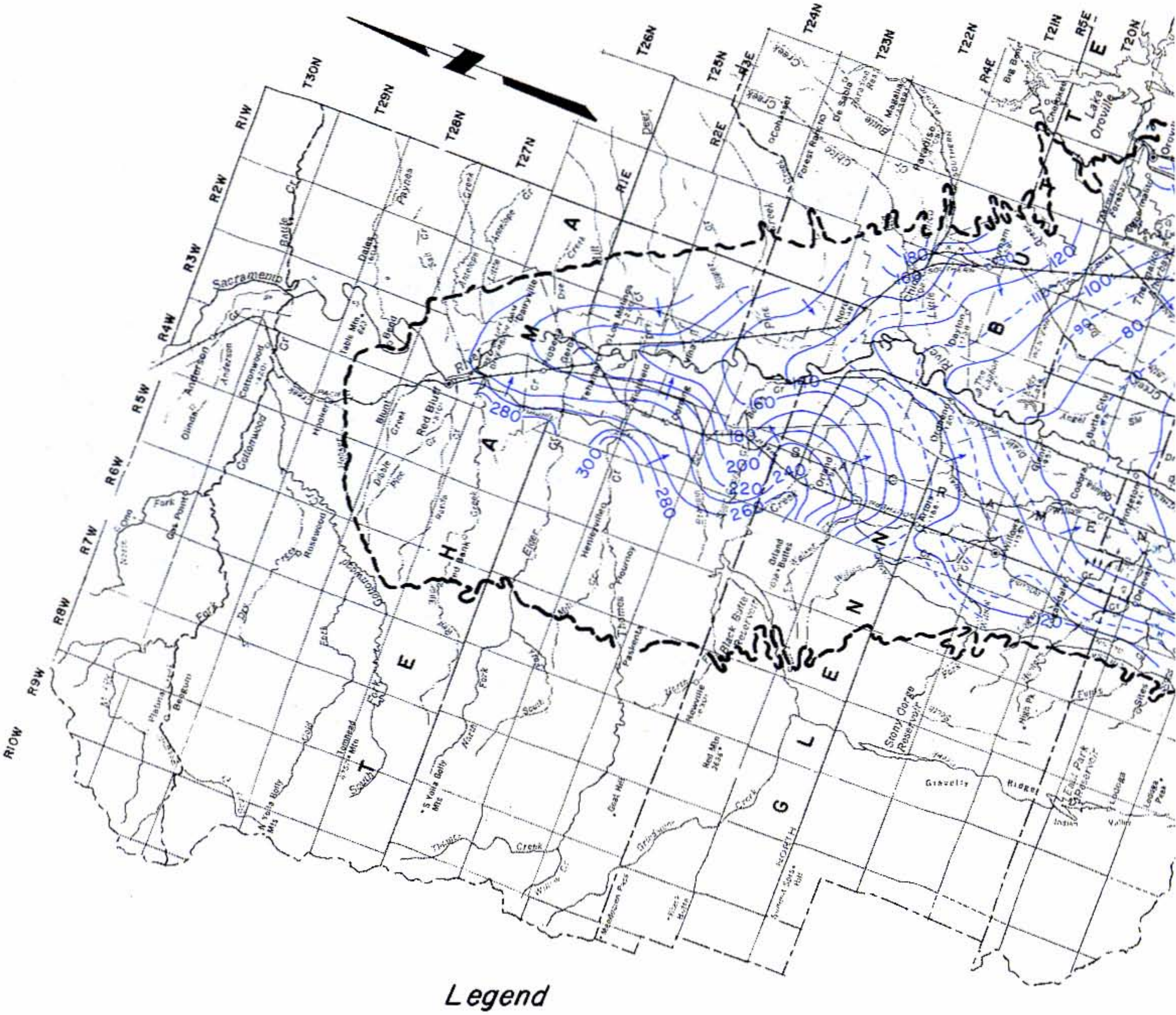

T30N
T29N
T28N
T27N
T26N
T25N
T24N
T23N
T22N
T21N
T20N
T19N
R1W
R2W
R3W
R4W
R5W
R6W
R7W
R8W
R9W
R10W
R1E
R2E
R3E
R4E
R5E
Ground Water Basin Boundary
Ground Water Basin Boundary
10 to 40
10 to 40
0 to 10
Sacramento
Red Bluff
Red Bank
Paradise
Lake Oroville
Oroville
Black Butte Reservoir
Stony Gorge Reservoir
East Park Reservoir
Depth to Ground Water
0 to 10 Feet (0 to 3 metres)
10 to 40 Feet (3 to 12 metres)
40 to 80 Feet (12 to 24 metres)
Over 80 Feet (Over 24 metres)
Not measured but generally over 80 Feet (Over 24 metres)

Figure 7



DEPTH TO GROUND WATER
SPRING OF 1965

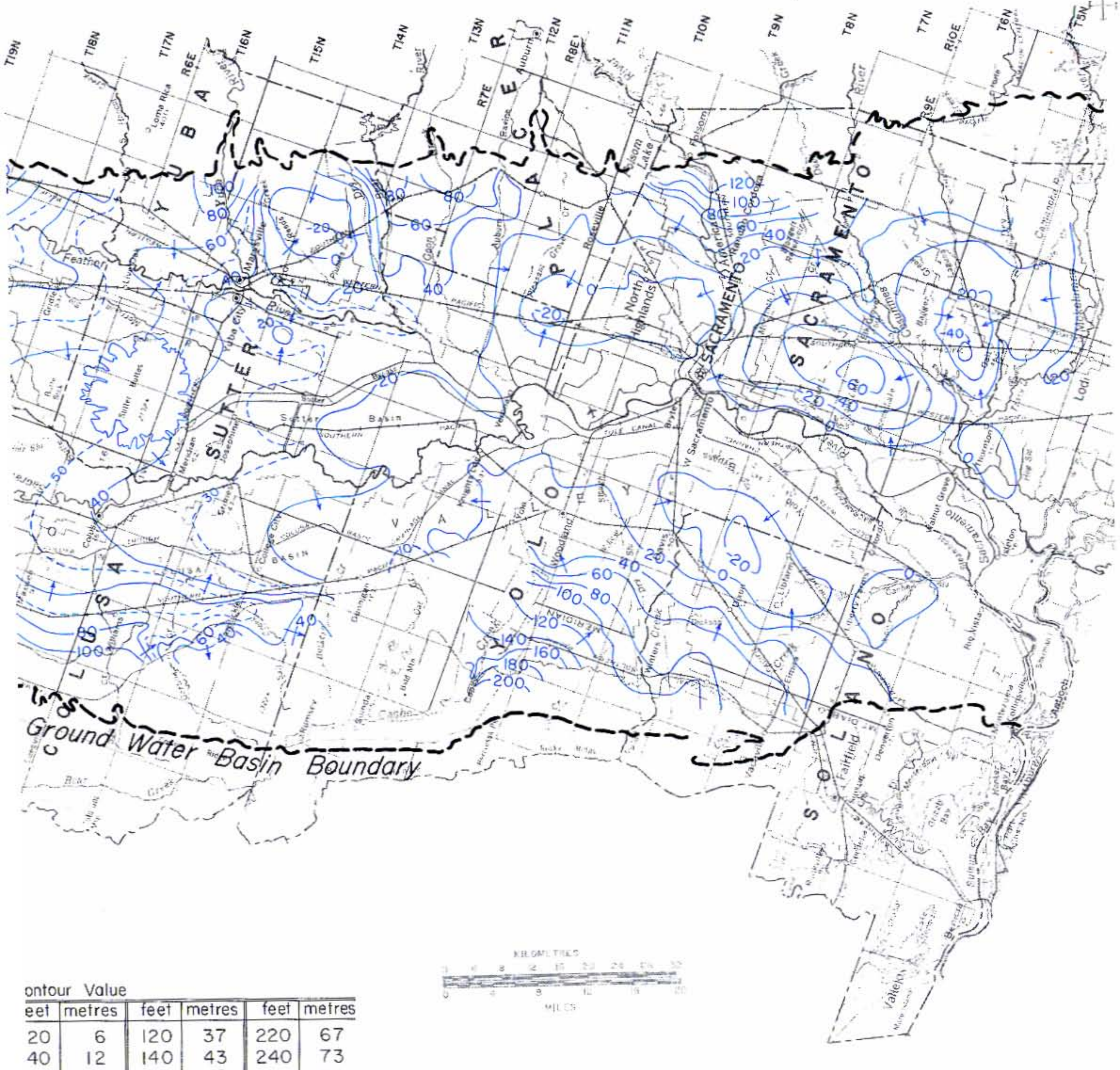


Legend

—100— Water level contour in feet. Arrow indicates direction of ground water movement; contour interval is 20 feet, datum is mean sea level.

- - -30- - - Intermediate 10-foot contour

Figure 8



ontour Value

eet	metres	feet	metres	feet	metres
20	6	120	37	220	67
40	12	140	43	240	73
60	18	160	49	260	79
80	24	180	55	280	85
00	30	200	61	300	91

etric conversions are approximate.

LINES OF EQUAL ELEVATION
OF
GROUND WATER IN WELLS
SPRING 1971

charge or is less than discharge. This section describes the long-term changes in water levels from the earliest ground water level measurements in 1912–13 up to the spring of 1971.

The earliest water level measurements, by the U. S. Geological Survey in 1912–13, (Bryan, 1923), provided a ground water elevation contour map based on measurements of 2,500 wells. This was used to prepare Figure 5A in Appendix A. Again in 1929, about 200 wells were measured in connection with the Sacramento River Basin study by the California Division of Water Resources (1931). Measurements of many of these wells have continued to the present, but there are time gaps in the records.

In 1956 ground water data for the entire basin were collected on a systematic basis by the Department of Water Resources. By the early 1960s many measurement data were available and more were to follow. Figure 8A in Appendix A was prepared by the U. S. Geological Survey using all then-available measurements; modifications followed from new data and use of computed levels from a ground water model. The 1961 map shows that the general pattern of contours north of Sutter Buttes remained about the same as compared to the "Natural Conditions" map (Figure 5A, Appendix A). However in the south Sacramento Valley, contours show the development of several closed or nearly closed patterns indicating ground water pumping depressions. Contour patterns were considerably changed on the east side of Marysville to Sacramento County and south of Davis in Solano County on the southwest side.

Change of water level elevations during the 1913 to 1961 period is shown in Figure 9A, Appendix A. This map shows that in 1961, the north Sacramento Valley had only a small area along Stony Creek near Orland and two smaller areas in Butte County with water levels 3 metres lower than under "natural conditions". Most of the declines in water levels since 1912–13 have occurred in the four areas previously mentioned, all of them south of Sutter Buttes: (1) 16 kilometres southeast of Marysville, Yuba County, lower by 12 metres; (2) south of the Bear River, Placer and Sutter Counties, lower by 9 metres; (3) two areas in Sacramento County, lower from 15 to 18 metres; and (4) south of Davis in Solano County, water levels 15 metres lower in 1961 than in 1912–13.

Water level contours for 1971 are shown in Figure 10A, Appendix A and Figure 8. Comparison of these levels with water levels in 1961 is shown on Figure 11A, Appendix A. This map shows that water levels continued to decline in two of the four significant areas—southeast of Marysville and in south Sacramento County. In the first area, water levels had declined an additional 5 metres, and in south Sacramento County they were lower by 1.5 to 3 metres. Water levels have risen 10 metres in each of the other two areas, south of the Bear River and south of Davis.

Hydrographs of fluctuation of water levels in wells are shown in Figure 9. For each of the ten counties in the Sacramento Valley one hydrograph was chosen, representing wells situated in areas of moderate–to–intense ground water use and for which long records were available. All records date back at least to the immediate post–World War II period, when use of ground water was accelerated, and some measurements date back to the 1920s.

In Figure 9, the record of water levels in well T26N/R3W–34P1, 13 kilometres south of Red Bluff in Tehama County, 96 metres deep, dates back to 1921. Although there was a long break in the record, from 1931 to 1948, spring water levels remained at an elevation of 70 to 73 metres with a few exceptions. Near Orland in Glenn County, well T22N/R3W–21F1, has been measured since 1929 with breaks in the record between 1934 and 1947. Levels in this 24–metre well have fluctuated between 73 and 76 metres elevation with no persistent decline.

In Butte County, 13 kilometres northwest of Chico, well T23N/R1W–14R1, 48 metres deep, was first measured in 1948. At sometime during the period of no record from 1954 to 1957, the maximum spring water levels declined from about 52 metres to about 50 metres elevation and remained constant to 1971. Near Arbuckle, in Colusa County, water levels in well T14N/R2W–34N1, 30 metres deep, declined from 30 metres in 1950 to 18 metres elevation in the mid–1960s due to intensive pumping and inadequate recharge. This hydrograph represents the only area where levels have declined in Colusa County. With importation of a surface water supply from the Colusa drain, pumping was reduced and water levels started rising in the late 1960s.

Yolo County is represented by well T10N/R2E–34M1, 49 metres deep and located near Woodland. When first measured in 1941, levels were at an elevation of about 14 metres and declined to about 8 metres over the next 20 years, approximately 0.3 metre per year. From 1961 to 1971, spring water levels have remained virtually constant.

In Figure 9 (continuation), the hydrograph for well T14N/R5E–30Q1, 67 metres deep, located 19 kilometres southeast of Marysville in Yuba County, shows a rapid decline between 1948 and 1962. From 1962 to 1971 spring levels remained at a near–constant elevation. Thirteen kilometres northwest of Roseville in Placer County, well T12N/R5E–35E2, 107–metres deep, showed a similar decline, about 12 metres from 1950 to the mid–1960s, but with a partial recovery beginning in 1967. The rise in ground water levels can be attributed to the greater use of surface water, with a reduction of ground water pumping, in the South Sutter Water District. In the mid–1960s, the

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English equivalents: 1 metre (m) = 3.28 feet (ft).

district imported water from its Camp Far West Reservoir on the Bear River.

Water levels in well T6N/R7E–28E1, 22 kilometres southeast of the State Capital in Sacramento County, declined 0.75 metre per year from 1952 to 1971, dropping from nearly 12 metres above sea level to 3 metres below. In Solano County, near Dixon, water levels declined to 6 metres below sea level as shown by the hydrograph of well T7N/R1E–12N2 with a depth of 30 metres. With the importation of water from the Solano Project and the greater use of surface water, ground water levels rose rapidly to 12 metres above sea level. This is the highest level ever recorded, since the "natural conditions" elevation of 1912–13. The hydrograph of well T15N/R3E–34L1, south of Yuba City in Sutter County, shows a decline of 3 metres during the mid–1960s from its highest level in 1957 and a return in 1971 to about 10 metres above sea level.

Aquifer Descriptions

Aquifers are geologic formations or parts of formations containing sufficient saturated permeable material that yield significant quantities of water to wells. In the Sacramento Valley they are only parts of formations because none are composed entirely of water–bearing materials, such as sand and gravel. Aquifers are necessary for significant well yield and for transmission from recharge source to well locations.

Finer material such as silt or sand with silt or clay, may yield water, but only poorly. However, they can transmit water from adjacent aquifers and constitute important ground water storage units. Stratigraphic units composed of these types of materials are called "aquitards". Materials composed of large amounts of clay are relatively impermeable and are called "aquicludes"; these neither yield water to wells nor transmit appreciably from recharge sources. They serve as boundaries to aquifer systems and aquitards and confine ground water beneath them.

Information for this study, on thickness, depth, extent, and location of the principal zones of sand and gravel, was provided by drillers' well logs and processed in a computer program developed by the Department of Water Resources, Central District. Materials described by well drillers were assigned numerical values of specific yield for computer processing.

Specific yield is the ratio of the volume of water a saturated material will yield by gravity to the volume of that material, expressed as a percentage. In general, it increases with increasing grain size of material from clay to course sand; however, the specific yield of gravel is less than that of coarse sand, because gravel has slightly less void space between particles.

All materials with specific yields above 13 percent are composed of fine sand or larger in size of materials and may be classified as aquifers—in this study specifically, materials with a specific yield of 13 to 25 percent. Materials with specific yields of less than 13 percent are classified as aquitards or aquicludes. This classification, although somewhat arbitrary, is useful because it relates to permeability of granular materials, identifies sand and gravel aquifers, and provides assignable values for storage capacities.

Average specific yield values, as well as transmissivity and the amount of water in storage for various layers, were determined by computer as follows:

1. One well log for the deepest well per quarter section, 64.75 hectares (160 acres), was selected from the Department's well log file. A specific yield value as selected and assigned to each type of material reported by drillers for the 7,000 logs which represented the valley.

2. A weighted average specific yield for each 3–metre (10–foot) depth increment was determined by computer.[1]

3. The averaged specific yield values were then converted to symbols for each of these intervals for the entire depth of the well. Four symbols appear on the computer print–out of each well log to represent four groupings of specific yield percentages as follows:

Symbol	*Range of Specific Yield (%)*	*Typical Material*
*	0	Rock
.	1 to 7	Clay and silt
-	8 to 12	Clay with fine sand
+	13 to 17	Fine sand
o	18 to 25	Coarse sand and gravel

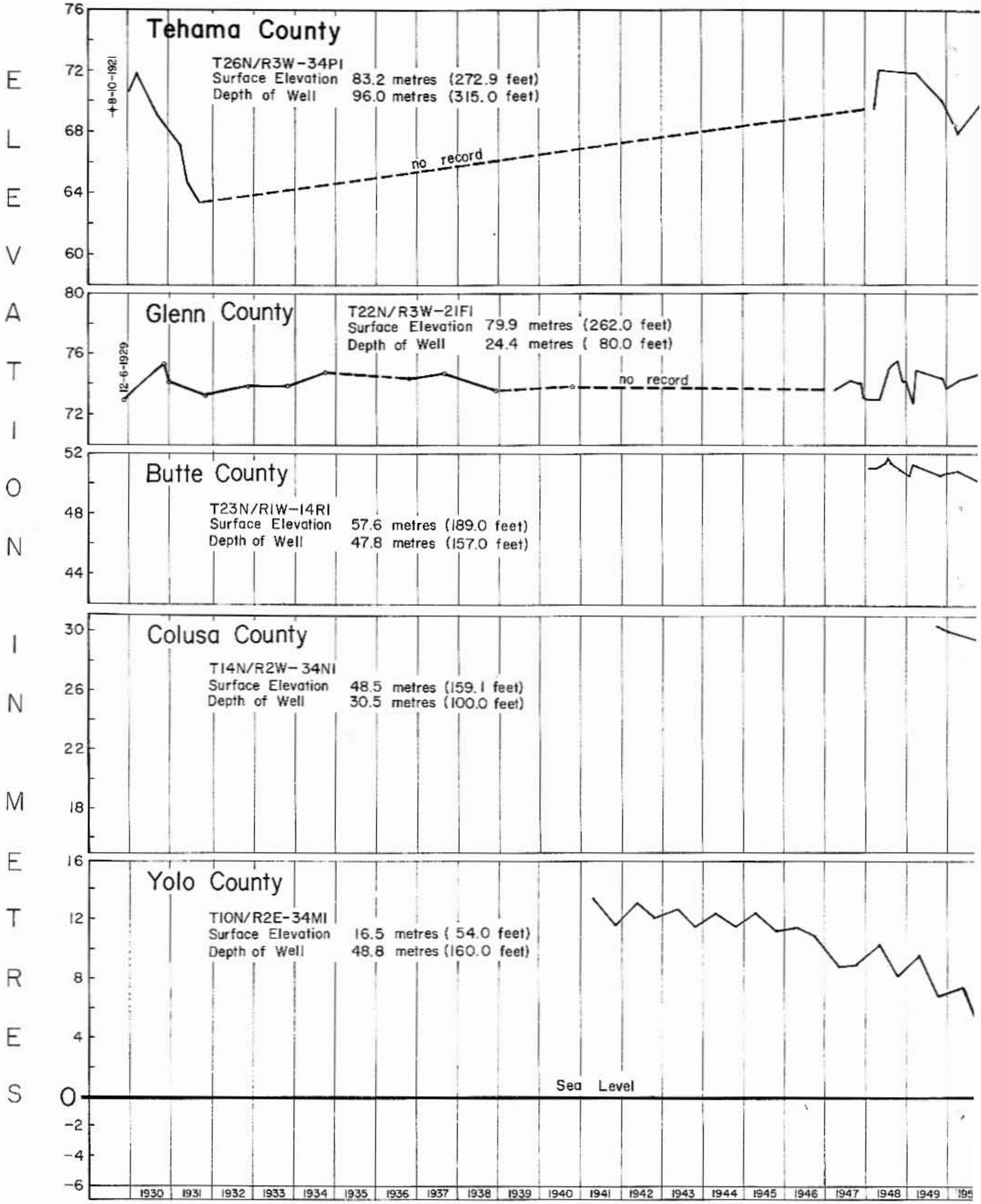
4. Specific yield symbols were also printed by computer on a four–township map with a scale of 1: 96 000, or 1 centimetre = 0.96 kilometre (approximately 0.6 inch = 1 mile). One map was printed for each 3–metre (10–foot) layer from the ground surface to a depth determined by the limits of the data. Two examples appear in Figure 10.

5. Geologic interpretation could then be made by comparing layers and tracing course–grained material downward and laterally. Aquifers were represented by the "+" symbol or an "o" symbol.

6. This procedure was followed for 57 nodes, imaginary points selected to present a given—in this case, four–township—area. Location of the nodes is shown in Figure 11.

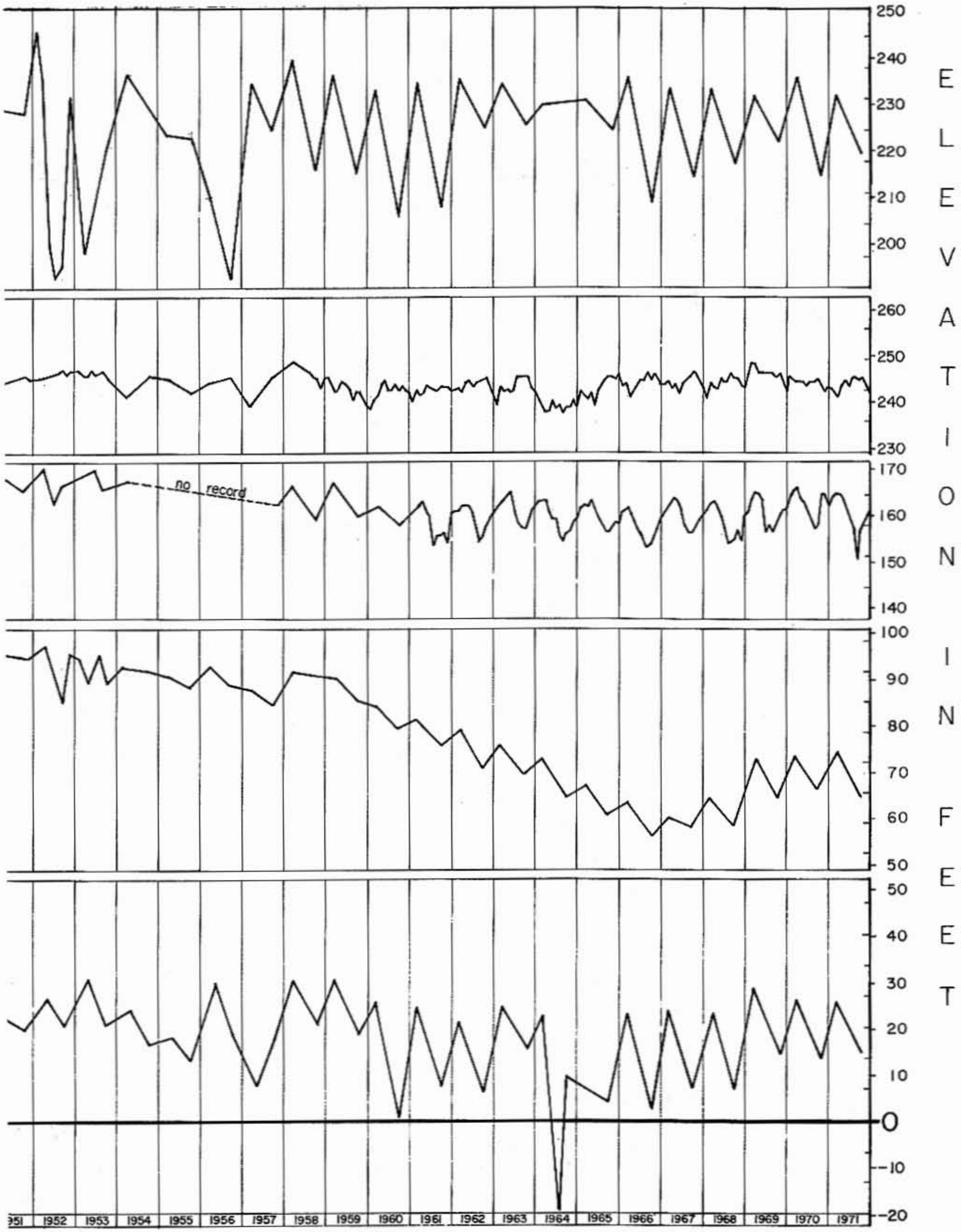
English equivalents: 1 kilometre (km) = 0.62 mile (mi).

[1] The computer program was designed to use English units of measure. Metric equivalents are provided, however. A closer rendering of 10 feet is 3.048 metres. For the sake of brevity, this is shortened to 3 metres.

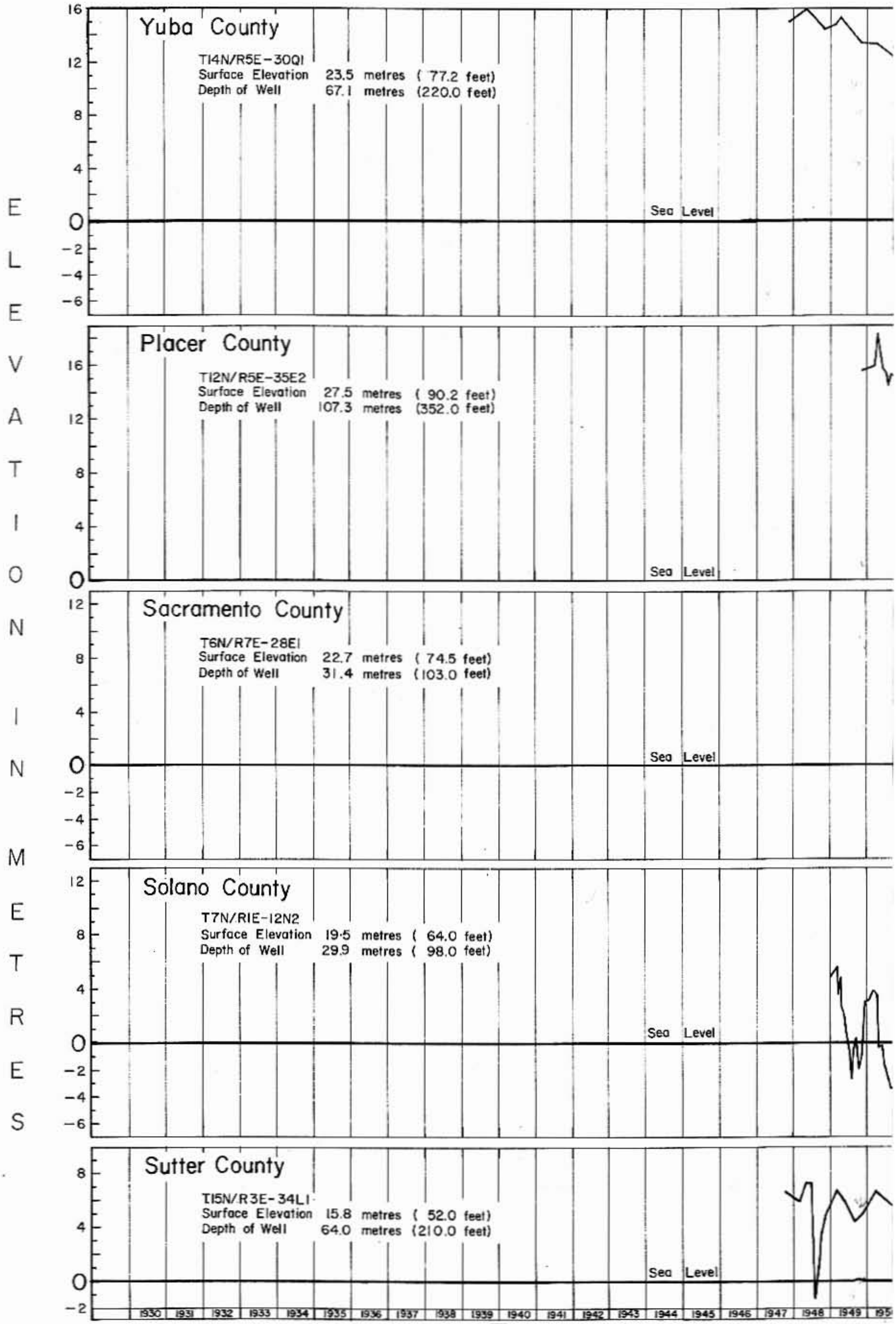


FLUCTUATION OF WATER

Figure 9

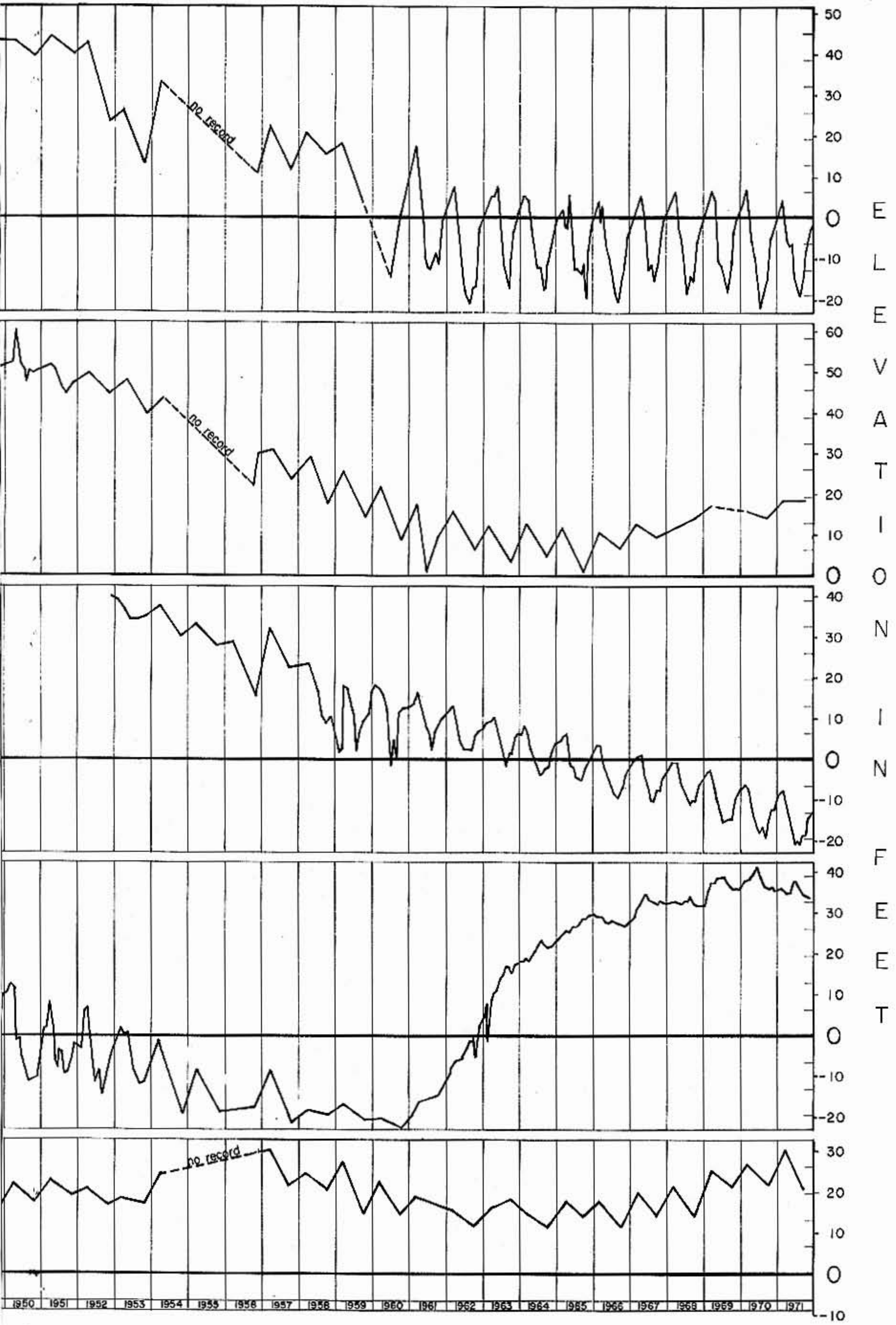


LEVEL IN WELLS

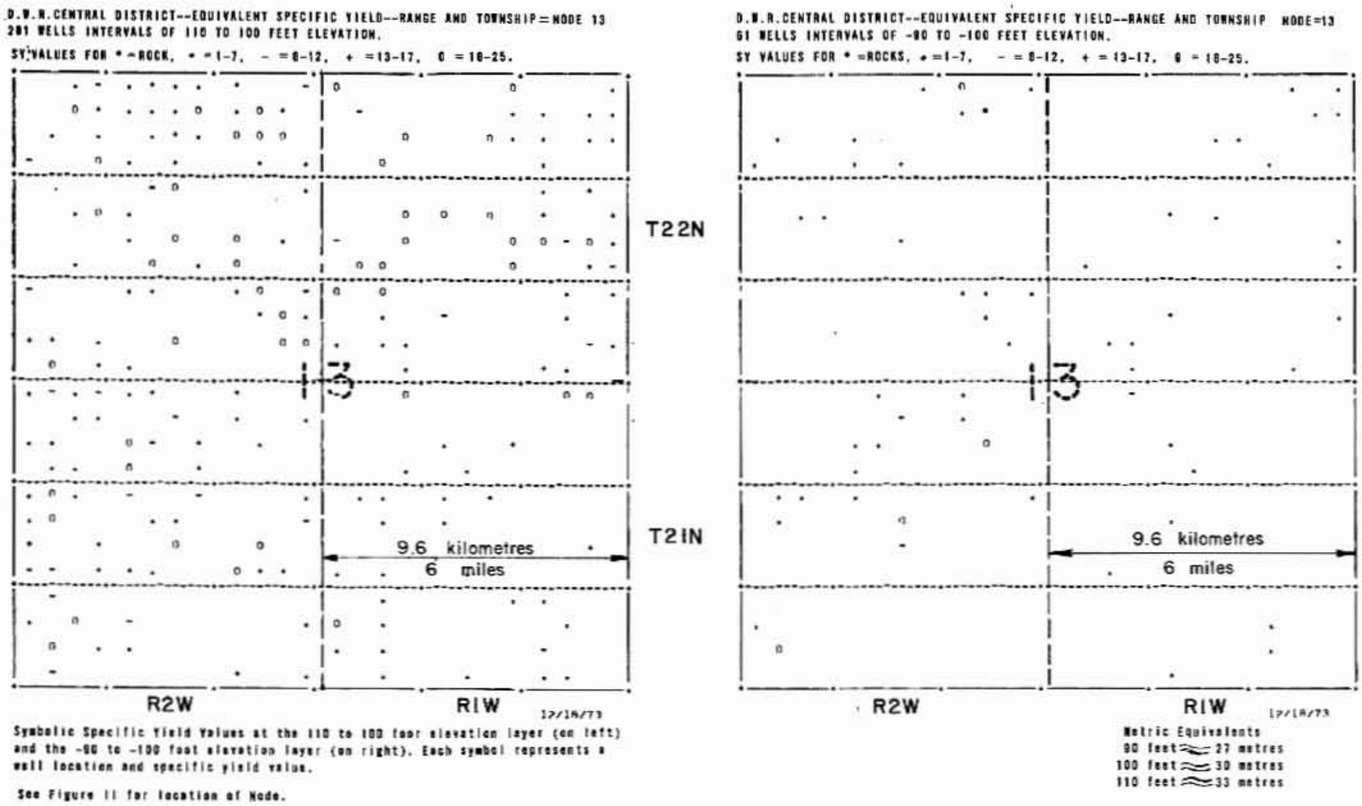


FLUCTUATION OF WATER

Figure 9
(continued)



LEVEL IN WELLS



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D.W.R.CENTRAL DISTRICT--EQUIVALENT SPECIFIC YIELD--RANGE AND TOWNSHIP=NODE 13
281 WELLS INTERVALS OF 110 TO 100 FEET ELEVATION.
SY VALUES FOR * -ROCK,  . =1-7,  - =8-12,  + =13-17,  0 =18-25.
```

