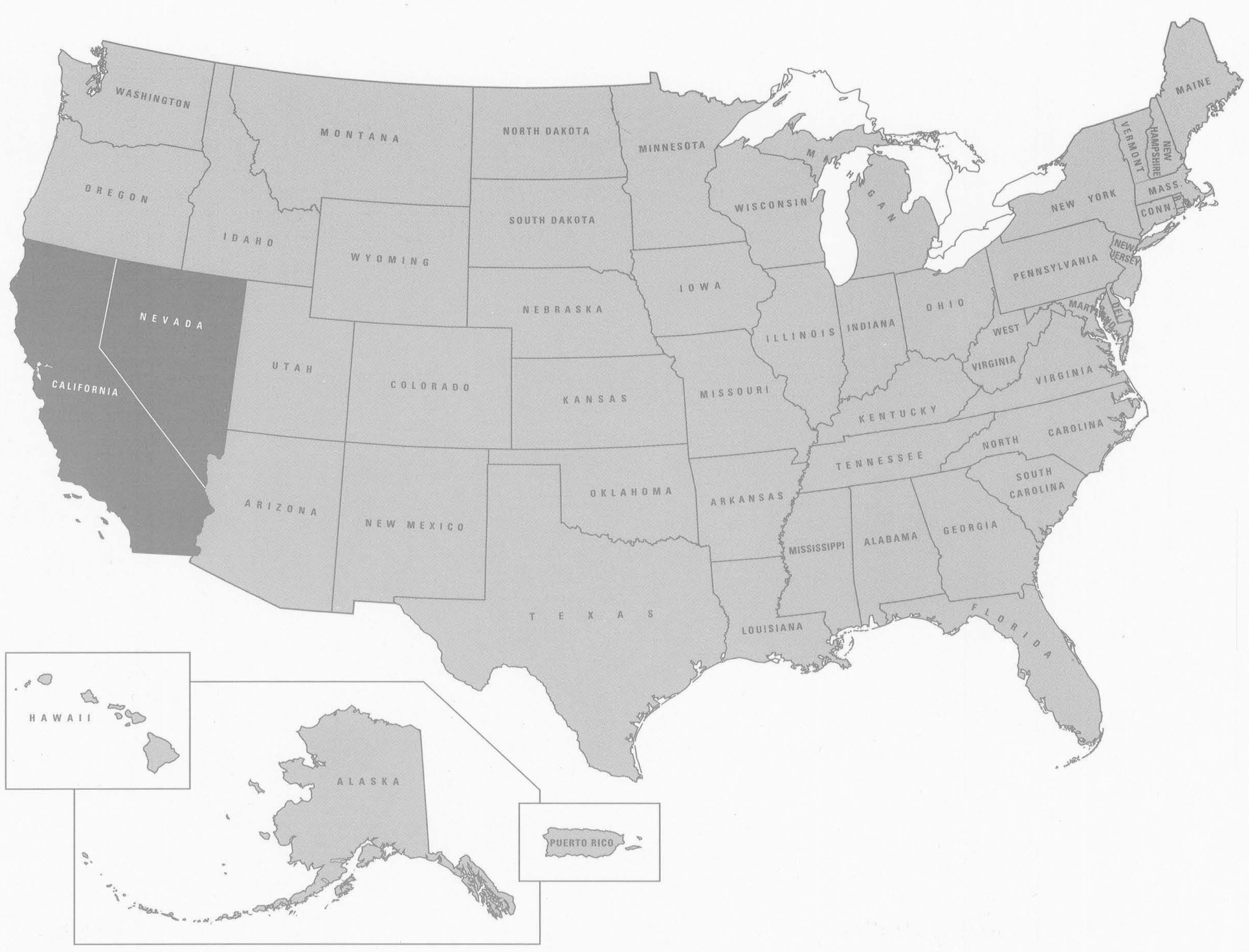
GROUND WATER ATLAS OF THE UNITED STATES

SEGMENT 1
California
Nevada



HYDROLOGIC INVESTIGATIONS ATLAS 730–B

U.S. Geological Survey

Reston, Virginia
1995

GROUND WATER ATLAS OF THE UNITED STATES
Hydrologic Investigations Atlas 730–B

FOREWORD

The Ground Water Atlas of the United States presents a comprehensive summary of the Nation's ground-water resources, and is a basic reference for the location, geography, geology, and hydrologic characteristics of the major aquifers in the Nation. The information was collected by the U.S. Geological Survey and other agencies during the course of many years of study. Results of the U.S. Geological Survey's Regional Aquifer-System Analysis Program, a systematic study of the Nation's major aquifers, were used as a major, but not exclusive, source of information for compilation of the Atlas.

The Atlas, which is designed in a graphical format that is supported by descriptive discussions, includes 13 chapters, each representing regional areas that collectively cover the 50 States and Puerto Rico. Each chapter of the Atlas presents and describes hydrogeologic and hydrologic conditions for the major aquifers in each regional area. The scale of the Atlas does not allow portrayal of minor features of the geology or hydrology of each aquifer presented, nor does it include discussion of minor aquifers. Those readers that seek detailed, local information for the aquifers will find extensive lists of references at the end of each chapter.

An introductory chapter presents an overview of ground-water conditions Nationwide and discusses the effects of human activities on water resources, including saltwater encroachment and land subsidence.

Gordon P. Eaton

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, *Secretary*

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, *Director*

CONVERSION FACTORS

For readers who prefer to use the International System (SI) units, rather than the inch-pound terms used in this report, the following conversion factors may be used:

Multiply inch-pound units	*By*	*To obtain metric units*
	Length	
inch (in)	25.4	millimeter (Mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi²)	2.590	square kilometer (km²)
	Volume	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m³/s)
billion gallons per day (Bgal/d)	3.785	million cubic meters per day (Mm³/d)
acre-foot	1,233	cubic meter (m³)
	Flow	
cubic foot per second (ft³/s)	0.02832	cubic meter per second (m³/s)
acre-foot per year	0.00003909	cubic meter per second (m³/s)
	Transmissivity	
foot squared per day (ft²/d)	0.0929	meter squared per day (m²/d)
	Temperature	
degree Fahrenheit (°F)	5/9(°F)–32=°C	degree Celsius (°C)

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

ATLAS ORGANIZATION

The Ground Water Atlas of the United States is divided into 14 chapters. Chapter A presents introductory material and nationwide summaries; chapters B through M describe all principal aquifers in a multistate segment of the conterminous United States; and chapter N describes all principal aquifers in Alaska, Hawaii, and Puerto Rico.

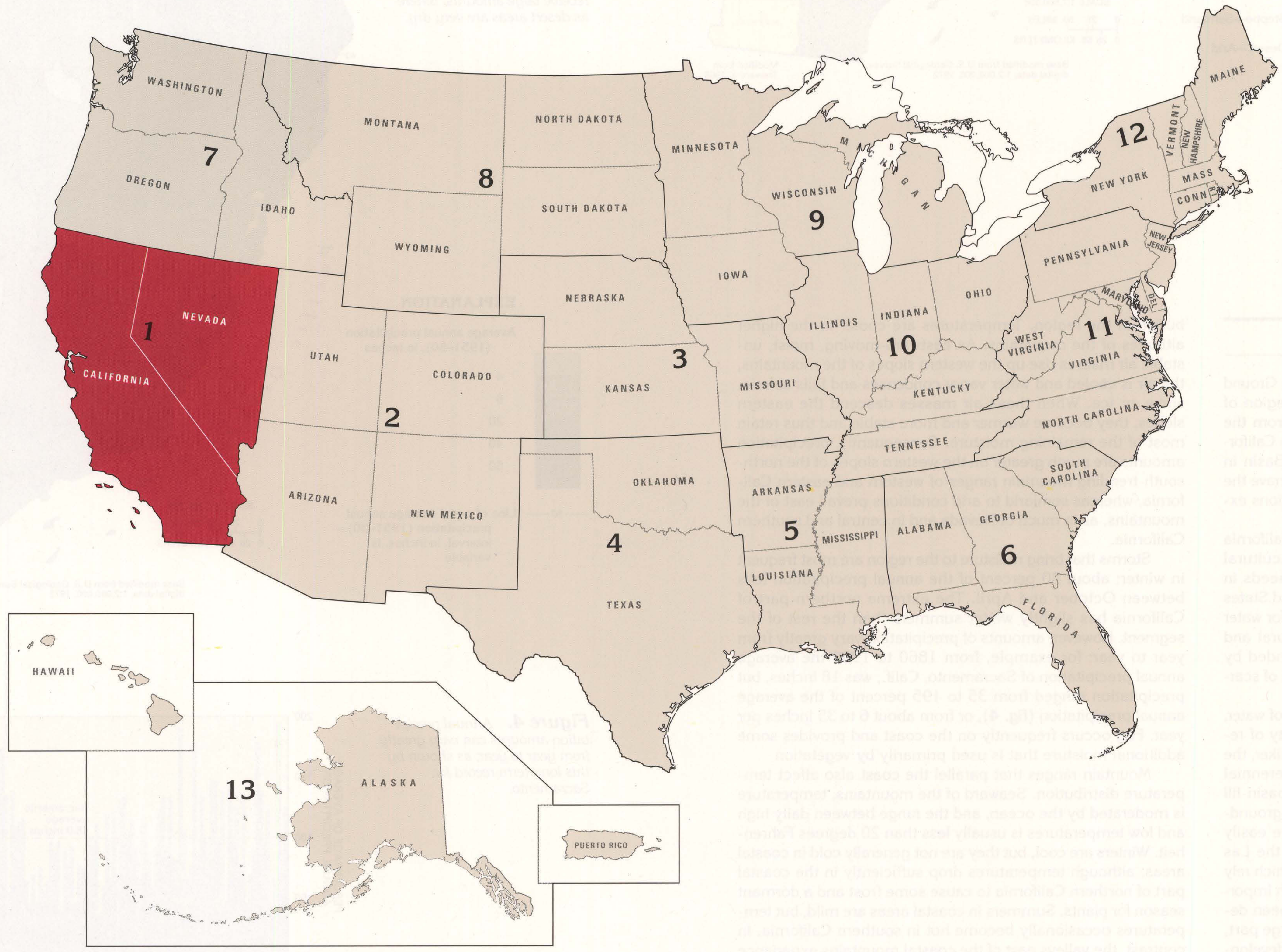
Segment Number	*Chapter content*	*Hydrologic Atlas Chapter*
—	Introductory material and nationwide summaries	730–A
1	California, Nevada	730–B
2	Arizona, Colorado, New Mexico, Utah	730–C
3	Kansas, Missouri, Nebraska	730–D
4	Oklahoma, Texas	730–E
5	Arkansas, Louisiana, Mississippi	730–F
6	Alabama, Florida, Georgia, South Carolina	730–G
7	Idaho, Oregon, Washington	730–H
8	Montana, North Dakota, South Dakota, Wyoming	730–I
9	Iowa, Michigan, Minnesota, Wisconsin	730–J
10	Illinois, Indiana, Kentucky, Ohio, Tennessee	730–K
11	Delaware, Maryland, New Jersey, North Carolina, Pennsylvania, Virginia, West Virginia	730–L
12	Connecticut, Maine, Massachusetts, New Hampshire, New York, Rhode Island, Vermont	730–M
13	Alaska, Hawaii, Puerto Rico	730–N

Ground Water Atlas of the United States

Segment 1

California, Nevada

By Michael Planert and John S. Williams



CONTENTS

Cartographic design and production by Cidney J. Freitag and Paul M. Olsen

Regional summary

Figure 1. Segment 1 has diverse climate types that range from cool and moist in coastal northern California to hot and dry in the deserts of Nevada and southern California.

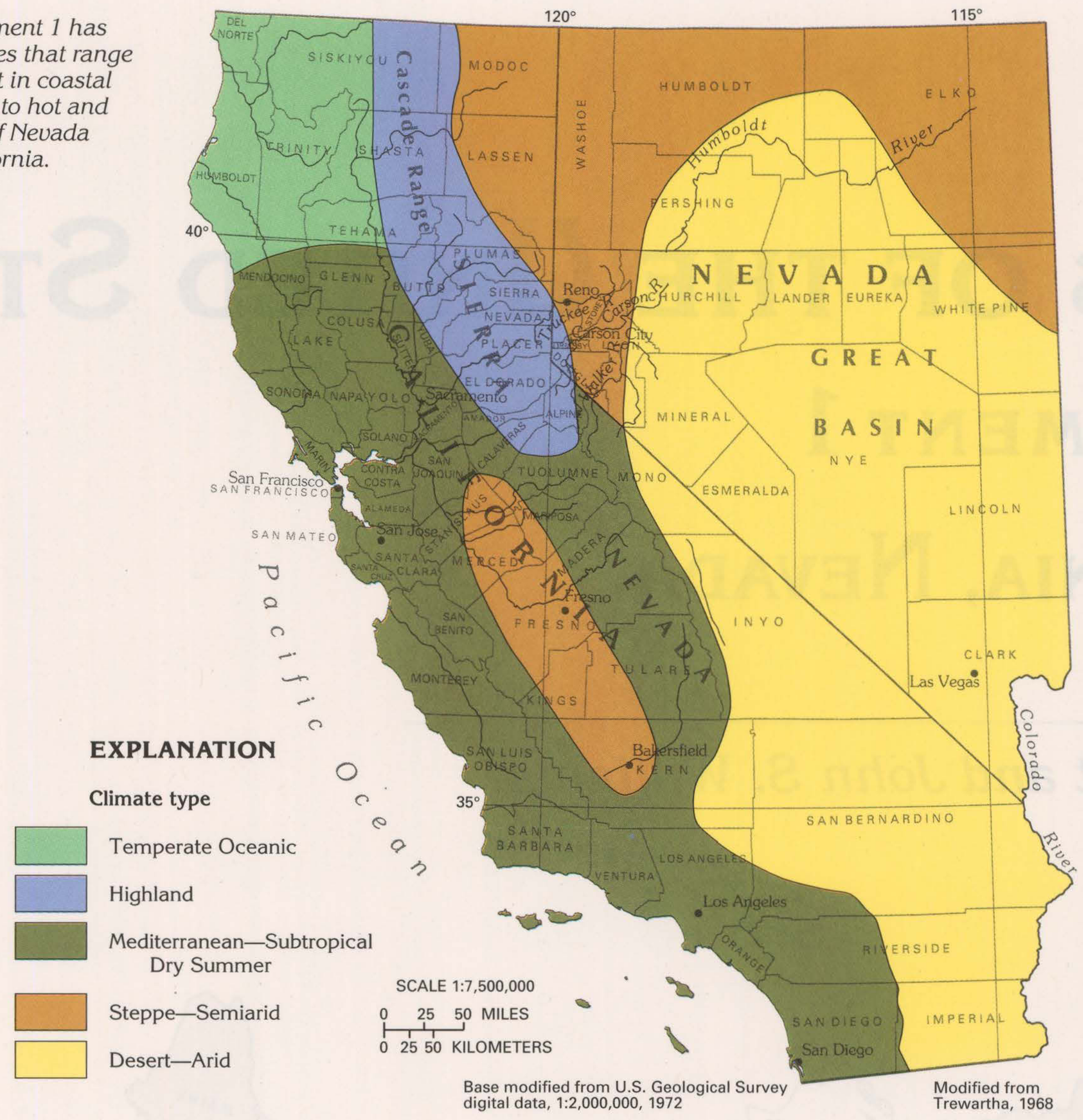
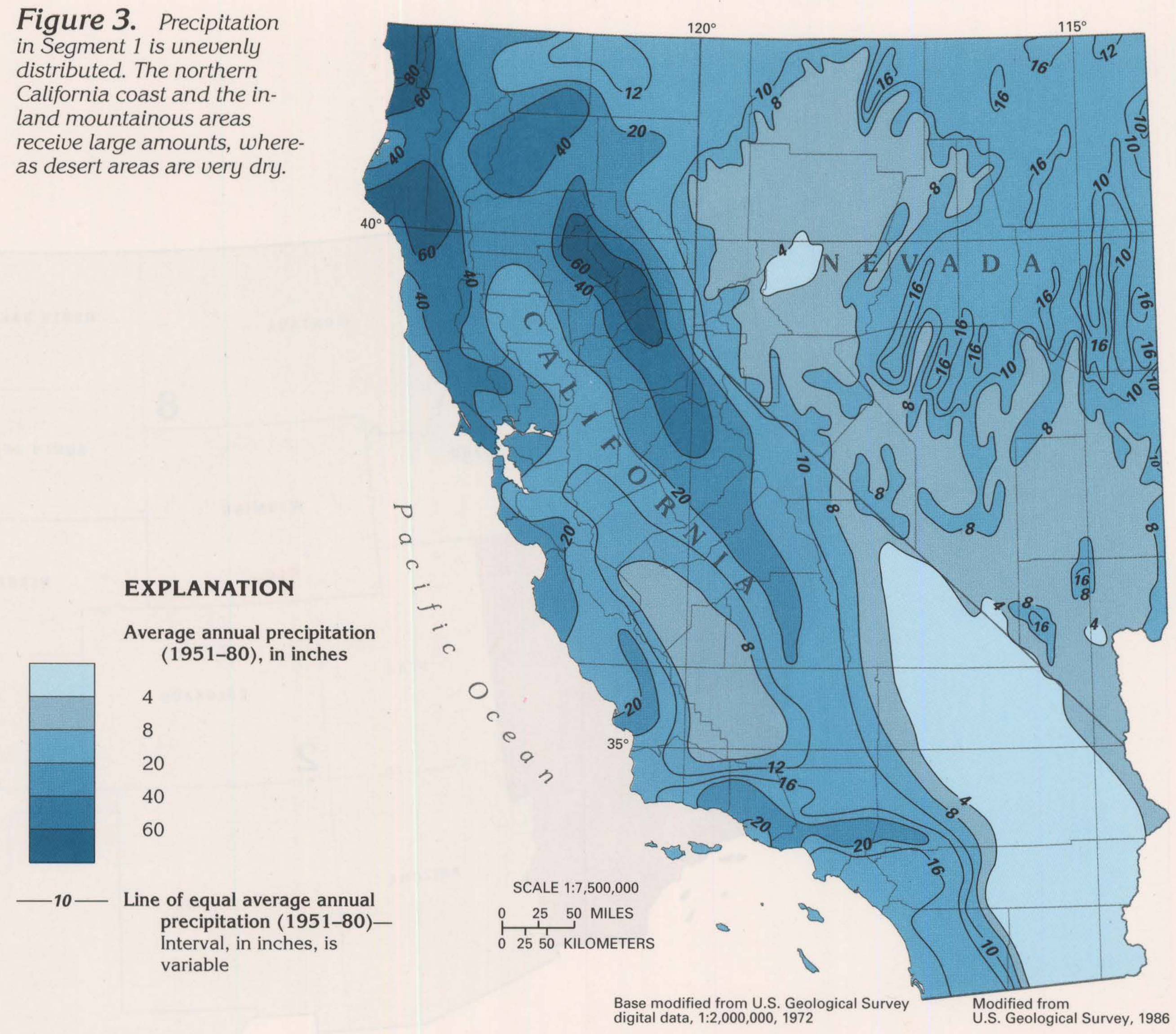


Figure 2. Annual snowfall in the mountains of eastern California and western Nevada can total 400 inches or more. Runoff from melting snow is the primary source of recharge for many of the aquifers in Segment 1.

Figure 3. Precipitation in Segment 1 is unevenly distributed. The northern California coast and the inland mountainous areas receive large amounts, whereas desert areas are very dry.



INTRODUCTION

California and Nevada compose Segment 1 of the Ground Water Atlas of the United States. Segment 1 is a region of pronounced physiographic and climatic contrasts. From the Cascade Mountains and the Sierra Nevada of northern California, where precipitation is abundant, to the Great Basin in Nevada and the deserts of southern California, which have the most arid environments in the United States, few regions exhibit such a diversity of topography or environment.

Since the discovery of gold in the mid-1800's, California has experienced a population, industrial, and agricultural boom unrivaled by that of any other State. Water needs in California are very large, and the State leads the United States in agricultural and municipal water use. The demand for water exceeds the natural water supply in many agricultural and nearly all urban areas. As a result, water is impounded by reservoirs in areas of surplus and transported to areas of scarcity by an extensive network of aqueducts.

Unlike California, which has a relative abundance of water, development in Nevada has been limited by a scarcity of recoverable freshwater. The Truckee, the Carson, the Walker, the Humboldt, and the Colorado Rivers are the only perennial streams of significance in the State. The individual basin-fill aquifers, which together compose the largest known ground-water reserves, receive little annual recharge and are easily depleted. Nevada is sparsely populated, except for the Las Vegas, the Reno–Sparks, and the Carson City areas, which rely heavily on imported water for public supplies. Although important to the economy of Nevada, agriculture has not been developed to the same degree as in California due, in large part, to a scarcity of water. Some additional ground-water development might be possible in Nevada through prudent management of the basin-fill aquifers and increased utilization of ground water in the little-developed carbonate-rock aquifers that underlie the eastern one-half of the State. The potential problem of withdrawals in excess of natural recharge, however, will require careful management of ground-water withdrawals.

CLIMATE

The diverse physiography and north-south extent of Segment 1 result in marked climatic contrasts within the region. Five climate types in the Segment are based primarily on differences in temperature and rainfall (**fig. 1**):

- Temperate Oceanic—Adequate precipitation in all seasons, moderate summers and mild winters, cloudy conditions prevail
- Highland—Altitude, for the most part, controls the weather, large amounts of precipitation as rain and snow in the mountains (**fig. 2**), large diurnal temperature ranges, rain shadows present on the leeward sides of mountain ranges
- Mediterranean (Subtropical Dry Summer)—Modest precipitation in winter, warm summers and mild winters, abundant sunshine
- Steppe (Semiarid)—Little precipitation, falling mostly in winter, large annual temperature range
- Desert (Arid)—High temperature, scant precipitation, large diurnal and annual temperature ranges, low relative humidity, little cloud cover

Precipitation and Temperature

In California, much of the climatic variation results from the patterns of global weather systems. Precipitation is greater in the northern part of the State than elsewhere (**fig. 3**). However, prominent mountain ranges in California and western Nevada also have an important influence on moisture distribution in the region. Temperatures are cooler in the higher altitudes of the mountains. As eastward-moving, moist, unstable air masses rise up the western slopes of the mountains, the air is cooled and water vapor condenses and falls as rain, snow, or ice. When these air masses descend the eastern slopes, they become warmer and more stable and thus retain most of the remaining moisture. Consequently, precipitation amounts are much greater on the western slopes of the north-south-trending mountain ranges of western and eastern California, whereas semiarid to arid conditions prevail east of the mountains, as in much of Nevada and in central and southern California.

Storms that bring moisture to the region are most frequent in winter; about 80 percent of the annual precipitation falls between October and April. The extreme northern part of California has slightly wetter summers than the rest of the segment. However, amounts of precipitation vary greatly from year to year; for example, from 1860 to 1980 the average annual precipitation of Sacramento, Calif., was 18 inches, but precipitation ranged from 35 to 195 percent of the average annual precipitation (**fig. 4**), or from about 6 to 35 inches per year. Fog occurs frequently on the coast and provides some additional moisture that is used primarily by vegetation.

Mountain ranges that parallel the coast also affect temperature distribution. Seaward of the mountains, temperature is moderated by the ocean, and the range between daily high and low temperatures is usually less than 20 degrees Fahrenheit. Winters are cool, but they are not generally cold in coastal areas, although temperatures drop sufficiently in the coastal part of northern California to cause some frost and a dormant season for plants. Summers in coastal areas are mild, but temperatures occasionally become hot in southern California. In contrast, the valleys east of the coastal mountains experience much greater temperature extremes. In these valleys, summer daytime temperatures can be greater than 90 degrees but fall to 55 degrees or less at night. Winters in the interior valleys are relatively mild, and freezes are uncommon.

Temperature ranges in the mountains of western California and eastern Nevada, as well as in the desert parts of Nevada and southern California, are much greater than in other parts of Segment 1. In the mountains and deserts very little moisture is in the air to absorb the rays of the sun, or to retain heat at night. Consequently, solar radiation is intense during the day, but the heat stored in the ground is released rapidly after sunset. Temperature extremes are hotter and colder in the desert than in other lowland areas elsewhere in the segment, but mountainous areas are warm in summer and extremely cold in winter.

Runoff

Runoff is the amount of water left from precipitation that can be measured as streamflow after losses to evaporation, transpiration by plants, and the replenishment of storage within the aquifers. The areal distribution of runoff from 1951 to 1980 (**fig. 5**) closely followed the areal distribution of precipitation for the same period (**fig. 3**), but the relative amounts of runoff varied as a result of climatic conditions. Runoff is greatest in the mountains, where the majority of precipitation falls as snow, which melts in the spring and runs off with minimal evapotranspiration (the process by which liquid water is converted to water vapor either by evaporation or by transpiration from plants). Runoff is greater than 40 inches per year in many mountainous areas. The basins in the arid parts of Nevada and southeastern California have virtually zero runoff because most precipitation that falls is evaporated almost immediately. However, high-intensity storms or rapid snowmelt in the mountains that border the basins may cause flash floods that reach the floors of the basins. Coastal areas have a direct relation between the amount of precipitation and runoff.

Figure 4. Annual precipitation amounts can vary greatly from year to year, as shown by this long-term record for Sacramento.

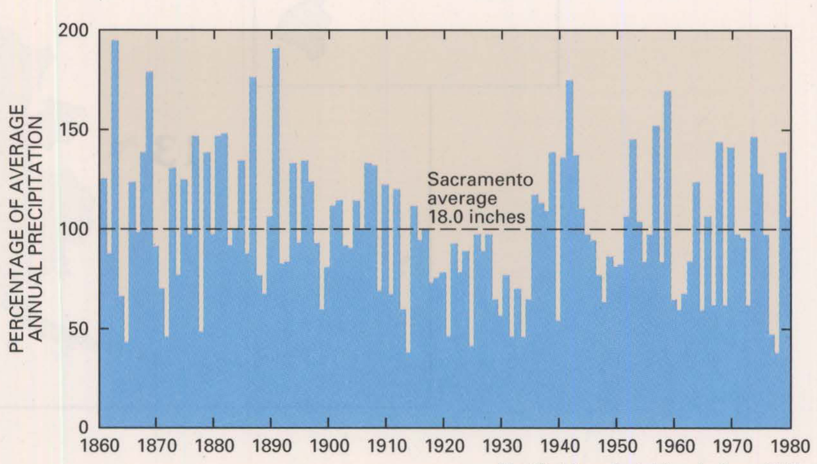
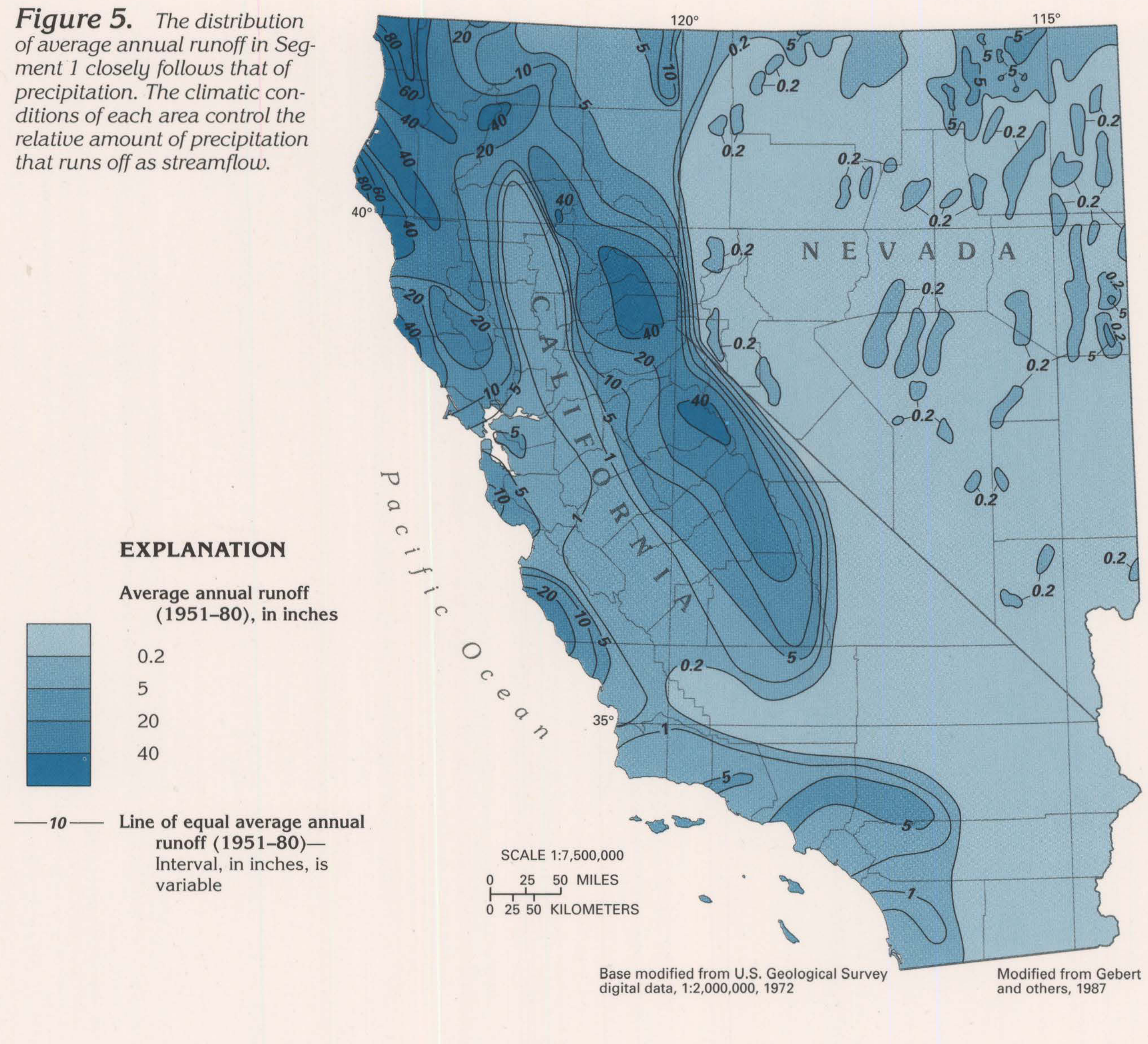


Figure 5. The distribution of average annual runoff in Segment 1 closely follows that of precipitation. The climatic conditions of each area control the relative amount of precipitation that runs off as streamflow.



Water Surplus and Deficit

The relation between precipitation and evapotranspiration is a major factor in water availability. Generally, if annual precipitation exceeds annual potential evapotranspiration, then there is a net surplus of water and streamflow is perennial. However, annual potential evapotranspiration can exceed annual precipitation, which causes a net deficit of water. A net annual moisture deficit is present almost everywhere in California and Nevada (**fig. 6**). The only areas with an annual moisture surplus are the northern California coast, which receives considerable rainfall from winter storms, and the mountainous regions of northern and east-central California, where condensation of water vapor in rising, moist air masses results in abundant rain or snow. Water is available to recharge aquifers only at times when precipitation or snowmelt is greater than actual evapotranspiration. Thus, not all areas mapped as having a net water surplus in **figure 6** are recharge areas.

In most of Nevada and in southern California, nearly all streams that head in the mountains are ephemeral and lose flow to alluvial aquifers within a short distance of where the streams leave the mountains and emerge onto the valley floors. In much of northern California and in the Humboldt, the Truckee, the Carson, and the Walker River drainages of Nevada, however, runoff is sufficient to support perennial streams. The Colorado River is supplied primarily by runoff from the Rocky Mountains. Before the inception of agriculture, the largest rivers in the vast Central Valley of California overflowed their banks during periods of peak winter flows and formed extensive marshlands. An elaborate flood control system and the lowering of the water table by withdrawals for irrigation now keep these rivers within their banks.

The geographical distribution of moisture in Segment 1 greatly influences patterns of agricultural and urban development. Much of Nevada receives little precipitation, and, consequently, ground- and surface-water supplies are limited. This limitation has severely restricted urban development and has put constraints on agricultural development. Las Vegas, the largest urban area in the State, obtains most of its water from the Colorado River, which is many miles away.

California receives relatively abundant precipitation. However, the precipitation is concentrated in areas of the State remote from most of the large urban centers and major agricultural areas. A further complication is the unpredictability of precipitation on an annual basis, which can often make surface-water supplies undependable. To provide a dependable, year-round supply of water to areas where it is most needed is a full-time, massive undertaking, and is accomplished by careful water management and an extensive water-transportation network (**fig. 7**).

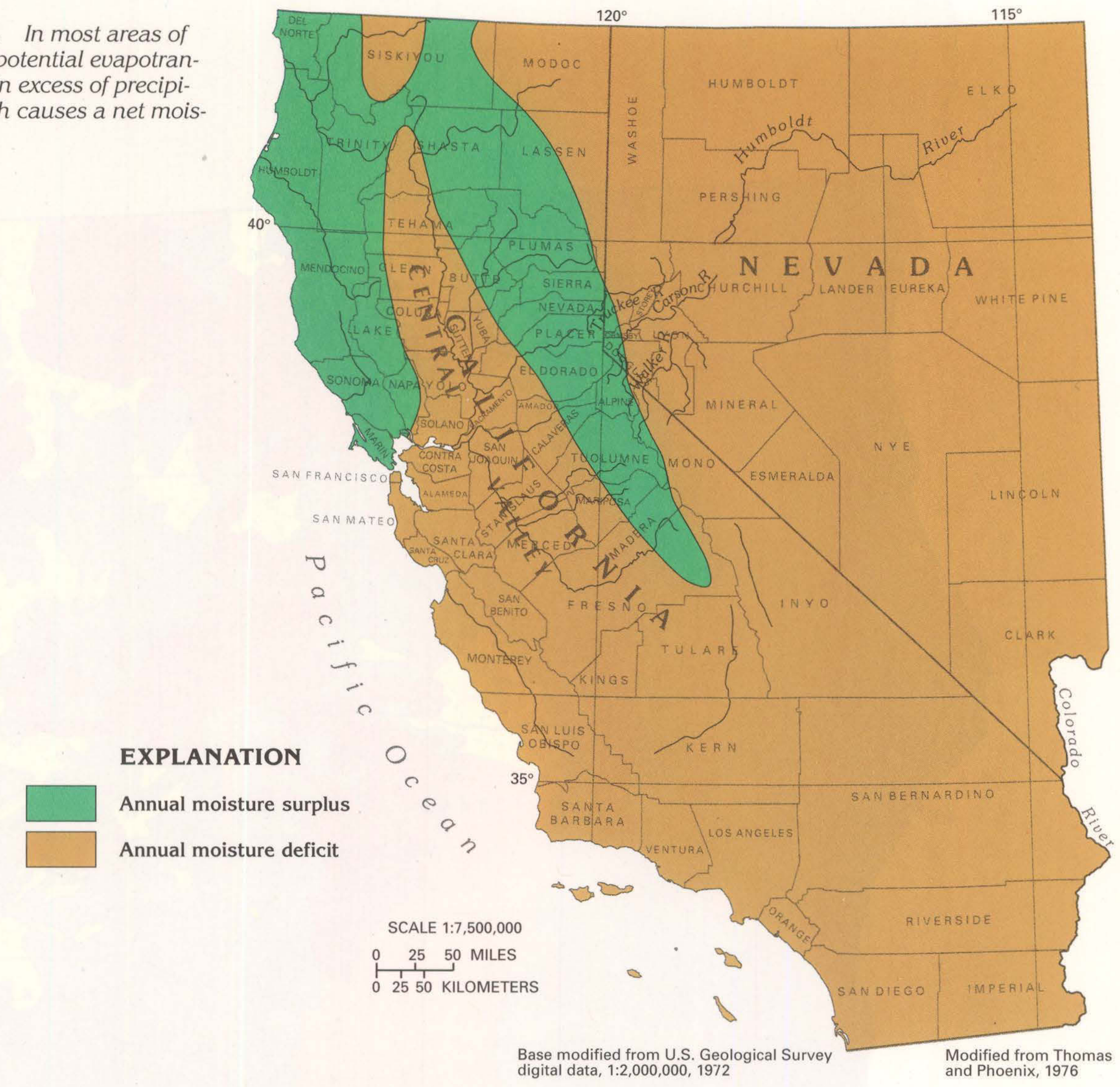


Figure 6. In most areas of Segment 1, potential evapotranspiration is in excess of precipitation, which causes a net moisture deficit.

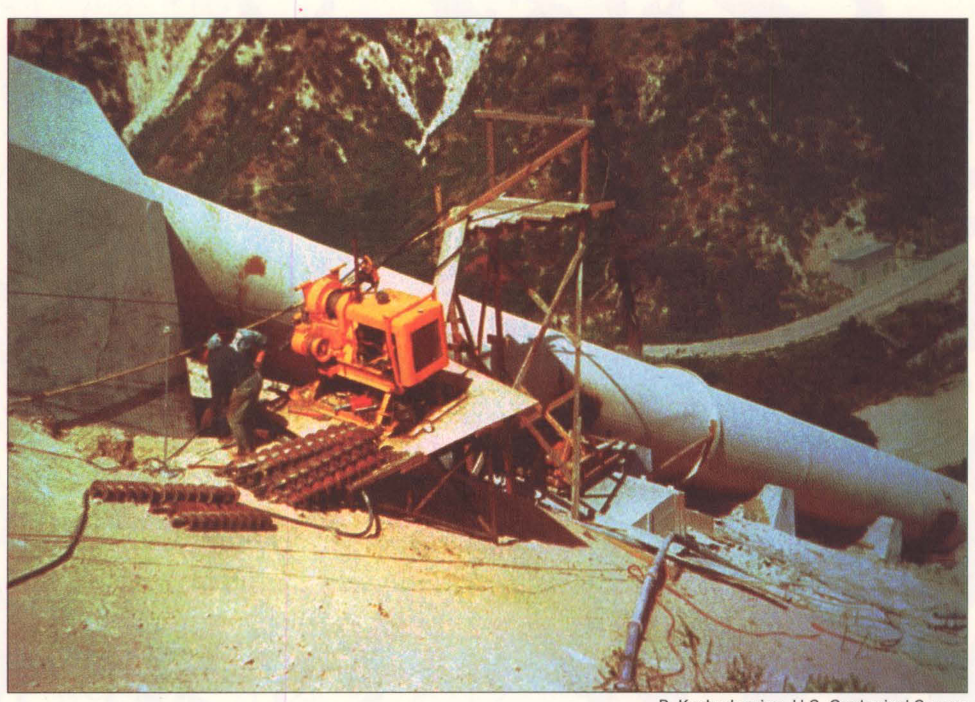


Figure 7. An extensive aqueduct system in California transports water from impoundments in areas of water abundance to population and agricultural centers in areas of water deficits.

R. Kachadoorian, U.S. Geological Survey

PHYSIOGRAPHY AND LAND USE

The physiography of the region (**fig. 8**) is a product of the geologic history of the area. Several coastal mountain ranges underlain by severely folded, faulted, commonly metamorphosed marine and continental sediments, form the Pacific Border and the Lower Californian Physiographic Provinces. In the interior, the granitic rocks that underlie the fault blocks of the Sierra Nevada and the volcanic rocks of the southern Cascade Mountains join to form the eastern border of the low-lying California Trough, which contains the Central Valley. East of the Sierra Nevada, the land is characterized by a series of low, north-south-trending mountain ranges and intervening valleys (**fig. 9**); the ranges and valleys were created by faulting that resulted in the horst and graben structures that form the Basin and Range Physiographic Province. In the extreme northeastern part of Nevada, the southernmost extent of the Columbia Plateaus Physiographic Province is formed by basalt lava flows.

Land use in Segment 1 is directly related to topography and the availability of water. Major land uses in California and Nevada are shown in **figure 10**. The flat floor of the Central Valley of California, one of the Nation's most important agricultural areas, is used almost entirely for growing crops. Most of the cropland, however, must be irrigated. The mountains that surround the Central Valley are areas of rugged topography and, accordingly, are used predominantly as forest and woodland, even though they receive large amounts of precipitation. Almost all of Nevada and large parts of southern California receive little precipitation; accordingly, most of the land in these areas is desert shrubland (compare **figs. 5 and 10**), although sufficient water is available to allow livestock to be grazed in some places.

The major cities in the coastal areas of California appear as large areas of urban sprawl on **figure 10**. Although coastal California receives moderate to large amounts of precipitation, surface-water and ground-water supplies in those urban areas are not sufficient to provide the water needs of the population. As a result, a huge network of reservoirs, canals, and aqueducts has been constructed in California to transport water to these urban areas and other areas of water deficit.

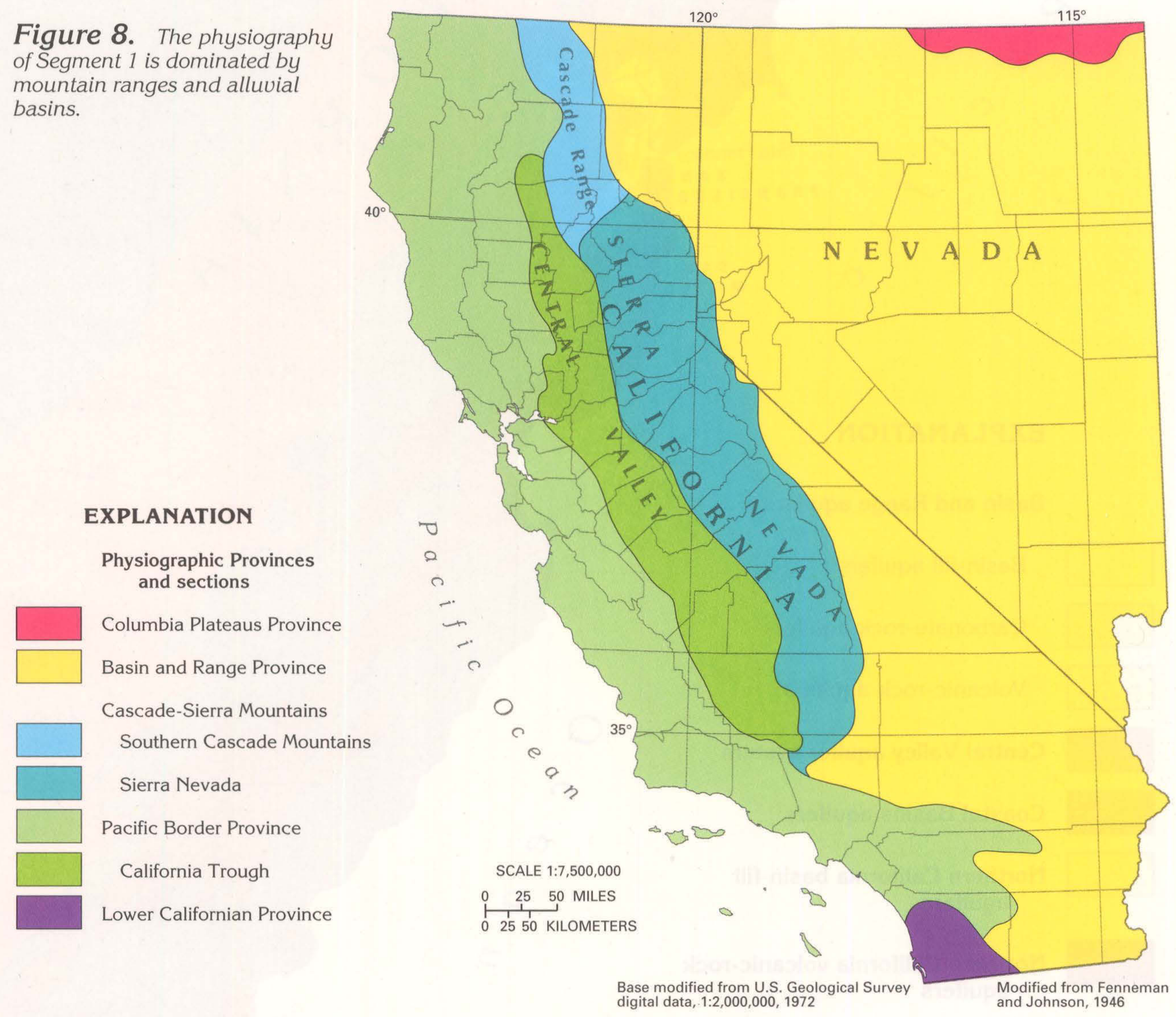


Figure 8. The physiography of Segment 1 is dominated by mountain ranges and alluvial basins.

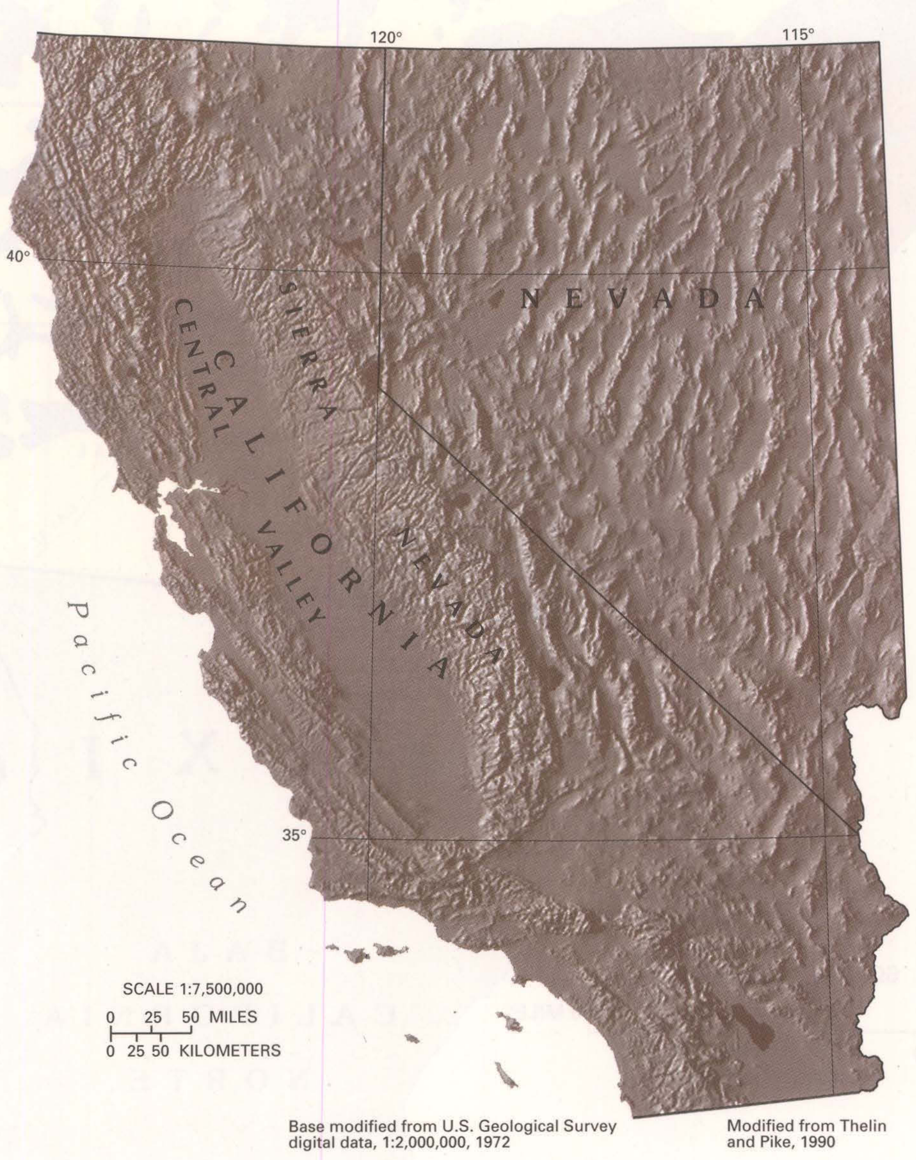


Figure 9. The alternating valleys and low mountain ranges of Nevada contrast sharply with the high, rugged California mountain ranges that surround the low-lying Central Valley.

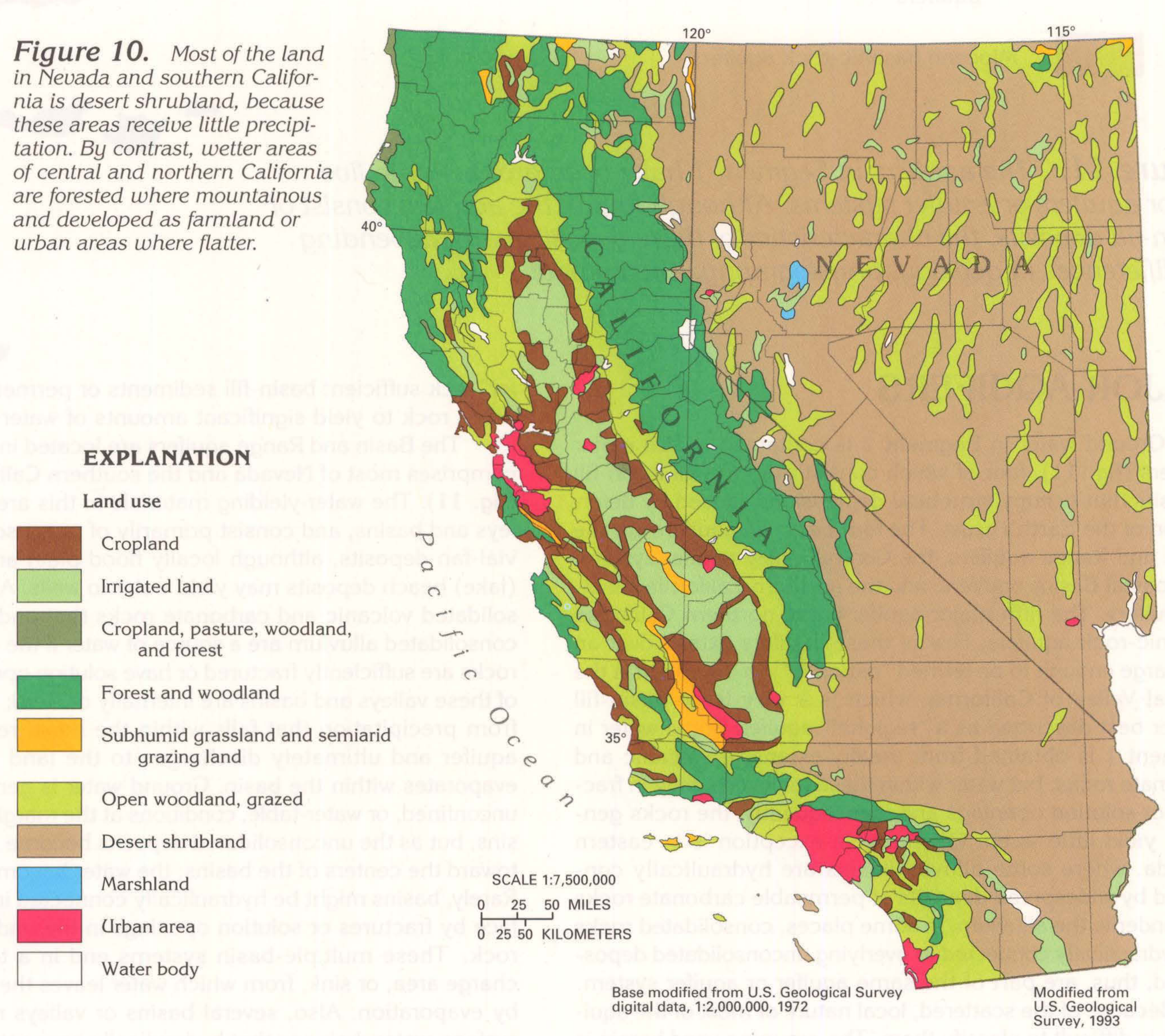


Figure 10. Most of the land in Nevada and southern California is desert shrubland, because these areas receive little precipitation. By contrast, wetter areas of central and northern California are forested where mountainous and developed as farmland or urban areas where flatter.

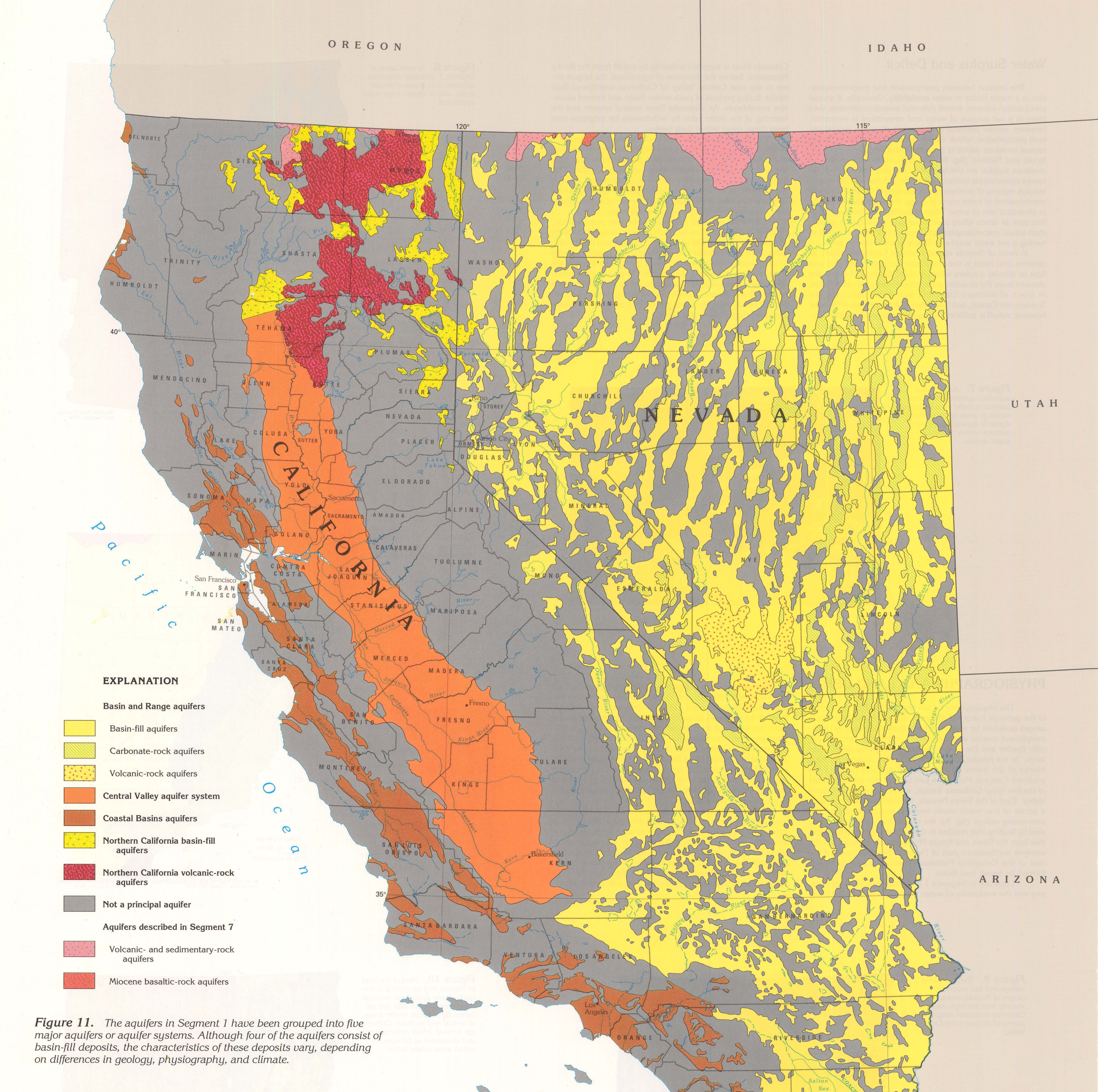


Figure 11. The aquifers in Segment 1 have been grouped into five major aquifers or aquifer systems. Although four of the aquifers consist of basin-fill deposits, the characteristics of these deposits vary, depending on differences in geology, physiography, and climate.

MAJOR AQUIFERS

Ground water in Segment 1 is contained in five major aquifers (**fig. 11**), four of which consist primarily of basin-fill deposits that occupy structural depressions caused by deformation of the Earth's crust. The four basin-fill aquifers are the Basin and Range aquifers, the Central Valley aquifer system, the Coastal Basins aquifers, and the northern California basin-fill aquifers. The fifth major aquifer is the northern California volcanic-rock aquifers. Few of these aquifers extend over an area large enough to be termed "regional." An exception is the Central Valley of California, which is a very large basin-fill aquifer best described as a "regional" aquifer. Some water in Segment 1 is obtained from areally-extensive volcanic and carbonate rocks, but water within these rocks is mostly in fractures or solution openings and, consequently, the rocks generally yield little water. One notable exception is in eastern Nevada, where some alluvial basins are hydraulically connected by widespread deposits of permeable carbonate rocks that underlie the alluvium. In some places, consolidated rocks are hydraulically connected to overlying unconsolidated deposits and, thus, are part of the same aquifer or aquifer system.

Because of the scattered, local nature of most of the aquifers, it is difficult to classify them. The grouping used herein is based on geology, physiography, and climate but is not the only one possible. The areas designated "not a principal aquifer" lack sufficient basin-fill sediments or permeable consolidated rock to yield significant amounts of water to wells.

The Basin and Range aquifers are located in an area that comprises most of Nevada and the southern California desert (**fig. 11**). The water-yielding materials in this area are in valleys and basins, and consist primarily of unconsolidated alluvial-fan deposits, although locally flood plain and lacustrine (lake) beach deposits may yield water to wells. Also, the consolidated volcanic and carbonate rocks that underlie the unconsolidated alluvium are a source of water if the consolidated rocks are sufficiently fractured or have solution openings. Many of these valleys and basins are internally drained; that is, water from precipitation that falls within the basin recharges the aquifer and ultimately discharges to the land surface and evaporates within the basin. Ground water is generally under unconfined, or water-table, conditions at the margins of the basins, but as the unconsolidated deposits become finer grained toward the centers of the basins, the water becomes confined. Rarely, basins might be hydraulically connected in the subsurface by fractures or solution openings in the underlying bedrock. These multiple-basin systems end in a terminal discharge area, or sink, from which water leaves the flow system by evaporation. Also, several basins or valleys may develop surface-water drainage that hydraulically connects the basins, and ground water flows between the basins, mostly through the unconsolidated alluvial stream/flood plain sediments.

MAJOR AQUIFERS—Continued

The Central Valley aquifer system (**fig. 11**) occupies most of a large basin in central California between the Sierra Nevada and the Coast Range Mountains. The Central Valley is the single most important source of agricultural products in the United States, and ground water for irrigation has been essential in the development of that industry. The basin contains a single, large, basin-fill aquifer system, the largest such system in the Nation. Although the valley is filled with tens of thousands of feet of unconsolidated sediments, most of the fresh ground water is at depths of less than 2,500 feet. Ground water in the valley is under unconfined to confined (artesian) conditions, primarily depending on depth; most of the shallow ground water is unconfined.

The Coastal Basins aquifers occupy a number of basins in coastal areas from northern to southern California (**fig. 11**). These basins have similar morphology and a Mediterranean climate. All are in structural depressions formed by folding and faulting, all are filled with marine and alluvial sediments, and all are drained by streams that contain water at least part of the year. Nearly all the large population centers in Segment 1 are located in these basins, and the available ground water is used primarily for municipal supplies. In most of the basins, however, population has grown to such an extent that local ground-water supplies are no longer adequate, and surface water must be transported from distant sources to meet demand. Ground water in the basins is under unconfined to confined conditions, and two or more vertically sequential aquifers can be present in a basin, separated by confining units that consist of fine-grained sediments. In nearly all basins that contain more than one aquifer, however, the aquifers are hydraulically connected to some degree. Seawater intrusion is a common problem in nearly all the Coastal Basins aquifers.

Interior northern California is sparsely populated, and most ground-water demand is for agricultural irrigation. The most productive and highly-utilized aquifers in the area are the northern California basin-fill aquifers (**fig. 11**). These aquifers are in unconsolidated alluvial sediments. However, in some basins, wells drilled into underlying volcanic rocks might produce large quantities of water, often more than wells completed in the unconsolidated sediments.

The northern California volcanic-rock aquifers consist of volcanic rocks that yield water primarily from fractures and locally from intergranular spaces in porous tuffs. Because water-yielding zones in these rocks are unevenly distributed, wells that yield water are outnumbered by dry holes; however, in some areas, wells completed in the volcanic-rock aquifers yield large volumes of water. The northern California volcanic-rock aquifers are relatively unexplored and undeveloped.

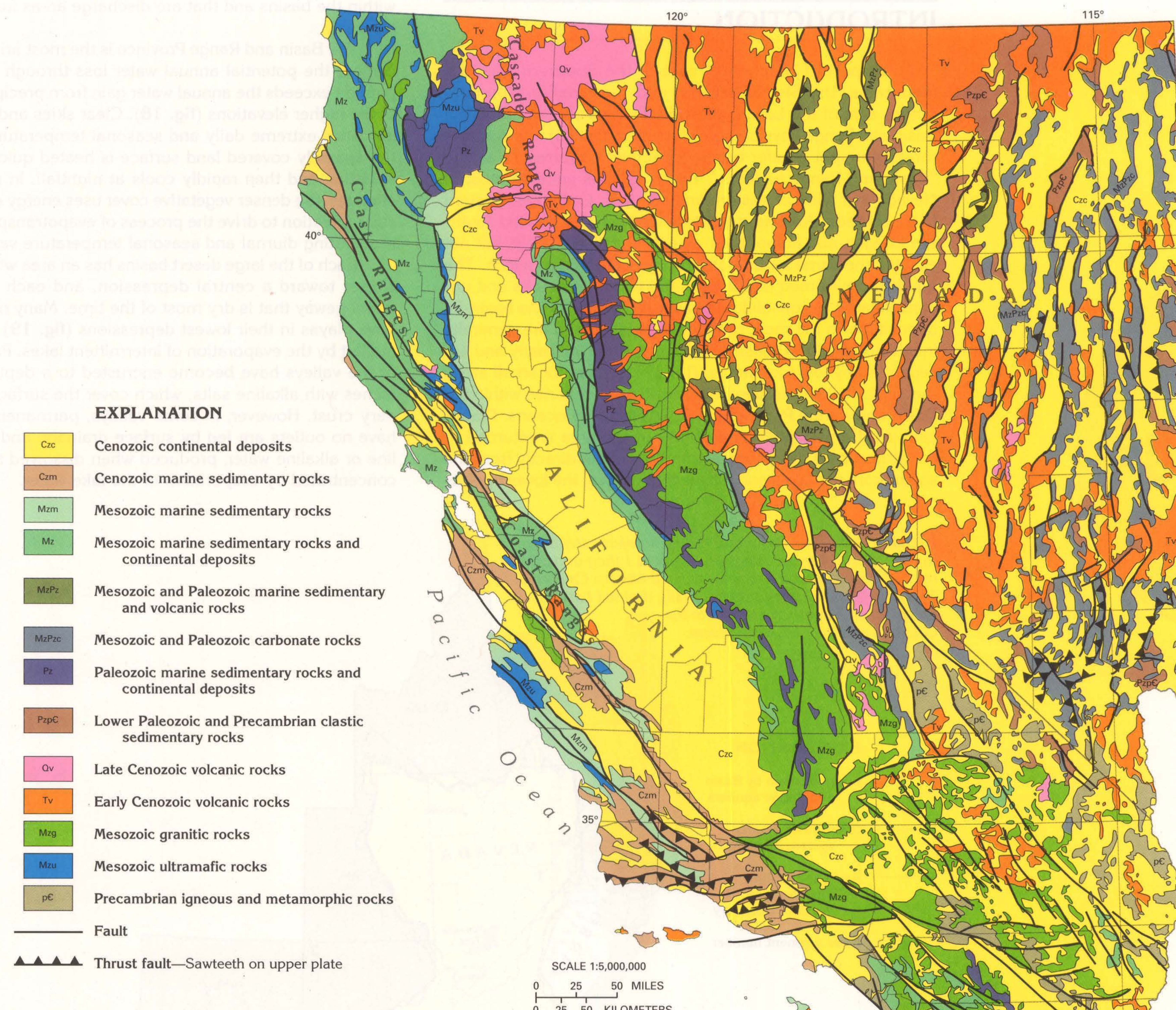


Figure 12. *The complex geology within Segment 1 is the result of repeated periods of mountain building alternating with periods of erosion. Most of the basins in the segment are bounded by faults and contain rocks of Cenozoic age. The mountains that separate the basins are formed on rocks of various ages.*

GEOLOGY AND GEOLOGIC HISTORY

Rocks and deposits exposed at the surface in Segment 1 range in age from Precambrian to Quaternary (**fig. 12**). They consist of igneous intrusive rocks, pyroclastic and extrusive volcanic rocks, and marine and continental sediments, many of which, particularly the older rocks (pre-Mesozoic) have been intensely metamorphosed, folded, and faulted.