```
D.W.R.CENTRAL DISTRICT--EQUIVALENT SPECIFIC YIELD--RANGE AND TOWNSHIP  NODE=13
61 WELLS INTERVALS OF -90 TO -100 FEET ELEVATION.
SY VALUES FOR * =ROCKS, . =1-7,   - = 8-12,  + = 13-17,  0 = 18-25.
```

Symbolic Specific Yield Values at the 110 to 100 foot elevation layer (on left) and the -90 to -100 foot elevation layer (on right). Each symbol represents a well location and specific yield value.

See Figure 11 for location of Node.

Metric Equivalents
90 feet ≈ 27 metres
100 feet ≈ 30 metres
110 feet ≈ 33 metres

Figure 10. Computer Printouts of Symbolic Specific Yield for Node 13

7. Data were further processed to determine volume of ground water in storage and transmissivity for each 3–metre (10–foot) layer in the node. An established relationship between specific yield and permeability was written into the program so that transmissivity value could be determined for the thickness of water–bearing material penetrated by wells.[1] An example of the transmissivity print–out is shown in Figure 12.

Computer data were too extensive for presentation in entirety in this report, nor was it possible to delineate all coarse–grained materials shown by print–out data. However, this information is on file with the Department of Water Resources and available for inspection.

Areas in the valley for which well log data were available for use in this computer program are shown in Figure 13. This map shows areas where data are abundant and where sparse or non–existent.

The computerized well log data were used in this report to construct three dimensional cross–sections of the valley at six locations. These sections, called "Specific Yield Diagrams" on Plates 3 and 4, depict three types of specific yield materials. These are: (1) rock with a yield of zero, (2) predominantly fine–grained materials (clay and silt and clay with fine sand) with a yield range of 1 to 12 percent, and (3) predominantly coarse–grained (fine sand and coarse sand and gravel) material having a specific yield range of 13 to 25 percent. These sections are basically intended to show relative amounts of coarse– and fine–grained materials. They do not necessarily delineate the extent of aquifers, but they do help locate aquifer–type bodies.

Specific–yield diagrams in Plate 3 illustrate the relative amounts of aquifer material in north Sacramento Valley. Diagram A, representing the Red Bluff area, shows considerable amounts of fine–grained sediments with thin coarse layers west of Red Bluff. These materials west of Red Bluff are part of the Tehama Formation. Coarse–grained layers are more abundant along the river and east of Red Bluff. These are largely stream–channel and floodplain deposits, but the deeper materials and rock shown at the extreme east end of the section are part of the Tuscan Formation.

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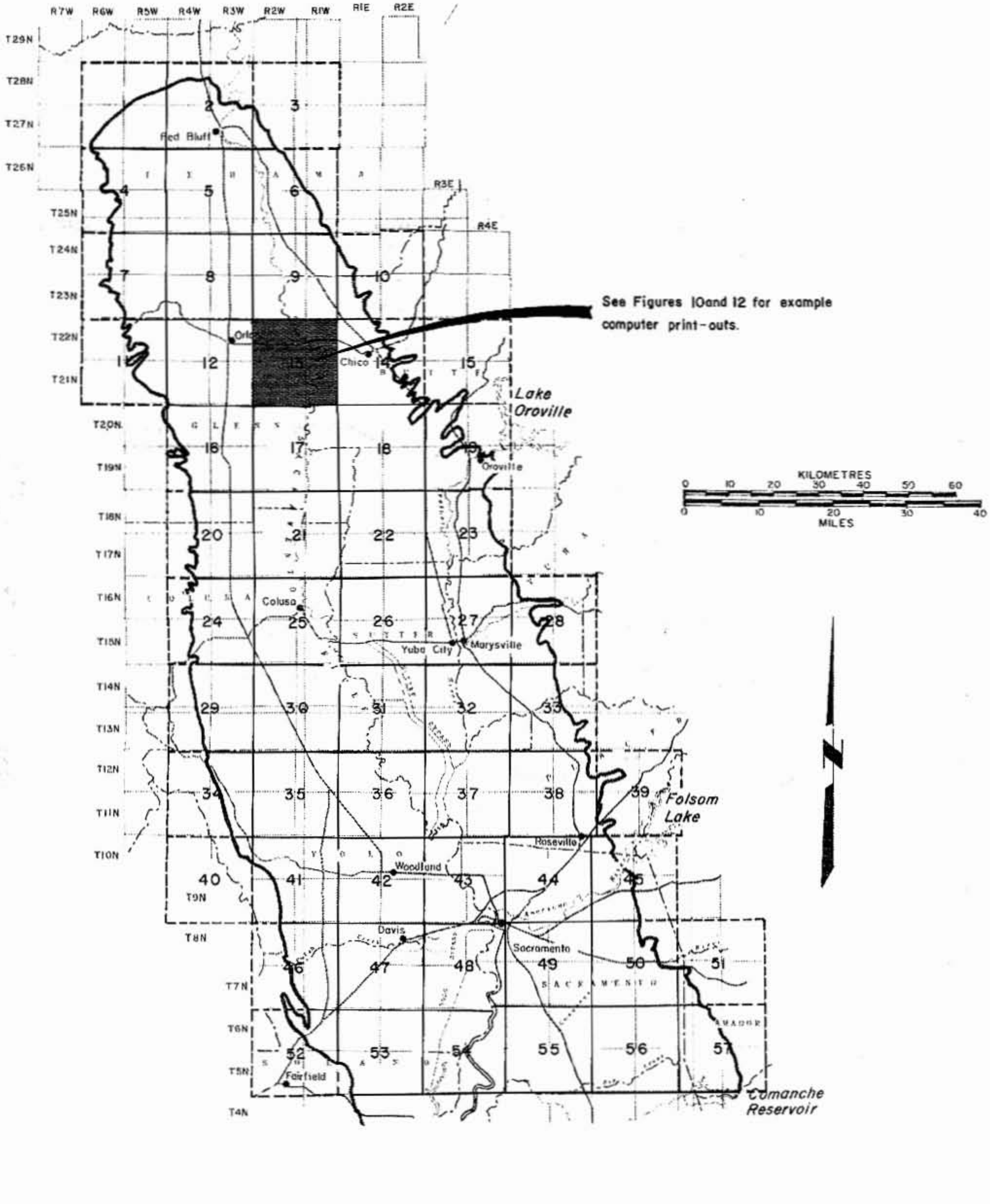
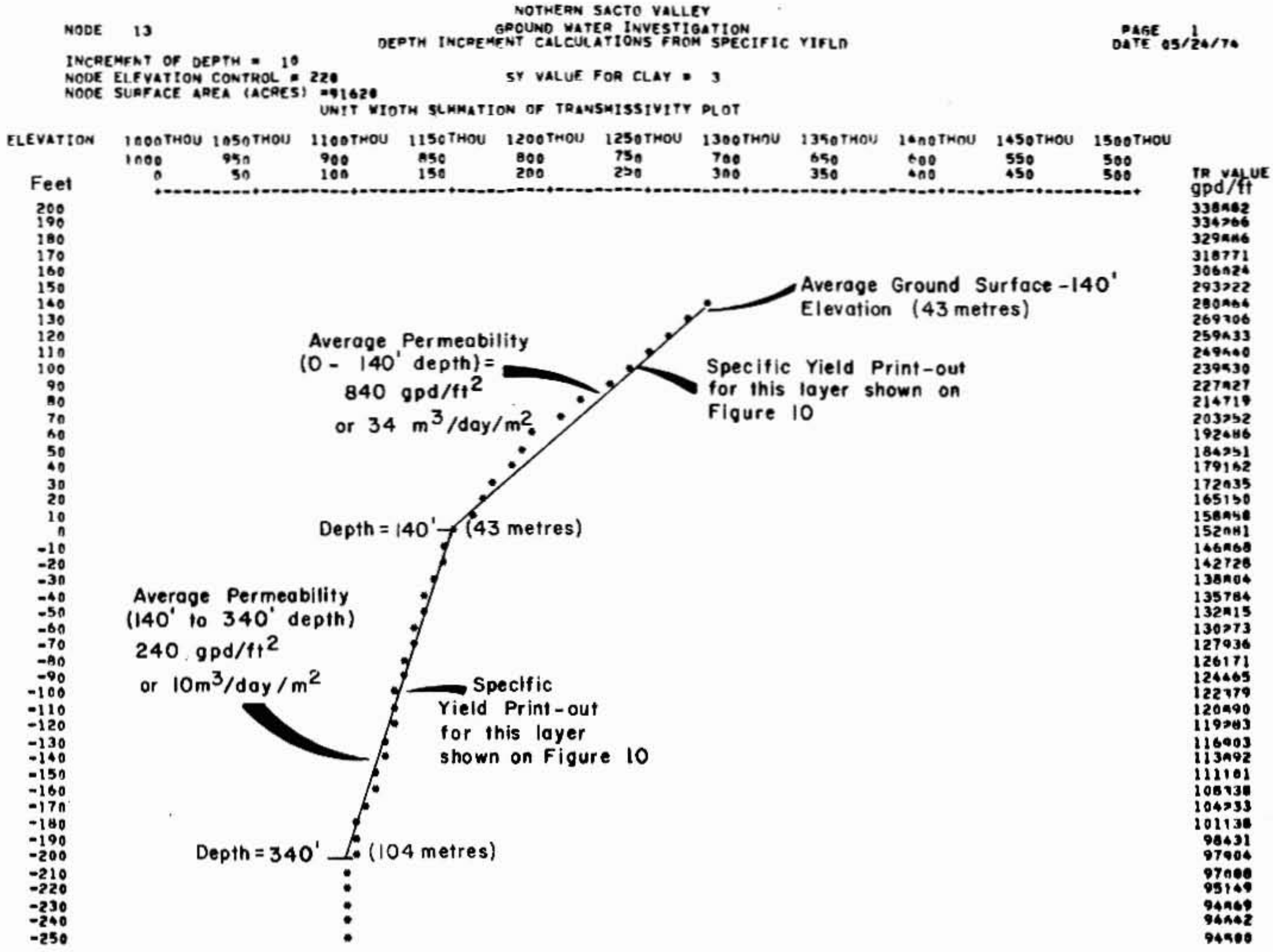
[1] Where permeability measures the rate at which water will flow through a unit cross–section of an aquifer, expressed in volume of water per day, transmissivity measures the flow–rate through the entire thickness of the aquifer per unit width. Transmissivity = permeability × thickness of aquifer.

English equivalents: 1 metre (m) = 3.28 feet (ft).



See Figures 10 and 12 for example computer print-outs.

Figure 11. Nodal Pattern for Aquifer Studies



```
                                        NOTHERN SACTO VALLEY
 NODE    13                          GROUND WATER INVESTIGATION                                      PAGE   1
                              DEPTH INCREMENT CALCULATIONS FROM SPECIFIC YIFLD                       DATE 05/24/74
 INCREMENT OF DEPTH =  10
 NODE ELEVATION CONTROL = 220                   SY VALUE FOR CLAY =  3
 NODE SURFACE AREA (ACRES) =91620
                          UNIT WIDTH SUMMATION OF TRANSMISSIVITY PLOT

ELEVATION  1000THOU 1050THOU 1100THOU 1150THOU 1200THOU 1250THOU 1300THOU 1350THOU 1400THOU 1450THOU 1500THOU
            1000      950      900      850      800      750      700      650      600      550      500
               0       50      100      150      200      250      300      350      400      450      500      TR VALUE
Feet          +---------+---------+---------+---------+---------+---------+---------+---------+---------+---------+     gpd/ft
 200                                                                                                                 338882
 190                                                                                                                 334766
 180                                                                                                                 329886
 170                                                                                                                 318771
 160                                                                                                                 306024
 150                                                                                                                 293722
 140                                                                                                                 280864
 130                                                                                                                 269706
 120                                                                                                                 259633
 110                                                                                                                 249640
 100                                                                                                                 239530
  90                                                                                                                 227827
  80                                                                                                                 214719
  70                                                                                                                 203752
  60                                                                                                                 192486
  50                                                                                                                 184751
  40                                                                                                                 179162
  30                                                                                                                 172035
  20                                                                                                                 165150
  10                                                                                                                 158858
   0                                                                                                                 152081
 -10                                                                                                                 146868
 -20                                                                                                                 142728
 -30                                                                                                                 138804
 -40                                                                                                                 135784
 -50                                                                                                                 132815
 -60                                                                                                                 130773
 -70                                                                                                                 127936
 -80                                                                                                                 126171
 -90                                                                                                                 124465
-100                                                                                                                 122979
-110                                                                                                                 120890
-120                                                                                                                 119783
-130                                                                                                                 116903
-140                                                                                                                 113892
-150                                                                                                                 111101
-160                                                                                                                 108938
-170                                                                                                                 104733
-180                                                                                                                 101138
-190                                                                                                                  98431
-200                                                                                                                  97904
-210                                                                                                                  97088
-220                                                                                                                  95149
-230                                                                                                                  94869
-240                                                                                                                  94642
-250                                                                                                                  94588
```

Figure 12. Computer Printout of Transmissivity

Diagram B, Orland to Chico, shows moderate amounts of fine-grained material west of Orland with a thin coarse layer at the surface. From Orland to the Sacramento River there are large amounts of coarse-grained materials at the surface, extending to depths of about 30 metres. These are part of the Stony Creek alluvial fan; the deeper fine-grained deposits are in the Tehama Formation. At the east end of the diagram, near Chico, alternating coarse- and fine-grained materials are in the Tuscan Formation. Zones of rock are Tuscan volcanic mudflows.

Diagram C, through Princeton and Biggs, shows predominantly fine-grained materials. Coarse-grained layers occur largely along the Sacramento River, Butte Creek, and the Feather River. These are part of the stream channels and floodplain deposits. The deeper fine-grained materials on the west are part of the Tehama Formation; those on the east are part of the Laguna Formation.

Plate 4 shows diagrams for the south portion of Sacramento Valley. Diagram D, Willows to Marysville, shows large amounts of fine-grained materials on the west side with increasing amounts of thin, coarse-grained layers near the river. Compared with the sections in the north valley, there does not appear to be as much coarse material along the river. From Meridian to Sutter, many well logs show thick layers of rock near Sutter Buttes. East of Sutter, particularly along the Feather and Yuba Rivers are thick coarse-grained deposits near the surface which represent stream channel and floodplain deposits of these rivers. The Yuba in particular has transported and deposited large amounts of sand and gravel.

Diagram E crosses the valley from Capay Valley to Roseville. All the material west of the Sacramento River was deposited on the Cache Creek alluvial fan. There are especially large amounts of sand and gravel along Cache Creek north of Esparto and numerous thick layers at depths to 120 metres in the area east to the Sacramento River. Many thick coarse-grained deposits are evident along the Sacramento near the confluence with the Feather. It is probable that these were transported by the Feather rather than the Sacramento River or Cache Creek. East of the Sacramento River to Roseville, the few well logs that are available indicate that predominant materials are fine-grained with thin layers of coarse materials in the Victor and Laguna Formations.

Diagram F shows relative amounts of coarse- and fine-grained materials along Putah Creek. Here, as along Cache Creek, numerous coarse layers occur to depths of 120 metres with no apparent change that might indicate the thickness of the alluvial fan. Thick layers of sand and gravel are evident at the east end of the sections. These may have been transported and deposited directly from the ancestral American River prior to its establishment at its present location.

It should be emphasized that in all diagrams where materials are shown to be predominantly fine-grained, thin zones of coarse materials that would yield water to wells are present. However, the amounts were not sufficient to cause the weighted average specific yield for each 3-metre layer to exceed 12 percent. Conversely, in the coarse materials there are thin fine-grained layers present but not in sufficient quantities to cause the average specific yield to be less than 13 percent.

As shown in the diagrams, vertical changes in specific yield are common throughout the valley. Changes in four-township areas were analyzed by computer in terms of transmissivity and permeability as explained in item 7 of "Aquifer Descriptions". An example of the computer print-out for Node 13 appears in Figure 12. The vertical changes in permeability appear abrupt on the graph, because variations are compiled and tabulated as if they all occurred at the node, which is merely a point designated to represent the entire four-township area. Usually, the changes are more gradual than shown on the graph.

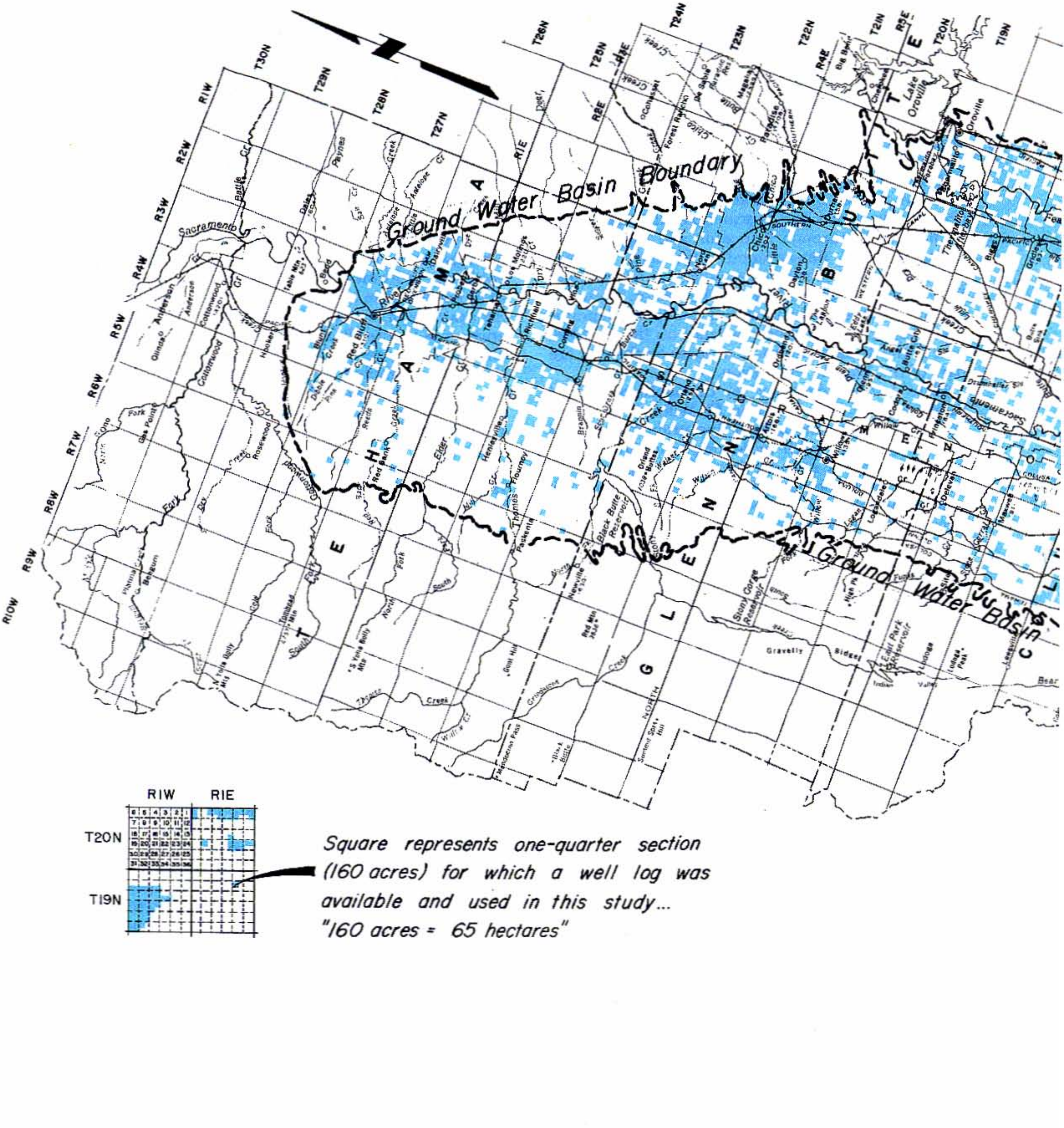
Accumulated transmissivity values are shown in this example for Node 13 (Figure 12), located in the lower portion of the Stony Creek fan. Here, a change of average specific yield (as well as permeability), occurs at a depth of 43 metres (140 feet). This change from coarse to more fine-grained material represents the change from alluvial fan-type materials to those characteristic of the Tehama Formation.

Specific-yield data for all other nodes were similarly processed. A summary of the information derived from all well data is presented in Table 3. This table shows changes in average specific yields, with depths, in terms of permeability, and includes interpretive remarks concerning the geologic significance.

Hydrologic Properties of Aquifers

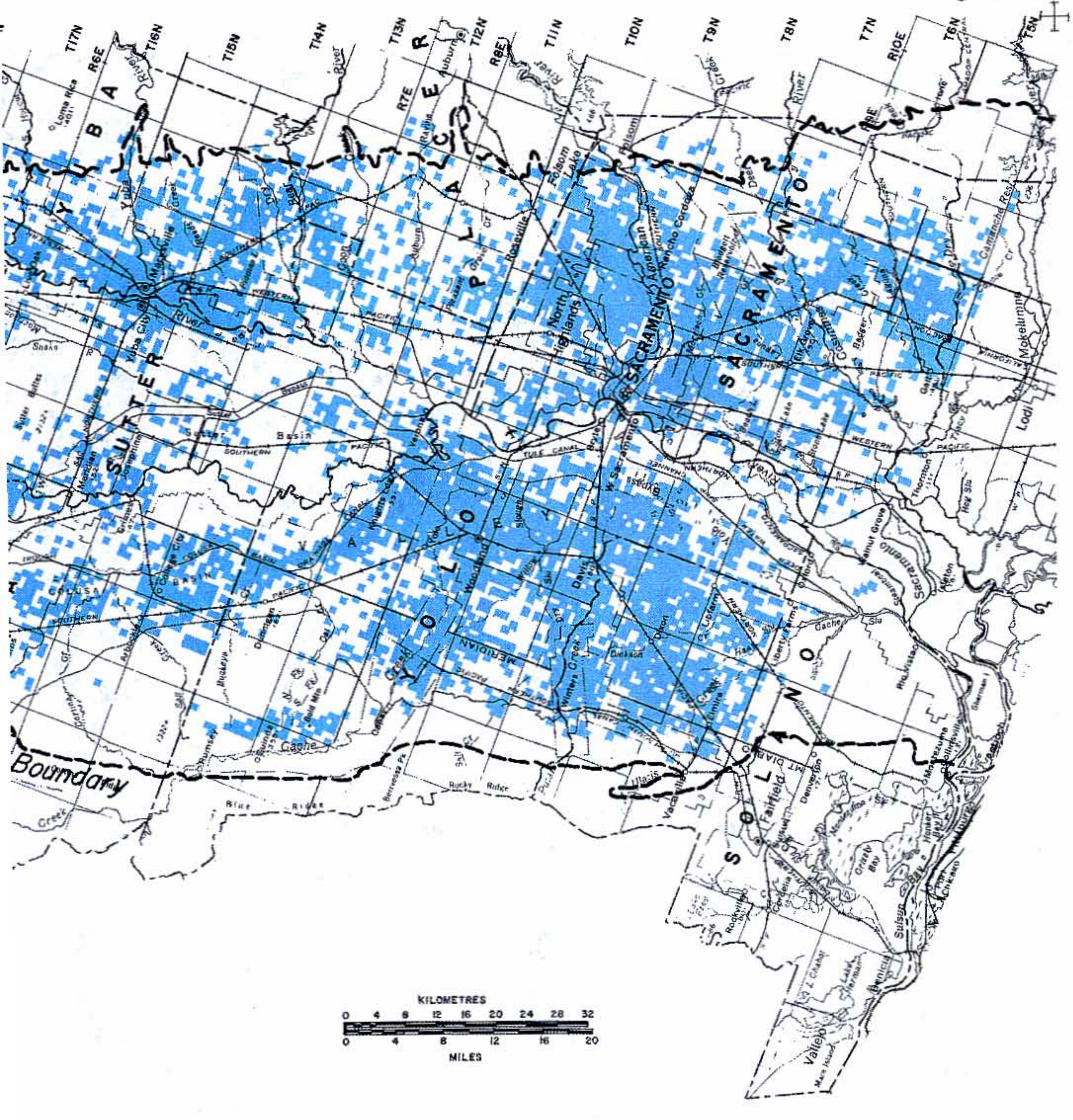
Most important among the hydrologic properties of aquifers and aquifer systems are (1) rate at which water can be transmitted through their porous media and (2) their ability to store water—transmissivity and storage coefficient. These properties, particularly transmissivity, govern yield and drawdown characteristics of a well. While yields are also related to such factors as pump size and well construction, transmissivity is most important. Specific capacity of a well, or the yield rate per unit, metre or foot of drawdown is directly related to transmissivity. These are discussed in following sections.

Transmissivity Distribution. The ability of an area to yield large, sustained amounts of ground water from wells depends on a continuous flow of ground water from a recharge source through materials with sufficient transmissive properties to sustain the yield. Low transmissivity of subsurface materials, com-



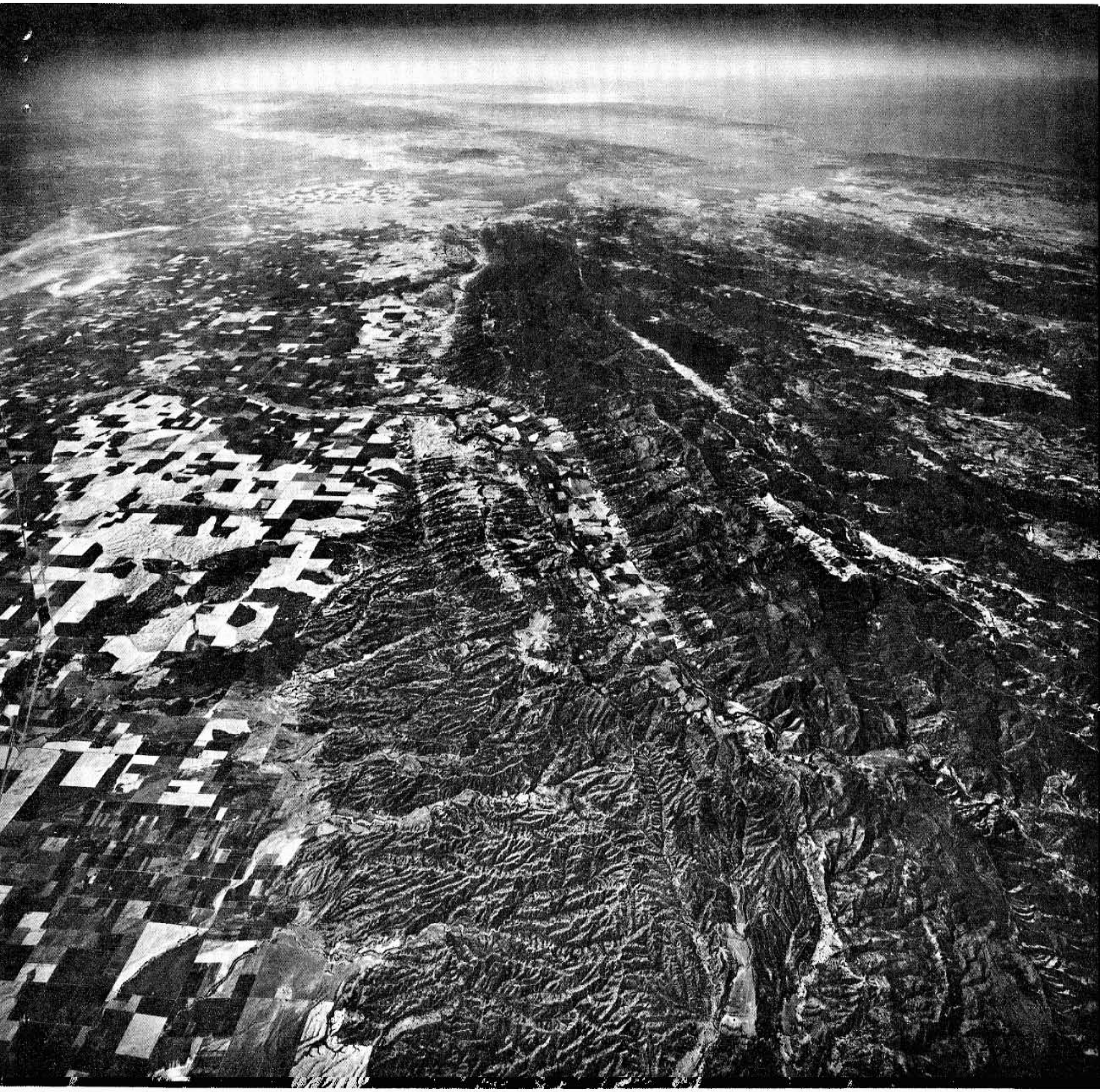
Square represents one-quarter section (160 acres) for which a well log was available and used in this study...
"160 acres = 65 hectares"

Figure 13



AVAILABILITY OF WELL LOG DATA

Putah Plain area of southwestern Sacramento Valley. Cache Creek on right and Putah Creek on left. Coastal Ranges in background.



Southwestern Sacramento Valley and Coast Ranges. Capay Valley in center.

TABLE 3

PERMEABILITY CHANGES WITH DEPTH FOR NODAL AREAS

Nodal Area Number	*Depth Interval*		*Approximate Average Permeability*		*Geologic Units and Materials Represented*
	Metres	*Feet*	*Metres^3/Day/Metre^2*	*Gal/Day/Ft^2*	
1	0–104	0–340	5	130	Tehama Formation
2	0–98	0–320	14	340	Tehama and Tuscan Formation; high permeability materials at 155–186 m may represent Tuscan Formation.
	98–155	320–510	8	210	
	155–186	510–610	23	570	
3	Insufficient Data				
4	Insufficient Data				
5	0–125	0–410	12	300	Tehama Formation; high permeability materials at 125–158 m are gravelly deposits laid down by the ancestrial Sacramento River.
	125–158	410–520	41	1,000	
	158–210	520–690	11	270	
6	0–21	0–70	30	730	Materials to a depth of 33 m are Sacramento River flood-plain deposits. Underlying materials are fanglomerate and Tuscan Formation.
	21–33	70–110	51	1,250	
	33–58	110–190	19	460	
	58–137	190–450	13	320	
7	0–73	0–240	5	130	Tehama Formation
8	0–174	0–570	10	240	Tehama Formation
9	0–40	0–130	30	740	High permeability material to 40 m represents Sacramento River flood plain materials. Underlying materials are fanglomerate and Tuscan Formation.
	40–125	130–410	6	160	
	125–198	410–650	2	40	
10	0–180	0–590	6	140	Fanglomerate
11	Insufficient Data				
12	0–40	0–130	22	530	Upper materials to 40 m are Stony Creek alluvial fan deposits; underlying materials are in the Tehama Formation.
	40–183	130–600	7	170	
13	0–43	0–140	34	840	Materials of high permeability to 43 m are Stony Creek alluvial fan deposits. Underlying materials are part of the Tehama Formation including some ancestrial Sacramento River alluvium.
	43–104	140–340	10	240	
	104–152	340–500	2	60	
14	0–36	0–120	12	300	Materials to a depth of 36 m represent in part Chico alluvial fan materials. From 36–168 m materials are fanglomerate and deep materials to 216 m are Tuscan Formation.
	36–168	120–550	4	100	
	168–216	550–710	17	420	
15	Out of basin				
16	0–204	0–670	9	220	Materials are thin west-side alluvial fans and Tehama Formation.
17	0–15	0–50	16	400	The high permeability materials to 33 m are Sacramento River flood plain deposits overlain by some flood basin deposits. Underlying materials are part of the Tehama Formation.
	15–33	50–110	47	1,160	
	33–55	110–180	15	370	
	55–100	180–330	4	110	
	100–116	330–380	44	1,080	
18	0–119	0–390	7	180	Materials throughout this depth zone are largely fine-grained with many intervals composed of sand which may be part of or derived from the Tuscan Formation.
	119–183	390–600	11	270	
19	0–40	0–130	28	680	Upper materials are Feather River alluvium underlain by old alluvium in the Victor and Laguna Formations.
	40–119	130–390	6	140	
20	0–104	0–340	2	40	West-side alluvial fan deposits underlain by Tehama Formation.
	104–222	340–730	8	210	
21	0–9	0–30	5	120	Shallow materials represent flood-basin deposits and underlying material is flood-plain deposits and Tehama Formation.
	9–149	30–490	20	500	
22	0–113	0–370	2	60	Materials throughout this depth zone are largely fine-grained with many intervals composed of sand which may be part of or derived from the Tuscan Formation.
	113–131	370–430	8	200	
	131–158	430–520	1	30	
23	0–33	0–110	18	450	Upper materials are Feather River alluvium underlain by old alluvium in the Victor and Laguna Formations.
	33–146	110–480	5	130	
24	0–21	0–70	9	220	Upper materials to 21 m represent thin alluvial fans; underlying material is Tehama Formation.
	21–180	70–590	2	60	
25	0–9	0–30	4	110	Upper material to 24 m represents flood-plain deposits; underlying materials are probably buried alluvial fans and Tehama Formation.
	9–24	30–80	32	780	
	24–76	80–250	8	200	
	76–97	250–320	32	780	
	97–250	320–820	13	330	
	250–265	820–870	75	1,850	
26	Sutter Buttes				

TABLE 3—Continued

PERMEABILITY CHANGES WITH DEPTH FOR NODAL AREAS

Nodal Area Number	*Depth Interval*		*Approximate Average Permeability*		*Geologic Units and Materials Represented*
	Metres	*Feet*	*Metres^3/Day/Metre^2*	*Gal/Day/Ft^2*	
27	0–12	0–40	21	520	Materials from 0–33 m represent stream channel and flood-plain deposits of the Feather and Yuba Rivers. Materials below 33 m are old alluvial deposits of the Victor and Laguna Formations.
	12–33	40–110	37	910	
	33–116	110–380	12	300	
	116–134	380–440	4	110	
	134–146	440–480	10	250	
28	Insufficient Data				
29	0–82	0–270	16	380	Materials in upper depth interval represent, in part, alluvial fans; underlying materials are in the Tehama Formation.
	82–198	270–650	8	200	
30	0–110	0–360	10	250	Most materials to 256 m are in the Tehama Formation. Alluvial fan and flood-basin deposits are included in upper interval.
	110–177	360–580	13	330	
	177–256	580–840	5	130	
31	0–6	0–20	4	100	Shallow deposits to 6 m are part of the Colusa and Sutter flood-basins; underlying materials probably represent the Tehama, Laguna, and Victor Formations.
	6–85	20–280	20	500	
	85–100	280–330	53	1,300	
	100–140	330–460	11	280	
32	0–30	0–100	20	500	Materials to 30 m represent Feather River stream channel and flood-plain deposits. Underlying less permeable materials are in the Laguna Formation.
	30–161	100–530	6	160	
33	0–24	0–80	11	260	Materials to 24 m represent, in part, Bear River flood-plain deposits and Victor Formation; underlying materials are in the Laguna Formation.
	24–46	80–150	3	70	
	46–168	150–550	6	160	
34	0–49	0–160	16	390	Materials in upper depth interval to 49 m are alluvial deposits in Capay Valley. These materials overlie the Tehama Formation.
	49–67	160–220	3	80	
	67–107	220–350	10	250	
35	Insufficient Data Dunnigan Hills				
36	0–30	0–100	20	480	Materials of moderate permeability to 30 m are mixed flood plain and alluvial fan deposits. Materials of high permeability from 43–174 m are in the south portion of node and appear to have been deposited by Cache Creek.
	30–43	100–140	6	140	
	43–146	140–480	22	530	
	146–174	480–570	36	890	
	174–189	570–620	7	180	
37	0–9	0–30	3	80	Shallow materials of low permeability represent flood-basin deposits and Victor Formation, underlying materials are in Laguna Formation.
	9–70	30–230	16	380	
	70–152	230–500	8	210	
38	0–140	0–460	6	140	Most of these materials to 152 m are in the Victor and Laguna Formations.
	140–152	460–500	21	510	
39	Insufficient Data				
40	Insufficient Data				
41	0–18	0–60	11	280	Materials from 0–55 m represent alluvial fan deposits; these deposits are underlain by Tehama Formation.
	18–55	60–180	20	500	
	55–168	180–550	8	210	
42	0–119	0–390	15	360	Alluvial fan deposits are included in the upper depth interval but are indistinguishable from the underlying Tehama Formation on the basis of permeability.
	119–143	390–470	36	880	
	143–195	470–640	13	310	
43	0–12	0–40	6	160	Materials in upper depth interval are alluvial fan deposits. High permeability material from 12–122 m represents buried Sacramento River channels on the east side of node.
	12–122	40–400	42	1,040	
	122–164	400–500	16	390	
44	0–79	0–260	4	100	Nearly all materials represent the Victor and Laguna Formation.
	79–140	260–460	16	380	
45	0–70	0–230	8	200	Most materials in this depth interval are Pleistocene gravels and Laguna Formation.
46	0–152	0–500	13	320	Most material in this depth interval is in the Tehama Formation.
47	0–110	0–360	13	310	Materials in upper depth interval are alluvial fan deposits laid down by Putah Creek. This material is indistinguishable from the underlying Tehama Formation on the basis of permeability.
	110–241	360–790	5	130	
	241–265	790–870	18	440	
	265–299	870–980	7	170	

TABLE 3—Continued

PERMEABILITY CHANGES WITH DEPTH FOR NODAL AREAS

Nodal Area Number	Depth Interval		Approximate Average Permeability		Geologic Units and Materials Represented
	Metres	Feet	Metres^3/Day/Metre^2	Gal/Day/Ft^2	
48	0–12	0–40	9	220	Shallow zone of low permeability represents alluvial fan and flood-basin deposits. Zones of high permeability beneath probably represent buried gravel channels of Putah Creek and Sacramento River.
	12–40	40–130	33	810	
	40–61	130–200	15	360	
	61–91	200–300	38	940	
	91–107	300–350	12	300	
	107–125	350–410	31	770	
	125–164	410–540	8	190	
49	0–91	0–300	6	150	Materials of low permeability are part of the Victor and Laguna Formations.
50	0–46	0–150	11	260	Materials of low permeability in upper depth interval are in the Laguna Formation. Underlying material of very low permeability may be Mehrten Tuff-breccia.
	46–85	150–280	1	20	
51	Insufficient Data				
52	0–104	0–340	10	250	Most of the material in all depth intervals is in the Tehama Formation.
	104–168	340–550	5	120	
	168–201	550–660	11	280	
53	0–137	0–450	8	200	Nearly all material is in the Tehama Formation.
	137–235	450–770	6	140	
	235–268	770–880	43	1,060	
54	0–6	0–20	6	150	Upper material of low permeability is flood-basin and fine-grained flood-plain deposits. Material of higher permeability to 73 m is probably buried stream channel deposits of the Sacramento River.
	6–21	20–70	48	1,170	
	21–73	70–240	21	510	
	73–91	240–300	7	180	
55	0–21	0–70	1	20	Materials to 58 m are largely part of the Victor and Laguna Formations. Low average permeability from 58–161 m may be due to tuff-breccia in the Mehrten Formation.
	21–58	70–190	11	260	
	58–161	190–530	1	20	
56	0–168	0–550	2	40	Low average permeability may be due mostly to presence of impervious tuff-breccia in Mehrten Formation.
57	Insufficient Data				

bined with large amounts of ground water withdrawals, can result in overdraft conditions. High transmissivity results in high yield rates over long periods, but can still result in overdraft conditions if the quantity pumped exceeds the supply.

As presented in the U. S. Geological Survey report (Appendix A) for the Sacramento Valley, transmissivity relates to the entire saturated thickness of post –Eocene deposits. Figure 3A of Appendix A shows distribution of transmissivity values as determined by ground water modeling by the USGS. Values range from 4 300 to 65 000 ft^2 per day (32,000 to 485,000 gallons per day per foot).[1] The area of highest transmissivity extends north from Sutter Buttes along the Sacramento River and east to the basin boundary. Except for the Stony Creek alluvial fan, transmissivity values decrease to the west due to the presence of the less permeable Tehama Formation and fine–grained materials from the Coast Ranges. Moderately high values along the northeast margin are a reflection of the Tuscan Formation, containing much volcanic sand. Transmissivities are lowest in the south Sacramento Valley except for small areas along the Sacramento River. Low values extend north along the east margin of the valley to Marysville and northwest along the west margin to Williams. However, transmissivity is high along the Feather River.