The principal water-yielding units are unconsolidated continental clastic deposits of Cenozoic age that partly fill structural basins created by faulting. Volcanic rocks, which are principally lava and pyroclastic flows of Cenozoic age, are important aquifers in scattered areas. Paleozoic limestones and dolomites associated with basin-fill Cenozoic clastic deposits in eastern Nevada are the only older rocks with significant water-yielding potential.

During Precambrian time and the Paleozoic Era, an almost uniform thickness of approximately 40,000 feet of marine sediments was deposited in the Cordilleran geosyncline. This geosyncline was an elongated trough that extended north to south in western North America and included the area that is now eastern Nevada and southern California. Sedimentation was marked by two periods of alternating clastic and carbonate deposition that resulted in the following sequence: quartzite and siltstone, limestone and dolomite, argillite and quartzite, and limestone.

At the end of the Paleozoic Era, volcanoes were active on a grand scale in eastern California and western Nevada. This volcanism marked the beginning of igneous activity that was to become increasingly important during Mesozoic time.

A number of shallow marine invasions inundated parts of the region during the Mesozoic Era. Conditions were such that marine formations alternated with nonmarine deposits derived from erosion of rocks in the continental interior. During this time, a coastal strip as much as 400 miles wide was formed by a combination of marine sedimentation and igneous activity, granitic intrusions, and subaerial volcanism, and was welded to the western margin of the preexisting continental mass.

The early Mesozoic seas spread inland as far as central Utah and Wyoming but were soon blocked by a narrow uplift in central Nevada. During the remainder of the Mesozoic Era, only intermittent subaerial deposition took place east of this uplift. West of the uplift, a thick sequence of Mesozoic marine and continental sediments was deposited, interspersed with lava flows, volcanic breccia, and tuff.

The close of middle Mesozoic time culminated in the first great orogeny in the western part of North America since Precambrian time. As mountain ranges rose, the marine, continental, and volcanic deposits of the Pacific Coast were folded, metamorphosed, and complexly faulted. Intense deformation of the older rocks spread eastward across most of Nevada. Late in the Mesozoic Era, the Pacific coastal region was again downwarped and the sea intruded.

During the Cenozoic Era, volcanic rocks and sedimentary deposits accumulated over wide areas of Segment 1, to thicknesses of as much as 50,000 feet. Early in the Cenozoic Era, the Basin and Range area was a high mountain surface with external drainage. During middle to late Cenozoic time, however, large-scale block faulting formed the Coast Range Mountains, the California Trough, and the Sierra Nevada and caused the Basin and Range structures. These structures are a sequence of alternating horsts and grabens that trend north-south and are reflected in the present-day topography. Volcanism, which still continues today, formed much of the Cascade Mountains.

In late Cenozoic time, the California Trough and the structural basins in the Coast Range were filled with marine and terrestrial deposits that ranged from a few thousand to as much as 50,000 feet in thickness. The grabens of the Basin and Range were filled with continental deposits and minor lava flows to thicknesses of generally less than 2,000 feet, but locally as much as 50,000 feet. The late Cenozoic also was the time of development of basins in the mountains of northern California and Nevada. These basins were filled with clastic sediments and numerous basaltic lava flows.

FRESH GROUND-WATER WITHDRAWALS

Ground water is an important resource in California and Nevada and accounted for nearly 40 percent of all freshwater used in the two States during 1985 (**fig. 13**). Fresh ground-water withdrawals in California during this period were about 16 times as much as those in Nevada. In Segment 1, irrigated agriculture accounts for the greatest amount of ground-water use, followed by withdrawals for public supplies. More than 25 million people, or about 66 percent of the population of the two-State area, depend on publicly supplied ground water.

Total withdrawals of fresh ground water during 1985, by county, are shown in **figure 14**. Counties with the largest withdrawals are those where vast areas are irrigated, such as the Central Valley of California, or counties having large population centers. The large withdrawals shown for central Nevada and some southern California counties are somewhat misleading. These areas are largely desert, and because of the extremely large size of some of the counties, small withdrawals in scattered pumping centers plot as unrealistically large withdrawals when totalled for counties that contain hundreds of thousands of square miles.

The Central Valley aquifer system had the largest ground-water withdrawal in Segment 1 during 1985 (**fig. 15**). Approximately 9,000 million gallons per day (about 10 million acre-feet per year) was withdrawn from the Central Valley aquifer system. Of that amount, approximately 8,000 million gallons per day, or 8.9 million acre-feet per year, was withdrawn for irrigation and accounted for about 11.5 percent of all ground-water withdrawals in the United States. One acre-foot, or 43,560 cubic feet of water, is the volume of water that will cover an area of 1 acre to a depth of 1 foot.

The Coastal Basins aquifers supply the largest population centers in Segment 1 and are second only to the Central Valley aquifer system in total ground-water withdrawals (**fig. 15**). Much ground water is withdrawn for agricultural use in these coastal basins, but public supply accounted for about 54 percent of the approximately 4,370 million gallons per day (about 4.9 million acre-feet per year) withdrawn during 1985; this is due primarily to the large population in the coastal cities of southern California that depend heavily on ground water for public supply.

Irrigated agriculture is the largest user of fresh ground water withdrawn from the Basin and Range aquifers. Although ground water is a significant source of water for public supplies, large population centers, such as Las Vegas, the Carson City area, and the Reno–Sparks area, depend heavily on surface water for their public supplies. The desert basins receive little precipitation during the year, and surface and ground water are scarce, which limits population growth in the region.

The northern California volcanic-rock aquifers and the northern California basin-fill aquifers together supplied only 5 percent of the total fresh ground water withdrawn in Segment 1 during 1985. These aquifers compose only a small part of the segment, and the demand for ground water in northern California is not great.

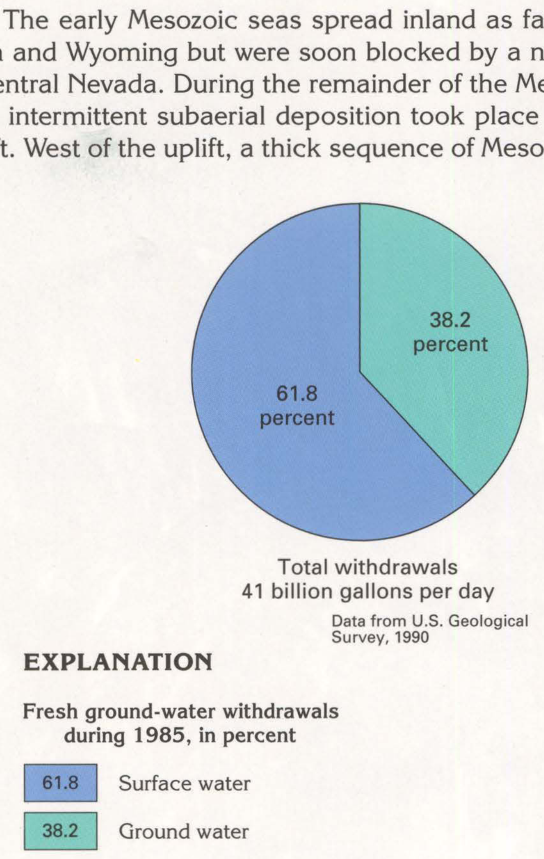


Figure 13. *Ground water accounted for nearly 40 percent of all freshwater used in Segment 1 during 1985.*

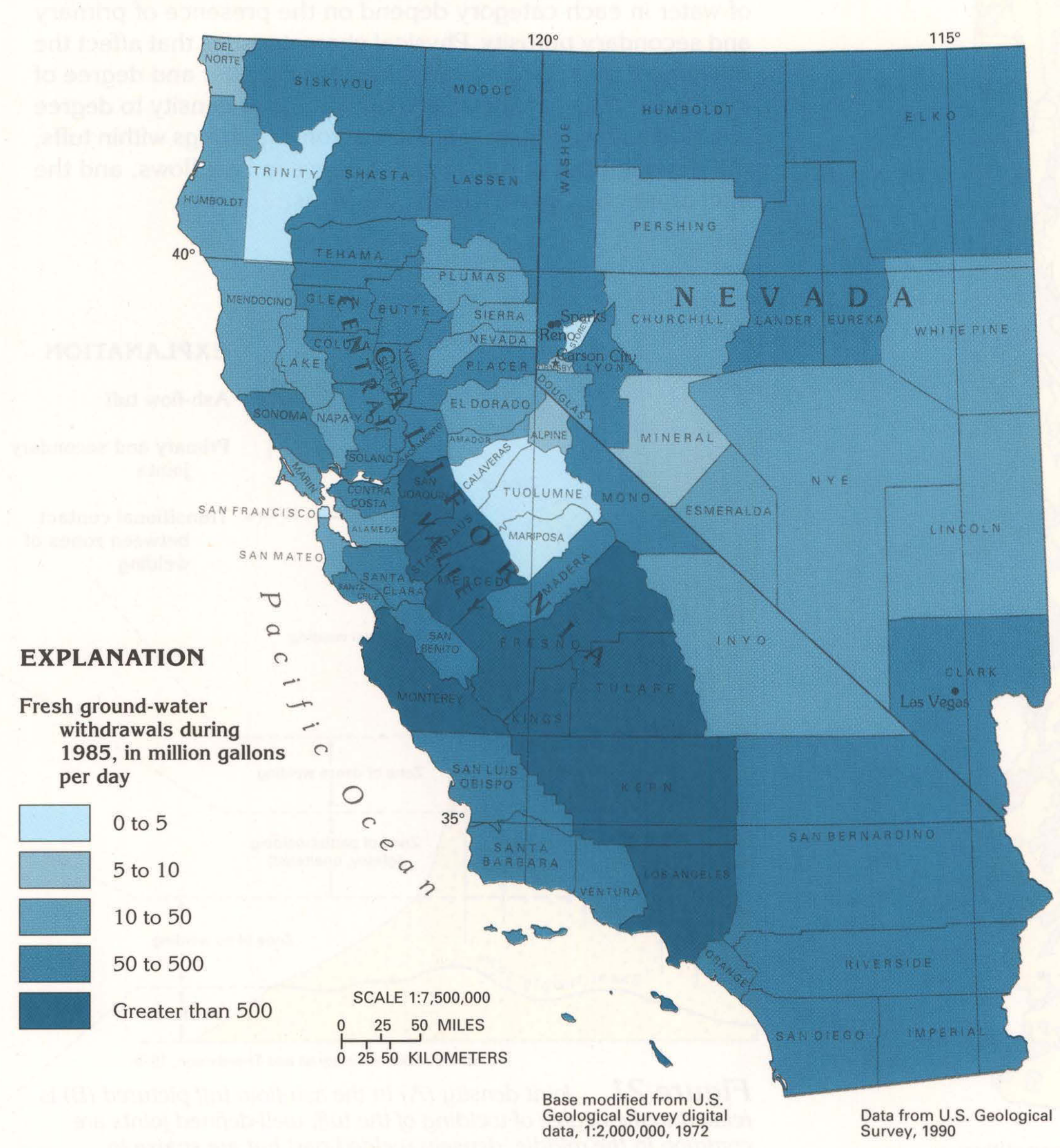


Figure 14. *Central and southern California withdraw far more ground water than most of the rest of the areas in Segment 1.*

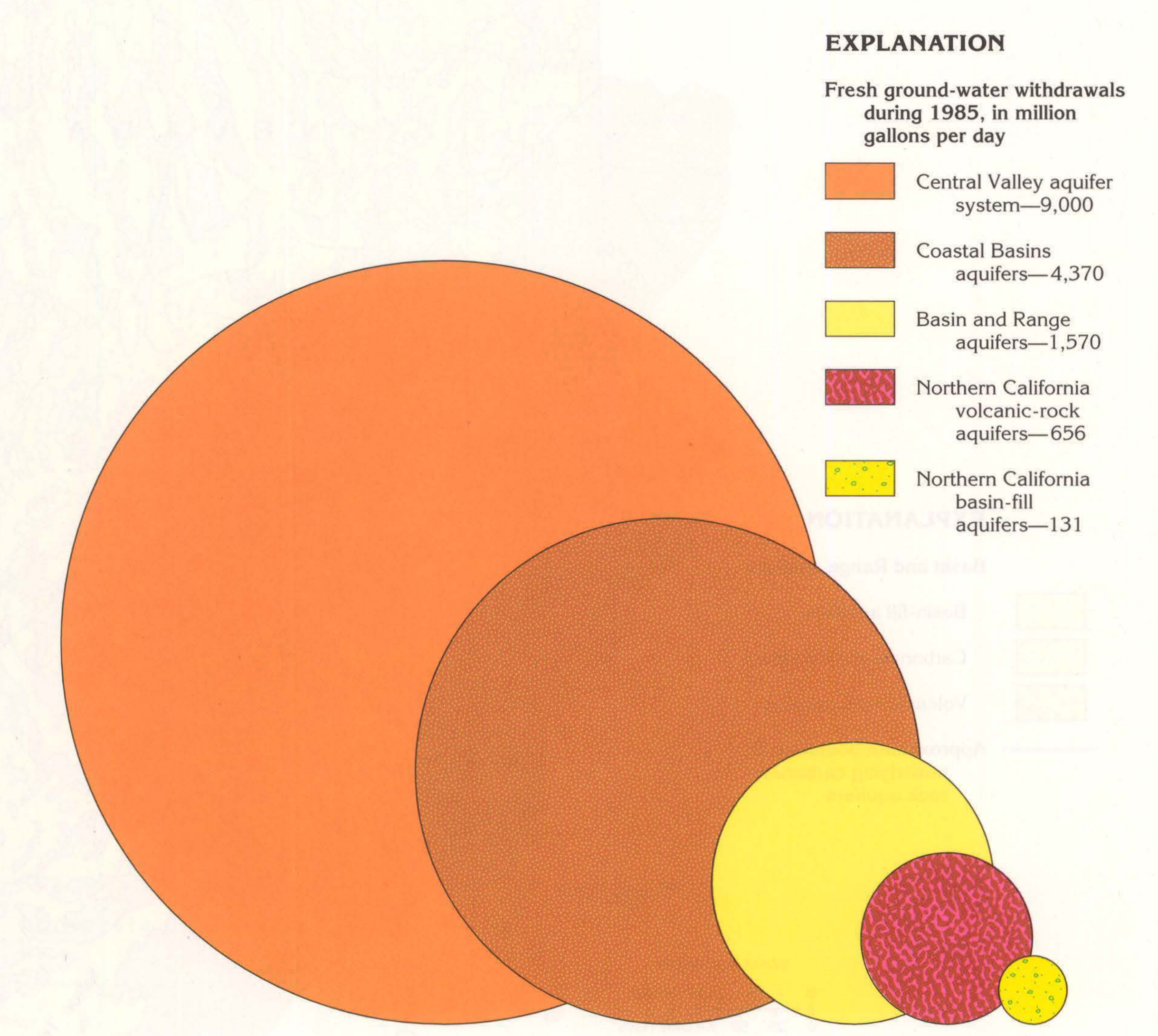


Figure 15. *Water use in the Central Valley aquifer system of California is more than that of the other Segment 1 aquifers combined and far more than that of any other single aquifer system in the United States.*

Basin and Range aquifers

INTRODUCTION

The part of Segment 1 east of the Southern Cascade Mountains, the Sierra Nevada, and the smaller mountain ranges east of the Los Angeles–San Diego area is called the Basin and Range Physiographic Province (**fig. 16**) and contains three principal aquifer types collectively referred to as the "Basin and Range aquifers." These aquifers underlie most of Nevada and parts of eastern and southern California, western Utah, southern Arizona, southwestern New Mexico, and southern Oregon and Idaho; their extent is approximately, but not exactly, the same as that of the physiographic province. The aquifers are formed of volcanic and carbonate rocks and unconsolidated to consolidated basin-fill deposits. The basin-fill deposits form the most productive aquifers and are generally in individual alluvial basins that are drained internally and are separated by low mountains (**fig. 17**). Except for small areas that drain to the Colorado River, no streams that rise within the Basin and Range Province carry water to the oceans. Practically all the precipitation that falls in the area is returned to the atmosphere by evapotranspiration, either directly from the soil or from the lakes and playas that occupy the lowest points within the basins and that are discharge areas for the alluvial aquifers.

The Basin and Range Province is the most arid area in the Nation; the potential annual water loss through evapotranspiration exceeds the annual water gain from precipitation even at the higher elevations (**fig. 18**). Clear skies and low humidity cause extreme daily and seasonal temperature ranges as the sparsely covered land surface is heated quickly by solar radiation and then rapidly cools at nightfall. In more humid climates, the denser vegetative cover uses energy derived from solar radiation to drive the process of evapotranspiration, thus moderating diurnal and seasonal temperature variations.

Each of the large desert basins has an area where the land slopes toward a central depression, and each has a main drainageway that is dry most of the time. Many of the valleys have playas in their lowest depressions (**fig. 19**). The playas are left by the evaporation of intermittent lakes. Parts of some of the valleys have become encrusted to a depth of several inches with alkaline salts, which cover the surface as a powdery crust. However, in some valleys, permanent lakes that have no outlets are fed by surface drainage and contain saline or alkaline water, produced when dissolved minerals are concentrated by evaporation of the lake water.

Figure 17. The basin-fill deposits of the Basin and Range aquifers are in basins that are separated by low mountains.

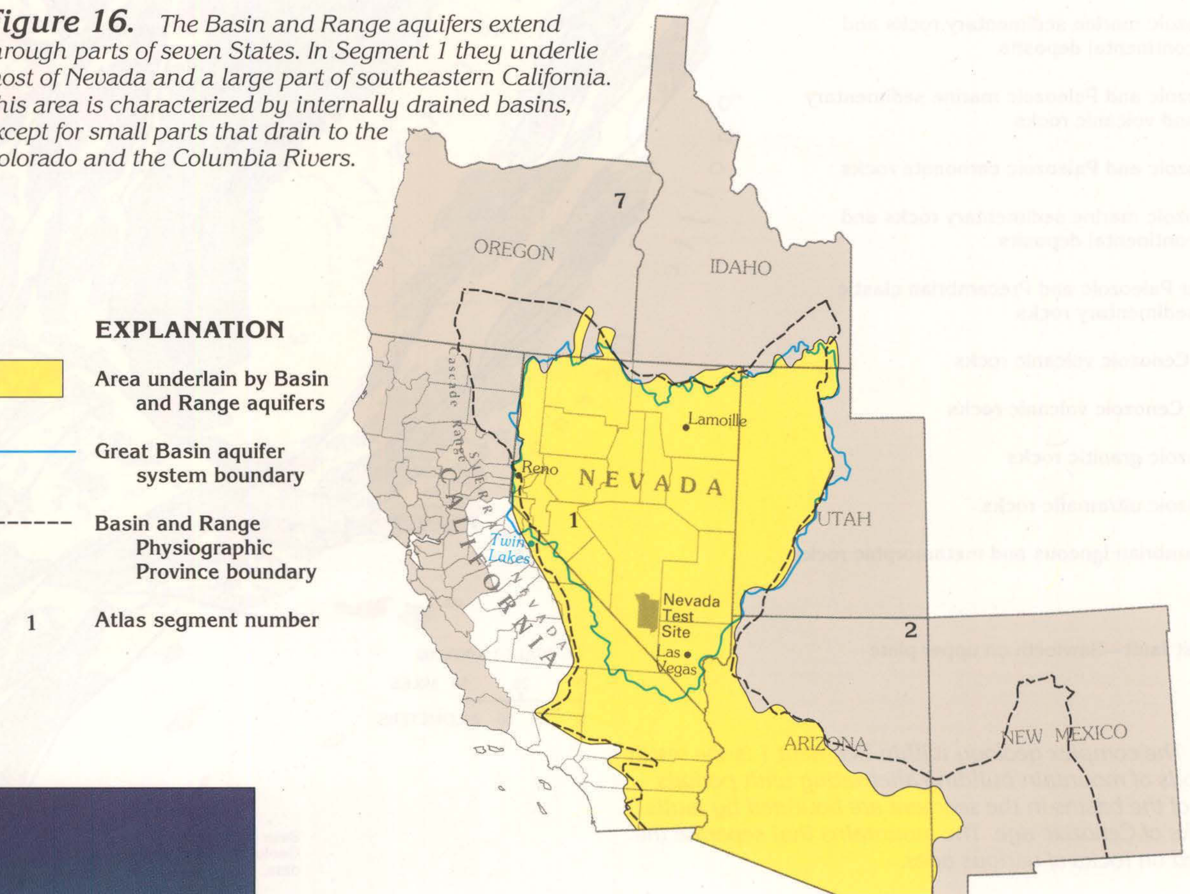


Figure 16. The Basin and Range aquifers extend through parts of seven States. In Segment 1 they underlie most of Nevada and a large part of southeastern California. This area is characterized by internally drained basins, except for small parts that drain to the Colorado and the Columbia Rivers.

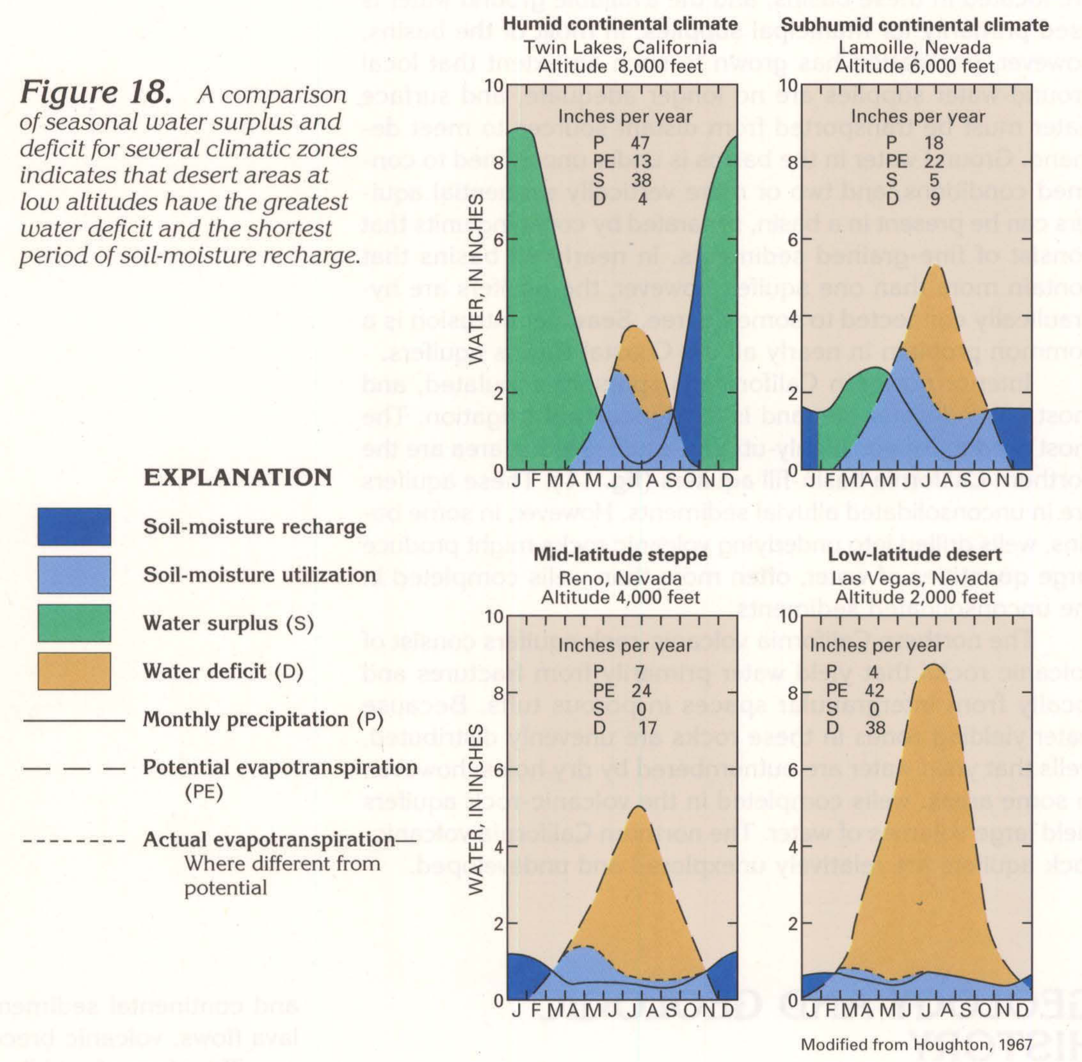


Figure 18. A comparison of seasonal water surplus and deficit for several climatic zones indicates that desert areas at low altitudes have the greatest water deficit and the shortest period of soil-moisture recharge.

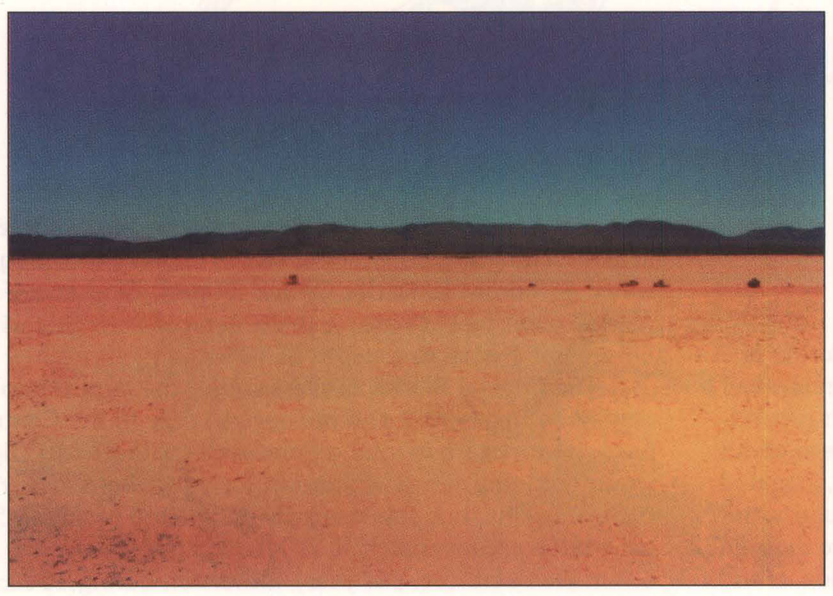


Figure 19. Playas, or dry lake beds, are in the central parts of many alluvial basins. The surface of this playa, northwest of Las Vegas, Nev., is a fine clay.

GEOHYDROLOGIC UNITS

Within the Basin and Range Province, aquifers are not continuous, or regional, because of the complex faulting in the region. Three principal aquifer types collectively called the Basin and Range aquifers in this report are volcanic-rock aquifers, which are primarily tuff, rhyolite, or basalt of Tertiary age; carbonate-rock aquifers, which are primarily limestones and dolomites of Mesozoic and Paleozoic age; and basin-fill aquifers, which are primarily unconsolidated sand and gravel of Quaternary and Tertiary age (**fig. 20**). Any or all three aquifer types may be in, or underlie, a particular basin and constitute three separate sources of water; however, the aquifers may be hydraulically connected to form a single source. Other rock types within the region have low permeability and act as boundaries to the flow of fresh ground water. The aquifers in the Great Basin part of the Basin and Range Province (**fig. 16**) were studied as part of the U.S. Geological Survey's Regional Aquifer-System Analysis (RASA) Program.

Volcanic-Rock Aquifers

The volcanic-rock aquifers (**fig. 20**) can be separated into three categories—welded tuffs, bedded tuffs, and lava flows. The different characteristics for the storage and transmission of water in each category depend on the presence of primary and secondary porosity. Physical characteristics that affect the movement of ground water include the number and degree of interconnection of joints, the relation of joint density to degree of welding and compaction, the horizontal partings within tuffs, the development of rubble zones between lava flows, and the interconnection of vesicles in the lavas.

Ash-flow tuffs are consolidated deposits of volcanic ash, which were emplaced by flowage of a turbulent mixture of gas and pyroclastic materials. Ash-flow deposits consist principally of glass shards and pumice fragments that are usually less than 0.15 inch in length, although some flows consist of ejecta of larger size. Typically, the deposits are nonsorted and do not exhibit bedding, in contrast with the generally pronounced bedding of ash-fall tuff deposits. In general, ash flows are tens of feet thick, but some are only a few feet thick, whereas others are hundreds of feet thick. After emplacement of an ash flow, compaction or welding of the ash can result in an average 50-percent reduction in the porosity of the original flow.

Welding within a single ash flow is variable, and each ash flow can be categorized by three distinct orders of welding—none, partial, or dense. Commonly, a zone of dense welding is underlain and overlain by zones of partial welding, which are, in turn, underlain and overlain by zones of no welding (**fig. 21**). However, in some thin, exceptionally hot flows, the entire unit of tuff can be densely welded. The degree of welding directly affects the interstitial porosity of the ash-flow tuff. In the nonwelded base or top of a fresh ash flow, the interstitial porosity can be greater than 50 percent; in the densely welded part, it can be less than 5 percent.

Columnar jointing characterizes the zones of dense and partial welding; these joints form in response to tensional forces that develop as the flow cools. Columnar-joint spacings range from a few tenths of an inch to many feet; the more closely spaced joints are usually in the zone of most intense welding. The joints are usually vertical, but departures from the vertical are common. Cooling joints are not common in the nonwelded parts of the ash flow (**fig. 21**).

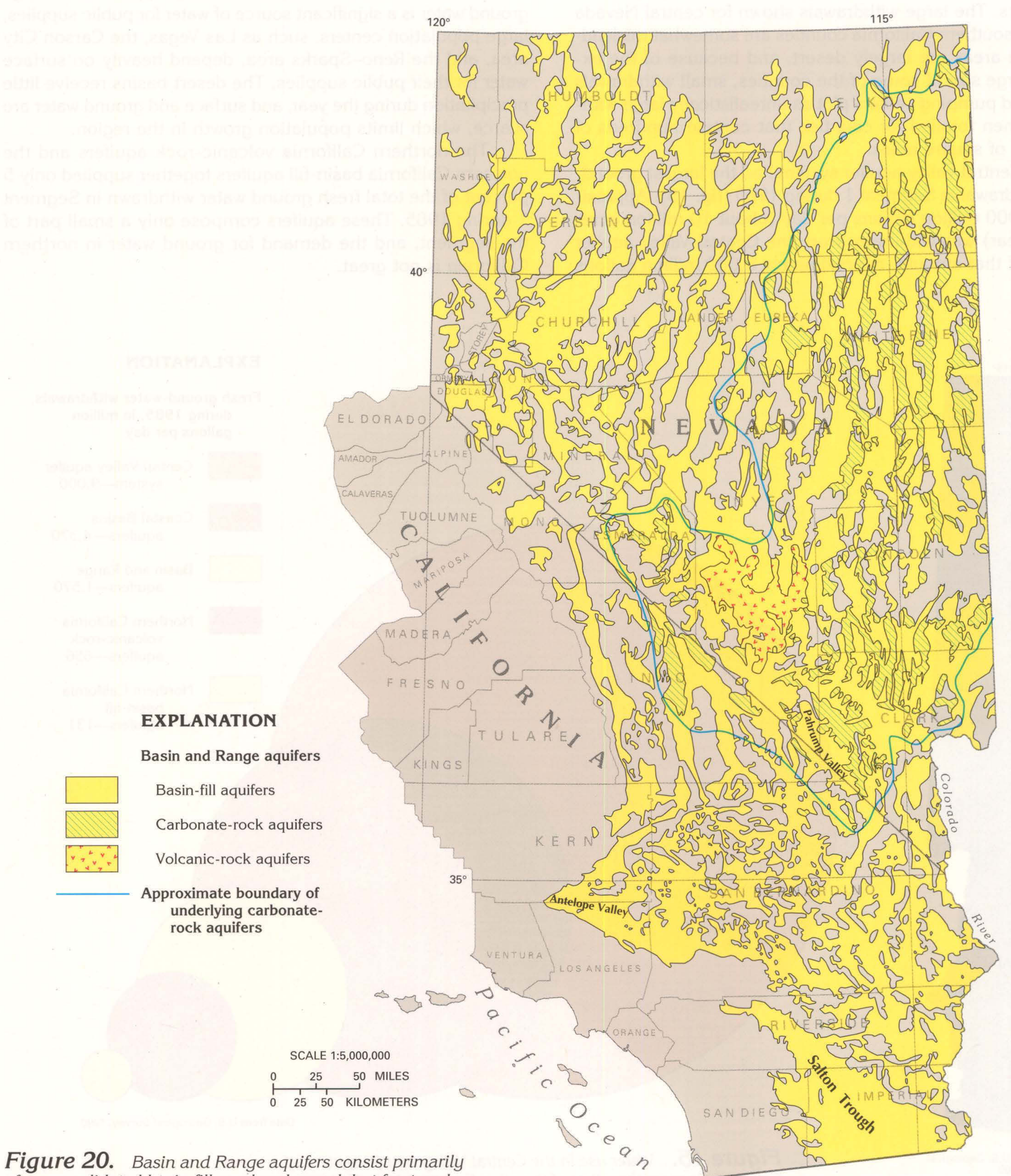


Figure 20. Basin and Range aquifers consist primarily of unconsolidated basin-fill sand and gravel, but fractured carbonate and volcanic rocks also underlie some basins and from important aquifers.

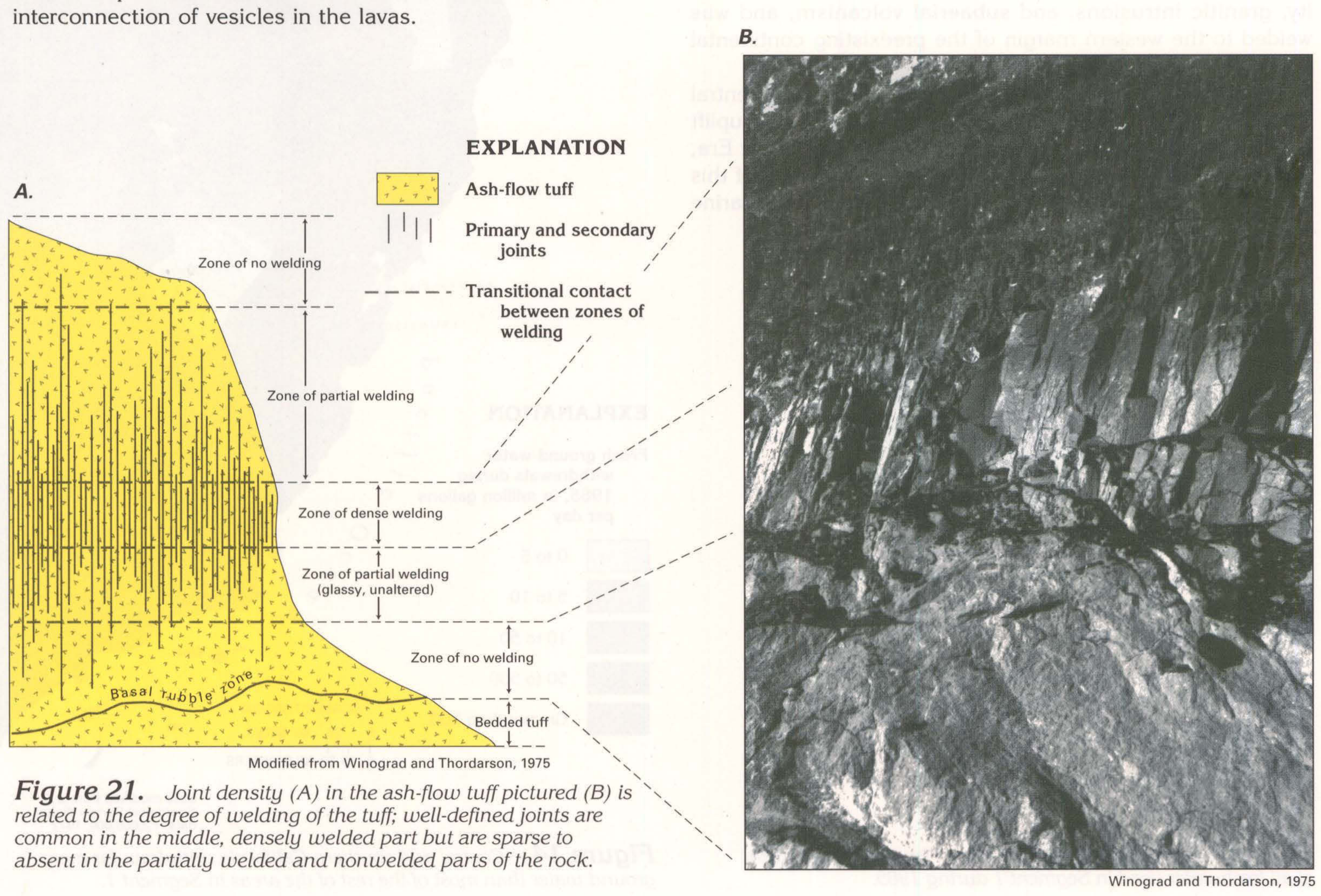


Figure 21. Joint density (A) in the ash-flow tuff pictured (B) is related to the degree of welding of the tuff; well-defined joints are common in the middle, densely welded part but are sparse to absent in the partially welded and nonwelded parts of the rock.

Volcanic-Rock Aquifers—Continued

The joints in outcrop in the ash-flow tuffs are polygonal joints that formed as the flow cooled and other joints that formed after cooling as a result of compaction of underlying, porous, bedded tuff or from regional tectonic stresses. Both types of joints are restricted mostly to the dense, brittle, welded tuff and die out or markedly decrease within the underlying and overlying partially welded zone (**fig. 21**). The polygonal structure is generally obscured by the joints that formed after cooling, except in the youngest welded tuffs. Horizontal partings are locally a few tenths of an inch wide and tens of feet long. Because the partings parallel the foliation within the welded zone or the contact between flows, they may represent breakage along a plane of primary weakness after the removal of overburden; therefore, the partings are not likely to be open at depth and are limited in extent.

The bedded-tuff aquifers are ash-fall tuffs that consist of poorly to well sorted, friable particles the size of fine sand to granules. Locally, the ash-fall tuffs either have been reworked by running water or were originally deposited in standing water. The friable nature of these rocks prevents the formation of open joints or faults within them; as an example, open fractures were not seen in hundreds of feet of tunnels dug through these rocks beneath Rainier Mesa on the Nevada Test Site near Las Vegas. Where glass shards are altered to clay minerals, the permeability of the ash-fall tuffs is reduced by several orders of magnitude.

The lava-flow aquifers consist of basalt or rhyolite and have not been studied in detail. No laboratory determinations for porosity and permeability have been done on these aquifers because the movement of ground water through them is controlled mostly by porosity developed along cooling joints and in rubble zones between individual lava flows. Basalt flows might be a texturally heterogeneous mass that laterally and vertically ranges from congealed, dense, impermeable lava to highly porous zones that consist of loosely consolidated cinders. The texture depends, for the most part, on the amount of gas present in the lava when the flow erupted. Permeable zones, which consist of masses of basalt rubble, are at the tops of some dense lava-flow surfaces and are overlain by subsequent flows or by sediments. The dense lava flows, which have minimal primary permeability, might be fractured by regional stresses, resulting in high secondary permeability. When fracture systems interconnect with highly permeable rubble and cinder zones, the rock mass tends to be highly transmissive.

Carbonate-Rock Aquifers

Thick sequences of Mesozoic and Paleozoic carbonate rocks underlie many of the alluvial basins in southeastern California and eastern Nevada within the Basin and Range Province; these rocks also extend into western Utah and southeastern Idaho. Results of deep drilling indicate that intervals of cavernous carbonate rock are as deep as 5,000 feet and might locally extend to depths of 15,000 feet. In some test wells, circulation of drilling fluid has been extremely difficult to maintain and, in a few, the downhole drilling equipment has suddenly dropped. Both conditions indicate that the carbonate rock is cavernous.

Quartzite, shale, siltstone, sandstone, and some limestone and dolomite of Early Cambrian and late Precambrian age underlie the carbonate rocks in the eastern part of the Basin and Range Province. However, these rocks have minimal primary and secondary permeability, and probably form the lower boundary of the carbonate-rock aquifers.

The carbonate-rock aquifers can be divided into two parts—an upper rock sequence of Late Triassic to Early Mississippian age that consists primarily of limestone with minor amounts of dolomite, interbedded with shale and sandstone, and a lower sequence of limestone and dolomite of Middle Devonian to Middle Cambrian age that contains little clastic material. The total thickness of carbonate rocks may be greater than 15,000 feet, but, as a result of the combination of deep erosion and structural deformation, this thickness is rare in any one location. The saturated thickness of the carbonate strata ranges from a few hundred to more than 10,000 feet and depends on the combined influence of geologic structure, erosion, and depth to water. In general, because of the great aggregate thickness and stratigraphic position of the rocks that compose the carbonate-rock aquifers, several thousand feet of an individual aquifer is within the zone of saturation throughout most of the areal extent of the aquifers. Such an aquifer is completely unsaturated only in the vicinity of its outcrop area and is totally absent only atop buried structural highs.

The carbonate rocks are highly fractured and are locally brecciated (**fig. 22**). Individual outcrops of the aquifers can exhibit three or more sets of joints, one or more high-angle faults, and one or more brecciated zones. For example, in the Nevada Test Site area near Las Vegas, Nev., the joints and most of the faults in the carbonate rocks are steeply inclined fractures. Brecciation commonly occurs along faults showing only a few feet of displacement and does not necessarily reflect movement of large magnitude. Joint density bears a strong relation to rock type; fine-grained carbonate rocks have the greatest joint density. Generally, the joints divide the rock into blocks that range from 1 inch to a few inches on a side. Medium-grained carbonate rocks are divided into blocks that range from a few inches to 1 foot on a side, whereas blocks of coarse-grained carbonate rocks commonly range from 6 inches to 2 feet on a side.

In outcrop, secondary openings are locally along bedding planes in the carbonate rocks, but no widespread connection of such openings is known. Some of the bedding-plane openings might have formed entirely by subaerial mechanical and chemical weathering, but some might have formed by partial dissolution of the rock. Dissolution, presumably in the subsurface, has created small, smooth, tabular openings along otherwise tightly closed bedding and joint planes (**fig. 22**).

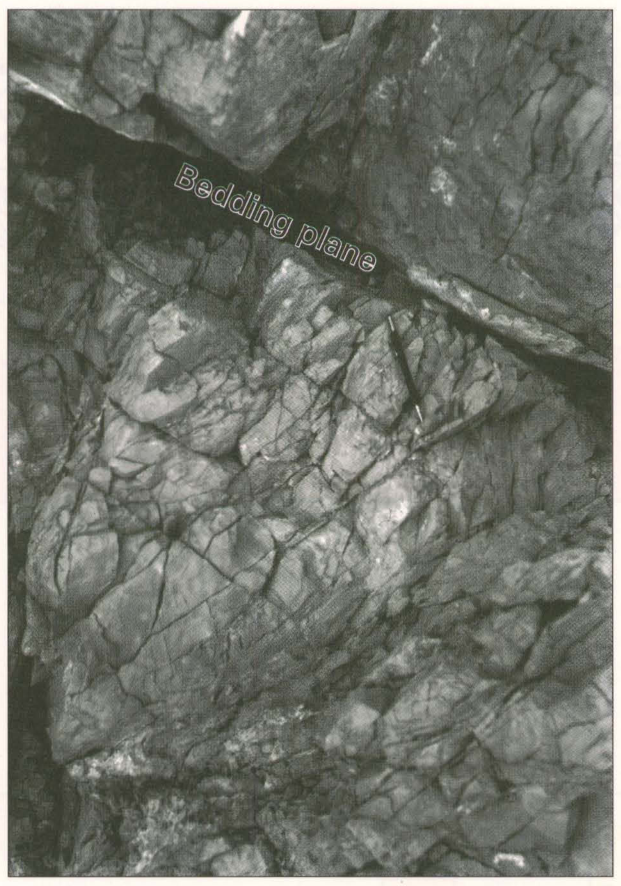


Figure 22. *Intensely fractured dolomite illustrates the potential for the production of large volumes of water from the carbonate-rock aquifers. Dissolution along bedding planes has greatly increased this potential.*

Basin-Fill Aquifers

Before the most recent period of tectonic activity, which began in middle Miocene time (about 17 million years before present), the Basin and Range region was characterized by moderate relief, and streams in the region did not have enough power to transport large volumes of sediments. As the mountains were uplifted, however, stream gradients increased and the transporting power of the streams greatly increased. Steep, narrow canyons and gulches were incised into the sharp escarpments that bounded the mountain ranges and enormous volumes of material were eroded from the mountains. In some places, blocks of sandstone greater than 10 feet in diameter were transported several miles from their outcrop areas onto flat areas beyond the mouths of canyons. The sediments eroded, transported, and deposited by the streams are the principal material of basin-fill aquifers (**fig. 23**). Some of the older basin-fill deposits (Miocene and Pliocene age) are consolidated; however, the basin fill consists mostly of unconsolidated deposits of Pliocene through Holocene age.

The most permeable basin-fill deposits are present in the depressions created by late Tertiary to Quaternary block faulting and can be classified by origin as alluvial-fan, lake-bed, or fluvial deposits. At the time of major deposition, the climate was more humid than the modern climate. Lakes were in most of the closed basins and some basins were connected by streams. In general, the coarsest materials (gravel and boulders) were deposited near the mountains, and the finer materials (sand and clay) were deposited in the central parts of the basins or in the lakes. Occasionally, torrential storms produced heavy runoff that carried coarse material farther from the mountains and resulted in the interfingering of fine and coarse material. The distribution of sediment size is directly associated with distance from the mountains. Three geomorphic landforms can be distinguished on the basis of the gradient of the land surface. Alluvial fans border the mountains and have the steepest surface slopes and the coarsest sediments (**fig. 24**). Basinward, individual alluvial fans flatten, coalesce, and form alluvial slopes of moderate gradient. A playa, or dry lake bed with a flat surface, is present in the lowest part of the basin, usually at or near the center of the basin (**fig. 19**), and most of the sediment deposited on the playa is fine grained.

The most important hydrologic features of the basins are the alluvial fans. The basin fill receives most of its recharge through the coarse sediments deposited in the fans. These highly permeable deposits allow rapid infiltration of water as streams exit the valleys that are cut into the almost impermeable rock of the surrounding mountains and flow out onto the surface of the fans. The coarse and fine sediments within the alluvial fans are complexly interbedded and interfingering (**fig. 24**) because the position of the distributary streams that transported the sediments continually shifted across the top of the fan.

Material deposited in perennial lakes or in playas consists principally of clay and silt with minor amounts of sand and is present in all of the basins. In most places, these sediments include some salts deposited by evaporation. The clay and salt deposits merge laterally into coarse-grained deposits of the alluvial slopes. Minor well-sorted beach sand and gravel locally are in the subsurface near the shores of once perennial lakes.

Fluvial deposits of Holocene age in the basins consist primarily of alluvial sand and gravel and are present along the courses of modern or ancestral streams that generally parallel the long axes of the basins. Quaternary fluvial deposits in stream channels usually exhibit a greater degree of sorting than the alluvial-fan deposits.

Figure 23. *Alluvial fans border the mountains at the outlets of stream channels and contain mostly coarse-grained sediments.*

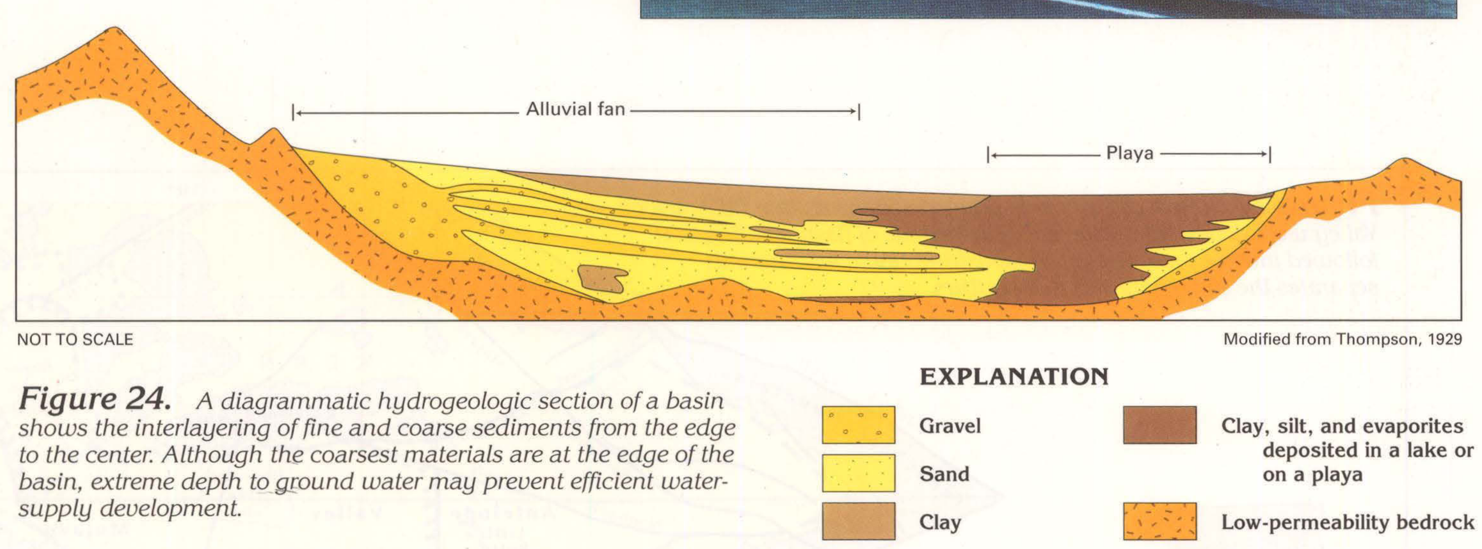


Figure 24. *A diagrammatic hydrogeologic section of a basin shows the interlayering of fine and coarse sediments from the edge to the center. Although the coarsest materials are at the edge of the basin, extreme depth to ground water may prevent efficient water-supply development.*

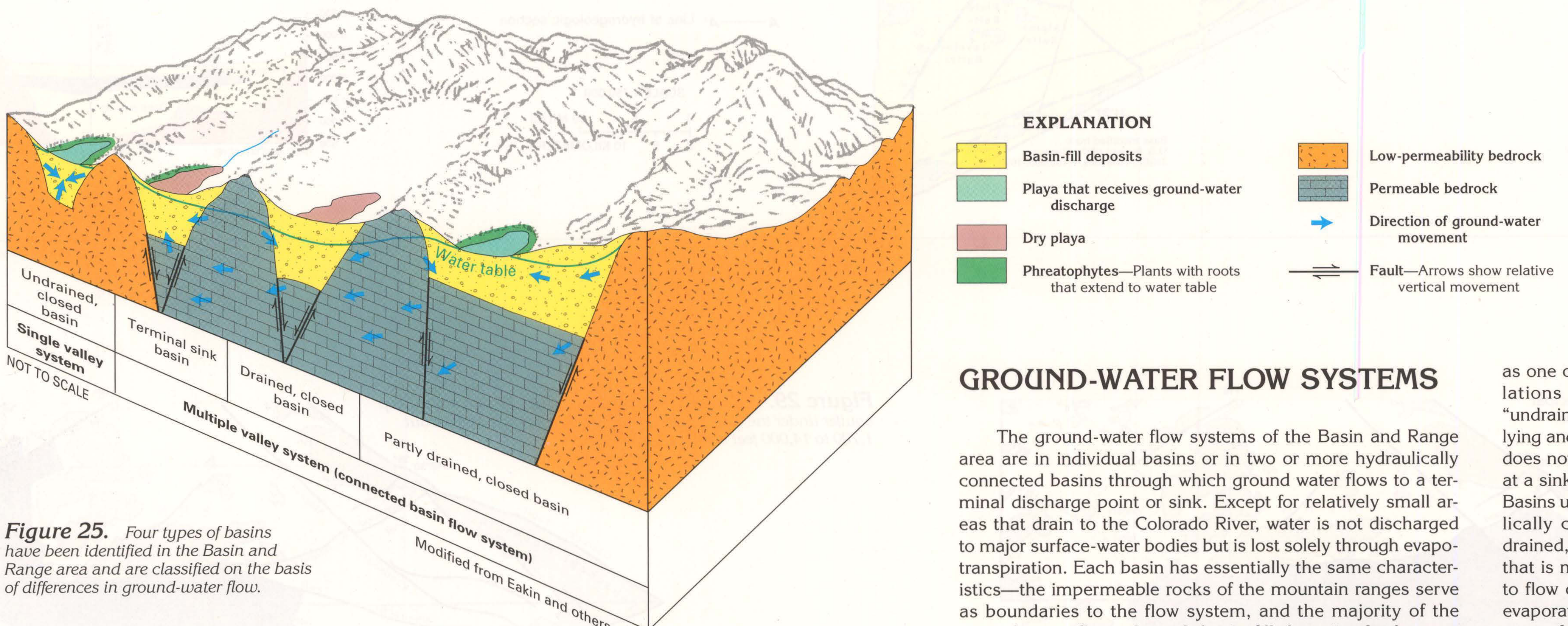


Figure 25. *Four types of basins have been identified in the Basin and Range area and are classified on the basis of differences in ground-water flow.*

Table 1. *Basin types in the Basin and Range are distinguished by their recharge-discharge relations*

[Modified from Eakin and others, 1976]

Basin type	Description
Single, undrained closed basin	Basin has no surface flow across boundary; all ground-water discharge is ultimately by evapotranspiration. Typified by valleys with wet playas and phreatophyte stands in shallow ground-water areas. Ground-water gradient is toward center, or low part, of valley.
Terminal sink basin	Basin has surface and (or) subsurface inflow across boundaries. All ground-water discharge ultimately is by evapotranspiration. Most sinks have playas that are large in proportion to the size of the area. Valley can contain a large volume of saline ground water.
Drained, closed basin	Basin has no surface flow across boundary. Almost all ground-water discharge is by subsurface outflow; the deep water table prevents evapotranspiration.
Partly drained, closed basin	Basin has no surface inflow or outflow. Valley has moist playa and stand of phreatophytes. Area of ground-water discharge can be small in comparison to undrained basins of similar size. Ground-water gradients may indicate subsurface outflow, if wells are strategically located.
Connected basin flow system	Basin system has surface and (or) subsurface outflow and (or) inflow that links several individual basins. Ground water discharges to playas and (or) springs or streams. Surface inflow and outflow is by ephemeral and perennial streams.

GROUND-WATER FLOW SYSTEMS

The ground-water flow systems of the Basin and Range area are in individual basins or in two or more hydraulically connected basins through which ground water flows to a terminal discharge point or sink. Except for relatively small areas that drain to the Colorado River, water is not discharged to major surface-water bodies but is lost solely through evapotranspiration. Each basin has essentially the same characteristics—the impermeable rocks of the mountain ranges serve as boundaries to the flow system, and the majority of the ground water flows through basin-fill deposits. In the area where carbonate rocks underlie the basins, substantial quantities of water can flow between basins through the carbonate rocks and into the basin-fill deposits, but this water also is ultimately discharged by evapotranspiration. Most recharge to the basin-fill deposits originates in the mountains as snowmelt, and, where the mountain streams emerge from bedrock channels, the water infiltrates into the alluvial fans and replenishes the basin-fill aquifer. Intense thunderstorms may provide some direct recharge to the basin-fill deposits, but, in most cases, any rainfall that infiltrates the soil is either immediately evaporated or taken up as soil moisture; little water percolates downward through the unsaturated zone to reach the water table in the valleys. In mountain areas underlain by permeable carbonate rocks, most of the recharge may enter the carbonate rocks and little water remains to supply runoff.

Because regional aquifers are not continuous within the Basin and Range area, the individual basins, which are encircled by topographic drainage divides, have been classified as one of four types based on similar recharge-discharge relations (**fig. 25 and table 1**). The simplest type is the "undrained, closed basin," a single valley in which the underlying and surrounding bedrock is practically impermeable and does not allow interbasin flow, and all recharge is discharged at a sink represented by a playa near the center of the basin. Basins underlain by permeable bedrock commonly are hydraulically connected as multiple valley systems. The "partly drained, closed basin" is underlain or surrounded by bedrock that is moderately permeable and allows some ground water to flow out of the basin. In this type of basin, some water is evaporated or transpired at the upgradient side of a playa, but most of the water continues to flow past the downgradient side of the playa and leaves the basin. The "drained, closed basin" has a deep water table that prevents evapotranspiration. The bedrock is sufficiently permeable to allow all recharge to flow through it and out of the basin. The "terminal sink basin" is underlain or surrounded by bedrock that is sufficiently permeable to conduct flow into the basin, and the playa in the basin is the discharge point for recharge from several connected basins.

In some places, an existing or ancestral stream course connects several basins that are not closed. The individual basins connected by such streams can also be classified as partly drained, drained, or terminal sink.

Examples of the individual type basins follow, except for the drained closed basin. With the exception that the water table in the drained closed basin is far below the playa, the partly drained and drained closed basins are sufficiently similar that discussion of each type is not warranted.

GROUND-WATER FLOW SYSTEMS—Continued

Single, Undrained, Closed Basin

Antelope Valley, Calif., which is an example of a single, undrained, closed basin, is a large topographic and ground-water basin in the western part of the Mojave Desert in southern California. Antelope Valley occupies part of a structural depression that has been downfaulted between the Garlock and the Cottonwood–Rosamond Faults and the San Andreas Fault Zone (**fig. 26**). Consolidated rocks that yield virtually no water underlie the basin and crop out in the highlands that surround the basin. They consist of igneous and metamorphic rocks of pre-Tertiary age that are overlain by indurated continental rocks of Tertiary age interbedded with lava flows.

Alluvium and interbedded lacustrine deposits of Quaternary age are the important aquifers within the closed basin and have accumulated to a thickness of as much as 1,600 feet (**fig. 27**). The alluvium is unconsolidated to moderately consolidated, poorly sorted gravel, sand, silt, and clay. Older units of the alluvium are more compact and consolidated, somewhat coarser grained, more weathered, and more poorly sorted than the younger units. The rate at which water moves through the alluvium (the hydraulic conductivity of the alluvium) decreases with increasing depth.

During the depositional history of Antelope Valley, a large intermittent lake occupied the central part of the basin and was the site of accumulation of fine-grained material. The rates of deposition varied with the rates of precipitation. During periods of relatively heavy precipitation, massive beds of blue clay formed in a deep perennial lake. During periods of light precipitation, thin beds of clay and evaporative salt deposits formed in playas or in shallow intermittent lakes. Individual beds of the massive blue clay can be as much as 100 feet thick and are interbedded with lenses of coarser material as much as 20 feet thick. The clay yields virtually no water to wells, but the interbedded coarser material can yield considerable volumes of water.

During deposition of the lacustrine deposits, alluvial material that was supplied from the San Gabriel Mountains encroached upon the lake and forced it northward, which resulted in a northward transgression of alluvium over lacustrine deposits. The subsurface extent of the buried lacustrine deposits is shown in **figure 27**. The lacustrine deposits underlie the central part of the basin and have a somewhat lenticular shape. The thickest section is near the center of the basin, and the deposits thin towards the edges of the basin. Near Little Buttes and near the east and north edges of Rogers Lake, the deposits pinch out (**fig. 27, section *B–B'***). Along the northern and southern boundaries of the basin, the lacustrine deposits are about 100 and 400 feet thick, respectively, where they abut buried escarpments of consolidated rocks (**fig. 27, section *A–A'***). Near the southern limit of the basin, southeast of Lancaster, the lacustrine deposits are buried beneath about 800 feet of alluvium, but near Rosamond Lake, they are exposed at the surface (**fig. 27, section *A–A'***).

Two aquifers, which are separated by the lacustrine deposits, are in the alluvial material (**fig. 27**). The upper aquifer is the principal and most used aquifer and contains water under unconfined, or water table, conditions. Where the lower, or deep, aquifer underlies lacustrine deposits, it contains water under confined, or artesian, conditions; elsewhere, unconfined conditions prevail.

Transmissivity values for the principal aquifer (**fig. 28**) are estimated to range from less than 1,000 to more than 10,000 feet squared per day. The transmissivity of an aquifer is a measure of how rapidly water will pass through the aquifer; the greater the transmissivity, the faster the movement of the water and the more water the aquifer will yield to wells. Where the principal aquifer is thin, either near its boundaries or on the uplifted parts of fault blocks, its transmissivity is low; where the aquifer is thick or consists of coarse-grained deposits, or both, the transmissivity is high.

The estimated transmissivity of the deep aquifer (**fig. 29**) ranges from about 2,000 to 10,000 feet squared per day and is greatest where the aquifer is thick. The transmissivity of the deep aquifer varies less than that of the principal aquifer (compare **figs. 28 and 29**) probably because the thickness of the deep aquifer is more uniform than that of the principal aquifer.

Ground water in the Antelope Valley Basin moves from the base of the San Gabriel and the Tehachapi Mountains toward Rosamond Lake in the north-central part of the basin (**fig. 30**). As ground water moves eastward across the western limit of the lacustrine deposits, part of the water moves above the lacustrine deposits to recharge the principal aquifer and part moves below the lacustrine deposits to recharge the deep aquifer. Major faults that cut the alluvial deposits in Antelope Valley, especially the Randsburg–Mojave Fault (**fig. 30**), act as partial barriers to the movement of ground water. Water-level differences of more than 300 feet in the same aquifer are present across the Randsburg–Mojave Fault. Along several other faults, the water table is several tens of feet higher on the upgradient side of the fault than on the downgradient side.

An estimate of the shape of the predevelopment potentiometric surface of the principal aquifer in 1915 (**fig. 30**) shows that before extensive pumping began, the water table was near the land surface in the central part of the basin; ground water moved northward and northeastward, and discharged by evapotranspiration at Rosamond Lake, which was dry. Withdrawal of ground water from the principal aquifer and the subsequent lowering of the water table reduced this natural discharge. By 1961, the direction of ground-water movement in the principal aquifer had been reversed from northeastward to southward and southeastward, toward the center of the basin in the area immediately southeast of Rosamond Lake (**fig. 31**). The main change in the potentiometric surface was the development of areas of low water levels near the withdrawal centers and the resultant reversal in the direction of ground-water flow near these areas.

Ground water leaks through the lacustrine deposits between the principal and deep aquifers even though the lacustrine deposits do not readily yield water to wells. Based on the hydraulic heads for the two aquifers, water leaks downward along the western and southern periphery of the lacustrine deposits. In the north-central part of the area underlain by the lacustrine deposits, water leaks upward. Because of the large withdrawals from the principal aquifer, the area of upward leakage has expanded toward the areas of concentrated withdrawal (**fig. 31**).

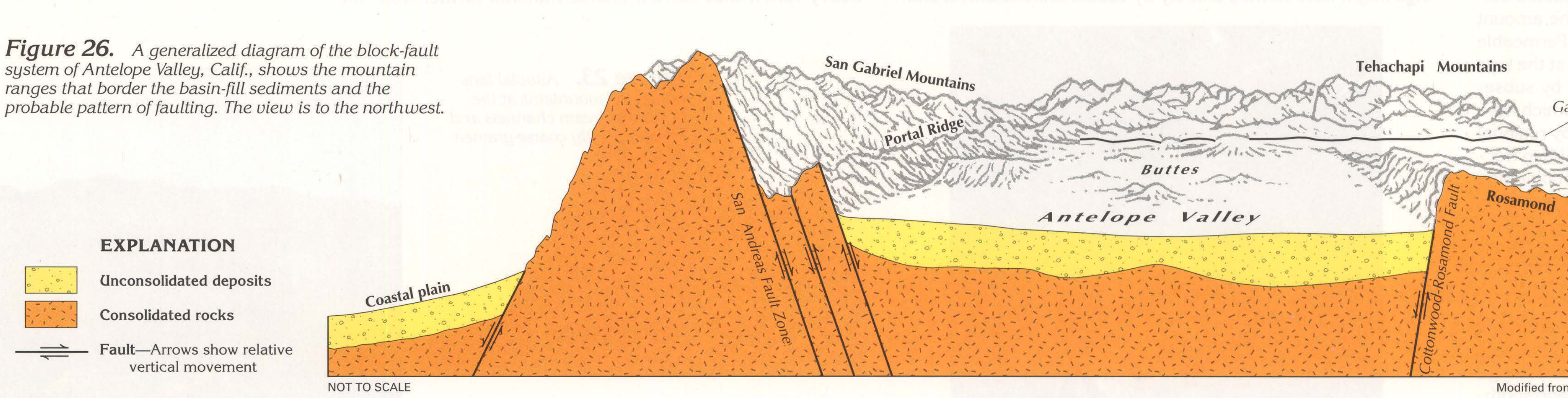


Figure 26. A generalized diagram of the block-fault system of Antelope Valley, Calif., shows the mountain ranges that border the basin-fill sediments and the probable pattern of faulting. The view is to the northwest.