Low values of 4300 to 8700 ft^2 per day (32,000 to 65,000 gal/day/ft) along the west and southeast margins are reflections of more consolidated and fine–grained materials in the Pliocene Formations. These include the Mehrten and Laguna Formations on the east and the Tehama on the west beneath the alluvial fans of Putah Plain. High values in the center of the valley are due to the presence of coarse alluvial deposits which occur along the Sacramento River in decreasing amounts south to the American River.

Storage Coefficient. As stated in Chapter One, storage coefficient is the volume of water an aquifer takes into storage or releases from storage per unit surface area of the aquifer per unit change in head. ("Head", in this case, refers to elevation of water table.) Distribution of storage coefficient, as determined by the U. S. Geological Survey, is shown in

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English equivalents: 1 metre (m) = 3.28 feet (ft).

[1] The USGS reports transmissivity in ft^2/day. This unit is equivalent to ft^3/day/ft. For gallons per day per foot, multiply by 7.48.ft^3/day/ft = 0.0929 m^3/d/m.

Figure 4A, Appendix A. For the purposes of the USGS study, the water body was assumed to be unconfined; therefore, values of storage coefficient are equal to specific yield.

The values on Figure 4A are approximate and represent an average for the area indicated. They range from 0.04 to 0.12 (4 to 12 percent specific yield). High-yield materials, those with specific yields up to 25 percent, undergo reduced specific yield when mixed with finer-grained materials, causing them to fall within the ranges shown in this illustration. Values of 12 percent, therefore, can be understood to represent areas containing substantial amounts of coarse-grained materials.

As shown in Figure 4A, higher values of storage coefficient, from 0.08 to 0.12, occur along stream courses, while smaller values occur along valley margins in interstream areas. Also, the south valley contains materials having lower values than the north valley. These correspond with the trends shown in the transmissivity map.

Well Yields and Specific Capacity. Data concerning discharge of wells and specific capacity of wells were obtained from pump efficiency tests made by the Pacific Gas and Electric Company and the Sacramento Municipal Utility District. These were supplemented by information contained in drillers' reports on wells for which pump tests were conducted.

The average discharge or yield of wells was determined for each township where data were available without regard to well depth. For many townships no data were available; in such cases estimates were made on the basis of geologic conditions and well-yield data from adjacent townships with similar geology. Because many wells are not being pumped at their maximum yield rates or yield data are for shallow wells, values were adjusted to better reflect available yield from properly constructed wells of moderate depth (90 to 150 metres).

Figure 14 shows four categories of yield: low, moderate, moderately high, and highest, based on geology and known data. In any of the areas surveyed it would be possible to obtain greater yields if wells were unusually deep or pumped at their maximum capacities. The map is intended to describe relative average conditions for large areas rather than potential yields of individual wells or small areas. Well yields are also discussed in Appendix A and shown in Figure 7A.

Figure 14 shows that the highest yields are attainable in the central part of the basin from Orland to south of Sutter Buttes. This area corresponds to the area of large sand and gravel deposits in the floodplain of the Sacramento River and alluvial fan of Stony Creek. High yield rates are also possible in the Marysville and Woodland-Davis areas, where considerable sand and gravel deposits occur. Yield rates decrease to the east and west and are lowest along the west side of the basin, where wells would obtain water from the more fine-grained Tehama Formation or alluvial fans containing little coarse-grained material. Yields are low in the south portion of Sacramento County, where overall permeability of the Laguna and Mehrten Formations is low.

Specific capacity of a well—as stated earlier—is the discharge in litres per minute divided by the drawdown—the lowering of water from the static level to the pumping level—in metres. Specific capacity is not only a measure of the productivity of the well, but also of the aquifer transmissivity. High specific capacities usually indicate high transmissivities for the aquifers supplying the well, while low values indicate low transmissivity or poor construction resulting in inefficient wells. Figure 15 shows values for three ranges: low, moderate, and high, compiled on a township basis.

Areas of high specific capacity do not necessarily correspond to areas of highest well yield. For example, high pump lifts may cause yields to be low, but the amount of water obtained per unit of drawdown may be high. In two areas, yield and capacity correspond roughly. Areas of highest specific capacity wells in the north central part of the valley, from near Red Bluff to Colusa, correspond to the area of highest potential well yields. Also, the Woodland area has wells of high specific capacity and high yield because of the abundance of water-bearing gravel in the Cache Creek alluvial fan. The Davis area, situated on the Putah Creek alluvial fan, has lower specific capacity wells than the Woodland area, but yields remain high.

Specific capacity of wells decreases to the east and west because of the lower transmissivity of the older geologic formations present at the edges of the basin. In a general way, specific capacity and well yield maps reflect the varying values of transmissivity shown on Figure 3A of Appendix A.

Replenishment of Ground Water

Under natural conditions, ground water is replenished by percolation of streamflow into underlying permeable materials and direct infiltration of precipitation falling on permeable soils. A third source in the Sacramento Valley, subsurface inflow from the Tuscan Formation, which bounds the basin between Oroville and Red Bluff, will not be examined in this report, as its magnitude cannot be determined. However, it is considered small compared to recharge from other sources. For inventory purposes and for the USGS model, subsurface inflow is assumed to be zero. Under present-day conditions of basin-use, a fourth source of replenishment is deep percolation of water applied for irrigation. Each re-

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English equivalents: 1 metre (m) = 3.28 feet (ft).

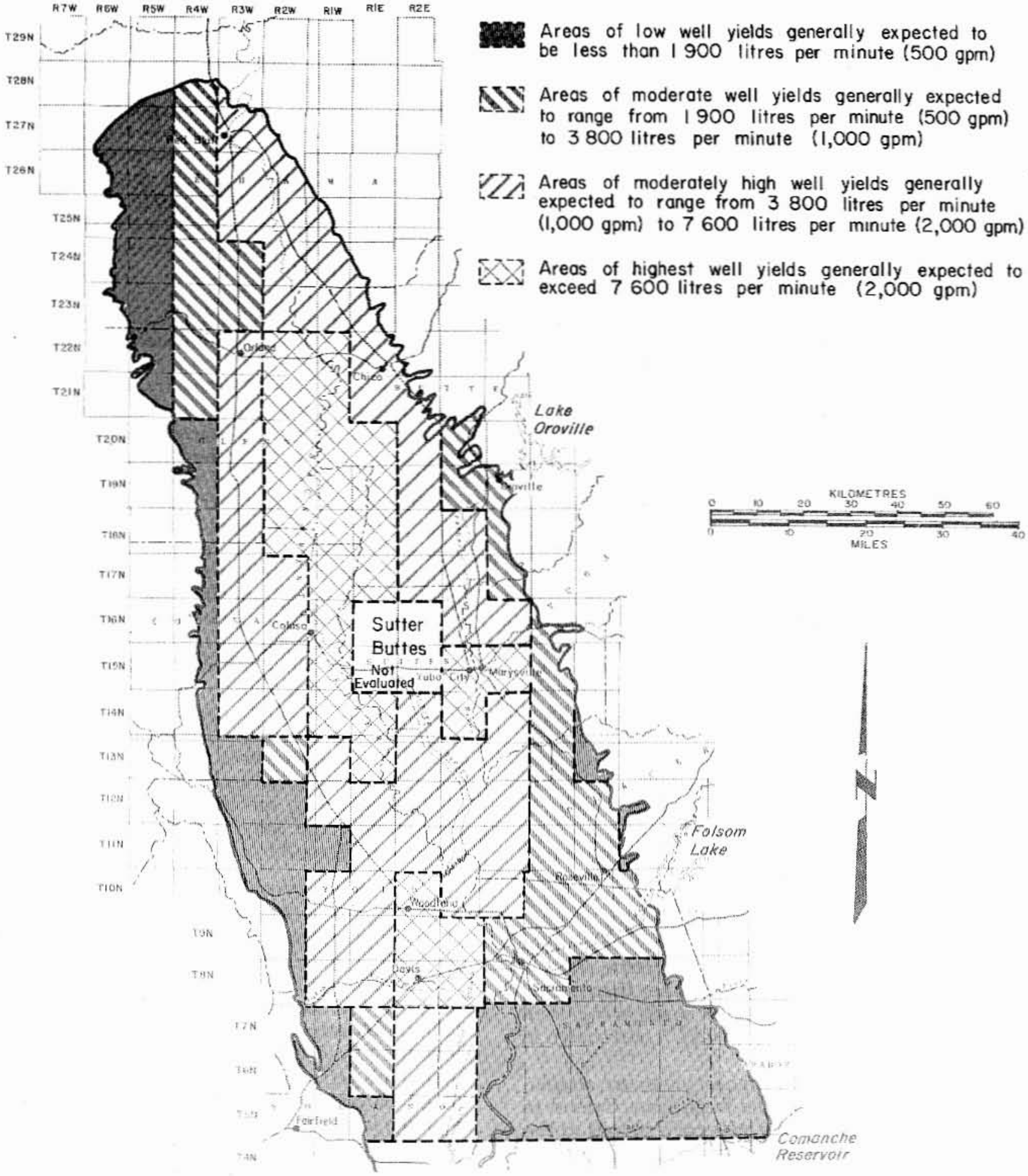

Figure 14. Well Yields

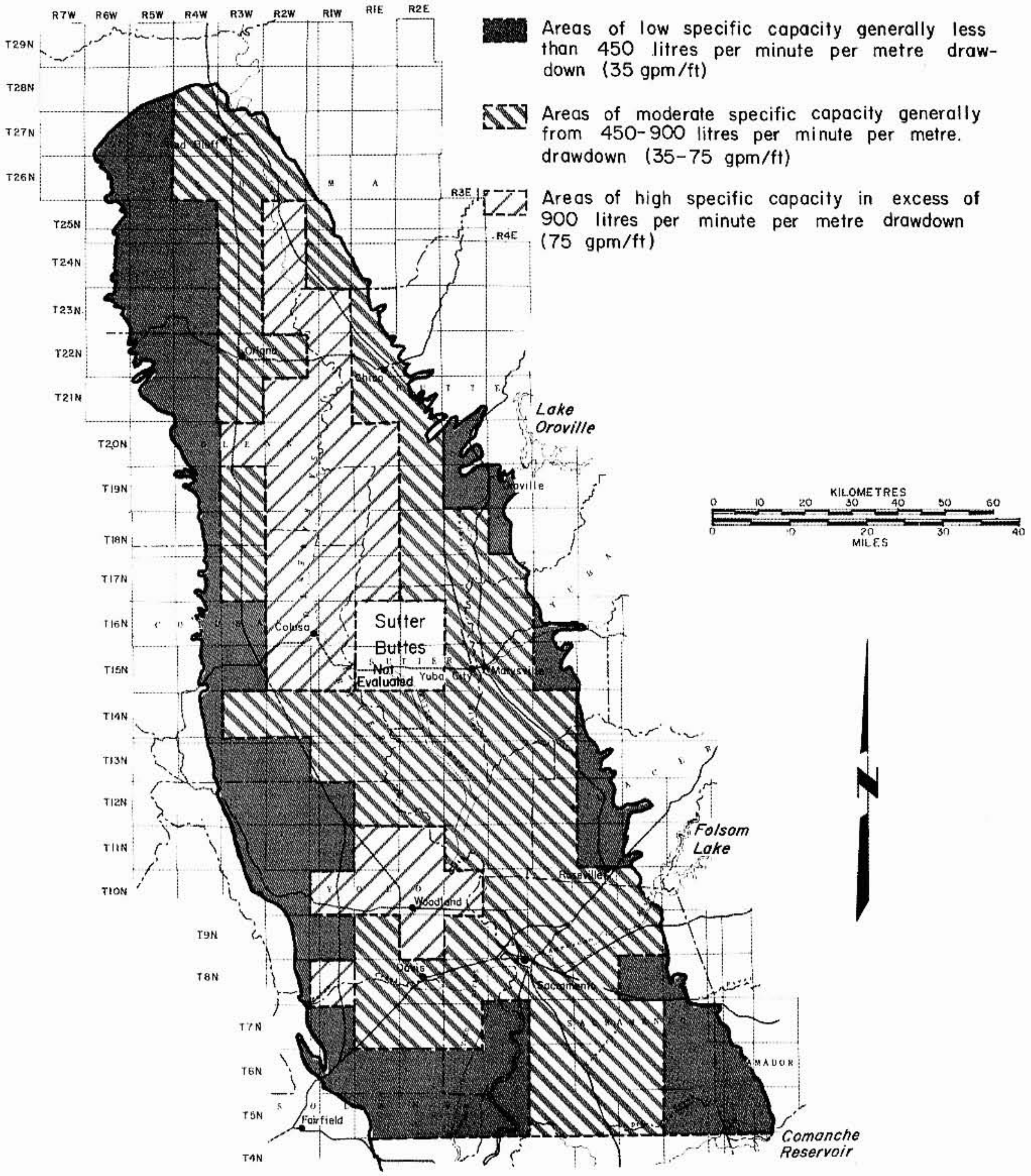

Figure 15. Specific Capacity of Wells

Sacramento River near Red Bluff

Mill Creek east of Los Molinos. The stream is incised into sedimentary rocks of the Fanglomerate unit.

charge source is discussed briefly below and at greater length in Chapter IV, which presents an inventory of water supply and disposal.

Deep percolation of streamflow is a substantial source of ground water replenishment. Most occurs along major streams with sustained flow and coarse gravel deposits. The major streams tributary to the Sacramento River have existed in approximately the same location throughout the Quaternary period. During this period, thick deposits of sand and gravel have accumulated and promote recharge.

Major recharge areas determined by the USGS lie adjacent to major streams entering the basin around its margin. Analysis was made by assigning values for transmissivity and head (water level elevation) and solving for flux (net percolation). Thus, recharge for various areas around the margin of the valley takes into consideration both stream percolation and deep percolation of precipitation. Percentage of total valley recharge was determined for various areas under natural conditions as shown in Figure 6A, Appendix A.

The greatest amount of natural recharge, 20.7 percent of the valley total, occurs in the Stony Creek area. This is followed by 10.1 percent for the Thomes Creek area. Between Red Bluff and Thomes Creek, 3.4 percent of the recharge occurs. Thus over one–third of the total natural recharge occurs along the northwest margin of the valley. Other areas of recharge are along the northeast side of the valley between Red Bluff and Chico (7.4 percent) and in the Chico area (6.5 percent). These and other identified recharge areas north of Sutter Buttes account for over two–thirds of the total valley recharge under natural conditions. The remaining one–third occurs in the Yuba, Bear, and American River areas, in small areas along the west side, and in the Sacramento River area.

Deep percolation of water derived from the unconsumed portion of water applied for irrigation is also an important source of replenishment. The total amount of water applied in 1970, for example, amounted to 7 780 hm^3 as determined by land and water use surveys (see Table 6, Appendix A for distribution by township). Of this amount, only a small portion percolated to the ground water reservoir. The remainder was consumed by evapotranspiration or ran off as streamflow. As discussed in Chapter IV, the importance of this source is secondary to the combination of streamflow and precipitation.

Only lands with sufficiently permeable soil permit percolation. Soils containing hardpan occupy over half the valley on the east side of the Sacramento River (see Figure 5), and these severely restrict downward movement of water. Clayey soils also impede percolation and occupy over one–half the west side, along with small areas of hardpan. Soils with few barriers to vertical flow exist along the Sacramento River, Stony Creek fan, Chico fan, Feather River, American River, Cache and Putah Creeks, and other smaller streams.

Ground Water Discharge

As ground water moves from areas of intake, it must either fill the storage space available or be discharged from the system. If the basin is at full capacity, there can be no increase in storage and ground water discharges at the low points in the system, directly to the Sacramento River or other streams, and by evapotranspiration from vegetation.

Because ground water levels at the Delta are at sea level or below, no discharge takes place via subsurface outflow. There, the hydraulic gradient is either flat, allowing for no flow, or reversed from the normal delta gradient.

The USGS reports that under natural conditions, the largest part of the total discharge of about 1 000 cubic hectometres (830,000 acre–feet) per year occurs in the north valley. Discharge in this area is due partly to the barrier effect of Sutter Buttes. As ground water moves southward, it is forced to go around Sutter Buttes. Since the basin cannot accommodate this much water moving around the Buttes, it is forced to rise and discharge to the surface or to be disposed of by transpiration. The remainder of the discharge occurs on the south valley floor and the central valley floor.

Pumpage

Ground water is extracted by pumping for irrigation, municipal, industrial, and domestic consumption. Pumpage may substantially exceed consumption, but some returns to the ground water reservoir through percolation and is eventually available again for pumping.

Pumpage estimates were determined by land and water use surveys, the first for the entire basin in 1961. Later surveys were done on a county basis between 1967 and 1970. From these, estimates were made of the area served only by ground water. For surveys made prior to 1970, the data were extended to 1970 by use of reports on crop production from county agricultural commissioners. Pumpage was determined for each year from 1961 to 1970 on 1/4 township–size areas. Distribution of pumpage for 1961 and 1970 is shown graphically by township on Figure 16 and tabulated in Table 4. Areas where ground water was used for irrigation in 1970 are shown on Plate 1.

Total ground water pumpage for 1961 was estimated at 2 228 cubic hectometres (hm^3). Although agriculture expanded during the next 10 years, pumpage increased only slightly to 2 242 hm^3. More wells were drilled, but increases in ground water use for some areas were offset by shifts to surface water

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English equivalents: 1 metre (m) = 3.28 feet (ft). 1 hectare (ha) = 2.47 acres (ac). 1 cubic hectometre (hm^3) = 810.7 acre–feet (ac–ft).

TABLE 4

GROUND WATER PUMPAGE BY TOWNSHIP SACRAMENTO VALLEY 1961 and 1970

Township	*1961*		*1970*	
	Cubic Hectometres	*(Acre-feet)*	*Cubic Hectometres*	*(Acre-feet)*
4N/8E	6.0	4,900	5.1	4,100
4N/7E	56.7	46,000	62.8	50,900
4N/6E	32.0	25,900	40.1	32,500
4N/5E	0	0	0	0
4N/4E	0	0	0	0
4N/3E	0.7	600	1.1	900
4N/2E	2.2	1,800	4.0	3,200
4N/1E	0	0	0	0
5N/8E	0	0	0	0
5N/7E	8.9	7,200	17.3	14,000
5N/6E	35.8	29,000	36.6	29,700
5N/5E	22.6	18,300	31.4	25,500
5N/4E	4.1	3,300	3.8	3,100
5N/3E	0	0	0	0
5N/2E	0	0	0	0
5N/1E	0	0	0.1	100
5N/1W	0	0	0	0
6N/8E	0	0	0	0
6N/7E	13.1	10,600	14.3	11,600
6N/6E	30.1	24,400	32.4	26,300
6N/5E	35.3	28,600	39.0	31,600
6N/4E	6.7	5,400	6.5	5,300
6N/3E	0	0	0	0
6N/2E	5.1	4,100	4.6	3,700
6N/1E	4.4	3,600	4.7	3,800
6N/1W	0	0	0	0
7N/8E	0.5	400	0	0
7N/7E	18.3	14,800	18.5	15,000
7N/6E	20.0	16,200	20.2	16,400
7N/5E	41.0	33,200	26.8	21,700
7N/4E	1.8	1,500	1.8	1,500
7N/3E	1.1	900	2.0	1,600
7N/2E	34.4	27,900	35.6	28,900
7N/1E	4.1	3,300	3.0	2,400
7N/1W	4.0	3,200	5.7	4,600
8N/8E	0	0	0	0
8N/7E	6.2	5,000	6.2	5,000
8N/6E	24.7	20,000	24.2	19,600
8N/5E	38.9	31,500	43.5	35,300
8N/4E	12.3	10,000	13.3	10,800
8N/3E	22.6	18,300	20.1	16,300
8N/2E	33.2	26,900	51.3	41,600
8N/1E	30.6	24,800	33.9	27,500
8N/1W	32.8	26,600	37.2	30,200
8N/2W	0.2	200	0.1	100
9N/7E	0.2	200	0.2	200
9N/6E	18.4	14,900	27.4	22,200
9N/5E	33.2	26,800	47.9	38,800
9N/4E	29.7	24,100	34.4	27,900
9N/3E	8.6	7,000	5.7	4,600
9N/2E	38.5	31,200	29.8	24,200
9N/1E	5.6	4,500	9.9	8,000
9N/1W	4.2	3,400	7.9	6,400
9N/2W	0.4	300	1.8	1,500

TABLE 4—Continued

GROUND WATER PUMPAGE BY TOWNSHIP
SACRAMENTO VALLEY
1961 and 1970

	1961		*1970*	
Township	*Cubic Hectometres*	*(Acre-feet)*	*Cubic Hectometres*	*(Acre-feet)*
10N/8E	0	0	0	0
10N/7E	0.1	100	0.1	100
10N/6E	13.9	11,300	16.8	13,600
10N/5E	21.8	17,700	22.0	17,800
10N/4E	6.2	5,000	5.4	4,400
10N/3E	4.7	3,800	2.8	2,300
10N/2E	39.5	32,000	39.5	32,000
10N/1E	23.3	18,900	22.3	18,100
10N/1W	20.8	16,900	16.6	13,500
10N/2W	1.5	1,200	1.8	1,500
11N/6E	0.5	400	0.9	700
11N/5E	20.5	16,600	6.4	5,200
11N/4E	28.0	22,700	24.6	19,900
11N/3E	11.1	9,000	11.1	9,000
11N/2E	25.0	20,300	21.2	17,200
11N/1E	27.8	22,500	28.6	23,200
11N/1W	0.5	400	0.5	400
11N/2W	1.8	1,500	3.0	2,400
12N/6E	0	0	0	0
12N/5E	23.6	19,100	13.7	11,100
12N/4E	42.7	34,600	23.9	19,400
12N/3E	2.2	1,800	2.1	1,700
12N/2E	0.6	500	0.6	500
12N/1E	0	0	0	0
12N/1W	12.6	10,200	16.4	13,300
12N/2W	0.1	100	1.0	800
13N/6E	0	0	0.2	200
13N/5E	33.6	27,200	12.3	10,000
13N/4E	42.9	34,800	29.0	23,500
13N/3E	12.3	10,000	12.6	10,200
13N/2E	0	0	0	0
13N/1E	0.6	500	0.2	200
13N/1W	23.2	18,800	11.5	9,300
13N/2W	22.4	18,200	22.2	18,000
13N/3W	0.4	300	0.5	400
14N/5E	28.0	22,700	26.0	21,100
14N/4E	43.2	35,000	48.2	39,100
14N/3E	42.3	34,300	44.8	36,300
14N/2E	0	0	0	0
14N/1E	4.8	3,900	1.7	1,400
14N/1W	11.1	9,000	7.3	5,900
14N/2W	23.1	18,700	15.2	12,300
14N/3W	3.8	3,100	7.0	5,700
15N/5E	3.0	2,400	3.4	2,800
15N/4E	30.3	24,600	28.6	23,200
15N/3E	51.3	41,600	50.7	41,100
15N/2E	18.5	15,000	17.2	13,900
15N/1E	5.3	4,300	5.3	4,300
15N/1W	8.5	6,900	4.6	3,700
15N/2W	8.5	6,900	8.7	7,100
15N/3W	10.7	8,700	7.6	6,200
15N/4W	0.5	400	1.0	800

TABLE 4—Continued

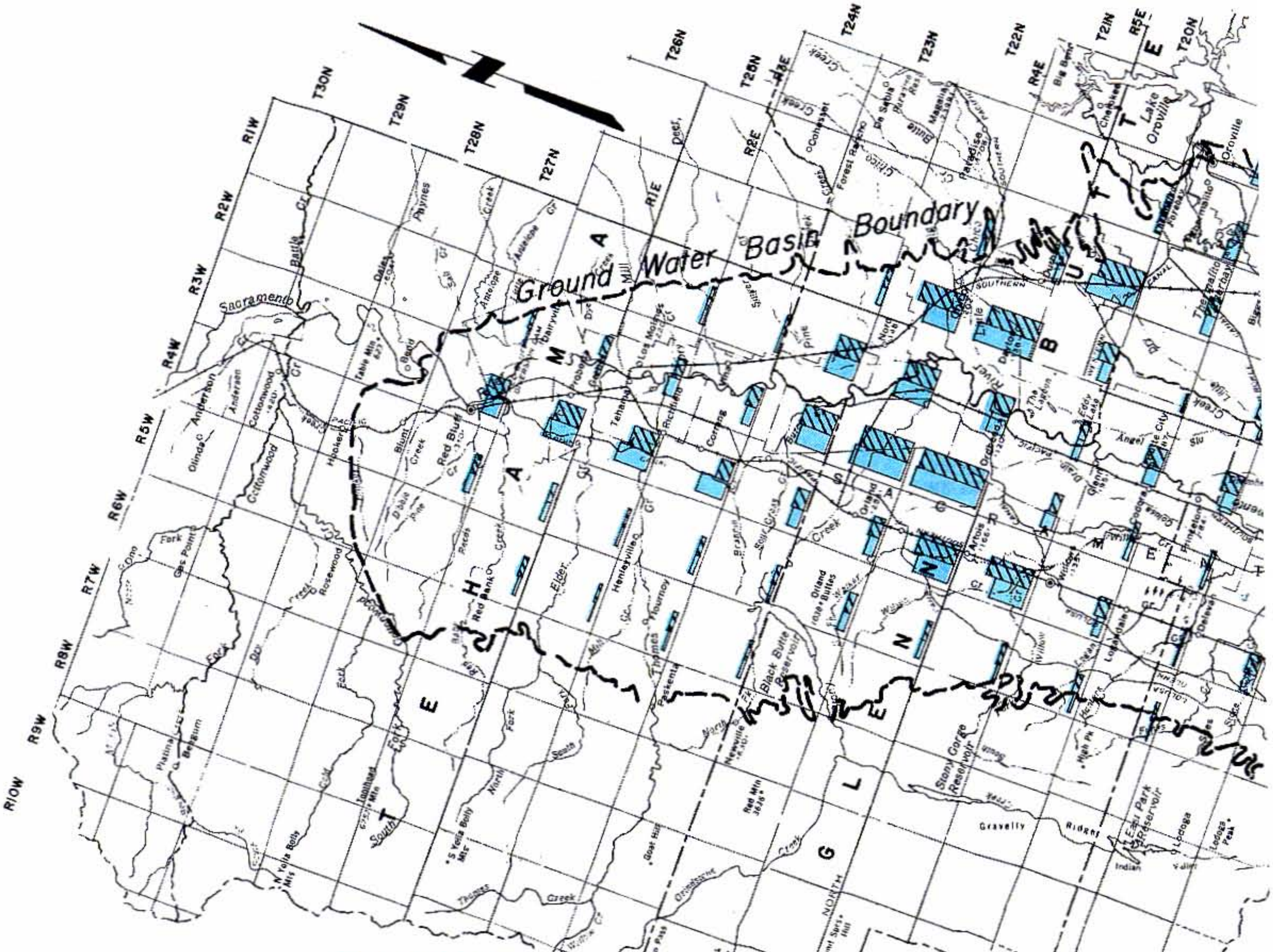
GROUND WATER PUMPAGE BY TOWNSHIP
SACRAMENTO VALLEY
1961 and 1970

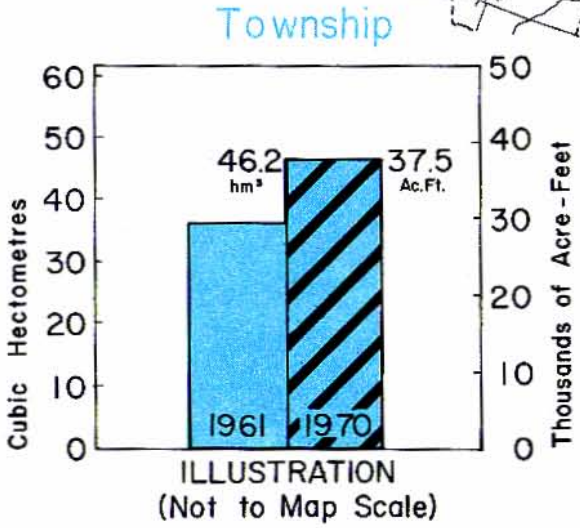
	1961		*1970*	
Township	*Cubic Hectometres*	*(Acre-feet)*	*Cubic Hectometres*	*(Acre-feet)*
16N/5E	0	0	0	0
16N/4E	13.1	10,600	5.4	4,400
16N/3E	32.4	26,300	34.7	28,100
16N/2E	1.6	1,300	2.8	2,300
16N/1E	2.3	1,900	2.2	1,800
16N/1W	5.8	4,700	4.9	4,000
16N/2W	12.0	9,700	7.3	5,900
16N/3W	0.1	100	0.1	100
16N/4W	1.1	900	0.6	500
17N/4E	5.4	4,400	5.9	4,800
17N/3E	8.3	6,700	8.9	7,200
17N/2E	9.0	7,300	11.0	8,900
17N/1E	14.4	11,700	13.9	11,300
17N/1W	3.8	3,100	3.6	2,900
17N/2W	4.3	3,500	9.4	7,600
17N/3W	8.6	7,000	9.4	7,600
18N/4E	4.7	3,800	9.4	7,600
18N/3E	16.6	13,500	17.6	14,300
18N/2E	4.9	4,000	5.3	4,300
18N/1E	1.7	1,400	9.7	7,900
18N/1W	11.8	9,600	15.8	12,800
18N/2W	2.2	1,800	2.0	1,600
18N/3W	0.6	500	1.1	900
18N/4W	0.5	400	0.9	700
19N/4E	7.3	5,900	7.8	6,300
19N/3E	10.7	8,700	10.5	8,500
19N/2E	8.4	6,800	10.4	8,400
19N/1E	0.1	100	0	0
19N/1W	11.0	8,900	15.4	12,500
19N/2W	1.8	1,500	2.6	2,100
19N/3W	5.7	4,600	8.5	6,900
19N/4W	2.3	1,900	4.0	3,200
20N/3E	4.6	3,700	4.3	3,500
20N/2E	42.7	34,600	36.3	29,400
20N/1E	8.4	6,800	12.6	10,200
20N/1W	4.8	3,900	4.7	3,800
20N/2W	7.5	6,100	5.9	4,800
20N/3W	26.6	21,600	36.8	29,800
20N/4W	0.7	600	1.7	1,400
21N/3E	0.4	300	0.4	300
21N/2E	5.4	4,400	10.1	8,200
21N/1E	47.4	38,400	40.8	33,100
21N/1W	13.8	11,200	15.2	12,300
21N/2W	52.8	42,800	51.9	42,100
21N/3W	30.6	24,800	32.8	26,600
21N/4W	2.1	1,700	2.5	2,000

TABLE 4—Continued

GROUND WATER PUMPAGE BY TOWNSHIP
SACRAMENTO VALLEY
1961 and 1970

	1961		*1970*	
Township	*Cubic Hectometres*	*(Acre-feet)*	*Cubic Hectometres*	*(Acre-feet)*
22N/2E	2.7	2,200	3.7	3,000
22N/1E	26.6	21,600	33.7	27,300
22N/1W	27.6	22,400	26.2	21,200
22N/2W	40.7	33,000	39.5	32,000
22N/3W	7.1	5,800	8.0	6,500
22N/4W	5.1	4,100	5.1	4,100
23N/1E	3.7	3,000	3.7	3,000
23N/1W	20.4	16,500	20.0	16,200
23N/2W	25.2	20,400	27.4	22,200
23N/3W	9.2	7,500	10.0	8,100
23N/4W	1.1	900	1.8	1,500
23N/5W	0.6	500	0.5	400
24N/1W	0.4	300	1.1	900
24N/2W	7.5	6,100	9.7	7,900
24N/3W	20.6	16,700	11.2	9,100
24N/4W	2.1	1,700	3.1	2,500
24N/5W	0	0	0.6	500
25N/1W	0.1	100	0.2	200
25N/2W	8.3	6,700	8.0	6,500
25N/3W	25.5	20,700	21.3	17,300
25N/4W	0.5	400	0.5	400
26N/2W	2.7	2,200	4.3	3,500
26N/3W	24.7	20,000	22.7	18,400
26N/4W	1.6	1,300	2.6	2,100
26N/5W	1.0	800	1.2	1,000
27N/2W	0.1	100	0.2	200
27N/3W	12.7	10,300	15.7	12,700
27N/4W	3.6	2,900	4.0	3,200
TOTAL (Rounded)	2 228	1,806,000	2 242	1,818,000



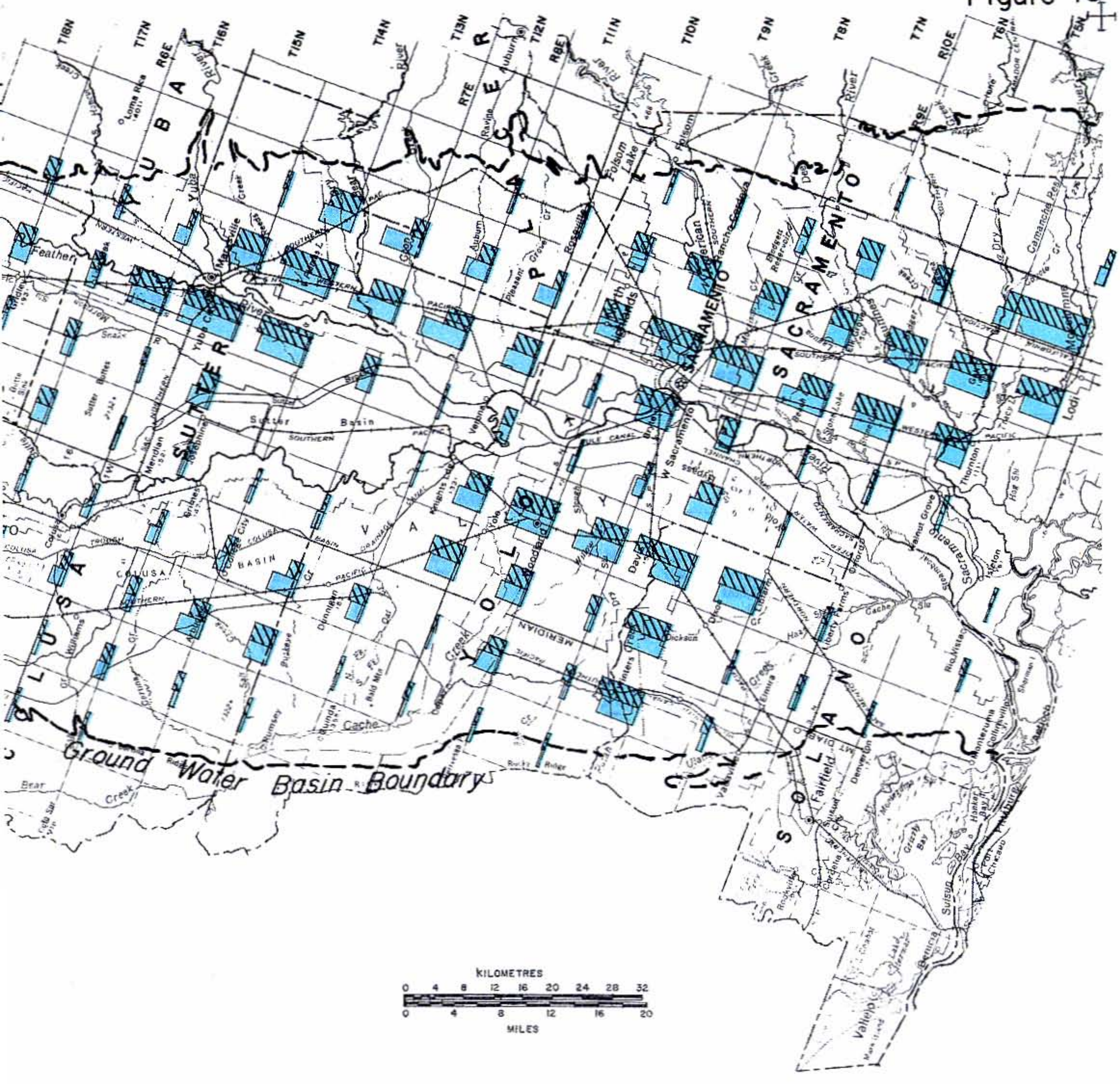


NOTE:

Height of bars represents annual pumpage by township for each of two years 1961 and 1970. Bar extending full height of township represents 50 000 Acre-Feet (62 cubic hectometres). Only irrigation and municipal use considered.

Map Scale for determining pumpage from height of bars.

Figure 16



GROUND WATER PUMPAGE
BY TOWNSHIP
1961 and 1970

in others. A study of 1970 pumpage figures north and south of Sutter Buttes shows that two–thirds, about 1 500 hm^3, occurs south of the Buttes and one–third, or about 740 hm^3, occurs to the north. (Pumpage figures include Township 4 North, not included in inventory figures in Chapter IV.)

Ground Water in Storage

Ground water in storage for 1965 water levels has been estimated for six depth zones: 6 to 30 metres and for approximately each 30 metres thereafter to 180 metres as measured from the ground surface. Storage quantities are reported from the upper surface of the zone of saturation, usually averaging about 6 metres in depth, for a nodal area comprising four townships, about 37 300 hectares (or that portion which lies within the basin).

In areas of deeper water levels, the upper surface of the upper zone was adjusted downward accordingly. Quantities of ground water in storage for each 30–metre depth zone are shown on Table 5 by nodal area. These quantities are also shown graphically on Figure 17 by nodal areas. On this figure the six depth zones shown in Table 5 were combined into three 60–metre depth zones, 6 to 60, 60 to 120 and 120 to 180 metres (20 to 200; 200 to 400; and 400 to 600 feet).

Ground water in storage is the volume of water that would be released from storage from each depth

TABLE 5

GROUND WATER IN STORAGE SACRAMENTO VALLEY

Nodal Area Number	Depth Zones											
	6–30 m (20–100 ft)*		*30–60 m (100–200 ft)*		*60–90 m (200–300 ft)*		*90–120 m (300–400 ft)*		*120–150 m (400–500 ft)*		*150–180 m (500–600 ft)*	
	hm^3	Ac ft	hm^3	Ac ft	hm^3	Ac ft	hm^3	Ac ft	hm^3	Ac ft	hm^3	Ac ft
1	0	0	0	0	232	188,000	228	185,000	—	—	—	—
2	278	225,000	548	444,000	491	398,000	433	351,000	406	329,000	592	480,000
3	57	46,000	54	44,000	43	35,000	42	34,000	67	54,000	94	76,000
4	0	0	0	0	303	246,000	329	267,000	491	398,000	414	336,000
5	361	293,000	788	639,000	1414	1,146,000	770	624,000	1127	914,000	773	627,000
6	470	381,000	556	451,000	410	332,000	479	388,000	690	559,000	730	592,000
7	0	0	189	153,000	344	279,000	266	216,000	380	250,000	260	211,000
8	0	0	733	594,000	717	581,000	701	568,000	707	573,000	561	455,000
9	813	659,000	755	612,000	587	476,000	576	467,000	470	381,000	476	386,000
10	44	36,000	99	80,000	96	78,000	95	77,000	97	79,000	101	82,000
11	Insufficient Data		—	—	—	—	—	—	—	—	—	—
12	580	470,000	747	606,000	583	473,000	632	512,000	641	520,000	651	528,000
13	983	797,000	865	701,000	678	550,000	611	495,000	484	392,000	512	415,000
14	392	318,000	369	299,000	373	302,000	349	283,000	348	282,000	454	368,000
15	Insufficient Data		—	—	—	—	—	—	—	—	—	—
16	403	327,000	603	489,000	623	505,000	565	458,000	571	463,000	471	382,000
17	847	687,000	849	688,000	572	464,000	833	700,000	—	—	—	—
18	548	444,000	599	486,000	651	528,000	660	535,000	713	578,000	653	529,000
19	414	336,000	374	303,000	301	244,000	329	267,000	355	288,000	428	347,000
20	326	264,000	321	260,000	364	295,000	411	333,000	496	402,000	463	375,000
21	722	585,000	979	794,000	846	686,000	889	721,000	813	659,000	702	569,000
22	556	451,000	485	393,000	463	375,000	533	432,000	544	441,000	426	345,000
23	506	410,000	522	423,000	481	390,000	488	396,000	508	412,000	513	416,000
24	347	281,000	389	315,000	366	297,000	335	272,000	349	283,000	401	325,000
25	751	609,000	661	536,000	886	718,000	784	636,000	794	644,000	702	569,000
26	Sutter Buttes		—	—	—	—	—	—	—	—	—	—
27	881	714,000	678	550,000	687	557,000	713	578,000	581	471,000	545	442,000
28		0	90	73,000	114	93,000	—	—	—	—	—	—
29	Insufficient Data		—	—	—	—	—	—	—	—	—	—
30	320	260,000	682	553,000	688	558,000	756	613,000	749	608,000	690	559,000
31	733	594,000	868	704,000	902	731,000	914	741,000	628	509,000	379	307,000
32	723	586,000	617	500,000	593	481,000	595	482,000	649	526,000	646	524,000
33	255	207,000	333	270,000	342	277,000	308	250,000	301	244,000	282	229,000
34	Excluded from study—Rumsey Hills											
35	Insufficient Data—Dunnigan Hills											
36	859	696,000	855	693,000	783	635,000	974	790,000	909	737,000	908	736,000
37	701	568,000	789	640,000	775	628,000	681	552,000	686	556,000	805	653,000
38	53	43,000	634	514,000	645	523,000	602	488,000	675	547,000	746	605,000
39	Insufficient Data		—	—	—	—	—	—	—	—	—	—
40	Insufficient Data		—	—	—	—	—	—	—	—	—	—

TABLE 5—Continued

GROUND WATER IN STORAGE
SACRAMENTO VALLEY

	Depth Zones											
Nodal Area Number	*6*–30 m (20–100 ft)*		*30–60 m (100–200 ft)*		*60–90 m (200–300 ft)*		*90–120 m (300–400 ft)*		*120–150 m (400–500 ft)*		*150–180 m (500–600 ft)*	
	hm^3	Ac ft	hm^3	Ac Ft	hm^3	Ac ft	hm^3	Ac ft	hm^3	Ac ft	hm^3	Ac ft
41	587	476,000	592	480,000	507	411,000	504	409,000	445	361,000	430	349,000
42	416	337,000	797	646,000	792	642,000	744	603,000	1013	821,000	743	602,000
43	1012	821,000	1087	882,000	1169	948,000	990	803,000	789	640,000	664	538,000
44	176	143,000	507	411,000	644	522,000	696	564,000	667	541,000	497	403,000