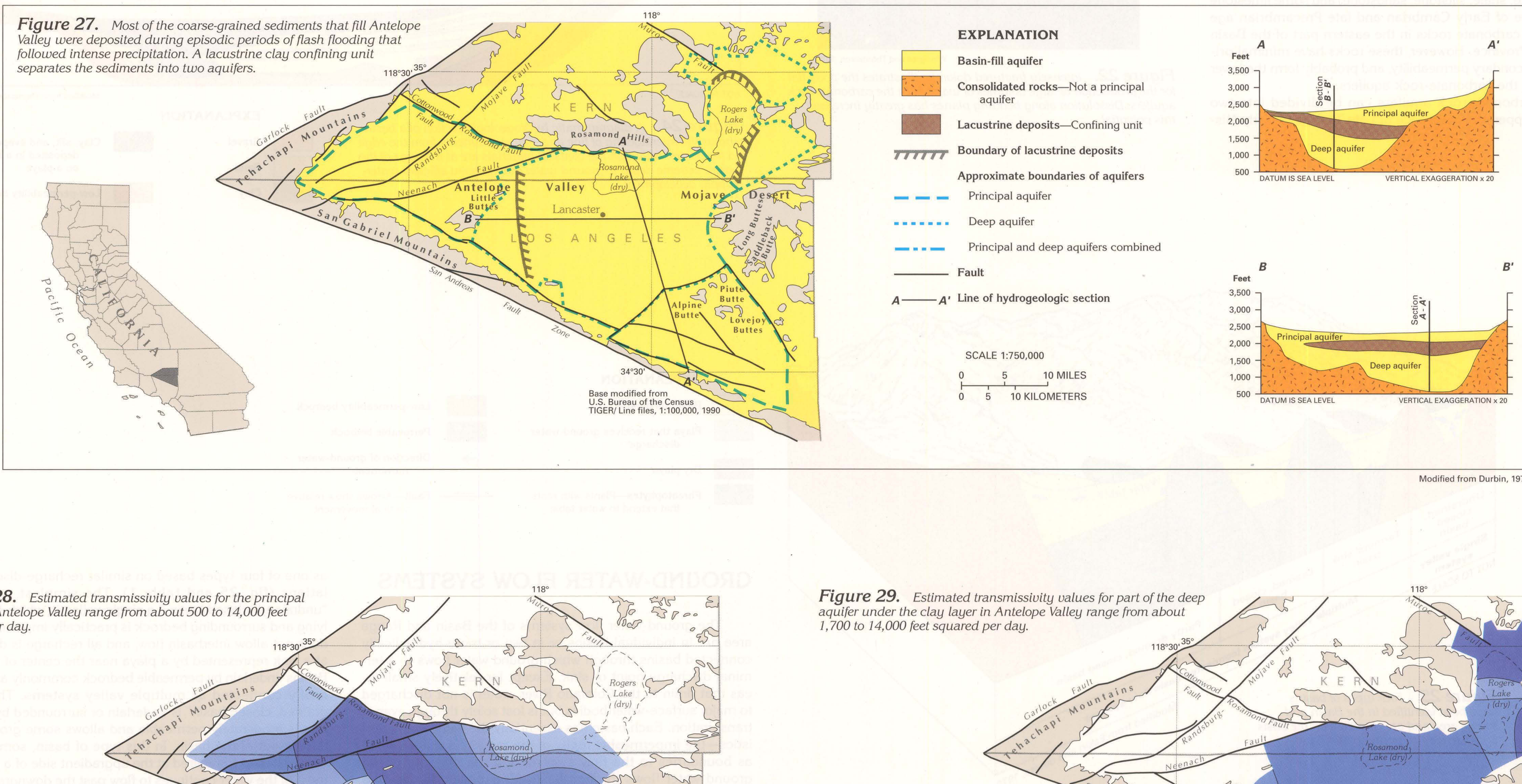


Figure 27. Most of the coarse-grained sediments that fill Antelope Valley were deposited during episodic periods of flash flooding that followed intense precipitation. A lacustrine clay confining unit separates the sediments into two aquifers.

Figure 28. Estimated transmissivity values for the principal aquifer in Antelope Valley range from about 500 to 14,000 feet squared per day.

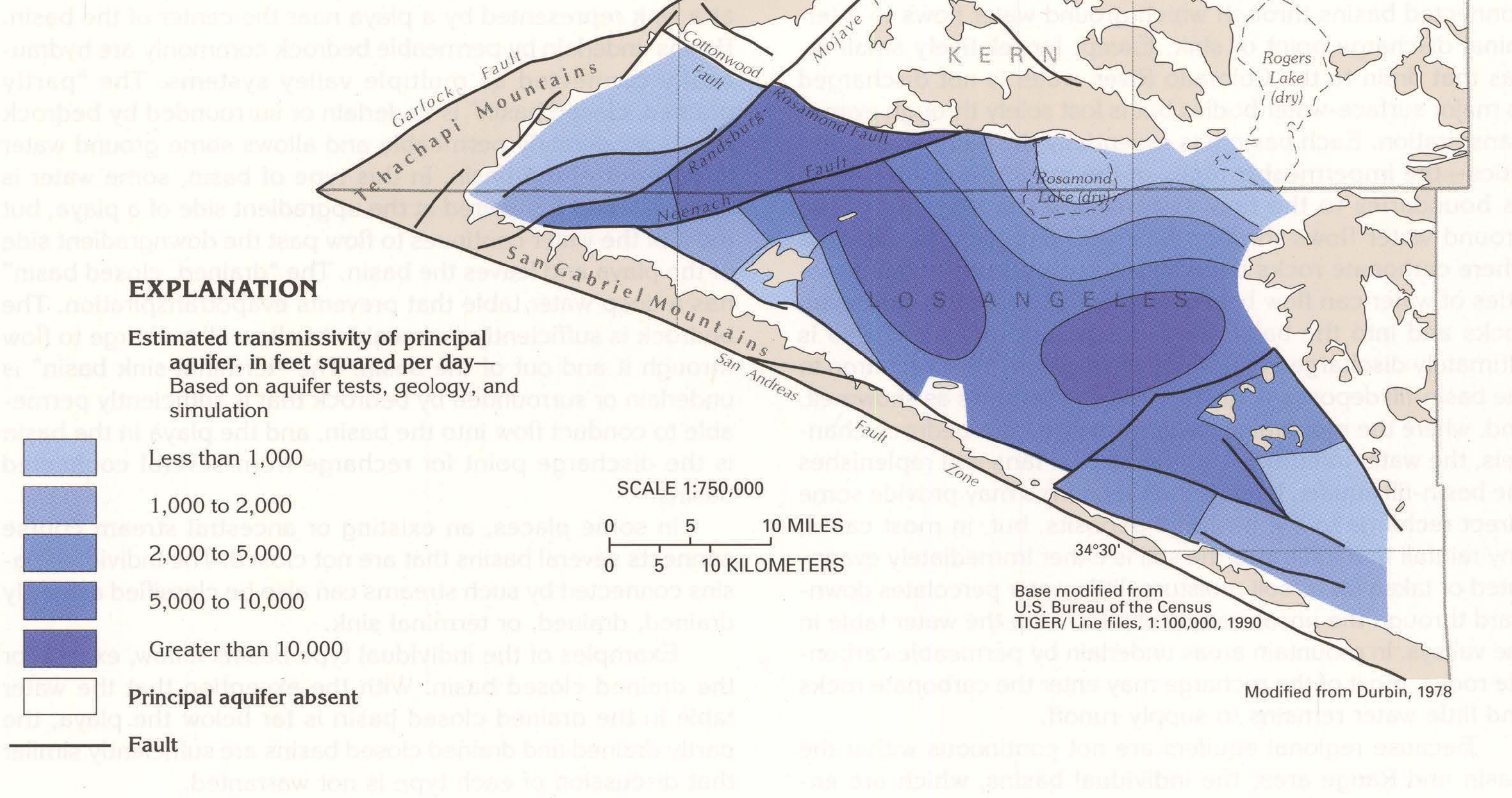
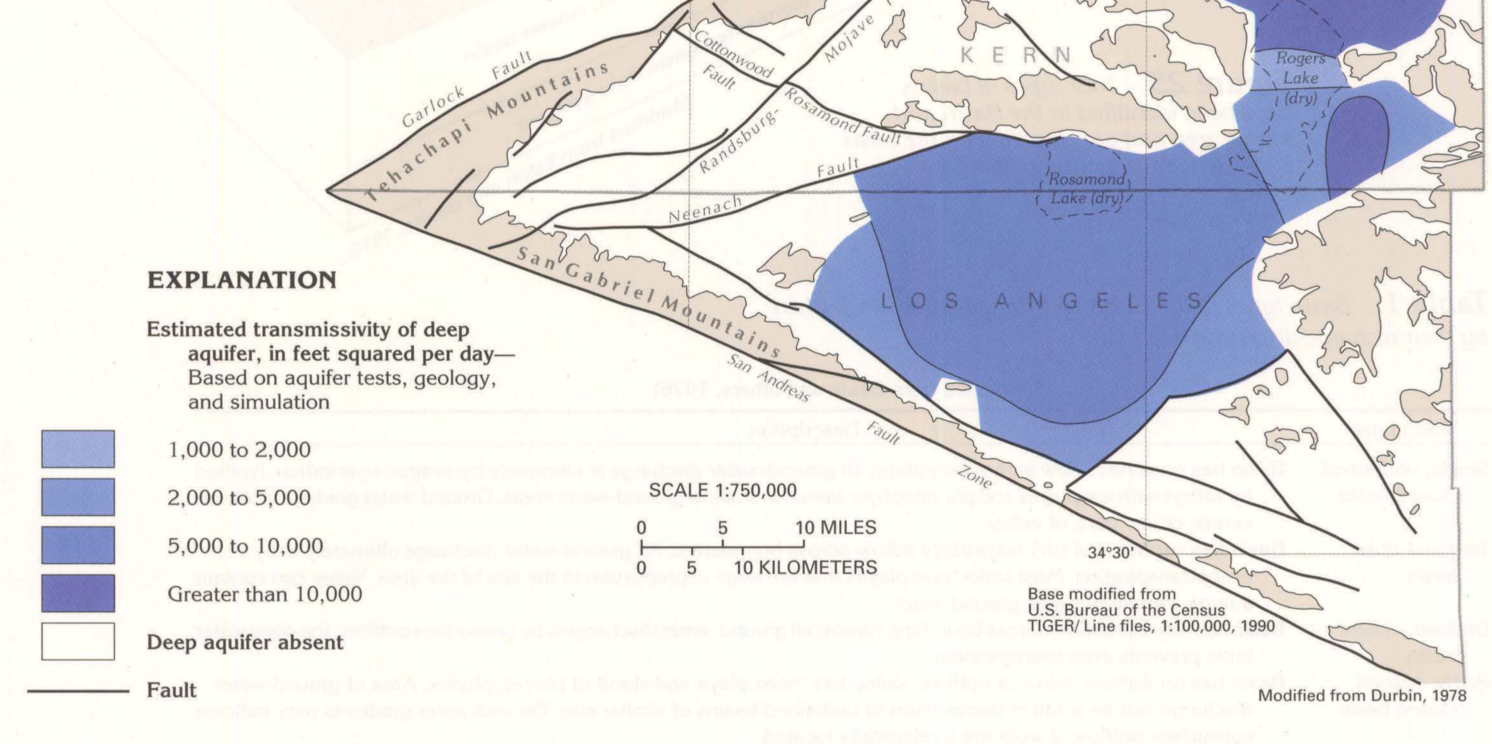


Figure 29. Estimated transmissivity values for part of the deep aquifer under the clay layer in Antelope Valley range from about 1,700 to 14,000 feet squared per day.



The aquifers in Antelope Valley are recharged primarily by infiltration of streamflow that originates in the mountainous areas that surround the valley. The average annual precipitation on the valley floor is less than 10 inches, and runoff is minor. For the most part, streamflow that enters the valley is intermittent. During storm periods, streamflow enters the valley along its perimeter and moves across the surface of the alluvial fans toward the playas at Rosamond and Rogers Lakes. As the streams flow across the alluvial fans, all the streamflow generally infiltrates the permeable surficial deposits on the fans. Because of the desert conditions, much of the infiltrating water is quickly lost by evaporation or as transpiration by riparian vegetation. The remainder of the water infiltrates downward through the alluvial deposits until it reaches the water table.

The drainage area tributary to Antelope Valley is about 385 square miles. Runoff from about 20 percent of this area is measured and the collective average annual discharge at the measured points is about 24,300 acre-feet. By calculating the measured runoff per unit area and extrapolating this value to unmeasured areas, the total runoff that enters the valley was estimated to be 40,700 acre-feet.

Evapotranspiration is the major natural discharge of ground water in Antelope Valley. Ground water generally discharges by evaporation from the water table where the water table is within 10 feet of the land surface, and, where vegetation is present, transpiration may also occur. Evaporation from an open body of water in Antelope Valley was measured at about 114 inches per year, which is an upper limit for evaporation of ground water. Because evapotranspiration from the ground-water system is complex, exact values cannot be determined.

The use of ground water for agriculture in Antelope Valley began about 1880, when wells were drilled near the center of the valley and yielded flowing water in quantities sufficient for irrigation. In 1891, more than 100 wells were in use, but most had stopped flowing. About 1915, intense use of ground water began when a large number of wells were drilled and equipped with pumps. An estimate of annual withdrawal rates from 1915 to 1975 is shown in **figure 32**. The maximum rate of withdrawal of about 400,000 acre-feet per year is about 10 times the estimated annual recharge to the basin. Water removed from storage in the aquifers was a major part of the ground-water withdrawals, and severe water-level declines resulted. By about 1950, studies showed that ground-water withdrawals in the valley were greatly in excess of natural recharge and withdrawals were curtailed.

The geographic distribution of withdrawals was generally unchanged between 1915 and 1960. After 1960, withdrawals were redistributed by abandoning some wells and adding some new wells. With the new distribution, the center of withdrawal was split into two areas; one was approximately 5 miles southeast, and the other approximately 10 miles southwest of Rosamond Lake (**fig. 31**).

Withdrawals from the deep, or confined, aquifer in Antelope Valley have caused an increase in leakage to the deep aquifer from the principal aquifer along the western and southern peripheries of the lacustrine deposits. This leakage has locally lowered the water table in the principal aquifer and has resulted in the reduction of natural discharge from the aquifer. Most of the declines in the principal aquifer, however, are the consequence of withdrawals from that aquifer. Field data are not available to show the effects of water-level declines on the amount of natural discharge, but the results of a digital flow model indicate that most of the natural evapotranspiration from the center of the valley might have ceased by 1950 (**fig. 33**) because water levels in the principal aquifer were too deep to allow evaporation or transpiration.

Ground water in closed basins is commonly highly mineralized because discharge by evapotranspiration increases the concentrations of minerals in the water. Some of the minerals might precipitate at or near the center of the basin. However, dissolved-solids concentrations in ground water remained practically the same or decreased slightly in Antelope Valley between 1908 and 1955 (**fig. 34**); this was probably caused by the reduced evapotranspiration that resulted from declining water levels in the principal aquifer.

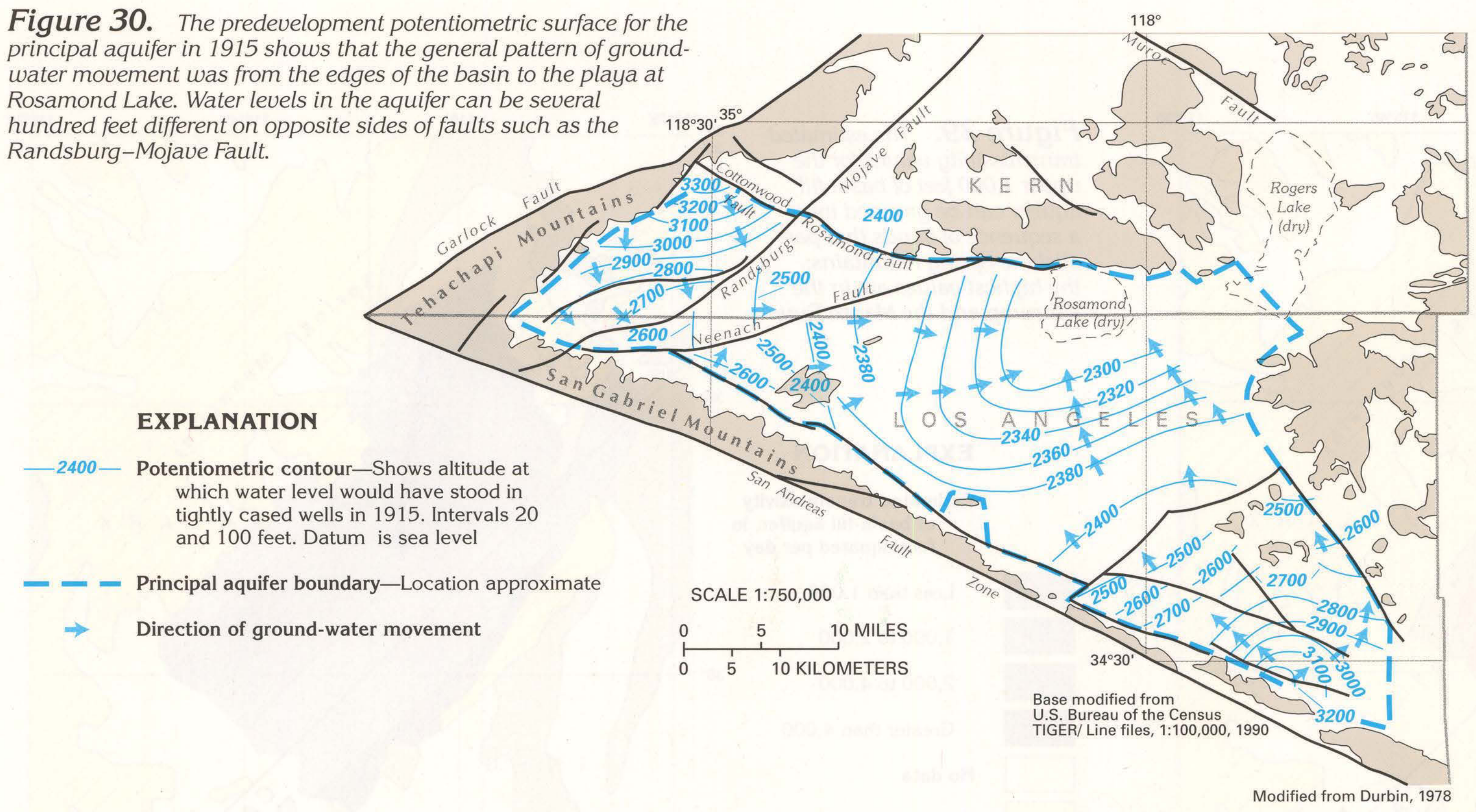


Figure 30. *The predevelopment potentiometric surface for the principal aquifer in 1915 shows that the general pattern of ground-water movement was from the edges of the basin to the playa at Rosamond Lake. Water levels in the aquifer can be several hundred feet different on opposite sides of faults such as the Randsburg–Mojave Fault.*

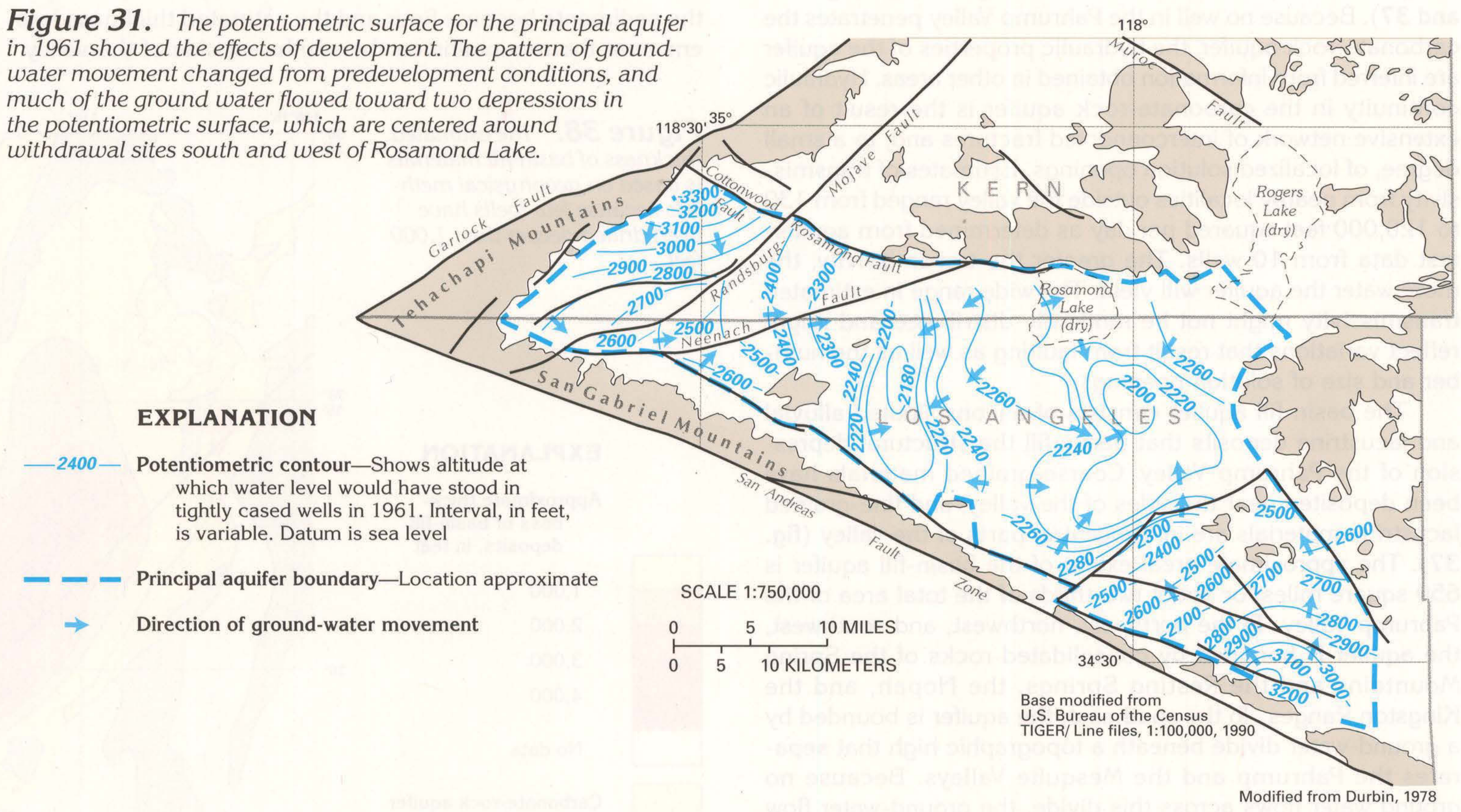


Figure 31. *The potentiometric surface for the principal aquifer in 1961 showed the effects of development. The pattern of ground-water movement changed from predevelopment conditions, and much of the ground water flowed toward two depressions in the potentiometric surface, which are centered around withdrawal sites south and west of Rosamond Lake.*

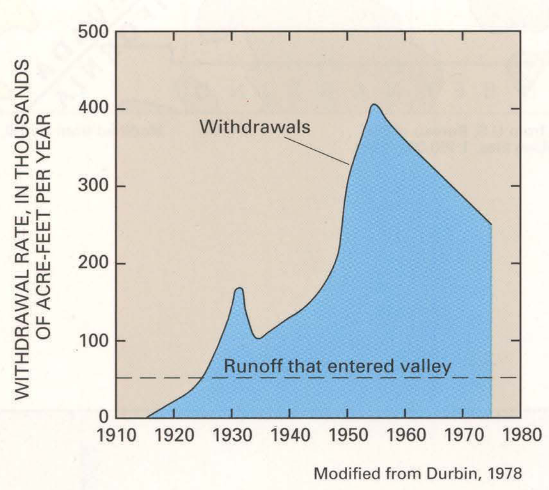


Figure 32. *Estimated withdrawals from 1915 to 1975 for the principal aquifer in Antelope Valley ranged from zero during 1915 to a maximum of over 400,000 acre-feet per year during 1950, compared to average annual runoff of 40,700 acre-feet that entered the valley. Withdrawals in excess of recharge resulted in water-level declines, which required a reduction in withdrawals after 1950.*

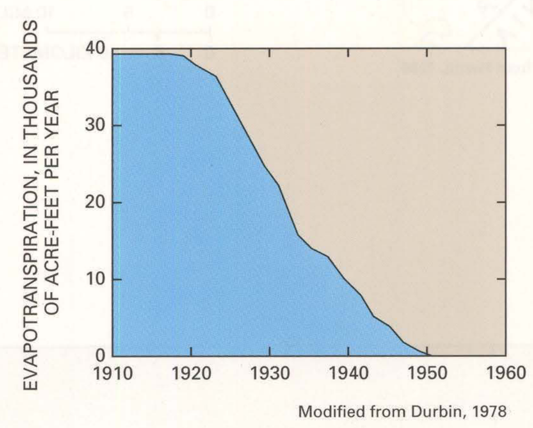


Figure 33. *Natural discharge by evapotranspiration from the principal aquifer in Antelope Valley declined from a maximum of about 39,000 acre-feet per year before 1919 to zero during 1950 as the water table declined as a result of ground-water withdrawals.*

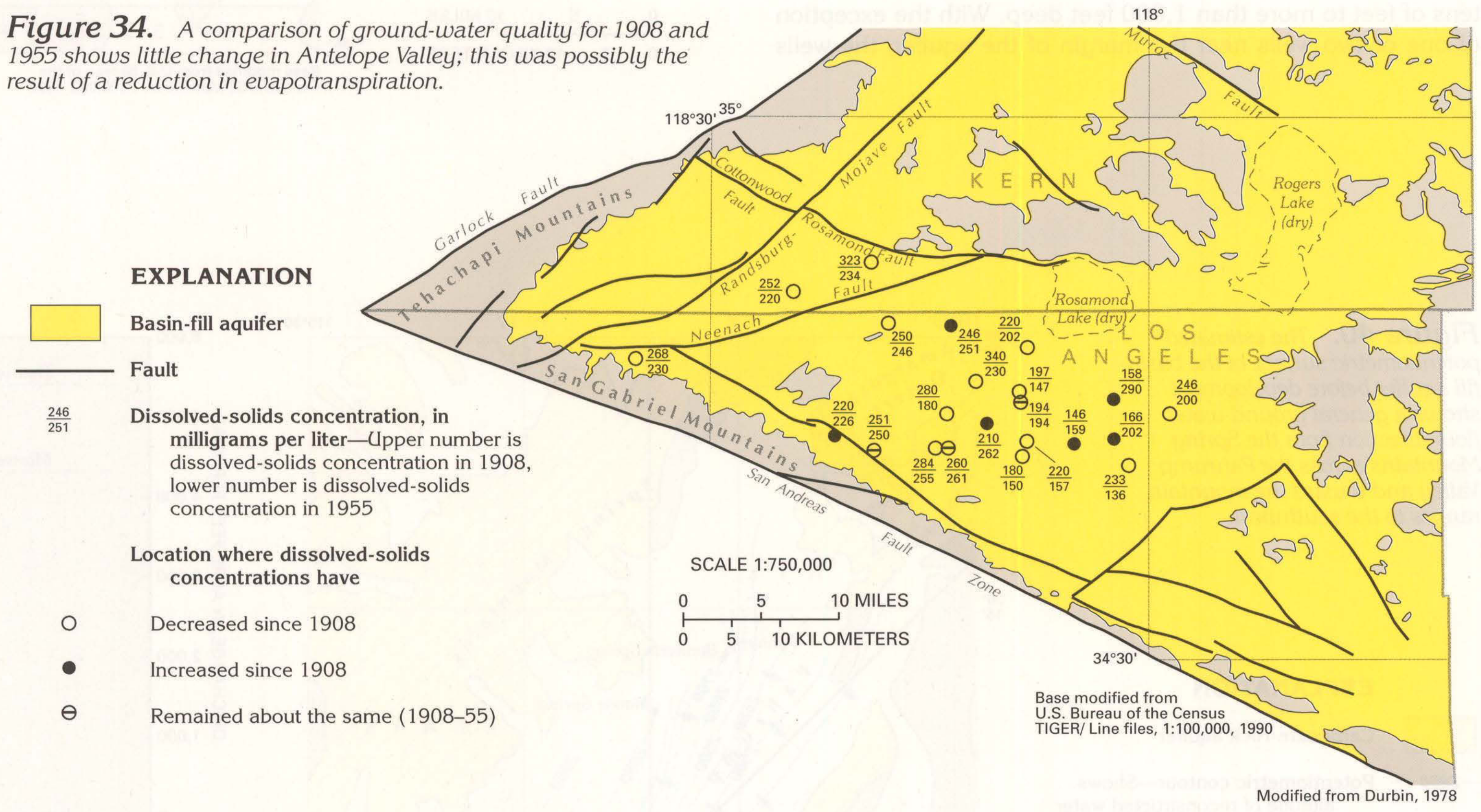


Figure 34. *A comparison of ground-water quality for 1908 and 1955 shows little change in Antelope Valley; this was possibly the result of a reduction in evapotranspiration.*

Partly Drained, Closed Basin

The Pahrump Valley, an example of a partly drained, closed basin, covers about 1,050 square miles in Nye and Clark Counties, Nev., and Inyo and San Bernardino Counties, Calif. (**fig. 35**). The Spring Mountains, which form the northeastern border of the basin, are the dominant topographic feature and are the source of all the water that enters the basin. The southwestern side of the Spring Mountains is characterized by large alluvial fans that head high in the canyons that lead from Charleston Peak. The most prominent of these fans have coalesced to form the Pahrump and the Manse Fans.

The Pahrump Valley is part of an intervalley ground-water flow system. The regional movement of ground water is generally southwestward to low areas adjacent to the Amargosa River. The major areas of ground-water discharge downgradient from the Pahrump Valley are between the towns of Tecopa and Shoshone, Calif., which are 10 to 15 miles southwest of the topographic boundary of the Pahrump Valley (**fig. 35**).

Mountain-building activity in southern Nevada has affected the ground-water flow system in the Pahrump Valley. Several large thrust faults are exposed in the Spring Mountains and at the northern end of the Nopah Range (**fig. 36**). In some places, low-permeability clastic rocks have been displaced by the faulting so that they are above or adjacent to water-yielding carbonate rocks and thus restrict ground-water movement in the carbonate rocks. Under some conditions, permeable zones of broken rock along the fault planes might be conduits for ground water. Springs and stands of mesquite along the northwestern sides of these faults, however, suggest that the faults are barriers to ground-water flow and that the ground water moves upward along the barriers until it emerges at the land surface. Folding, associated with the faults, produced joints and fractures in some of the rocks, resulting in significant secondary permeability.

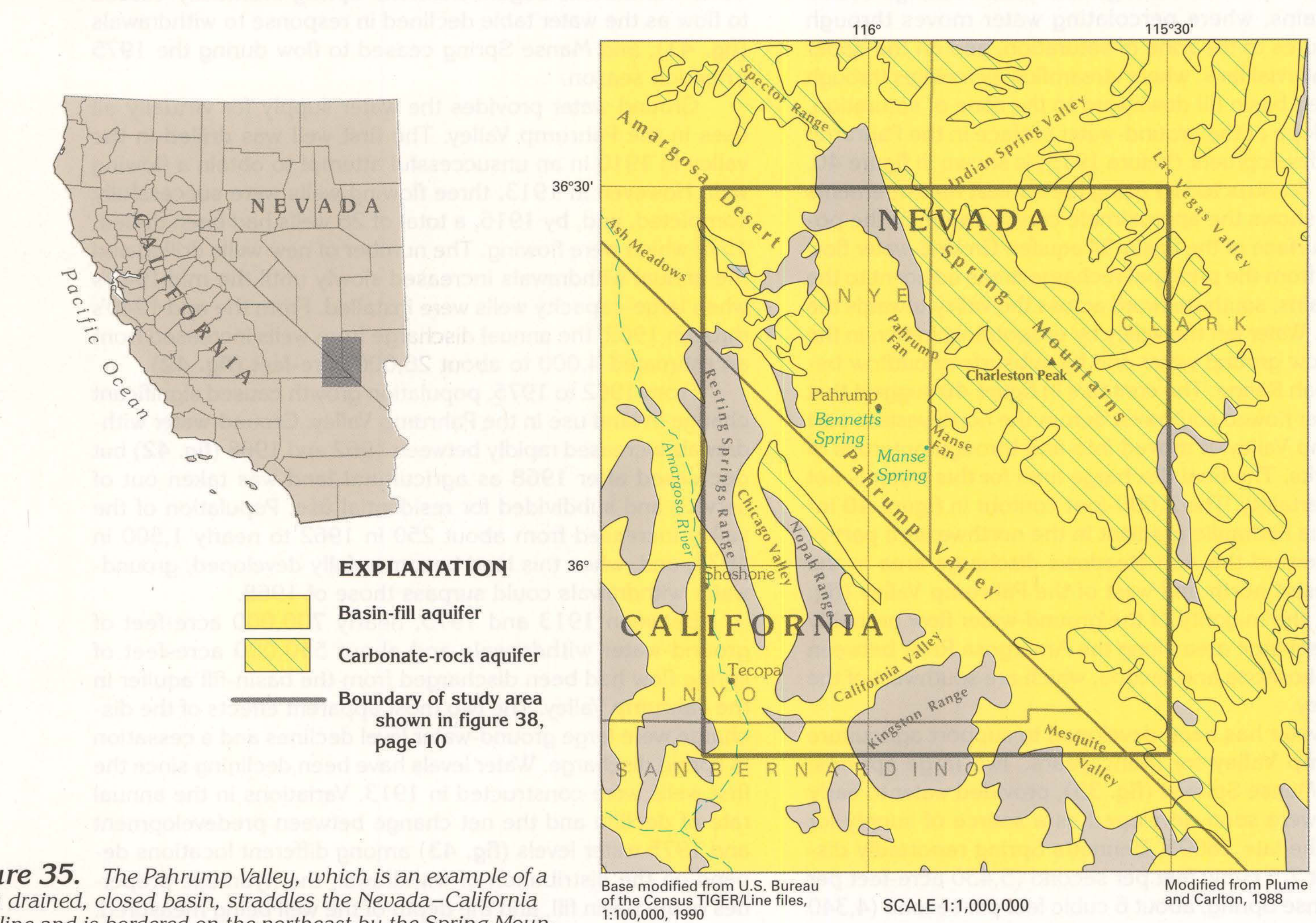


Figure 35. *The Pahrump Valley, which is an example of a partly drained, closed basin, straddles the Nevada–California State line and is bordered on the northeast by the Spring Mountains and on the southwest by the Resting Springs, the Nopah, and the Kingston Ranges.*

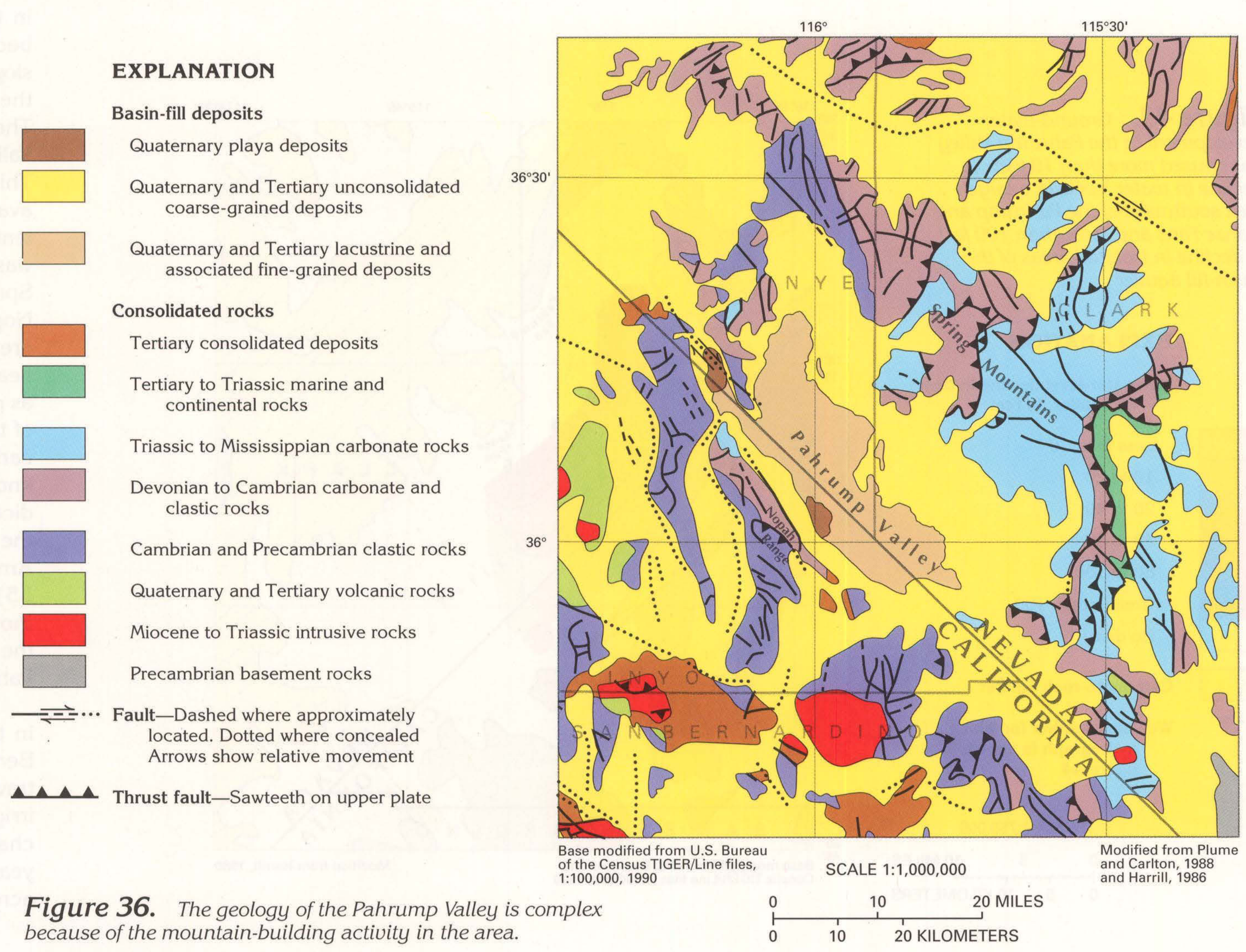


Figure 36. *The geology of the Pahrump Valley is complex because of the mountain-building activity in the area.*

Partly Drained, Closed Basin—Continued

Two distinct aquifers are in the Pahrump Valley—the carbonate-rock aquifer, formed of carbonate rocks that bound and underlie the valley, and the basin-fill aquifer, which consists of unconsolidated deposits that have accumulated in the structural depression of the valley (**fig. 37**). The carbonate rocks transmit water readily and carry significant ground-water flow from the Pahrump Valley into the adjacent Chicago and Amargosa River Valleys to the southwest. The carbonate-rock aquifer is virtually undeveloped and significant future development is improbable because it is necessary to drill wells to great depths in order to obtain adequate yields. The basin-fill aquifer is, therefore, the source of virtually all withdrawals.

The carbonate-rock aquifer consists primarily of carbonate rocks of Triassic to Cambrian age that crop out in the Spring Mountains (**fig. 36**) and underlie the basin fill of the Pahrump Valley (**fig. 37**). The aquifer extends westward and southwestward through the Nopah and the Resting Springs Ranges into the California and the Chicago Valleys (**figs. 35 and 37**). Because no well in the Pahrump Valley penetrates the carbonate-rock aquifer, the hydraulic properties of the aquifer are inferred from information obtained in other areas. Hydraulic continuity in the carbonate-rock aquifer is the result of an extensive network of interconnected fractures and, to a small degree, of localized solution openings. Estimates of transmissivity from nearby localities outside the valley ranged from 130 to 120,000 feet squared per day as determined from aquifer-test data from 10 wells. The greater the transmissivity, the more water the aquifer will yield. The wide range in estimated transmissivity might not be randomly distributed and might reflect variations that result from faulting as well as the number and size of solution openings.

The basin-fill aquifer consists of unconsolidated alluvial and lacustrine deposits that partly fill the structural depression of the Pahrump Valley. Coarse-grained materials have been deposited near the sides of the valley, and fine-grained lacustrine materials are in the central parts of the valley (**fig. 37**). The approximate areal extent of the basin-fill aquifer is 650 square miles, or about two-thirds of the total area of the Pahrump Valley. To the northeast, northwest, and southwest, the aquifer is bounded by consolidated rocks of the Spring Mountains and the Resting Springs, the Nopah, and the Kingston Ranges. To the southeast, the aquifer is bounded by a ground-water divide beneath a topographic high that separates the Pahrump and the Mesquite Valleys. Because no ground water flows across this divide, the ground-water flow systems of the two valleys are separate.

Wells drilled into the basin-fill aquifer range from several tens of feet to more than 1,000 feet deep. With the exception of one or two wells near the margin of the aquifer, the wells do not fully penetrate the basin fill. Therefore, the thickness of the basin-fill aquifer was estimated from geophysical measurements. The maximum thickness of the aquifer is about 4,800 feet in the central part of the valley (**fig. 38**). In general, the thickest accumulations of basin fill parallel the axis of the valley. The area of maximum thickness is offset slightly toward the south end of the valley, suggesting some faulting or folding in that area.

Estimates of the transmissivity of the basin-fill aquifer (**fig. 39**) are representative only of the upper 1,000 feet of the aquifer, which is the part penetrated by most wells. Variations in transmissivity are related to the deposition of the coarser materials and the position of the water table. Transmissivity values increase from the edge of the Spring Mountains, where the saturated materials are thin, toward the center of the valley, where the land surface is flatter, the water table approaches the land surface, and the aquifer is thickest. The increase in saturated thickness within the zone of coarse materials provides the highest transmissivity values; values are greater than 4,000 feet squared per day in the Pahrump and the Manse Fans. Transmissivity values decrease in nearly parallel bands across the valley to less than 1,000 feet squared per day as the sediments become finer and the saturated thickness lessens near the mountains on the southwest side of the valley.

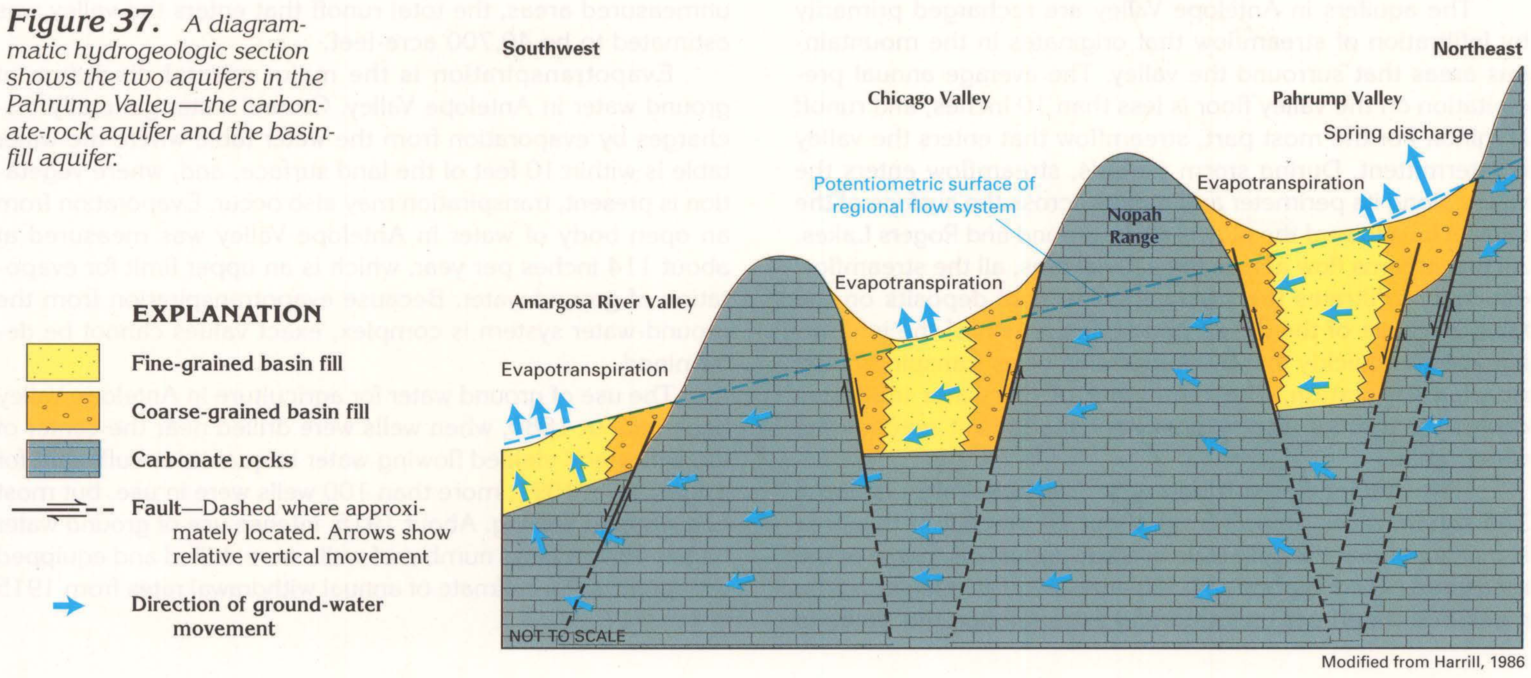


Figure 37. A diagrammatic hydrogeologic section shows the two aquifers in the Pahrump Valley—the carbonate-rock aquifer and the basin-fill aquifer.

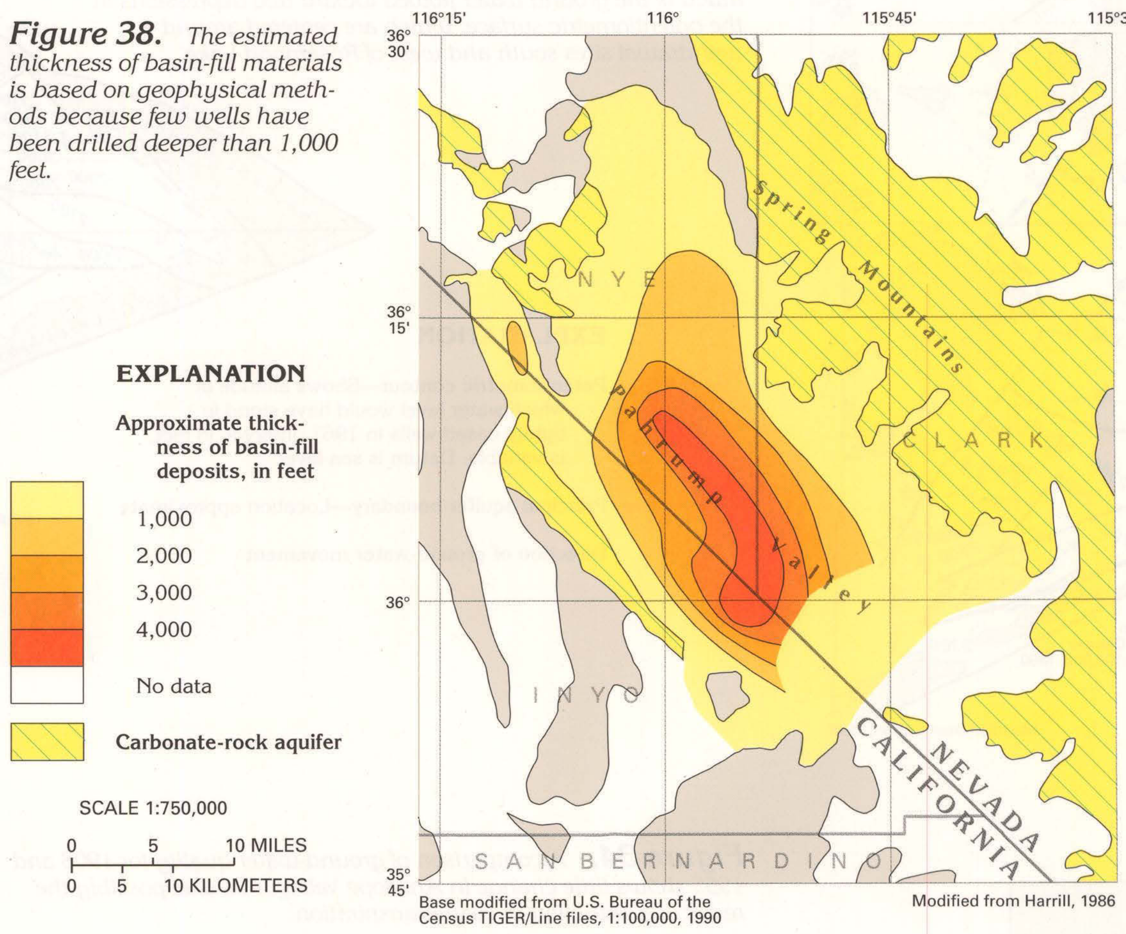


Figure 38. The estimated thickness of basin-fill materials is based on geophysical methods because few wells have been drilled deeper than 1,000 feet.

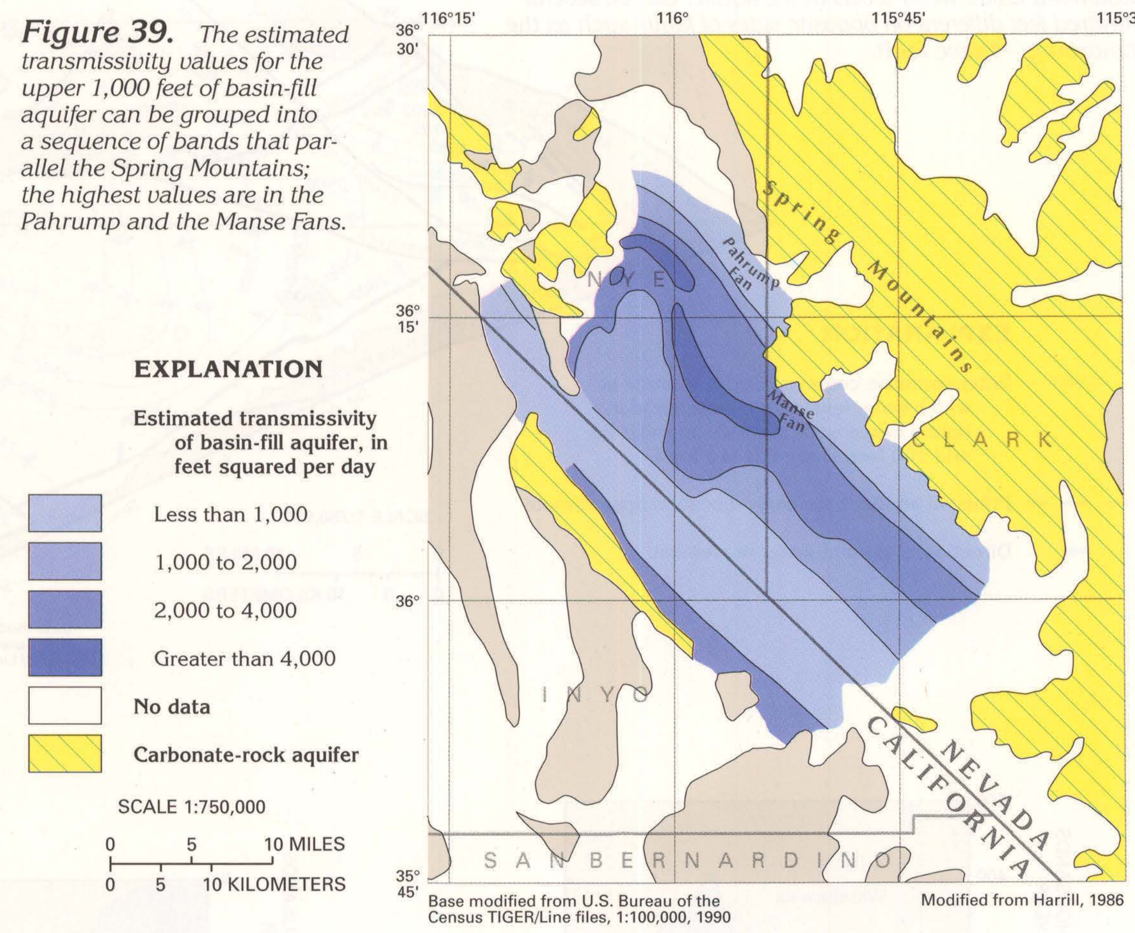


Figure 39. The estimated transmissivity values for the upper 1,000 feet of the basin-fill aquifer can be grouped into a sequence of bands that parallel the Spring Mountains; the highest values are in the Pahrump and the Manse Fans.

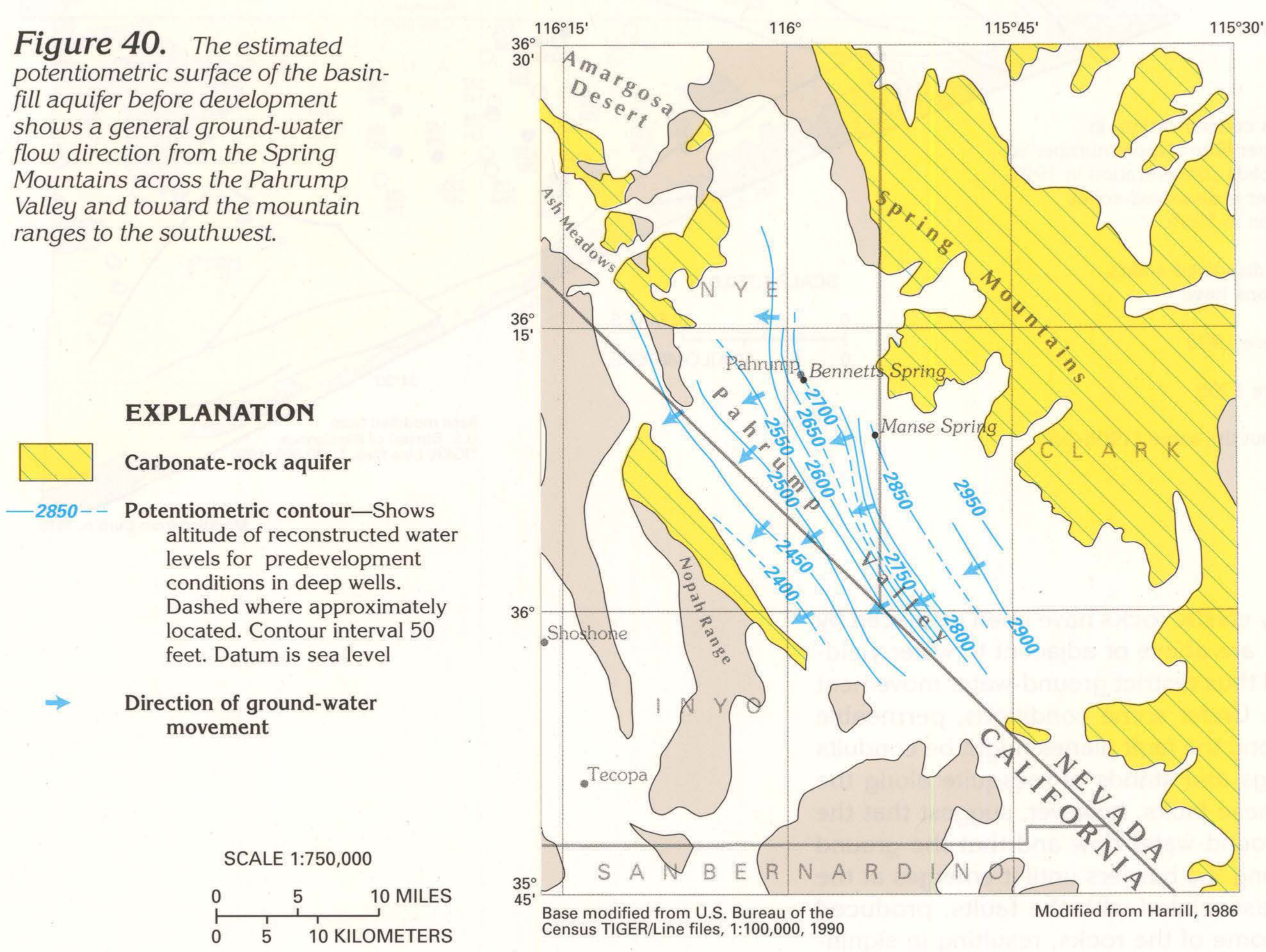


Figure 40. The estimated potentiometric surface of the basin-fill aquifer before development shows a general ground-water flow direction from the Spring Mountains across the Pahrump Valley and toward the mountain ranges to the southwest.

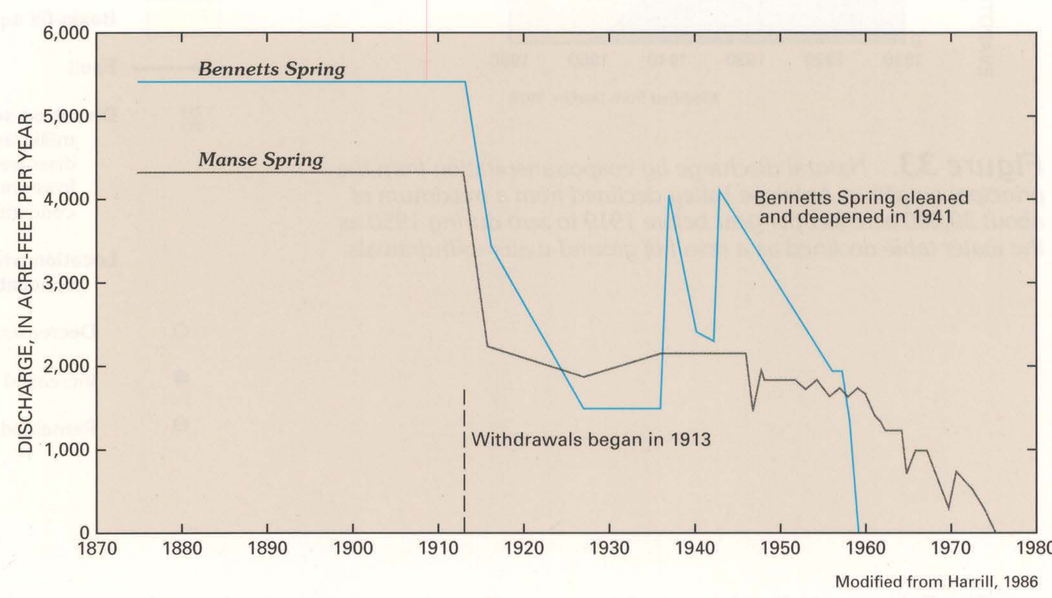


Figure 41. The annual discharge of the two largest springs in the Pahrump Valley showed a marked decrease in response to increased ground-water development.

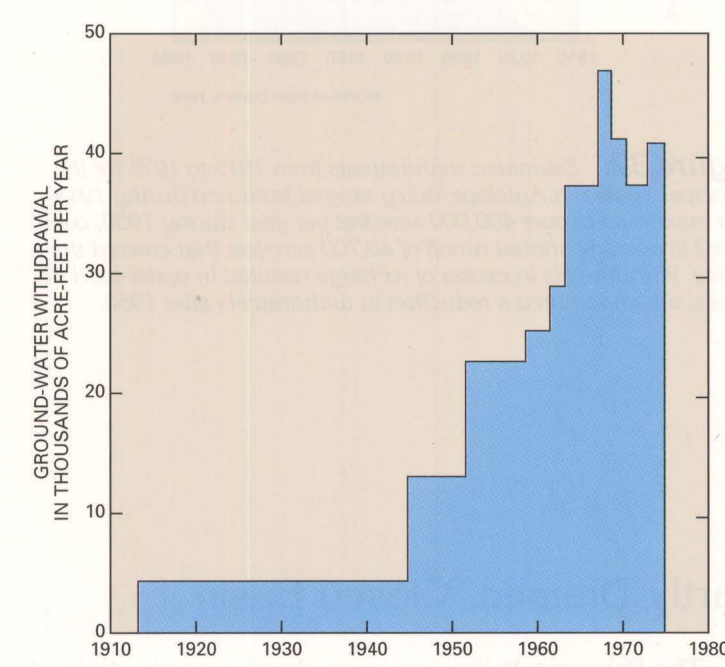


Figure 42. Ground-water withdrawals increased dramatically after 1945 when the first large-capacity wells were installed in the Pahrump Valley. Maximum yearly withdrawals during the late 1960's reached nearly 50,000 acre-feet.

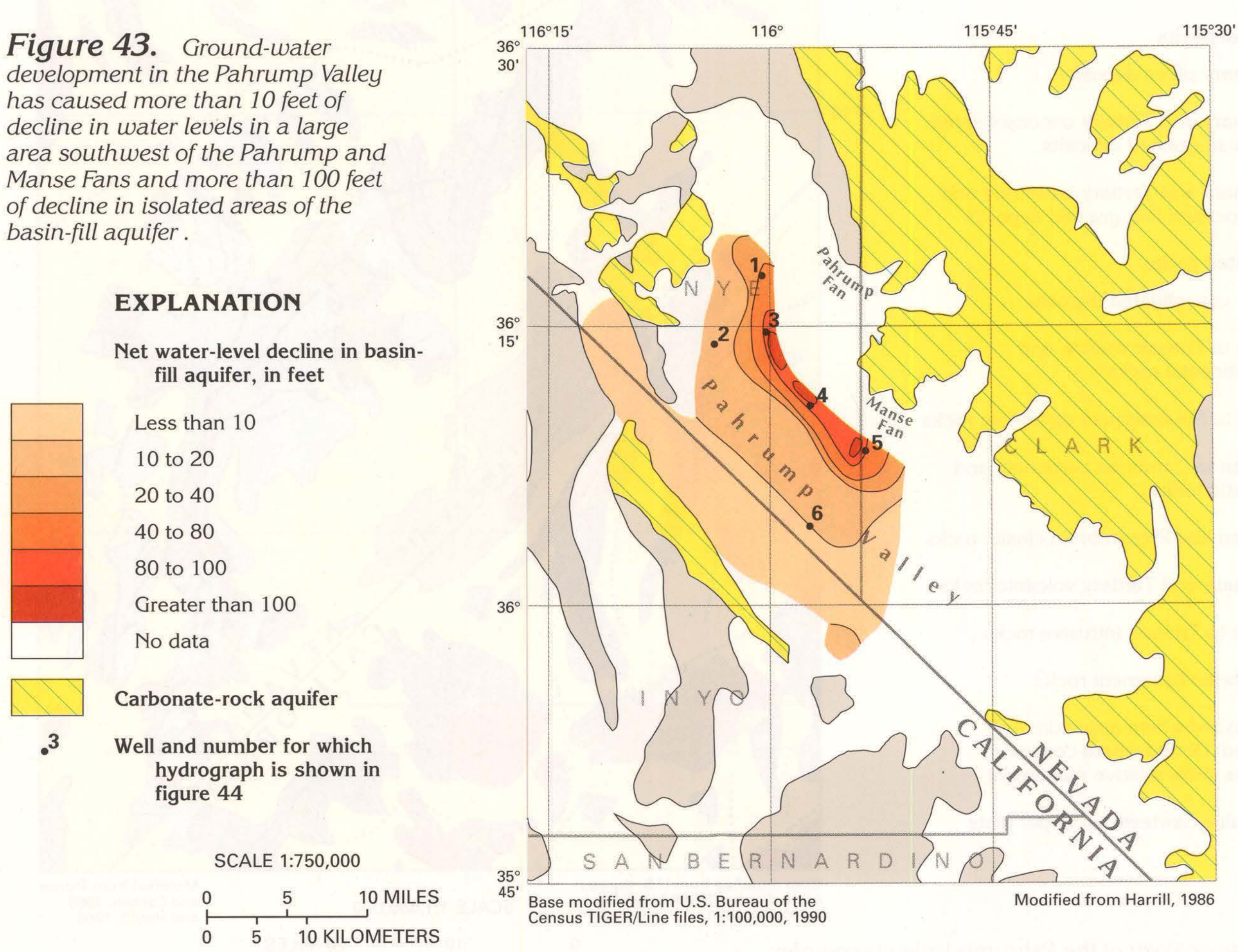


Figure 43. Ground-water development in the Pahrump Valley has caused more than 10 feet of decline in water levels in a large area southwest of the Pahrump and Manse Fans and more than 100 feet of decline in isolated areas of the basin-fill aquifer.

Virtually all the ground water in the Pahrump Valley is derived from precipitation. Most ground-water recharge occurs in the mountains, where percolating water moves through bedrock fractures to the zone of saturation, and on the upper slopes of the alluvial fans, where streamflow percolates through the unsaturated basin fill downward to the zone of saturation. The general slope of the ground-water surface in the Pahrump Valley before development (before 1913) is shown in **figure 40**. This map was constructed by using the earliest measurements available and shows the approximate configuration of the potentiometric surface of the basin-fill aquifer. Ground-water flow was generally from the principal recharge areas adjacent to the Spring Mountains, southwestward across the valley towards the Nopah Range. Water left the valley by evapotranspiration in the areas of shallow ground water and by subsurface outflow beneath the Nopah Range. The contours in **figure 40** suggest that as ground water flowed southwest across the northwestern part of the Pahrump Valley, it moved into and through outcrops of carbonate rocks. The final discharge area for this water is not known with certainty. The 2,600-foot contour in **figure 40** indicates that the hydraulic gradient in the northwestern part of the valley is toward the Ash Meadows discharge area in the Amargosa Desert north and west of the Pahrump Valley (**fig. 35**). However, the majority of the ground-water flow probably moved to a discharge area along the Amargosa River between the towns of Shoshone and Tecopa, which are southwest of the Pahrump Valley.

Ground water has been developed to support agriculture in the Pahrump Valley for many years. Two large springs, Bennetts and Manse Springs (**fig. 35**), provided water to early travelers and were soon developed as a source of supply for irrigation. In the late 1800's, Bennetts Spring reportedly discharged about 7.5 cubic feet per second (5,430 acre-feet per year), and Manse Spring, about 6 cubic feet per second (4,340 acre-feet per year); most of this water was diverted to agriculture. Spring flow decreased dramatically in 1913 when ground-water withdrawals began. Bennetts Spring eventually ceased to flow as the water table declined in response to withdrawals (**fig. 41**), and Manse Spring ceased to flow during the 1975 irrigation season.

Ground water provides the water supply for virtually all uses in the Pahrump Valley. The first well was drilled in the valley in 1910 in an unsuccessful attempt to obtain a flowing well. However, in 1913, three flowing wells were successfully completed, and, by 1916, a total of 28 wells had been drilled, 15 of which were flowing. The number of new wells drilled and the annual withdrawals increased slowly until the mid-1940's when large-capacity wells were installed. From the mid-1940's through 1962, the annual discharge from wells increased from an estimated 4,000 to about 28,000 acre-feet (**fig. 42**).

From 1962 to 1975, population growth caused significant change in land use in the Pahrump Valley. Ground-water withdrawals increased rapidly between 1962 and 1968 (**fig. 42**) but decreased after 1968 as agricultural land was taken out of service and subdivided for residential use. Population of the valley increased from about 250 in 1962 to nearly 1,500 in 1975, and, when this land becomes fully developed, ground-water withdrawals could surpass those of 1968.

Between 1913 and 1975, nearly 700,000 acre-feet of ground-water withdrawals and about 550,000 acre-feet of spring flow had been discharged from the basin-fill aquifer in the Pahrump Valley. The two most apparent effects of the discharge were large ground-water level declines and a cessation in spring discharge. Water levels have been declining since the first wells were constructed in 1913. Variations in the annual rate of decline and the net change between predevelopment and 1975 water levels (**fig. 43**) among different locations depend on the distribution of withdrawal, the hydraulic properties of the basin fill, and the depth of the well being measured.

Hydrographs of six wells are shown in **figure 44** to illustrate the typical response of water levels to withdrawals in various parts of the valley. Generally, the greatest water-level declines (about 100 feet) were along the terminal parts of the Pahrump and the Manse Fans. Two wells located in the central part of the valley, away from the major concentration of withdrawal, showed substantially less water-level decline.

Withdrawals in the Pahrump Valley are distributed to capture ground-water flow downgradient of the Pahrump and Manse Fans and capture the discharge of Bennetts and Manse Springs in an effective manner (**fig. 45**). Consequently, spring discharge began to decrease shortly after withdrawals began and continued to decrease until 1975, when discharge of both springs ceased entirely during the irrigation season (**fig. 41**). Bennetts Spring ceased to flow in 1959; as of 1975, Manse Spring was dry during the summer irrigation season but recovered to discharge about 200 acre-feet during the winter months. The changes in spring discharge from 1875 through 1975 are shown in **figure 41**. The amount by which spring discharge has decreased is the amount of water captured by withdrawals. Thus, as of 1975, about 9,800 acre-feet per year of spring discharge had been captured by ground-water withdrawals.

Figure 44. *Water levels in individual wells have been drawn down by different amounts in the Pahrump Valley. The decline depends on the proximity of the wells to large centers of ground-water withdrawal. The locations of the wells are shown in figure 43.*

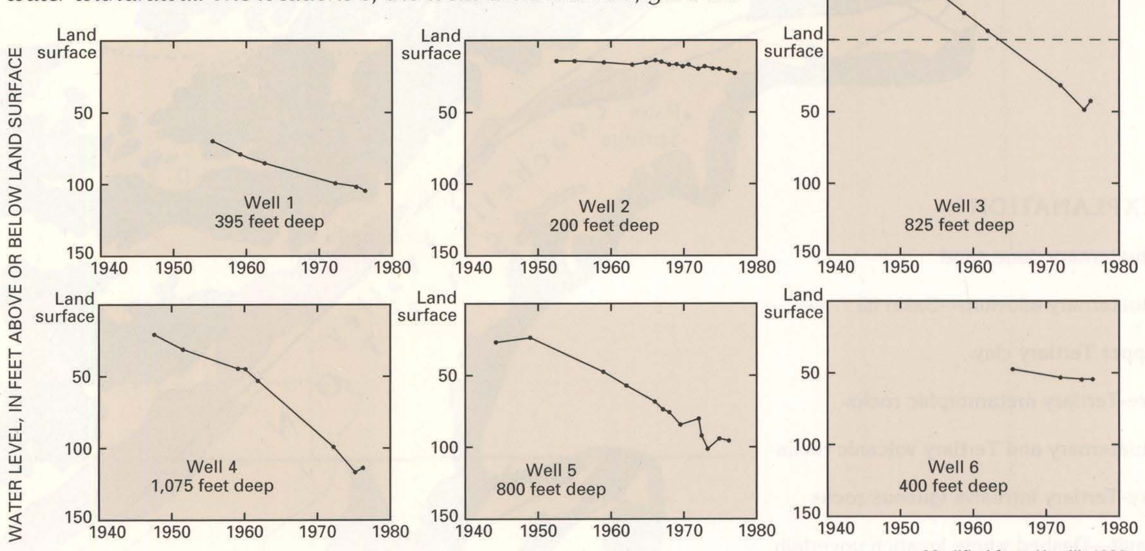
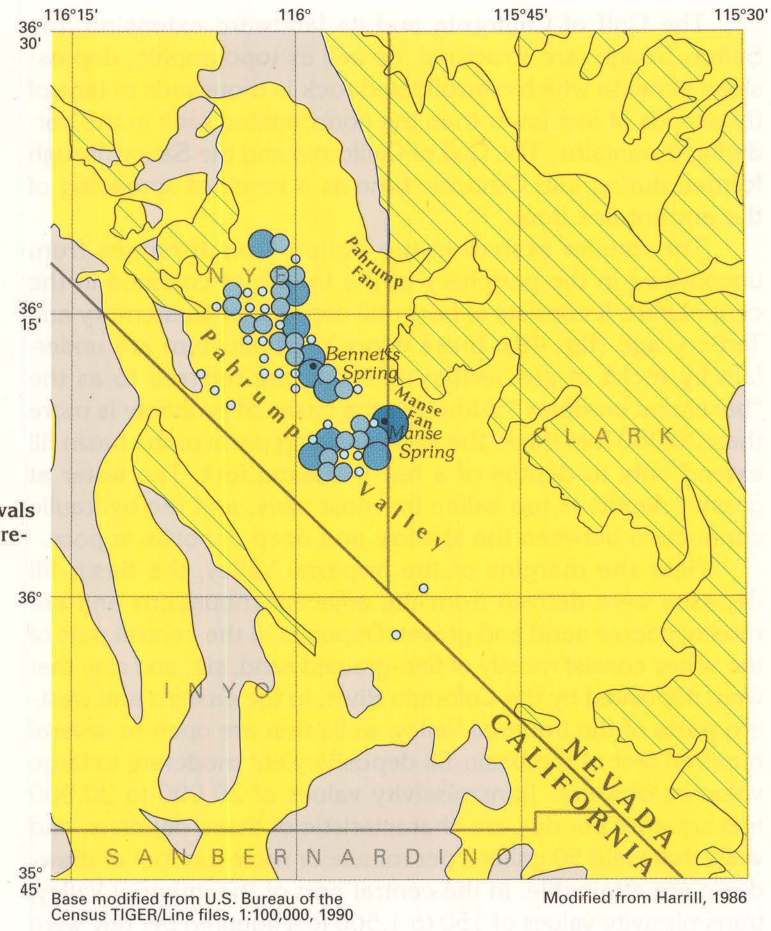


Figure 45. *The distribution of withdrawals during 1975 was primarily designed to capture ground-water flow downgradient of the Pahrump and the Manse Fans.*



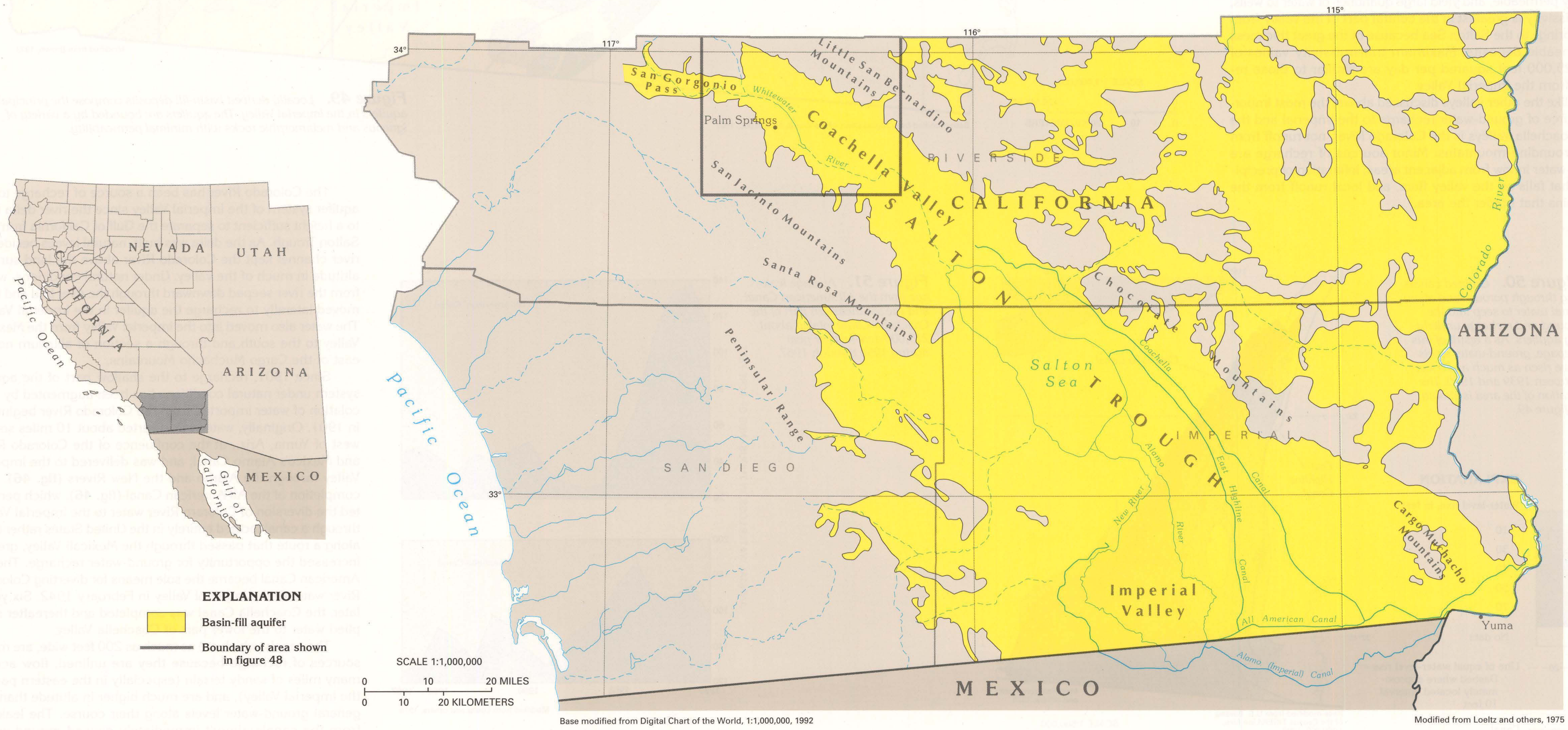
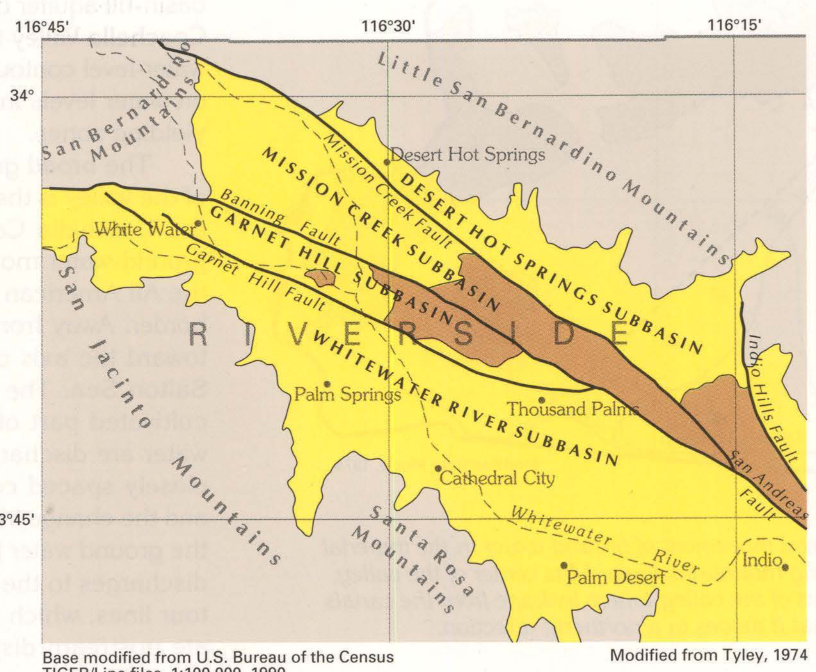


Figure 46. *The Salton Trough in southern California is divided by the Salton Sea into the Coachella Valley to the north and the Imperial Valley to the south.*

Figure 47. *Ancient Lake Cahuilla occupied the Imperial Valley and carved shorelines into the alluvial deposits that partly filled the valley.*

Loeltz and others, 1975

Figure 48. *Faults have divided the upper Coachella Valley into four ground-water subbasins. Water levels between the subbasins might differ by as much as 400 feet.*



GROUND-WATER FLOW SYSTEMS — Continued

Terminal Sink Basin

The Salton Trough is a topographic and structural trough that extends from southeastern California into Mexico, is an example of a terminal sink basin. The Salton Trough is divided into two parts by the Salton Sea—the Imperial Valley to the south and the Coachella Valley to the north (**fig. 46**). The Imperial Valley is the largest area of desert irrigation development in the United States. Importation of water from the Colorado River has transformed 500,000 acres of parched desert lands into one of the most productive agricultural areas in the Nation. The Coachella Valley has experienced dramatic declines in ground-water levels due to public water supply demands for a growing population, stimulated by the attraction of the Palm Springs area.

The desert climate of the Salton Trough is characterized by extreme aridity and high summer temperatures. Average annual precipitation is slightly less than 3 inches on the valley floor and about 40 inches at the crests of the San Jacinto Mountains. Maximum summer temperatures commonly exceed 104 degrees Fahrenheit, and winter minimums are seldom below 32 degrees Fahrenheit.

The Salton Trough is about 130 miles long and as much as 70 miles wide (**fig. 46**). The trough is a landward extension of the depression that is partially filled by the Gulf of California. The trough and gulf are separated by the broad fan-shaped subaerial delta of the Colorado River. Much of the land surface of the trough is below sea level and, before the delta was formed, the trough may have been part of the Gulf of California. The lowest part of the trough is occupied by the Salton Sea, whose surface is at an elevation of more than 200 feet below sea level. Most of the surface drainage is intermittent and is toward the Salton Sea in the central part of the valley. Surface water moves northwestward to the Salton Sea from the boundary between the United States and Mexico and southeastward from the San Gorgonio Pass.

The Imperial Valley occupies the wider southern part of the Salton Trough. The valley ends at the Salton Sea to the northwest and continues southward into Mexico as the Mexicali Valley. The Chocolate Mountains border the valley to the northeast, and the Peninsular Range of Baja California and southern California borders it to the southwest. The floor of the valley slopes northwestward from about sea level at the international boundary to about 230 feet below sea level at the Salton Sea. The Salton Trough was once occupied by prehistoric Lake Cahuilla. In the eastern and western parts of the trough, several ancient lake shorelines (**fig. 47**) are at elevations of 42 to 50 feet above sea level.

The central part of the Imperial Valley is a large area of cultivated land entirely within the shorelines of prehistoric Lake Cahuilla. Most of the central Imperial Valley is a monotonous plain dissected by the Alamo and the New Rivers, which have incised trenches as much as 40 feet deep in soft, silty lacustrine deposits. Much of the entrenchment took place during 1905 through 1907 when virtually the entire Colorado River flowed uncontrolled in these channels and established the present-day Salton Sea. Before 1905, the center of the trough had been a playa. The lowest point of the surface of the trough is beneath the southern part of the Salton Sea and is about 275 feet below sea level.

The Coachella Valley in the northwestern part of the Salton Trough (**fig. 46**) extends from the east end of San Gorgonio Pass southeastward to the Salton Sea. It is bordered on the north and east by the Little San Bernardino Mountains and on the southwest by the San Jacinto and the Santa Rosa Mountains. The Whitewater River is the main drainage in the valley.

The Coachella Valley is affected by the San Andreas Fault system, which is a complex strike-slip fault system that includes the Mission Creek, the Banning, the Garnet Hill, and the Indio Hills Faults and associated folds (**fig. 48**). These faults act as barriers to ground-water flow and, combined with constrictions in the basin width and changes in permeability of the water-yielding units, have compartmentalized the Coachella Valley into the Desert Hot Springs, the Mission Creek, the Garnet Hill, and the Whitewater River ground-water subbasins (**fig. 48**). The Whitewater River subbasin is the largest of the four and contains the most productive aquifer.

The Gulf of California and its landward extension, the Salton Trough, are structural, as well as topographic, depressions beneath which consolidated rock is thousands to tens of thousands of feet lower than the consolidated rock in the bordering mountains. The Gulf of California and the Salton Trough formed during late Cenozoic time as a result of spreading of the ancient sea floor.

The aquifer system in the Salton Trough ranges from unconfined in the periphery of the trough to confined in the central part. It consists of basin-fill deposits of Quaternary and Tertiary age (**fig. 49**); these deposits of alluvium are underlain by rocks of pre-Tertiary age that are referred to as the "basement complex." Although the basin fill probably is more than 20,000 feet thick, the water-yielding parts of the basin fill extend only to depths of a few thousand feet. The water at greater depths is too saline for most uses, and the hydraulic connection between the shallow and deep deposits is poor.

Near the margins of the Imperial Valley, the basin-fill deposits were derived from the adjacent mountains and are mostly coarse sand and gravel. Deposits in the central part of the valley consist mostly of fine-grained sand, silt, and clay that were deposited by the Colorado River. In the eastern and western parts of the Imperial Valley, wells that are open to several hundred feet of the basin-fill deposits yield moderate to large volumes of water. Transmissivity values of 20,000 to 30,000 feet squared per day are characteristic of these deposits, and wells that yield 50 gallons per minute or more per foot of drawdown are attainable. In the central part of the Imperial Valley, transmissivity values of 150 to 1,500 feet squared per day were calculated from two aquifer tests of wells completed in the upper 500 feet of the fine-grained deposits.

Aquifer material in the Coachella Valley is mostly coarse-grained sediments, and the aquifer is generally unconfined. These deposits are more than 3,000 feet thick, are moderately to highly permeable, and yield large quantities of water to wells. Transmissivity is greatest in the central part of the valley from Palm Springs to the Salton Sea because of the great thickness of permeable deposits. Maximum transmissivity values of about 25,000 feet squared per day are similar to those reported from the Imperial Valley.

Unlike the other valleys discussed above, the most important source of ground-water recharge to the Imperial and the lower Coachella Valleys is the Colorado River, not runoff from the surrounding mountains. Minor sources of recharge are ground-water inflow from adjacent areas, infiltration of precipitation that falls on the valley floor, and local runoff from the mountains that border the area.

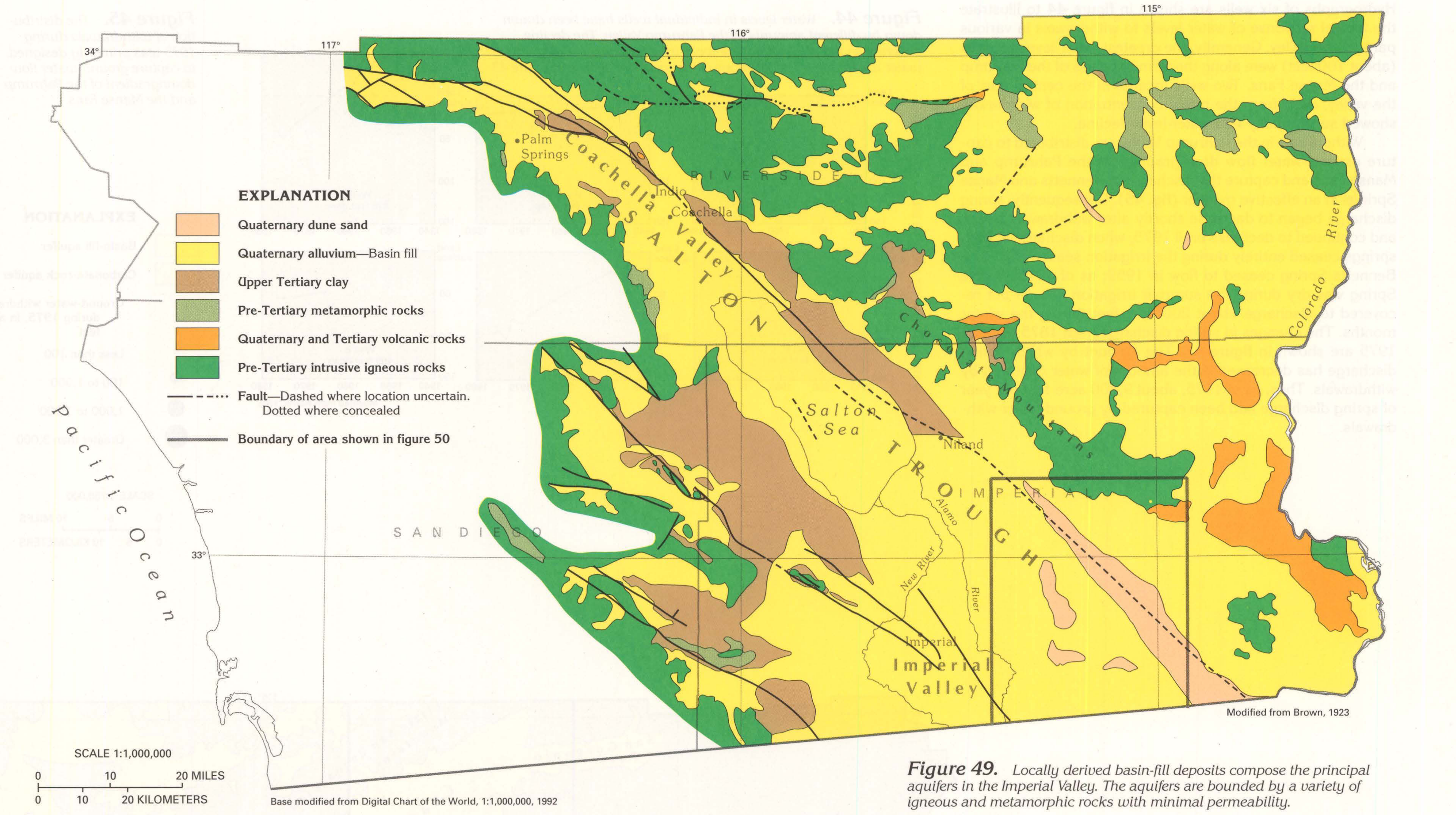


Figure 49. *Locally derived basin-fill deposits compose the principal aquifers in the Imperial Valley. The aquifers are bounded by a variety of igneous and metamorphic rocks with minimal permeability.*

Figure 50. *Unlined canals dug through porous sand allow canal water to seep into the ground and recharge underlying aquifers. As a result of this seepage, ground-water levels have risen as much as 70 feet between 1939 and 1960. The location of the area is shown in figure 49.*

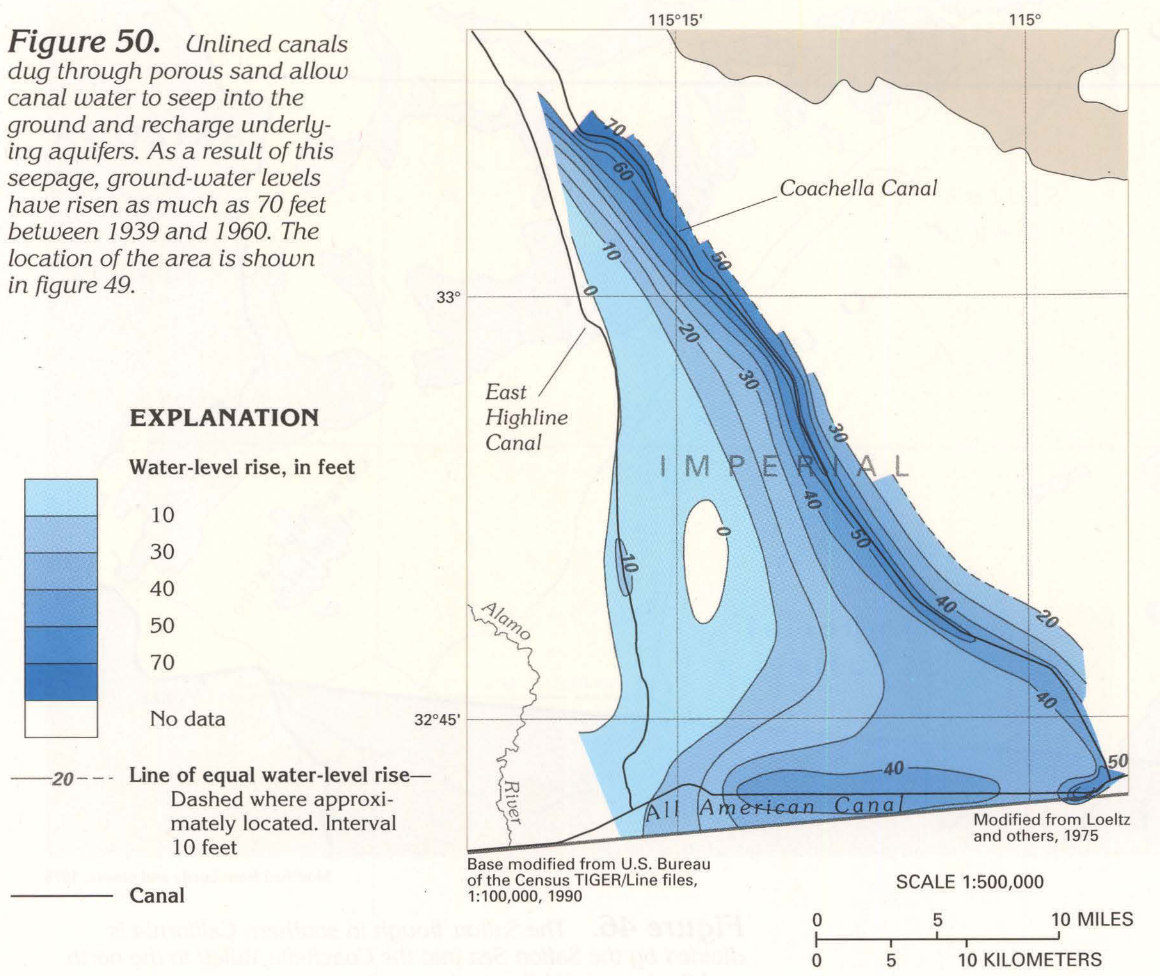
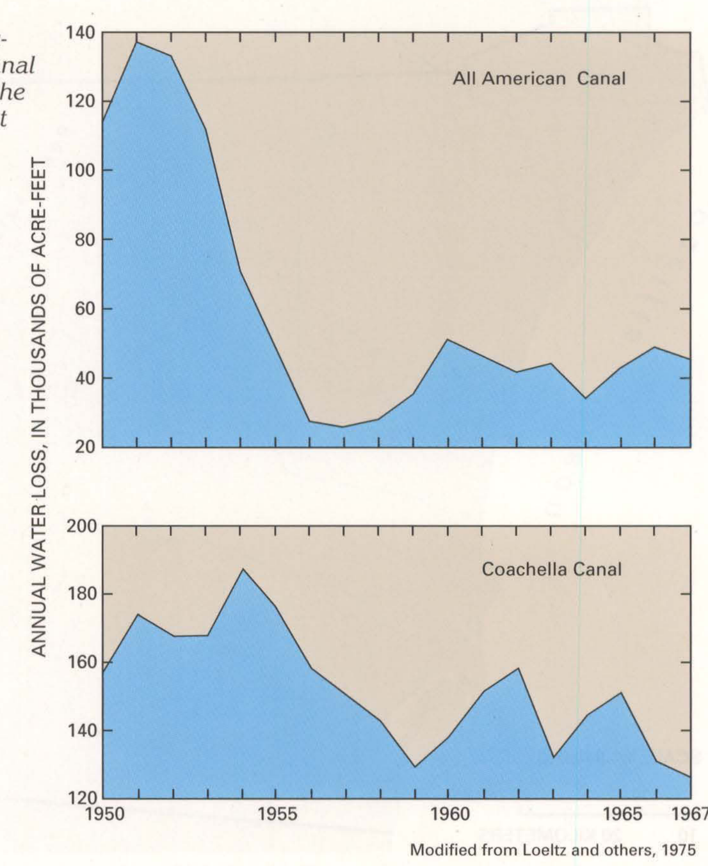


Figure 51. *Average leakage from the All American Canal and the southeastern part of the Coachella Canal totaled about 215,000 acre-feet per year during 1950 through 1967.*



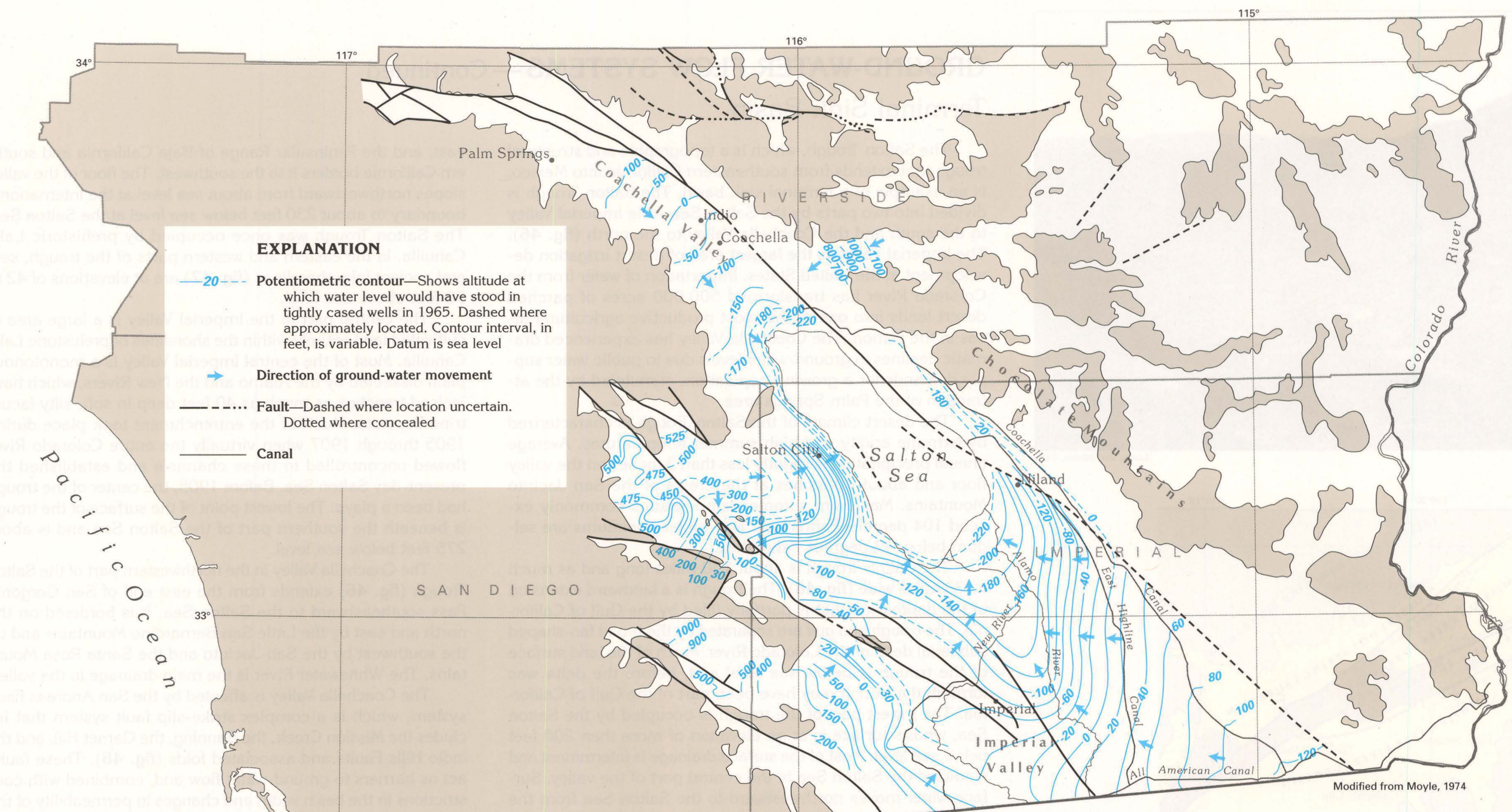


Figure 52. *The general movement of ground water in the Imperial Valley is from the bordering mountains toward the center of the valley, except in the southern part of the valley where leakage from the canals has altered the flow so that it moves in a northerly direction.*

The Colorado River has been a source of recharge to the aquifer system of the Imperial Valley since the river delta built to a height sufficient to separate the Gulf of California from the Salton Trough. As the delta was built, natural levees beside the river channel kept the Colorado River above the land surface altitude in much of the valley. Under natural conditions, water from the river seeped downward through the river bed and then moved laterally to recharge the aquifer in the Imperial Valley. The water also moved into the Imperial Valley from the Mexicali Valley to the south and through a section of alluvium northeast of the Cargo Muchacho Mountains.

Since 1901, recharge to the shallow part of the aquifer system under natural conditions has been augmented by percolation of water imported from the Colorado River beginning in 1901. Originally, water was diverted about 10 miles southwest of Yuma, Ariz., at the confluence of the Colorado River and Mexico's Alamo Canal, and was delivered to the Imperial Valley through the Alamo and the New Rivers (**fig. 46**). The completion of the All American Canal (**fig. 46**), which permitted the diversion of Coloraro River water to the Imperial Valley through a canal located entirely in the United States rather than along a route that passed through the Mexicali Valley, greatly increased the opportunity for ground-water recharge. The All American Canal became the sole means for diverting Colorado River water to the Imperial Valley in February 1942. Six years later, the Coachella Canal was completed and thereafter supplied water to the lower part of Coachella Valley.

The canals, which are as much as 200 feet wide, are major sources of recharge because they are unlined, flow across many miles of sandy terrain (especially in the eastern part of the Imperial Valley), and are much higher in altitude than the general ground-water levels along their course. The leakage from the canals almost immediately caused ground-water mounds to form beneath the canals, and, over time, ground-water levels rose to the water level in the canals. The leakage also spread horizontally, thereby causing water levels to rise over large areas. Water levels eventually rose to the point that much of the leakage, especially from the All American Canal, was discharged to drains and areas of natural discharge, rather than continuing to add to the quantity of ground water stored in the aquifer system.

The rise in water levels that resulted from leakage from the easternmost canals between 1939 (before the canals were completed) and 1960 is shown in **figure 50**. The water-level rise along the All American Canal was generally more than 40 feet, and the rise along the Coachella Canal was about 40 feet near the junction of the canal with the Colorado River and gradually increased northward to more than 70 feet. Throughout most of the length of the East Highline Canal, which began operating in 1942, the original water table was shallow, and the water-level rise was small.

Water losses along selected reaches of the All American and the Coachella Canals are shown in **figure 51**. The annual flows are generally 3,000,000 to 4,000,000 acre-feet in the reach of the All American Canal and are about 500,000 acre-feet in the reach of the Coachella Canal. From 1950 through 1967, the average leakage from the two reaches was about 215,000 acre-feet per year.

The general direction of ground-water movement in the basin-fill aquifer of the Imperial Valley and the lower part of the Coachella Valley is shown by the arrows superimposed on the water-level contour lines in **figure 52**. The contours were based on water levels in 1965 in wells completed in the main water-yielding zones.

The broad ground-water mound in the southeastern part of the valley is the result of leakage from the All American and the Coachella Canals. Between the canals, the direction of ground-water movement is principally westward, but south of the All American Canal, the movement is toward the Mexican border. Away from the canals, ground water moves generally toward the axis of the valley and then northwestward to the Salton Sea. The principal area of discharge is the central, cultivated part of the valley. Substantial amounts of ground water are discharged to the Alamo River, as indicated by the closely spaced contour lines on the eastern side of the river and the change in direction of the contours which indicates that the ground water flows primarily northward. Ground water also discharges to the New River, but the configuration of the contour lines, which show a relatively wider spacing and moderate upstream displacement, indicates that considerably less ground water moves to the New River than to the Alamo River.

Figure 53. The movement of ground water in the upper Coachella Valley in 1936 was primarily controlled by several faults. Water-level differences in the same aquifer were more than 300 feet across some of the faults.

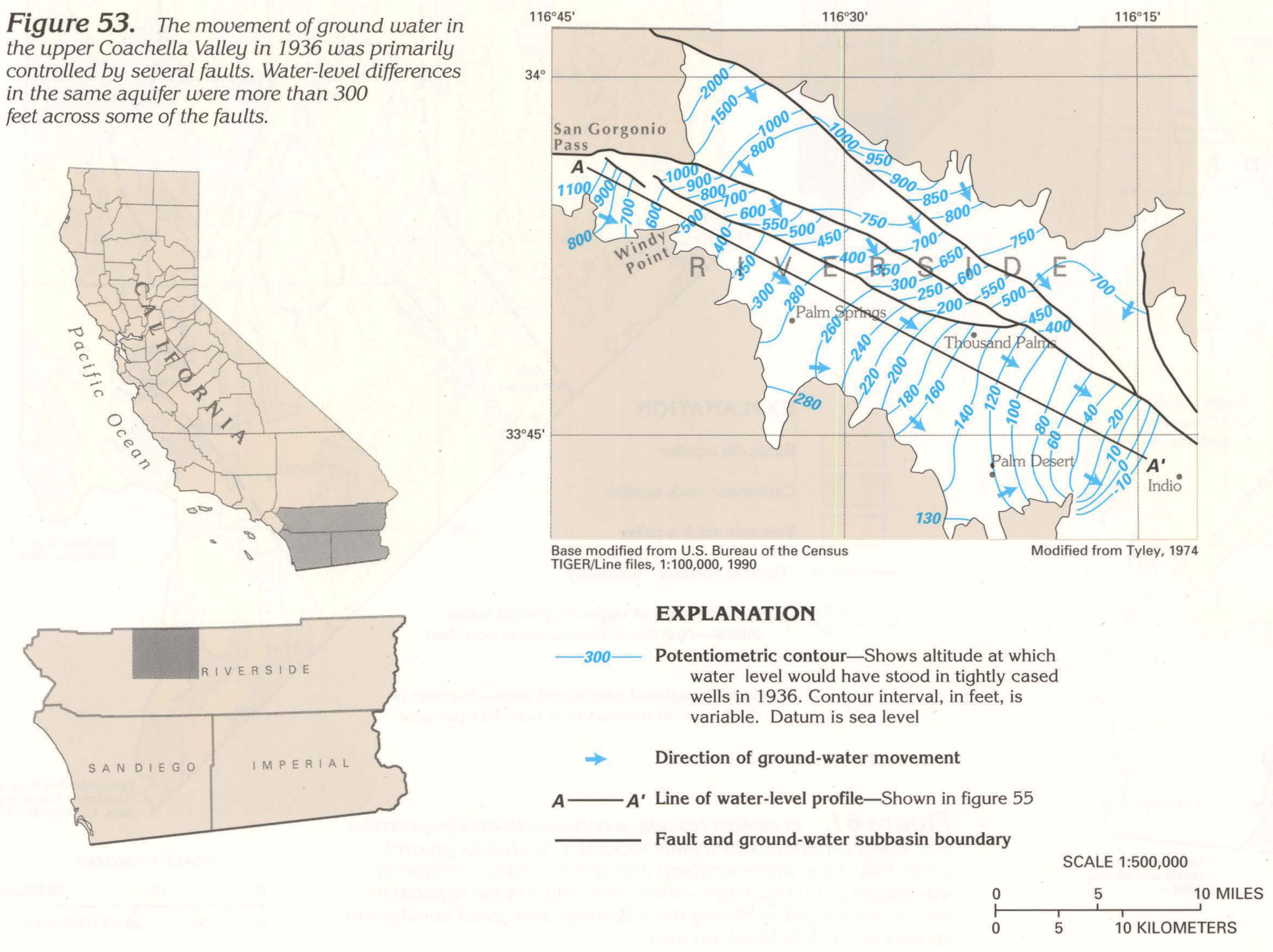


Figure 54. By 1967, ground-water development was centered in the southern one-half of the valley. Development increased the water-level differences across the faults to as much as 400 feet.

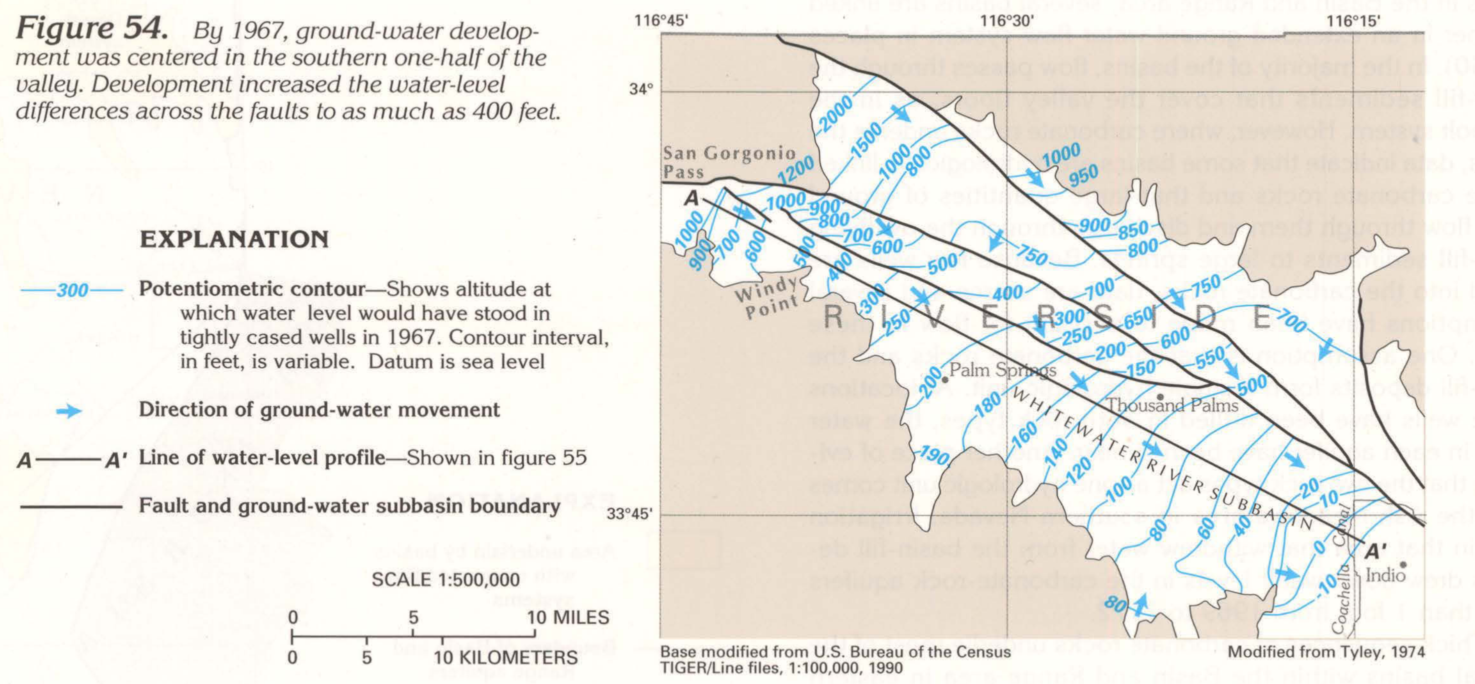
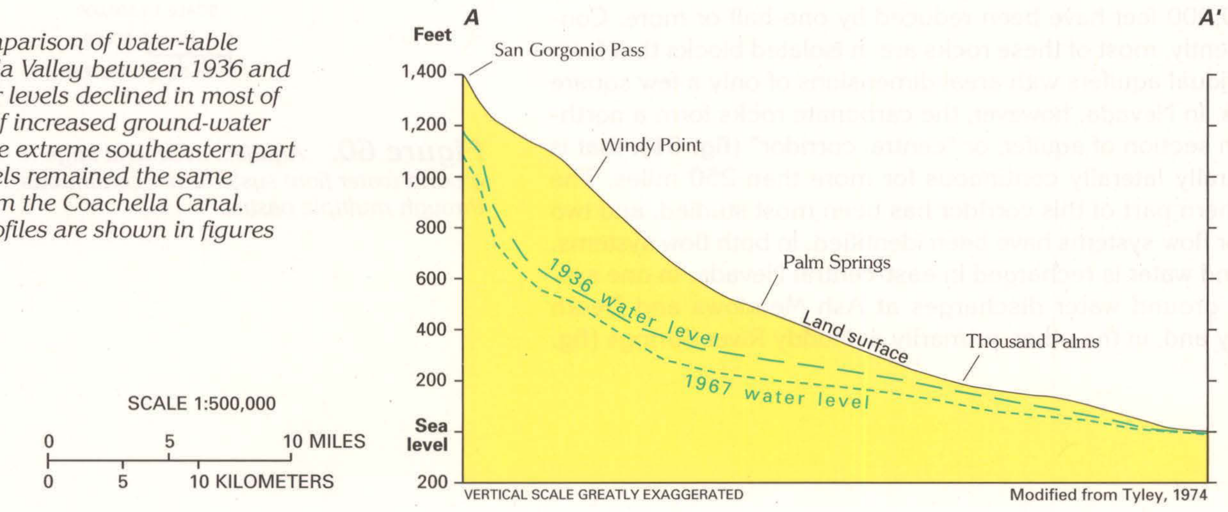


Figure 55. A comparison of water-table profiles in the Coachella Valley between 1936 and 1967 shows that water levels declined in most of the valley as a result of increased ground-water withdrawals, but in the extreme southeastern part of the valley water levels remained the same because of leakage from the Coachella Canal. The locations of the profiles are shown in figures 53 and 54.



For ground water that moves from the adjacent mountains toward the center of the valley, a wide range of contour spacing can be seen in **figure 52** that indicates changes in the hydrogeologic conditions within the aquifer. Some of the seemingly abrupt changes in contour spacing are caused by faults that are barriers to ground-water flow. The closely spaced contours west of the Coachella Canal, near Niland, and west of the Salton Sea, near Salton City, result from ground-water flow through deposits with low permeability.

Ground-water movement in and through the basin-fill aquifer of the upper Coachella Valley is affected by the San Andreas Fault System. Faults that are part of this system, as well as constrictions in basin width and changes in permeability of the water-yielding units, have compartmentalized the valley into four ground-water subbasins (**fig. 48**).

The general direction of ground-water movement in the upper Coachella Valley was determined from water-level contour maps of the basin for 1936 and 1967 (**figs. 53 and 54**). Water-level contours during the autumn of 1936 are shown in **figure 53**. The water-level profile for 1936 (**fig. 55**) shows the slope of the ground-water surface to be very steep in places and to exceed 50 feet per mile from the San Gorgonio Pass to Windy Point. This steep gradient decreased to less than 10 feet per mile just south of Palm Springs because of the increased width of the basin. From the Thousand Palms area southward, the gradient was about 20 feet per mile.

A water-level profile for 1967 (**fig. 55**) shows that while water levels declined in most places in the valley, the steep water-level gradient from the San Gorgonio Pass to Windy Point remained the same as in 1936. However, the water-level gradient at the south boundary decreased to about 10 to 15 feet per mile from the 1936 gradient of 20 feet per mile. The lowered water-level altitudes resulted from increased withdrawals within the Whitewater River subbasin. Water levels for 1967 were about the same as those for 1936 in the extreme southern part of the upper valley as a result of leakage from the Coachella Canal.

The general direction of ground-water flow in 1967 is shown in **figure 54** by arrows that represent flow lines, which are the shortest possible paths between adjacent water-level contours. Ground-water movement in the Whitewater River subbasin was primarily parallel to the axis of the valley from Windy Point to Indio. The flow lines near the faults that mark the borders of the subbasins indicate that ground water flowed across the faults; exactly how much is unknown.

Ground-water development in the Salton Trough has been primarily in the Coachella Valley. The growth of agriculture and, since the early 1950's, of tourism has drawn heavily on the ground-water resources of the upper Coachella Valley. Ground-water levels have declined as annual withdrawals increased more than tenfold during 1936 to 1967 (**fig. 56**). In the lower Coachella Valley, concern over the diminishing ground-water supply as a result of agricultural development prompted the construction of the Coachella Canal. Water delivery began in 1949 when large quantities of Colorado River water were brought to the area between Indio and the Salton Sea. However, the upper Coachella Valley received only small quantities of the canal water and, consequently, water levels continued to decline as ground-water use increased in that area.

Water levels began to decline before 1945 (**fig. 57**) in the southernmost part of the upper Coachella Valley but did not change significantly in the remainder of the upper valley until about 1945 when major withdrawals began (**fig. 56**). Water levels continued to decline throughout most of the upper valley through 1965 with the exception of an area near the southern boundary where water levels had ceased to decline and began rising. The rise is documented by observation wells 7 and 8 in 1949 and 1954, respectively (**fig. 57**). The water-level rise in these two wells can be attributed to water from the Coachella Canal leaking downward to the aquifer. The effect of leakage appeared to be moving up the valley in 1955, as indicated by the hydrograph of well 6 (**fig. 57**), in which water levels ceased to decline, indicating recharge to the aquifer by leakage.

From 1936 to 1967, water-level changes in the upper Coachella Valley (**fig. 58**) were most prominent in the Whitewater River subbasin. The Palm Springs area in that subbasin showed the largest water-level decline (nearly 80 feet) because of a concentration of withdrawals in an area with a relatively low aquifer storage capacity located near where the aquifer abuts the nearly impermeable bedrock of the San Jacinto Mountains. Decreases in water levels were probably amplified between 1946 and 1967 because of a prolonged drought in the upper Coachella Valley, as in most of southern California, during those years. A representative plot of the departure from average precipitation in the San Jacinto, the Santa Rosa, and the San Bernardino Mountains (**fig. 59**) indicates that during the dry period from 1947 through 1964 only four years were wet—1952, 1954, 1957, and 1958. This extended dry period greatly reduced the natural inflow available to the valley. The other three ground-water subbasins showed very little water-level decline because withdrawals in those subbasins were small. A well field for the town of Desert Hot Springs on the east side of the Mission Creek Fault showed some decline because the storage capacity of the aquifer in that area is limited by the juxtaposition of the aquifer with a relatively impermeable fault and the nearly impermeable bedrock of the Little San Bernardino Mountains.

Figure 56. Ground-water withdrawals remained fairly constant from 1936 until about 1945, when development of the upper Coachella Valley resulted in an increase in withdrawal. The highest annual withdrawal rate was about 55,000 acre-feet during 1965.

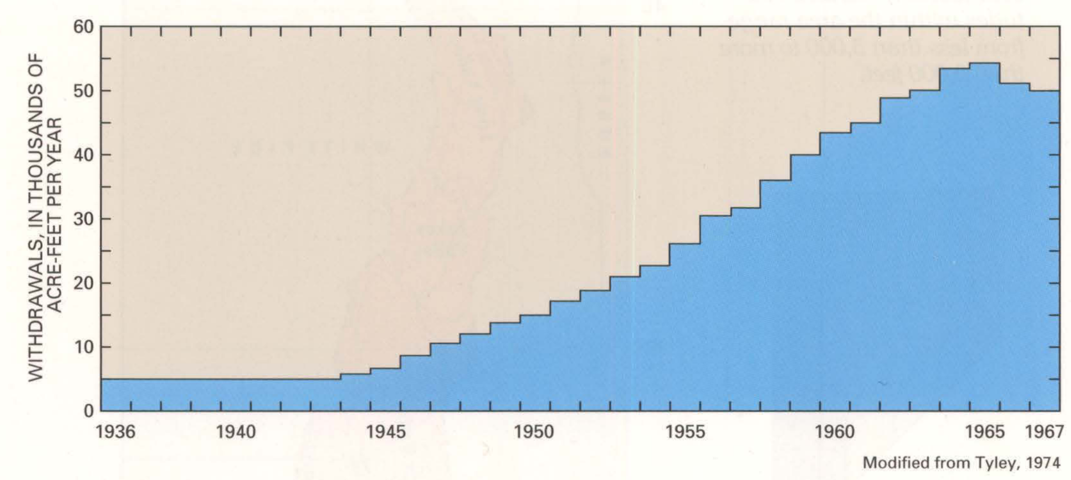


Figure 57. Hydrographs for wells in the upper Coachella Valley show a general water-level decline from 1936 to 1965. The exceptions are the wells near the Coachella Canal, where imported water locally raised ground-water levels.

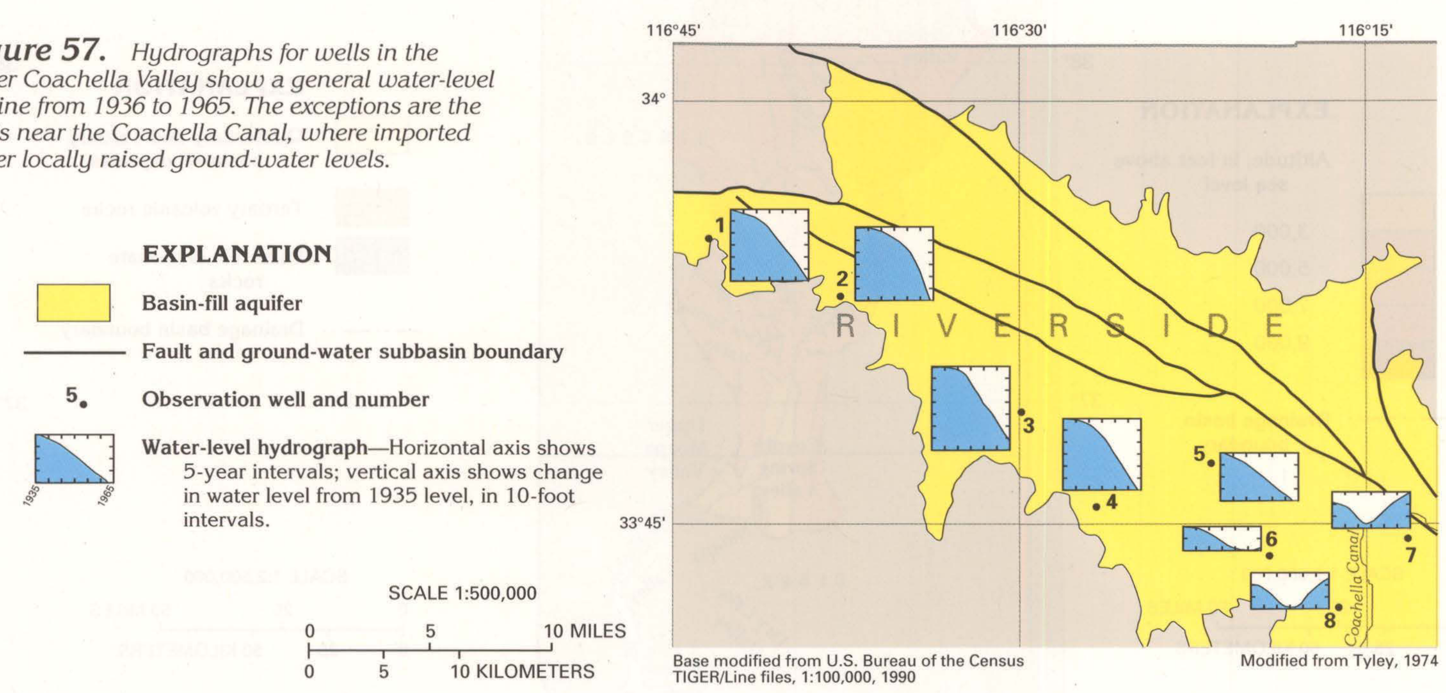


Figure 58. From 1936 to 1967, changes in water levels in the upper Coachella Valley were greatest in the Palm Springs area, where water levels declined nearly 80 feet.

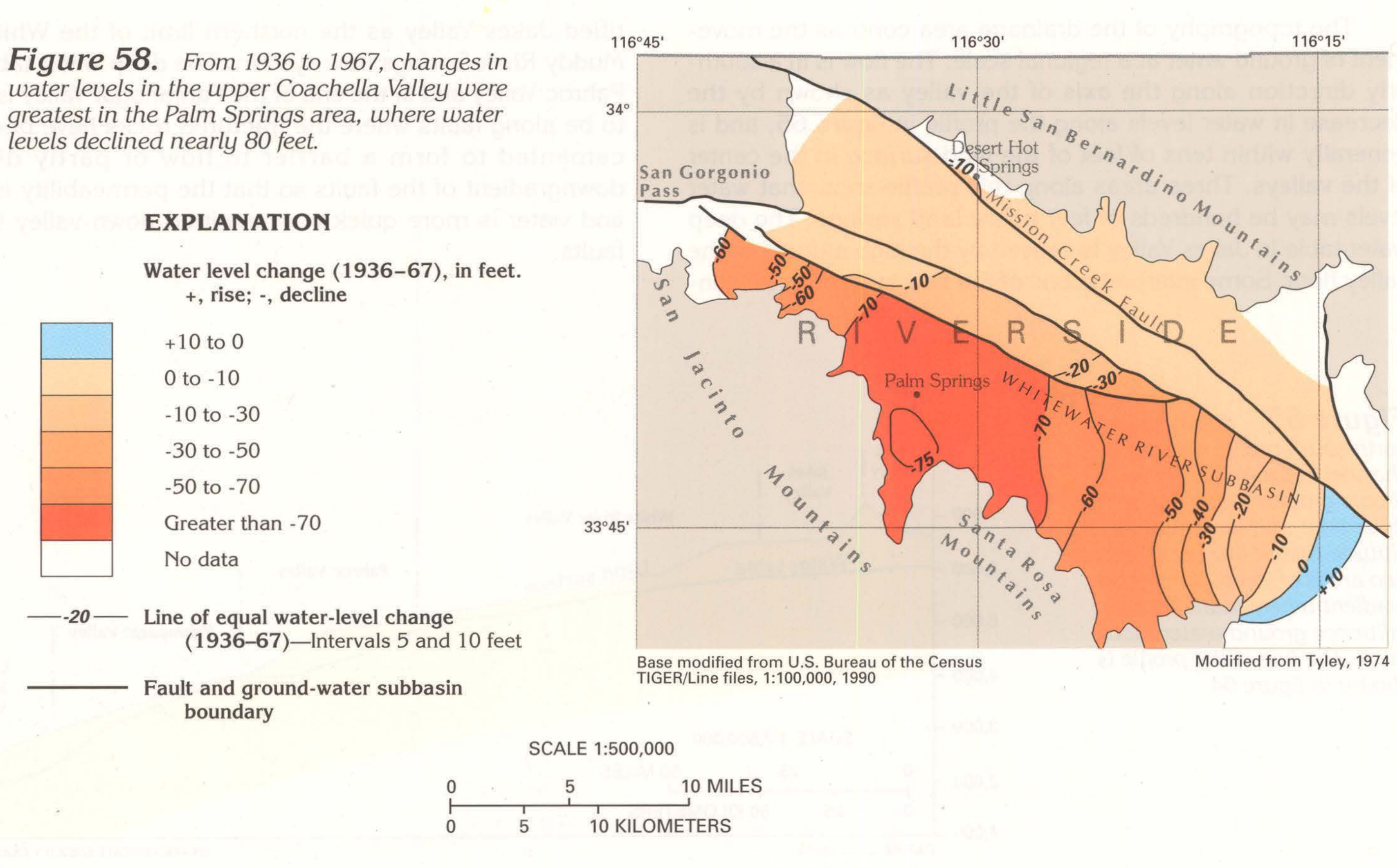
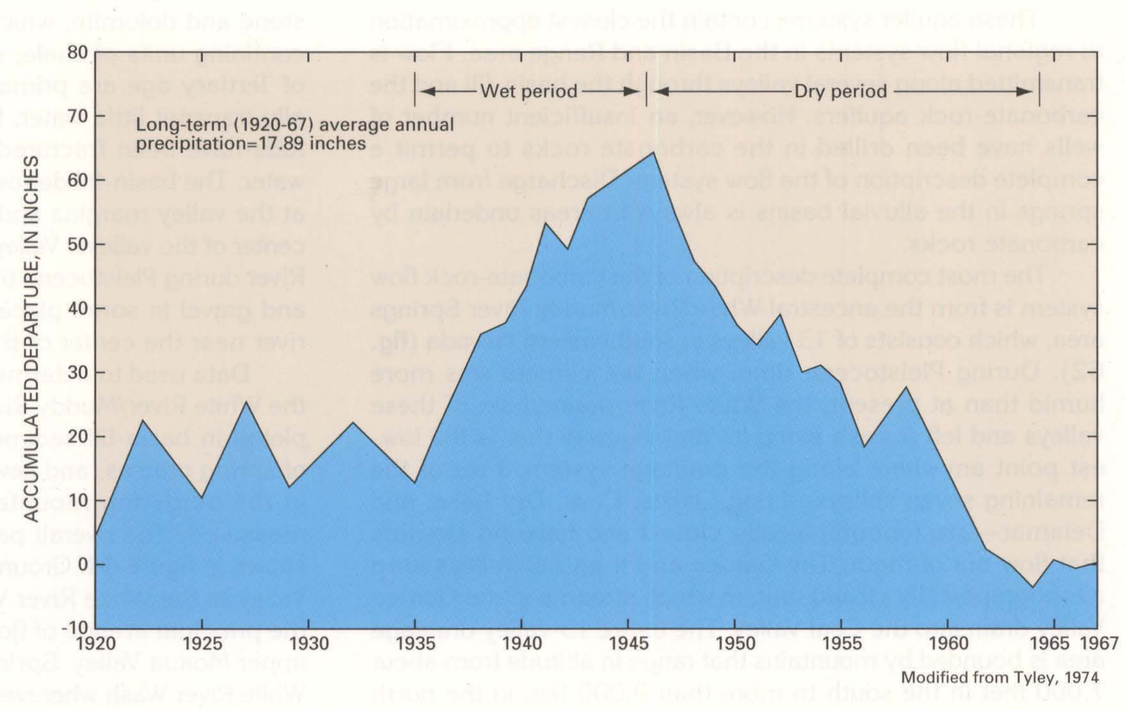


Figure 59. The accumulated departure from long-term average annual precipitation for the upper Coachella Valley shows a wet period from 1936 to 1946 and a dry period from 1947 to 1967.