45	79	64,000	215	174,000	169	137,000	117	95,000	107	87,000	68	55,000
46	137	111,000	321	260,000	300	243,000	280	227,000	296	240,000	236	191,000
47	525	426,000	714	579,000	745	604,000	697	565,000	617	500,000	587	476,000
48	744	603,000	872	707,000	1069	867,000	876	710,000	686	556,000	613	497,000
49	353	286,000	590	478,000	577	468,000	419	340,000	385	312,000	90	73,000
50	65	53,000	407	330,000	307	249,000	282	229,000	154	125,000	69	56,000
51	Insufficient Data		—	—	—	—	—	—	—	—	—	—
52	155	126,000	182	148,000	178	144,000	159	129,000	160	130,000	185	150,000
53	640	519,000	686	556,000	659	534,000	620	503,000	601	487,000	580	470,000
54	930	754,000	910	738,000	708	574,000	493	400,000	569	461,000	—	—
55	278	225,000	590	478,000	444	360,000	439	356,000	434	352,000	237	192,000
56	26	21,000	280	227,000	253	205,000	265	215,000	297	241,000	245	199,000
57	Insufficient Data		—	—	—	—	—	—	—	—	—	—
Total (Rounded)												
hm^3	20 000	—	25 800	—	25 900	—	24 500	—	23 400	—	20 600	—
Ac ft	—	16,200,000	—	20,900,000	—	21,000,000	—	19,900,000	—	19,000,000	—	16,700,000
Cumulative Total (Rounded)												
hm^3	20 000	—	45 800	—	71 700	—	96 200	—	119 600	—	—	—
Ac ft	—	16,200,000	—	37,100,000	—	58,100,000	—	78,000,000	—	97,000,000	140,200	113,700,000

*Storage is reported from the upper surface of the zone of saturation. In nodes of deeper water levels than 6 metres (20 ft) this depth was adjusted accordingly.

zone or the amount required to resaturate the zone. Unconfined conditions are assumed, since lowering water levels in a confined aquifer as manifested in a well does not necessarily indicate general lowering or dewatering of the aquifer.

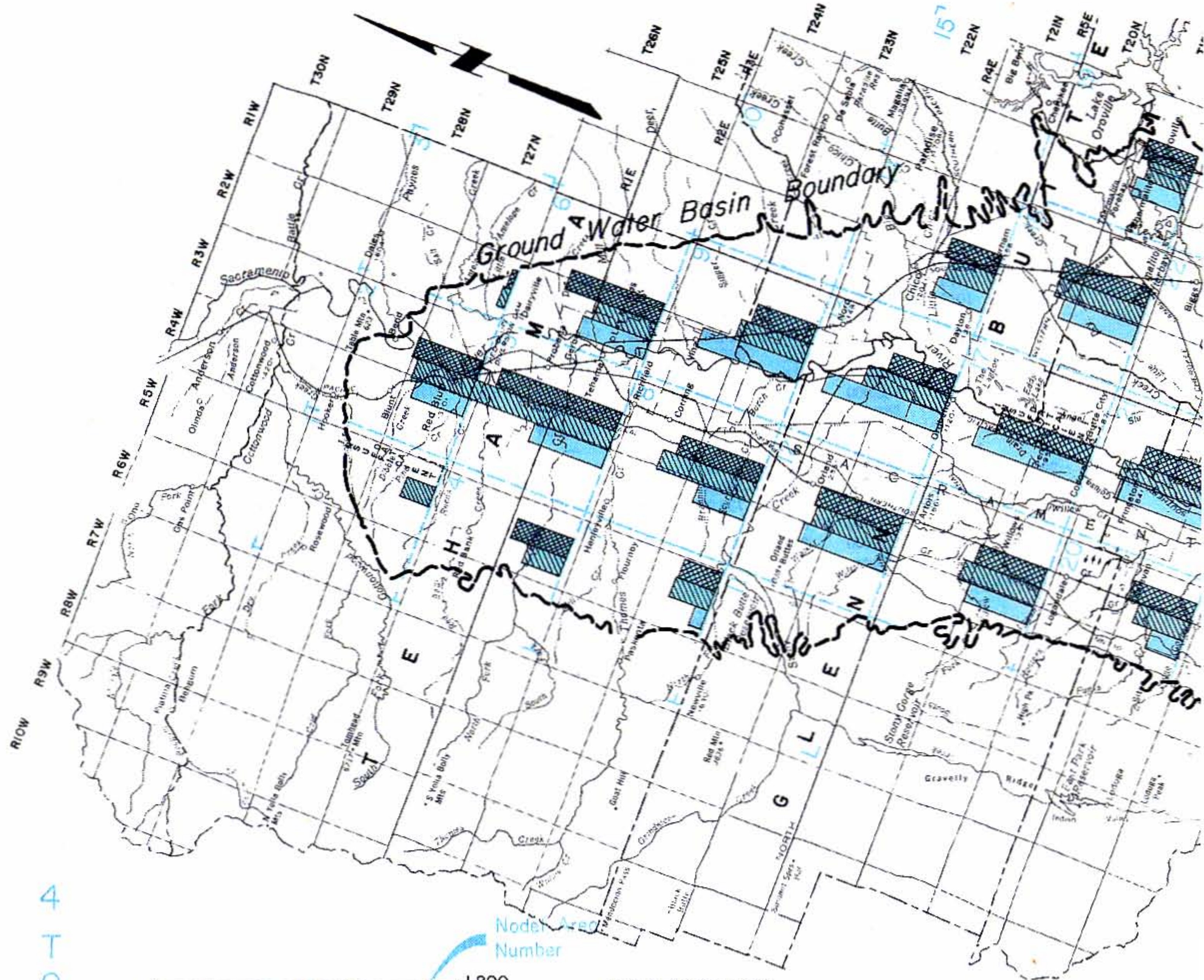
Storage capacity was estimated through use of a computer program (designed for English units of measure) which determines average specific yield for each 10–foot interval, and multiplies this times volume of the prism measuring 12 miles by 12 miles by 10 feet (assuming four full townships). Specific yields are the same as those used to identify aquifers and range from 1 to 25 percent.

Storage calculated from the average depth to water in each of the four–township areas in 1965, to a depth of 180 metres (600 feet), was estimated for the entire basin at 140 200 cubic hectometres (converted from 113,700,000 acre–feet). Water at these depths represents a significant resource potential. With proper well construction and conjunctive use of surface and ground sources, it would be possible to use much of the water in the lower zones.

Ground Water Chemistry

Different rock types characterize the three geomorphic provinces that provide the runoff to recharge the Sacramento Valley ground water basin. Under natural conditions, the Sacramento River acts as a central drain for the Coast Ranges to the west, the Cascade Range, and the Sierra Nevada to the east, and hydrologically separates the eastern and western portions of the valley. In general, ground water moves westward to the river from the Cascade and Sierra and eastward from the Coast Ranges.

Ground water chemistry of the valley is directly affected by the rock types present in the surrounding drainage. This relationship can be quite complex and in some cases is not well known. Many factors besides mineral composition of the primary rock type influence ground water quality. Minor soluble constituents, such as salt or gypsum, have disproportionate influences. Connate waters from springs in marine sedimentary rocks have a similar effect. Mining activity in the drainage area, past or present, is another factor. Within the ground water basin, redeposition



4 TOWNSHIP AREA

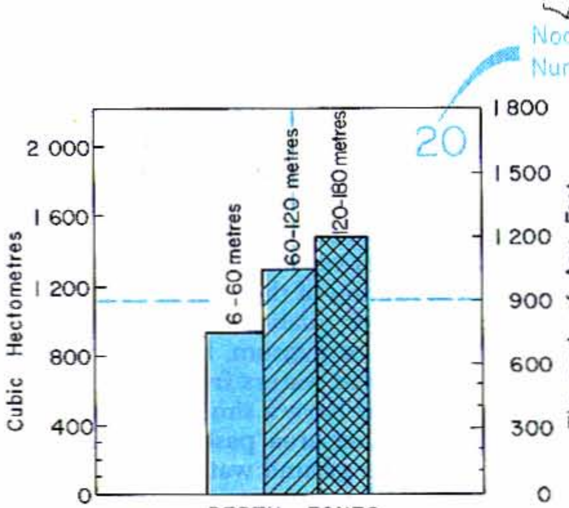
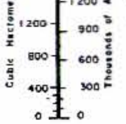


ILLUSTRATION
(Not to Map Scale)

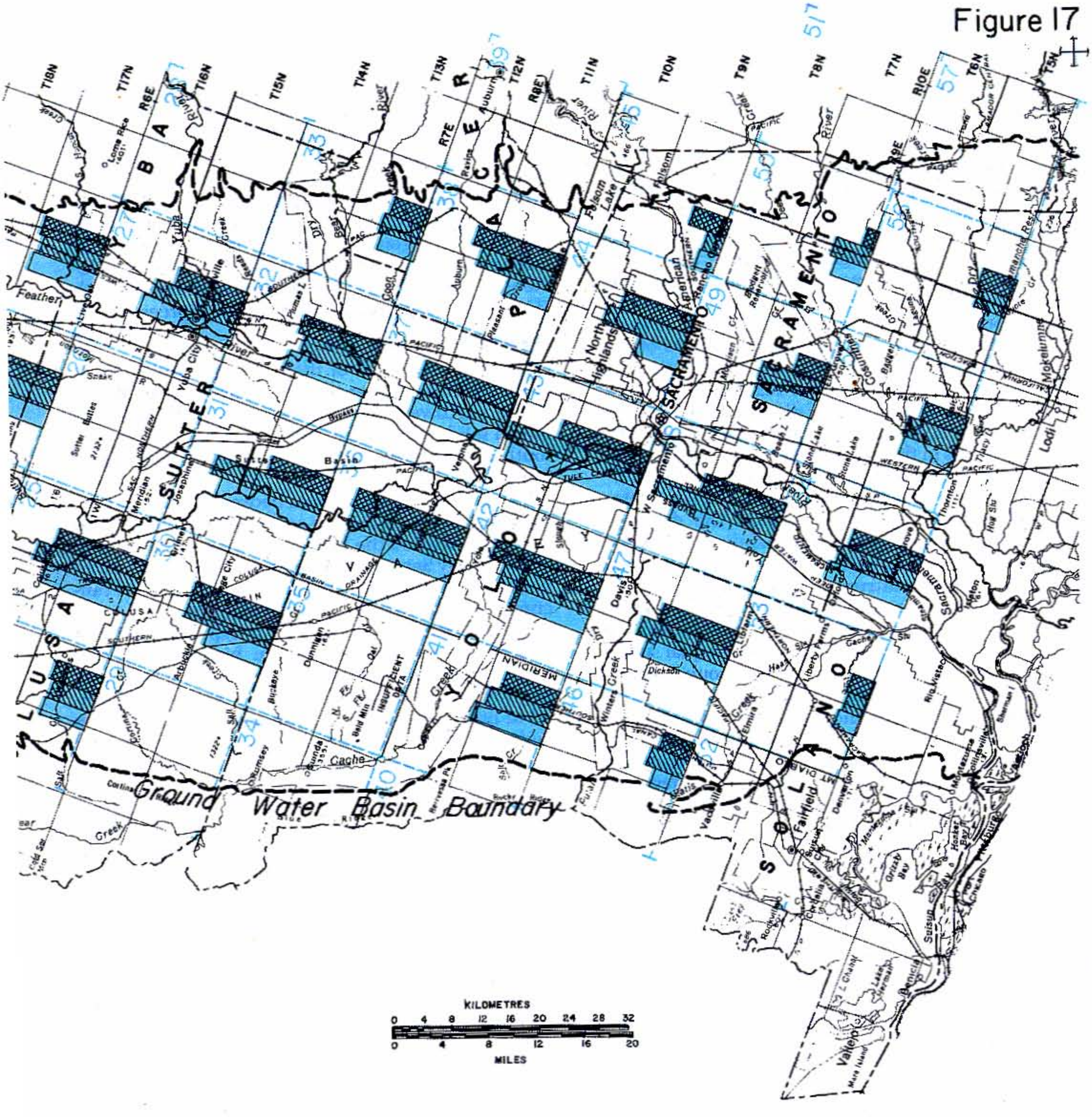
EXPLANATION:

Ground water in storage for each of three depth zones in a nodal area of four townships (or that portion which lies within the basin) is shown by height of the bars. The upper zone is from a depth of approximately 6 metres to 60 metres (20 to 200 feet); the lower two depth zones are 60 to 120 metres (200 to 400 feet), and 120 to 180 metres (400 to 600 feet).



Map Scale for determining storage from height of bar

Figure 17



GROUND WATER IN STORAGE
By Four-Township Areas
1965

of dissolved constituents, ion exchange reactions, and surface pollution sources are important considerations.

Eastern Sacramento Valley

With few exceptions, ground water in the eastern portion of the Sacramento Valley is of excellent quality, with low total dissolved solids (TDS), generally less than 250 to 300 milligrams per liter (mg/l). Its character is principally magnesium and magnesium–calcium–sodium bicarbonate and reflects its origin, having been derived by recharge from streams draining the igneous and metamorphic rocks of the Sierra and the volcanic terrane of the Cascades. These rocks have high erosion resistance and contribute only small amounts of dissolved solids to the surface runoff. Typical stream analyses indicate total dissolved solids in the range of 60 mg/l, with relatively small seasonal fluctuations due to spring runoff.

The amount of calcium or sodium in surface water depends on the type of feldspar in the drainage rocks. The Sierran foothills are mainly mafic metavolcanic rocks rich in sodic feldspars. The abundant granitic and mafic intrusives of the Sierra and the volcanic rocks of the Cascades are typically rich in calcic feldspars. Mixing of surface waters from the two terranes may explain the almost–equal abundance of sodium and calcium in the ground water.

The amount of potassium released into solution is dependent on the presence of potassium feldspars. While these are common in the granitic intrusives of the Sierra, potassium concentration is substantially lower than both calcium and sodium. This phenomenon is due to the capability of potassium to recombine with clays to form diagenetic minerals that are relatively stable and resistant to weathering.

An anomaly in the eastern portion of the valley is the predominance of magnesium as the principal cation. The source may be iron– and magnesium–rich materials of the mafic metavolcanics that outcrop along the foothills of the Sierra Nevada.

Bicarbonate is the prevalent anion. A few sulfate anomalies do occur, but they are local in extent. Areas of high sodium chloride occur near the mouth of Salt Creek in northeast Sacramento Valley, south of the Sutter Buttes near Robbins, and in a few scattered areas along the eastern edge of the valley, particularly near Lincoln and Wheatland.

Salt Creek salinity east of Red Bluff is derived from Tuscan Springs. Previously a popular mineral spa, the springs are also relatively high in boron and sulfate. The high concentration of sodium and chlorine in the vicinity of Robbins has been linked to connate waters originating in the marine sediments flanking the Sutter Buttes. The source of the salinity in the few wells along the eastern edge of the valley may be brackish water from the Ione Formation. These wells may have tapped the formation, but a general lack of well depth information prevents confirmation.

A local ground water quality problem exists in the southeastern portion of the valley where excessive amounts of iron and manganese occur. Current drinking water standards of the California Administrative Code, Title 17 include a recommended limit of 0.3 mg/l for iron and 0.05 mg/l for manganese. Of wells tested in Sacramento County for these two elements, 71 percent showed an excess in one or both (California Department of Water Resources, 1974).

Western Sacramento Valley

In the western half of the valley, ground water is of significantly poorer quality in many areas. Water in the northwest valley is excellent, with total dissolved solids of less than 250 mg/l, but ground water south of Willows contains TDS frequently in excess of 500 mg/l.

The western drainage area bedrock sequence consists of Cretaceous marine sedimentary units. These have been named the Franciscan Formation and the Great Valley Sequence. A major fault zone with large blocks of associated serpentinites separates the Franciscan from the Great Valley Sequence.

Runoff from the Franciscan is expected to be of calcium or calcium–magnesium bicarbonate types with a significant amount of sodium and a relatively low TDS. Serpentinites in the fault zone are expected to produce a high magnesium–iron solution. The fault zone also has several mineralized sulfur and carbonate springs associated with it; sulfate and chloride may be high near these.

The Great Valley Sequence is composed of marine shales and sandstones which are not metamorphosed. These rocks are often folded and sheared and tend to erode rapidly. Salt springs, fed by saline water and a few oil–seeps occur in this belt. Boron, presumably from igneous intrusive activity, is locally present. High calcium content of water draining from these rocks is derived from the abundant $CaCO_3$ cement in the sandstones. Dissolved solids increase considerably as stream waters traverse this rock belt.

The Tehama and Red Bluff Formations probably do not significantly add to the TDS of the surface drainage. However, base exchange reactions may occur in the clay layers, whereby calcium originally in the water may be exchanged for sodium.

The westside streams show significant seasonal fluctuations in mineral content. For example, flows from Elder Creek in the spring are of excellent quality and average 180 mg/l TDS. Analyses of fall flows indicate the water to be a poor–quality sodium–magnesium chloride type with average TDS of 618 mg/l. During periods of high seasonal runoff, mineral waters emanating from the springs apparently are less of an influencing factor on the overall composition than at lower stages of flow.

The valley from Red Bluff to Willows is underlain by calcium magnesium bicarbonate ground water. The predominant calcium ion is derived from dissolution of calcium carbonate cement in Coast Range rocks.

Some serious ground water quality problems occur around the towns of Maxwell, Williams, and Arbuckle (Bertoldi, 1976 and Fogleman, 1975). Unusually high concentrations of sodium, chloride, and sulfate occur in this region. TDS average around 500 mg/l, but some samples are well over 1 000 mg/l. The source of salinity is numerous mineral springs in the Rumsey Hills area.

High magnesium waters occur east of the Dunnigan Hills. The source is unknown, but it may result from rising magnesium-rich water along a fault which is thought to occur along the eastern base of the Dunnigan Hills.

The ground water region south of the Dunnigan Hills in the Putah Plain receives recharge from Cache and Putah Creek drainages. The most significant features of these basins are highly mineralized springs discharging high concentrations of boron, sodium, and magnesium. This is reflected in ground water, which is commonly a magnesium–sodium or sodium–magnesium biocarbonate type with TDS frequently in excess of 500 mg/l.

Base of Fresh Water

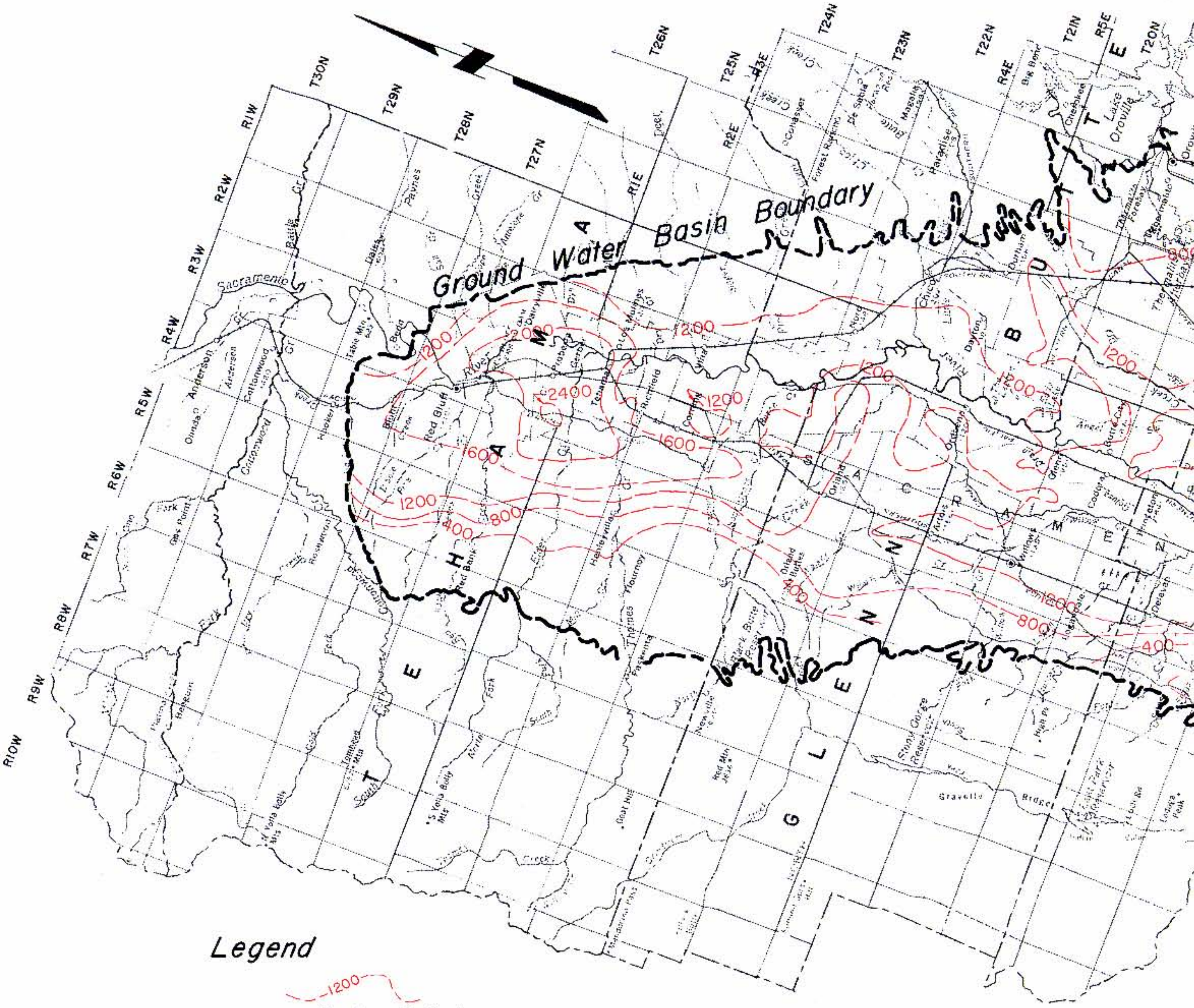
Fresh ground water occurs in the post–Eocene continental deposits to depths of as much as 1 000 metres in the southwest portion of the valley, but depth is generally much less. Depth to the base is highly variable and generally reflects the valley structure. The greatest depths are in the central trough area in the north valley and along the west side in the south valley, where the synclinal trough is deepest.

Configuration of the base of fresh water is shown on Figure 18. This map was prepared with reference to a similar map by the U. S. Geological Survey (Berkstresser, 1973), in which saline water was defined as having a specific conductance of 3 millisiemens/cm (3 000 micromhos). This corresponds to a TDS of about 2,000 mg/l.

As shown in Figure 18, the base of fresh water in the north valley occurs at about 365 metres (–1,200–foot contour) below sea level in a large area, and in the extreme north near Red Bluff, the greatest depth is about 730 metres below sea level (–2,400–foot contour).

Saline water occurs at a shallow depth west of the Sutter Buttes near Colusa and also in south Sutter County. The source is believed to be marine sediments surrounding Sutter Buttes. Saline water apparently has been flushed from the uplifted Cretaceous sediments. In south Sutter County, saline water is believed to be rising along a permeable zone associated with a fault (Curtin, 1971).

In south Sacramento Valley the base of fresh water is generally deeper and more uneven. From its greatest depth, 1 000 metres south of Davis, the base gradually rises eastward along the same slope as the base of the post–Eocene continental deposits and more sharply on the west. As shown in the geologic sections, Figure 6, the base of fresh water extends below the post–Eocene deposits on the east and west. Presumably the saline water in the Eocene and pre–Eocene deposits has been flushed out toward the valley trough.



Legend

Contour in feet.

Contour on base of fresh water with specific conductance generally less than 3,000 micromhos per centimetre. Contour interval 400'.

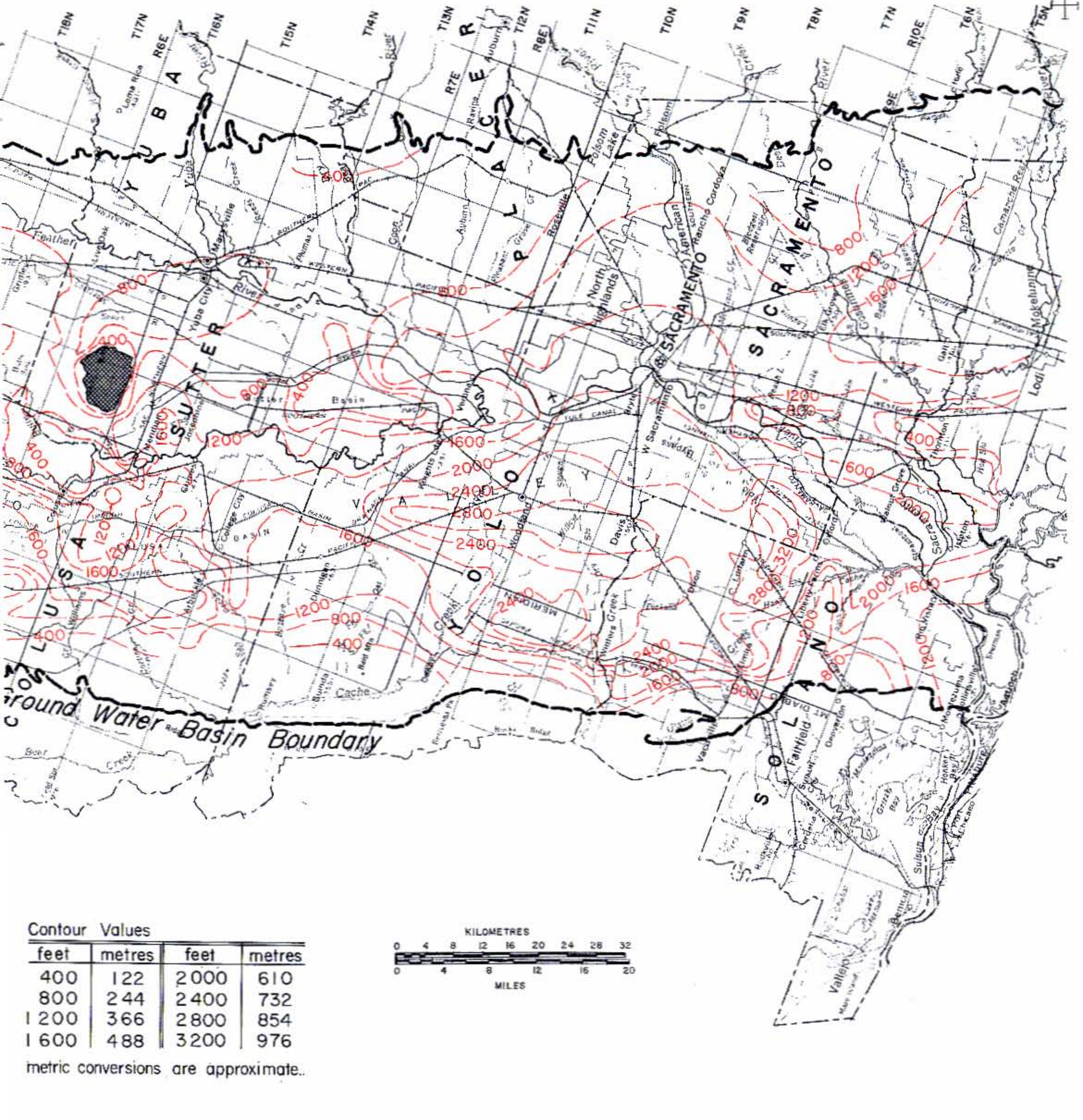
Contour Elevations are below Sea Level.

● *Sutter Buttes*
Marine sediments surrounding igneous core.

Note

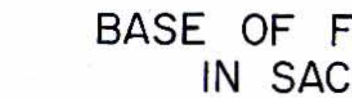
Contours are from- U.S. Geological Survey Map WRI 40-73, "Base of Fresh Ground Water in the Sacramento Valley and Sacramento-San Joaquin Delta, California" by: C.F. Berkstresser, Jr.; dated: December, 1973.

Figure 18



Contour	Values		
feet	metres	feet	metres
400	122	2000	610
800	244	2400	732
1200	366	2800	854
1600	488	3200	976

metric conversions are approximate.



BASE OF FRESH GROUND WATER
IN SACRAMENTO VALLEY

CHAPTER IV. HYDROLOGIC INVENTORY

This chapter presents an inventory or an accounting, of discharge, recharge, and change in quantity of ground water in the Sacramento Valley ground water basin. The inventory covers a period of 10 years from 1961–70 and includes an evaluation of supply sources and amounts of discharge within the basin. It also provides information on the relative importance of supply and discharge sources. Because the inventory is based on reconnaissance–level information, values are approximate.

The inventory was made by developing information on all components of the hydrologic equation, which states that ground water recharge is equal to ground water discharge plus or minus change in storage. As stated earlier, recharge is the sum of deep percolation of precipitation, streamflow, applied agricultural water, and subsurface inflow to the basin. Discharge is the sum of ground water pumpage from wells, consumptive use by natural vegetation and irrigated crops, direct discharge to streams, and subsurface outflow from the basin. When all items of recharge are equal to the sum of all items of discharge, there is no change of storage in the ground water body.

Conversely, an imbalance between recharge and discharge must be reflected by a change in storage in the basin. Therefore change in storage is an approximate representation of net recharge, which can be either negative or positive. The basic area for which items of supply and disposal determinations were made is a quarter–township. Aggregate quantities were used to develop inventories of larger areas, generally comprising four townships.

Study Period

Ground water levels rise and fall largely in response to precipitation which falls on the valley floor and adjacent areas. Local precipitation is important, even where major streams with controlled flows provide recharge. Precipitation in the valley serves as an index to the water supply available.

The study period selected should represent the long–term water supply as closely as possible. By analysis of long–term precipitation records, a short study period can be selected and compared with long–term averages. Ideally, hydrologic conditions during the selected study period should represent average long–term conditions, both wet and dry years, and be within the period of available records. Dry periods prior to the beginning and end of the study period would minimize differences in amounts of water in transit from surface to water table (vadose water) and ensure greater accuracy. Ideally, ground water levels should be similar at the beginning and end of the period.

The 1961–70 base period does not meet these requirements in all parts of the valley. However, it does include wet and dry years and represents the long–term average reasonably well. Water levels are similar at the beginning and end of the period for most of the basin, but ideal conditions of dry periods at both ends of the study did not occur. The differences in amount of water in transit at the beginning and end could not be accounted for in a reconnaissance–level study. However, the amount of water in transit in this basin, where relatively shallow water levels occur, is not great.

The guiding criterion in this study was availability of basic data. Most of the basic data were obtained by land and water use surveys. Information developed from these surveys includes amounts of pumpage, applied water, and consumptive use of crops. Such surveys were first made for all counties in the valley in 1961. A second survey was made between 1967 and 1971. The period of 1961–70, therefore, was the most suitable for obtaining the needed data.

Precipitation

Six stations were selected to represent variation in precipitation throughout the valley; Red Bluff, Chico, and Willows for the north valley and Marysville, Woodland, and Sacramento for the south. All stations have records dating back to the late 1800s. Figures 19 and 20 show the cumulative deviation from the mean for each station. Combined average cumulative precipitation is also shown for the three stations.

The "Index of Wetness" for each year is shown in Table 6. A wetter or drier year than average will have an index of more or less than 100, respectively.

From these data, it is seen that the driest year of the study period was 1964 and the wettest year 1969. The second wettest year was 1967, but that year's precipitation had substantially less effect on water levels than that of 1969. Altogether, during the 10–year study period there were 5 years of below–normal precipitation—1961, 1962, 1964, 1966, and 1968; 2 years near normal, 1965 and 1970; and 3 years well above normal, 1963, 1967, and 1969.

Recharge

This section discusses the recharge factors of the hydrologic equation—percolation of irrigation water, precipitation and streams, and subsurface inflow.

Applied Irrigation Water

Determination of volumes of total applied water for the basin requires data on area of irrigated land and reliable estimates of unit use of applied water by crops. A detailed land–use survey was completed for

TABLE 6

INDEX OF WETNESS FOR SIX STATIONS 1961–70

	Precipitation											
	75-Year Mean		*Index No.*									
Station	*mm*	*in*	*1960–61*	*1962*	*1963*	*1964*	*1965*	*1966*	*1967*	*1968*	*1969*	*1970*
Red Bluff	572.8	22.6	*97*	*93*	*103*	*56*	*103*	*79*	*112*	*74*	*135*	*98*
Willows	440.2	17.3	96	92	114	54	108	77	136	88	134	107
Chico	654.4	25.4	92	86	135	69	102	80	138	86	149	124
Marysville	527.6	20.8	74	81	134	77	87	65	142	77	141	107
Woodland	430.8	17.0	75	80	144	68	88	66	160	68	157	116
Sacramento	497.3	19.6	65	83	133	62	101	63	141	60	139	96

the valley in 1961. This was resumed in 1967 on a county–by–county basis and completed in 1970. Supplemental data were furnished by county agricultural commissioners, who report annually on crops grown in their respective counties. From these sources it was possible to reconstruct the irrigated land–use for the study period 1961–1970.

Volumes of applied water for surface sources were computed for each year, separately from those derived from ground water sources. Values for each source of water were computed on a one–fourth township basis by multiplying land use areas for six crop–categories by the appropriate unit value. The crop–categories are orchard, forage, row crops, vineyard, rice, and safflower. The one–quarter township values were then combined into four–township areas.

Values for deep percolation were calculated on a scale of 0 to 30 percent of total applied water. This assumes that irrigation efficiency is 70 percent and that the unconsumed portion, 30 percent, goes to deep percolation or runoff. Deep percolation is influenced by soil type. In township areas where soils contain clayey zones or hardpan layers, low values of deep percolation were used, usually less than 10 or 15 percent, while in areas of highly permeable soils, values up to 30 percent of applied water were assigned. Where water tables are higher, low values were used because aquifers are nearly saturated.

Stream Percolation and Precipitation

Estimation of percolation rates for all streams draining into the Sacramento Valley was beyond the scope of this study. That portion of stream percolation that contributes recharge to each township area is included with deep percolation of precipitation, and both together are calculated as the unknown in the hydrologic equation. These values were compared with those obtained from a computer program that produced data on amount of precipitation available for deep percolation or runoff. If sufficient water was not available from precipitation to account for the calculated recharge, it was assumed that the difference was attributable to percolation from streams which originated outside the basin.

Subsurface Inflow

Subsurface inflow from water–bearing areas outside the basin is believed to be negligible. Most of the basin is surrounded by rocks that are generally impervious compared to the sediments in the basin. Rocks on the west side of the basin, mostly sandstone and shale, are entirely consolidated. On the east side, from south of Oroville to the south end of the study area, there are granitic and metamorphic rocks of the Sierra Nevada. Only in the area between Oroville and Red Bluff, along the northeast side of the valley, is subsurface inflow possible from the Tuscan Formation. Most of this probably occurs in the Chico area, where the formation is composed of the most permeable materials. While subsurface inflow is not a major factor in overall recharge of the basin, it is an important source in the area southwest of Chico.

Discharge

This hydrologic inventory includes ground water pumpage as the only item of discharge. Loss from evapotranspiration, direct discharge to streams, and minor amounts from subsurface outflow was not calculated.

Pumpage

Ground water is extracted by pumpage from irrigation wells, and industrial and municipal wells. The amount pumped was determined by the land use method as previously described for applied water. In the land use surveys, irrigated areas served by ground water were segregated from those served by surface water (Plate 1). By applying the proper unit water–use factor to crop areas served by ground water, total pumpage was determined for each quarter–township area. These data were combined for township areas and then again for four–township areas.