Connected Basin Flow Systems

Although most flow systems are confined to one or two basins in the Basin and Range area, several basins are linked together in an extended ground-water flow system in places (**fig. 60**). In the majority of the basins, flow passes through the basin-fill sediments that cover the valley floors, as in the Humbolt system. However, where carbonate rocks underlie the basins, data indicate that some basins are hydrologically linked by the carbonate rocks and that large quantities of ground water flow through them and discharge through the overlying basin-fill sediments to large springs. Because few wells are drilled into the carbonate rocks, data are scarce and several assumptions have been made to account for flow in these rocks. One assumption is that the carbonate rocks and the basin-fill deposits form a single hydrologic unit. At locations where wells have been drilled in both rock types, the water levels in each aquifer have been similar. Another piece of evidence that the two rock types act as one hydrologic unit comes from the Ash Meadows area in southern Nevada. Irrigation wells in that area that withdrew water from the basin-fill deposits drew down water levels in the carbonate-rock aquifers more than 1 foot from 1969 to 1972.

Thick sequences of carbonate rocks underlie most of the alluvial basins within the Basin and Range area in eastern Nevada and southeastern California (**fig. 60**); these rocks also extend into western Utah, northwestern Arizona, and southeastern Idaho. The carbonate rocks have been faulted, deformed, and eroded through geologic time; original thicknesses of up to 40,000 feet have been reduced by one-half or more. Consequently, most of these rocks are in isolated blocks that form individual aquifers with areal dimensions of only a few square miles. In Nevada, however, the carbonate rocks form a north-south section of aquifer, or "central corridor" (**fig. 61**), that is generally laterally continuous for more than 250 miles. The southern part of this corridor has been most studied, and two major flow systems have been identified. In both flow systems, ground water is recharged in east-central Nevada. In one system, ground water discharges at Ash Meadows and Death Valley and, in the other, primarily at Muddy River Springs (**fig. 61**).

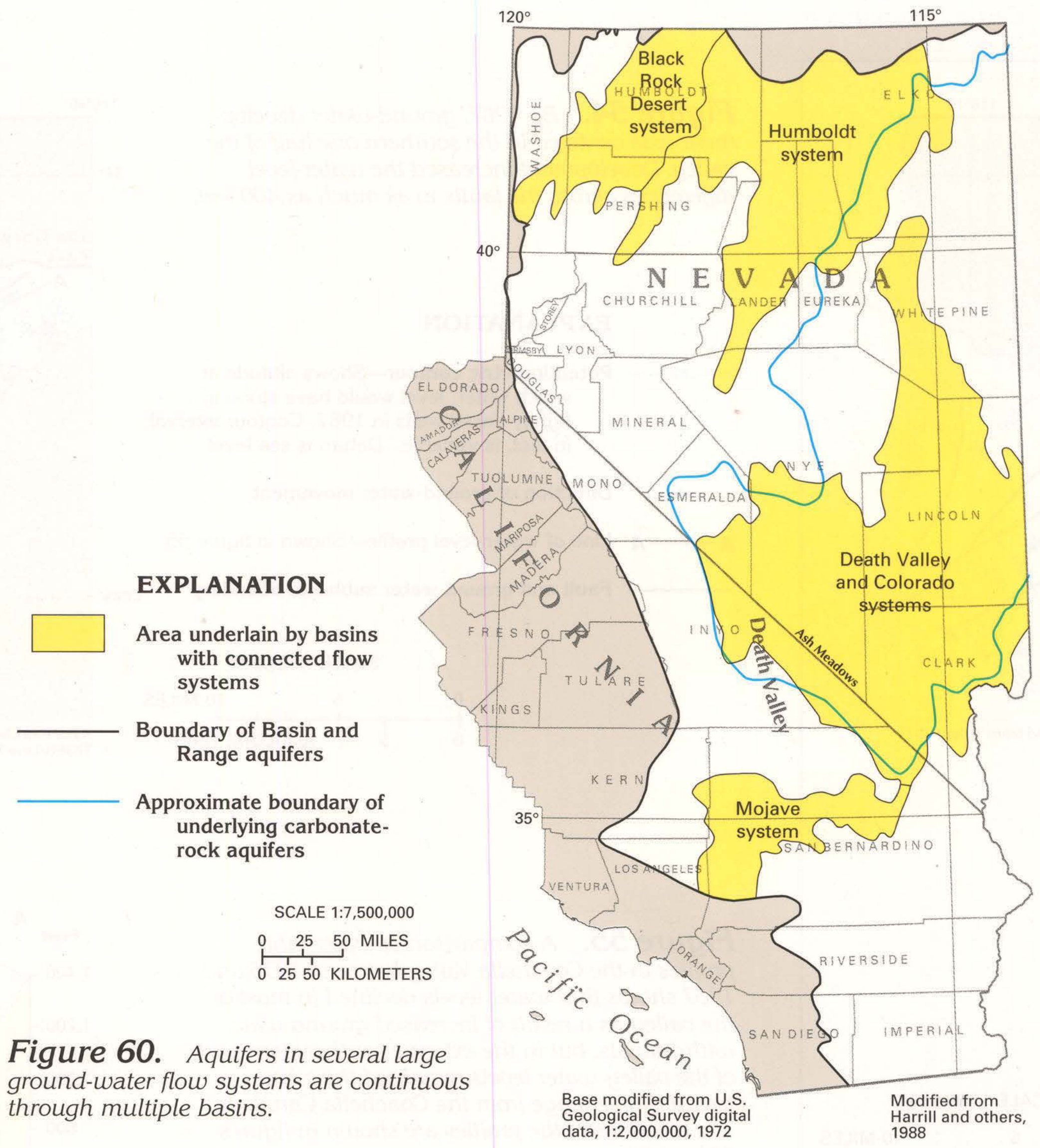


Figure 60. Aquifers in several large ground-water flow systems are continuous through multiple basins.

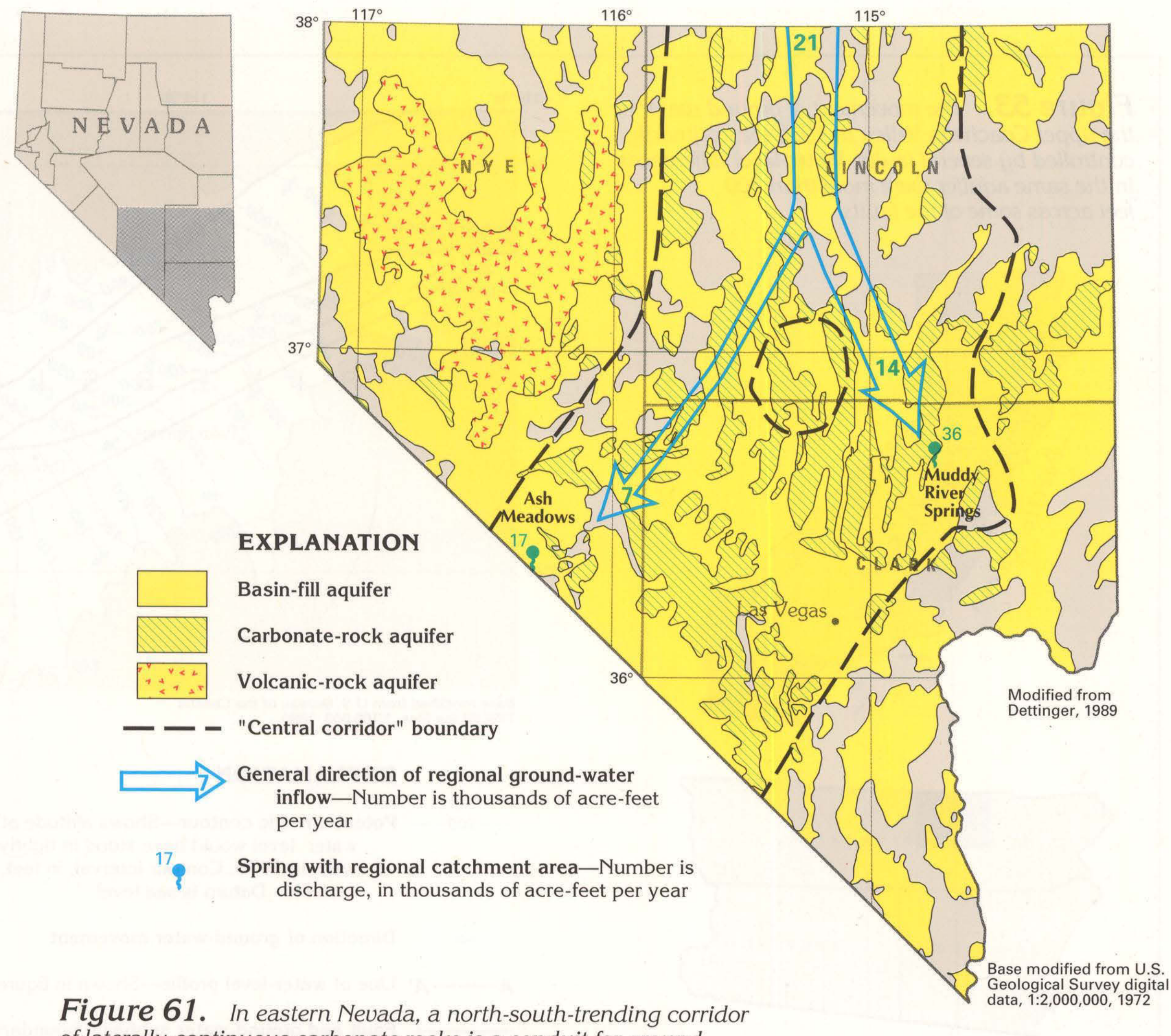


Figure 61. In eastern Nevada, a north-south-trending corridor of laterally continuous carbonate rocks is a conduit for ground-water flow. Flow in the southern part of the "central corridor" is discharged at two localities—about two-thirds of the regional inflow is discharged to Muddy River Springs, and about one-third to springs in the Ash Meadows area.

Figure 62. The White River/Muddy River Springs drainage area is located in southeastern Nevada. Altitudes within the area range from less than 3,000 to more than 9,000 feet.

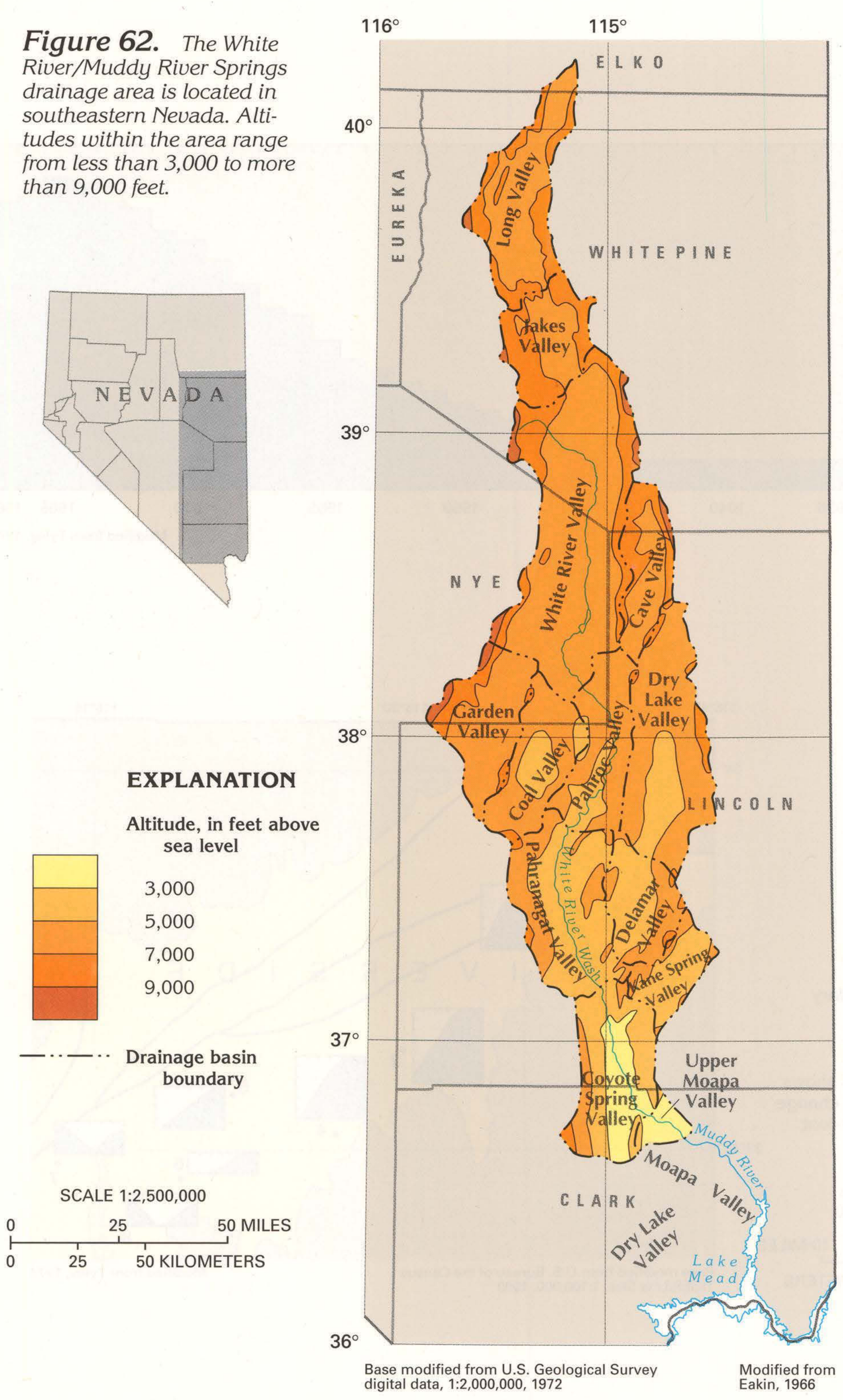


Figure 63. The geology of the White River/Muddy River Springs Basin can be generalized into three categories—basin-fill deposits, volcanic rocks, and carbonate rocks.

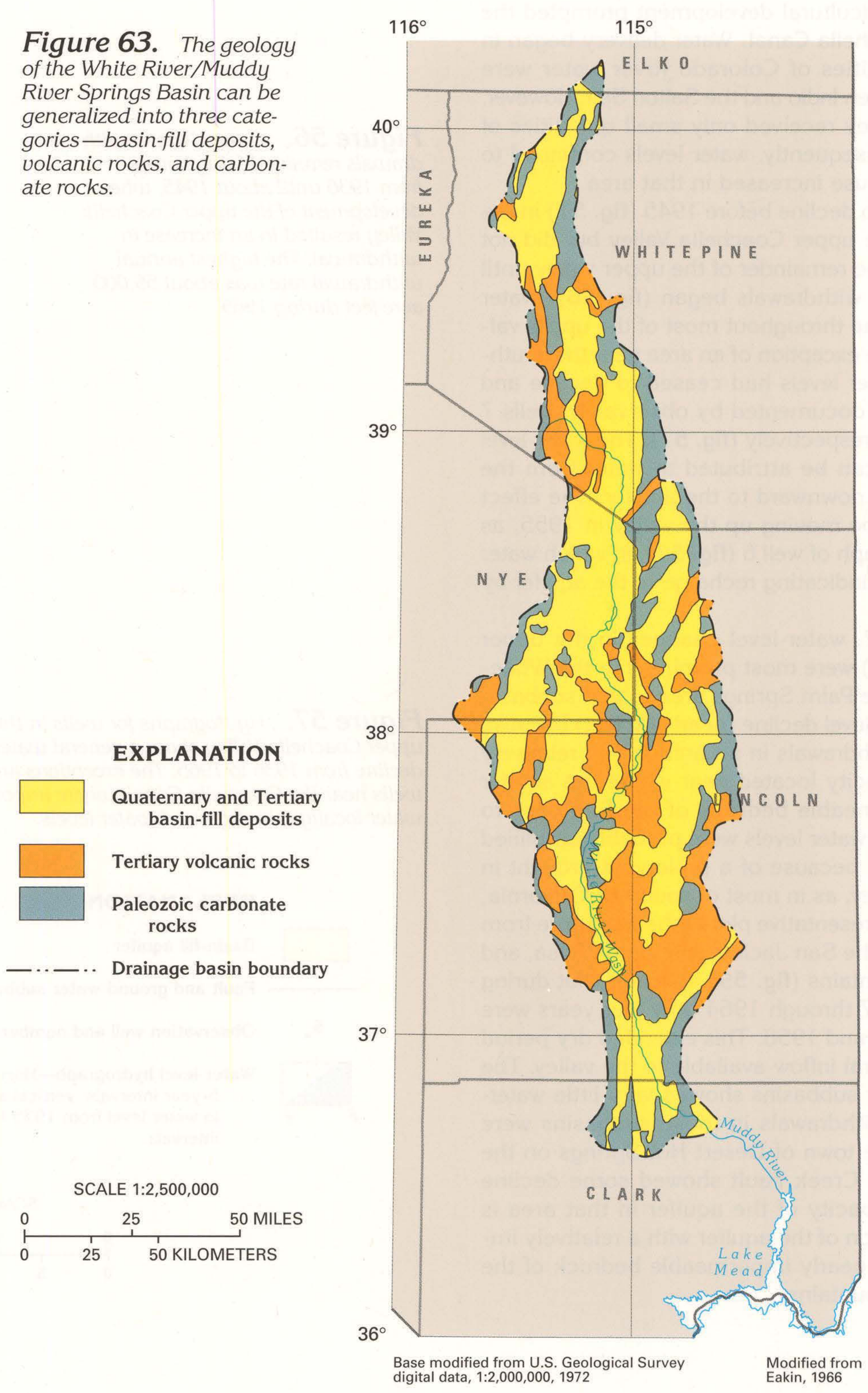
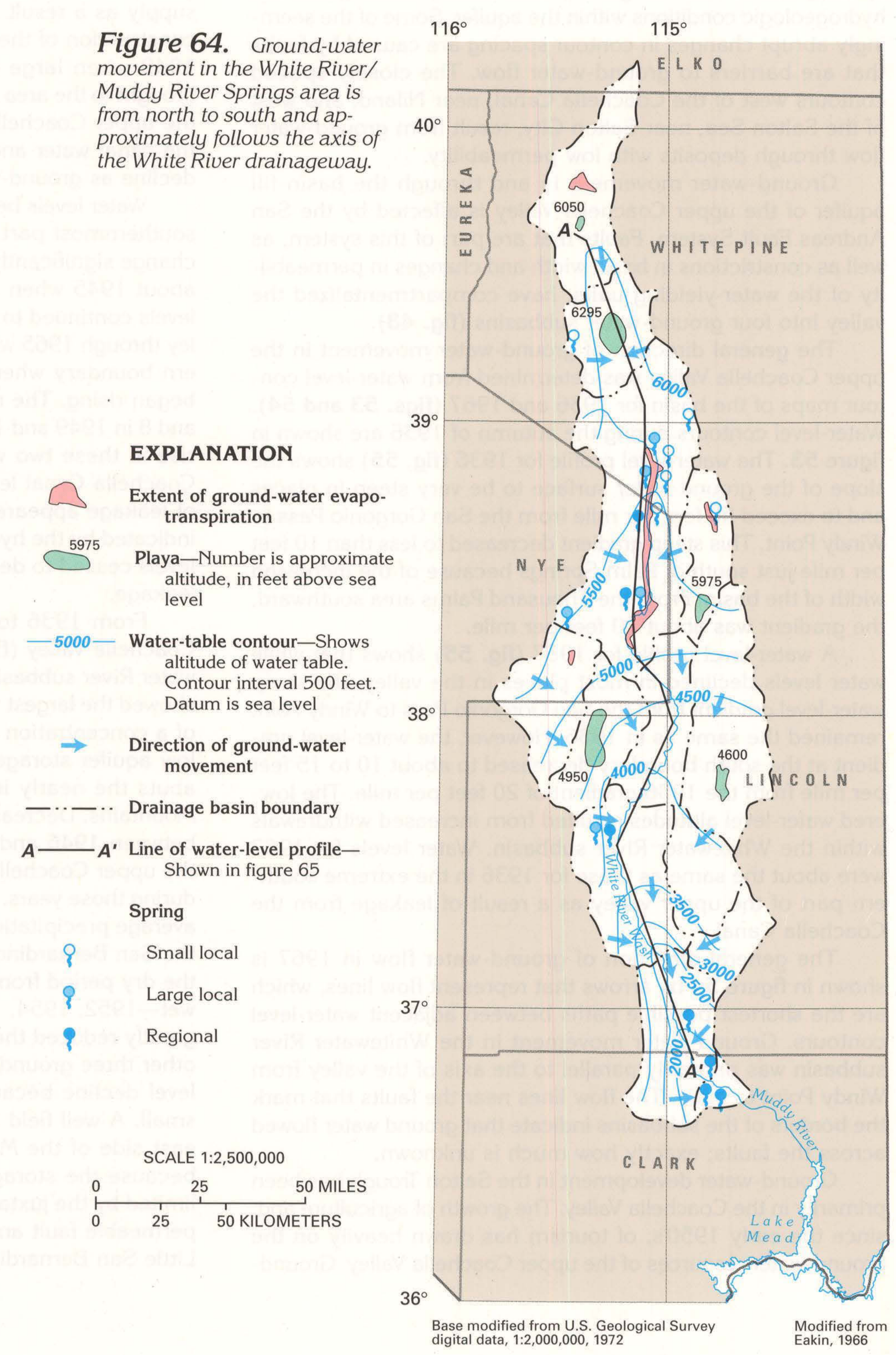


Figure 64. Ground-water movement in the White River/Muddy River Springs area is from north to south and approximately follows the axis of the White River drainageway.



These aquifer systems contain the closest approximation to regional flow systems in the Basin and Range area. Flow is transmitted along several valleys through the basin-fill and the carbonate-rock aquifers. However, an insufficient number of wells have been drilled in the carbonate rocks to permit a complete description of the flow system. Discharge from large springs in the alluvial basins is always in areas underlain by carbonate rocks.

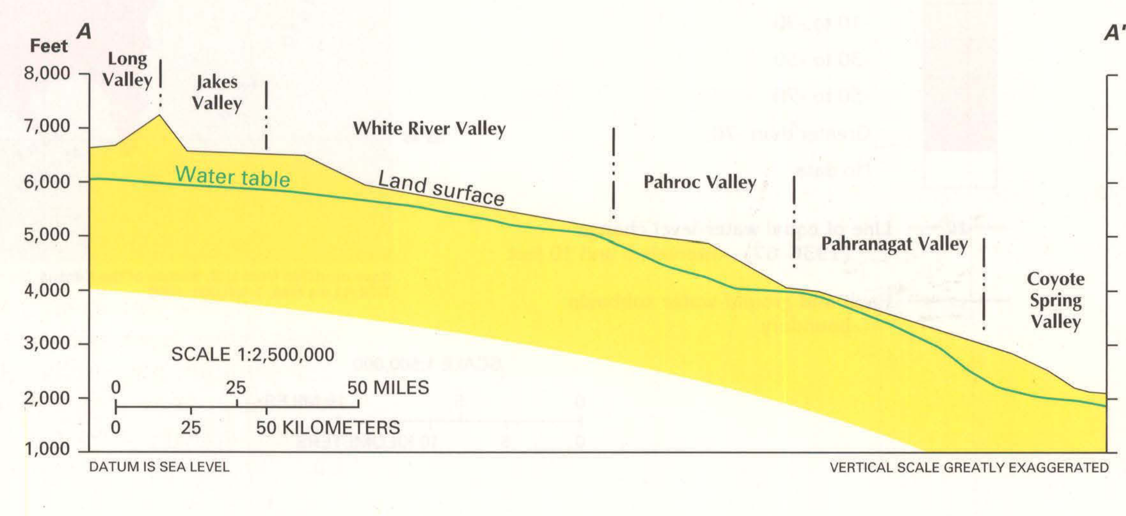
The most complete description of the carbonate-rock flow system is from the ancestral White River/Muddy River Springs area, which consists of 13 valleys in southeastern Nevada (**fig. 62**). During Pleistocene time, when the climate was more humid than at present, the White River drained six of these valleys and left a wash along its drainageway that is the lowest point anywhere along the drainage system. Five of the remaining seven valleys—Long, Jakes, Cave, Dry Lake, and Delamar—are topographically closed and have no streams that flow out of them. The Garden and the Coal Valleys form a topographically closed unit, in which streams in the Garden Valley drain into the Coal Valley. The entire 13-valley drainage area is bounded by mountains that range in altitude from about 7,000 feet in the south to more than 9,000 feet in the north (**fig. 62**).

Consolidated rocks (**fig. 63**) of Paleozoic and Tertiary age form the boundaries of and underlie the basins, which are filled with unconsolidated deposits of Tertiary and Quaternary age. The principal water-yielding rocks of Paleozoic age are limestone and dolomite, which are bounded above and below by confining units of shale, sandstone, and quartzite. The rocks of Tertiary age are primarily tuff and welded tuff and generally transmit little water. However, in areas where the welded tuffs have been fractured, they can yield large quantities of water. The basin-fill deposits consist of coarse sand and gravel at the valley margins and grade to fine silt and clay near the center of the valleys. Valleys that were transversed by the White River during Pleistocene time contain channel deposits of sand and gravel in some places along the ancestral course of the river near the center of the valley.

Data used to determine the movement of ground water in the White River/Muddy River Springs area are from wells completed in basin-fill sediments and carbonate rocks, altitudes of spring orifices, and several mine shafts in carbonate rocks in the bordering mountains where water levels have been measured. The overall pattern of ground-water movement is shown in **figure 64**. Ground water moves southward from Long Valley to the White River Valley. The White River Wash defines the principal avenue of flow from the White River Valley to the upper Moapa Valley. Springs issue at several places along the White River Wash wherever the water table is at or near the land surface. Valleys that border the main drainageway of the White River—the Garden, the Coal, the Cave, the Dry Lake, and the Delamar Valleys—do not drain directly to the main drainageway but rather to the south where the ground water leaves them.

The topography of the drainage area controls the movement of ground water at a regional scale. The flow is in a southerly direction along the axis of the valley as shown by the decrease in water levels along the profile in **figure 65**, and is generally within tens of feet of the land surface in the center of the valleys. Three areas along this profile show that water levels may be hundreds of feet below land surface. The deep water table in Jakes Valley is caused by the high altitude of the valley floor. Some interpretations of the flow system have identified Jakes Valley as the northern limit of the White River/Muddy River Springs flow system. The deep water table in the Pahroc Valley and at the end of the Pahranagat Valley is thought to be along faults where the fractured rocks have been either cemented to form a barrier to flow or partly dissolved downgradient of the faults so that the permeability is greater and water is more quickly transmitted down-valley from the faults.

Figure 65. A generalized north-south profile along the channel of the White River shows ground-water levels (blue line) and land surface altitude (black line) and reveals two areas of steep water-level gradient where faults might influence ground-water movement. The line of the profile is shown in figure 64.



The intervalley ground-water flow pattern and the estimated water budget for the flow system are shown in **figure 66**. The estimated recharge to the valleys was based on the relation of altitude to annual precipitation (**table 2**). Because of the orographic effect of the mountains, the amount of precipitation increases as the altitude increases. Conversely, the amount of evapotranspiration decreases as altitude increases, as a consequence of lower temperatures at higher altitudes. Because of higher altitudes and lower temperatures in the northern one-half of the White River/Muddy River Springs drainage area, about 70 percent of the recharge is estimated to be in this one-half of the area. From measurements of spring discharge, about 62 percent of the discharge of the system has been determined to be in the Pahranagat and the upper Moapa Valleys in the southern one-half of the area. This distribution of recharge and discharge is additional evidence of interbasin flow. The substantial amount of ground water that moves from the northern to the southern one-half of the area must flow through the carbonate rocks.

Interbasin flow within the carbonate rocks also is indicated by the water chemistry of perennial springs. Three classifications of the types of flow systems that feed the springs have been defined in the White River/Muddy River Springs area—regional, large local, and small local. Chemical analyses of water that discharges from perennial springs indicates that increased concentrations of dissolved constituents associated mostly with carbonate rocks are observed with regional systems characterized by long flow paths. Gypsum, anhydrite, halite, and scattered clay minerals in the carbonate rocks are dissolved more readily than carbonate minerals and they contribute sodium, potassium, chloride, and sulfate ions to ground water. Concentrations of these ions increase the longer the ground water is in circulation through the carbonate rocks. At each perennial spring that issues from the carbonate rocks, an indication of the relative distance the water has traveled can be determined by the concentration of these ions. Also, the temperature of the water discharged from a spring indicates the probable depth of ground-water circulation; higher temperatures are associated with the deep circulation of regional systems.

The concentration of tritium in water that issues from perennial springs has been used to determine places where ground water has had a short residence time in an aquifer. Before 1954, tritium, a hydrogen isotope, was scarce in the atmosphere. Beginning in 1954, detonation of thermonuclear bombs released large concentrations of tritium to the atmosphere in the northern hemisphere. Springs with water that contains tritium in concentrations of 200 units or more (**fig. 67**) are likely to be discharging a large percentage of ground water that has been in the aquifer for only a short time, perhaps only a few months.

A plot of concentrations of sodium and potassium ions against chloride and sulfate ions in water from the carbonate rocks in Nevada (**fig. 68**) shows the relation of these ions to the regional, large local, and small local flow systems. Regional flow systems are characterized by interbasin flow, long flow paths, and one or more local systems that feed the regional system. Springs connected to these systems have large perennial discharges and small seasonal ranges in discharge. Discharge waters contain relatively large concentrations of sodium, potassium, chloride, and sulfate ions but have small concentrations of tritium (**fig. 68**). Some springs discharge thermal water (greater than 80 degrees Fahrenheit).

Large local flow systems are characterized by predominantly interbasin flow and flow paths that are typically confined to one basin. Springs connected to these systems have moderate to large discharges and moderate seasonal ranges in discharge. Discharge waters contain moderate concentrations of sodium plus potassium and chloride plus sulfate (**fig. 68**) and no significant concentrations of tritium. Discharge waters have temperatures that typically range from 50 to 60 degrees Fahrenheit.

Small local flow systems are generally characterized by very short flow paths, usually no more than a few miles in length. Springs connected to these systems have highly variable annual ranges in discharge. Discharge waters have small concentrations of dissolved sodium plus potassium and chloride plus sulfate, large concentrations of tritium, and water temperatures that commonly approach average air temperatures.

The evidence of regional flow in the carbonate rocks can be used to evaluate the water-supply potential of the White River/Muddy River Springs Basin. Even if the carbonate-rock aquifer, as yet undeveloped, can supply additional water, the effect of such development upon the aquifer remains uncertain. The effect could be minimal if development can merely capture ground water currently being lost to evapotranspiration in the southern part of the White River/Muddy River Springs area. More information about the aquifer system, particularly data that pertains to aquifer boundaries, is needed in order to accurately determine the potential effects of development

Table 2. *Recharge to the White River/Muddy River Springs ground water system can be estimated from assumed values of precipitation on the basis of altitude zones, and percentages of those values used to infiltrate as recharge*

[From: Eakin, 1966]

Precipitation zone, (inches)	Altitude zone, (feet above sea level)	Assumed average annual precipitation, (feet)	Assumed average annual recharge to ground water, as a percentage of average precipitation
Less than 8	Below 6,000	Variable	Negligible
8 to 12	6,000 to 7,000	0.83	3
12 to 15	7,000 to 8,000	1.12	7
15 to 20	8,000 to 9,000	1.46	15
More than 20	More than 9,000	1.75	25

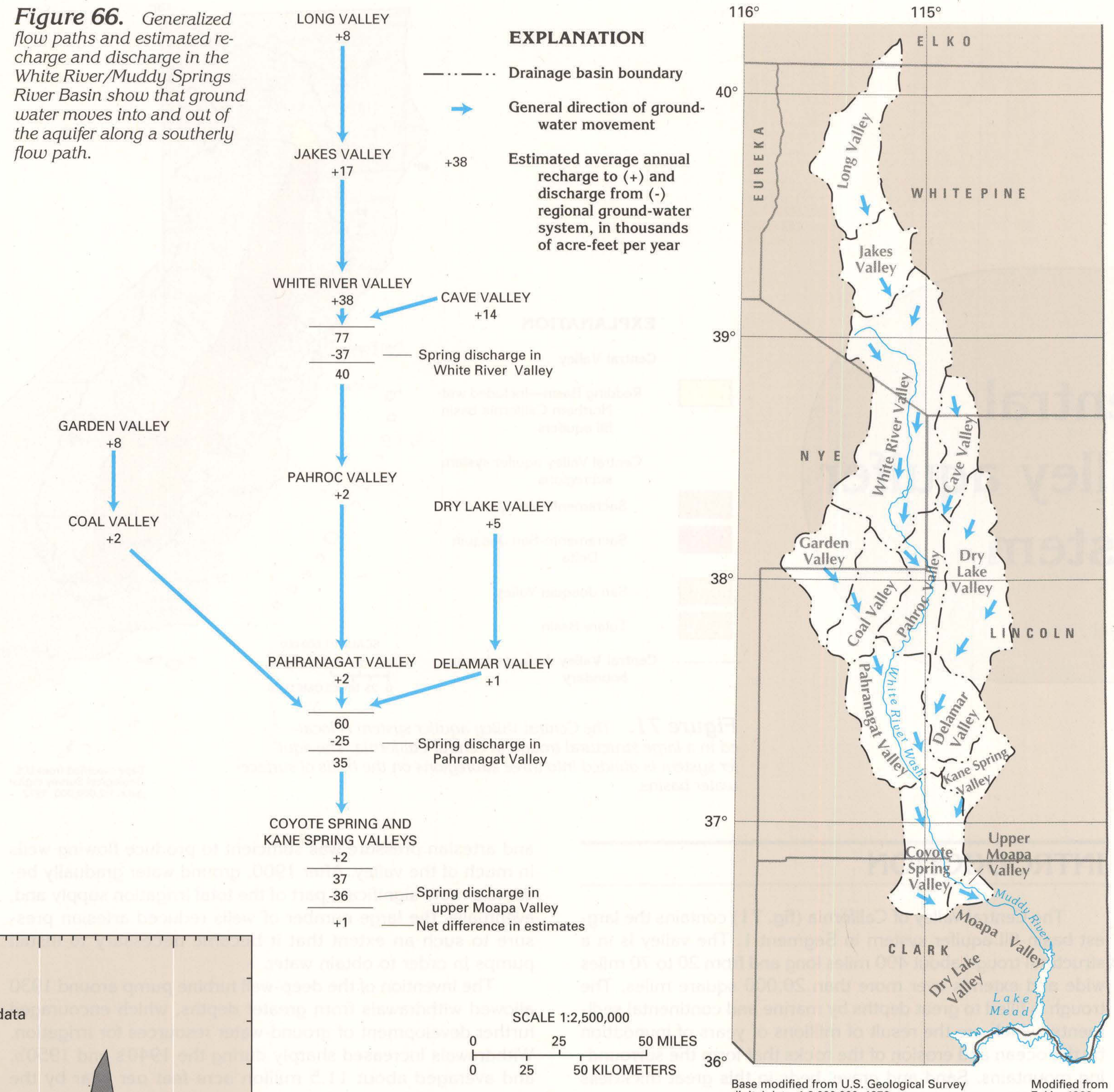


Figure 66. *Generalized flow paths and estimated recharge and discharge in the White River/Muddy Springs River Basin show that ground water moves into and out of the aquifer along a southerly flow path.*

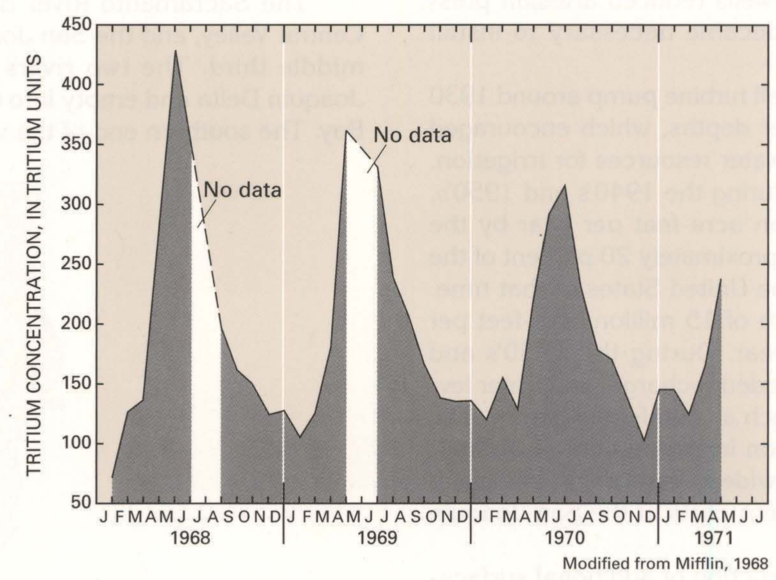


Figure 67. *Large seasonal variations in tritium concentrations in water from Cave Creek Spring, northwest of Long Valley, indicate that ground water moves along short flow paths from recharge areas to the springs and that the water is in contact with aquifer minerals for only a short time.*

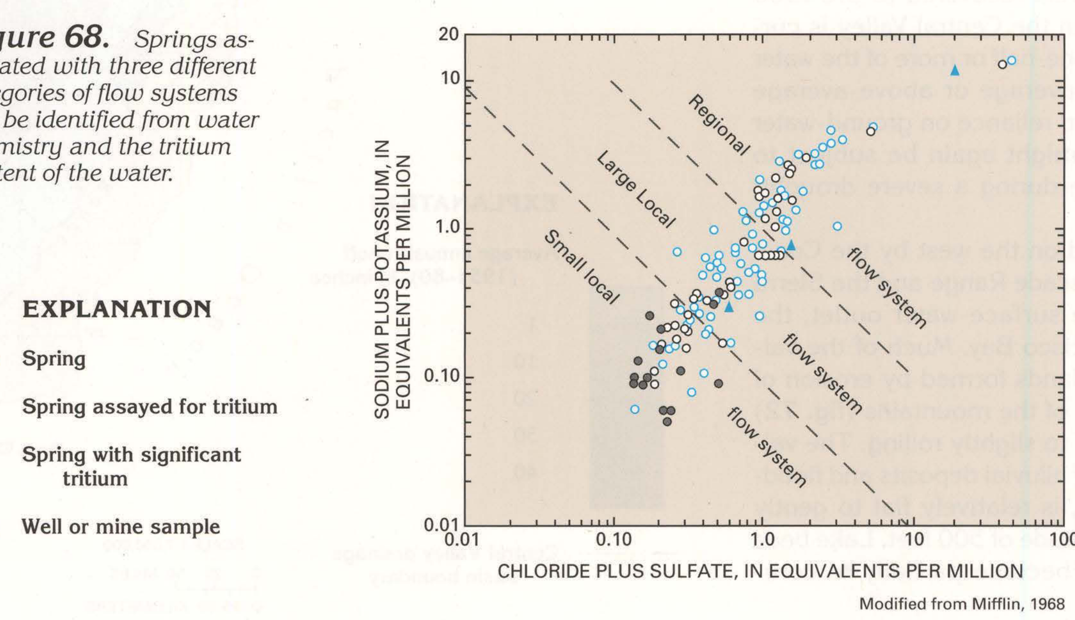


Figure 68. *Springs associated with three different categories of flow systems can be identified from water chemistry and the tritium content of the water.*

FRESH GROUND-WATER WITHDRAWALS

An estimated 1,760,000 acre-feet per year of freshwater was withdrawn from aquifers in the Basin and Range area during 1985 (**fig. 69**). Withdrawals for irrigated agriculture accounted for almost 77 percent of the total. Public supply accounted for almost 18 percent of withdrawals. All other categories totaled less than 6 percent of fresh ground-water withdrawals.

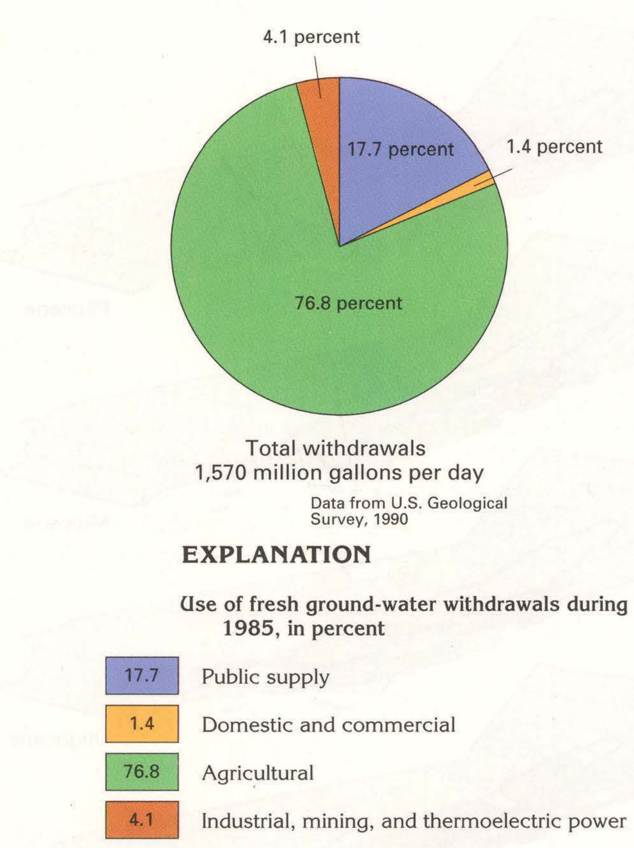


Figure 69. *Agriculture (primarily irrigation) is by far the greatest use of ground water withdrawn from the Basin and Range aquifers.*

GROUND-WATER QUALITY

The quality of ground water in unconsolidated deposits in the Basin and Range area varies from basin to basin; dissolved-solids concentrations range from less than 500 milligrams per liter (freshwater) to more than 10,000 milligrams per liter, as shown in **figure 70**. Generally, at the basin margins and on the slopes of alluvial fans, the ground water is fresh. Locally, saline water is present near some thermal springs associated with indurated sedimentary rocks or igneous rocks and in areas where the basin-fill aquifers include large amounts of soluble salts, such as in the upper and middle parts of the Humbolt River Basin. In discharge, or sink, areas such as the Carson and Salton Sinks and Death Valley, however, the dissolved-solids concentration can exceed that of ocean water (about 35,000 milligrams per liter). The ground water beneath playas in small closed valleys may be brackish, but ordinarily the dissolved-solids concentrations are not as large as those in water from the major terminal sinks. Although highly mineralized water is common beneath playas, a deeper freshwater flow system might be present in some areas. For example, water from a well 1,200 feet deep on the northern margin of a playa in a valley near Tonapah, Nev. (**fig. 70**), has a dissolved-solids concentration of less than 350 milligrams per liter. This concentration apparently reflects deep freshwater circulation in the basin-fill aquifer. In valleys with subsurface discharge into an extensive ground-water system, the water throughout the basin-fill aquifer is generally fresh.

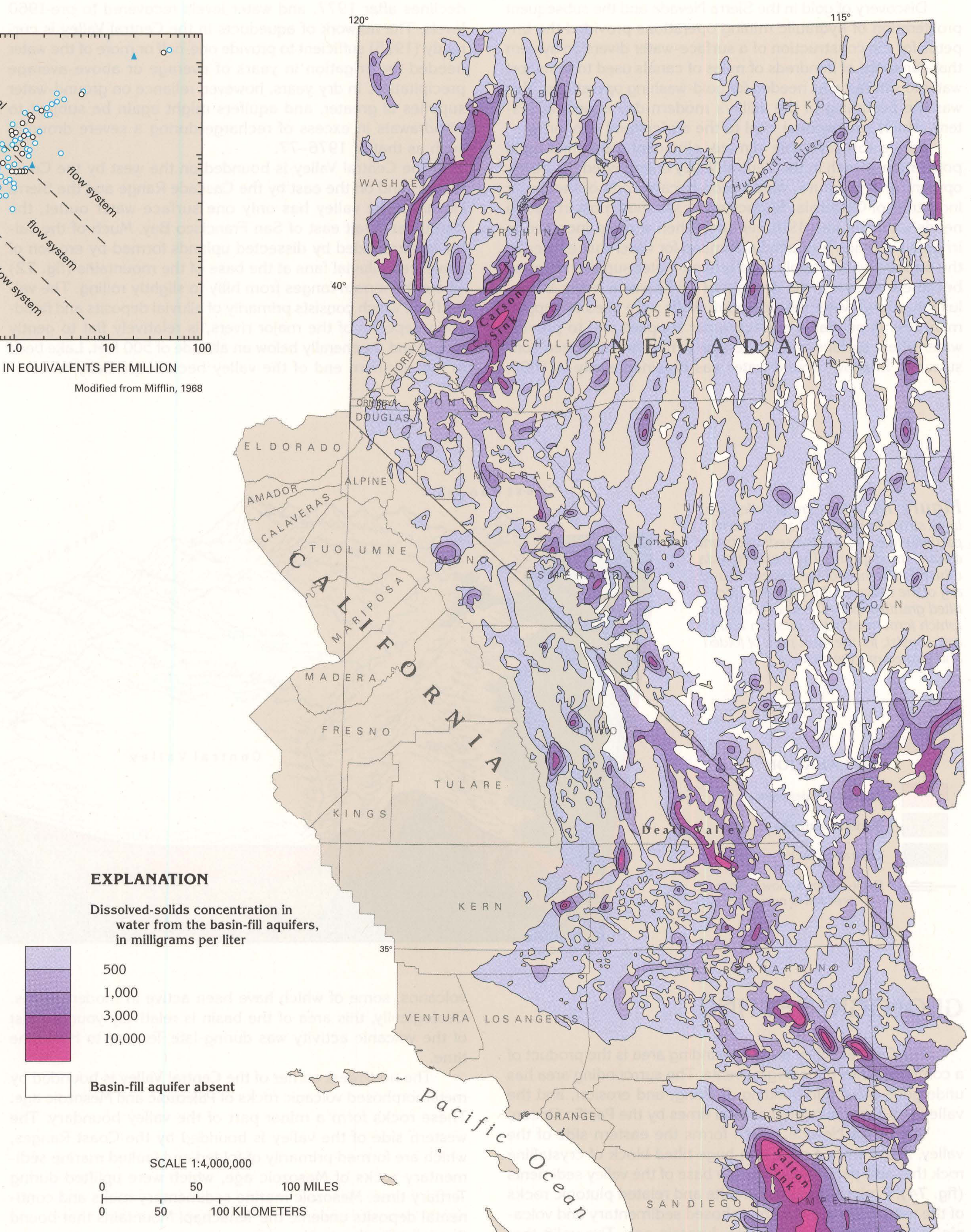


Figure 70. *Dissolved-solids concentrations in water from the unconsolidated basin-fill aquifers generally increase from the basin borders, where the aquifers are recharged by the influx of water from the mountains, to the center of the basins, where evapotranspiration concentrates the minerals dissolved in the ground water.*

Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972

Modified from Thompson and Chappell, 1984; and Thompson and others, 1984

Central Valley aquifer system

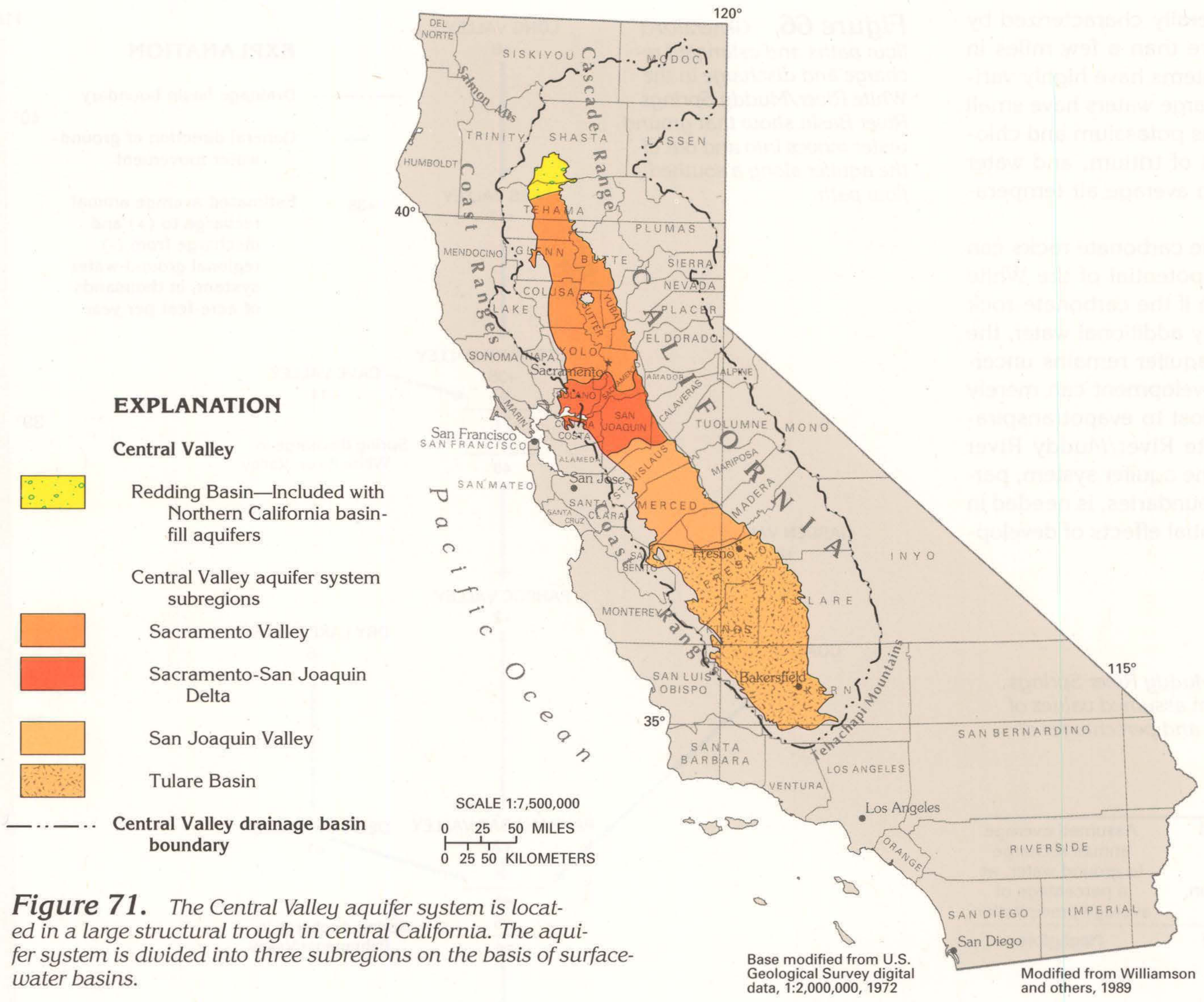


Figure 71. *The Central Valley aquifer system is located in a large structural trough in central California. The aquifer system is divided into three subregions on the basis of surface-water basins.*

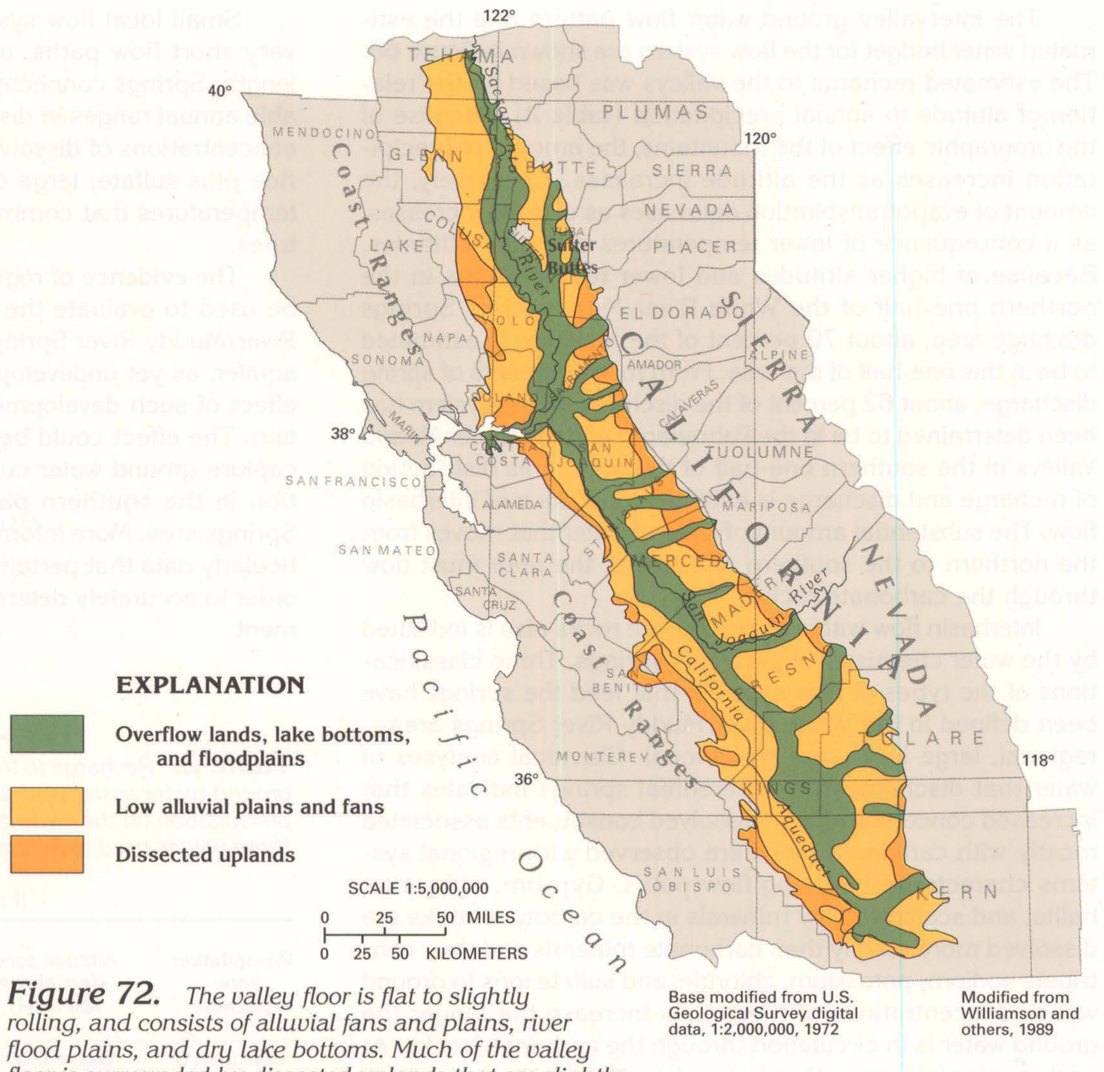


Figure 72. *The valley floor is flat to slightly rolling, and consists of alluvial fans and plains, river flood plains, and dry lake bottoms. Much of the valley floor is surrounded by dissected uplands that are slightly rolling to hilly.*

INTRODUCTION

The Central Valley of California (**fig. 71**) contains the largest basin-fill aquifer system in Segment 1. The valley is in a structural trough about 400 miles long and from 20 to 70 miles wide and extends over more than 20,000 square miles. The trough is filled to great depths by marine and continental sediments, which are the result of millions of years of inundation by the ocean and erosion of the rocks that form the surrounding mountains. Sand and gravel beds in this great thickness of basin-fill material form an important aquifer system. From north to south, the aquifer system is divided into the Sacramento Valley, the Sacramento–San Joaquin Delta, and the San Joaquin Valley subregions, on the basis of different characteristics of surface-water basins.

The Central Valley is one of the most important agricultural areas in the world. No single region of comparable size in the United States produces more fruits, vegetables, and nuts. More than 7 million acres are currently (1995) under irrigation. During 1985, crop irrigation accounted for 96 percent of the surface water and 89 percent of the ground water withdrawn in the Central Valley.

Discovery of gold in the Sierra Nevada and the subsequent proliferation of hydraulic mining operations provided the impetus for the construction of a surface-water diversion system that consisted of hundreds of miles of canals used to transport water to where it was needed for gold-washing operations. This was the beginning of the valley's modern-day aqueduct system, which has become vital to the agricultural economy.

Fertile soil, favorable climate, abundant water, and rapid population growth in the Central Valley encouraged the development of agriculture, which soon became one of the major industries of California. Surface water satisfied most irrigation needs until the late 19th century, when a rapid increase in irrigated acreage produced a demand for water that exceeded the surface-water supply, and ground-water supplementation became necessary; the drought of 1880 was a major stimulus for ground-water development. Wells were used to supplement less dependable surface-water supplies and to provide water where surface-water diversion canals had not been constructed. Shallow ground water was obtained easily in 1880, and artesian pressure was sufficient to produce flowing wells in much of the valley. After 1900, ground water gradually became a more significant part of the total irrigation supply and, eventually, the large number of wells reduced artesian pressure to such an extent that it became necessary to install pumps in order to obtain water.

The invention of the deep-well turbine pump around 1930 allowed withdrawals from greater depths, which encouraged further development of ground-water resources for irrigation. Withdrawals increased sharply during the 1940's and 1950's, and averaged about 11.5 million acre-feet per year by the 1960's and 1970's, which was approximately 20 percent of the total irrigation withdrawals for the United States at that time. Withdrawals reached a maximum of 15 million acre-feet per year during 1977, a drought year. During the 1960's and 1970's, withdrawals greatly exceeded recharge, and water levels declined precipitously, as much as 400 feet in places. The declines caused a major reduction in the amount of ground-water in storage and resulted in widespread land subsidence, mainly in the western and southern parts of the San Joaquin Valley.

Increased rainfall and construction of additional surface-water delivery systems halted most of the serious water-level declines after 1977, and water levels recovered to pre-1960 levels. The network of aqueducts in the Central Valley is currently (1995) sufficient to provide one-half or more of the water needed for irrigation in years of average or above-average precipitation. In dry years, however, reliance on ground-water supplies is greater, and aquifers might again be subject to withdrawals in excess of recharge during a severe drought, such as that of 1976–77.

The Central Valley is bounded on the west by the Coast Ranges and on the east by the Cascade Range and the Sierra Nevada. The valley has only one surface-water outlet, the Carquinez Strait east of San Francisco Bay. Much of the valley is surrounded by dissected uplands formed by erosion of coalesced alluvial fans at the base of the mountains (**fig. 72**) where the terrain ranges from hilly to slightly rolling. The valley floor, which consists primarily of alluvial deposits and flood-plain deposits of the major rivers, is relatively flat to gently rolling and is generally below an altitude of 500 feet. Lake beds in the southern end of the valley become partially to completely flooded in wet years. A prominent feature, Sutter Buttes, which is the remnant of a volcanic plug, rises nearly 1,500 feet above the valley floor in the central Sacramento Valley.

The Sacramento River drains the northern end of the Central Valley, and the San Joaquin River drains much of the middle third. The two rivers join in the Sacramento–San Joaquin Delta and empty into the upper end of San Francisco Bay. The southern end of the valley is occupied by the Tulare Basin, in which drainage is completely internal and the inflowing water is removed by evapotranspiration.

The climate of the Central Valley is Mediterranean and Steppe, characterized by hot summers and mild winters, thus allowing for a year-around growing season; at least one crop is under cultivation at all times. About 85 percent of the precipitation falls from November to April. Most of the precipitation that falls on the valley floor evaporates before it can infiltrate downward to become recharge. Much of the moisture that moves inland from the Pacific Ocean is intercepted by the Coast Ranges, so that annual precipitation in the valley is relatively low. Annual precipitation decreases from north to south, with an average of about 23 inches in the northern part of the Sacramento Valley, to about 6 inches in the southern part of the San Joaquin Valley. Rainfall amounts vary greatly from year to year. Annual precipitation is exceeded by potential evapotranspiration throughout the entire valley, which causes a net annual moisture deficit.

In contrast, the mountains that surround the Central Valley intercept moisture from eastward-moving weather systems and have an annual surplus of moisture in the form of rain and snow. Precipitation can exceed 80 inches annually in the Sierra Nevada. Annual runoff from rainfall and snowmelt is approximately 32 million acre-feet; most of the runoff originates in the Cascade Range and the northern Sierra Nevada (**fig. 73**). This water flows to the valley in perennial streams and provides nearly all the average annual 12 inches of recharge the valley aquifer system receives. Runoff from the Coast Ranges is principally on the western slopes to the Pacific Ocean.

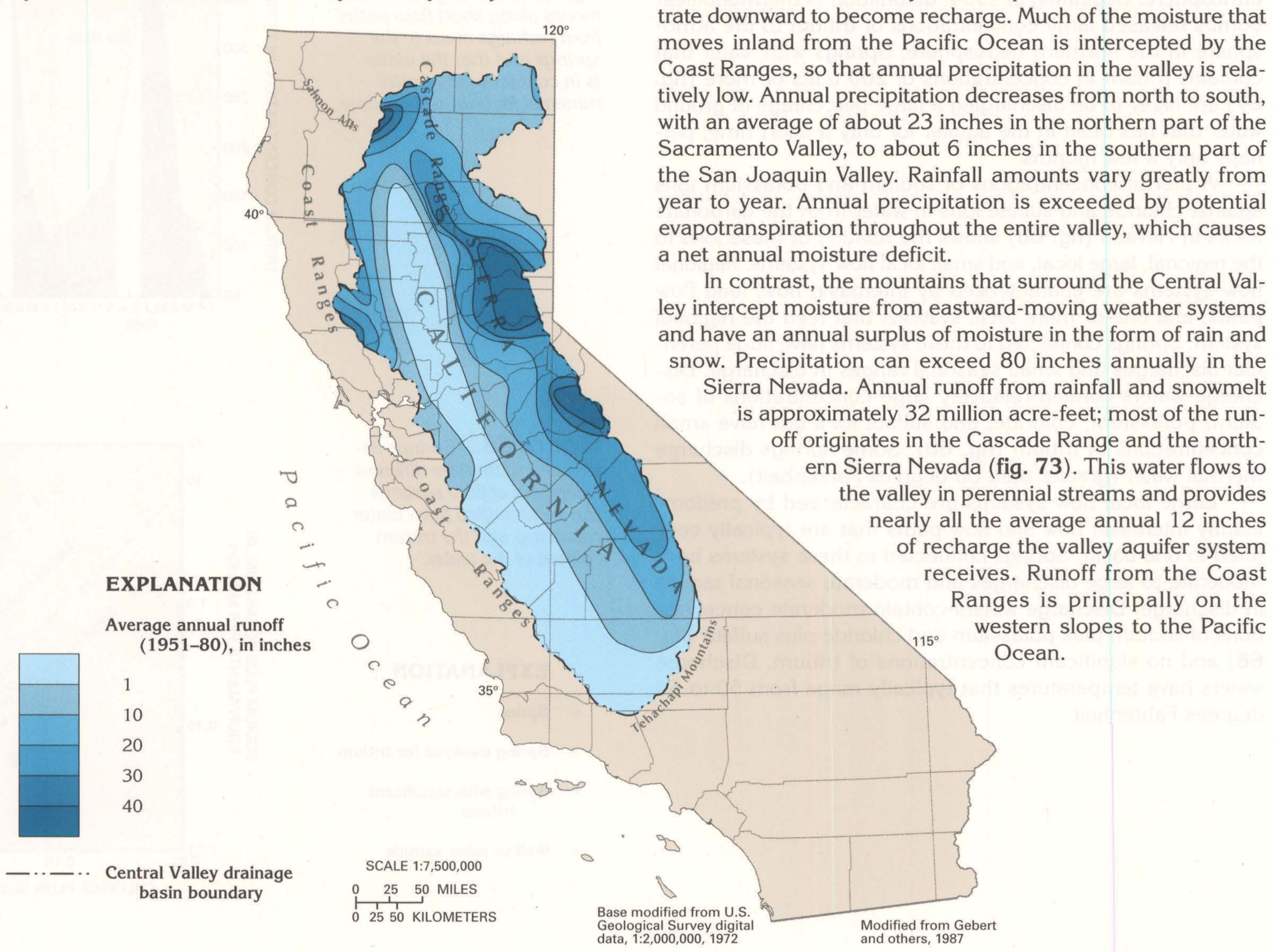


Figure 73. *Nearly all the recharge received by the Central Valley aquifer system is provided by runoff from the mountains that surround the Central Valley.*

Figure 74. *The Central Valley is a large structural trough that has been partially filled by marine sediments and continental deposits. The Sierra Nevada, which forms most of the eastern boundary of the valley, is the edge of a huge tilted granite block. The Coast Ranges, which form most of the western boundary, consist, for the most part, of folded and faulted marine rocks.*

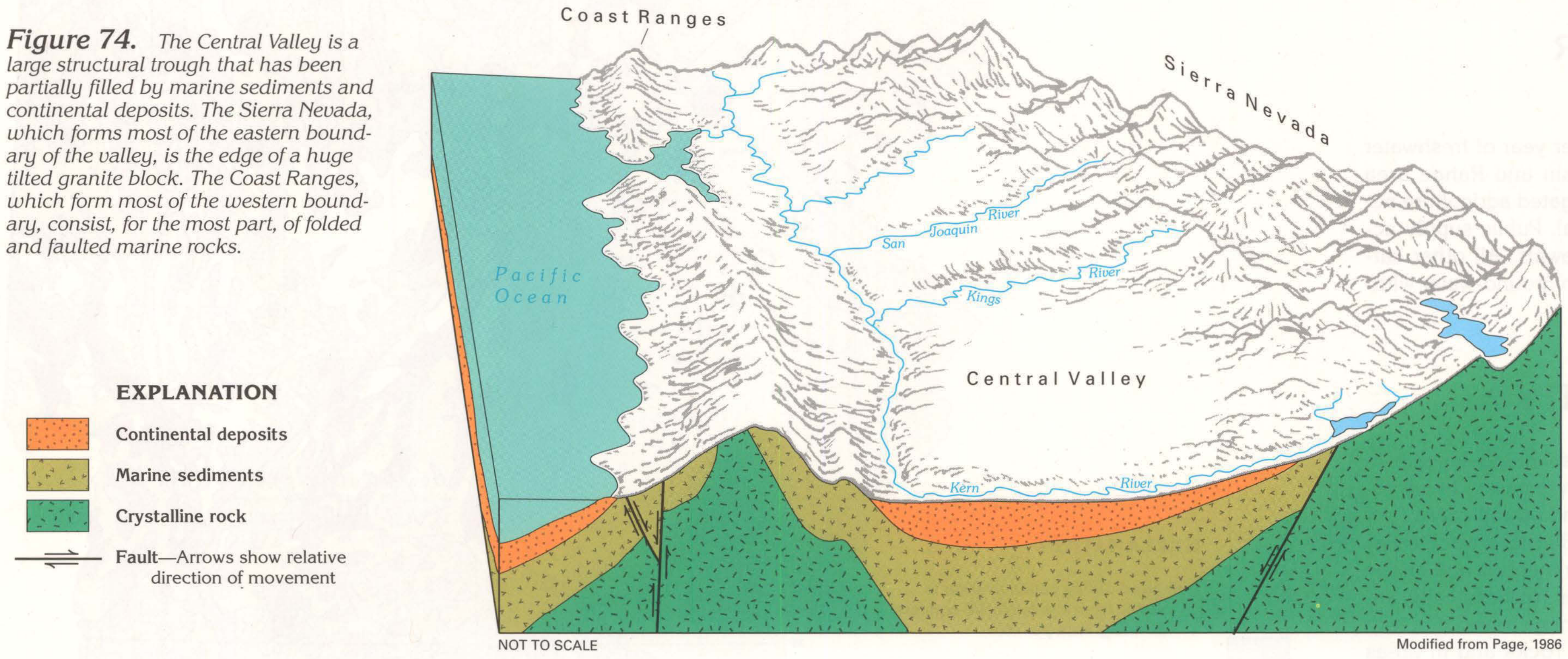
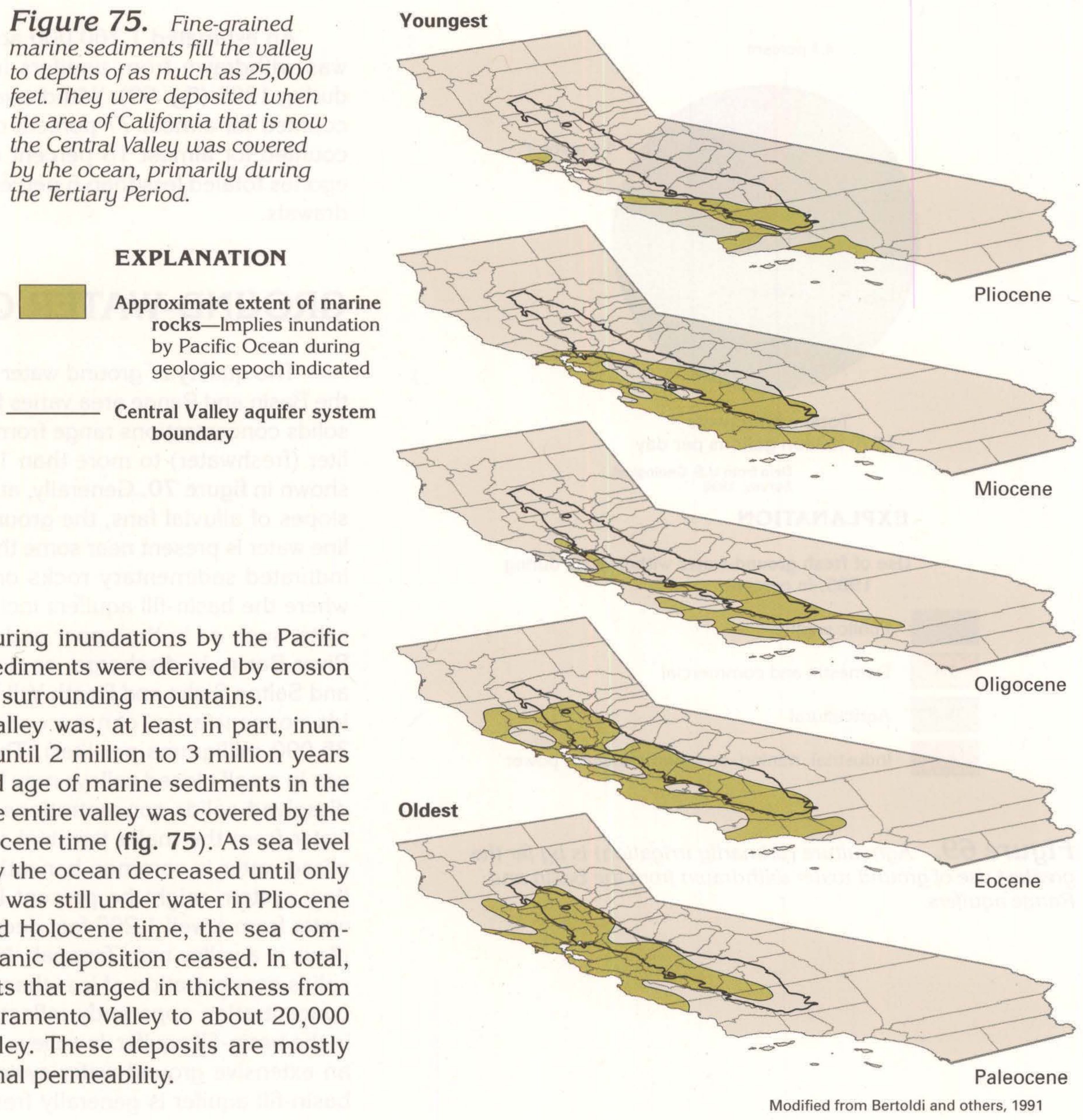


Figure 75. *Fine-grained marine sediments fill the valley to depths of as much as 25,000 feet. They were deposited when the area of California that is now the Central Valley was covered by the ocean, primarily during the Tertiary Period.*



GEOLOGIC SETTING

The Central Valley and surrounding area is the product of a complex series of geologic events. The surrounding area has undergone mountain building, faulting, and erosion, and the valley has been inundated several times by the Pacific Ocean.

The Sierra Nevada, which forms the eastern side of the valley, is the eroded edge of a huge tilted block of crystalline rock that also partially defines the base of the valley sediments (**fig. 74**). Embedded in the granite and related plutonic rocks of the mountains are metamorphosed sedimentary and volcanic rocks of Ordovician to Late Jurassic age. The uplift that formed the Sierra Nevada probably took place between Late Jurassic and Late Cretaceous time.

The northeast corner of the basin is the southern terminus of the Cascade Range. This is an area of lava plateaus and volcanos, some of which have been active in modern times. Geologically, this area of the basin is relatively young; most of the volcanic activity was during late Tertiary to Holocene time.

The northwest corner of the Central Valley is bounded by metamorphosed volcanic rocks of Paleozoic and Mesozoic age. These rocks form a minor part of the valley boundary. The western side of the valley is bounded by the Coast Ranges, which are formed primarily of folded and faulted marine sedimentary rocks of Mesozoic age, which were uplifted during Tertiary time. Mesozoic marine sedimentary rocks and continental deposits underlie the Tehachapi Mountains that bound the valley to the south.

A huge volume of sediments, which is as thick as about 50,000 feet in the Sacramento Valley and about 32,000 feet in the Tulare Basin, fills the Central Valley. These sediments are marine and continental in origin; the marine sediments are the product of deposition during inundations by the Pacific Ocean, and the continental sediments were derived by erosion of the rocks that formed the surrounding mountains.

The ancestral Central Valley was, at least in part, inundated by the Pacific Ocean until 2 million to 3 million years ago. The location, depth, and age of marine sediments in the valley indicates that nearly the entire valley was covered by the sea during Paleocene and Eocene time (**fig. 75**). As sea level declined, the area covered by the ocean decreased until only the southern end of the basin was still under water in Pliocene time. During Pleistocene and Holocene time, the sea completed its retreat, and all oceanic deposition ceased. In total, the ocean left behind deposits that ranged in thickness from about 25,000 feet in the Sacramento Valley to about 20,000 feet in the San Joaquin Valley. These deposits are mostly consolidated and have minimal permeability.

GEOLOGIC SETTING—Continued

From the time when the valley first began to form, sediments derived from erosion of igneous and metamorphic rocks and consolidated marine sediments in the surrounding mountains have been transported into the valley by streams. These continental sediments are as thick as 9,000 feet at the southern end of the valley and have an average thickness of about 2,400 feet (**fig. 76**). The continental sediments consist mostly of fluvial, basin-fill, or lake deposits of sand and gravel interbedded and admixed with clay and silt (**fig. 77**). Depending upon location, deposits of fine-grained materials—mostly clay and silt—make up as much as 50 percent of the thickness of the valley-fill sediments.

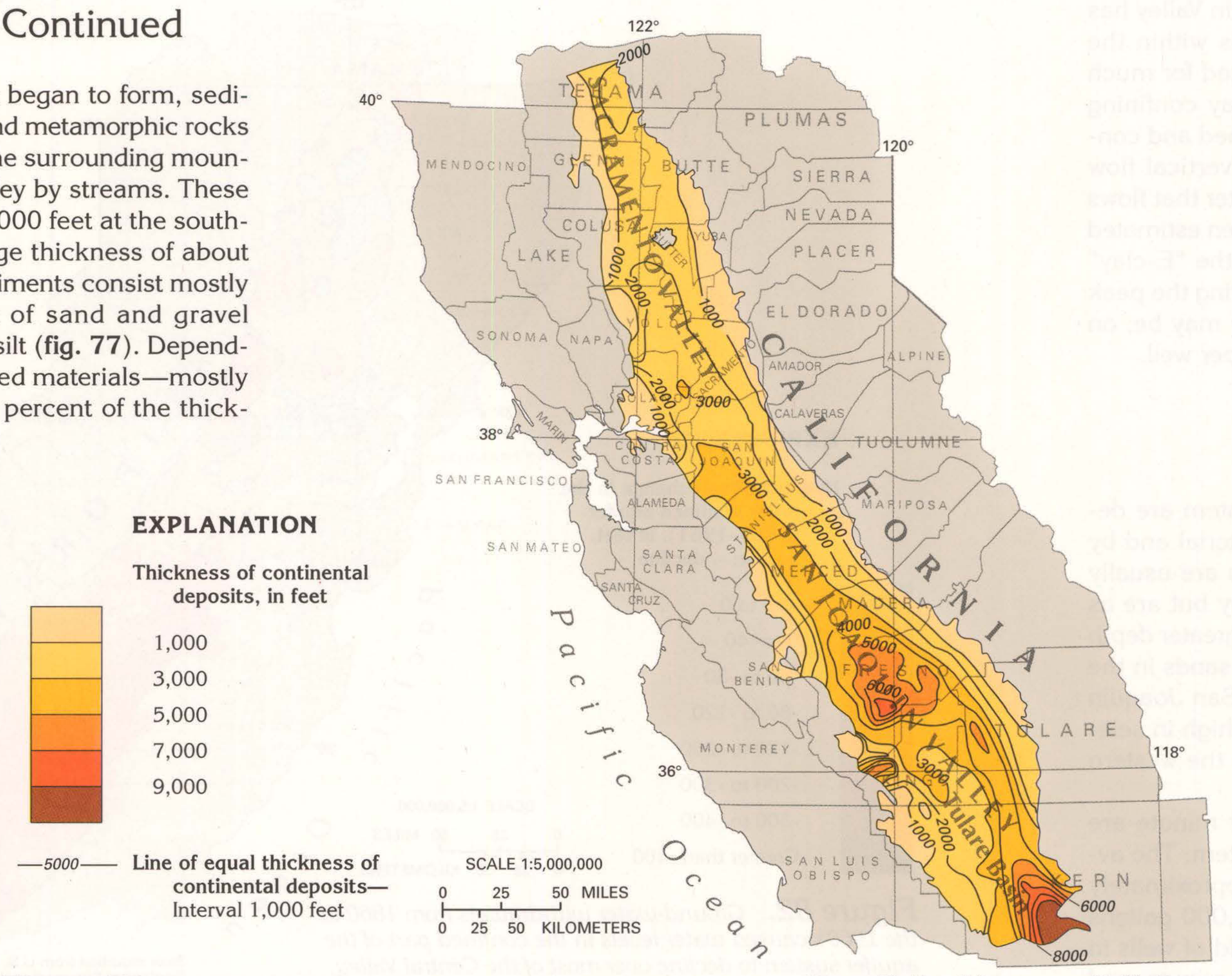
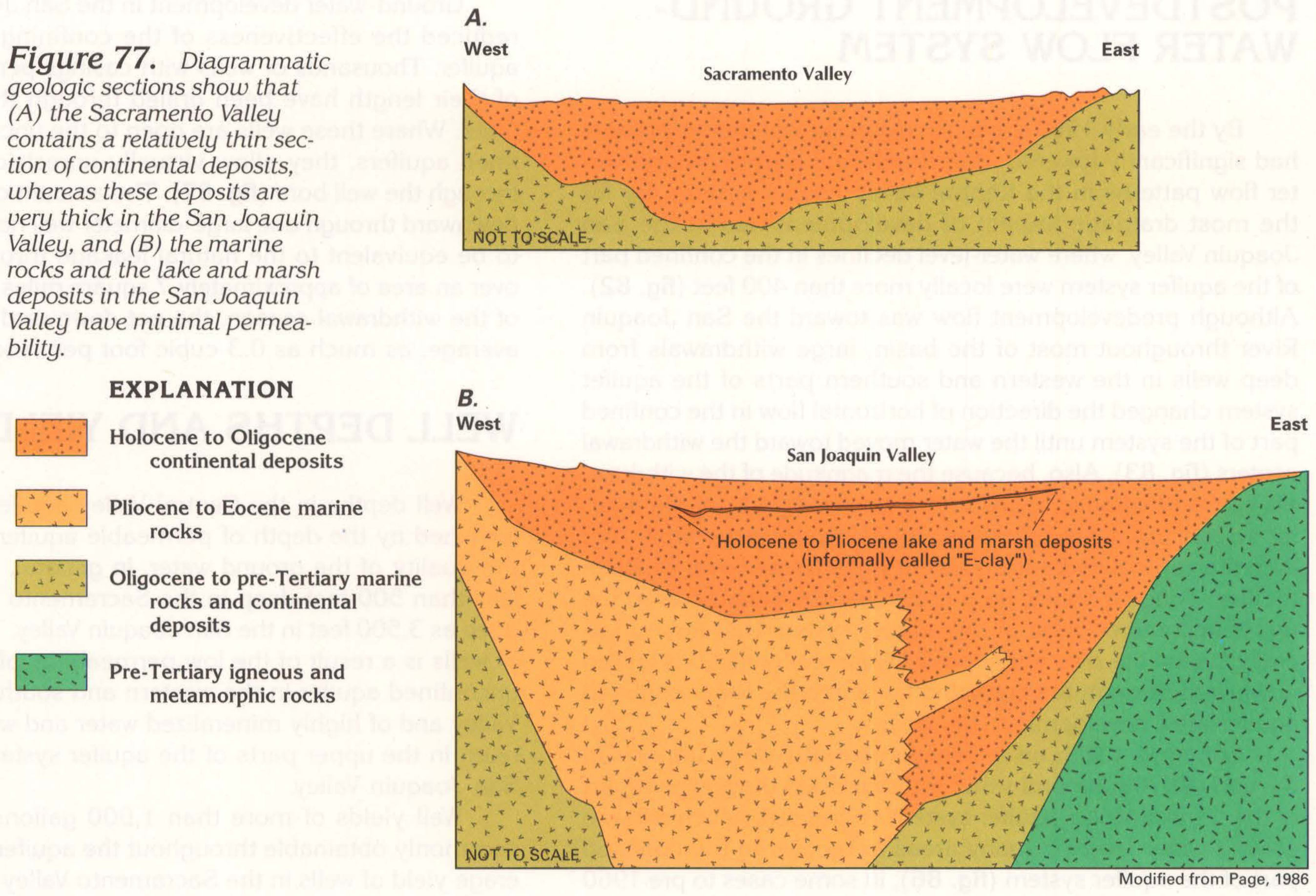


Figure 76. *Continental sediments form the Central Valley aquifer system. These sediments average 2,400 feet in thickness but are more than 9,000 feet thick in the Tulare Basin.*

Figure 77. *Diagrammatic geologic sections show that (A) the Sacramento Valley contains a relatively thin section of continental deposits, whereas these deposits are very thick in the San Joaquin Valley, and (B) the marine rocks and the lake and marsh deposits in the San Joaquin Valley have minimal permeability.*



GEOHYDROLOGIC SETTING

Drainage Basins

Three hydrologic subregions coincide with drainage basins within the Central Valley (**fig. 71**). These subregions are hydraulically connected and compose the Central Valley aquifer system and associated surface-water drainages. The northernmost subregion is the Sacramento Valley, which extends over the northern one-third of the Central Valley and is drained by the Sacramento River. Although the Redding Basin extends over about 500 square miles at the northern end of the Sacramento Valley and is a topographic extension of the valley, it is not included as part of the Central Valley aquifer system because of its separate ground-water flow system. Adjoining the Sacramento Valley to the south is the Sacramento–San Joaquin Delta subregion, where a network of meandering channels has formed at the junction of the Sacramento and the San Joaquin Rivers. The southernmost subregion is the San Joaquin Valley, which extends over two-thirds of the Central Valley. The San Joaquin River drains the northern part of the San Joaquin subregion; the southern part, which is called the Tulare Basin, is characterized by interior drainage. The Tulare Basin is named for Tulare Lake, a lake that covered much of the basin during the Pleistocene Epoch.

Under natural, or predevelopment, conditions, recharge from rainfall and snowmelt entered the aquifer system as seepage from streams that channel runoff from the surrounding mountains into the valley. Most recharge is at the margins of the valley, and the ground water moves in the subsurface to lower altitudes and discharges into surface-water bodies that drain each basin.

Aquifers and Confining Units

The consolidated volcanic and metamorphic rocks that surround and underlie the Central Valley are almost impermeable, and flow through them is not significant. Little water flows through the extensive deposits of consolidated marine and mixed marine and continental sediments that overlie the crystalline rocks (**fig. 77**) because the permeability of the deposits is generally minimal. The marine sediments usually contain saltwater or brine, but near the northwestern, western, and southeastern margins of the San Joaquin Valley, some freshwater is withdrawn from these deposits.

The Central Valley aquifer system is formed primarily of sand and gravel with significant amounts of silt and clay, all of which have been eroded mainly from older rocks at the boundaries of the valley. The environments in which the continental sediments were deposited varied, but most were deposited in fluvial environments; however, the deposits contain some lacustrine beds. Locally, volcanic rocks and dune deposits are part of the aquifer system. Specific geologic formations can be related to specific aquifers within the Central Valley aquifer system only with difficulty because many of the formations are lithologically similar, and cannot be distinguished easily in the subsurface.

Beds and lenses of fine-grained materials, such as silt and clay, constitute a significant percentage of the Central Valley aquifer system. In most parts of the valley, fine-grained materials compose 50 percent or more of the aquifer system. The most extensive clay bed, which is informally named the "E-clay" (**fig. 77**), consists primarily of the Corcoran Clay Member of the Tulare Formation and underlies much of the western San Joaquin Valley. Because beds of silt and clay do not readily transmit water under natural conditions, they act as barriers to vertical flow and cause differences in hydraulic head with depth.

Early investigators thought that the Sacramento Valley contained a single unconfined aquifer and that the San Joaquin Valley contained an upper unconfined to semiconfined aquifer separated from a lower aquifer confined by the Corcoran Clay or "E-clay" (**fig. 78**). However, recent investigations indicate that the Central Valley contains a single heterogeneous aquifer system that contains water under unconfined, or water-table, conditions in the upper few hundred feet; these conditions grade into confined conditions with depth. The confinement is the result of numerous overlapping lens-shaped clay beds. Geophysical well logs indicate that the "E-clay," although probably the largest single confining bed, constitutes only a small percentage of the total thickness of clay layers in the aquifer system. This indicates that the significance of the "E-clay" as a barrier to vertical flow may have been exaggerated. Further, the difference in hydraulic head directly above and below the "E-clay" is small when compared to head differences within intervals of the deep parts of the aquifer system.

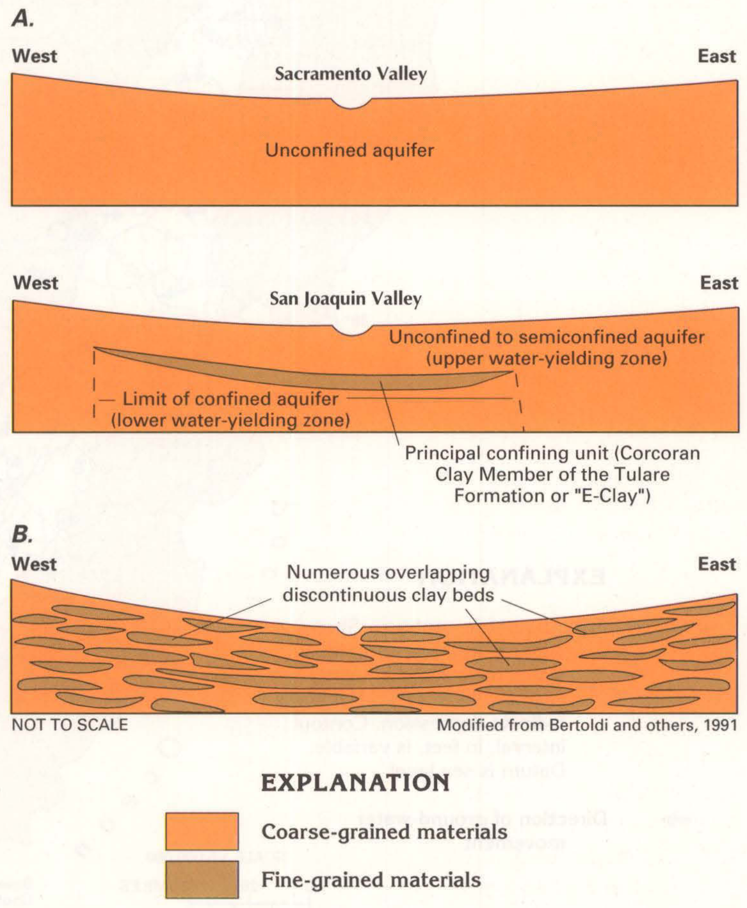


Figure 78. *According to early concepts of the aquifer system (A), it was generally considered to be unconfined in the Sacramento Valley and confined where the Corcoran Clay Member of the Tulare Formation, or "E-clay," is present in the San Joaquin Valley. However, recent studies suggest that the entire aquifer system is a single heterogeneous system (B) in which vertically and horizontally scattered lenses of fine-grained materials provide increasing confinement with depth.*

Figure 79. *Under unstressed, predevelopment conditions, ground water in the upper part of the Central Valley aquifer system flowed from upland recharge areas at the valley margins to discharge areas, such as rivers, lakes, and marshes on the valley floor.*

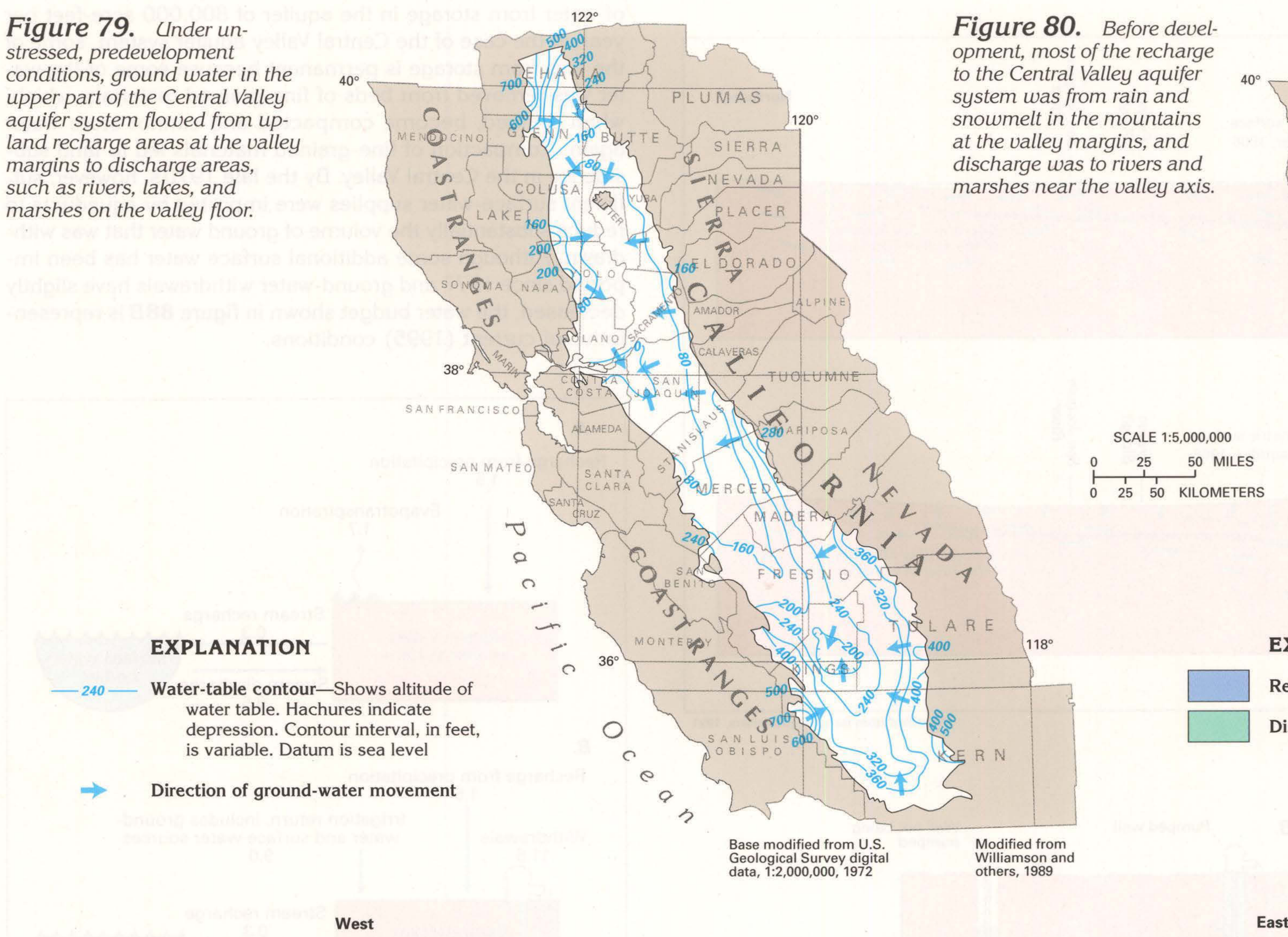


Figure 80. *Before development, most of the recharge to the Central Valley aquifer system was from rain and snowmelt in the mountains at the valley margins, and discharge was to rivers and marshes near the valley axis.*

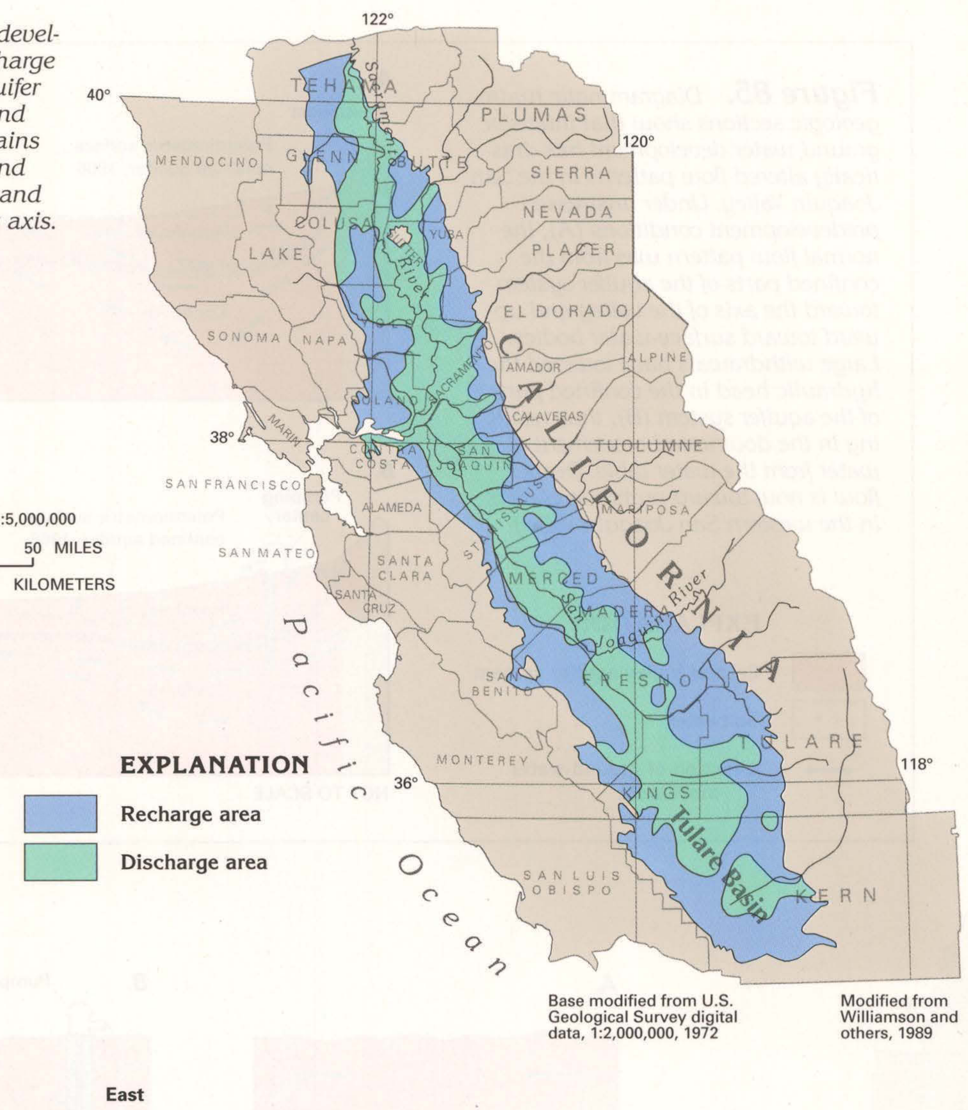
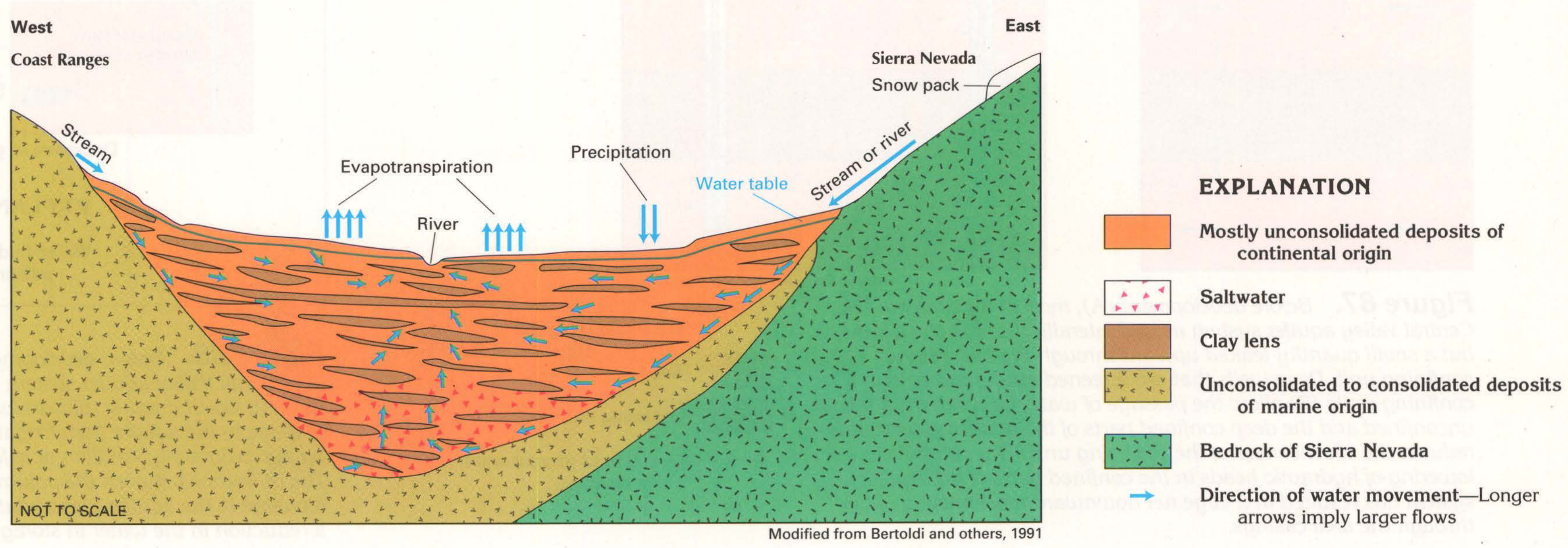


Figure 81. *A diagrammatic hydrogeologic section shows that before development, water that recharged the aquifer at the valley margins moved downward and laterally into the aquifer system and then moved upward to discharge at rivers and marshes at the valley axis.*



GROUND-WATER FLOW SYSTEM

Before development began, the aquifer system was under steady-state conditions in which natural recharge balanced natural discharge. Ground water in the shallow part of the aquifer system flowed from areas of high altitude at the valley margins, where most of the recharge took place, downgradient to discharge into rivers and marshes near the valley axis (**fig. 79**). The aquifer system was recharged primarily by streams emanating from the Coast and Cascade Ranges and the Sierra Nevada. Most of the recharge was in the northern and eastern parts of the valley. Precipitation falling on the valley floor during the rainy season provided only a small part of the total recharge. Ground water that was not evaporated or transpired by plants discharged either into the Sacramento and the San Joaquin Rivers that drained to San Francisco Bay or into the Tulare Basin from which it was eventually removed by evaporation or transpiration. The areas of recharge and discharge in the Central Valley before development are shown in **figure 80**.

Under predevelopment conditions, the hydraulic head in the shallow water-table aquifer where water entered the aquifer system at the valley margins was greater than the head in the deeper confined aquifer; thus, ground water moved downward (**fig. 81**). Conversely, the head gradient was reversed where water left the aquifer, typically by discharge to surface-water bodies, and the hydraulic head in the water-table aquifer was less than that in the confined aquifer. The difference in hydraulic head created upward movement of the ground water toward rivers and marshes (**fig. 81**). Precipitation that fell on the valley floor and was not lost to evapotranspiration recharged the water-table aquifer and moved down the head gradient toward the rivers and surrounding marshes.

Upward vertical flow to discharge areas from the deep confined aquifer was impeded by confining clay beds, which caused a pressure head in the deep parts of the aquifer system. Because of the pressure head, wells that penetrated the deep aquifer in low-lying areas near the rivers and marshes flowed during the early years of ground-water development in the valley.

POSTDEVELOPMENT GROUND-WATER FLOW SYSTEM

By the early 1960's, intensive ground-water development had significantly lowered water levels and altered ground-water flow patterns in the Central Valley aquifer system. By far the most dramatic impact of development was in the San Joaquin Valley, where water-level declines in the confined part of the aquifer system were locally more than 400 feet (**fig. 82**). Although predevelopment flow was toward the San Joaquin River throughout most of the basin, large withdrawals from deep wells in the western and southern parts of the aquifer system changed the direction of horizontal flow in the confined part of the system until the water moved toward the withdrawal centers (**fig. 83**). Also, because the magnitude of the withdrawals caused hydraulic heads in the confined parts of the aquifer system to fall far below the altitude of the water table (**fig. 84**), the vertical hydraulic gradient was reversed over much of the San Joaquin Valley. As a result, much of the water in the upper unconfined zone of the aquifer system that flowed laterally toward the river under predevelopment conditions leaked downward through the confining beds into the lower confined aquifer after development (**fig. 85**).

Concurrent with an increase in surface-water imports in the early 1970's, ground-water withdrawals in the northern part of the Central Valley aquifer system decreased, which allowed ground-water levels in many areas to recover in the confined part of the aquifer system (**fig. 86**), in some cases to pre-1960 levels. However, in the San Joaquin Valley large withdrawals continued, especially in the western and southern parts of the valley, and water levels continued to decline. With few exceptions, the ground-water flow patterns in the aquifer system today (1995) are the same as those in the mid-1970's.

Ground-water development in the San Joaquin Valley has reduced the effectiveness of the confining beds within the aquifer. Thousands of wells with casings perforated for much of their length have been drilled through the clay confining units. Where these wells are open to the unconfined and confined aquifers, they allow virtually unrestricted vertical flow through the well bore (**fig. 87**). The amount of water that flows downward through one large-diameter well has been estimated to be equivalent to the natural leakage through the "E-clay" over an area of approximately 7 square miles. During the peak of the withdrawal season, the net downward flow may be, on average, as much as 0.3 cubic foot per second per well.

WELL DEPTHS AND YIELDS

Well depths in the Central Valley aquifer system are determined by the depth of permeable aquifer material and by the quality of the ground water. In general, wells are usually less than 500 feet deep in the Sacramento Valley but are as deep as 3,500 feet in the San Joaquin Valley. The greater depth of wells is a result of the low permeability of the sands in the unconfined aquifer in the western and southern San Joaquin Valley and of highly mineralized water and water high in selenium in the upper parts of the aquifer system in the western San Joaquin Valley.

Well yields of more than 1,000 gallons per minute are commonly obtainable throughout the aquifer system. The average yield of wells in the Sacramento Valley is approximately 800 gallons per minute, but yields as large as 4,000 gallons per minute have been recorded. The average yield of wells in the San Joaquin Valley is about 1,100 gallons per minute, and the maximum expected yield is about 3,200 gallons per minute.

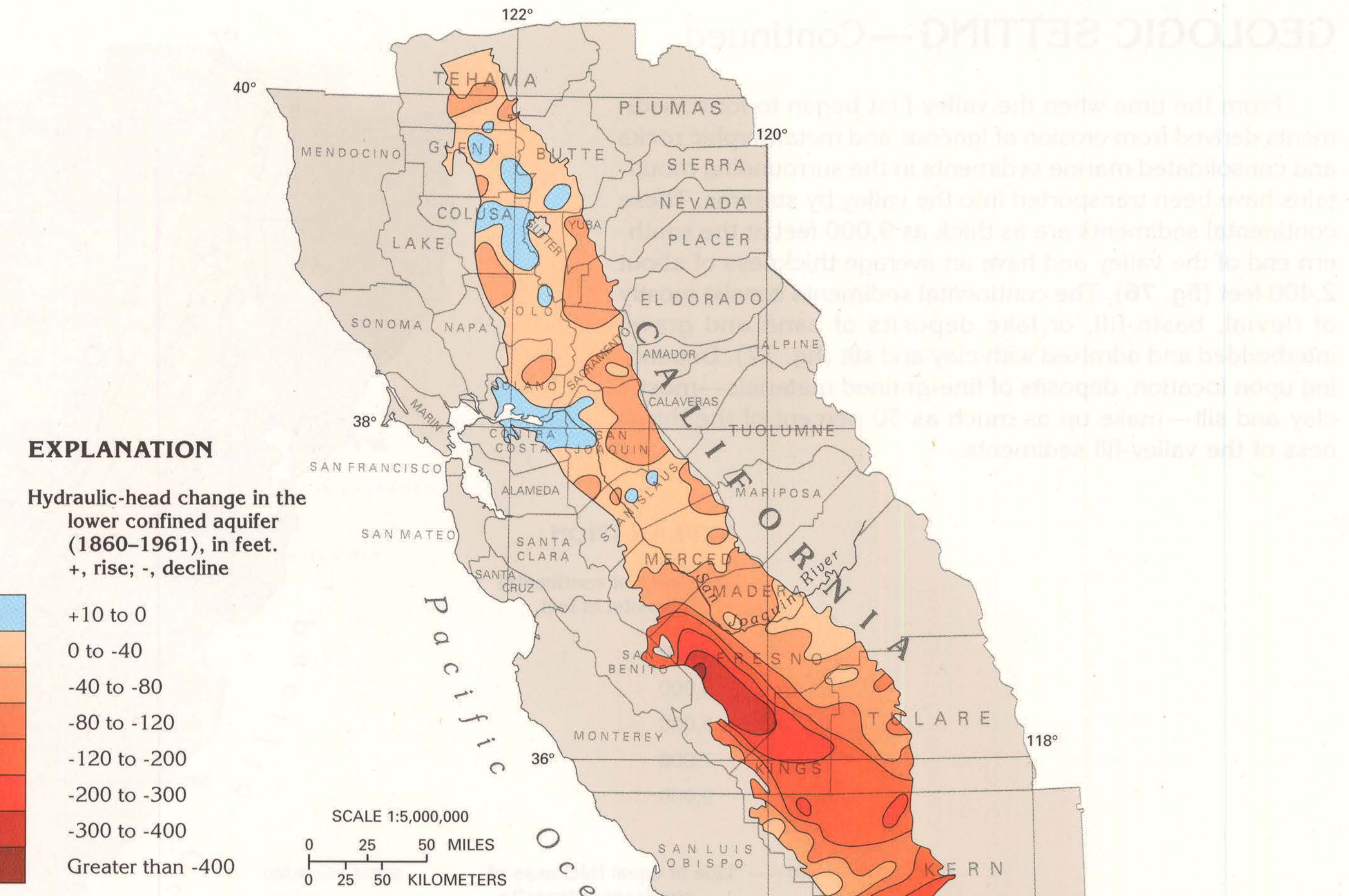


Figure 82. Ground-water withdrawals from 1860 to the 1960's caused water levels in the confined part of the aquifer system to decline over most of the Central Valley, in some areas more than 400 feet.

Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972

Modified from Williamson and others, 1989

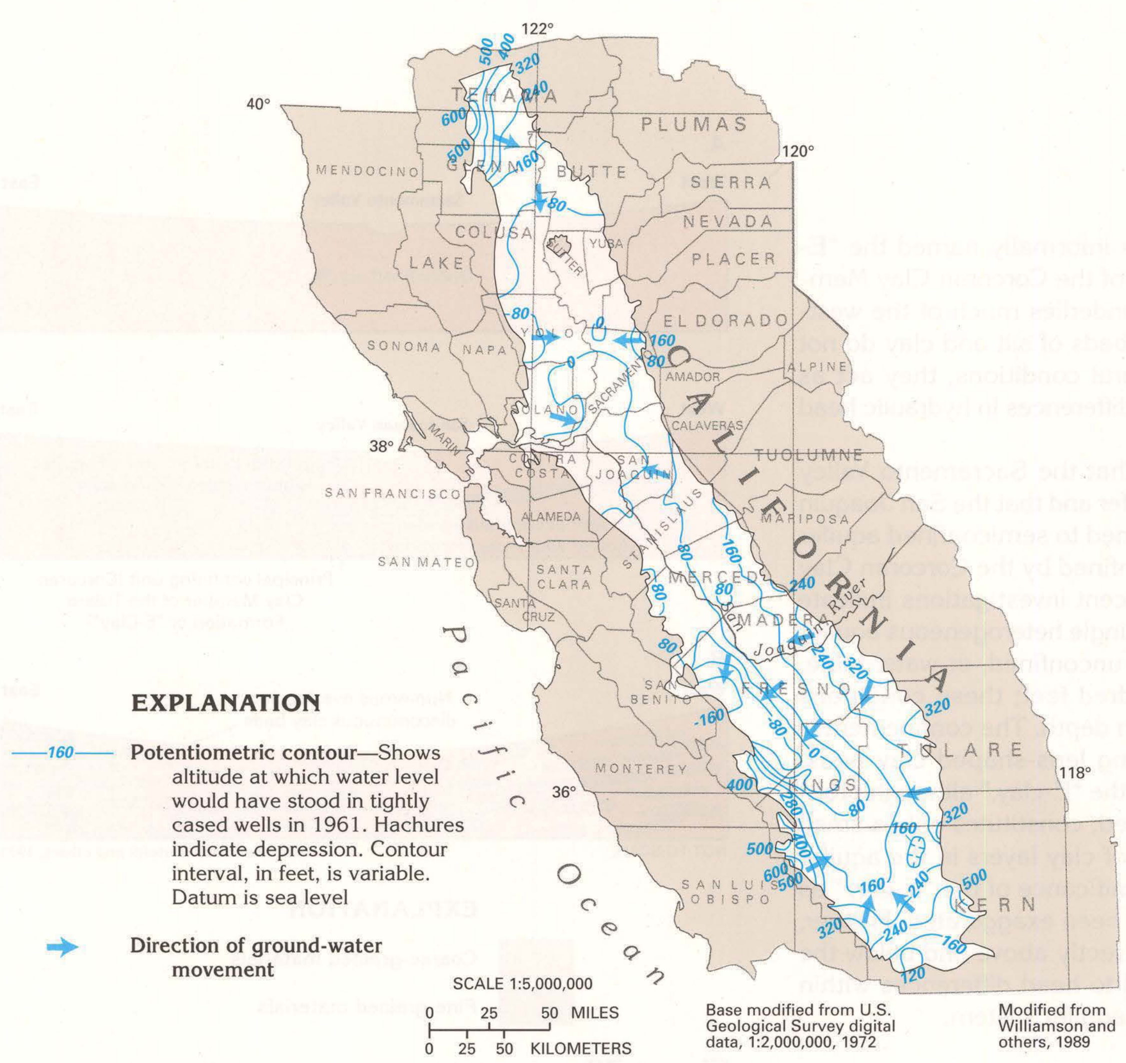


Figure 83. Agricultural use of ground water from the late 1800's to the 1960's dramatically altered the ground-water flow pattern in the Central Valley aquifer system. Water in the deep confined parts of the aquifer system once flowed toward surface water bodies in the center of the valley, but now discharges in large part at pumping centers, notably those in the western and southern parts of the San Joaquin Valley.

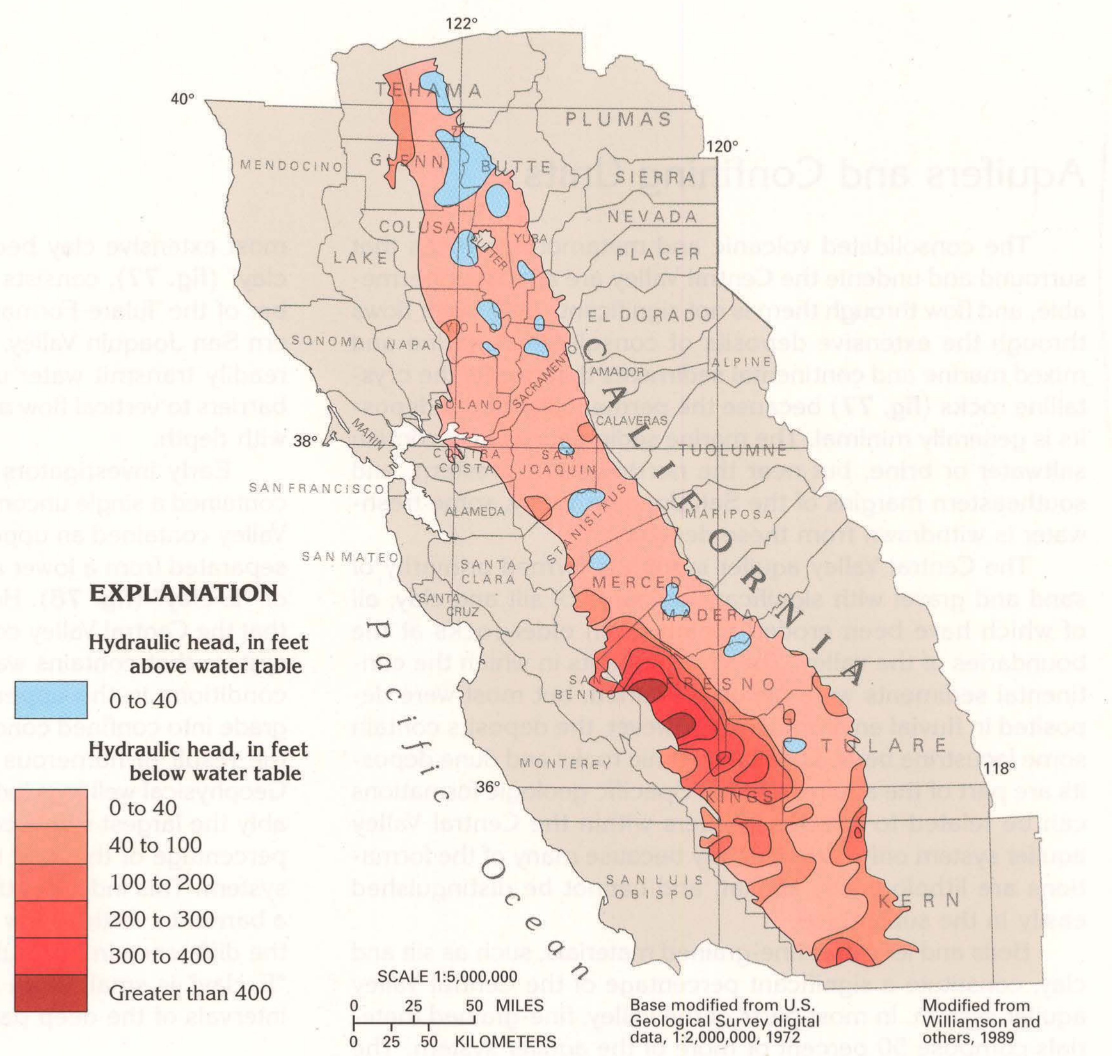


Figure 84. The large rate of withdrawal in the deep confined parts of the aquifer system has caused the hydraulic head to fall far below the altitude of the water table over much of the Cental Valley. By 1961, the difference in head was more than 400 feet in some parts of the San Joaquin Valley.

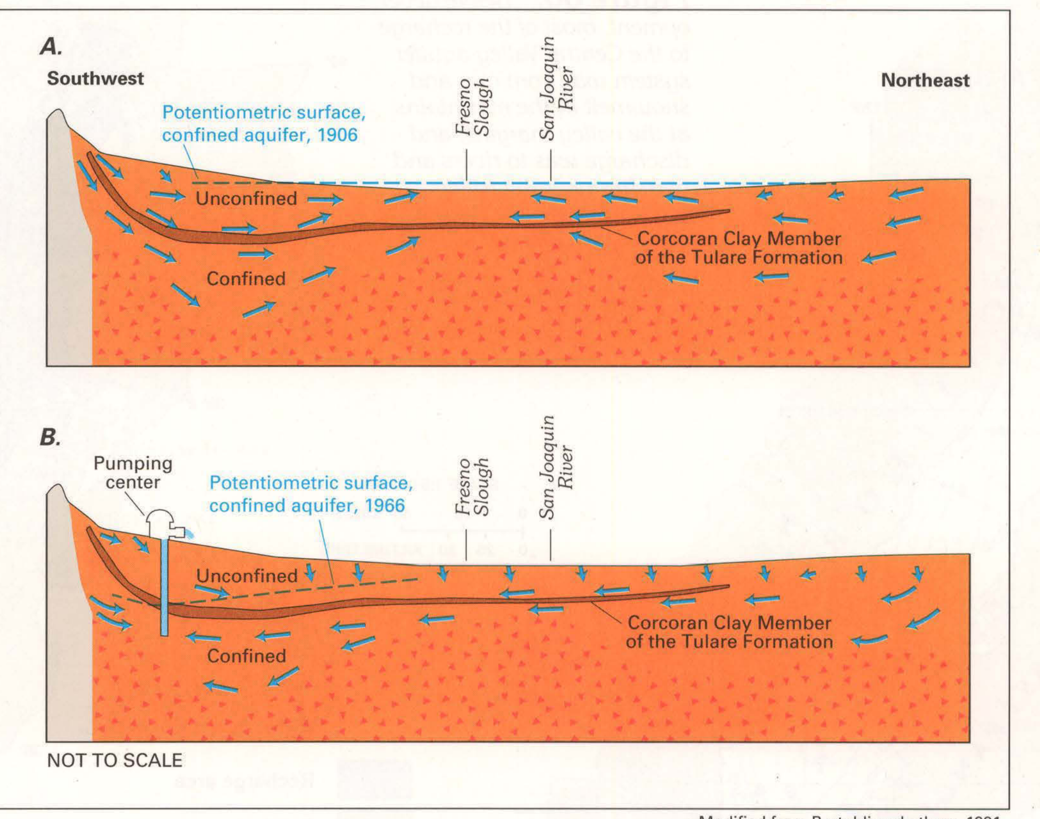
WATER BUDGET OF THE AQUIFER SYSTEM

A water budget is a method of quantitatively accounting for water movement in a hydrologic system. A computer-simulated approximation of the annual Central Valley aquifer system water budget under predevelopment and development conditions is shown in **figure 88**. The figure depicts only water that circulates through the aquifer system and does not account for water that enters the valley but does not interact with the aquifer system. This excludes most surface-water flow and water that is lost to evaporation almost immediately after it falls on the valley floor.

Before development, the net circulation through the aquifer system was approximately 2 million acre-feet per year (**fig. 88*A***). Of an average annual 12.4 million acre-feet of precipitation that fell on the valley floor, 10.9 million acre-feet was lost to evaporation because of the arid conditions that characterize the valley; thus, only 1.5 million acre-feet of precipitation entered the aquifer system as recharge. Water that moved from surface-water bodies to the aquifer system provided the remaining 500,000 acre-feet per year of recharge. The recharge was balanced by discharge from the aquifer system to rivers (300,000 acre-feet) and evapotranspiration (1.7 million acre-feet).

Development added two components to the water budget—withdrawals and return flow from irrigation—and increased the volume of water that flowed through the ground-water system approximately sixfold from 1961 through 1977. Ground-water withdrawals for irrigation, municipal supply, and industrial use totaled about 11.5 million acre-feet annually. Seepage from irrigation returned about 9 million acre-feet to the ground-water system (**fig. 88*B***). During the period 1961 through 1977, the rate of ground-water withdrawals from the aquifer system was greater than the net recharge from all sources. Withdrawals in excess of recharge resulted in a loss of water from storage in the aquifer of 800,000 acre-feet per year. In the case of the Central Valley aquifer system, some of the loss from storage is permanent because some of the water was removed from beds of fine-grained materials, which, when drained, become compacted and cannot store water again. Compaction of fine-grained materials led to land subsidence in the Central Valley. By the late 1970's, however, sufficient surface-water supplies were imported by aqueducts to reduce substantially the volume of ground water that was withdrawn. Although some additional surface water has been imported since 1977 and ground-water withdrawals have slightly decreased, the water budget shown in **figure 88*B*** is representative of current (1995) conditions.

Figure 85. Diagrammatic hydrogeologic sections show that intensive ground-water development has drastically altered flow patterns in the San Joaquin Valley. Under unstressed predevelopment conditions (A), the normal flow pattern was from the confined parts of the aquifer system toward the axis of the valley and upward toward surface-water bodies. Large withdrawals have lowered the hydraulic head in the confined parts of the aquifer system (B), thus resulting in the downward movement of water from the water table. Deeper flow is now toward pumping centers in the western San Joaquin Valley.



Modified from Bertoldi and others, 1991

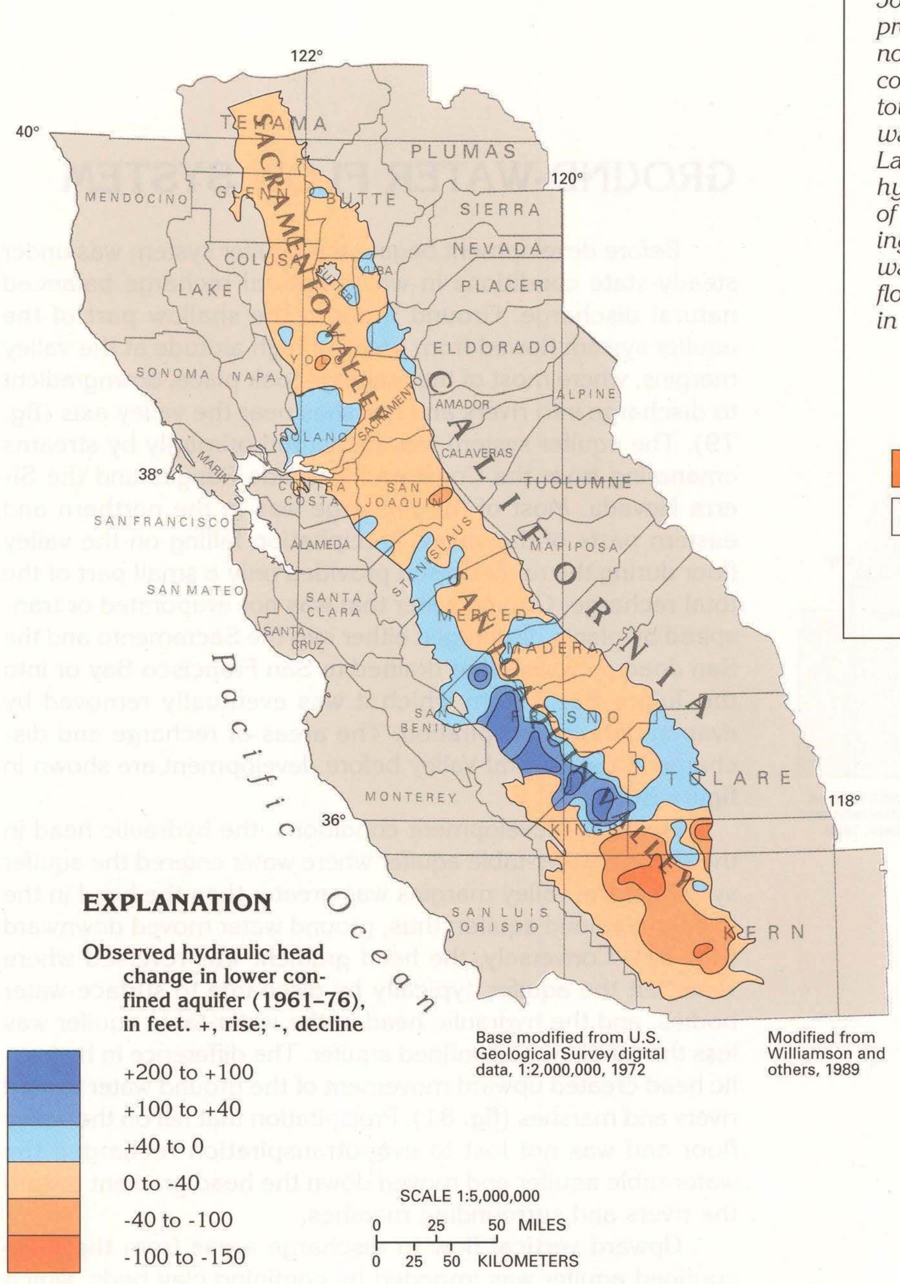


Figure 86. As a result of increased surface-water importation during the 1960's and 1970's, ground-water withdrawals were reduced and water levels rose in the deep confined aquifer in many areas from 1961 to 1976. However, declines continued in the southern part of the San Joaquin Valley.

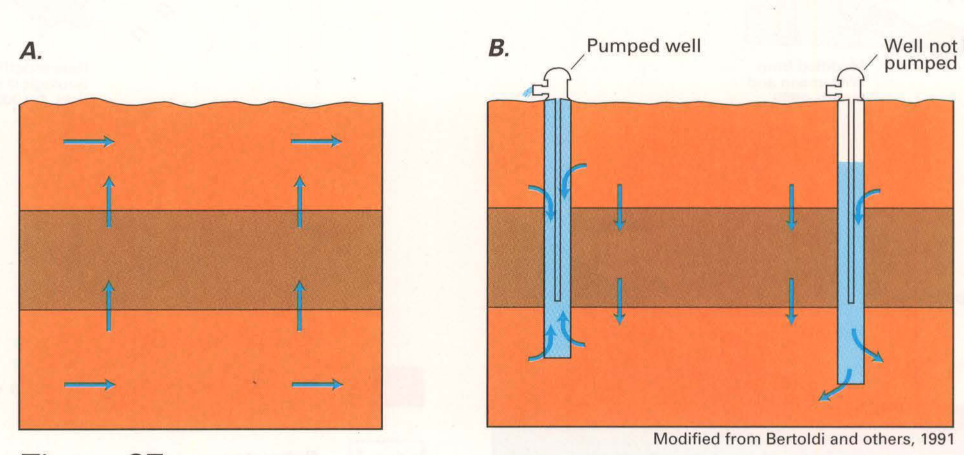


Figure 87. Before development (A), most of the water in the Central Valley aquifer system moved laterally through the aquifers but a small quantity leaked upward through the intervening confining unit. Deep wells that are screened above and below confining units (B) allow the passage of water between the shallow unconfined and the deep confined parts of the aquifer system; this reduces the effectiveness of the confining units. The dramatic lowering of hydraulic heads in the confined parts of the aquifer system has resulted in a large net downward movement of water through the well casings.

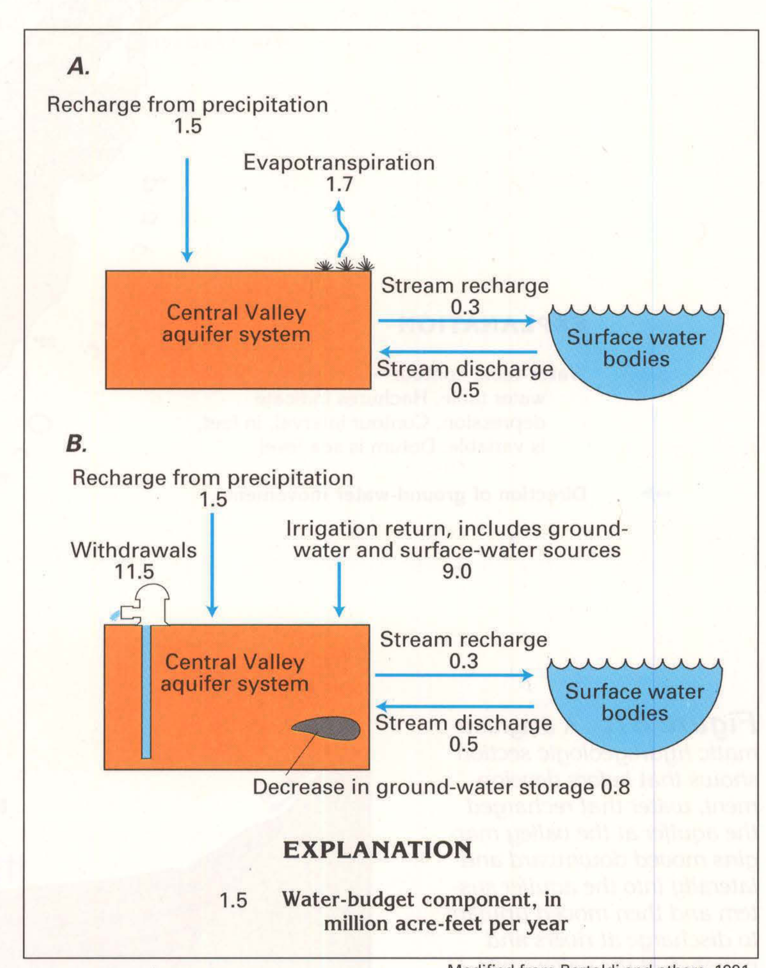


Figure 88. Before development, annual net circulation through the Central Valley aquifer system was estimated to be 2 million acre-feet (A). Ground-water withdrawals, primarily for irrigation, and seepage to the aquifer from irrigation had increased the circulation by approximately 9 million acre-feet during 1961 through 1977 (B). The difference between the volume of water withdrawn and the net recharge to the aquifer system was about 800,000 acre-feet and came from a reduction in the water in storage in the aquifer.

FRESH GROUND-WATER WITHDRAWALS

Ground-water withdrawal from the Central Valley aquifer system varies seasonally. The highest demand is generally during the peak growing season in spring and summer, which are the driest seasons of the year. Demand for ground water is greatest in the semiarid San Joaquin Valley where natural recharge is least. Withdrawal rates increase significantly during dry years (**fig. 89**).