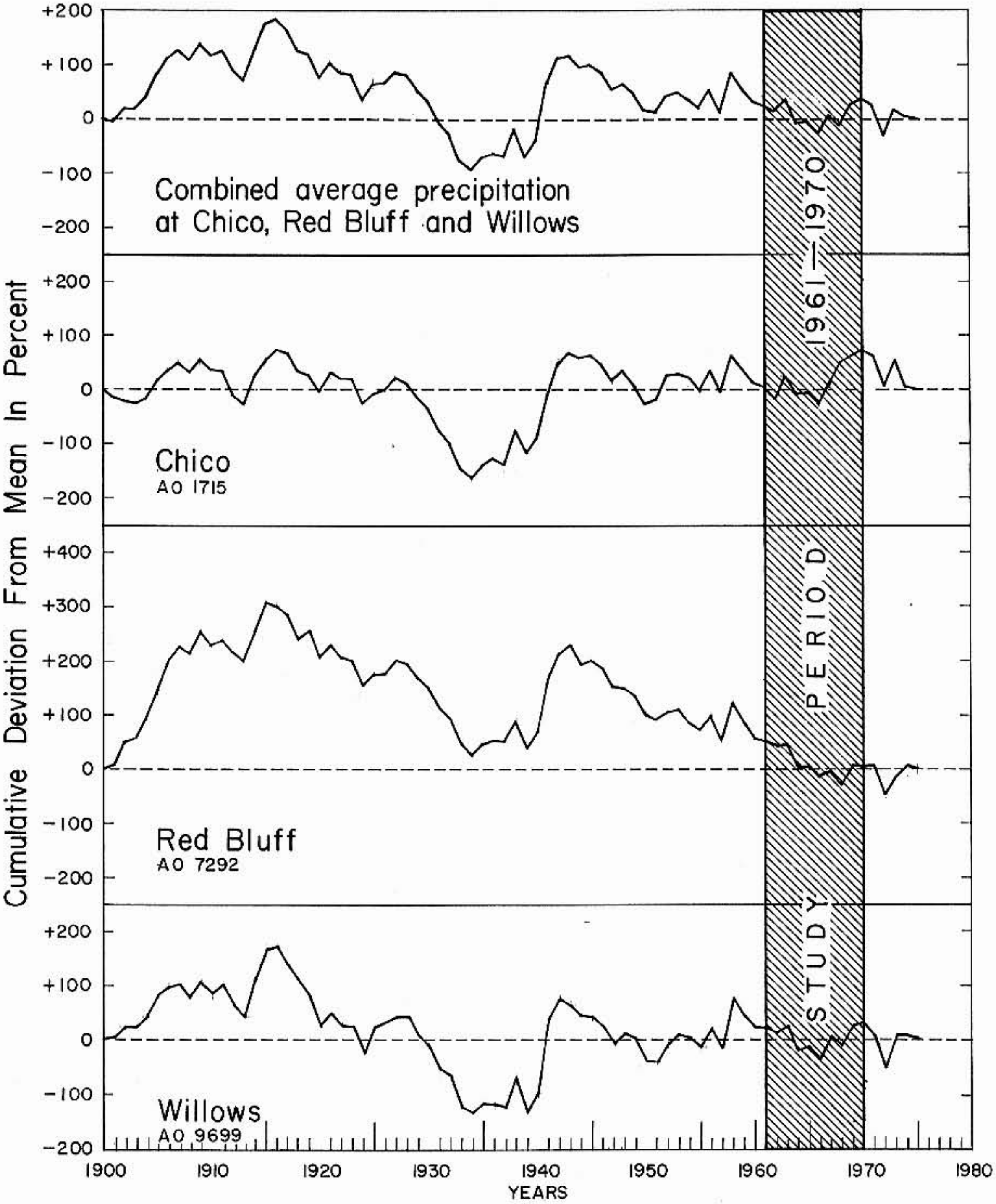


Figure 19. Long Term Variation of Precipitation, 1900-1975 - North Sacramento Valley

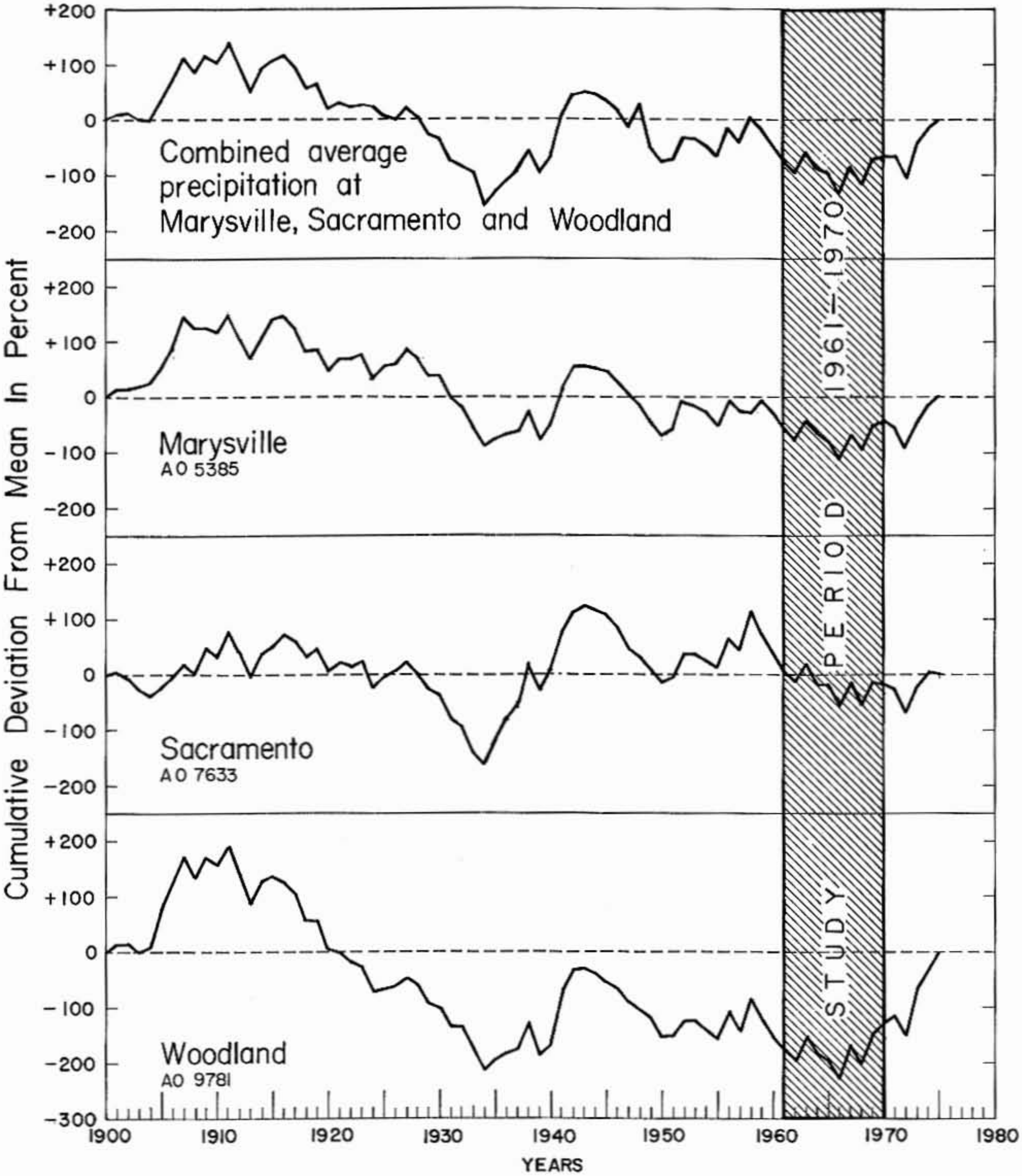


Figure 20. Long Term Variation of Precipitation, 1900-1975 - South Sacramento Valley

Evapotranspiration

Evapotranspiration from crops and natural vegetation is a major item of discharge. In the inventory this amount was not calculated directly but evapotranspiration from irrigated crops was accounted for as part of ground water pumpage calculations. Of the total amount of ground water pumpage, 70 percent (assumed irrigation efficiency) was discharged to the atmosphere. The remaining 30 percent is returned to the basin or runs off at the surface as previously described.

Direct Discharge to Streams

In areas where ground water movement is toward streams, as indicated by ground water elevation contours, discharge occurs directly to the surface. This condition is prevalent in the northern Sacramento Valley along the Sacramento and Feather Rivers as described in Chapter III. Under natural conditions this condition was more prevalent as described in Appendix A. The amount of discharge to streams could not be calculated. During the 10–year study period, some of the water discharged in the north repercolated in the south valley along both rivers due to the lowering of water levels there. Although the total amount of water discharged is not known, the net amount is believed to represent a small but perhaps significant amount of the total ground water discharge.

Subsurface Outflow

Subsurface outflow can occur only at the south end of the basin, where water–bearing sediments of the valley merge with the Delta sediments. Here there are no barriers to movement of ground water, but the hydraulic gradient is virtually zero and therefore no outflow takes place. As shown in Figure 8, ground water levels are near or below sea level. Where they are below, as in Sacramento and Solano Counties, the ground water gradient is reversed and no outflow is possible.

Change in Storage

Change in storage was computed on a township basis for each year of the study period. The procedure for computing this required determination of average annual water level changes by township from spring to spring. These changes were multiplied by average specific yield in the zone of change to determine quantity of water represented by average water level change in each township area. Specific yields were determined by computer, using one well log from each of some 7,000 quarter–sections. Average specific yields generally ranged from 5 to 10 percent for each township area.

Inventory Results

Table 7, "Ground Water Inventory by Township Area, 1961–70", shows the inventory results for each of the 45 township areas, numbered 101–145 and shown in Figure 21. Total recharge is divided into two sources: applied water, and precipitation and stream percolation. Sufficient data were not available to evaluate independently the amount of recharge from streams and precipitation. Therefore, these items are calculated as the amount required to balance the hydrologic equation.

The discharge, recharge, and change in storage determined for each township area were averaged for the 10–year study period. The averages, along with possible sources of stream recharge, are shown in Table 7. During the study period, most township areas had a positive net recharge, as indicated by a gain in storage. In five areas—113, 117, 119, 132 and 133—ground water discharge approximately equaled recharge. For these areas, pumping or other means of discharge was balanced by an equal amount of recharge under the prevailing water level conditions. While it would appear that these areas are on the verge of being overdrawn, overdraft conditions would not necessarily have resulted had pumping increased, because future lowering of water levels due to increased use might well be accompanied by increased recharge (providing adequate recharge supply was available).

In 11 township areas—108, 111, 122, 123, 127, 130, 134, 139, 140, 143, and 144—average annual ground water discharge exceeded recharge, resulting in substantial negative change in storage ranging from –1.5 to –13.8 hm^3 annually. In Areas 108 and 111 in western Glenn County, there was apparent overdraft due to pumpage in a small area west of Interstate 5. Lowering of water levels was sufficient to cause both township areas to average out with a negative change in storage of –1.8 and –1.5 hm^3 annually. Recharge to this area is partially restricted because of a structural barrier (Willows arch) which prevents movement of ground water into the pumping depression from the Stony Creek fan. Also, the recharge of small streams draining the Coast Ranges in this area is not sufficient to maintain water levels.

Areas 122, 123, and 127 in the Dunnigan–Arbuckle vicinity had negative change in storage ranging from an average annual –1.7 to –6.0 hm^3. These areas were in apparent overdraft because of intensive pumping in the early–to–mid 1960s. Recharge from small streams flowing from the Coast Ranges and Rumsey Hills was not sufficient to maintain water levels, even though the alluvial fans are quite absorptive. Because of structural barriers (fault and anticline) in the Tehama Formation beneath the fans, ground water was apparently unable to flow into the pumping depression from areas of storage in the valley east of Interstate 5. In the late 1960s, water levels were rising, and in some years there was an increase in storage due to less ground water pumping.

English equivalents: 1 cubic hectometre (hm^3) = 810.7 acre–feet (ac–ft).

TABLE 7

GROUND WATER INVENTORY BY TOWNSHIP AREA
1961–70

Township Area Number	*Area*	*Average Annual Discharge (pumpage)*	*Average Annual Recharge*		*Average Annual Change in Storage*	*Principal Stream Source of Recharge*
			Applied Water	*Precipitation and Streams*		
	hectares *(acres)*	*hm^3* *(Ac ft)*	*hm^3* *(Ac ft)*	*hm^3* *(Ac ft)*	*hm^3* *(Ac ft)*	
101	32 600 (80,500)	18.5 (15,000)	3.0 (2,400)	17.7 (14,400)	+2.2 (+1,800)	Minor streams north and west of Red Bluff
102	35 400 (87,400)	1.1 (900)	0.1 (100)	3.9 (3,200)	+2.9 (+2,400)	Minor streams west of Red Bluff
103	36 900 (91,300)	49.0 (39,700)	5.9 (4,800)	48.4 (39,200)	+5.3 (+4,300)	Red Bank and Elder Creeks
104	24 100 (59,500)	12.0 (9,700)	4.6 (3,700)	8.6 (7,000)	+1.2 (+1,000)	Mill and Deer Creeks
105	25 900 (64,100)	0.7 (600)	0 (0)	2.1 (1,700)	+1.4 (+1,100)	Thomes Creek
106	37 000 (91,500)	29.1 (23,600)	3.8 (3,100)	28.6 (23,200)	+3.3 (+2,700)	Thomes Creek
107	42 000 (103,800)	58.5 (47,400)	14.2 (11,500)	50.1 (40,600)	+5.8 (+4,700)	Various eastside streams
108	50 400 (124,500)	46.7 (37,900)	17.5 (14,200)	27.4 (22,200)	−1.8 (−1,500)	Stony Creek
109	37 100 (91,600)	133.1 (107,900)	50.3 (40,800)	88.3 (71,600)	+5.5 (+4,500)	Stony Creek
110	23 700 (58,600)	82.0 (66,500)	24.4 (19,800)	58.3 (47,300)	+0.7 (+600)	Big Chico, Little Chico and Butte Creeks
111	32 500 (80,300)	44.8 (36,300)	22.3 (18,100)	21.0 (17,000)	−1.5 (−1,200)	Walker Creek
112	37 100 (91,700)	27.3 (22,100)	17.6 (14,300)	11.9 (9,600)	+2.2 (+1,800)	Butte Creek in north position
113	36 800 (91,000)	54.8 (44,400)	19.0 (15,400)	35.8 (29,000)	0 (0)	Butte Creek and Cherokee Canal
114	19 500 (48,100)	21.2 (17,200)	3.0 (2,400)	19.1 (15,500)	+0.9 (+700)	Feather River on east side of area
115	26 400 (65,200)	10.7 (8,700)	6.4 (5,200)	5.0 (4,100)	+0.7 (+600)	Various small westside streams
116	38 000 (94,000)	27.8 (22,500)	10.4 (8,400)	19.4 (15,700)	+2.0 (+1,600)	
117	39 600 (97,800)	37.3 (30,200)	9.9 (8,000)	27.4 (22,200)	0 (0)	
118	31 200 (77,000)	38.6 (31,300)	11.7 (9,500)	30.0 (24,300)	+3.1 (+2,500)	Feather River
119	26 000 (64,200)	11.6 (9,400)	7.3 (5,900)	4.3 (3,500)	0 (0)	
120	43 100 (106,600)	34.4 (27,900)	26.4 (21,400)	10.8 (8,800)	+2.8 (+2,300)	
121	58 000 (143,300)	133.3 (108,100)	53.2 (43,100)	86.8 (70,400)	+6.7 (+5,400)	Feather and Yuba Rivers
122	23 900 (59,000)	6.0 (4,900)	0 (0)	0 (0)	−6.0 (−4,900)	Salt, Sand and Cortina Creeks
123	36 100 (89,200)	70.4 (57,100)	35.4 (28,700)	30.6 (24,800)	−4.4 (−3,600)	
124	45 500 (112,400)	13.8 (11,200)	14.9 (12,100)	2.7 (2,200)	+3.8 (+3,100)	

TABLE 7—Continued

GROUND WATER INVENTORY BY TOWNSHIP AREA

1961–70

Township Area Number	*Area*	*Average Annual Discharge (pumpage)*	*Average Annual Recharge*		*Average Annual Change in Storage*	*Principal Stream Source of Recharge*
			Applied Water	*Precipitation and Streams*		
	hectares *(acres)*	*hm^3* *(Ac ft)*	*hm^3* *(Ac ft)*	*hm^3* *(Ac ft)*	*hm^3* *(Ac ft)*	
125	37 200 (91,800)	135.4 (109,800)	47.1 (38,200)	91.5 (74,200)	+3.2 (+2,600)	Feather and Bear Rivers
126	24 700 (61,100)	44.2 (35,800)	9.7 (7,900)	35.8 (29,000)	+1.3 (+1,100)	Bear River
127	35 600 (88,000)	19.0 (15,400)	2.7 (2,200)	14.6 (11,800)	−1.7 (−1,400)	
128	38 500 (95,100)	51.8 (42,000)	31.0 (25,100)	24.9 (20,200)	+4.1 (+3,300)	
129	37 600 (92,800)	70.6 (57,200)	25.0 (20,300)	50.0 (40,500)	+4.4 (+3,600)	Feather River
130	39 600 (97,800)	31.6 (25,600)	2.6 (2,100)	27.4 (22,200)	−1.6 (−1,300)	Various small east side streams
131	31 000 (76,500)	28.1 (22,800)	11.5 (9,300)	17.9 (14,500)	+1.3 (+1,000)	Cache Creek
132	37 800 (93,400)	103.4 (83,800)	29.7 (24,100)	73.7 (59,700)	0 (0)	Cache Creek
133	35 300 (87,300)	55.8 (45,200)	27.9 (22,600)	27.9 (22,600)	0 (0)	Possibly Sacramento River
134	37 100 (91,800)	98.7 (80,000)	15.0 (12,200)	76.0 (61,600)	−7.7 (−6,200)	American River in south portion
135	16 200 (40,000)	-	Insufficient data		-	
136	20 300 (50,200)	40.3 (32,700)	12.2 (9,900)	35.1 (28,500)	+7.0 (+5,700)	Putah Creek
137	37 900 (93,700)	115.8 (93,900)	41.3 (33,500)	90.5 (73,400)	+16.0 (+13,000)	Putah Creek
138	35 700 (88,200)	37.7 (30,600)	14.9 (12,100)	26.6 (21,600)	+3.8 (+3,100)	Putah Creek and Sacramento River
139	37 000 (91,500)	113.6 (92,100)	18.9 (15,300)	88.4 (71,700)	−6.3 (−5,100)	American and Sacramento Rivers
140	33 700 (83,200)	25.4 (20,600)	5.1 (4,100)	9.2 (7,500)	−11.1 (−9,000)	Cosumnes River
*141	44 100 (108,900)	9.4 (7,600)	11.4 (9,200)	5.9 (4,800)	+7.9 (+6,400)	
142	36 400 (89,900)	10.5 (8,500)	9.0 (7,300)	2.5 (2,000)	+1.0 (+800)	Possibly Sacramento River
143	37 700 (93,100)	138.9 (112,600)	42.9 (34,800)	90.2 (73,100)	−5.8 (−4,700)	Sacramento and Cosumnes Rivers
144	38 300 (94,700)	30.1 (24,400)	7.0 (5,700)	9.3 (7,500)	−13.8 (−11,200)	Mokelumne River
145	21 400 (52,900)	-	Insufficient Data		-	
Totals (Rounded)		2 123 (1,721,000)	726 (589,000)	1 436 (1,164,000)	+39 (+32,000)	

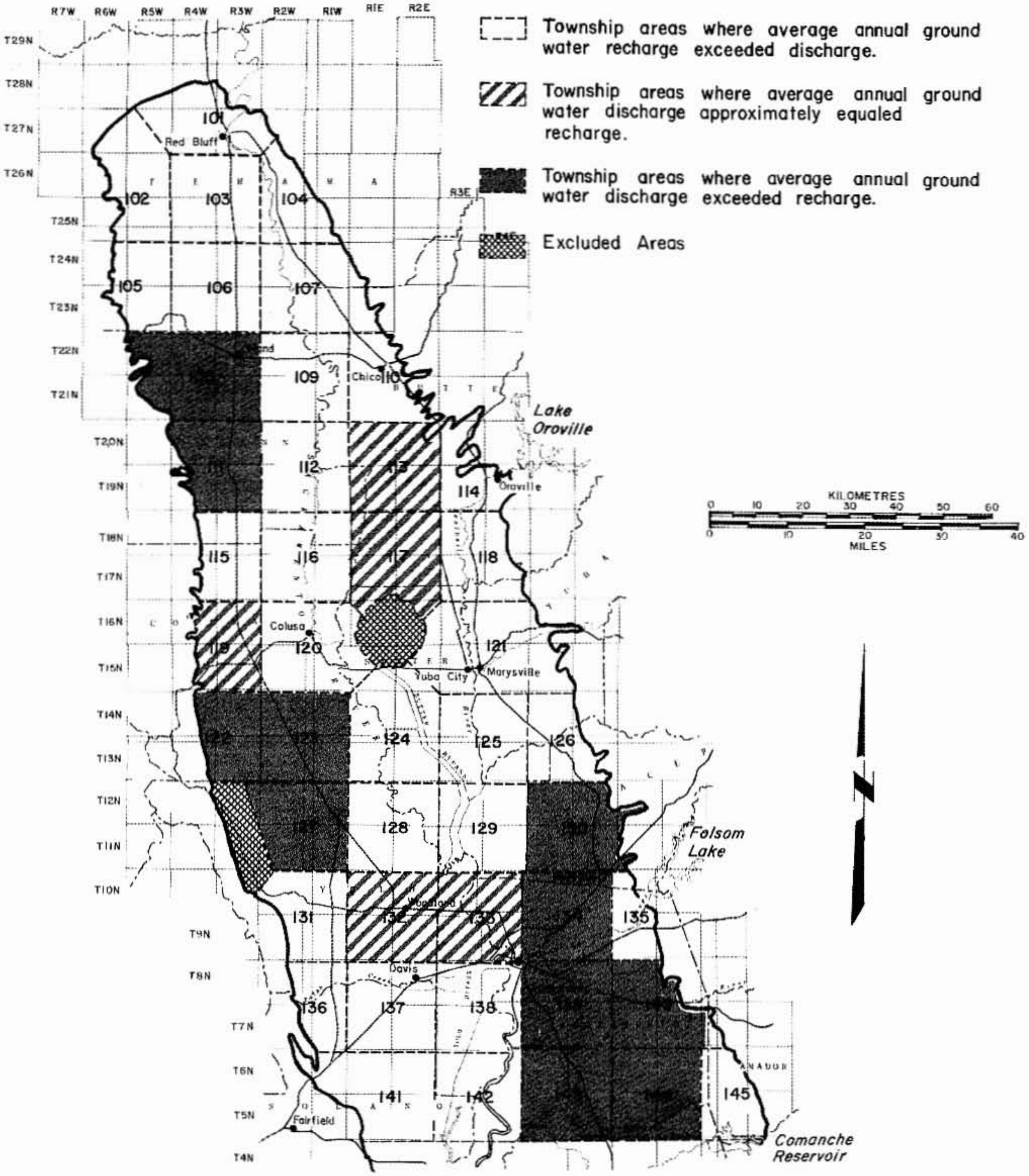


Figure 21. Relationship of Recharge to Discharge by Township Areas, 1961-1970

Township area 130 in Placer County and areas 134, 139, 140, 143, and 144 in Sacramento County all had average net recharge (change in storage) ranging from –1.6 to –13.8 hm^3 annually. With the possible exception of the American and Cosumnes Rivers' alluvial deposits, recharge rates are low due to low transmissivity of the Laguna and Mehrten Formations. In addition, hardpan soils occupy much of the areas where intensive pumping occurs, and recharge from applied water is restricted.

Table 8 summarizes inventory results for the entire basin. These figures represent the total of the individual township areas for each year of the study period. Of a 10–year average annual recharge of approximately 2 162 hm^3 (726 + 1 436 hm^3), 34 percent, or 727 hm^3, was in the north Sacramento Valley (north of Sutter Buttes) and the remainder 1 435 hm^3, or 66 percent, in the south Sacramento Valley. Note that this percentage is nearly opposite the recharge distribution under natural conditions as indicated by the USGS model studies in Appendix A.

In that study it was determined that about two–thirds of the total valley recharge (about 1 000 hm^3 or 830,000 acre–feet) was in the north valley under natural conditions and one–third in the south valley. The difference arises from the greater amount of pumpage in the south and replenishment of that pumpage, which results in greater recharge. In the north, the basin has remained nearly full and most potential recharge is rejected.

The table also shows that recharge in the north valley has exceeded discharge, resulting in an average annual change in storage of 34 hm^3, while in the south valley recharge has nearly equaled discharge, resulting in only a slight increase in storage. These annual changes in pumping, and recharge for the north valley, south valley and total valley are shown graphically in Figure 22. The accumulated change in storage during the study period, for the entire valley amounted to about 390 hm^3. For the north and south portions, the accumulated change was 340 hm^3 and 50 hm^3 respectively. These changes are shown in Figure 23.

Table 8 shows that recharge from streams and precipitation is about twice that derived from applied irrigation water. Streams and precipitation provided 66 percent of the 10–year average recharge in the entire valley. This source accounted for 70 percent in the north valley and 65 percent in the south.

English equivalents: 1 cubic hectometre (hm^3) = 810.7 feet (ac–ft).

TABLE 8

GROUND WATER INVENTORY
SACRAMENTO VALLEY
1961–1970

			Recharge					
Water Year	*Discharge (Pumpage)*		*Applied Water*		*Streams and Precipitation*		*Change in Storage*	
	hm^3	*Ac ft*	hm^3	*Ac ft*	hm^3	*Ac ft*	hm^3	*Ac ft*
			Total Sacramento Valley					
1961	2 130.5	1,727,200	680.8	551,900	1 202.8	975,100	−247.0	−200,200
1962	2 204.0	1,786,800	711.8	577,100	1 566.6	1,270,000	+74.4	+60,300
1963	2 094.2	1,697,800	691.6	560,700	1 458.0	1,182,000	+55.4	+44,900
1964	2 198.2	1,782,100	707.9	573,900	1 087.2	881,400	−403.1	−326,800
1965	2 131.0	1,727,600	731.1	592,700	1 446.9	1,173,000	+47.0	+38,100
1966	2 179.5	1,766,900	748.0	606,400	1 443.9	1,170,600	+12.5	+10,100
1967	2 031.3	1,646,800	740.0	599,900	1 464.9	1,187,600	+173.6	+140,700
1968	2 096.1	1,699,300	737.4	597,800	1 475.3	1,196,000	+116.6	+94,500
1969	2 035.4	1,650,100	760.2	616,300	1 917.4	1,554,400	+642.2	+520,600
1970	2 129.6	1,726,500	754.0	611,300	1 294.2	1,049,200	−81.4	−66,000
Avg. (Rounded)	2 123	1,721,000	726	589,000	1 436	1,164,000	+39	+32,000
			North Sacramento Valley					
1961	675.1	547,300	218.8	177,400	437.2	354,400	−19.1	−15,500
1962	682.2	553,100	220.3	178,600	537.1	435,400	+75.1	+60,900
1963	687.6	557,400	221.4	179,500	451.7	366,200	−14.4	−11,700
1964	692.7	561,600	211.0	171,100	251.9	204,200	−229.8	−186,300
1965	691.5	560,600	224.7	182,200	524.0	424,800	+57.2	+46,400
1966	686.0	556,100	224.0	181,600	491.7	398,600	+29.7	+24,100
1967	688.5	558,200	224.9	182,300	489.4	396,800	+25.8	+20,900
1968	695.0	563,400	227.8	184,700	563.5	456,800	+96.3	+78,100
1969	705.1	571,600	231.9	188,000	790.7	641,000	+317.5	+257,400
1970	727.2	589,500	235.8	191,200	493.2	399,800	+1.8	+1,500
Avg. (Rounded)	693	562,000	224	182,000	503	408,000	+34	+28,000
			South Sacramento Valley					
1961	1 455.4	1,179,900	462.0	374,500	765.6	620,700	−227.8	−184,700
1962	1 521.8	1,233,700	491.6	398,500	1 029.5	834,600	−0.7	−600
1963	1 406.4	1,140,200	470.2	381,200	1 006.0	815,600	+69.8	+56,600
1964	1 505.2	1,220,300	496.8	402,800	835.1	677,000	−173.3	−140,500
1965	1 439.5	1,167,000	506.4	410,500	922.9	748,200	−10.2	−8,300
1966	1 493.8	1,211,000	524.0	424,800	952.5	772,200	−17.3	−14,000
1967	1 343.0	1,088,800	515.1	417,600	975.7	791,000	+147.8	+119,800
1968	1 401.1	1,135,900	509.6	413,100	911.8	739,200	+20.2	+16,400
1969	1 330.3	1,078,500	528.3	428,300	1 126.7	913,400	+324.7	+263,200
1970	1 402.5	1,137,000	518.2	420,100	800.9	649,300	−83.3	−67,500
Avg. (Rounded)	1 430	1,159,000	502	407,000	933	756,000	+5	+4,000

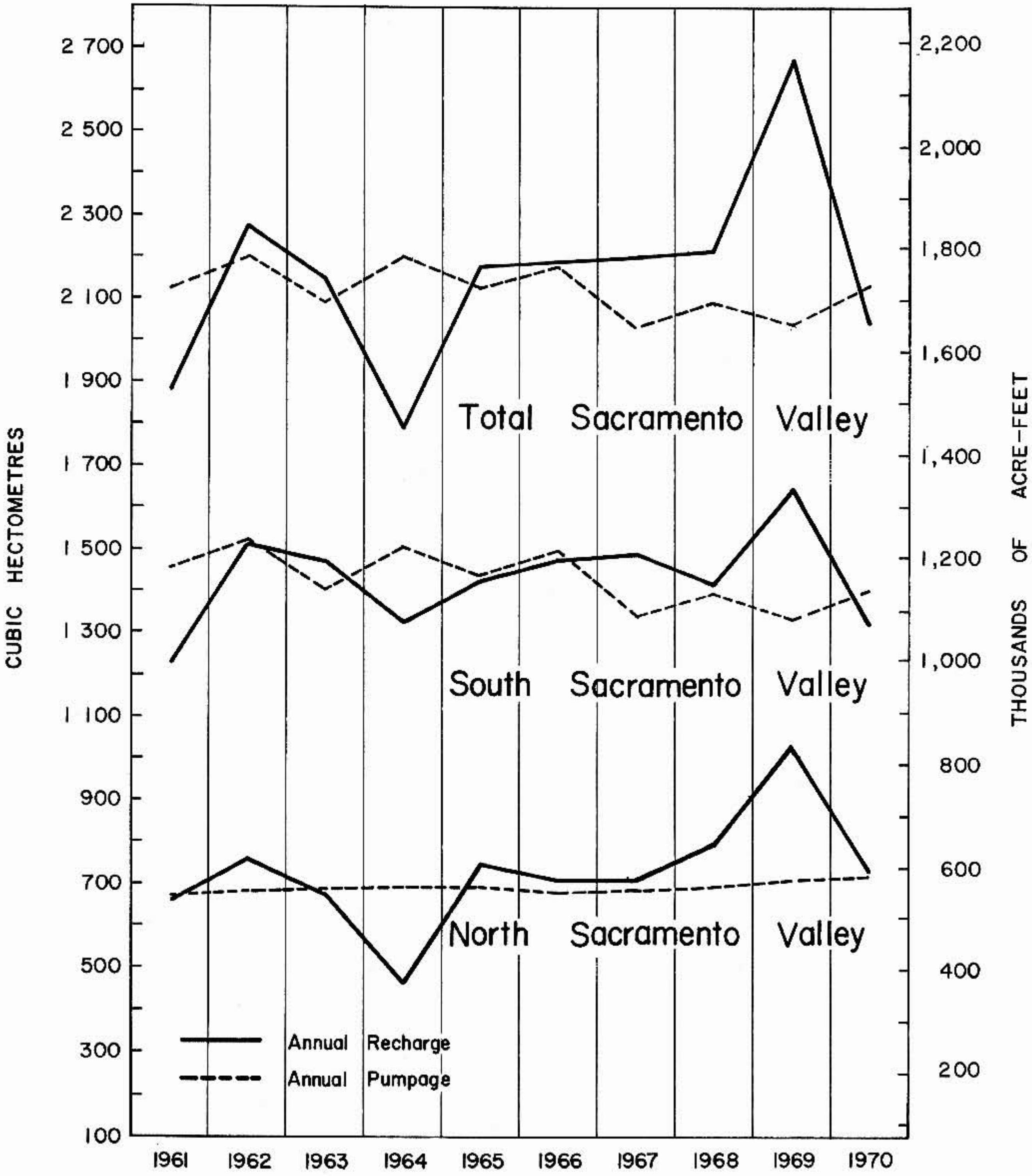


Figure 22. Annual Ground Water Pumpage and Recharge - Sacramento Valley 1961-70

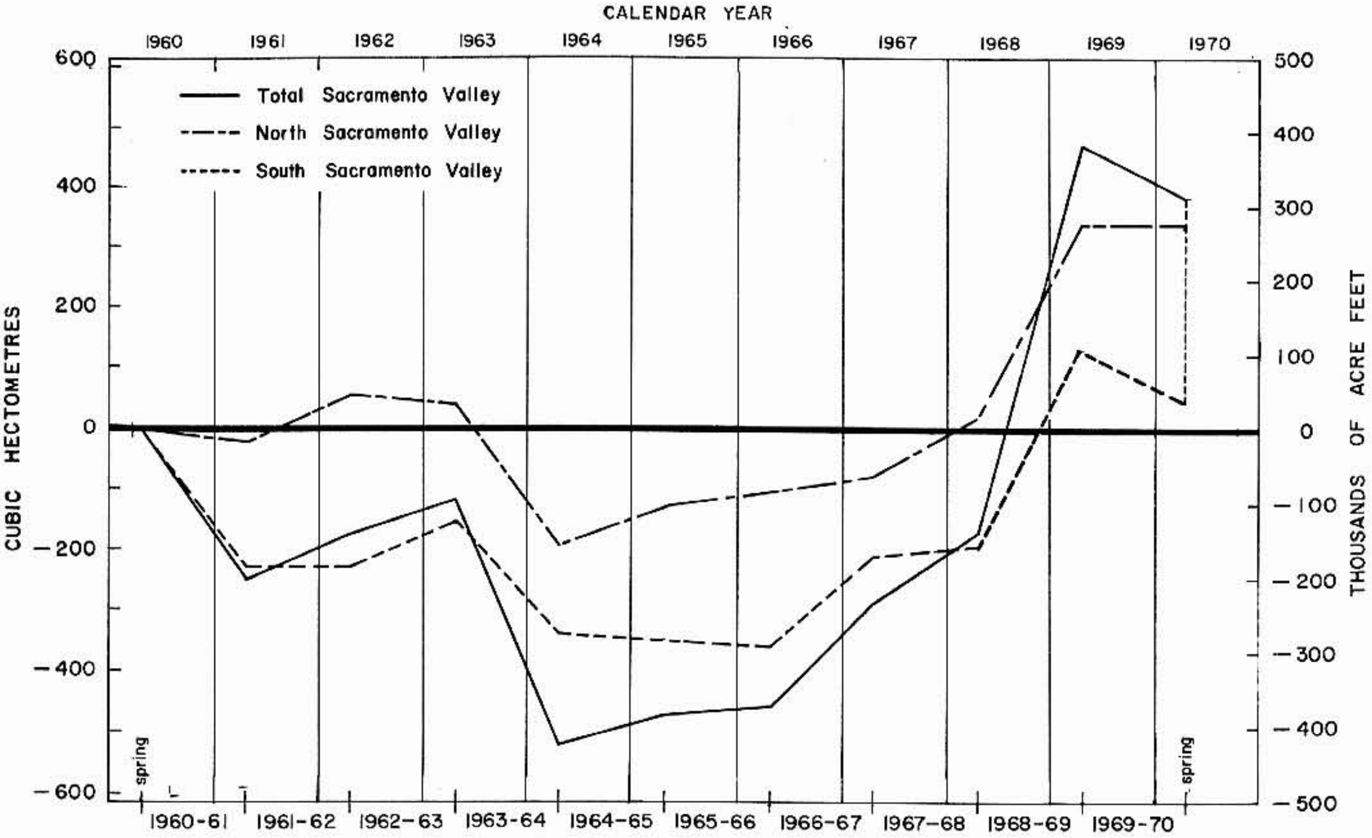


Figure 23. Accumulated Change in Storage, 1961-1970

APPENDIX A

REPORT OF THE U. S. GEOLOGICAL SURVEY— GROUND WATER CONDITIONS IN THE SACRAMENTO VALLEY, CALIFORNIA, 1912, 1961, and 1971

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GROUND-WATER CONDITIONS IN THE SACRAMENTO VALLEY, CALIFORNIA, 1912, 1961, and 1971

by

R. M. Bloyd, Jr.

Menlo Park, California
1978

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CONVERSION TABLE

For readers who require metric units, the following conversion factors are presented for the English units used in this report.

Multiply English unit	*By*	*To obtain metric unit*
inches (in)	25.4	millimeters
feet (ft)	0.3048	meters
miles (mi)	1.609	kilometers
acre-feet (acre-ft)	0.001233	cubic hectometers
square miles (mi^2)	2.590	square kilometers
feet squared per day (ft^2/d)	0.0929	meters squared per day
gallons per minute (gal/min)	0.06309	liters per second
cubic feet per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meters per second per square kilometer

GROUND-WATER CONDITIONS IN THE SACRAMENTO VALLEY, CALIFORNIA, 1912, 1961, and 1971

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ABSTRACT

Continental deposits of post-Eocene age in the Sacramento Valley compose one of the Nation's larger ground-water basins. Average annual ground-water recharge is about 830,000 acre-feet. The greatest amounts of natural recharge occur in the Stony Creek and Thomes Creek areas at the north end of the valley. Fresh ground water in storage is estimated to be 395 million acre-feet. This is 3.2 times the water in storage in Lake Tahoe and 89 times that in Shasta Lake. Average well yields greater than 1,000 gallons per minute are possible in 30 percent of the study area.

Estimated ground-water pumpage was 1.8 million acre-feet in both 1961 and 1970. Little change in natural ground-water flow patterns has occurred north of Sutter Buttes, but significant changes have occurred to the south.

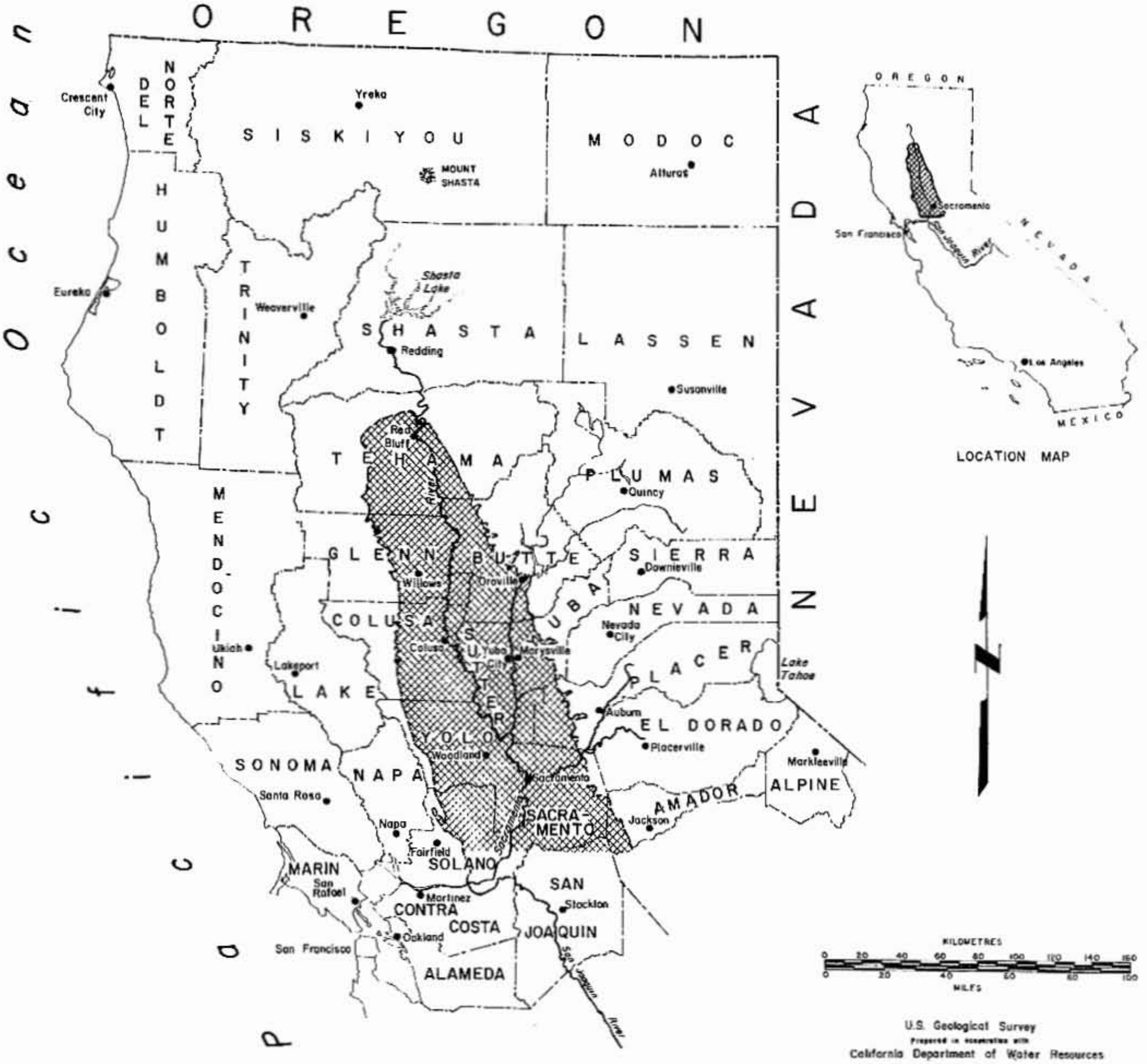


Figure 1A. Location of Sacramento Valley

INTRODUCTION

Location and General Features

The study area, which consists of about 4,900 mi^2, primarily is the floor of the Sacramento Valley (Figure 1A), a broad structural trough occupying the northern one-third of the Great Central Valley of California. The valley is bounded by the Sierra Nevada on the east, the Cascade Range on the northeast, and the Coast Ranges on the west. The north end is just north of Red Bluff, and a south line passes through Sacramento and Solano Counties (Figure 1A).

The valley floor, although seemingly flat, is not a featureless plain but is characterized by various types of topography. Olmsted and Davis (1961, pl. 1) defined 16 geomorphic units in the valley, of which the most extensive are: (1) low alluvial plains and fans on the east side of the valley just west of the Sierra Nevada, (2) low alluvial plains and fans on the west side of the valley, (3) dissected alluvial uplands west of the Sierra Nevada, (4) low hills and dissected uplands on the west side of the valley, (5) flood basins, and (6) river flood plains. The only prominent topographic feature on the valley floor is Sutter Buttes (Figure 2A), a circular mass of intrusive volcanic rocks remaining as the erosional remnant of a volcano.

Purpose and Scope

In general terms, the major purpose of the study was to obtain detailed knowledge of the ground-water system in the Sacramento Valley. Such knowledge is necessary to developers and managers if the large ground-water resource is to be optimally utilized. The work was done in cooperation with the California Department of Water Resources (DWR).

A major intent of this study was to make maximum use of available geohydrologic data and only in passing, so to speak, collect more data. Numerous previous studies and data-collection programs resulted in voluminous quantities of information, much of which is summarized in reports of previous studies. Olmsted and Davis (1961) presented an exhaustive reference list of historical reports on various aspects of the geohydrology of Sacramento Valley. This list is not repeated here. If any one report can be considered a predecessor to this report, it is the Olmsted and Davis report. Likewise, Olmsted and Davis (1961, p. 8) considered Bryan's report (1923) a predecessor to theirs.

Information was not uniformly available for all parts of the study area. Data were scanty or nonexistent for the undeveloped part; in contrast, data were available in abundance for the extensively developed part.

Complicating the problem of nonuniform areal distribution of data was the fact that data were gathered or recorded by numerous agencies under different degrees of quality control. For example, ground-water levels in wells in the Sacramento Valley are measured by at least 15 agencies. By further example, at least a dozen well drillers provided logs of wells. Further complicating the problem, some types of data were available for different time periods and (or) in varying amounts from year to year. For instance, ground-water-level data, ground-water-pumpage data, and surface-water-irrigation data were available for different 1-, 5-, or 10-year periods. Also, abundant ground-water-level measurements were available only for the period since 1964.

In this study a mathematical model programmed on a digital computer was used to synthesize data for natural conditions. With such an approach, the problem of the variability of data, especially data for natural conditions, was surmountable. In areas where ground-water-level data were scanty for example, an estimate of conditions was made, the model was used to evaluate the estimate, and changes were made where necessary in light of known conditions. Using the model as a tool it was also possible to evaluate estimates of the areal variation of the transmissivity of the major aquifer in the study area. A more in-depth discussion of the use of the model is presented in the following section of this report.

The scope of the study included:

1. Construction of a ground-water-level contour map for natural conditions. The water levels in 1912 and 1913 were assumed to approximate natural conditions.

2. Construction of ground-water level contour maps for 1961 and 1971.

3. Determination of the base and thickness of the major aquifer.

4. Estimation of hydraulic conductivity of the major aquifer.

5. Estimation of storage coefficient of the major aquifer.

6. Calculation of transmissivity of the major aquifer.

7. Estimation of soil permeabilities.

8. Computation of natural ground-water recharge and discharge.

9. Estimation of ground-water pumpage and applied surface-water irrigation for 1961 to 1971.

The study was made in cooperation with the State of California Department of Water Resources as a facet of the overall investigation of the geohydrology of Sacramento Valley.

General Discussion of the Ground-Water Model

A digital ground-water model is an idealized representation of a ground-water system and describes in mathematical language how the ground-water system functions under various conditions.

Simplifying assumptions or approximations are generally required if development of a model is to be feasible. This is because physical processes of the natural environment are seldom simple enough to be described exactly by any practical model.