Ground water accounted for only a small part of the water withdrawn for irrigation before 1900. Streams and distribution canals supplied most of the demand. However, the need to continue irrigation in dry years when surface-water supplies are undependable, as well as the expansion of agriculture into areas distant from surface-water sources, prompted increased ground-water development. By the 1960's, ground-water withdrawals from the Central Valley aquifer system averaged 11.5 million acre-feet per year, which was one-half or more of the water withdrawn from all sources (**fig. 90**) and was about 20 percent of the total irrigation withdrawals for the entire United States. During that same period, withdrawals for domestic and industrial uses accounted for about 5 percent of all ground-water withdrawals in the Central Valley. Historically, the largest withdrawal of ground water—15 million acre-feet—was during 1977, a drought year.

Increased importation of surface water for irrigation since 1977, as well as generally wetter weather through 1985, resulted in decreased ground-water withdrawals. During 1985, ground water accounted for only about 37 percent of the total withdrawals in the Central Valley (**fig. 91**); total ground-water withdrawals were 10.1 million acre-feet (**fig. 92**). Of that amount, agricultural withdrawal accounted for 8.8 million acre-feet, all of which was used for irrigation (**fig. 92*A***). This amount was about 11.5 percent of all ground water withdrawn in the United States for all purposes during 1985. The remaining 1.3 million acre-feet was used for public supply and industrial purposes, and by domestic and commercial users. Almost one-half of the water was withdrawn from the Tulare Basin (**fig. 92*B***).

Although gains have been achieved by importing surface water from areas of surplus to areas of deficit, projected water needs in the San Joaquin Valley may require temporary withdrawal of ground water in excess of recharge in the future. The California Department of Water Resources has estimated that by 2010 demand for water in the Sacramento Valley, the San Joaquin Valley (exclusive of the Tulare Basin), and the Tulare Basin would be 7, 8, and 9 percent greater, respectively, than 1980 demands. The Sacramento Valley is expected to have sufficient supplies to meet agricultural demand until at least 2010. However, without increased surface-water imports, the San Joaquin Valley (exclusive of the Tulare Basin) and the Tulare Basin might require withdrawals of 150,000 and 2,400,000 acre-feet per year, respectively, in excess of recharge. Those estimates probably underestimate additional increased demand that would result from sustained dry weather. Occasional large withdrawals from an aquifer are a viable solution to the problem of reduced surface-water supplies in dry periods, provided the aquifer is replenished during wet years. However, continual withdrawal of ground water in excess of recharge can increase the cost of pumping, reduce water availability, and, in certain hydrogeologic settings, can cause land subsidence.

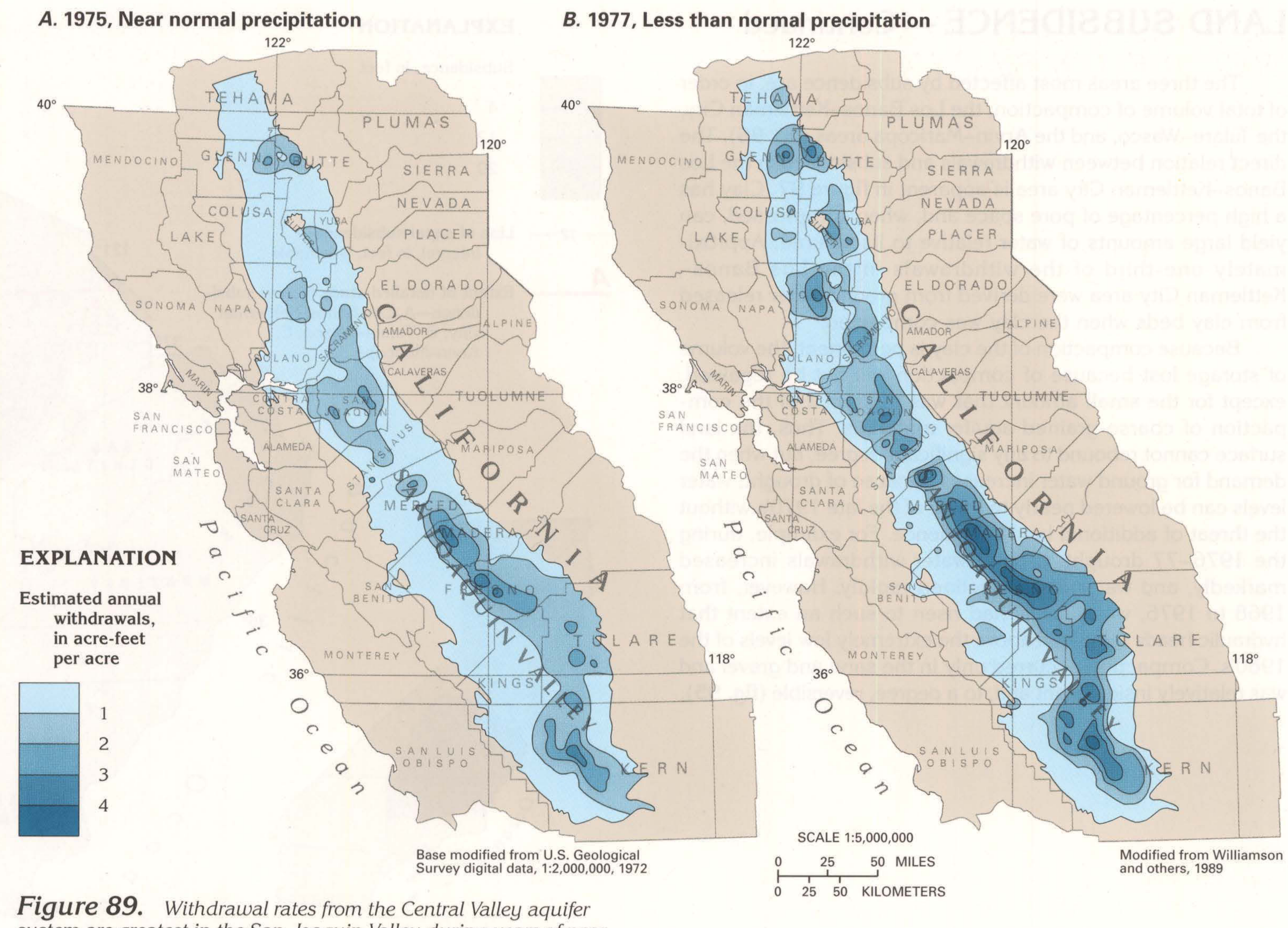


Figure 89. Withdrawal rates from the Central Valley aquifer system are greatest in the San Joaquin Valley during years of near normal precipitation (A) and less than normal precipitation (B). Decreased recharge and reduced surface-water supplies in dry years result in increased ground-water withdrawals, as in 1977.

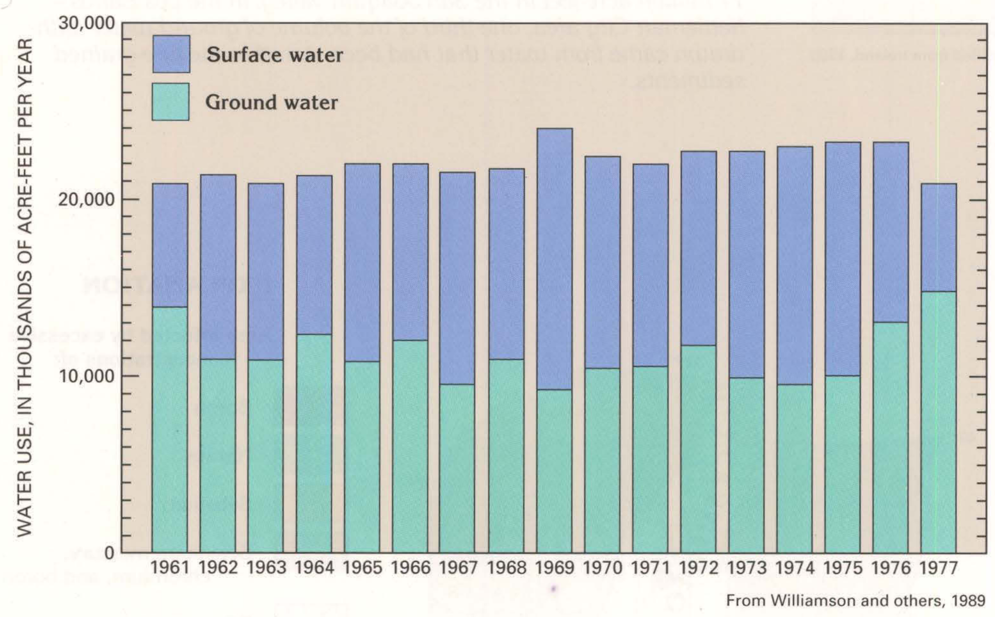


Figure 90. The volume of surface water used for irrigation has increased since the early 1960's in response to withdrawal of ground water in excess of natural recharge. In dry years such as 1977, however, the increased withdrawal of ground water is unavoidable.

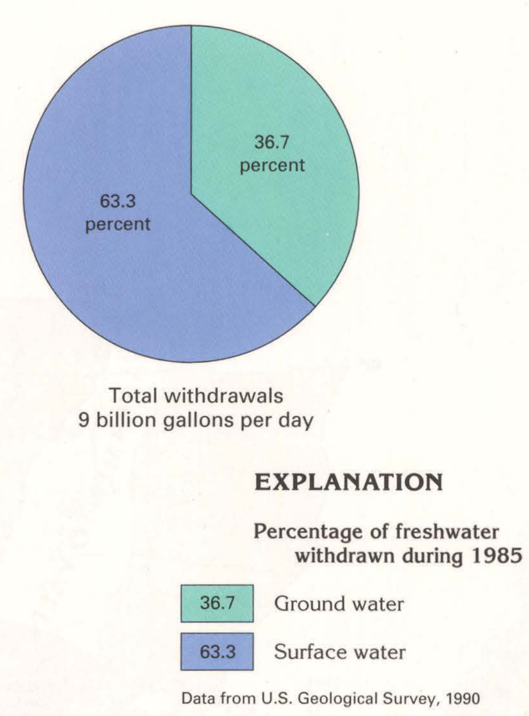


Figure 91. Ground-water withdrawals from the Central Valley aquifer system were about 37 percent of total freshwater withdrawals during 1985.

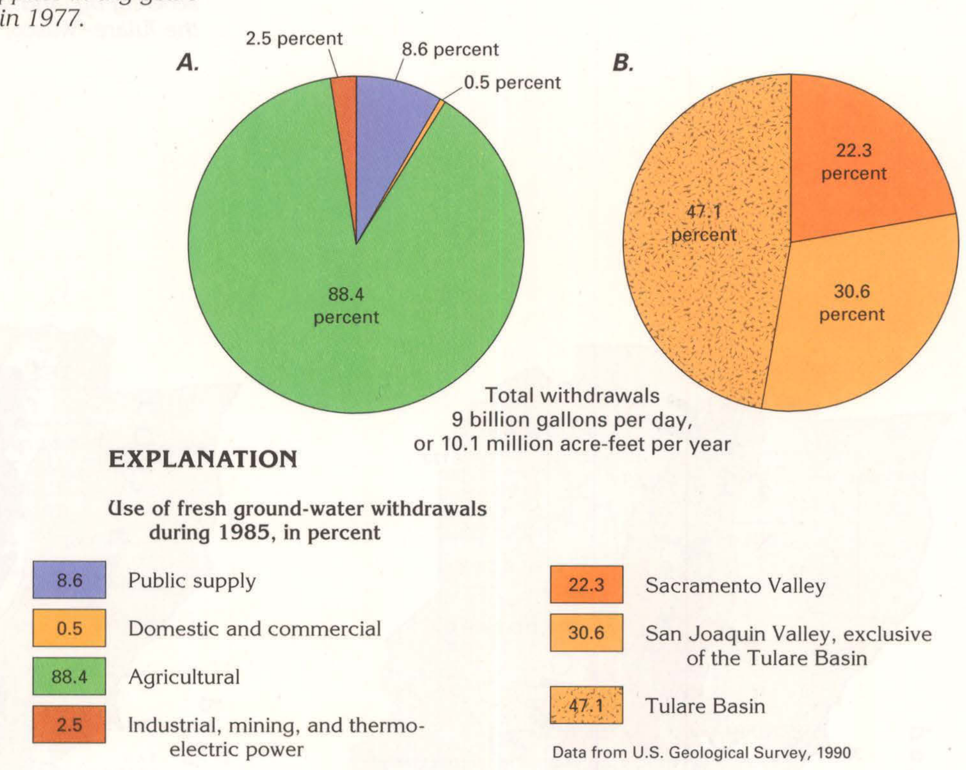


Figure 92. Agricultural irrigation is by far the major ground-water use in the Central Valley (A). More ground water is withdrawn in the Tulare Basin than elsewhere (B), because the basin is the driest area of the valley.

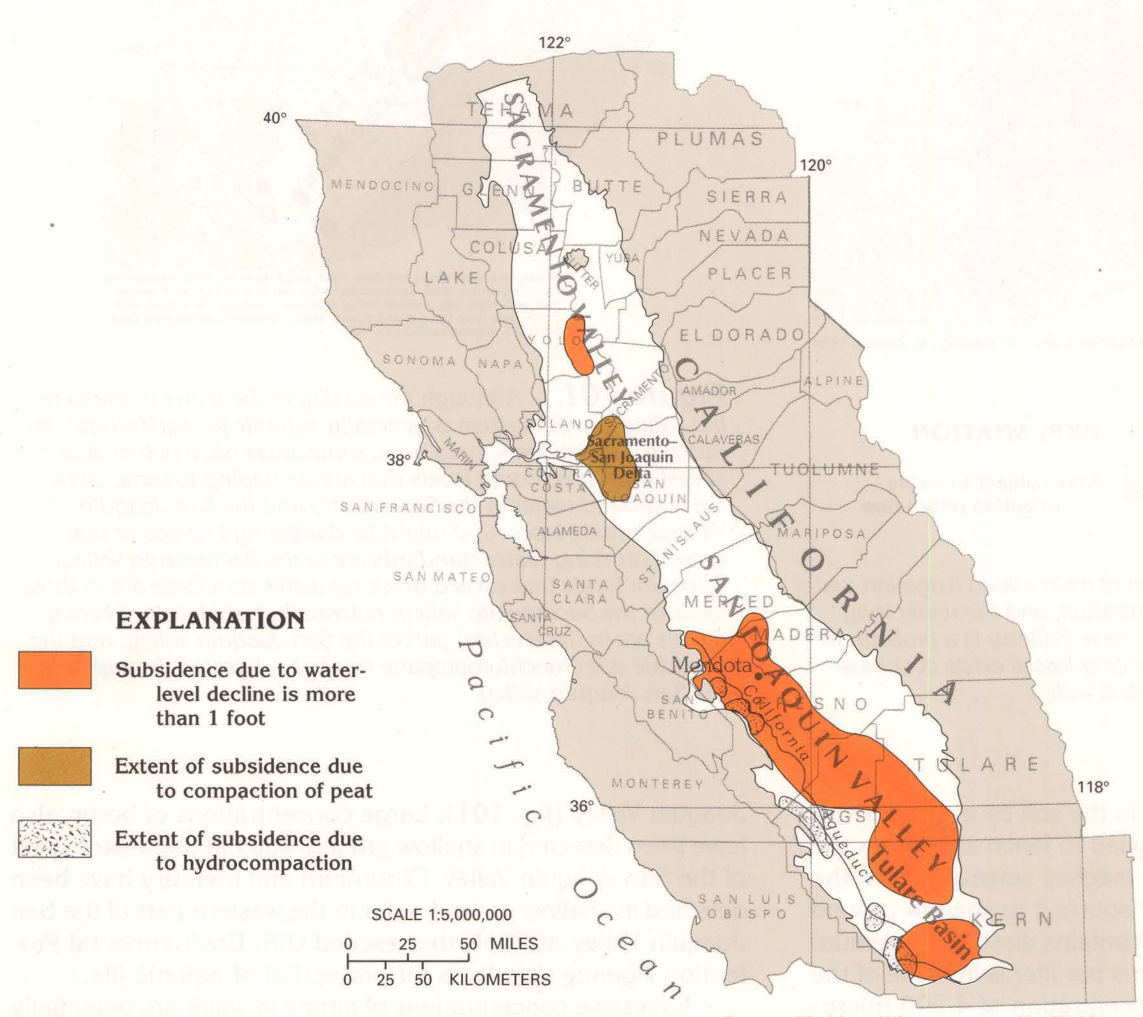


Figure 93. Land subsidence has affected large areas of the Central Valley. Most of the subsidence is the result of compaction of fine-grained sediments, which has been caused by large withdrawals of ground water.

Figure 94. Some of the most severe recorded land subsidence in history occurred in the western San Joaquin Valley near Mendota, where the land surface has subsided nearly 30 feet.

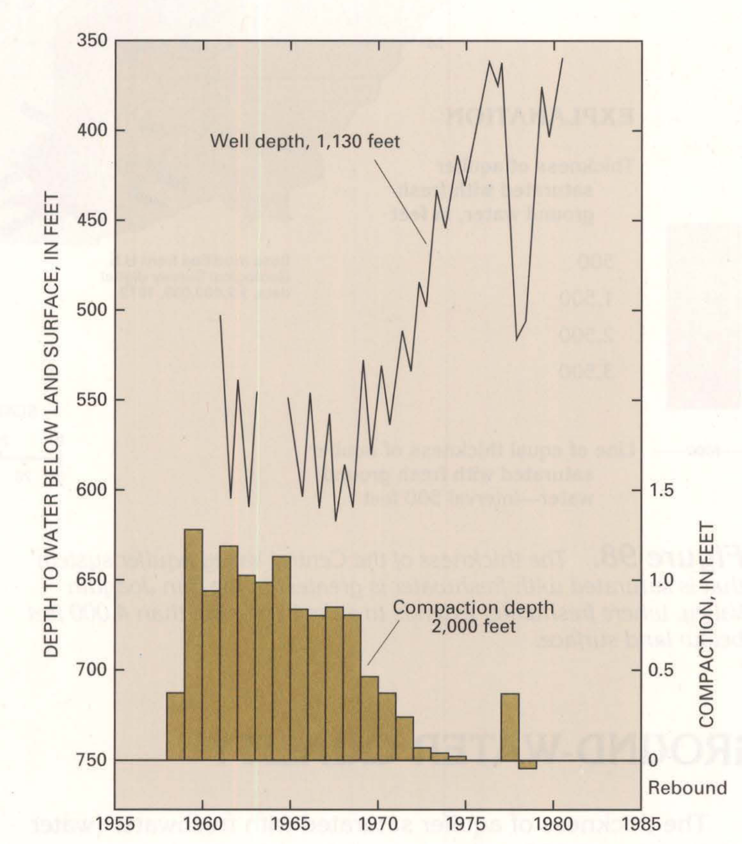


Figure 95. Compaction of fine-grained sediments in the Central Valley aquifer system occurred before 1975, as water levels declined because of ground-water withdrawals. However, compaction ceased as water levels recovered when withdrawals decreased. Increased withdrawals during the 1976–77 drought again caused compaction, which ceased, and was even reversed in 1978, as withdrawals were reduced.

LAND SUBSIDENCE

Land subsidence is widespread in the Central Valley (**fig. 93**), and has resulted in damage to buildings, aqueducts, well casings, bridges, and highways; has caused flooding; and has cost millions of dollars. The three processes that caused most of the subsidence are oxidation and compaction of peat, hydrocompaction, and compaction of fine-grained sediments due to withdrawal of ground water in excess of recharge. Of these, the third process has caused the most widespread and severe subsidence.

Human-induced subsidence probably began in the middle 1800's when peat soils in marshes of the Sacramento–San Joaquin Delta were first drained for cultivation. In the delta, shallow ground water is drained into ditches to dry the fields before planting and then pumped from the ditches into nearby natural channels. During the growing season, water is siphoned back into the drainage ditches to raise the water table to the root zone. When the peat soils are drained and exposed to the atmosphere they oxidize and compact, and (or) are reduced in thickness by wind erosion; thus, the land surface is permanently lowered with each yearly cycle. To dry the fields each year, the water table must be lowered below that of the previous year, which requires an increase in withdrawals and a decrease in the volume of ground water in storage. Subsidence due to oxidation and compaction of peat soils has lowered the land surface in the delta as much as 6 to 15 feet.

Hydrocompaction is caused when formerly unsaturated soils become saturated, which allows the soil particles to reorient into a more compact form. Irrigation of clayey alluvial-fan soils has resulted in hydrocompaction and subsidence of 3 to 15 feet on the western and southern margins of the San Joaquin Valley (**fig. 93**). Soils in many areas crossed by the California Aqueduct were intentionally hydrocompacted before aqueduct construction to avoid subsidence problems. Subsequent subsidence due to hydrocompaction in these areas has been minimal.

The primary cause of land subsidence in the Sacramento and the San Joaquin Valleys has been the compaction of fine-grained sediments (predominantly clay) in the aquifer system following severe, long-term withdrawal of ground water in excess of recharge (**fig. 93**). The amount of such subsidence in an area is related to the amount of withdrawal and the percentage of the withdrawal zone composed of clay beds. Compaction occurs when the hydraulic head in the confined parts of the aquifer system is lowered, thus reducing the hydraulic head in the clay beds, which, in turn, reduces the pore pressure in the clay. The weight of overlying sediments compacts the clay and squeezes water out of the clay until equilibrium is reached with the pore pressure in the clay. Compaction seems to happen more readily when the wells are open only to the confined part of the aquifer system than when they are open to the shallow water-table aquifer as well. When ground water is withdrawn from above and below the confining units, head differential is less between the shallow and deep aquifers and reduction in pore pressure in the clay is less.

Subsidence due to compaction of fine-grained sediments began in the San Joaquin Valley in the 1920's and in the Sacramento Valley in the 1950's. The area most affected has been in the southern and western parts of the San Joaquin Valley (**fig. 93**). Approximately one-half of the valley, or about 5,200 square miles, had subsided at least 1 foot by 1977; the total volume of subsidence was greater than 17 million acre-feet. The land surface declined nearly 30 feet from the 1920's to the late 1970's in an area southwest of Mendota (**fig. 94**). Importation of surface water and reduction in ground-water withdrawals during the 1970's slowed or stopped the decline of ground-water levels. In many cases, this allowed recovery to pre-1960's water levels and prevented further land subsidence.

Compaction and declining water levels are directly related (**fig. 95**). As water levels declined severely during the 1960's, fine-grained sediments lost water from pore spaces and became compacted. When withdrawal rates decreased and water levels were allowed to recover, compaction rates slowed significantly. Increased withdrawals during the 1976–77 drought caused additional subsidence, some of which was the result of compaction of coarse-grained sediments. When water levels recovered, the fine-grained sediments remained compacted; however, the land surface rebounded in 1978 because the compacted coarse-grained sediments regained some of their original volume when the former or near former pore pressure was attained.

LAND SUBSIDENCE—Continued

The three areas most affected by subsidence are, in order of total volume of compaction, the Los Banos–Kettleman City, the Tulare–Wasco, and the Arvin–Maricopa areas (**fig. 96**). The direct relation between withdrawals and subsidence in the Los Banos–Kettleman City area is apparent in **figure 97**. Clay has a high percentage of pore space and, when compressed, can yield large amounts of water relative to its volume. Approximately one-third of the withdrawals in the Los Banos–Kettleman City area were derived from ground water released from clay beds when the clay was compacted.

Because compaction of the clay is permanent, the volume of storage lost because of compaction will not be regained, except for the small amount that was the result of the compaction of coarse-grained aquifer materials. Thus, the land surface cannot rebound to any significant degree, but when the demand for ground water increases because of drought, water levels can be lowered nearly to those of the late 1970's without the threat of additional land subsidence. For example, during the 1976–77 drought, ground-water withdrawals increased markedly, and water levels declined rapidly. However, from 1968 to 1976, water levels had risen to such an extent that hydraulic heads remained above the extremely low levels of the 1960's. Compaction occurred only in the sand and gravel and was relatively insignificant and, to a degree, reversible (**fig. 95**).

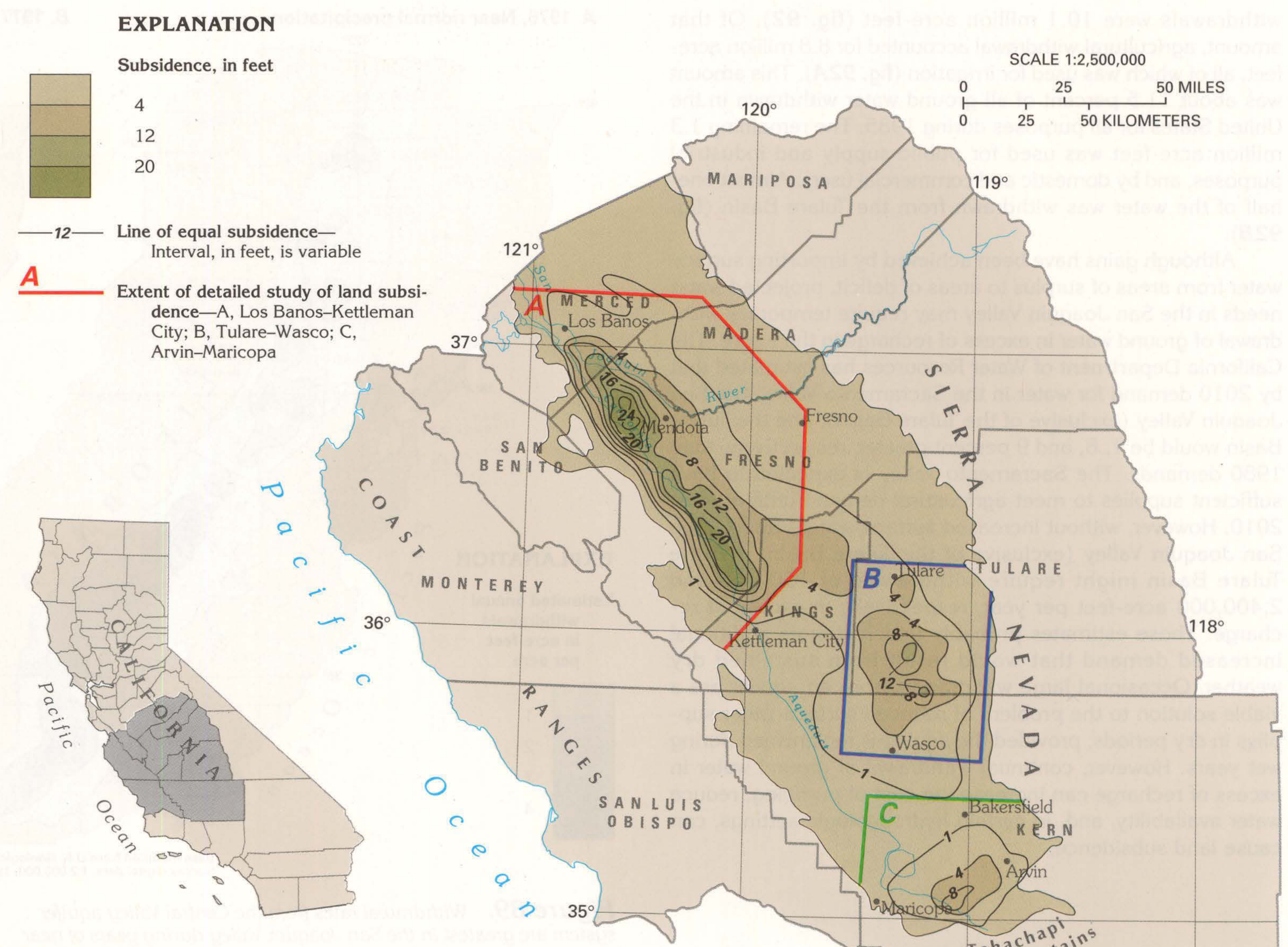


Figure 96. *The places in the Central Valley affected most severely by land subsidence are the Los Banos–Kettleman City, the Tulare–Wasco, and the Arvin–Maricopa areas.*

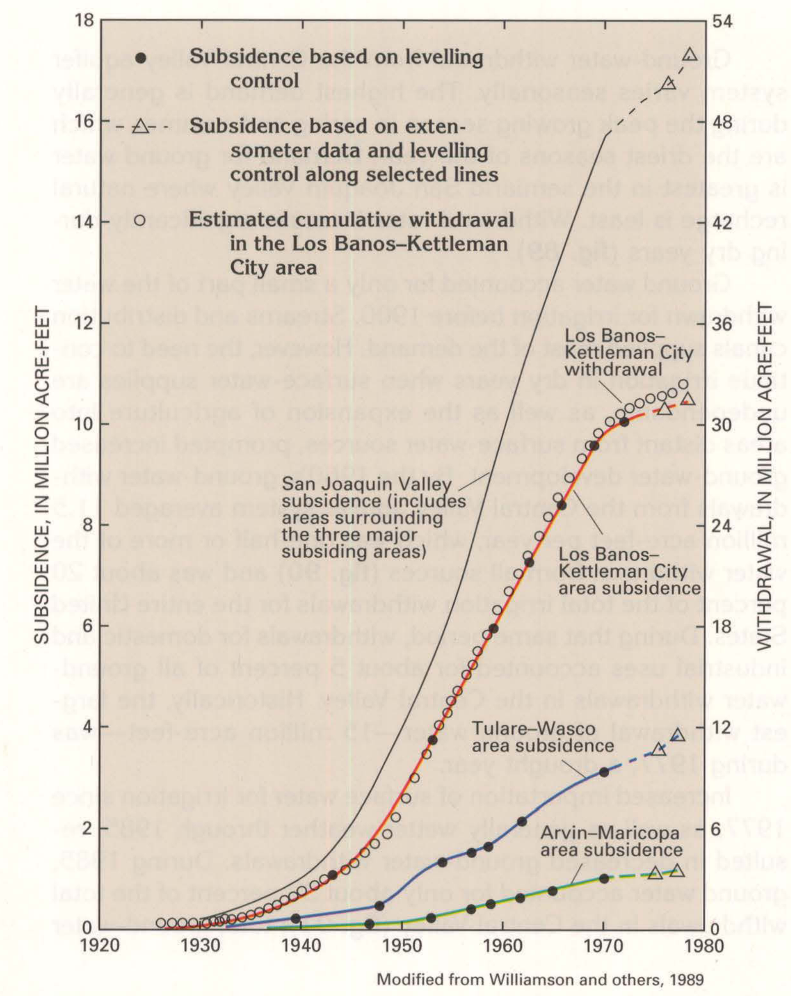


Figure 97. *By 1977, the volume of subsidence was more than 17 million acre-feet in the San Joaquin Valley. In the Los Banos–Kettleman City area, one-third of the volume of ground water withdrawn came from water that had been stored in the fine-grained sediments.*

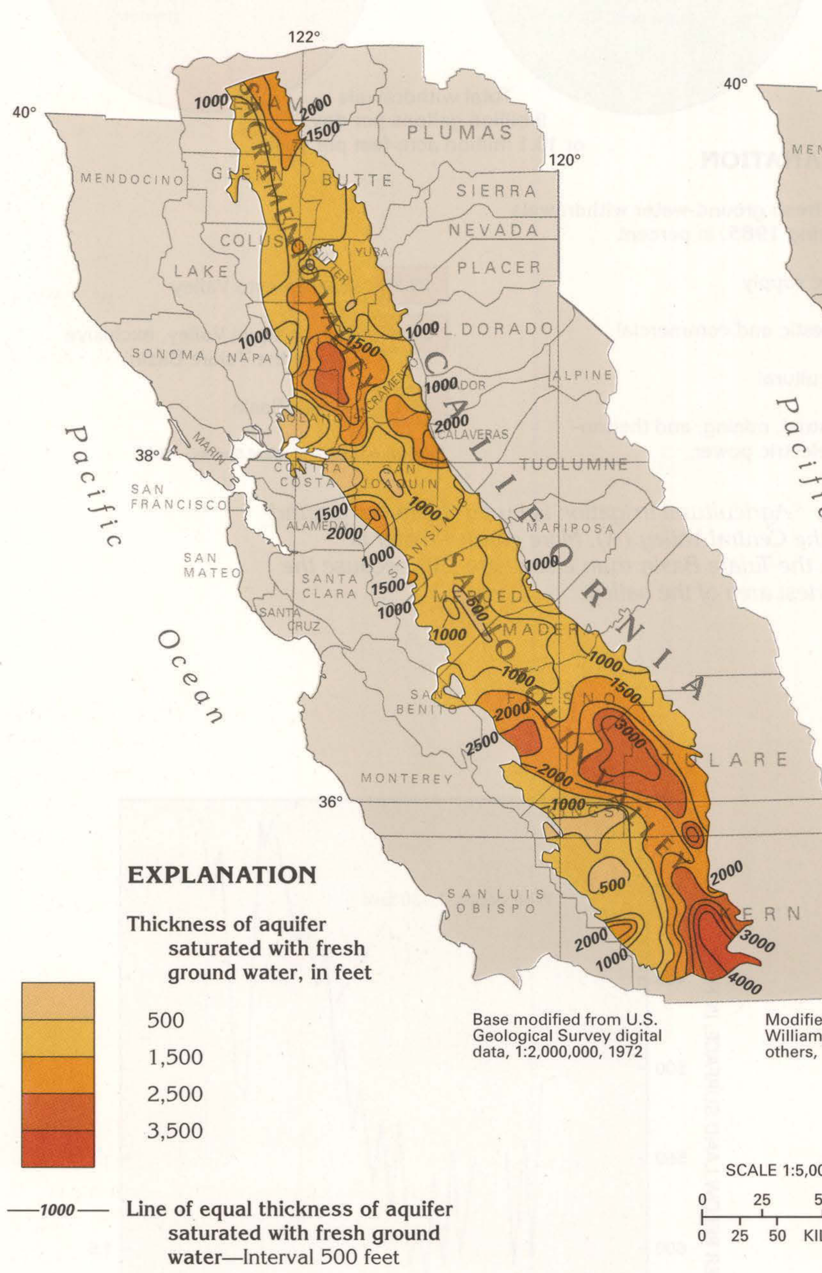


Figure 98. *The thickness of the Central Valley aquifer system that is saturated with freshwater is greatest in the San Joaquin Valley, where freshwater extends to a depth of more than 4,000 feet below land surface.*

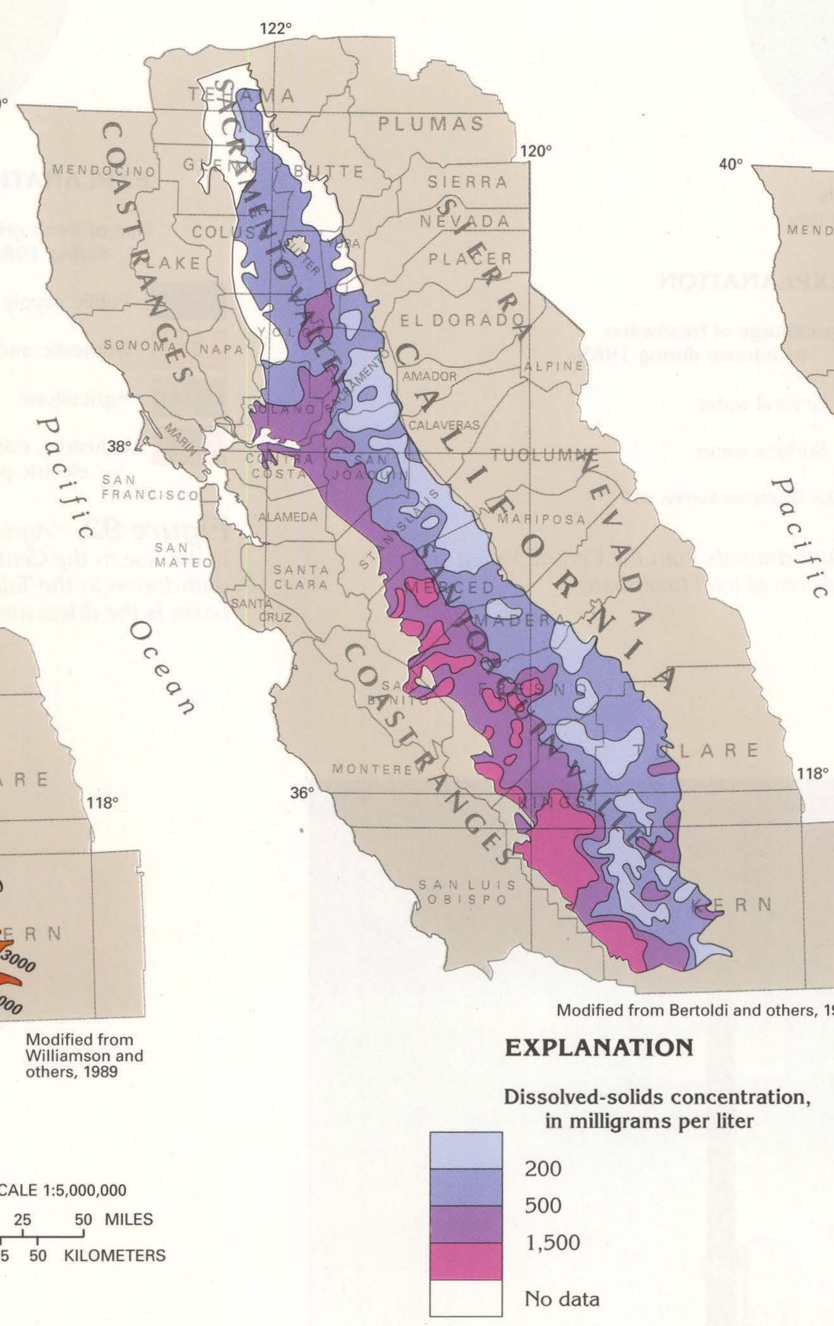


Figure 99. *Ground water in most of the confined aquifers is fresh; however, in some areas of the southwestern San Joaquin Valley, the water has large concentrations of dissolved solids.*

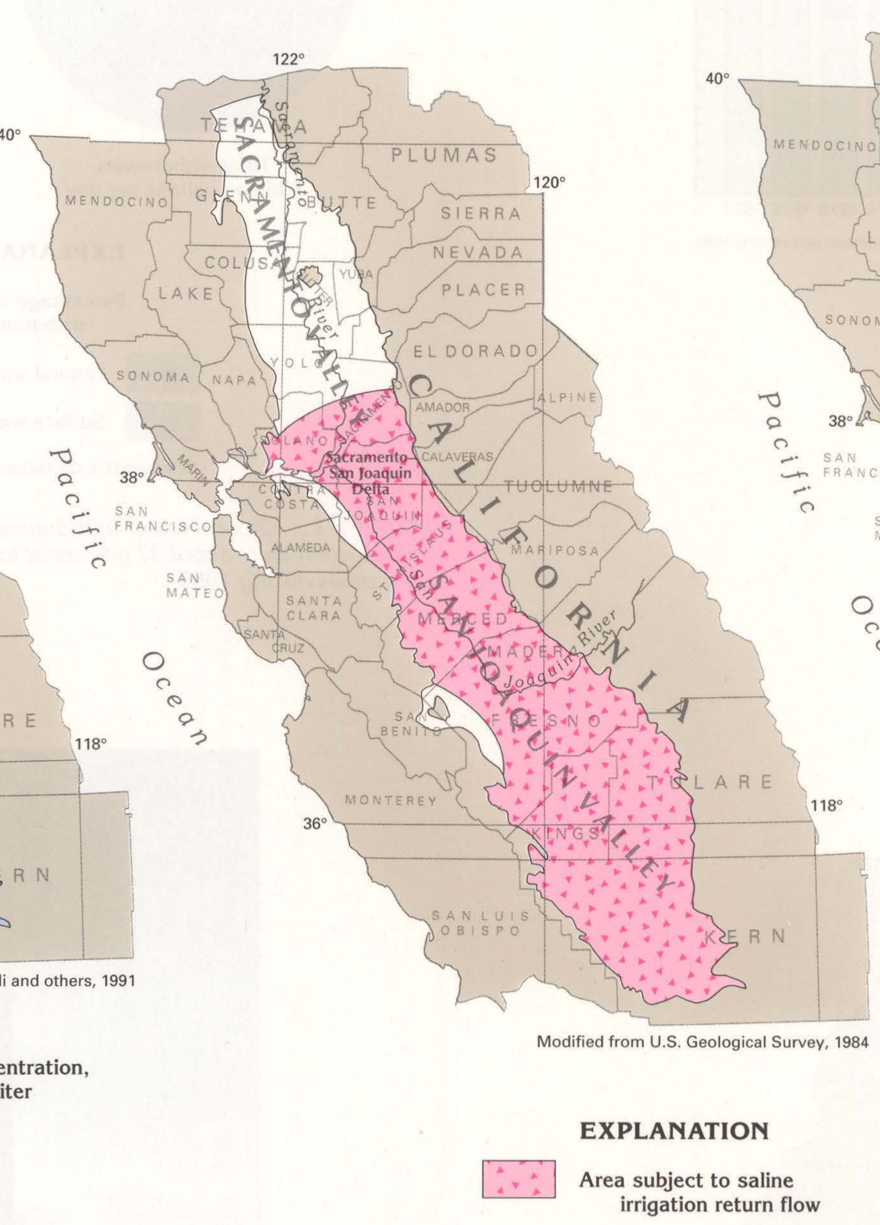


Figure 100. *Evapotranspiration of recirculated irrigation water increases the dissolved-solids concentration, and the water may become too saline for salt-intolerant crops. Salinity is a problem in many localities, and the potential for crop losses exists over most of the southern two-thirds of the Central Valley.*

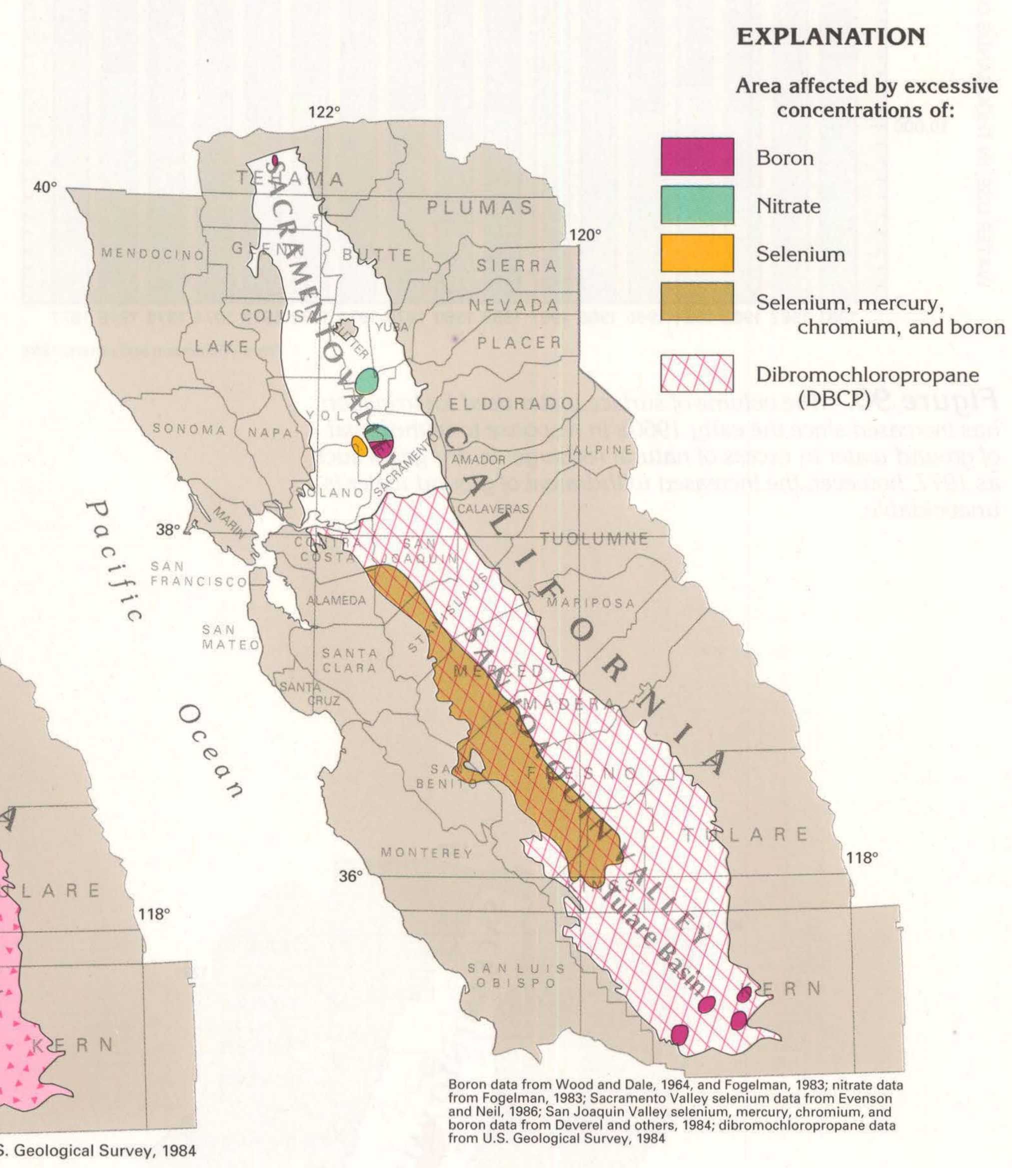


Figure 101. *Although the quality of the water in the Central Valley aquifer system is generally suitable for agricultural, industrial, and public-supply uses, some areas have potential or actual problems. Boron levels that are damaging to some crops are in ground water in the Sacramento and the San Joaquin Valleys; nitrate levels that might be damaging to crops or that exceed drinking-water standards are in the Sacramento Valley; selenium levels that exceed drinking-water standards are in three wells in the Sacramento Valley; potentially toxic levels of heavy metals are in the western part of the San Joaquin Valley; and the pesticide dibromochloropropane has been detected throughout the San Joaquin Valley.*

GROUND-WATER QUALITY

The thickness of aquifer saturated with freshwater (water with less than 1,000 milligrams per liter dissolved-solids concentration) in the Central Valley aquifer system varies greatly (**fig. 98**) and depends, for the most part, on the depth to and permeability of the rocks that underlie continental deposits. In the Sacramento Valley, the base of freshwater generally coincides with the base of continental deposits. The several isolated lenses of saline water that are within the freshwater zone may be evaporation residues or estuarine water that was trapped by subsequent sedimentation. The depth to the base of freshwater is as much as 2,500 feet in the Sacramento Valley.

In the San Joaquin Valley, the pattern is more complex. Freshwater is mainly in continental deposits, but also is in Tertiary marine rocks on the southeastern side of the valley and in pre-Tertiary igneous and metamorphic rocks. However, sediments of continental origin are the primary source of freshwater. The thickness of aquifer saturated with freshwater in the San Joaquin Valley ranges from 100 to more than 4,000 feet (**fig. 98**).

Freshwater is available throughout most of the Central Valley. The concentration of dissolved solids in the ground water reflects the general chemical character of water in the streams that recharge the aquifer system. Dissolved-solids concentrations in the streams, in turn, are directly related to the type of rocks that form the mountains in which the streams rise. Stream water from the Cascade Range and the Sierra Nevada, which are underlain primarily by igneous rocks, has much smaller dissolved-solids concentrations than water from the Coast Ranges, which are underlain by marine sedimentary rocks. Thus, ground water in the Sacramento Valley and the east side of the San Joaquin Valley has generally smaller dissolved-solids concentrations than water from wells on the west side of the valley (**fig. 99**).

In general, dissolved-solids concentrations increase with depth in the Central Valley aquifer system. Therefore, the generally deeper wells in the western and southern parts of the San Joaquin Valley are likely to produce water with larger dissolved-solids concentrations than the generally shallower wells in the Sacramento Valley and the eastern part of the San Joaquin Valley.

Ground water in agricultural areas can become excessively saline and damaging to crops because evaporation of sprayed irrigation water and evapotranspiration of soil moisture and shallow ground water leaves behind dissolved salts. As a result, the concentration of salts in the soil and shallow ground water increases and may reach levels detrimental to plant growth. Shallow irrigation wells worsen the problem by recirculating the saline shallow ground water, thus accelerating the process. The only remedy for this problem is to provide subsurface drainage to remove the shallow saline ground water.

The potential for crop damage due to saline irrigation-return flow is widespread in the Sacramento–San Joaquin Delta and the San Joaquin Valley (**fig. 100**). Although several individual irrigation return-water drainage systems are operated, no current (1995) valleywide system removes shallow saline ground water. An estimated 400,000 to 700,000 acres of arable land may be lost by 2010 because of increasing soil and water salinity with an accompanying loss of from $32 million to $320 million annually.

Soils on the western side of the San Joaquin Valley are derived primarily from the marine rocks that form the western boundary of the aquifer system and contain relatively large amounts of selenium, which also is in ground water in the marine rocks and is concentrated in the soil by evapotranspiration. Excess irrigation water applied to leach salts from the soil, thus preventing salt buildup, leaches selenium from the soil and the marine rocks and transports it to shallow ground water or surface drains. Water that contains dissolved-selenium concentrations of 1,400 micrograms per liter is in some of the regional surface drains, and a concentration of 4,200 micrograms per liter was reported in water from the drainage system on one farm. Concentrations of dissolved selenium as large as 3,100 micrograms per liter have been detected in shallow ground water in the western part of the San Joaquin Valley; the largest concentrations are west of the San Joaquin River flood plain.

Although large local concentrations of selenium are in the western part of the San Joaquin Valley, evidence that drinking-water supplies in the Central Valley are currently (1995) at serious risk because of selenium contamination is lacking. The large selenium concentrations in the western part of the San Joaquin Valley are known only to be in the shallow ground water and not in the deeper parts of the aquifer system from which most wells that supply municipalities obtain water. A 1986 survey of wells outside of the western part of the San Joaquin Valley indicated selenium concentrations to be larger than 10 micrograms per liter in water from only 3 of 113 wells sampled in the Central Valley (**fig. 101**).

Boron is an essential micronutrient but may be toxic to sensitive plants in concentrations as low as 0.5 milligram per liter. Currently (1995), the U.S. Environmental Protection Agency has no standards for boron in drinking water. Boron is found in concentrations potentially harmful to plants in the northern and southwestern parts of the Sacramento Valley and in the Tulare Basin in the extreme southern part of the San Joaquin Valley (**fig. 101**). Large concentrations of boron also have been detected in shallow ground-water in the western part of the San Joaquin Valley. Chromium and mercury have been detected in shallow ground water in the western part of the San Joaquin Valley at levels that exceed U.S. Environmental Protection Agency standards for protection of aquatic life.

Excessive concentrations of nitrate in water are potentially harmful to infants and young children, and the maximum recommended for drinking water by the U.S. Environmental Protection Agency is 10 milligrams per liter. Some crops may be affected by nitrate concentrations as low as 5 milligrams per liter. During a survey conducted in 1983, nitrate levels in ground water were found to exceed 10 milligrams per liter in three areas in the Sacramento Valley (**fig. 101**). The contaminated wells were shallow, and the source of nitrate pollution was attributed to effluent from waste-treatment facilities, discharge from septic tanks, or leaching of nitrogen fertilizers. Occurrences of nitrate in concentrations of greater than 5 milligrams per liter are sporadic in the San Joaquin Valley and seem to be confined mainly to the shallow parts of the aquifer. The contamination is usually attributable to local sources, such as septic tanks, feed lots, and dairies.

Agricultural use of pesticides is widespread in the Central Valley. Dibromochloropropane (DBCP), which is a potential carcinogenic nematocide, is in ground water in every county in the San Joaquin Valley (**fig. 101**), and has been detected in 2,522 of 8,190 private and public-supply wells sampled from 1979 through 1984; in California, DBCP has been outlawed from use since August 1977. At least 50 other pesticides, including 1,2-dichloropropane and ethylene dibromide, had been detected in ground water in the Central Valley by 1984.

Coastal Basins aquifers

INTRODUCTION

The California coastal region has been subjected to intense tectonic forces for millions of years. Folding, faulting of marine sediments, and associated volcanism resulted in the formation of the Klamath and the Salmon Mountains in northern California and the Coast Ranges that extend along most of the California coast. Terrestrial, marine, and volcanic rocks deposited in intermontane valleys compose the aquifers herein called the Coastal Basins aquifers (**fig. 102**). The California Department of Water Resources considers more than 100 coastal basins to be "significant" because of the amount of ground water potentially obtainable or the scarcity of surface-water sources in a basin. Nearly all of the large population centers in California are located in the coastal basins.

The climate along the coast of California is moderated by the Pacific Ocean and is essentially Mediterranean, characterized by cool winters and warm summers. Precipitation is seasonal and usually in the form of rain. The greatest amounts of precipitation fall during late autumn, winter, and early spring. Precipitation amounts are greatest in northern California and progressively decrease southward. Altitude also influences precipitation patterns; the greatest amounts of precipitation fall in the mountains. Potential annual evaporation in the valleys exceeds annual precipitation from San Francisco Bay southward. As a result, most unregulated rivers in southern California are dry in their lower reaches during the summer months.

GEOLOGIC SETTING

The intermontane basins in the coastal mountains of California are structural troughs or depressions that parallel the coastline and formed as a result of folding and faulting (**fig. 103**). Most of the folds and faults trend northwestward and result from the deformation of older rocks by the intense pressures of colliding continental plates. The rocks that underlie the basins and form the surrounding mountains are primarily marine sediments and metamorphic and igneous rocks, all of which are of Mesozoic age but locally include rocks of Cenozoic age.

The basins are partly filled with unconsolidated and semiconsolidated marine sedimentary rocks that were deposited during periodic encroachment of the sea and with unconsolidated continental deposits that consist of weathered igneous and sedimentary rock material which was transported into the basins primarily by mountain streams. These marine sediments and continental deposits are tens of thousands of feet thick in some basins. In the basins just north of San Francisco Bay, permeable basalt and tuff compose a portion of the materials overlying the older consolidated rocks. In most basins, however, almost all of the permeable material consists of unconsolidated continental deposits, primarily sand and gravel (**fig. 103**).

GEOHYDROLOGIC SETTING

In all the basins, most of the freshwater is contained in aquifers that consist of continental deposits of sand and gravel that might be interbedded with confining units of fine-grained material, such as silt and clay. The aquifers and confining units compose an aquifer system. Water enters a typical coastal-basin aquifer in several ways. Runoff from precipitation in the surrounding mountains infiltrates the permeable sediments of the valley floor either at the basin margins or through streambeds where the water table is lower than the water level in the stream. Precipitation that falls on the valley floor provides some direct recharge, but in the coastal basins, most of the precipitation evaporates or is transpired by plants. In a few basins that are hydraulically connected to other basins, water can enter an aquifer system as lateral subsurface flow from an adjacent basin. Of these methods of recharge, runoff from the mountains and percolation through streambeds provide the largest amounts of water to the ground-water system.

Natural movement of water in the aquifers is generally parallel to the long axis of the basin (**fig. 103**) because of impermeable rocks that commonly form a barrier between the basin and the sea. However, in a few coastal basins, most notably in the Los Angeles–Orange County coastal plain, the coastal barrier is absent, and the natural direction of flow is perpendicular to the long axis of the basin or from the inland mountains to the sea. Before major development, ground water in all the basins discharged directly into the ocean or into bays connected to the ocean. After development, however, most or all the ground water is withdrawn by wells in the basins.

Although all the coastal basins have similar hydrogeologic settings, each is different in its geologic history and land- and water-use characteristics. Because it is beyond the scope of this Atlas to describe all of the coastal basin aquifers, only the basins with the largest ground-water withdrawals are described in this section.

FRESH GROUND-WATER USE AND MANAGEMENT

During the early years of ground-water development in the coastal basins, from the 1850's to early 1900's, the principal use of water was for irrigated agriculture. Although agricultural ground-water use remains substantial, urbanization has gradually replaced most agricultural land in the larger basins and the greatest collective ground-water demand is now for public supply. The largest water users are cities and suburbs from San Francisco southward, but because of the unequal distribution of rainfall, most of the freshwater is in northern California. Accordingly, it has become necessary to regulate streamflow and import water into many coastal basins from the Sierra Nevada, the Colorado River, the Owens Valley, and northern California through an extensive system of aqueducts.

For many years, rapidly growing populations in several basins resulted in ground-water withdrawals that exceeded natural recharge on a long-term basis; this led to marked water-level declines. The consequences of these excessive withdrawals ranged from mild, such as increased pumping costs, to severe, such as land subsidence and seawater intrusion. Today (1995), ground water in the coastal basins of California is carefully managed. The current supply of water from all sources, including imported water, approximately balances demand. However, because the natural recharge to many basins, especially southward from the San Francisco Bay area, is far less than the volume of ground water currently (1995) withdrawn, increases in population will require either additional imports, more conservation, an increase in the amount of water now reclaimed, or a combination of all three. More than any other environmental factor, water availability will likely determine the size of the population these basins can support.

EUREKA AREA BASINS

The Eureka area basins, which consist of the Mad River Valley, the Eureka Plain, and the Eel River Valley, are located southwestward of the Klamath Mountains at the north end of the Coast Ranges (**fig. 104**). The basins are not densely populated; agriculture and timber are the major industries in the area, and pastureland accounts for most of the agricultural acreage.

The predominant feature of the Eureka area is Humboldt Bay, which is separated from the ocean by spits. Humboldt Bay, the northern end of which is known as Arcata Bay, extends 12 miles parallel to the coastline and is 0.5 to 4 miles wide. The land on the inland side of the bay is flat to gently rolling. The shoreline of the bay has a well-developed beach from which dunes extend inland a short distance over the alluvial plain.

The major streams that drain the area are the Eel River, which flows into the Pacific Ocean south of Humboldt Bay, and the Mad River, which flows into the Pacific Ocean north of the bay. Several small streams also flow into Humboldt Bay. All the streams are tidally influenced and have brackish-water marshes and mud flats along their banks for as much as 1 to 2 miles inland.

Coastal northern California has a Temperate Oceanic climate, which is characterized by moderate temperature and precipitation. Dense fog is frequent and tends to attenuate temperature fluctuations. The average annual precipitation at Eureka is approximately 40 inches per year, most of which falls during the autumn and winter months. Precipitation increases with altitude, and amounts are greater inland in the foothills and mountains.

Aquifers and Confining Units

Unconsolidated deposits of sand, gravel, silt, and clay, which are Pliocene and younger and primarily of alluvial origin, compose the Eureka area aquifers (**fig. 104**). Near the coast, the alluvial deposits interfinger with estuarine sediments and locally are underlain by marine sediments. The thickness of the unconsolidated deposits ranges from only a few feet to as much as 1,000 feet (**fig. 105**). The unconsolidated deposits range from coarse to fine grained. The most permeable deposits are surficial alluvium and dune sands. Virtually all fresh ground water is withdrawn from these deposits, but deeper beds yield water in some places. The permeability of the unconsolidated sediments varies with location, however, and well yields vary accordingly. Consolidated and semiconsolidated rocks of minimal permeability form the boundaries of the aquifer system.

Distinct confining units are scarce in the unconsolidated deposits, but large total thicknesses of fine-grained sediments can impede vertical flow sufficiently to create an increase in hydraulic head with depth. Consequently, depending upon the permeability and depth of the water-yielding deposits at a particular location, ground water can be either confined or unconfined conditions.

Figure 102. The Coastal Basins aquifers are located in the valleys of the Klamath Mountains and the Coast Ranges and are distributed along the Pacific coast of California.

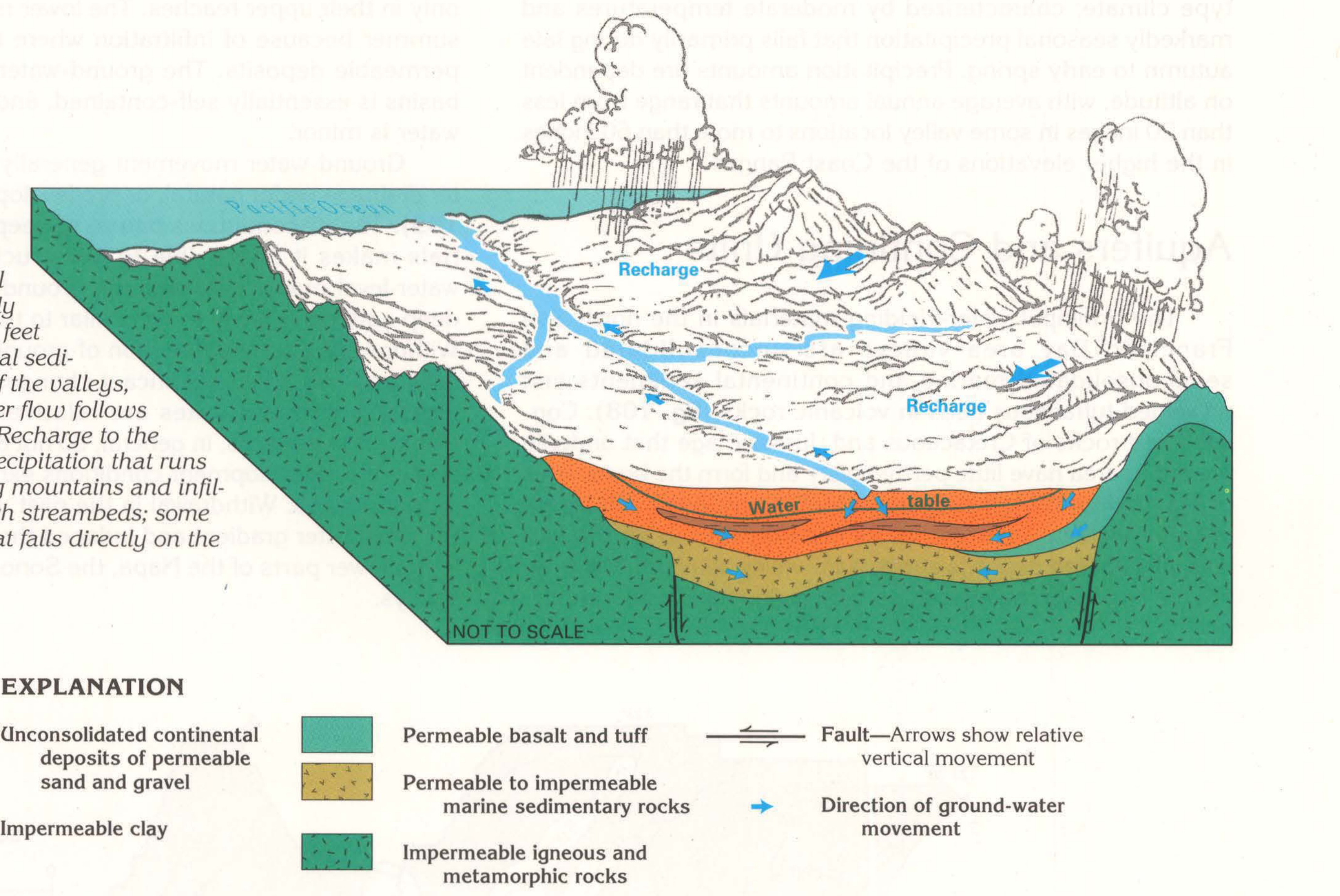


Figure 103. The valleys that contain the Coastal Basins aquifers are formed by structural troughs that are typically filled with thousands of feet of marine and continental sediments. In the majority of the valleys, the natural ground-water flow follows the axis of the troughs. Recharge to the aquifers is mostly by precipitation that runs off from the surrounding mountains and infiltrates as leakage through streambeds; some recharge is from rain that falls directly on the valley floor.

The primary fresh ground-water body in the Eureka area is in the Eel River Valley, where ground water under unconfined, or water-table, conditions is available nearly everywhere at depths of 30 feet or less. An exception is in the vicinity of Ferndale, where sediments are fine grained, have minimal permeability, and yield little water to wells except near the mouths of streams, where the sediments are coarse grained and fluvial. A perched water table is above clay beds that form a local confining unit in terrace deposits near the Eel River. Water in the deeper parts of the aquifer in the Eel River Valley, near Humboldt Bay in the Eureka Plain, and in the Mad River Valley, between Eureka and Arcata, is under confined or partially confined conditions

Ground-Water Movement

The aquifer is recharged primarily by runoff from the hills that surround the stream valleys and by seepage from the upper reaches of streams. Minor recharge is by lateral movement of water from adjacent rocks and by direct precipitation. Deeply-buried sediments are recharged by precipitation where they crop out and by leakage from shallower water-yielding beds to which they are hydraulically connected, especially where withdrawals from the deep sediments are sufficient to cause a downward hydraulic gradient. Ground-water movement in the surficial deposits is generally toward the coast (**fig. 106**), where the water mostly discharges into estuarine reaches of the rivers; some water discharges directly into Humboldt Bay or the Pacific Ocean, or is withdrawn by wells. Water in the deeper sediments is discharged by vertical flow to shallower deposits where the hydraulic gradient is upward, or is withdrawn by deep wells.