General assumptions made in this study are:

1. There is only one aquifer in the study area. Shallow perched or semiperched aquifers that exist along most of the flanks of the valley were ignored.

2. The ground-water and surface water systems in the study area are hydraulically connected.

3. Vertical flow components within the aquifer are negligible compared with horizontal flow components.

4. The following discrete form of the Darcy equation can be used to describe the flow conditions in the idealized aquifer of the Sacramento Valley:

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right)=S\frac{\partial h}{\partial t}+W \quad (1)$$

where

$\frac{\partial}{\partial x}$, $\frac{\partial}{\partial y}$, and $\frac{\partial}{\partial t}$ are first partial derivatives

T_{xx} = transmissivity in the x direction,

T_{yy} = transmissivity in the y direction,

h = hydraulic head,

S = storage coefficient,

t = time, and

W = flux, which is the net rate of pumping per unit area.

A detailed theoretical development of the mathematics of digital modeling, such as the development of Pinder and Bredehoeft (1968), is not presented here. For the purposes of this report, a short summary presentation is considered appropriate. The model used is a modification of that presented by Trescott (1972).

In order to solve the equation of flow in most practical applications, finite-difference approximations of equation 1 are used. In the finite-difference approximation, the derivative is replaced by the difference quotients at separate discrete points commonly referred to as nodal points. The network of nodal points is referred to as the grid network.

The equation of flow is written for each node of the finite difference network. The result is N equations in N unknowns, where N is the number of nodes in the network.

To model the Sacramento Valley, a 116 × 19 nodal network (Figure 3A) was used. Therefore, there is a total of 2,204 points for which data must be specified. Nodal spacing is 3 mi in the x, or east-west, direction and 1, 2, or 3 mi in the y, or north-south, direction. The lines in the x direction are called rows and the lines in the y direction are called columns.

Boundary conditions for the model area must be specified mathematically. Model boundaries encompass about 4,900 mi^2 of the valley floor. Two types of boundary conditions were assumed. A constant-head boundary was assumed along the southern boundary of the model area. Along this boundary ground-water levels are assumed constant with time. Actually, there has been a small water-level decline historically, but probably not enough to invalidate the assumption. A constant-flux boundary was assumed along other boundaries of the model area. Along these boundaries no flow was assumed. To simulate no flow, zero transmissivity was specified at the boundary nodes.

Although there probably is some subsurface inflow across many of the boundaries of the model area, the assumption was made that the effect of such flow on model results would be minimal. Therefore, no-flow boundaries were arbitrarily assumed.

THE GROUND-WATER BASIN

The continental deposits of post–Eocene age that fill the ground–water basin are considered to constitute the aquifer of the study area. Berkstresser (1973) determined that fresh ground water in this area is contained almost exclusively in these deposits. Fresh water, as used by Berkstresser, is water with a specific conductance of less than 3,000 micromhos per centimeter at 25°C. This implies a dissolved–solids concentration of about 2,000 mg/l (milligrams per liter).

The post–Eocene deposits consist predominantly of valley–fill sediments of late Tertiary and Quaternary age. Olmsted and Davis (1961) defined and discussed in detail 11 major geologic units of this group that yield water more or less freely to wells.

The structure of the base of the continental deposits is that of a large syncline whose axis closely parallels the principal axis of the valley (Page, 1974, Figure 2). Nearly everywhere beneath the Sacramento Valley, the post–Eocene deposits lie unconformably on sedimentary rocks of either Cretaceous or Eocene age. But beneath some areas in the valley, principally on the eastern side, the deposits overlie basalt of Tertiary age.

Page (1974) determined that the continental deposits range in thickness from 0 ft near the margins of the Sacramento Valley to about 3,500 ft a short distance south of Davis (Figure 2A). For informative purposes, Page's Figure 3 is duplicated in this report (Figure 2A). The thickest sections occur along the axis of the syncline. Sutter Buttes, however, interrupts the trend of the syncline. Adjacent to the buttes, the continental deposits are thinner than anywhere else in the central part of the valley.

AQUIFER CHARACTERISTICS

Estimated transmissivity for the idealized aquifer in the study area (Figure 3A) ranges from about 4,300 ft^2/d to about 65,000 ft^2/d depending on the locality. Transmissivity is a measure of the gross ability of the aquifer to transmit water. It is equal to the hydraulic conductivity multiplied by the saturated thickness of the aquifer. Variation in transmissivity results because of the variation in hydraulic conductivity of the various geologic formations and because of the areal variation in aquifer thickness.

A method was adopted to make initial estimates of transmissivity for the entire study area and, therefore, for each nodal point of the model. The steps in the method are:

1. Determine the "type section" for each geologic formation.

2. Determine the thickness of the various material components of the type section. In other words, determine the thickness of fine sand, of gravel, of silt, and of the various other materials.

3. Determine the percentage of the section composed of each of the material components. For example, fine sand 60 percent, gravel 30 percent, and silt 10 percent.

4. Assign each component a hydraulic conductivity in the range of hydraulic conductivities given by Johnson (1963). A point of emphasis here is that Johnson suggests a range of values. There is no one correct value presented.

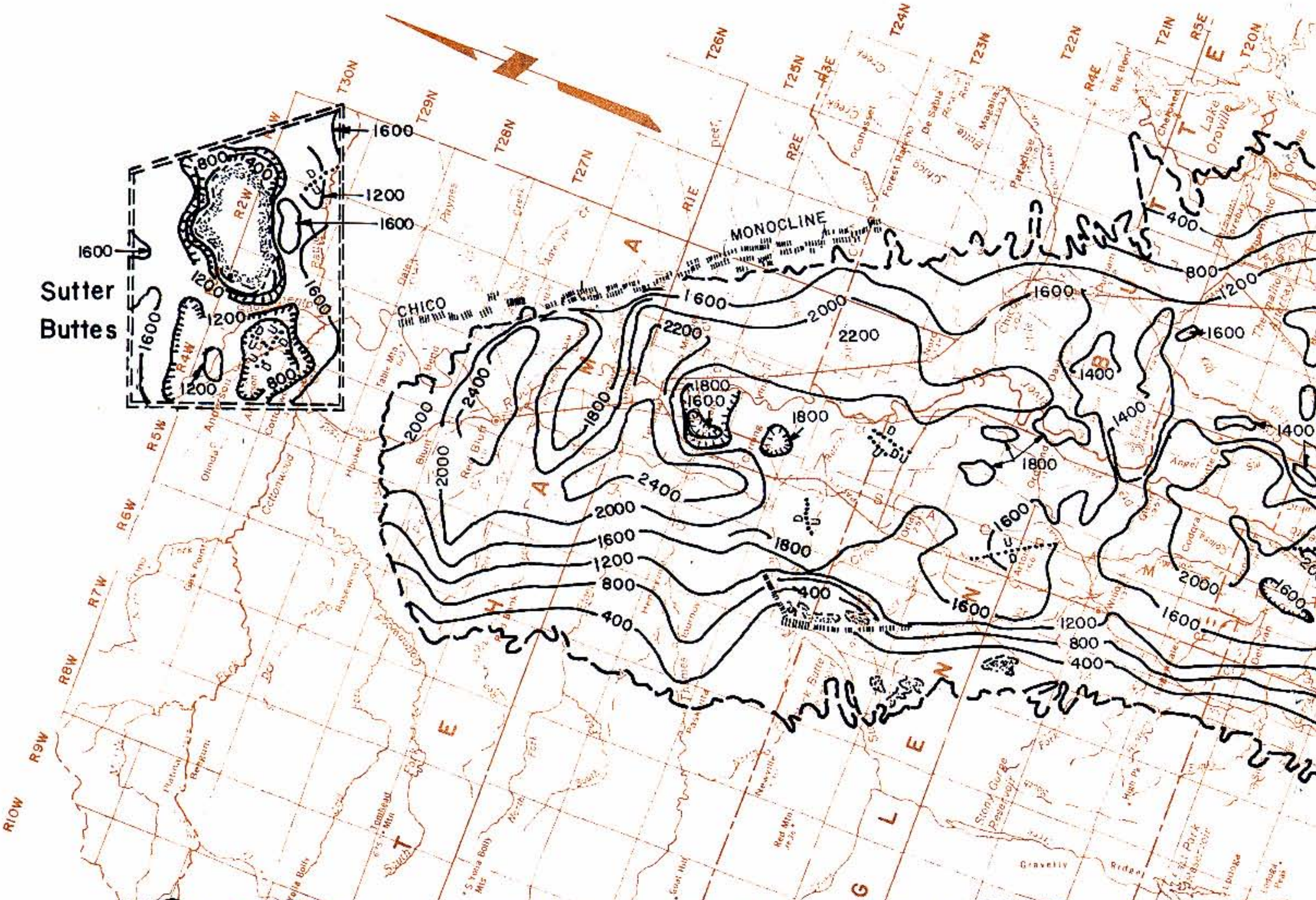
5. Multiply the percentage value of each component by the assigned hydraulic conductivity to get a component hydraulic conductivity.

6. Sum the weighted values to get a formation hydraulic conductivity.

7. Overlay the digital model nodal network on a map showing the areal distribution of adjusted hydraulic conductivities and determine the hydraulic conductivity at each nodal point.

8. Likewise, overlay the nodal network on a map showing thickness of post–Eocene continental deposits (Page, 1974) and determine the formation thickness at each nodal point.

9. Multiply the hydraulic conductivity times the thickness to determine transmissivity at each nodal point.



1600 LINE OF EQUAL THICKNESS OF POST-EOCENE CONTINENTAL DEPOSITS__ Intervals between lines, 200 and 400 feet.

OUTCROP____Eocene and pre-Eocene sedimentary rocks and some post-Eocene igneous rocks.

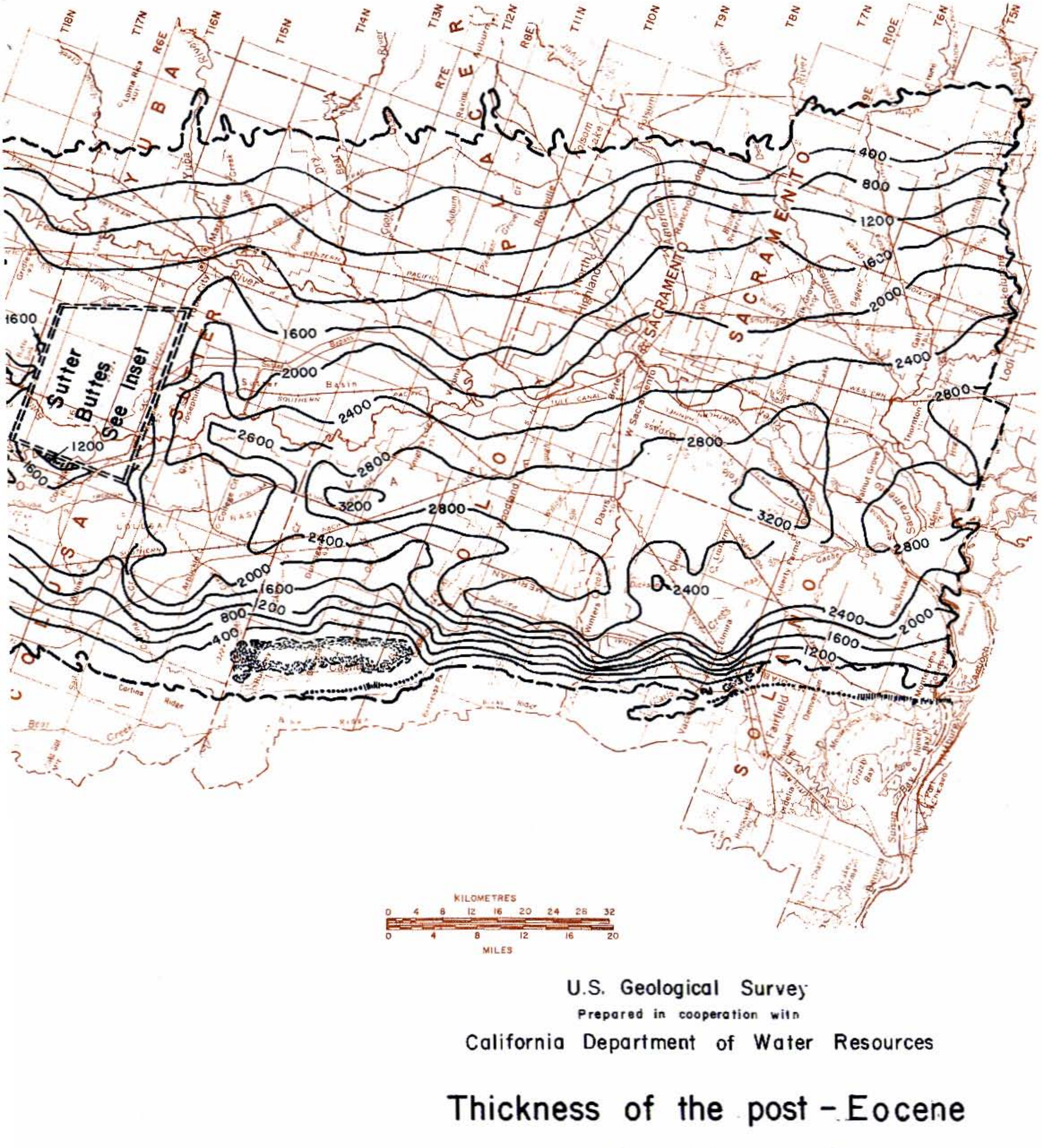
U D FAULT, APPROXIMATELY LOCATED___ Dashed where concealed. U, upthrown side; D, downthrown side

REFERENCES Outcrop pattern of Eocene and pre-Eocene rocks after California Division of Mines and Geology 1960-1966.

Faulting Modified after Barger and Sullivan, 1966; Beecroft, 1964; Bowen, 1962; Bruce, 1958; Burnett, 1963; California Division of Mines, 1960b; California Division of Mines and Geology 1960-1966; California Division of Oil and Gas, 1960; Land, 1970; and Thomasson and Others, 1960.

Modified from Page, R.W. 1974, Figure 3 (see Appendix "B")

Figure 2 A



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Thickness of the post-Eocene continental deposits

The initial estimates of transmissivity were adjusted on the basis of scanty aquifer test data and on the basis of model results. The final estimates of transmissivity (Figure 3A) are about one-half the original estimates.

The lowest transmissivity in the study area is in Yolo and Solano Counties (Figure 3A).

Low transmissivity in Solano County was suggested in the results of three aquifer tests by Thomasson and others (1960). Actually, their values for computed transmissivity varied widely.

Data from a test in Sec. 20, T. 8 N., R. 1 E., Yolo County, suggests a transmissivity as high as 25,000 ft^2/d. However, the high transmissivity applies only to a thin 30-ft saturated thickness of older alluvium (Thomasson and others, 1960, p. 217).

Data from a test in Sec. 6 T. 7 N., R. 1 E., suggests a transmissivity as high as 21,000 ft^2/d. Again, the high transmissivity applies only to a thin section of older alluvium (Thomasson and others, 1960, p. 215).

Finally, data from a well in Sec. 32, T. 7 N., R. 1 E., suggests a transmissivity of only 4,000 to 6,700 ft^2/d. In this test, the transmissivity applies to a 144-ft thickness of sediments deposited in part by Putah Creek and in part by smaller frontal streams to the south.

The highest transmissivity in the study area occurs adjacent to several reaches of the Sacramento River (Figure 3A).

On the basis of yield characteristics of irrigation wells in the Sacramento Valley, Olmsted and Davis (1961, table 2) found that transmissivity is fairly high in the Orland-Willows area. In this area there are significant thicknesses of coarse, clean saturated sand and gravel in the form of tongues in the alluvial fan of Stony Creek.

Olmsted and Davis (1961, p. 186–188) also suggested that the transmissivity of the western part of the alluvial fan of Big Chico and Butte Creeks is relatively high. The greatest proportion of sand and gravel is found in the western part of the fan.

The storage coefficient in the study area ranges from 0.04 to 0.12 (Figure 4A). The storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. In a confined aquifer the water derived from storage with decline in head comes from expansion of the water and compression of the aquifer; similarly, water added to storage with a rise in head is accommodated partly by compression of the water and partly by expansion of the aquifer. In an unconfined aquifer the amount of water derived from storage by expansion of the water or by compression of the aquifer generally is negligible compared to that involved in gravity drainage or filling of pores. In an unconfined aquifer the storage coefficient corresponds to the specific yield and usually is greater than 0.01. For the purposes of this study the subsurface system in the study area is assumed to be unconfined. Hence, the specific yield is equated to storage coefficient.

The assumption of unconfined conditions appears justified in most of the Sacramento Valley. According to Byran (1923, p. 91), "Only a small number of flowing wells have been obtained in Sacramento Valley, and of these only a few have strong flows. There is no large area of artesian flow, as in San Joaquin Valley."

A method was used to estimate specific yield on the basis of available well-drillers' logs. Essentially, the method is that of Olmsted and Davis (1961, p. 144–152). The steps followed in the present study are:

1. Select drillers' logs for the 10 deepest wells logged in each township in the study area. If 10 logs are not available, use as many as are available.

2. Group materials of the subsurface, as described in the drillers' logs, into classes on the basis of hydrologic character of the materials. The materials as logged were grouped into five general classes (Table 1).

3. Assign arbitrary specific yield values to each of the five classes of materials in the well logs (Table 1).

4. Determine the thickness of the various materials in each well log.

5. Determine the percentage of the log consisting of each class of material.

6. Multiply the percentage value of each class by the assigned specific yield to get a weighted specific yield.

7. Sum the weighted values to get a formation specific yield for each well site.

8. Determine the average of the specific yields in a township to get a township specific yield.

Table 1.—*Specific yield, classified by subsurface material*

(After Olmsted and Davis, 1961)

Material	*Specific yield (percent)*
Gravel	25
Sand, including sand and gravel, and gravel and sand	20
Tight sand, hard sand, fine sand, sandstone and related deposits	10
Clay and gravel, gravel and clay, cemented gravel, and related deposits	5
Clay, silt, sandy clay, lava rock, and related fine-grained deposits	3

GROUND-WATER OCCURRENCE AND MOVEMENT UNDER NATURAL CONDITIONS

Prior to the entry of man into the Sacramento Valley the ground–water basin was in a natural equilibrium, or steady–state condition: recharge equaled discharge and, considering periods of several years, the water levels in the ground–water basin remained unchanged with time.

The water–level data for the autumns of 1912 and 1913 (Bryan, 1923) compose the oldest fairly comprehensive set of data available, and they are assumed to approximate natural conditions more closely than any later data. Although 1912 and 1913 were very dry years, the depth to water was less than 25 ft in more than 80 percent of the Sacramento Valley (Bryan, 1923, p. 82). With the water table so close to land surface even during dry years, it appears that annual fluctuations in ground–water levels would have been small. Also, the oldest set of data should best approximate natural conditions because the effect of ground–water pumping has generally increased with time.

Bryan's analysis of ground–water levels and his water–level contour map were accepted almost without change. However, Bryan lacked sufficient data to define the water–level distribution along the flanks of the Sacramento Valley. He also did not define water levels in the valley south of Sacramento. The estimated water levels for natural conditions in these areas (Figure 5A) are based on subjective extrapolation of sparse data. Water levels in the Chico and Arbuckle area and in the extreme northwestern part of the study area were especially difficult to estimate.

The ground–water levels shown on Figure 5A indicate that under natural conditions ground water in the study area was migrating from areas of recharge toward and into the Sacramento River and eventual discharge from the study area.

The Lodi–Sacramento Delta area was, under natural conditions, a hydrologic sink. In fact, the Sacramento Delta was a hydrologic sink for much of the San Joaquin Valley as well as for the Sacramento Valley. In the sink area there was an accumulation of water. Under natural conditions the water evaporated from the tule swamps or was discharged as surface water into the Pacific Ocean.

The presence of Sutter Buttes, an impermeable volcanic plug, complicates the hydrology in the center of the valley. North of the Buttes, the general ground–water and surface–water flow patterns suggest that water flows from the borders of the valley towards the center and then southward. The Buttes are a barrier to flow, however, which results in accelerated ground–water discharge to the Sacramento River north of the Buttes. South of the Buttes, some of the surface water from both the Sacramento and Feather Rivers percolates into the ground and becomes ground water.

The natural condition of water levels remaining unchanged with time can be expressed in equation form as:

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial hss}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial hss}{\partial y}\right) = Wss \qquad (2)$$

where

$\frac{\partial}{\partial x}, \frac{\partial}{\partial y}$, and $\frac{\partial}{\partial t}$ are first partial derivatives

T_{xx} = transmissivity in the x direction,

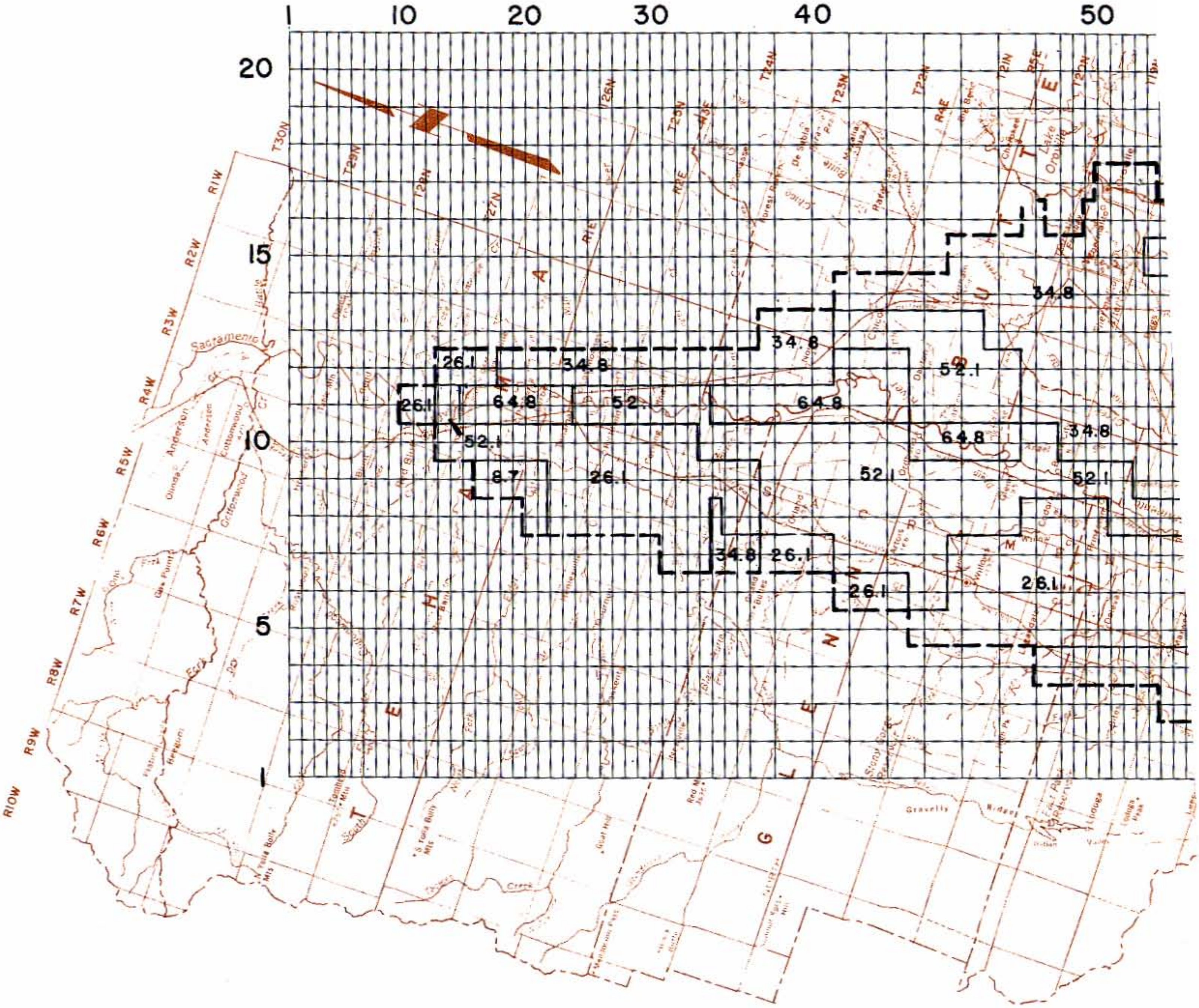
T_{yy} = transmissivity in the y direction,

hss = hydraulic head for natural conditions or steady state, and

Wss = flux for natural conditions. Flux is the net rate of ground-water recharge or discharge per unit area.

A solution to the discrete form of equation 2 was programmed on a digital computer and used to synthesize data for natural conditions. In equation 2 there are three variables, namely transmissivity (T), head (h), and flux (W). If a distribution for any two variables can be defined, a distribution for the third variable can be systematically computed. In this study, W was solved for on the basis of known and/or estimated distributions of T and h. This approach was taken because more data were available to define T and h than to define W. The solution for W is an explicit computation and does not require the solution of simultaneous equations as in the traditional modeling approach. The computer program used in the study was a condensation and modification of the general–purpose U. S. Geological Survey ground–water model program (Trescott, 1972).

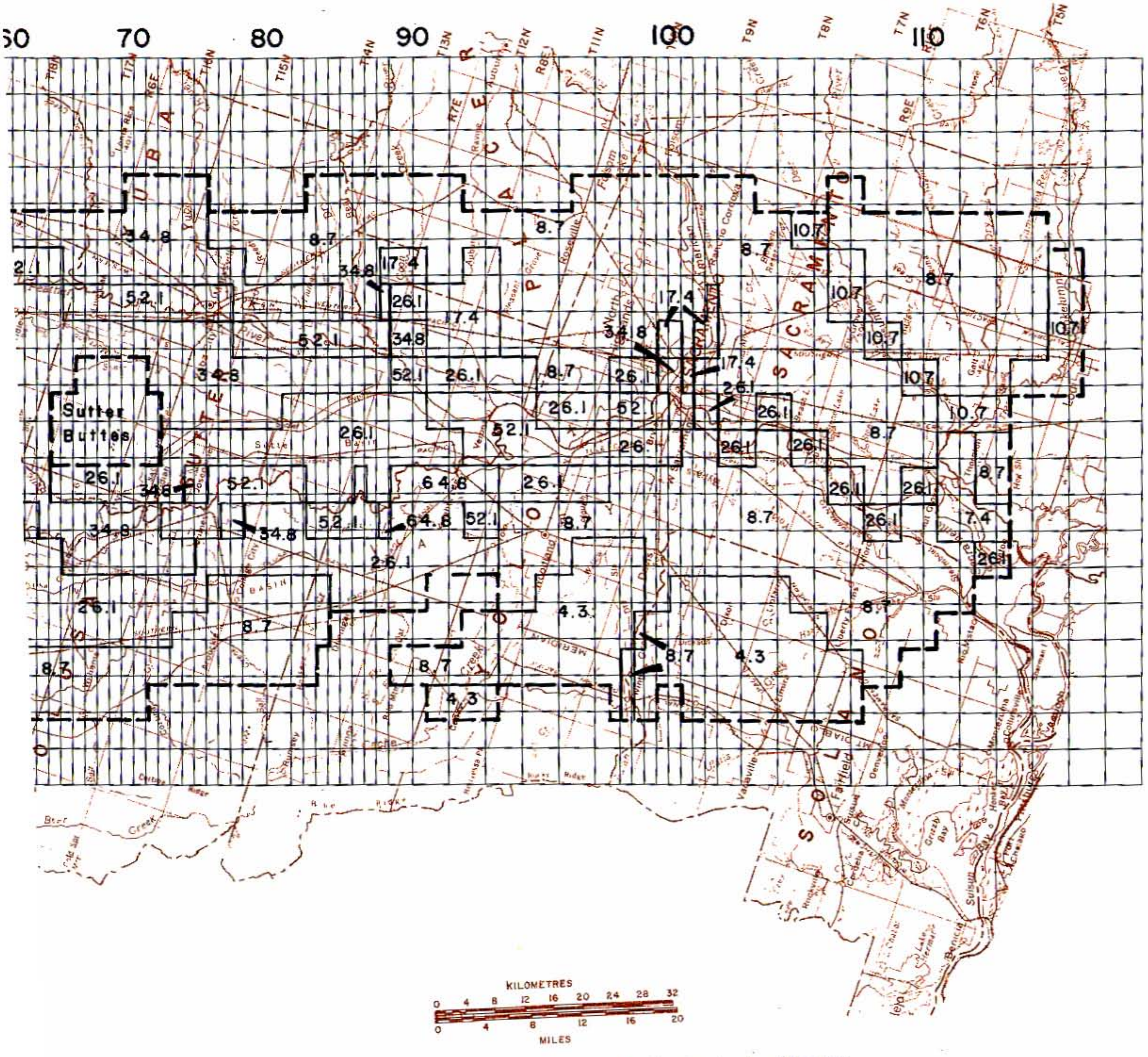
Numerous computer runs were made to estimate flux for natural conditions. After each run the signs (+ or −) and numerical values of W were plotted on a map. Then the plotted values were compared. Any individual value that differed considerably from neighboring values without a valid reason for such a difference was adjusted in a subsequent computer run by modifying T and/or h. Care was taken, however, in modifying T and h because small changes in the h distribution can produce large changes in computed flux. This modification process continued until a set of values for T, h, and W was



— — — Model boundary

26.1	Transmissivity, in thousands of feet squared per day

Figure 3A



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Finite-difference grid and transmissivity distribution

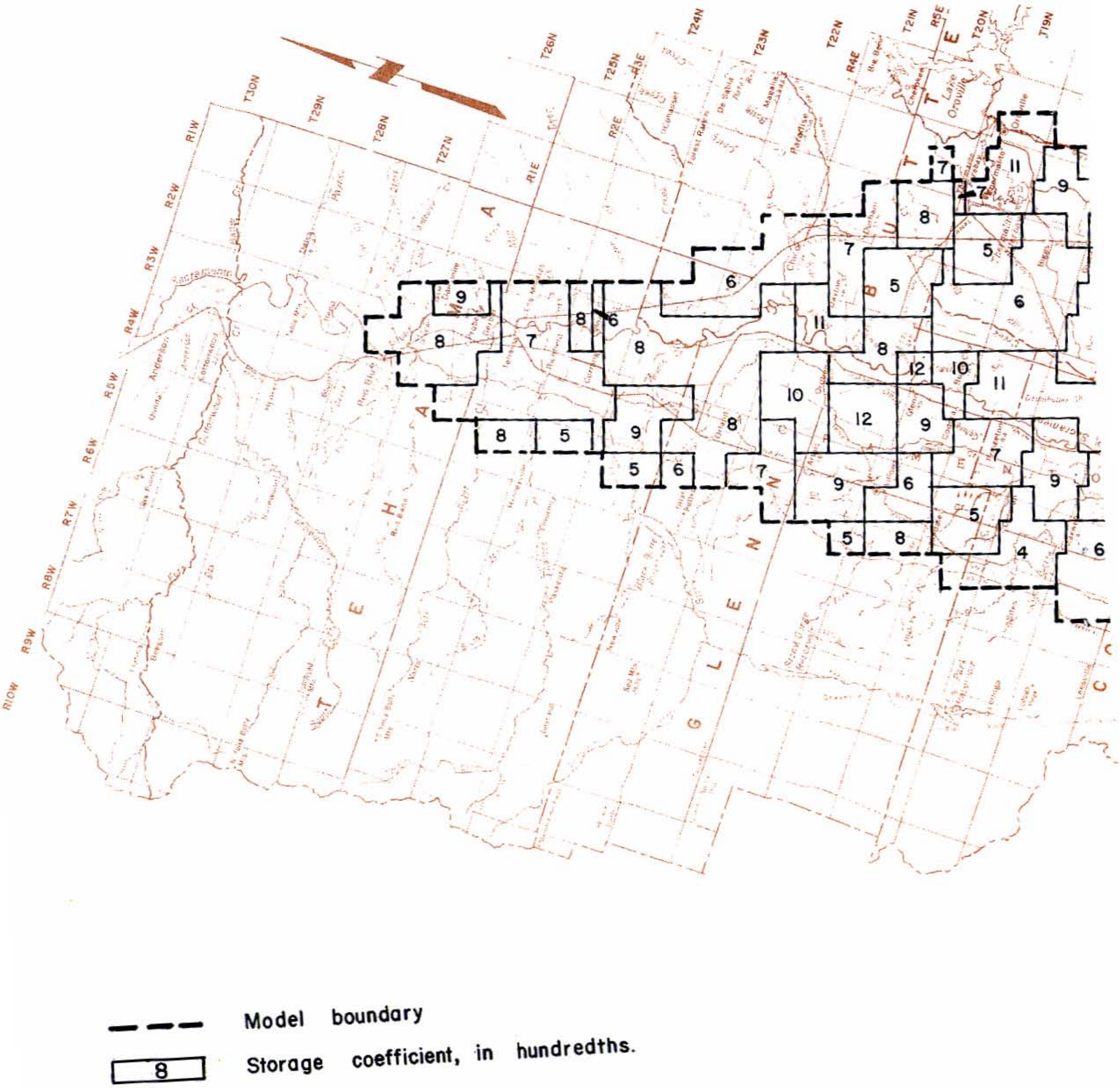
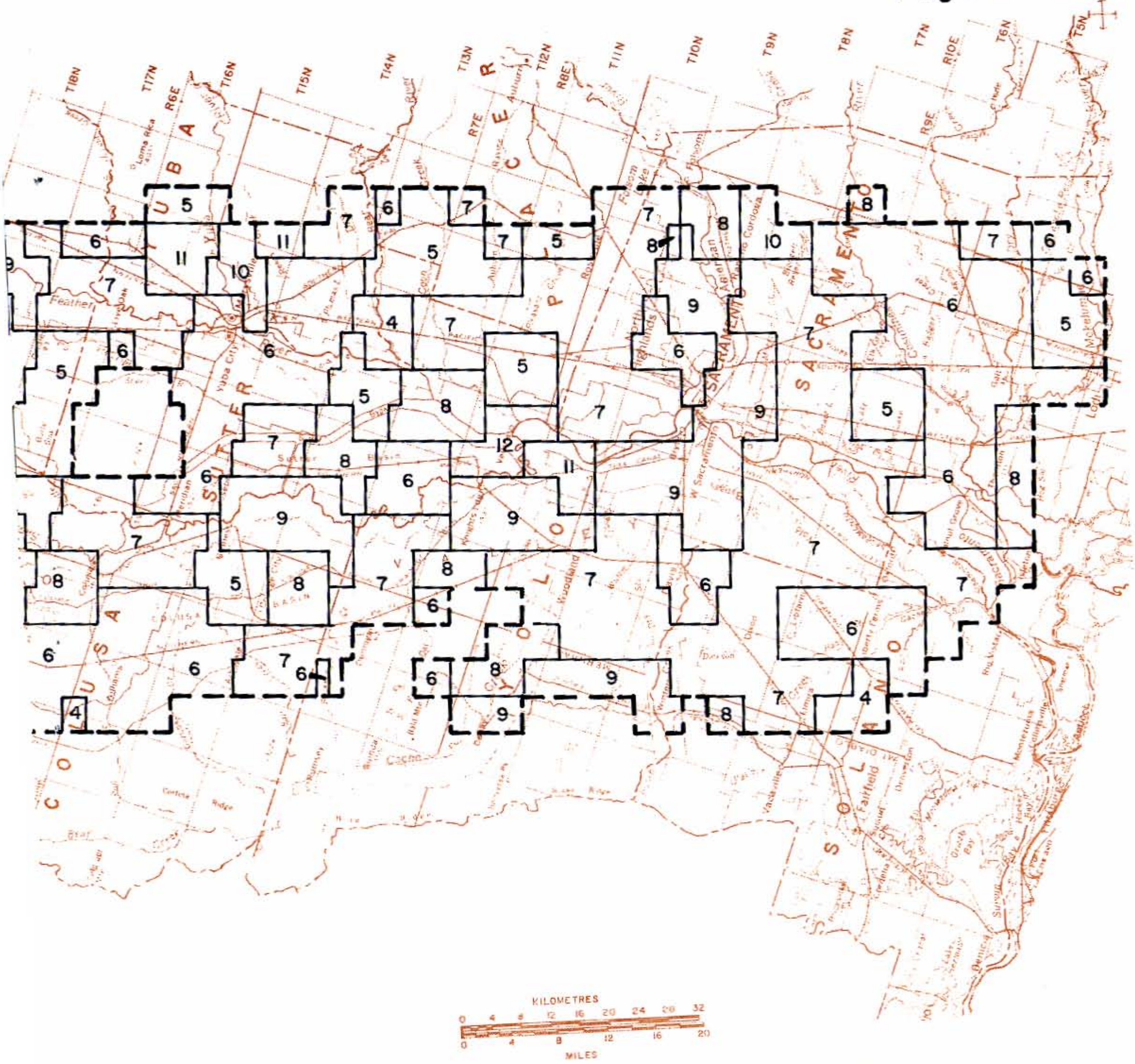

T30N
T29N
T28N
T27N
T26N
T25N
T24N
T23N
T22N
T21N
T20N
T19N
R1W
R2W
R3W
R4W
R5W
R6W
R7W
R8W
R9W
R10W
R1E
R2E
R3E
R4E
R5E
TEHAMA
BUTTE
GLENN
Lake Oroville
Paradise
Chico
Sacramento
Model boundary
8
Storage coefficient, in hundredths.

Figure 4A



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Storage-coefficient distribution

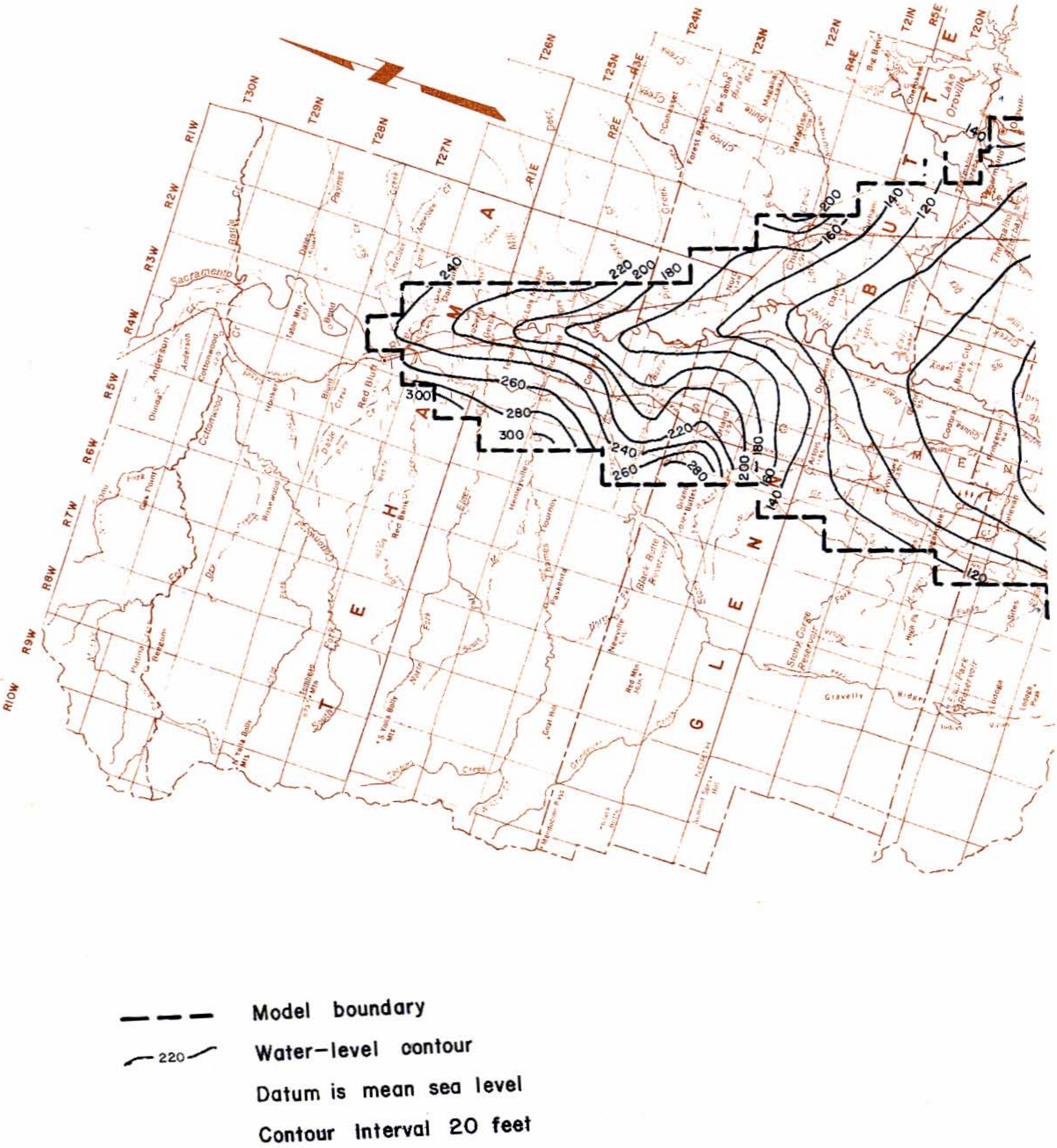
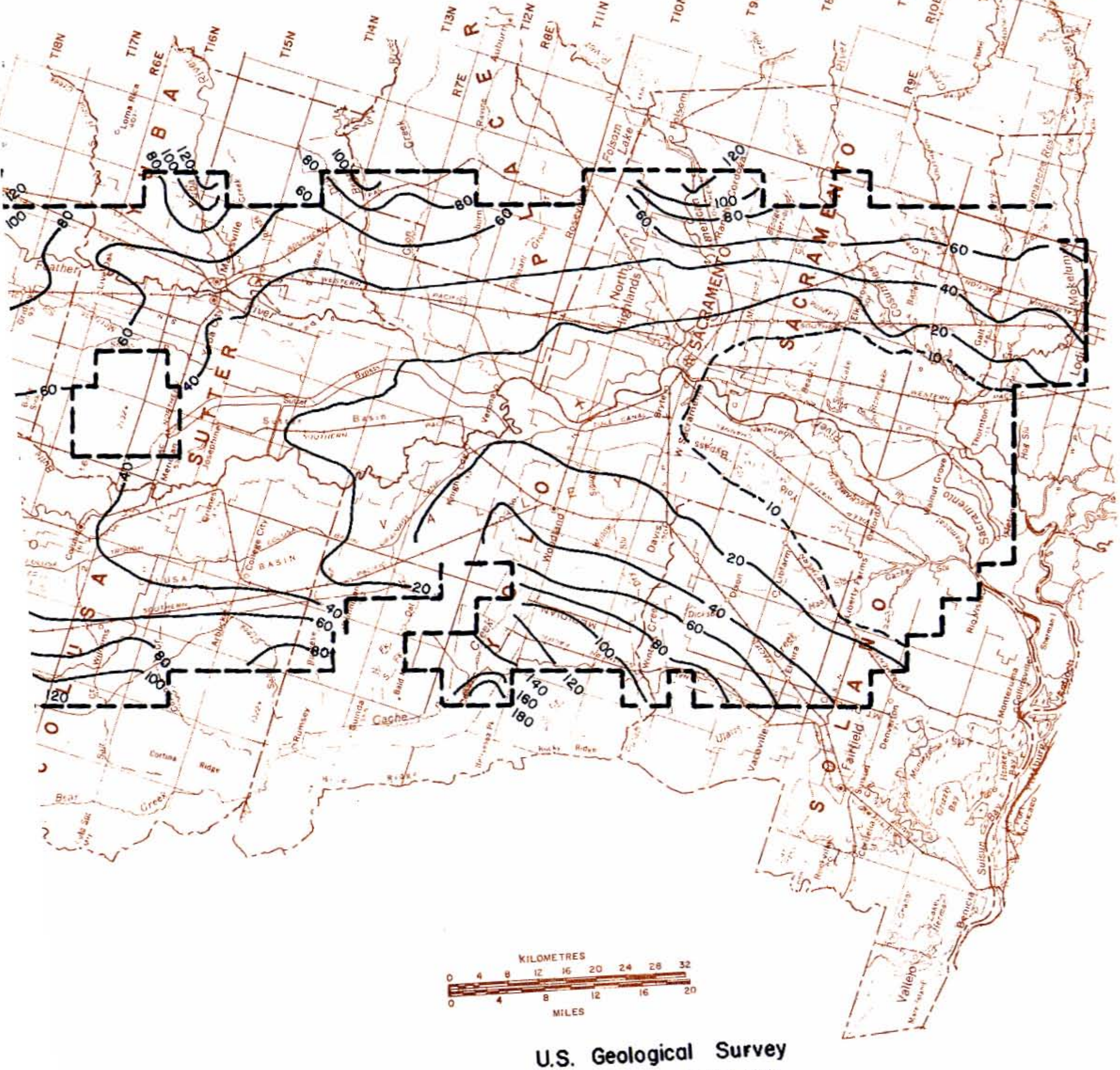

T30N
T29N
T28N
T27N
T26N
T25N
T24N
T23N
T22N
T21N
T20N
R1W
R2W
R3W
R4W
R5W
R6W
R7W
R8W
R9W
R10W
R1E
R2E
R3E
R4E
R5E
T E H A M A
G L E N N
B U T T E
Sacramento
Red Bluff
Red Bank
Lake Oroville
Black Butte Reservoir
Stony Gorge Reservoir
East Park Reservoir
Paradise
Chico
Orland
300
280
260
240
220
200
180
160
140
120
Model boundary
220
Water-level contour
Datum is mean sea level
Contour interval 20 feet

Figure 5A



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Water-level contours for natural conditions, assumed to have occurred in 1912.

generated wherein the T and h values did not yield W values that were judged to be unreasonably large or small. Also, adjusted values of T and h were checked for consistency with adjacent values of T and h.

Estimated average recharge under natural conditions in the study area is about 830,000 acre–ft/yr, or about 0.23 $(\mathrm{ft}^3/\mathrm{s})/\mathrm{mi}^2$. The ground–water basin is recharged naturally by infiltration of streamflow that originates in the mountain areas contiguous to the basin and by deep percolation of precipitation. The greatest amounts of natural recharge occurred in the Stony Creek and Thomes Creek areas (Figure 6A and Table 2). Significant amounts of natural recharge also occurred in the Chico Creek and Yuba River areas. In the Stony Creek, Chico Creek, and Yuba River areas, there are few barriers to the vertical flow of water (Bertoldi, 1974, Figure 3). Also, in all the above–mentioned areas the relatively shallow deposits contain significant amounts of permeable sand and gravel. For example, coarse sand and gravel deposits make up more than 35 percent of the alluvial deposits of the Stony Creek fan (Olmsted and Davis, 1961, p. 190).

The estimated recharge is of reasonable magnitude. Previous computations (Bloyd, 1974, Table 5, and Bloyd, 1975, Table 5) yielded similar values of recharge per square mile for basins in other parts of the United States. In the glaciated areas of the Ohio Region, estimated ground–water recharge ranges from 0.11 to 0.32 $(\mathrm{ft}^3/\mathrm{s})/\mathrm{mi}^2$. In the Upper Mississippi Region, estimated recharge ranges from 0.05 to 0.35 $(\mathrm{ft}^3/\mathrm{s})/\mathrm{mi}^2)$. Estimated recharge is also of similar magnitude in two basins in northern California. Estimated natural recharge in the San Juan Valley ground–water basin, San Benito County, is 0.29 $(\mathrm{ft}^3/\mathrm{s})/\mathrm{mi}^2$ (Faye, 1974, Figure 9). Estimated natural recharge in the northern Napa Valley ground–water basin is 0.36 $(\mathrm{ft}^3/\mathrm{s})/\mathrm{mi}^2$ (Faye, 1973, Table 3).

The largest part of natural ground–water discharge was into the Sacramento River between Red Bluff and Sutter Buttes and from the northern valley floor. Evapotranspiration of ground water from the valley floor was possible because water was readily available to some of the vegetation. The depth to ground water was less than 10 ft in much of the valley floor during the natural–condition period 1912–13 (Bryan, 1923, Plate IV).

Table 2.—*Computed percentage of natural annual ground-water recharge by subareas*

[Roman numerals correspond to those in figure 6]

Subarea	*Percentage of total recharge*
I. Red Bluff	3.4
II. Thomes Creek	10.1
III. Stony Creek	20.7
IV. West Side (Willows Area)	3.9
V. West Side (Williams-Arbuckle Area)	3.8
VI. Cache Creek	3.2
VII. Northeast Side	7.4
VIII. Big Chico Creek	6.5
IX. East Side	0.9
X. Feather River	2.8
XI. East Side (Honcut Area)	1.8
XII. Sutter Buttes	4.1
XIII. Yuba River	8.4
XIV. Bear River	2.3
XV. Placer County	1.6
XVI. American River	2.7
XVII. Cosumnes-Mokelumne Rivers	2.9
XVIII. Central valley floor	4.4
XIX. Southern valley floor	9.1
Total	100.0

HYDROLOGIC BUDGET FOR NATURAL CONDITIONS (1912)

A hydrologic budget was employed to estimate the amount of water migrating through the Sacramento Valley under natural conditions, such as are assumed to have prevailed in 1912. Average annual amounts of precipitation, surface inflow, surface outflow, evapotranspiration, and ground–water recharge were determined. Subsurface inflow and outflow were assumed negligible and equated to zero. A summary of the budget is presented in Table 3.

At steady state, or during natural conditions in the Sacramento Valley:

1. Change in ground–water storage was approximately zero.

2. Subsurface inflow and outflow were approximately equal, and therefore:

3. Surface inflow plus precipitation equaled surface outflow plus evapotranspiration.

The last item is a statement of the hydrologic equation for the study area.

Estimated long–term average surface inflow to the study area is about 22 million acre–ft/yr (Table 4). Except for the Bear River at Wheatland and Stony Creek near Orland, the surface inflow data were extracted from a report by the California Region Framework Study Committee (App. V, Table 31, 1971). The extracted data are for the period 1931–60 at the nine selected gaging stations. Mean annual surface runoff for this 30-year period did not differ greatly from that of the long term (California Region Framework Study Committee, App. V, 1971, p. 215). Surface inflow in the Sacramento and Feather Rivers is 56 percent of the study area total. In other words, a majority of the inflow is from the north and northeast. The American River is the only relatively large river entering the southern half of the study area.

Surface inflow from small streams and from ungaged areas (items 12 and 13, Table 4) is the product of estimated runoff per unit area and drainage area. Estimates of runoff per unit were made on the basis of available streamflow records.

Average annual precipitation in the study area is about 17 inches or about 4.33 million acre-ft. This is based on the mean annual precipitation for 1931–60 (California Region Framework Study Committee, App. V, maps 33 and 35, 1971).

Estimated long-term average surface outflow from the study area is 17.3 million acre-ft/yr. This is the sum of estimated average annual flow in the Sacramento River at Sacramento and from the ungaged area downstream from Sacramento. The estimate of flow in the Sacramento River at Sacramento is based on a 22-year streamflow record. Even though the flow was not adjusted to the period 1931–60, it can still be used to make order-of-magnitude estimates. Average flow in the Sacramento River at Sacramento is 23,590 ft^3/s or 17.09 million acre-ft/yr. Estimated flow from the ungaged area downstream from Sacramento is 181,000 acre-ft/yr. This is the product of ungaged drainage area and estimated runoff rate per unit area. The drainage area is 1,010 mi^2. The estimated runoff rate is 0.25 $(ft^3/s)/mi^2$.

Estimated long-term average evapotranspiration is 9.2 million acre-ft/yr. This is the arithmetic difference of total inflow and surface-water outflow (Table 3).

Table 3.—*Summary of hydrologic budget for natural conditions (1912)*

Item	*Quantity (million acre-feet per year)*
A. Surface inflow (total)	22.2*
1. Sacramento River	8.0
2. Feather River	4.3
3. Yuba River	2.3
4. Bear River	0.3
5. American River	2.6
6. Cosumnes River	0.4
7. Mokelumne River	0.7
8. Thomes Creek	0.2
9. Stony Creek	0.5
10. Cache Creek	0.5
11. Putah Creek	0.4
12. Remaining area—East side	1.3
13. Remaining area—West side	0.7
B. Precipitation	4.3
C. Surface outflow	17.3
D. Evapotranspiration	9.2

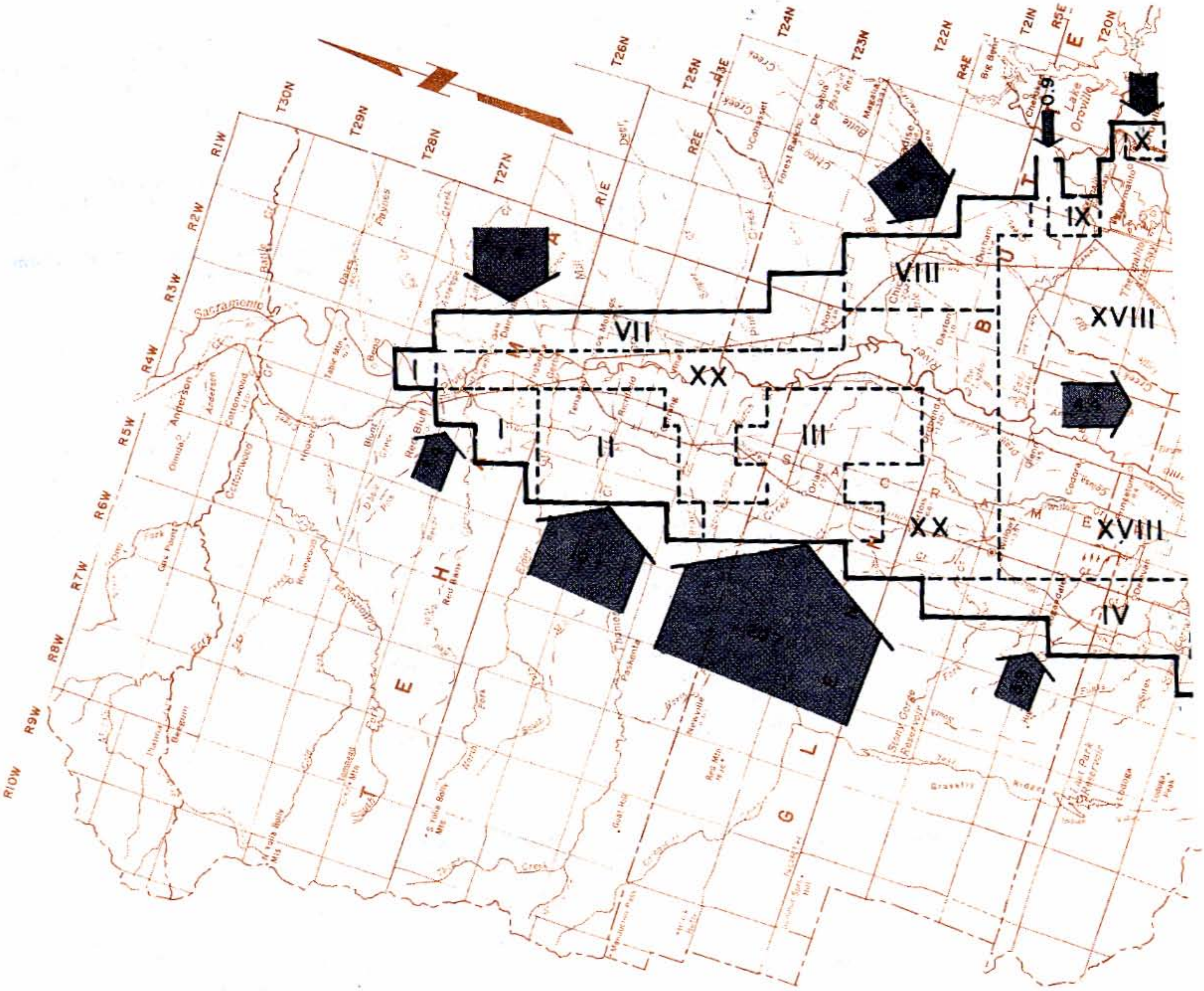
* Quantities from table 4 were rounded.

Table 4.—*Long-term average surface inflow*

		Average flow		
Stream	*Drainage area (square miles)*	*(million acre-feet per year)*	*(cubic feet per second)*	*(cubic feet per second) per square mile)*
1. Sacramento River near Red Bluff	8,900	7.984	11,030	1.24
2. Feather River at Oroville	3,624	4.308	5,950	1.64
3. Yuba River near Marysville	1,339	2.259	3,120	2.33
4. Bear River near Wheatland [1]	292	0.313	430	1.47
5. American River at Fair Oaks	1,888	2.597	3,590	1.90
6. Cosumnes River at McConnell	724	0.390	540	0.75
7. Mokelumne River below Camanche Dam	627	0.712	980	1.56
8. Thomes Creek at Paskenta	194	0.194	270	1.39
9. Stony Creek near Orland [2]	737	0.448	620	0.84
10. Cache Creek near Capay	1,044	0.473	650	0.62
11. Putah Creek near Winters	574	0.354	490	0.85
12. Remaining area East side	1,120	1.316	—	1.15–2.05
13. Remaining area West side	934	0.695	—	0.50–1.45
Total		22.043		

[1] Record period 1929–1960.

[2] Record period 1956–1972.



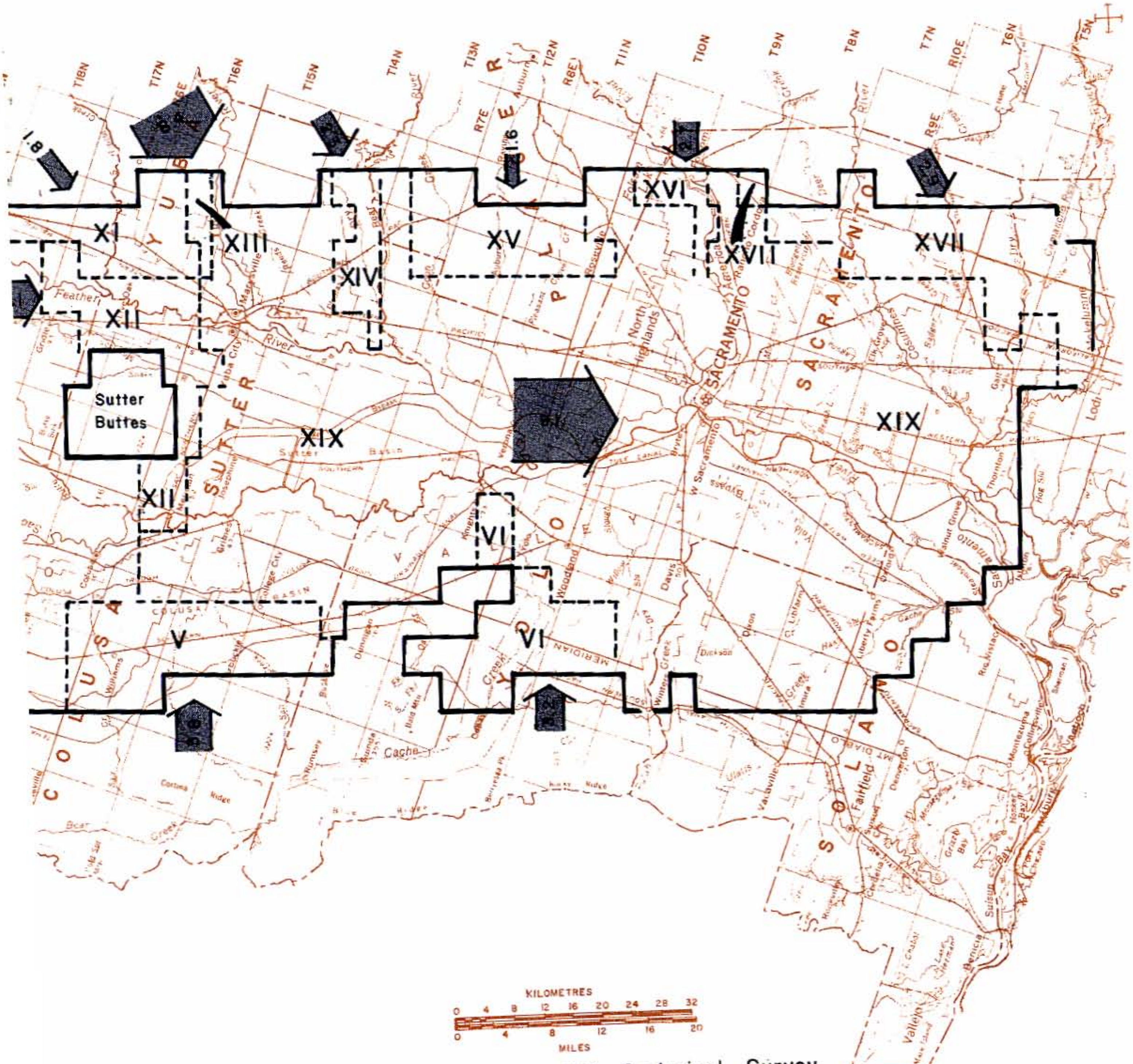
Model boundary

Amount of recharge in percentage of study area total.

XX Subarea boundary

NOTE = See table 2 for list of subareas

Figure 6.A



U.S. Geological Survey

Prepared in cooperation with

California Department of Water Resources

Ground-water recharge
during natural conditions

FRESH GROUND WATER IN STORAGE

Except for a limited discussion of fresh ground water in storage, no attempt is made in this report to evaluate water quality in the study area. This does not mean, however, that water quality was not considered in the study. Water–quality investigations were started in the northern part of the valley. The study procedures and initial results were reported by Bertoldi (1976). Also as a part of this study, Berkstresser (1973) mapped the base of fresh water in the Sacramento Valley and the Sacramento–San Joaquin Delta.

Although not all ground water in storage is recoverable by development, estimates of the amounts of fresh water contained in storage are presented for illustrative purposes. No attempt was made to calculate the amount of saline ground water in storage.

For purposes of assessing the ground water in storage, only the water present in the continental deposits of post–Eocene age is considered. The assumption is made that the water in these deposits contains less than 2,000 mg/l in dissolved solids. The assumption is also made that the ground water in storage is equal to the product of the surface area of the aquifer, the saturated thickness of the aquifer, and the specific yield. Specific yield is used rather than porosity. Because specific yield is less than porosity, the results of the computation are considered conservative with respect to the total volume of water present.

Computed fresh ground water in storage in the continental deposits of post–Eocene age in the study area is about 395 million acre–ft. This is 3.2 times the water in storage in Lake Tahoe, 89 times that in Shasta Lake, and 390 times that in Folsom Lake.

PRODUCTIVITY OF AQUIFERS

Olmsted and Davis (1961, Figure 3A) estimated the rates at which aquifers in the Sacramento Valley can yield water to wells. These estimates, used in this study, were prepared primarily on the basis of the performance of 2,783 large–capacity irrigation, industrial, and municipal wells in 21 subareas of the Sacramento Valley. The results are summarized here by subarea (Table 5). The subareas are ranked in terms of average discharge or yield. Olmsted and Davis ranked the areas in terms of average yield factor for saturated thickness, which is a measure of hydraulic conductivity of the saturated material penetrated by the wells.

Average well yields greater than 1,000 gal/min are possible in 30 percent of the study area. The highest average yields are from wells along a 40–mile strip adjacent to the Sacramento River in the Colusa area (Figure 7A).

Average well yields of 500 to 1,000 gal/min are possible in 45 percent of the study area.

In 25 percent of the study area, average well yields are 250–500 gal/min. The lowest average well yields are in the northern and eastern parts of the Sacramento County (Figure 7A).

Table 5.—*Yields of large-capacity wells in Sacramento Valley*

Area no. (see fig. 7A)	*Area*	*Number of wells tested*	*Average discharge (gal/min)*	*Average well depth (ft)*
6	Colusa	59	1,690	315
13	Woodland	198	1,350	256
12	Cache Creek	52	1,220	120
3	Orland-Willows	238	1,030	210
4	Chico	498	1,000	357
17	Davis	61	990	295
7	Gridley	119	980	258
11	South Sutter	121	960	324
10	Yuba-Bear	108	850	292
8	Honcut	23	840	200
19	Dixon	98	770	226
2	Los Molinos	46	770	268
16	Putah North	61	750	205
14	Verona-Knights Landing	45	740	303
9	Peach Bowl	261	730	182
5	Williams	103	620	494
20	Sacramento	125	490	219
1	Red Bluff-Corning	292	470	274
18	Vacaville	118	440	256
21	Cosumnes-American	103	380	317
15	North Sacramento-Fair Oaks	54	250	334

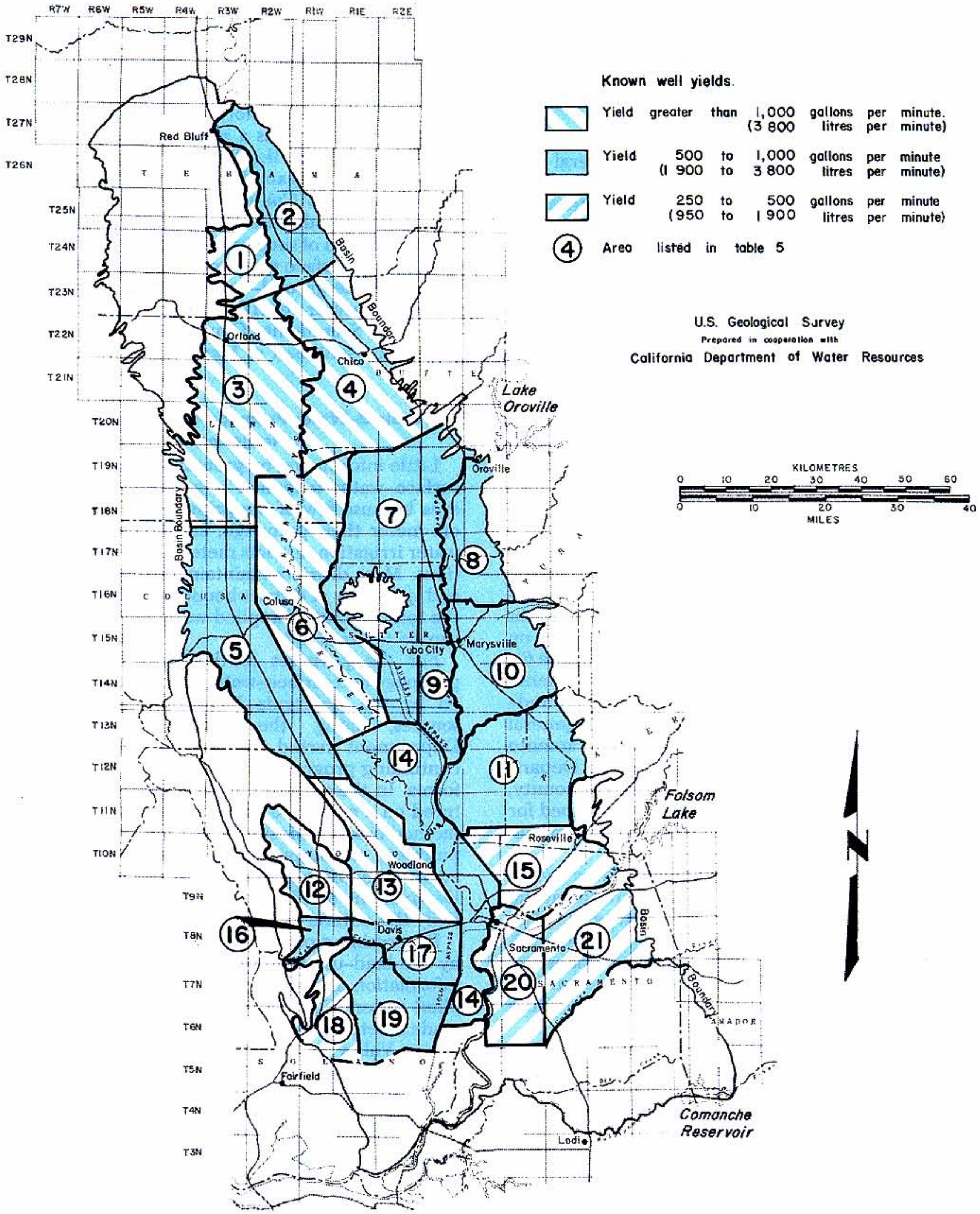


Figure 7A. Well Yield

GROUND-WATER CONDITIONS 1961–1971

Water Levels

The 1961 ground-water-level contour map (Figure 8A) suggests little change in the general flow pattern for natural conditions north of Sutter Buttes, but there are some significant changes south of the Buttes.

A pumping depression in Solano County between Davis and Rio Vista is the result of many years of ground-water withdrawal. The existence of a depression was noted as early as 1931 (Huberty and Johnston, 1941, Figure 8). In this part of the study area the number of wells increased from 128 in 1913 (Bryan, 1923, p. 227) to 301 in 1932 (Huberty and Johnston, 1941, p. 136).

New large-capacity wells were constructed between 1945 and 1950 for use on increased irrigated acreage, so that by 1950 a significant depression existed (Thomasson and others, 1960, p. L 11). In fact, estimated pumpage of ground water for irrigation in the Putah area (Thomasson and others, 1960, Figure 1) increased from 24,000 acre-ft in 1941 to 92,000 acre-ft in 1951. The greatest increase was in the water-level depression area. In 1961, estimated pumpage in Tps. 6, 7, and 8 N., Rs. 1 W. and 1 and 2 E., was about 120,000 acre-ft. This last estimate is based on computations using the land-use method (Table 6).

Three pumping depressions in Sacramento County also are the result of many years of ground-water pumping. From about 1940 to 1970 the general decline in ground-water levels in Sacramento County has been fairly uniform (California Department of Water Resources, 1974, p. 92). In the county, significant amounts of ground water are pumped for municipal and industrial use as well as for agricultural use.

Northwest of Roseville and southeast of Marysville, maximum ground-water-level declines from natural conditions to 1961 were about 40 ft (Figure 9A). The depression northwest of Roseville has induced additional ground-water recharge from the Sacramento, Feather, and Bear Rivers. The depression southeast of Marysville has induced additional recharge from the Yuba, Feather, and Bear Rivers.

The 1971 ground-water-level contour map for the study area (Figure 10A) shows no significant change in the general flow pattern of 1961. The 1971 contour map is based on an analysis of numerous ground-water-level measurements in wells.

A comparison of the 1961 and 1971 water-level contour maps reveals some significant ground-water-level rises in parts of the study area between 1961 and 1971. There was as much as 30 ft of rise in water levels in the pumping depression in Solano County and in the depression northwest of Roseville (Figure 11A). Also, there was a small rise in ground-water levels adjacent to the Feather River in the reach between the Yuba and Bear Rivers. The rise in water levels in Solano County resulted because of a decrease in ground-water pumping and an increase in the application of surface water for irrigation. Part of the applied surface water percolates downward and recharges the ground-water system.

Ground-water-level declines continued from 1961 to 1971 in Sacramento County and in the pumping depression southeast of Marysville.

Ground-Water Pumpage and Surface-Water Irrigation

Little information on ground-water pumpage and surface-water irrigation is available for the study area because few of the principal ground-water users meter their pumpage, and few of the surface-water irrigation districts meter plot-by-plot applications. Most districts maintain records of deliveries and spills only at district boundaries. Therefore, only the total volume of applied water within the district can be determined.

For the purposes of this study, ground-water pumpage and surface-water irrigation were estimated by the California Department of Water Resources, using the land-use method. The Department started a survey in 1940 which led to a continuing program of monitoring land use in California. In the program, land-use changes are monitored on a cycle of 5 to 10 years. A summary of the method used in this study to compute ground-water pumpage and surface-water irrigation was presented in a report on Sacramento County (California Department of Water Resources, 1974, p. 96–114). Only the outline of the method is presented here.

Determining pumpage and applied surface water by the land-use method requires irrigated acreage information and reliable estimates of crop-unit applied water. The Department of Water Resources made a detailed land-use survey of the entire Sacramento Valley in 1961. Lands irrigated with ground water were segregated from those irrigated from other sources. Repeat surveys were made on a county-by-county basis starting in 1967. With these two detailed pieces of land-use information and the agricultural commissioner's annual reports for the missing years, an annual picture of irrigated-land use was reconstructed for each Sacramento Valley county for each year of the 1961–1970 study period. Applied-water values or pumpage from ground water were computed for each year on a one-fourth township basis by multiplying land-use acreage (rice, grain, pasture, and so forth) by an appropriate unit applied water value.

Estimated total ground-water pumpage and surface water applied for irrigation in 1961 was 1.8 million acre-ft and 3.8 million acre-ft, respectively (Table 6).

Ground-water recharge in 1961 had to be greater than during natural conditions to allow for 1.8 million acre-ft of pumping without a resultant basinwide ground-water-level decline. The principal additional source of recharge was that part of the surface water applied for irrigation that percolated downward to the ground-water system.

Estimated total ground-water pumpage and surface water applied for irrigation in 1970 was 1.8 million acre-ft and 4.5 million acre-ft, respectively (Table 6).

SUMMARY

Post-Eocene deposits in the Sacramento Valley, California, form one of the Nation's largest ground-water basins. The basin was studied to define various hydrologic, hydraulic, and other physical characteristics and to evaluate changes in the basin from 1912 (natural conditions) to 1961, and from 1961 to 1971. A digital computer model was developed to synthesize data for natural conditions.

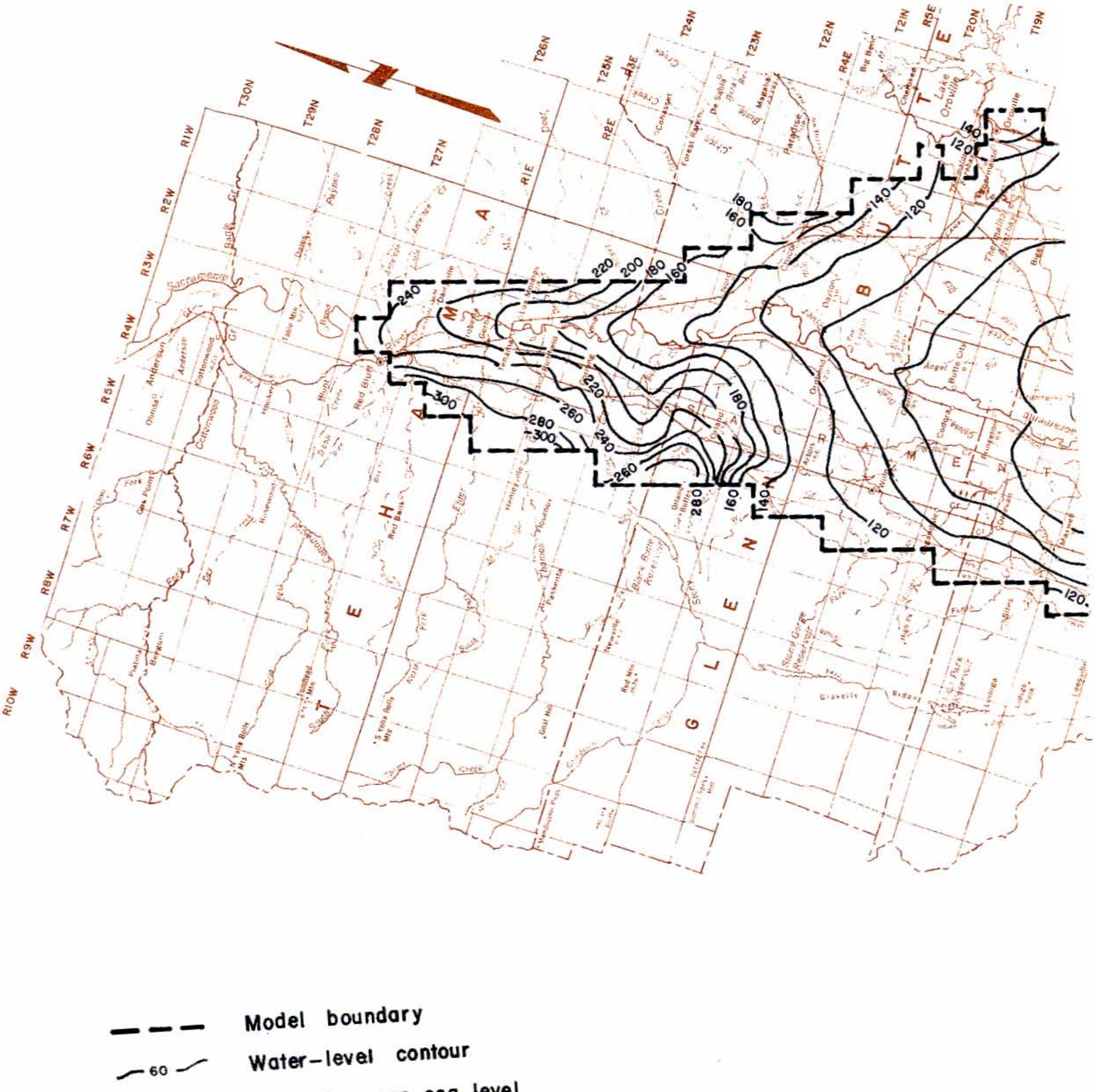
The post-Eocene deposits are more than 3,500 ft thick in the central part of the synclinal Sacramento Valley and thin toward the valley margins. The basin is estimated to contain 395 million acre-ft of fresh water (less than 2,000 mg/l dissolved solids). Transmissivity ranges from 4,300 to 65,000 ft^2/d; it is lowest in Yolo and Solano Counties and highest adjacent to several reaches of the Sacramento River. Storage coefficients range from 0.04 to 0.12.

In 1912 the depth to ground water was less than 25 ft in more than 80 percent of the valley. Ground water moved from recharge areas at the valley margins and in the northern parts of the study area toward the center of the valley and then south, discharging into the Sacramento River and then out of the study area. Under natural conditions, recharge (about 830,000 acre-ft/yr) was from infiltration of streamflow and deep percolation of precipitation. Discharge and evapotranspiration were about equal to recharge, with no change in ground-water storage.

The long-term hydrologic budget for the basin shows that surface inflow (22.2 million acre-ft) plus precipitation (4.3 million acre-ft) equaled surface outflow (17.3 million acre-ft) plus evapotranspiration (9.2 million acre-ft). Most surface inflow (56 percent) is from the Sacramento and Feather Rivers in the north and northeast parts of the basin. Well yields are greatest along a 40-mile strip adjacent to the Sacramento River near Colusa and lowest in the northern and eastern parts of Sacramento County. Well yields of 500 to 1,000 gal/min are possible in 45 percent of the study area; yields greater than 1,000 gal/min are possible in 30 percent of the study area.

In 1961 the ground-water flow pattern was similar to natural conditions in the study area north of Sutter Buttes, but it was significantly different south of the Buttes. There were pumping depressions in Solano County between Davis and Rio Vista, in three areas of Sacramento County, in an area northwest of Roseville, and in an area southeast of Marysville. The depressions are attributed to development of large-capacity wells for irrigation and, in Sacramento County, for municipal and industrial uses. In 1961, about 1.8 million acre-ft of water was pumped in the study area, with an additional 3.8 million-acre-ft of surface water applied for irrigation. Recharge was supplemented by the applied surface water and was greater than under natural conditions.

By 1970, pumpage had not increased significantly, but surface water applied for irrigation increased to 4.5 million acre-ft. Recharge continued to be greater than under natural conditions and, together with the increase in applied surface water, resulted in some recovery of water levels. Water levels in Solano County and in the depression northwest of Roseville were as much as 30 ft higher in 1970 than in 1961. Water-level declines continued in Sacramento County and in the area southeast of Marysville.



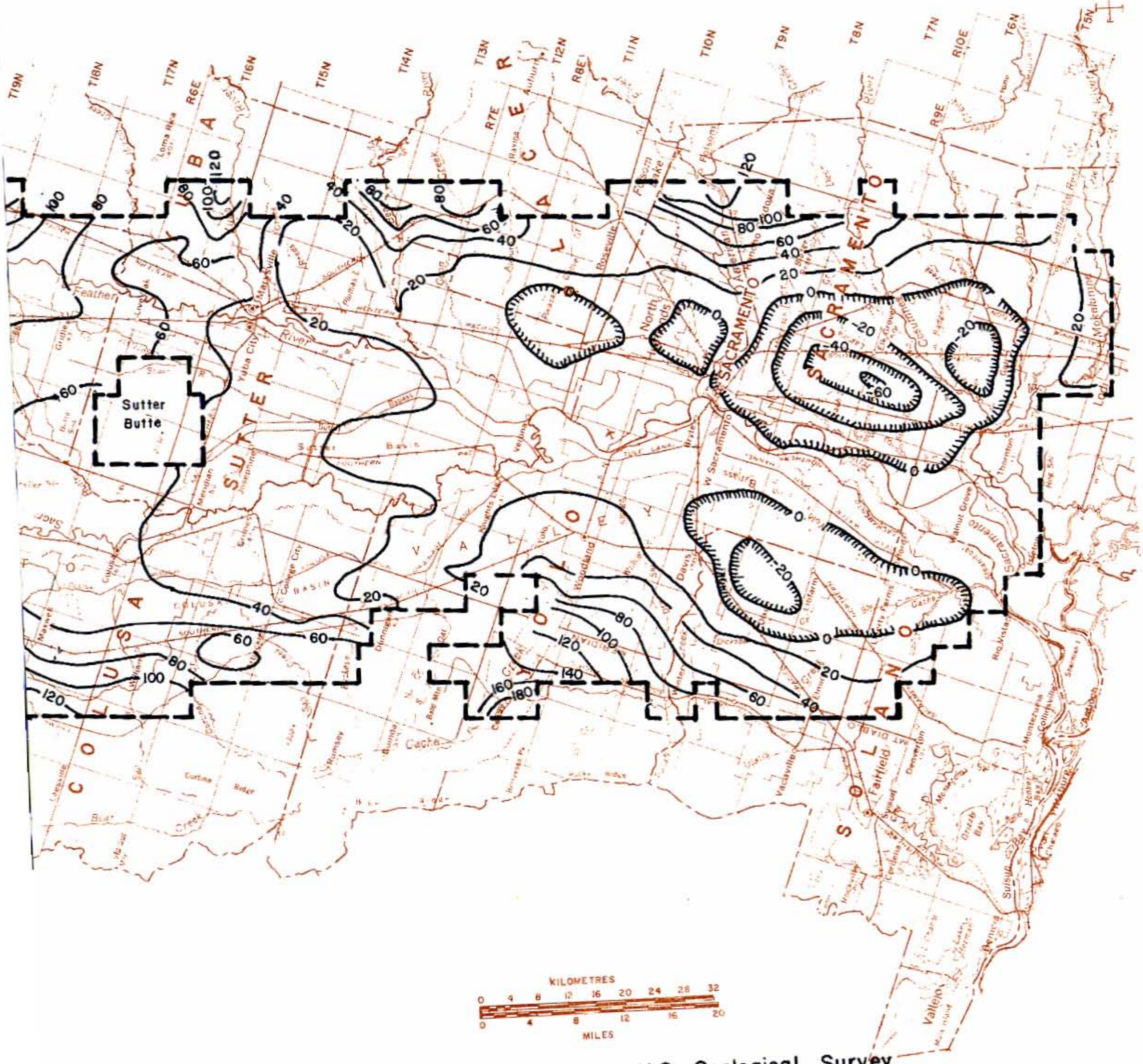
— — — Model boundary

—60— Water-level contour

Datum is mean sea level.

Contour Interval 20 feet.

Figure 8A



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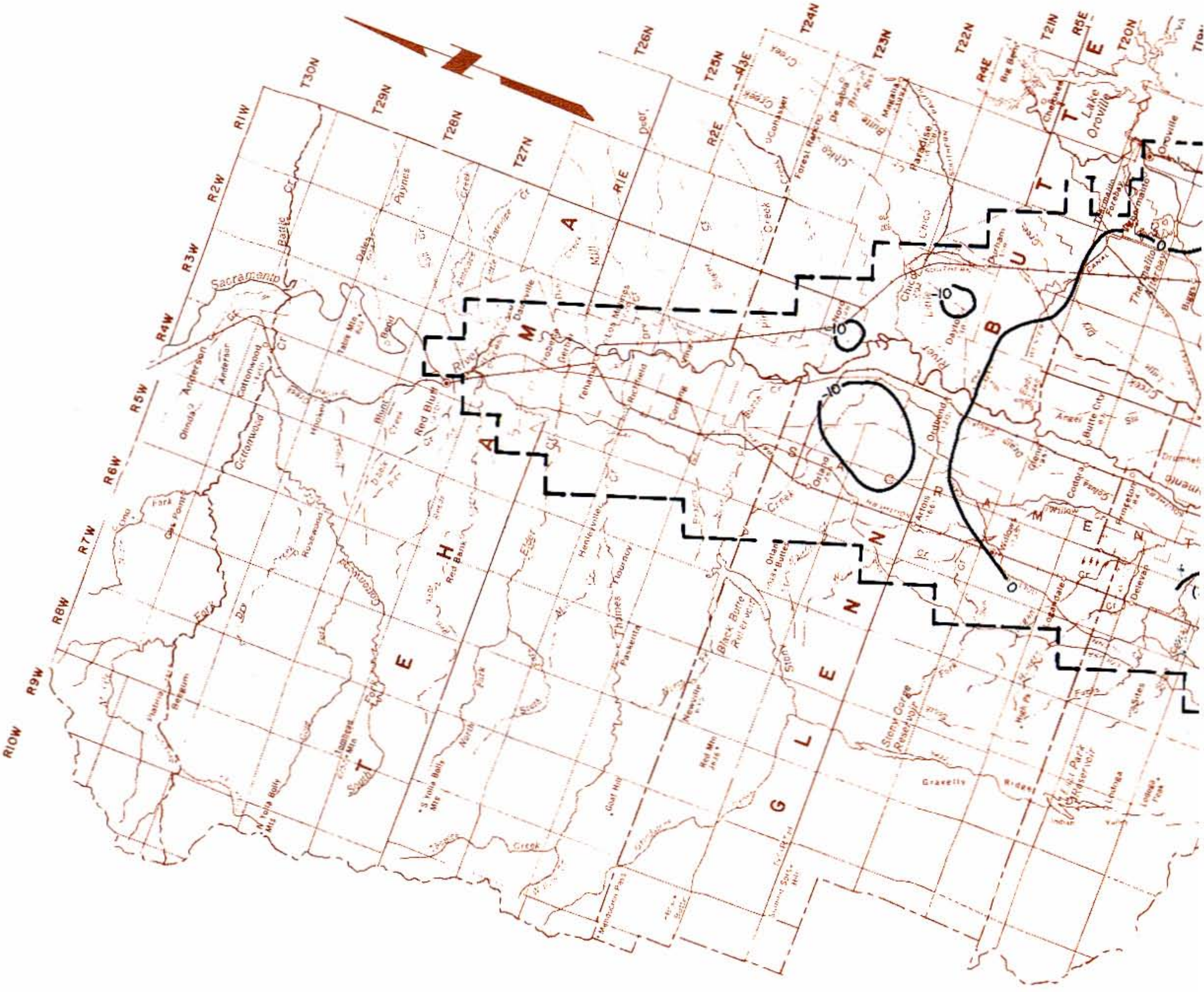
Water–level contours for 1961

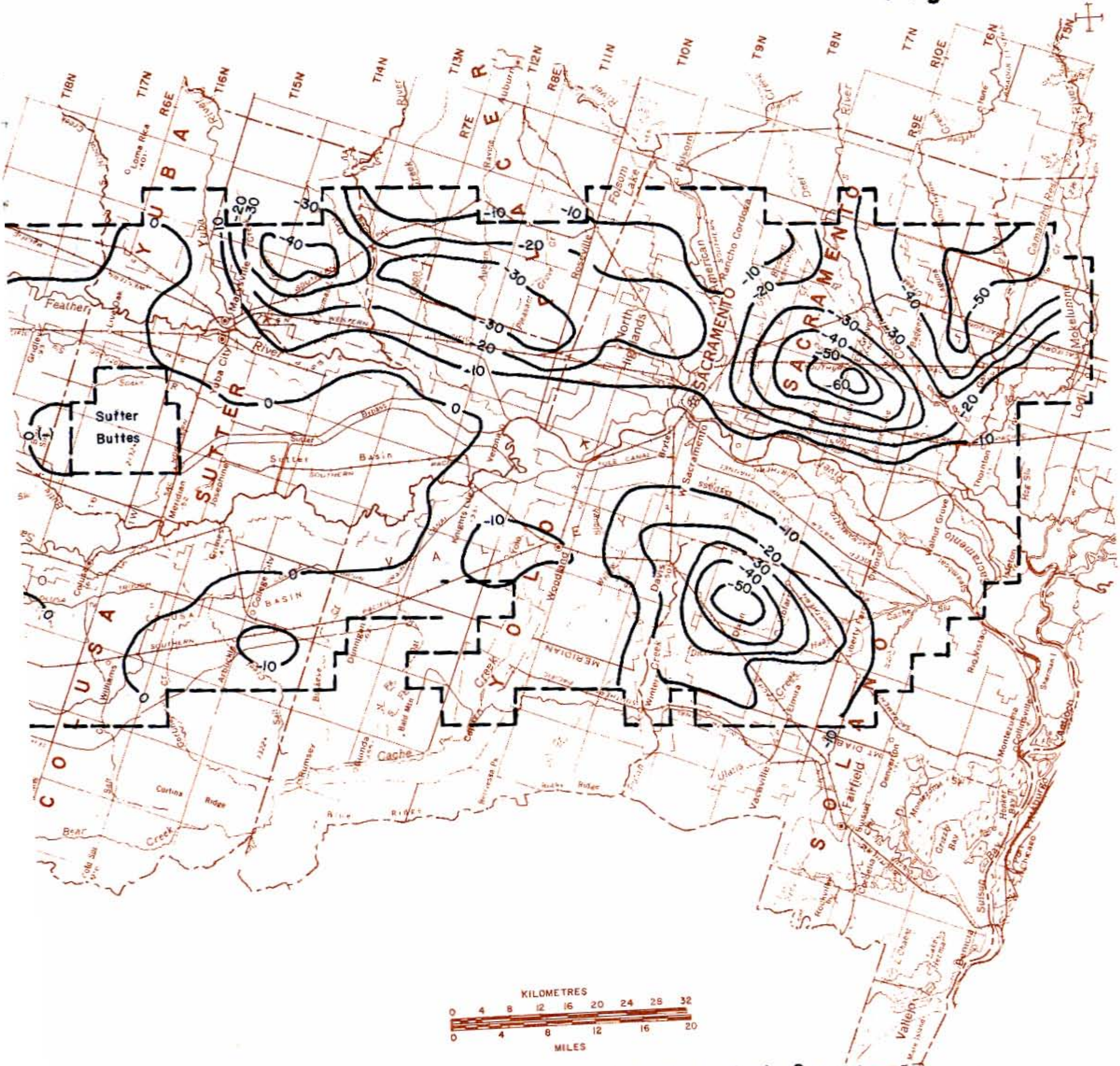


— — — **Model boundary**

— 60 — Line of equal water-level change, in feet
Negative symbol (-) indicates decline.

Contour interval 10 feet.

Figure 9 A



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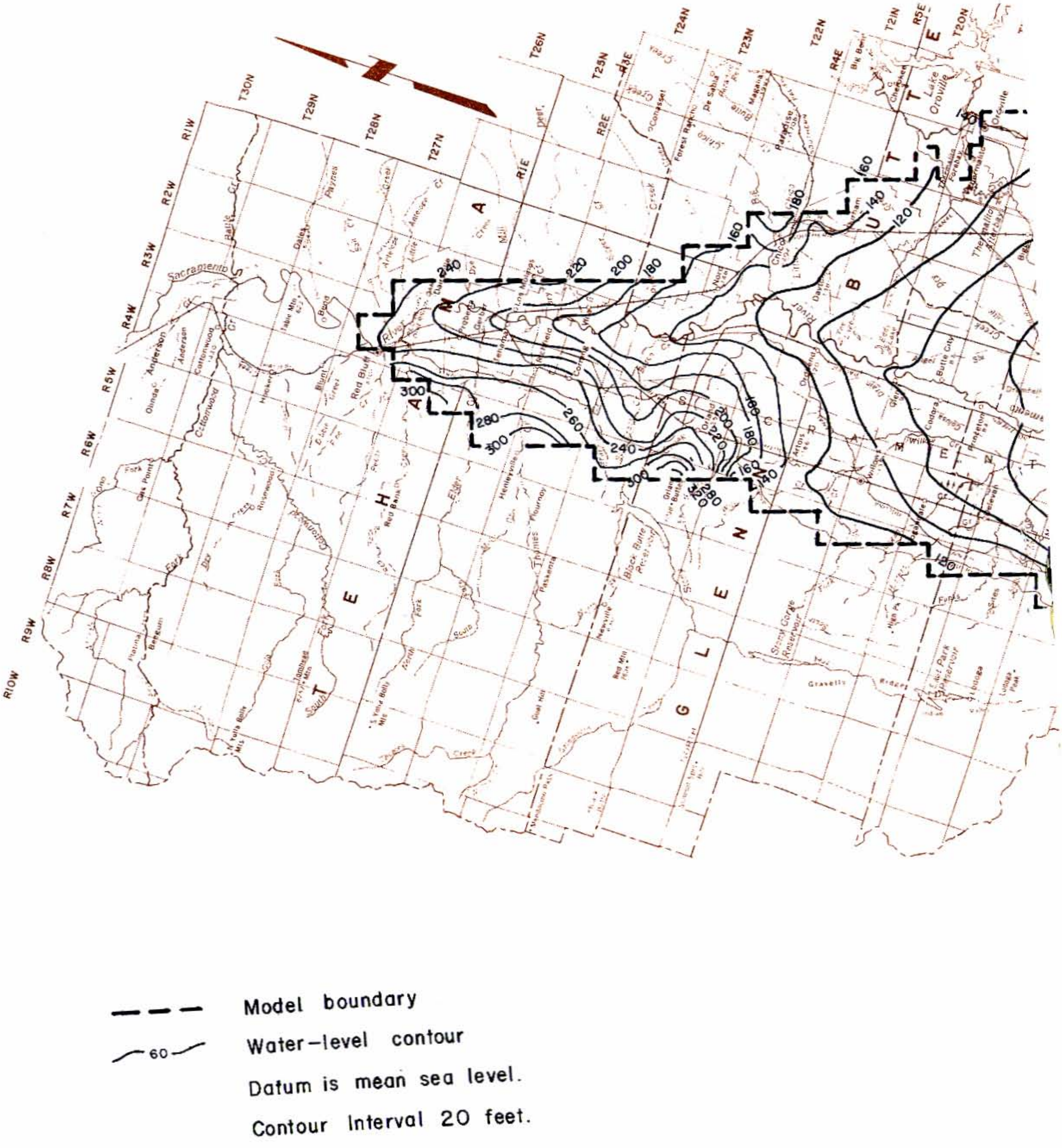
Ground-water-level change from 1912 (natural conditions) to 1961


T30N
T29N
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T27N
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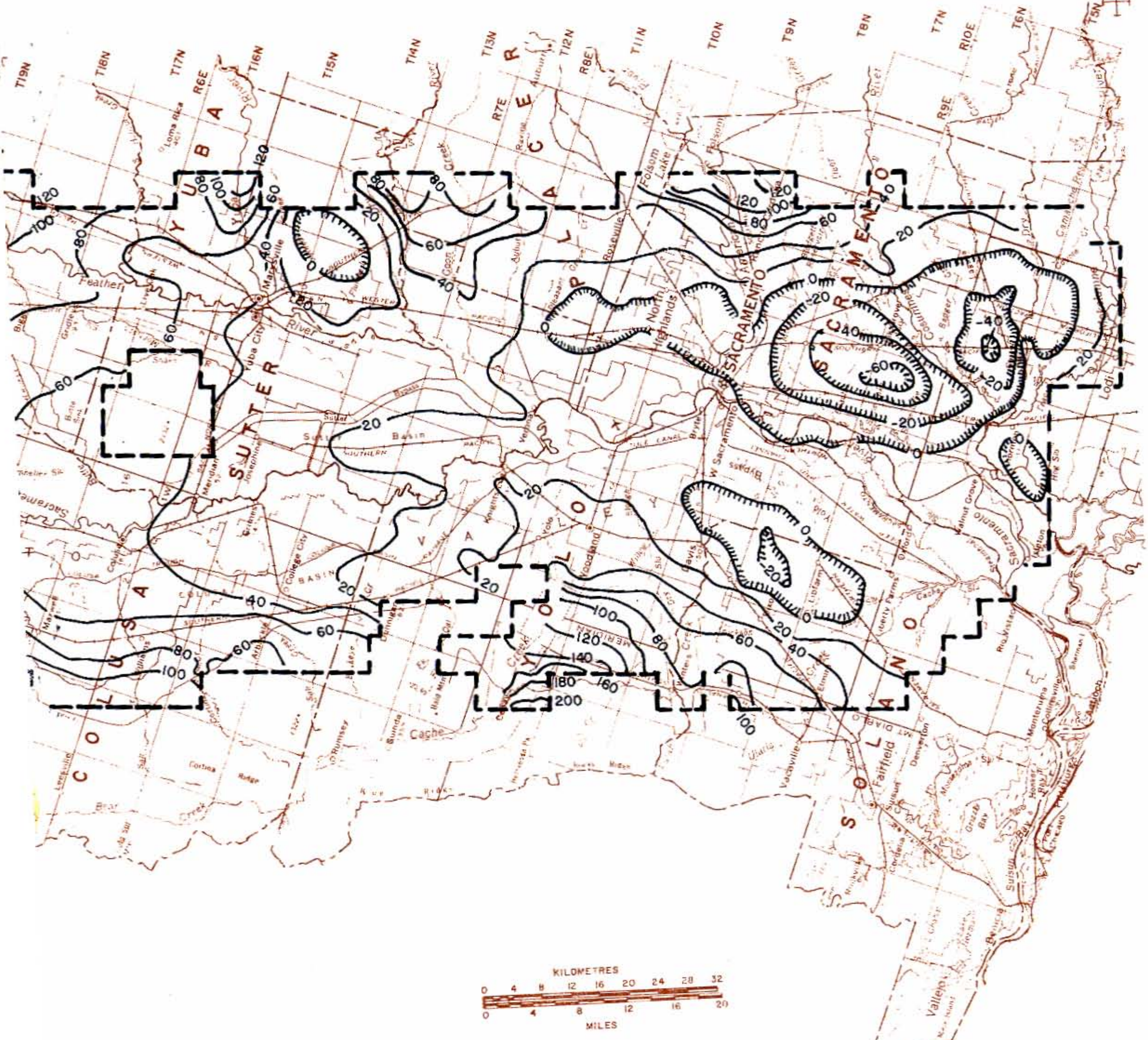
T24N
T23N
T22N
T21N
T20N
R1W
R2W
R3W
R4W
R5W
R6W
R7W
R8W
R9W
R10W
R1E
R2E
R3E
R4E
R5E
TEHAMA
BUTTE
GLENN
Sacramento
River
Red Bluff
Corning
Orland
Chico
Paradise
Lake Oroville
Oroville
Butte City
Willows
Artois
Hamilton City
Black Butte Reservoir
Stony Gorge Reservoir
East Park Reservoir
Thermalito Afterbay
300
280
260
240
220
200
180
160
140
120
320
Model boundary
Water-level contour
60
Datum is mean sea level.
Contour Interval 20 feet.

Figure 10 A



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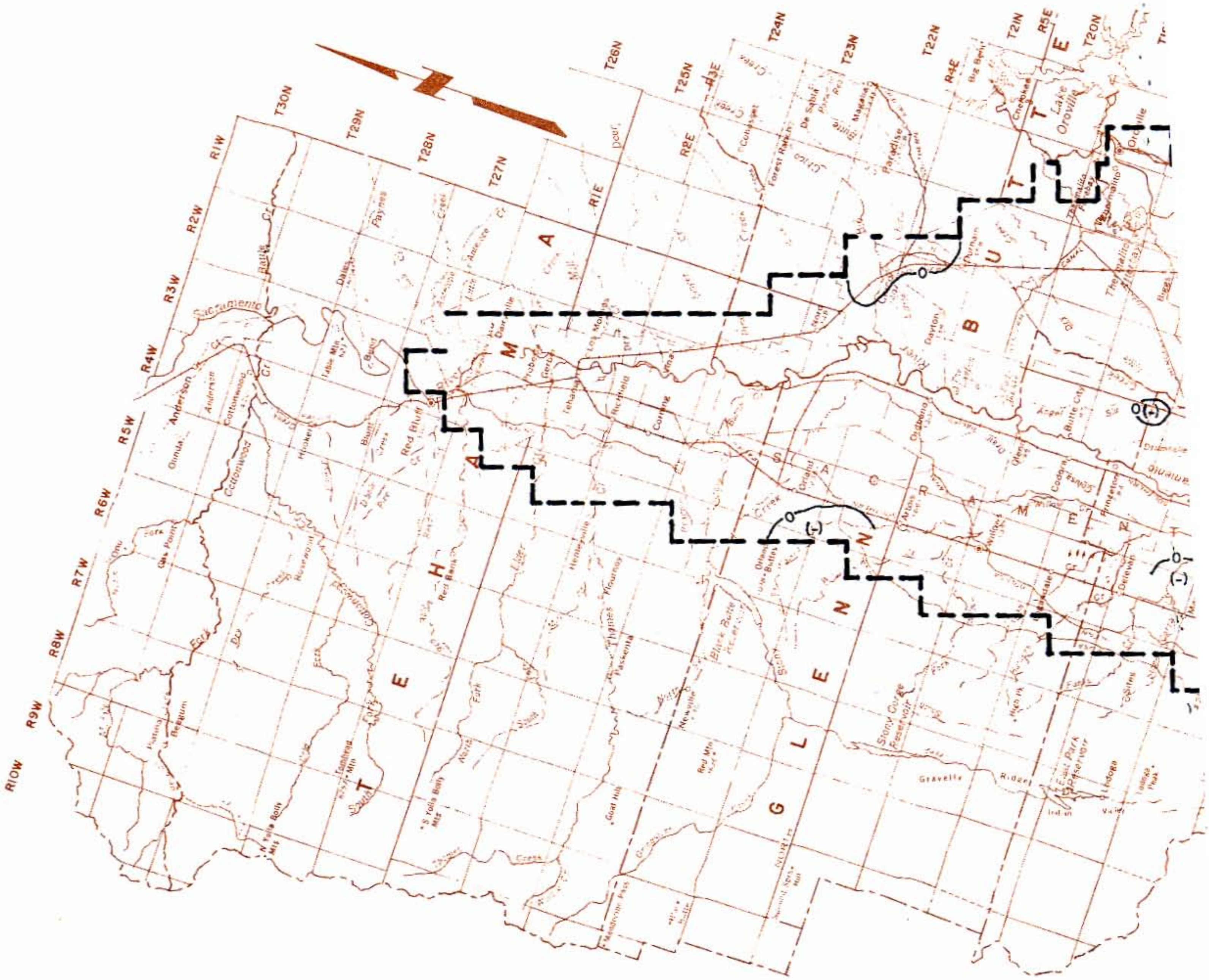
Water-level contours for 1971

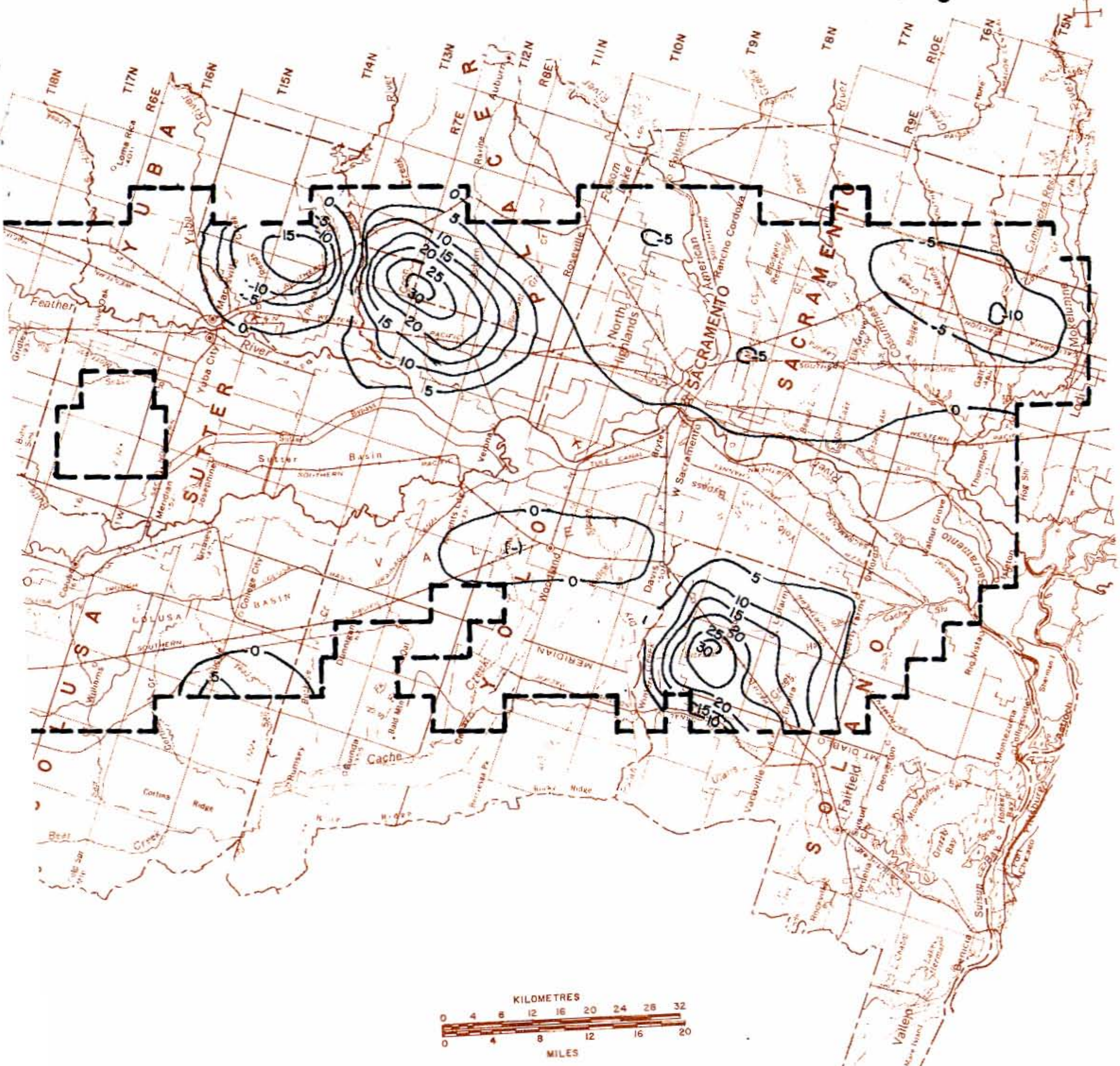


— — — Model boundary

—15— Line of equal water – level change, in feet. Negative symbol (–) indicates decline.

Contour interval 5 feet.

Figure 11A



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Ground-water-level change from 1961 to 1971

Table 6.—*Estimated ground-water pumpage and surface-water irrigation in 1961 and 1970*

	Quantity, in thousands of acre-feet			
	Ground-water pumpage		*Surface-water irrigation*	
Township	*1961*	*1970*	*1961*	*1970*
T. 27 N., R. 4 W.	2.9	3.2	0.3	0.3
3 W.	10.3	12.7	2.8	1.9
2 W.	—	—	7.3	6.2
T. 26 N., R. 5 W.	.8	1.0	—	—
4 W.	1.3	2.1	—	—
3 W.	20.0	18.4	.6	8.6
2 W.	2.2	3.5	19.3	17.8
T. 25 N., R. 4 W.	.4	.4	—	—
3 W.	20.7	17.3	1.4	12.5
2 W.	6.7	6.5	7.5	7.8
1 W.	—	.2	.5	.9
T. 24 N., R. 4 W.	1.7	2.5	.9	1.0
3 W.	16.7	9.1	1.9	10.6
2 W.	6.1	7.9	16.5	15.6
1 W.	0.3	0.9	5.4	6.3
T. 23 N., R. 4 W.	0.9	1.5	0.3	0.4
3 W.	7.5	8.1	—	1.2
2 W.	20.4	22.2	2.7	10.4
1 W.	16.5	16.2	—	0.3
1 E.	3.0	3.0	0.3	0.3
T. 22 N., R. 4 W.	4.1	4.1	3.4	4.2
3 W.	5.8	6.5	67.0	61.4
2 W.	33.0	32.0	21.1	13.5
1 W.	22.4	21.2	5.5	6.7
1 E.	21.6	27.3	2.1	2.9
2 E.	2.2	3.0	0.4	0.4
T. 21 N., R. 4 W.	1.7	2.0	—	—
3 W.	24.8	26.6	10.1	0.2
2 W.	42.8	42.1	9.3	7.1
1 W.	11.2	12.3	22.5	25.0
1 E.	38.4	33.1	3.0	16.8
2 E.	4.4	8.2	22.5	20.0
T. 20 N., R. 4 W.	0.6	1.4	—	—
3 W.	21.6	29.8	5.4	4.6
2 W.	6.1	4.8	98.2	100.7
1 W.	3.9	3.8	26.2	29.1
1 E.	6.8	10.2	47.7	65.2
2 E.	34.6	29.4	24.2	51.4
3 E.	3.7	3.5	2.7	2.4
T. 19 N., R. 4 W.	1.9	3.2	—	—
3 W.	4.6	6.9	81.1	88.1
2 W.	1.5	2.1	103.6	111.2
1 W.	8.9	12.5	28.4	30.1
1 E.	—	—	60.5	87.7
2 E.	6.8	8.4	76.0	95.5
3 E.	8.7	8.5	4.8	3.7
4 E.	5.9	6.3	0.4	0.8
T. 18 N., R. 4 W.	0.4	0.7	3.7	2.1
3 W.	0.5	0.9	69.3	63.6
2 W.	1.8	1.6	86.4	94.8
1 W.	9.6	12.8	25.9	17.8
1 E.	1.4	7.9	44.1	61.0
2 E.	4.0	4.3	85.9	96.0
3 E.	13.5	14.3	19.1	22.9
4 E.	3.8	7.6	—	4.0

Table 6.—*Estimated ground-water pumpage and surface-water irrigation in 1961 and 1970*—Continued

	Quantity, in thousands of acre-feet			
	Ground-water pumpage		*Surface-water irrigation*	
Township	*1961*	*1970*	*1961*	*1970*
T. 17 N., R 4 W.	—	—	1.8	3.6
3 W.	7.0	7.6	87.0	98.6
2 W.	3.5	7.6	86.2	68.9
1 W.	3.1	2.9	69.1	71.5
1 E.	11.7	11.3	10.1	20.1
2 E.	7.3	8.9	59.9	68.6
3 E.	6.7	7.2	42.3	40.1
4 E.	4.4	4.8	1.4	4.4
T. 16 N., R. 4 W.	0.9	0.5	15.8	11.5
3 W.	—	—	116.9	120.2
2 W.	9.7	5.9	44.9	47.3
1 W.	4.7	4.0	29.3	41.0
1 E.	1.9	1.8	0.4	1.9
2 E.	1.3	2.3	27.9	34.8
3 E.	26.3	28.1	19.7	35.9
4 E.	10.6	4.4	60.8	90.5
5 E.	—	—	3.1	7.1
T. 15 N., R. 4 W.	0.4	0.8	2.9	3.3
3 W.	8.7	6.2	55.6	58.0
2 W.	6.9	7.1	51.8	54.7
1 W.	6.9	3.7	36.9	44.7
1 E.	4.3	4.3	36.4	40.2
2 E.	15.0	13.9	45.1	53.6
3 E.	41.6	41.1	1.5	3.0
4 E.	24.6	23.2	12.5	21.5
5 E.	2.4	2.8	—	0.1
T. 14 N., R 3 W.	3.1	5.7	—	—
2 W.	18.7	12.3	15.6	16.4
1 W.	9.0	5.9	21.3	47.7
1 E.	3.9	1.4	45.7	56.8
2 E.	—	—	75.2	80.9
3 E.	34.3	36.3	3.6	6.2
4 E.	35.0	39.1	3.3	2.7
5 E.	22.7	21.1	5.1	4.1
T. 13 N., R 3 W.	0.3	0.4	—	—
2 W.	18.2	18.0	—	8.0
1 W.	18.8	9.3	29.5	30.9
1 E.	0.5	0.2	65.7	67.3
2 E.	—	—	64.2	84.5
3 E.	10.0	10.2	46.3	61.5
4 E.	34.8	23.5	9.1	23.5
5 E.	27.2	10.0	7.4	17.7
6 E.	—	0.2	—	0.2
T. 12 N., R. 2 W.	—	0.8	0.3	—
1 W.	10.2	13.3	3.7	3.3
1 E.	—	—	72.8	84.2
2 E.	0.5	0.5	65.4	96.1
3 E.	1.8	1.7	47.9	66.5
4 E.	34.6	19.4	2.8	30.5
5 E.	19.1	11.1	2.0	25.3
T. 11 N., R. 2 W.	1.5	2.4	—	—
1 W.	0.4	0.4	2.9	2.8
1 E.	22.5	23.2	9.4	6.3
2 E.	20.3	17.2	29.5	45.1
3 E.	9.0	9.0	37.1	47.2
4 E.	22.7	19.9	30.3	37.8
5 E.	16.6	5.2	—	1.6

Table 6.—*Estimated ground-water pumpage and surface-water irrigation in 1961 and 1970*—Continued

Township	*Quantity, in thousands of acre-feet*			
	Ground-water pumpage		*Surface-water irrigation*	
	1961	*1970*	*1961*	*1970*
T. 10 N., R. 2 W.	1.2	1.5	4.6	8.2
1 W.	16.9	13.5	22.7	23.2
1 E.	18.9	18.1	10.6	11.7
2 E.	32.0	32.0	5.6	4.9
3 E.	3.8	2.3	31.4	29.3
4 E.	5.0	4.4	57.5	83.0
5 E.	17.7	17.8	1.0	—
6 E.	11.3	13.6	1.1	0.6
7 E.	—	0.1	2.6	5.5
T. 9 N., R. 1 W.	3.4	6.4	37.3	42.8
1 E.	4.5	8.0	34.3	40.3
2 E.	31.2	24.2	24.7	22.5
3 E.	7.0	4.6	57.2	55.7
4 E.	24.1	27.9	38.4	20.3
5 E.	26.8	38.8	—	—
6 E.	14.9	22.2	1.5	—
T. 8 N., R. 1 W.	26.6	30.2	10.1	10.8
1 E.	24.8	27.5	16.2	16.0
2 E.	26.9	41.6	2.6	2.2
3 E.	18.3	16.3	15.1	9.0
4 E.	10.0	10.8	19.4	5.1
5 E.	31.5	35.3	2.4	0.1
6 E.	20.0	19.6	1.7	—
7 E.	5.0	5.0	3.8	1.4
T. 7 N., R. 1 W.	3.2	4.6	8.3	5.1
1 E.	3.3	2.4	43.3	39.4
2 E.	27.9	28.9	20.8	15.2
3 E.	0.9	1.6	31.2	39.8
4 E.	1.5	1.5	33.3	36.8
5 E.	33.2	21.7	1.3	2.2
6 E.	16.2	16.4	8.8	7.8
7 E.	14.8	15.0	—	2.7
8 E.	.4	—	2.7	3.1
T. 6 N., R. 1 W.	—	—	6.2	17.6
1 E.	3.6	3.8	7.9	37.4
2 E.	4.1	3.7	48.2	44.6
3 E.	—	—	40.2	39.4
4 E.	5.4	5.3	32.7	35.8
5 E.	28.6	31.6	12.4	78.4
6 E.	24.4	26.3	18.0	11.8
7 E.	10.6	11.6	7.1	10.8
8 E.	—	—	3.2	2.7
T. 5 N., R. 2 E.	—	—	29.8	33.3
3 E.	—	—	36.9	45.0
4 E.	3.3	3.1	38.1	41.1
5 E.	18.3	25.5	31.7	36.7
6 E.	29.0	29.7	17.8	22.9
7 E.	7.2	14.0	19.8	20.2
8 E.	—	—	3.8	3.1
T. 4 N., R. 2 E.	1.8	3.2	—	0.9
3 E.	0.6	0.9	36.5	32.9
4 E.	—	—	34.9	38.7
5 E.	—	—	58.2	58.2
6 E.	25.9	32.5	22.8	18.2
7 E.	46.0	50.9	12.4	8.0
8 E.	4.9	4.1	13.4	14.1
Total	1803.9	1814.1	3827.1	4489.7

APPENDIX B

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APPENDIX B

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