Fresh Ground-Water Withdrawals

Irrigation of pastureland accounts for most ground-water use in the Eureka area, followed by withdrawals for industry and public supply. Most of the withdrawals for irrigation are in the coastal plain of the Eel River Valley. The cities of Eureka and Arcata use surface water for their public supplies, whereas many of the smaller communities use ground water. Total estimated ground-water withdrawals during 1972 were 9,000 acre-feet in the Mad River Valley, 15,000 acre-feet in the Eureka Plain, and 10,000 acre-feet in the Eel River Valley. This is more than double the estimated total withdrawal of 15,000 acre-feet during 1952, but current (1995) rates of ground-water withdrawal do not appear to be in excess of natural recharge. Therefore, no shortage of water is likely as long as surface-water supplies remain adequate to supply municipal demands.

Ground-Water Quality

The quality of ground water in the Eureka area is generally acceptable for most uses, although concentrations of dissolved iron in water from many wells may exceed the U.S. Environmental Protection Agency's secondary drinking-water recommendation of 300 micrograms per liter. Chloride concentrations in excess of the 250 milligrams per liter drinking-water recommendation are reported in water from wells near the Eel River as much as 4 miles inland from the Pacific Ocean, suggesting that the source of the chloride is brackish water from the tidal reaches of the river. Shallow wells in the dune sands also are prone to seawater intrusion because they must obtain freshwater from a thin lens that floats on saltwater. Excessive withdrawals or minimal recharge lower the freshwater head in the dunes and allow salty water to be drawn into wells.

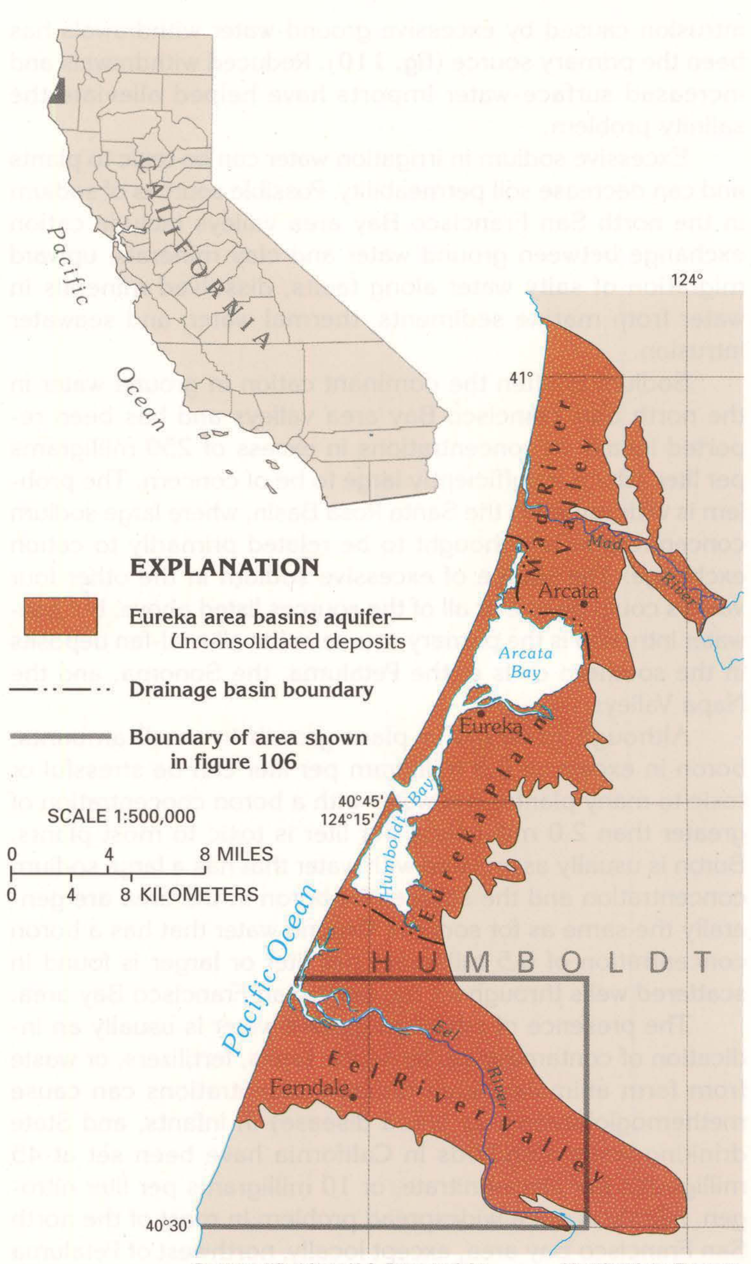


Figure 104. The Eureka area basins, located along the moist, heavily forested, sparsely populated northern California coast, consist of unconsolidated deposits and are bounded by consolidated and semiconsolidated rocks.

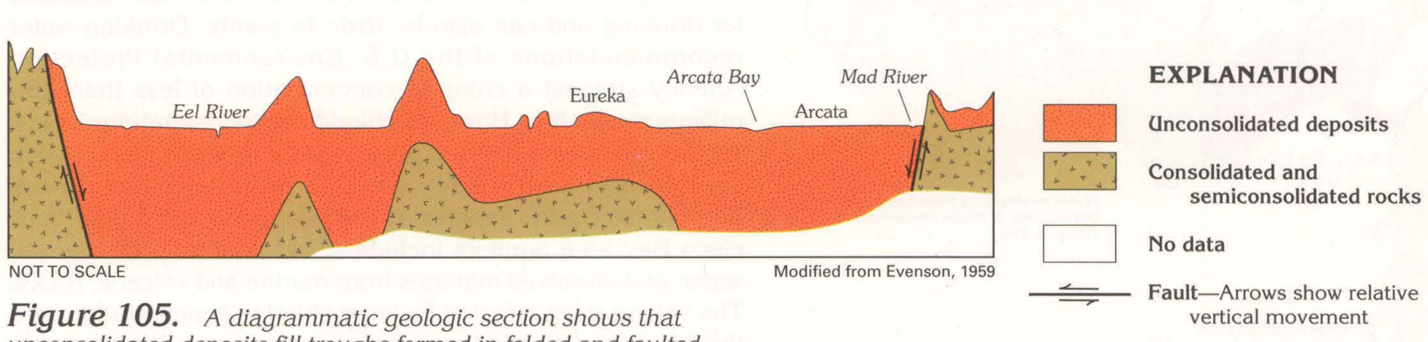


Figure 105. A diagrammatic geologic section shows that unconsolidated deposits fill troughs formed in folded and faulted consolidated and semiconsolidated rocks.

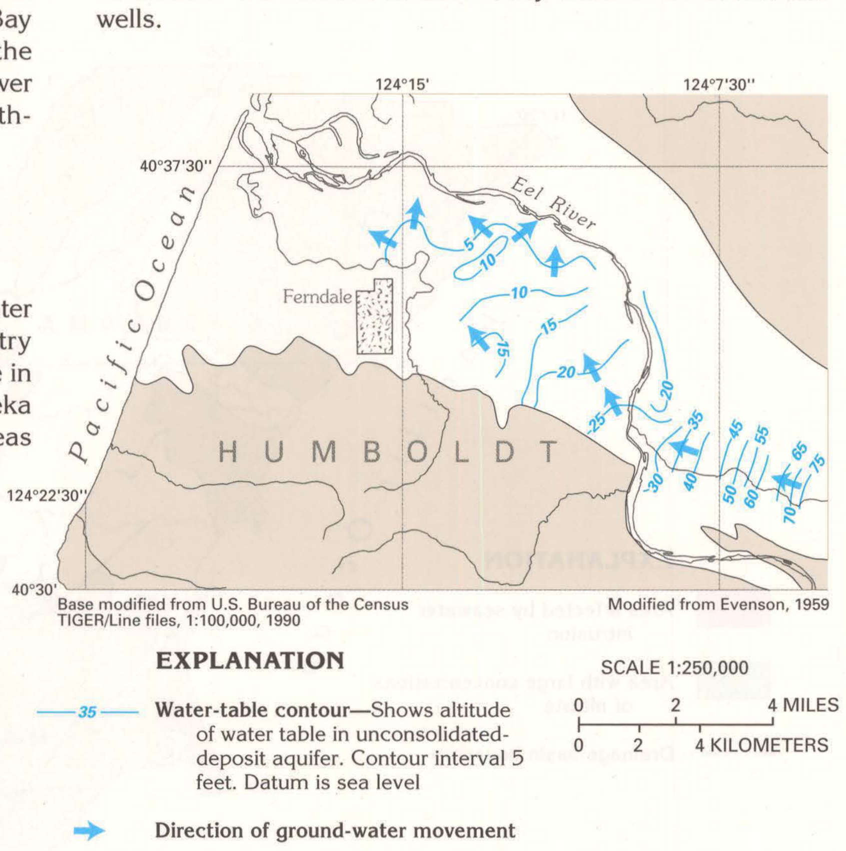


Figure 106. The direction of ground-water movement in the Eel River Valley is seaward and discharge from the aquifer is mostly to the lower reaches of the river.

NORTH SAN FRANCISCO BAY AREA VALLEYS

Among the Coast Ranges north of San Francisco Bay are several valleys underlain by aquifers from which moderate to large volumes of water are withdrawn (**fig. 107**).The Petaluma, the Sonoma, the Napa, and the Suisun–Fairfield Valleys drain into San Pablo Bay, and the Santa Rosa Basin drains into the Russian River, which empties into the Pacific Ocean.

The north San Francisco Bay area valleys contain a mixture of urban and agricultural lands. Population growth since the 1970's has been rapid and urban areas have replaced much of what was formerly agricultural land. Nonetheless, agriculture remains important to the local economy. Orchard crops are a significant part of the total agricultural output but are being replaced in many areas by vineyards. Many formerly unplanted hillsides now grow wine grapes.

Ground-water supplies in the area are limited by local availability and, to a degree, by the quality of the water. Most of the water used in the area is surface water, much of which is either derived from the Russian River or imported from the Central Valley. Ground water, however, remains the primary source of supply for agriculture, stock watering, and domestic uses and is an important source for municipal supply.

The five drainage basins of the north San Francisco Bay area valleys are structural troughs filled to great depths with marine and continental sediments and volcanic deposits. The basins each have a flat to gently rolling valley floor formed primarily on alluvial fan deposits. The slope of the fan steepens near the foothills at the base of the surrounding mountains. Some streams that drain mountain valleys are perennial only in their upper reaches because the water table falls below the level of the streambed during the dry season. The lower stream reaches are seasonally intermittent.

The North San Francisco Bay area has a Mediterranean-type climate, characterized by moderate temperatures and markedly seasonal precipitation that falls primarily during late autumn to early spring. Precipitation amounts are dependent on altitude, with average annual amounts that range from less than 20 inches in some valley locations to more than 60 inches in the higher elevations of the Coast Ranges.

Aquifers and Confining Units

The principal water-yielding materials in the north San Francisco Bay area valleys are unconsolidated and semiconsolidated marine and continental sediments and unwelded tuffaceous beds in volcanic rocks (**fig. 108**). Consolidated rocks of Cretaceous and Jurassic age that underlie the entire area have little permeability and form the boundaries of the ground-water flow system. The permeability and extent of water-yielding deposits varies considerably. In all the valleys, alluvial-fan deposits and stream-valley alluvium compose the major part of the aquifer. Locally, marine and estuarine deposits of sand beneath the Santa Rosa and the Petaluma Basins are an important source of ground water. Volcanic tuff of Pliocene age in the areas of volcanic rocks shown in **figure 108** yields water to wells in the Sonoma and the Petaluma Basins.

Ground water is under unconfined, or water-table, conditions in shallow alluvial deposits and locally where it is near the land surface in other types of rocks. The ground water is confined or semiconfined in deeper parts of the alluvial deposits and nonalluvial formations. Because of their lenticular nature, water-yielding deposits in the north San Francisco Bay area valleys are generally discontinuous and isolated. Further, many of the deep deposits are displaced by faults. As a result, the valleys are a collection of variously connected and isolated aquifers. Generally, the alluvial-fan and stream-valley alluvial deposits in each basin are sufficiently continuous to be considered single aquifers; however, because of the geologic complexity of the area and the limited availability of data, the exact extent and degree of continuity of many deep aquifers is unknown.

Ground-Water Flow System

Recharge to the ground-water flow system enters permeable sediments at the valley margins primarily as runoff from precipitation in the mountains and hills that surround the valleys. Other sources of recharge are precipitation that falls directly on permeable deposits in low-lying areas of the valleys and seepage through streambeds in areas where the water table is lower than the stream level and the streambed sediments are sufficiently permeable to permit infiltration into the aquifers. Discharge is by seepage to gaining reaches of streams, spring discharge, evapotranspiration, and withdrawals from wells.

All the basins are drained by streams that are perennial only in their upper reaches. The lower reaches become dry in summer because of infiltration where they are underlain by permeable deposits. The ground-water flow system in most basins is essentially self-contained, and interbasin transfer of water is minor.

Ground-water movement generally followed surface-water drainage under natural, or predevelopment, conditions (**fig. 109**). The discontinuous nature of deep water-yielding materials makes it impossible to construct accurate basinwide water-level maps. However, the ground-water flow pattern in deep aquifers is likely to be similar to that of shallow aquifers. Withdrawals alter the direction of ground-water movement locally and can affect significant changes in regional flow patterns if withdrawal rates are relatively large. Present-day (1995) flow patterns, in general, do not differ significantly from those of predevelopment conditions except locally near withdrawal centers. Withdrawal in the past, however, has reversed the freshwater gradient and induced the intrusion of saltwater in the lower parts of the Napa, the Sonoma, and the Petaluma Valleys.

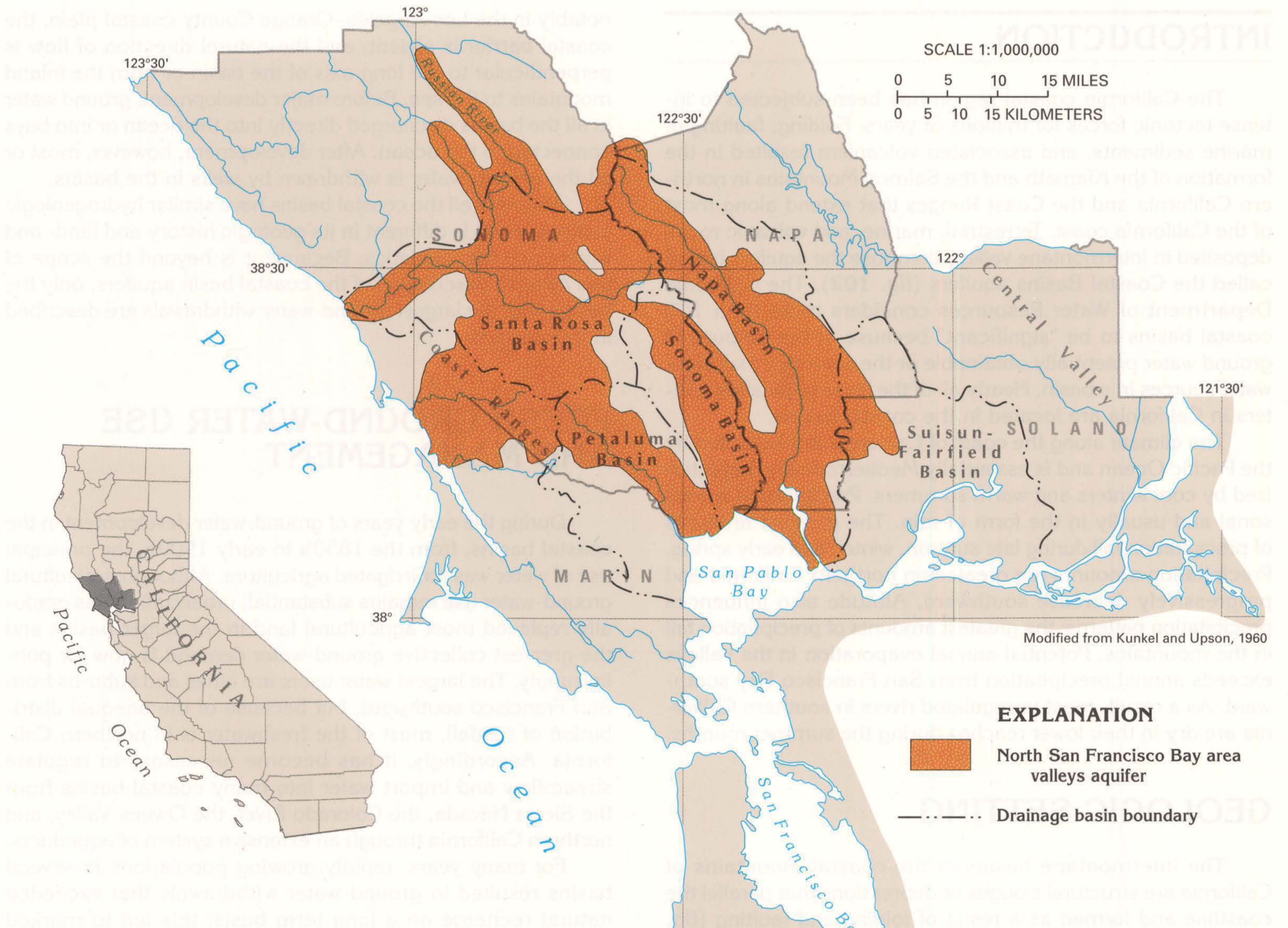


Figure 107. *The north San Francisco Bay area valleys are located just inland from the Pacific Ocean at the northern end of San Francisco Bay and are in parts of five contiguous basins, four of which drain into the bay; the fifth drains directly into the Pacific Ocean.*

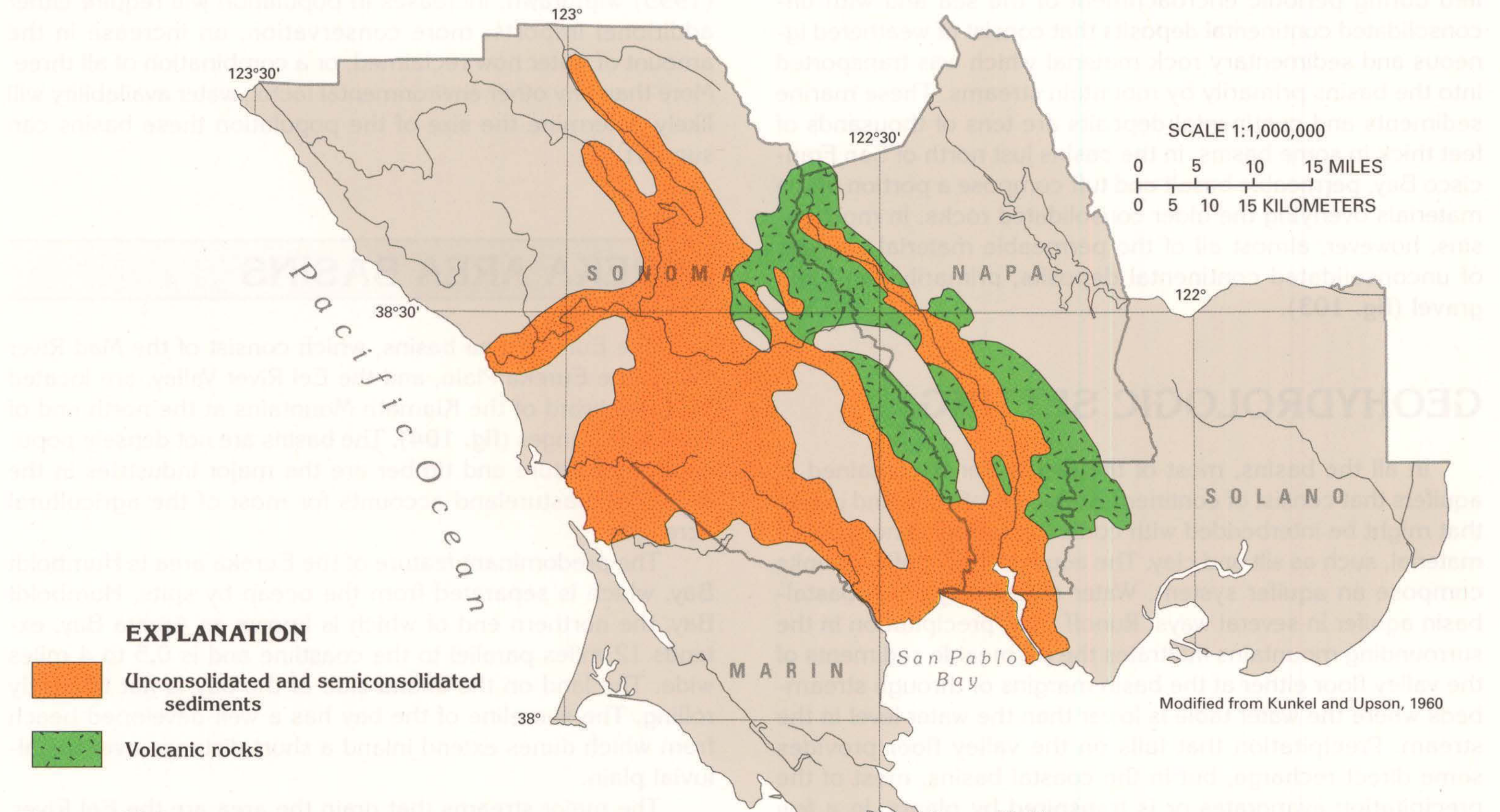


Figure 108. *Valley floors are underlain by permeable unconsolidated and semiconsolidated sediments and volcanic rocks. Consolidated sedimentary rocks form boundaries of the aquifers.*

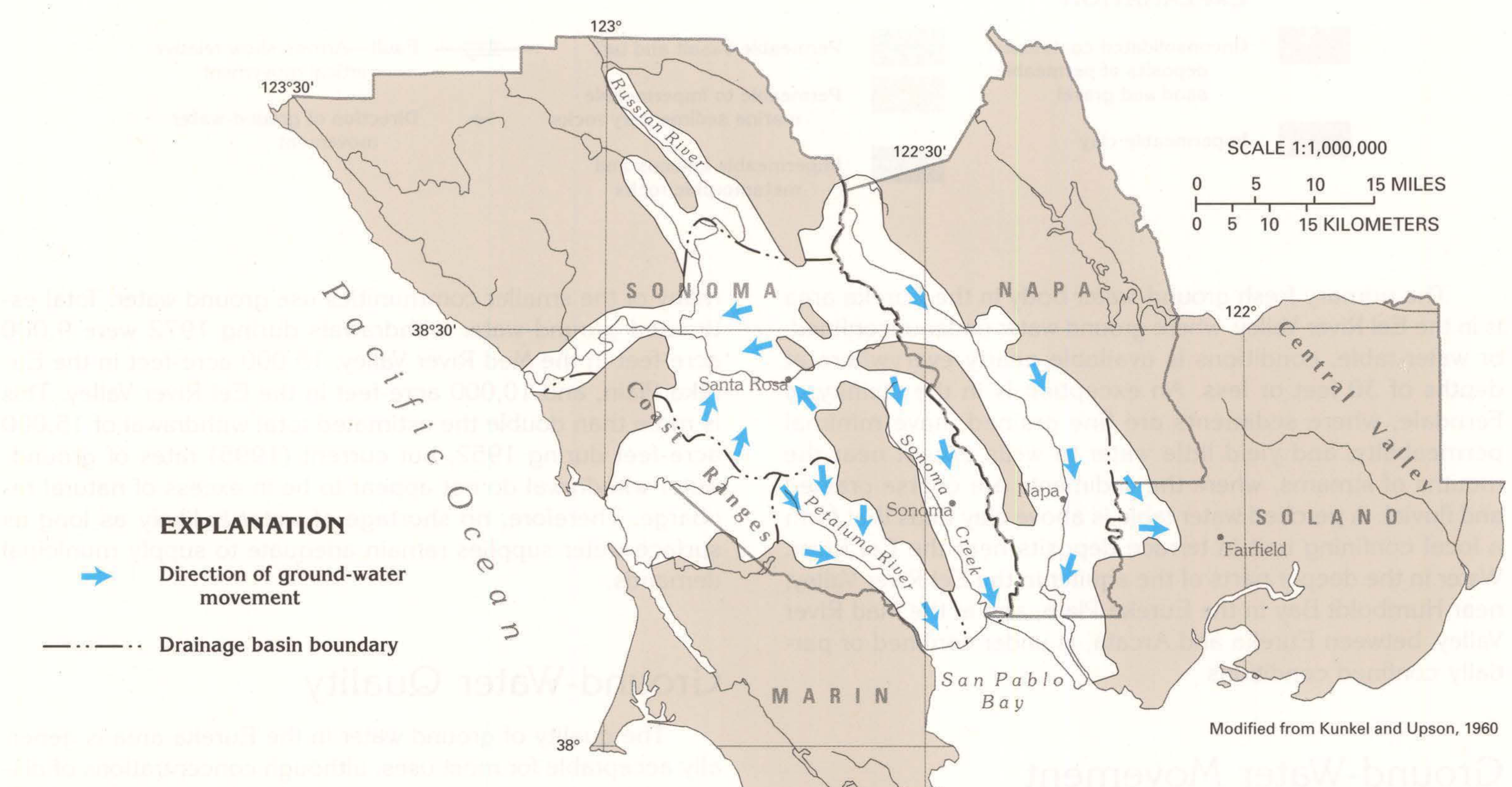


Figure 109. *Ground-water movement in each of the basins generally follows surface-water drainage and moves from higher to lower altitudes to ultimately discharge into rivers or San Pablo Bay.*

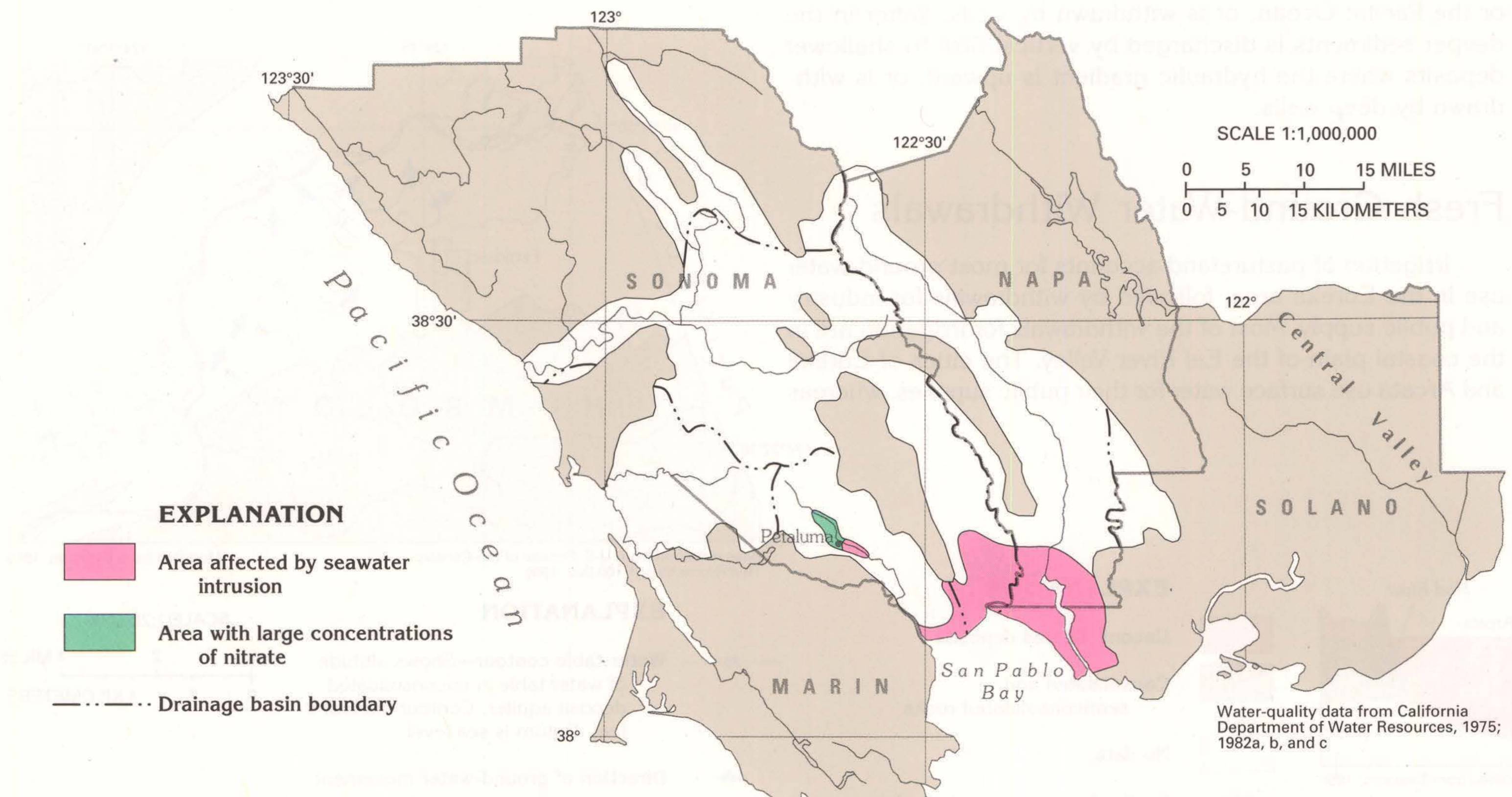


Figure 110. *Seawater intrusion caused by excessive ground-water withdrawals has been a problem in the lower parts of the valleys that border San Pablo Bay. An area of large nitrate concentrations in ground water is a concern in the Petaluma Valley.*

Fresh Ground-Water Withdrawals

Surface and ground water are used conjunctively in the north San Francisco Bay area valleys. Several municipalities obtain a significant amount of their supplies from imported surface water, either from the Russian River or the aqueduct systems that serve San Francisco Bay area cities to the south. Nonetheless, ground water is used for some municipal supplies, as well as for irrigation, stock watering, and domestic uses.

Currently (1995), ground-water recharge and discharge are approximately in balance on an average annual basis in most areas, and withdrawals in excess of recharge are not common. However, because of the relatively limited storage capacity of the aquifers, as well as water-quality concerns, the amount of additional ground water that can be withdrawn without adverse effects is restricted. Although lowering of the water table can allow infiltration of additional recharge that might normally be rejected, withdrawal in excess of recharge can deplete ground-water reserves and possibly cause the migration of poor-quality water into wells. Careful monitoring of local and regional water levels will always be necessary to ensure proper use of the resource.

Ground-Water Quality

The quality of ground water in the north San Francisco Bay area valleys is generally suitable for most purposes. However, some problems, such as locally large concentrations of chloride, sodium, boron, nitrate, iron, and manganese, might restrict use of ground water for some applications.

Large concentrations of chloride can make water unusable for drinking and can also be toxic to plants. Drinking-water recommendations of the U.S. Environmental Protection Agency suggest a chloride concentration of less than 250 milligrams per liter. However, chloride in concentrations as low as 106 milligrams per liter may be toxic to some plants; such concentrations have been detected in ground water in the Santa Rosa Basin. Sources of chloride in the north San Francisco Bay area aquifers include seawater intrusion, thermal water, and dissolved minerals from marine and volcanic rocks. The valleys most affected by large chloride concentrations are the Petaluma, the Sonoma, and the Napa, in which seawater intrusion caused by excessive ground-water withdrawals has been the primary source (**fig. 110**). Reduced withdrawals and increased surface-water imports have helped alleviate the salinity problem.

Excessive sodium in irrigation water can be toxic to plants and can decrease soil permeability. Possible sources of sodium in the north San Francisco Bay area valleys include cation exchange between ground water and clay minerals, upward migration of salty water along faults, dissolved minerals in water from marine sediments, thermal water, and seawater intrusion.

Sodium is often the dominant cation in ground water in the north San Francisco Bay area valleys and has been reported locally in concentrations in excess of 250 milligrams per liter, which is sufficiently large to be of concern. The problem is widespread in the Santa Rosa Basin, where large sodium concentrations are thought to be related primarily to cation exchange. The source of excessive sodium in the other four valleys could be one or all of the sources listed above, but seawater intrusion is the primary source in the alluvial-fan deposits in the southern ends of the Petaluma, the Sonoma, and the Napa Valleys.

Although essential to plant growth in small amounts, boron in excess of 0.5 milligram per liter can be stressful or toxic to many plants, and water with a boron concentration of greater than 2.0 milligrams per liter is toxic to most plants. Boron is usually associated with water that has a large sodium concentration and the sources for boron in the area are generally the same as for sodium. Ground water that has a boron concentration of 0.5 milligram per liter or larger is found in scattered wells throughout the north San Francisco Bay area.

The presence of nitrate in ground water is usually an indication of contamination by septic tanks, fertilizers, or waste from farm animals. Large nitrate concentrations can cause methemoglobinemia (a blood disease) in infants, and State drinking-water standards in California have been set at 45 milligrams per liter of nitrate, or 10 milligrams per liter nitrogen. Nitrate is not a widespread problem in most of the north San Francisco Bay area, except locally, northwest of Petaluma (**fig. 110**) where nitrate concentrations are as large as three times the maximum allowed for drinking water. The probable sources appear to be septic-tank leachate plus livestock and poultry manure that was placed in unlined pits.

SANTA CLARA VALLEY

The Santa Clara Valley is located at the southern end of San Francisco Bay (**fig. 111**). Once devoted largely to agriculture, most of the land in the valley is now dedicated to industrial and urban uses. Population growth has resulted in a large water demand, which has exceeded the valley's natural supply since the early 1940's. Withdrawals of ground water in excess of recharge caused large water-level declines, which were followed by seawater intrusion and land subsidence surpassed in California only by that in the San Joaquin Valley. Since the 1940's, importation of surface water has been essential to the control of these problems.

The Santa Clara Valley is in a structural trough that parallels the northwest-trending Coast Ranges. The drainage basin, which includes San Francisco Bay, is bounded by the Santa Cruz Mountains on the southwest and the Diablo Range on the northeast. The basin is about 75 miles long and has a maximum width of 45 miles. The San Andreas Fault is in the Santa Cruz Mountains to the southwest, and the Hayward Fault is on the northeast side of the valley and parallels the Diablo Range (**fig. 112**). The Santa Clara Valley, which occupies the southern end of the basin, is about 60 miles long, about 30 miles of which extends southeastward beyond San Francisco Bay. The valley has a maximum width of about 15 miles and a total area of about 590 square miles. The altitude of the valley floor ranges from about 350 feet at the southern end to sea level at San Francisco Bay.

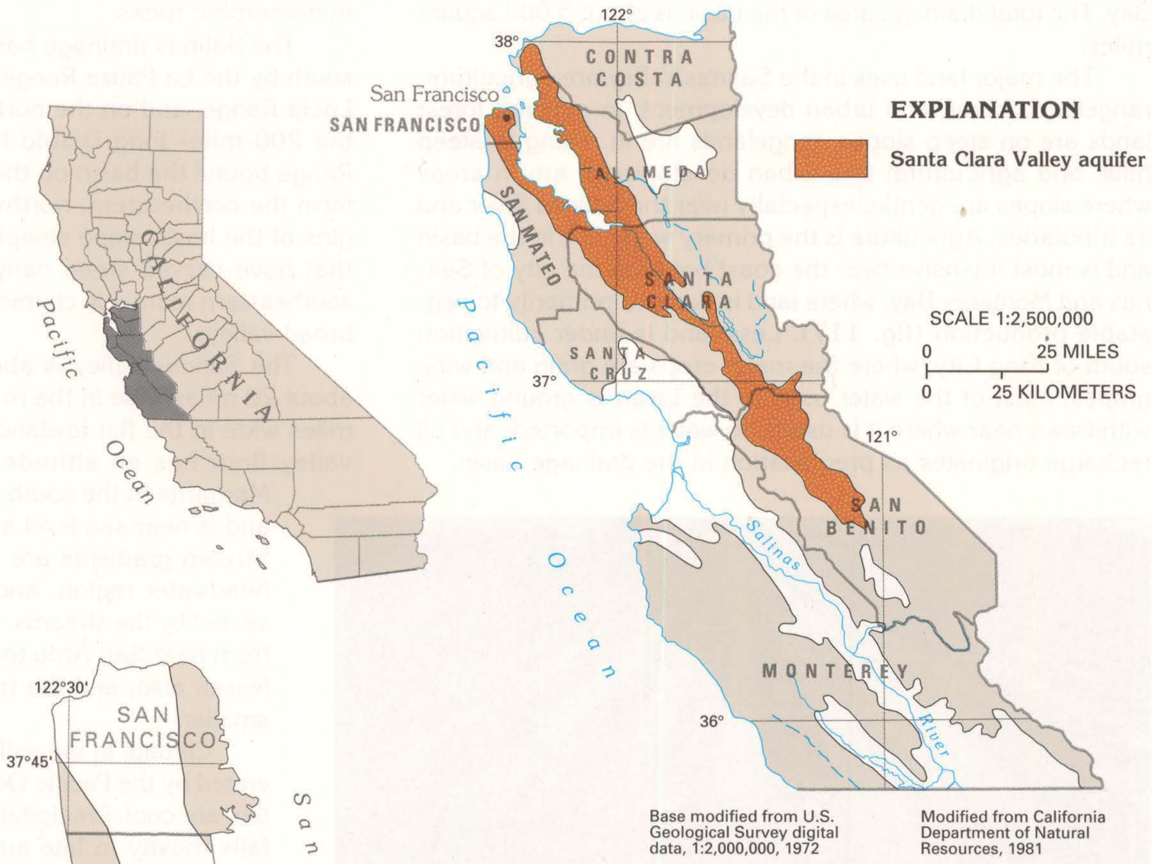
The Mediterranean climate of the valley is moderate and has distinct wet and dry seasons. The wet season extends from November to April. Average annual rainfall is about 14 inches on the valley floor.

Aquifers and Confining Units

The aquifer system of the Santa Clara Valley is bounded on three sides by the relatively impermeable consolidated rocks that form the mountains surrounding the valley (**fig. 112**) and underlie the valley at depth. Ground water in the valley is contained primarily in coarse-grained lenticular deposits of sand and gravel that alternate with discontinuous beds of fine-grained clay and silt that have minimal permeability. The combined thickness of the coarse- and fine-grained deposits is as much as 1,000 feet in some parts of the valley. The alluvial-fan and river-channel deposits near the valley margins contain a higher percentage of coarse-grained materials than deposits near the valley axis and are thus more permeable.

Although interspersed with coarse-grained channel deposits, the cumulative thickness of clay and silt is sufficient in the central two-thirds of the valley to produce confined conditions in the subsurface from southeast of San Jose to beneath San Francisco Bay. Water below a depth of 150 to 200 feet in that area is confined or semiconfined, whereas shallower water is generally unconfined. The confined part of the aquifer system is as much as 800 feet thick, but locally it contains beds of fine-grained deposits that separate it into zones of permeable material sufficiently distinct to be recognized as individual aquifers.

Figure 111. The Santa Clara Valley is located in the heavily urbanized and industrialized area surrounding and south of San Francisco Bay. The valley is filled with alluvium derived from the consolidated rocks that compose the surrounding mountains.



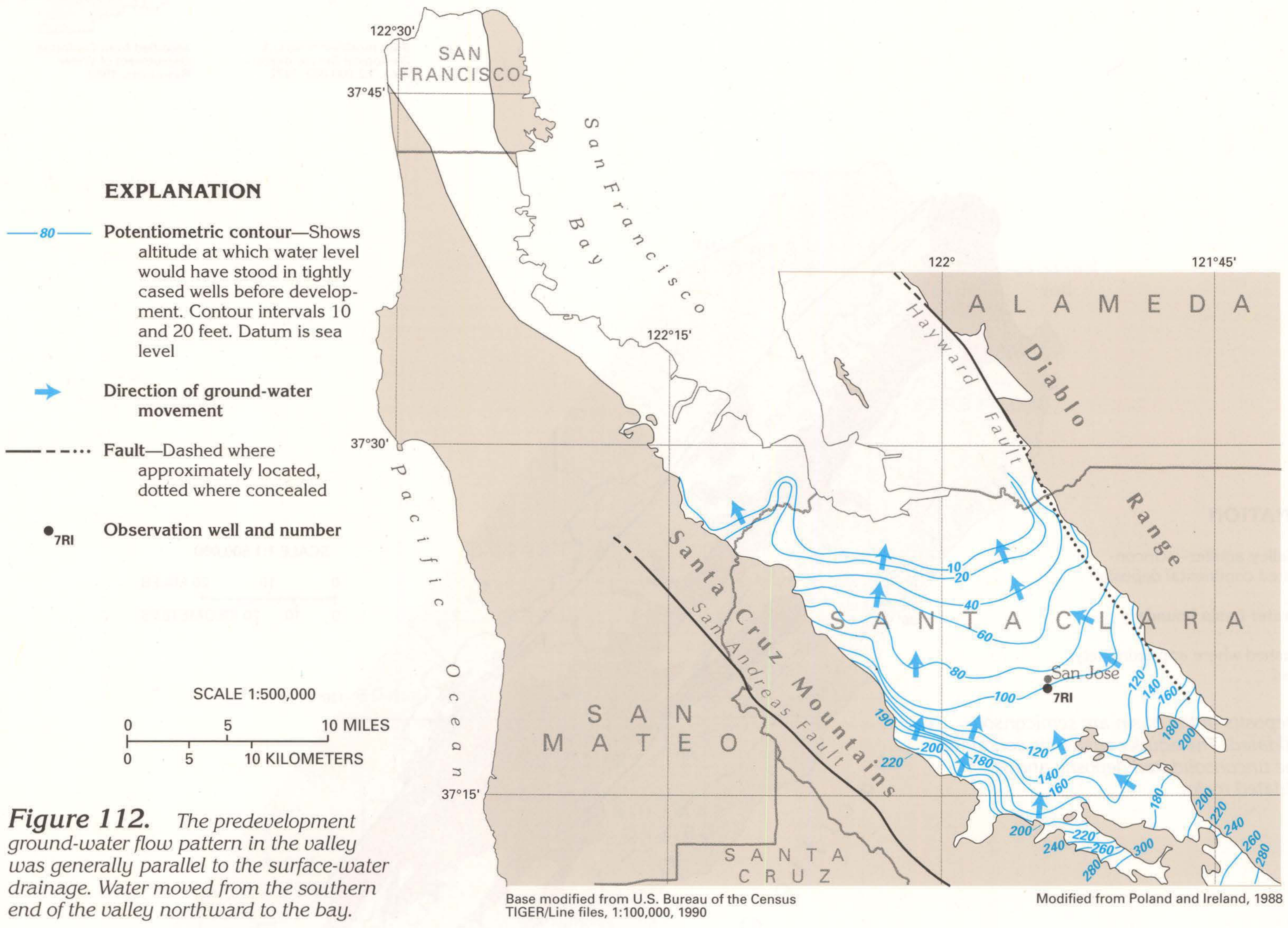


Figure 112. The predevelopment ground-water flow pattern in the valley was generally parallel to the surface-water drainage. Water moved from the southern end of the valley northward to the bay.

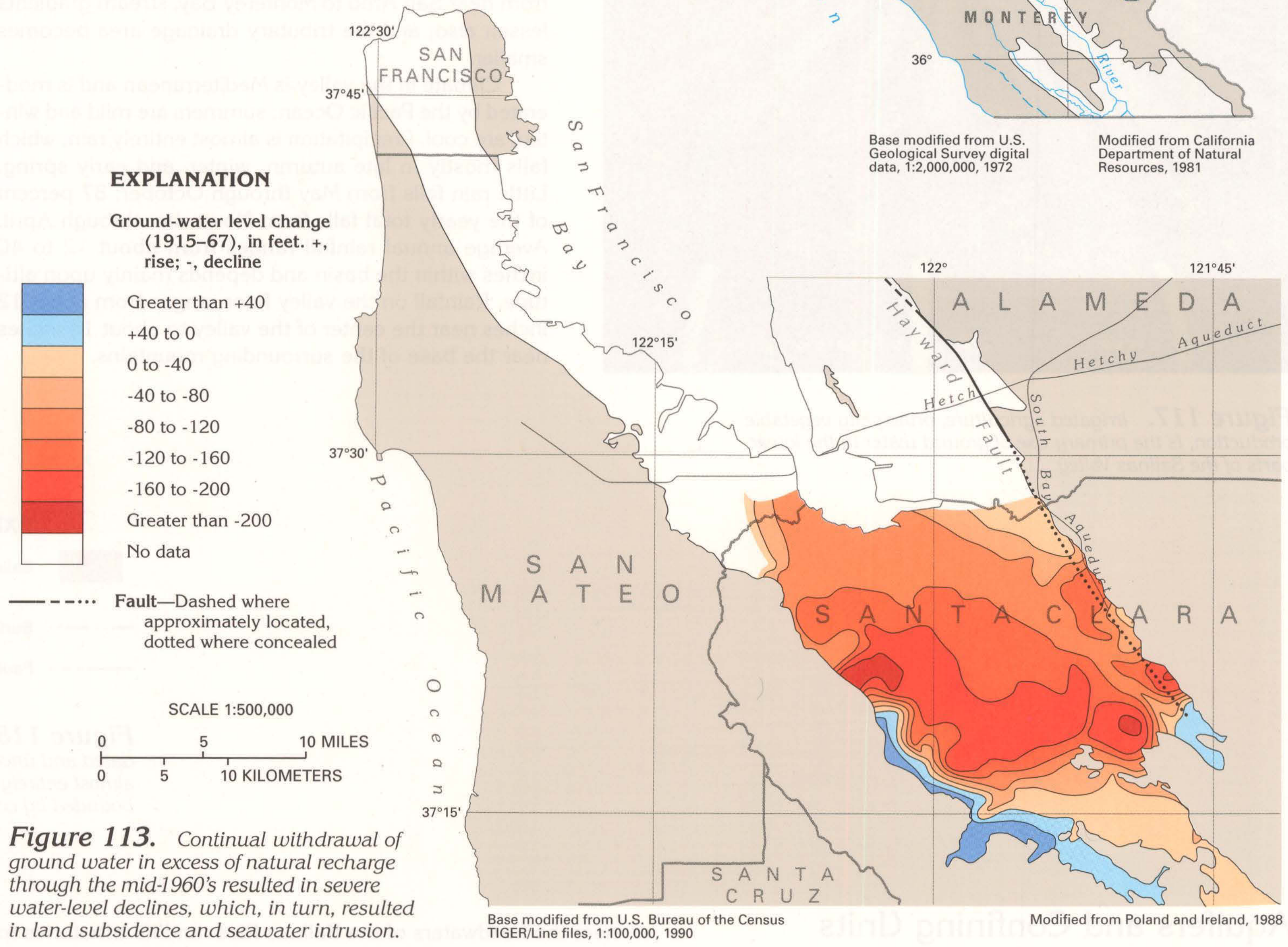
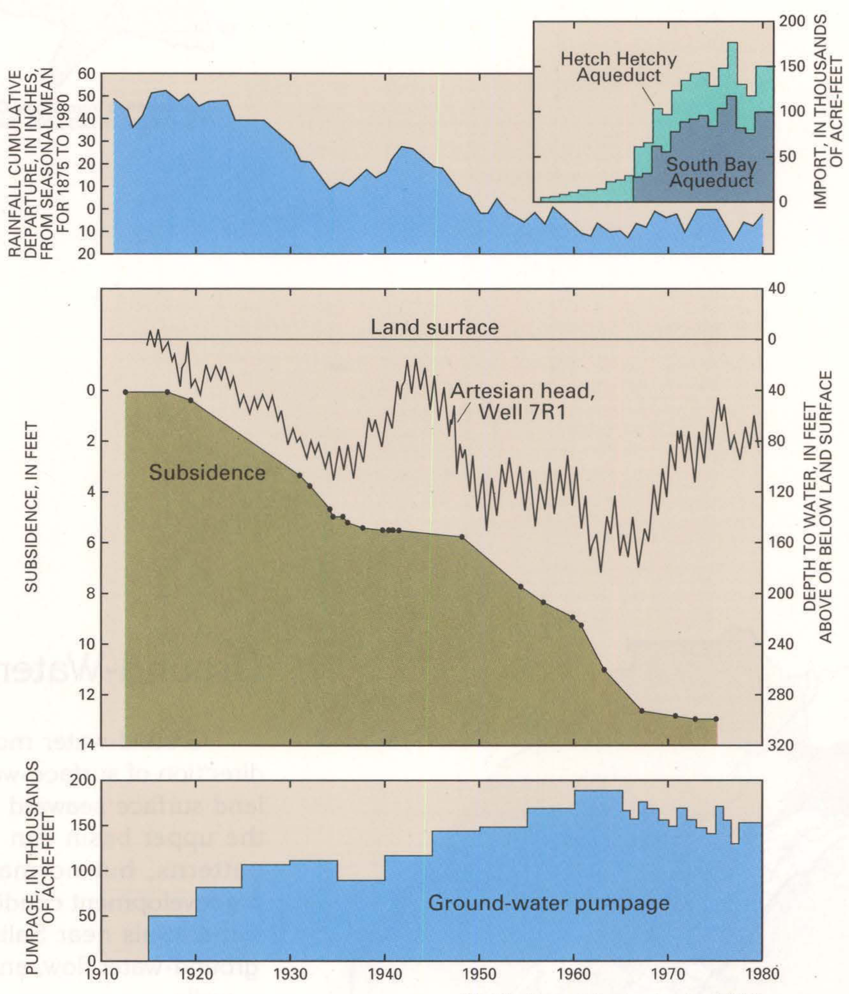


Figure 113. Continual withdrawal of ground water in excess of natural recharge through the mid-1960's resulted in severe water-level declines, which, in turn, resulted in land subsidence and seawater intrusion.

Figure 114. By the mid-1960's, rapid water-level declines in the Santa Clara Valley were alleviated by surface-water imports and decreased ground-water withdrawals. Land subsidence that resulted from declining water levels stopped when water levels stabilized. The location of the well is shown in figure 112.



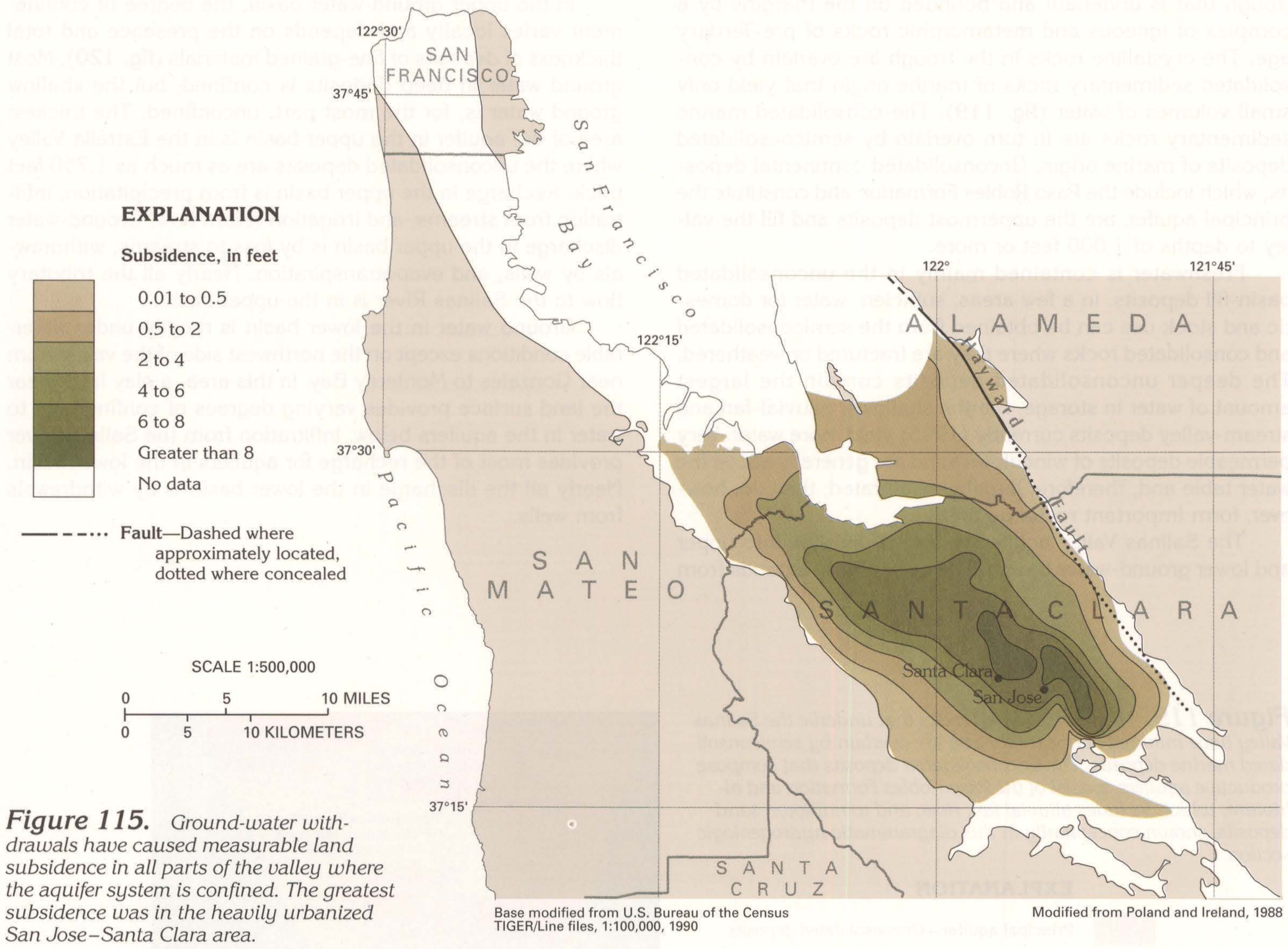


Figure 115. Ground-water withdrawals have caused measurable land subsidence in all parts of the valley where the aquifer system is confined. The greatest subsidence was in the heavily urbanized San Jose–Santa Clara area.

Ground-Water Flow System

Water enters the aquifer system at the valley margins by infiltration from the small streams that emanate from the mountains and by rainfall that falls directly on the valley floor. The natural, or predevelopment, flow pattern was generally parallel to the direction of stream drainage, and water that did not leave the aquifer system by way of evapotranspiration discharged into San Francisco Bay (**fig. 112**). The Hayward Fault acts as a major impediment to flow on the northeastern side of the valley.

In 1915, the hydraulic head was above land surface throughout much of the valley, and flowing wells were common. However, by 1967, an increase in ground-water withdrawals, as well as below-normal rainfall, resulted in water-level declines of more than 200 feet below 1915 levels in some parts of the valley (**fig. 113**). Large withdrawals lowered water levels to below sea level over much of the valley and reversed the freshwater gradient in the confined zone from seaward to landward. This reversal resulted in seawater intrusion that was detected in wells as far as 10 miles inland. The large withdrawals also caused widespread land subsidence.

Beginning in the mid-1960's, the decline in artesian head was halted and reversed by a combination of surface-water imports and decreased ground-water withdrawals (**fig. 114**). Water importation into the Santa Clara Valley began in about 1940 by way of the Hetch Hetchy Aqueduct and was increased in the mid-1960's through the South Bay Aqueduct. By 1980, surface-water imports approximately equaled ground-water withdrawals. Projections of future water demand made in 1983, however, indicated that by 2000 small amounts of additional surface water will have to be imported and the distribution system improved.

Fresh Ground-Water Withdrawals

Significant ground-water use in the Santa Clara Valley began about 1900 with the development of irrigated agriculture. Average annual agricultural withdrawals increased from about 40,000 acre-feet per year from 1915 to 1920 to a maximum 5-year average of about 103,000 acre-feet per year from 1945 to 1950. After 1945, urban and industrial development increased rapidly, and irrigated acreage began to decline; agricultural withdrawals decreased to an average 20,000 acre-feet per year from 1970 to 1975. Meanwhile, municipal and industrial withdrawals increased from about an average of 22,000 acre-feet per year from 1940 to 1945 to an average of 131,000 acre-feet per year from 1970 to 1975. Total withdrawals in the valley increased from 50,000 acre-feet per year from 1915 to 1920 to 185,000 acre-feet per year from 1960 to 1965, and then declined to about 150,000 acre-feet per year from 1970 to 1975 when surface-water imports increased sufficiently to offset the excessive ground-water withdrawals.

Municipal and industrial ground-water use began to exceed agricultural use early in the 1960's. Currently (1995), municipalities and industries account for about 90 percent of the water used in the valley. Ground water used for irrigated agriculture averaged about 14,000 acre-feet per year from 1975 to 1980, while the amount withdrawn for municipal and industrial use was about 150,000 acre feet per year. The combined annual agricultural, municipal, and industrial ground-water withdrawals of about 164,000 acre-feet were about one-half of the total water used in the valley.

Land Subsidence

The Santa Clara Valley is underlain by large amounts of clay that readily compacts as a result of excessive ground-water withdrawal, thus causing land subsidence. Land subsidence has been evident over much of the valley and is greater than 8 feet in some places (**fig. 115**). Subsidence has resulted in flooding in coastal areas and damage to roads, bridges, railroads, and sewer systems. The cost of remedial measures has been estimated to be between $30 million and $50 million annually. The rate of subsidence slowed in 1967 as increased surface-water imports and reduced ground-water withdrawals allowed the hydraulic head to stabilize and start to recover. Under current (1995) conditions of ground-water use and availability, further subsidence is not likely. However, because the compression of the clay is irreversible, land subsidence that has already occurred is permanent.

Ground-Water Quality

Ground-water quality is not a serious concern in the Santa Clara Valley, except near San Francisco Bay, where seawater has intruded locally as a result of large ground-water withdrawals. The encroachment has been arrested, for the most part, by a decrease in withdrawals and an increase in recharge from surface-water sources.

SALINAS VALLEY

The Salinas Valley, the largest southern California coastal basin, lies within the southern Coast Ranges between the San Joaquin Valley and the Pacific Ocean (**fig. 116**). The valley is drained by the Salinas River and extends approximately 150 miles from the headwaters to the mouth of the river at Monterey Bay. The total drainage area of the basin is about 5,000 square miles.

The major land uses in the Salinas Valley are agriculture, rangeland, forest, and urban development. In general, forest lands are on steep slopes, rangelands are in rolling to steep hills, and agricultural and urban development are in areas where slopes are gentle, especially near the Salinas River and its tributaries. Agriculture is the primary water use in the basin and is most intensive near the coast between the city of Salinas and Monterey Bay, where land is devoted primarily to vegetable production (**fig. 117**). Less land is under cultivation south of King City, where the major crops are grain and wine grapes. Most of the water used in the basin is ground water withdrawn near where it is used. No water is imported, and all recharge originates as precipitation in the drainage basin.

Figure 117. Irrigated agriculture, principally vegetable production, is the primary use of ground water in the lower parts of the Salinas Valley.

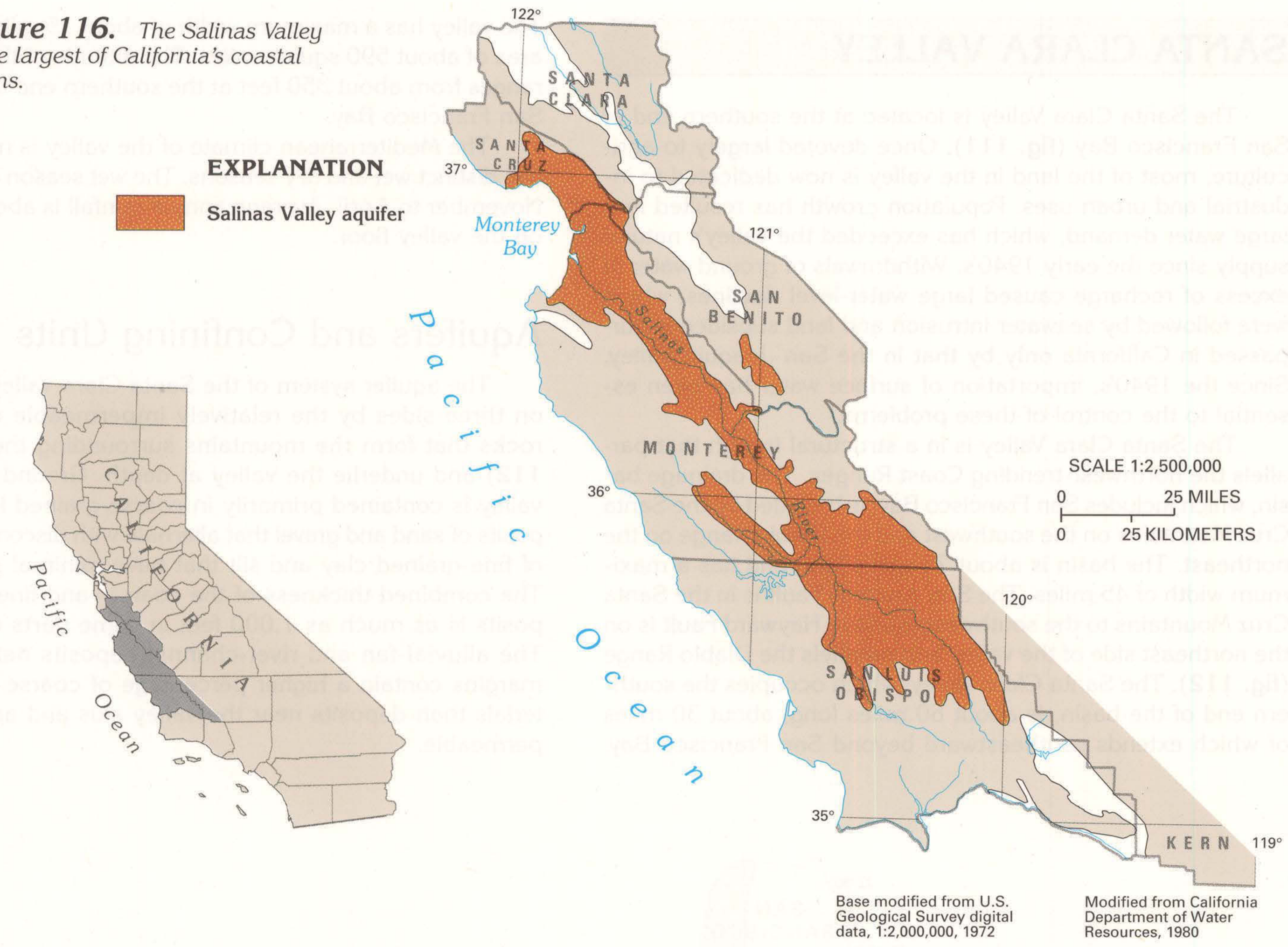
The Salinas Valley lies almost entirely in a northwest-trending structural trough filled principally by unconsolidated continental deposits. The valley is bounded by the San Andreas Fault on the northeast and by a series of aligned and interconnected faults on the southwest (**fig. 118**). The mountains that bound the valley were formed by uplift and deformation caused by crustal shortening and are underlain by consolidated marine sediments, intrusive igneous rocks, and metamorphic rocks.

The Salinas drainage basin (**fig. 118**) is bounded on the south by the La Panza Range, on the southwest by the Santa Lucia Range, and on the northwest by the Sierra de Salinas; the 200-mile- long Diablo Range and the shorter Gabilan Range bound the basin on the northeast. The mountains that form the northeastern, northwestern, and southwestern margins of the basin slope steeply and are dissected by streams that have carved steep canyons into the valley walls. The southeastern margin is characterized by gently rolling hills and broad valleys.

The Salinas Valley is about 30 miles wide in the south, about 20 miles wide in the middle of the valley, and about 10 miles wide in the flat lowland areas north of Greenfield. The valley floor has an altitude of about 1,200 feet at Santa Margarita in the south and about 400 feet at San Ardo, and is near sea level at the shoreline of Monterey Bay. Stream gradients are relatively steep in the southern headwater region, and the valley floor is deeply dissected by the streams. As the valley becomes less steep from near San Ardo to Monterey Bay, stream gradients lessen also, and the tributary drainage area becomes smaller.

Climate in the valley is Mediterranean and is moderated by the Pacific Ocean; summers are mild and winters are cool. Precipitation is almost entirely rain, which falls mostly in late autumn, winter, and early spring. Little rain falls from May through October; 87 percent of the yearly total falls from November through April. Average annual rainfall ranges from about 12 to 40 inches within the basin and depends mainly upon altitude. Rainfall on the valley floor ranges from about 12 inches near the center of the valley to about 16 inches near the base of the surrounding mountains.

Figure 116. The Salinas Valley is the largest of California's coastal basins.



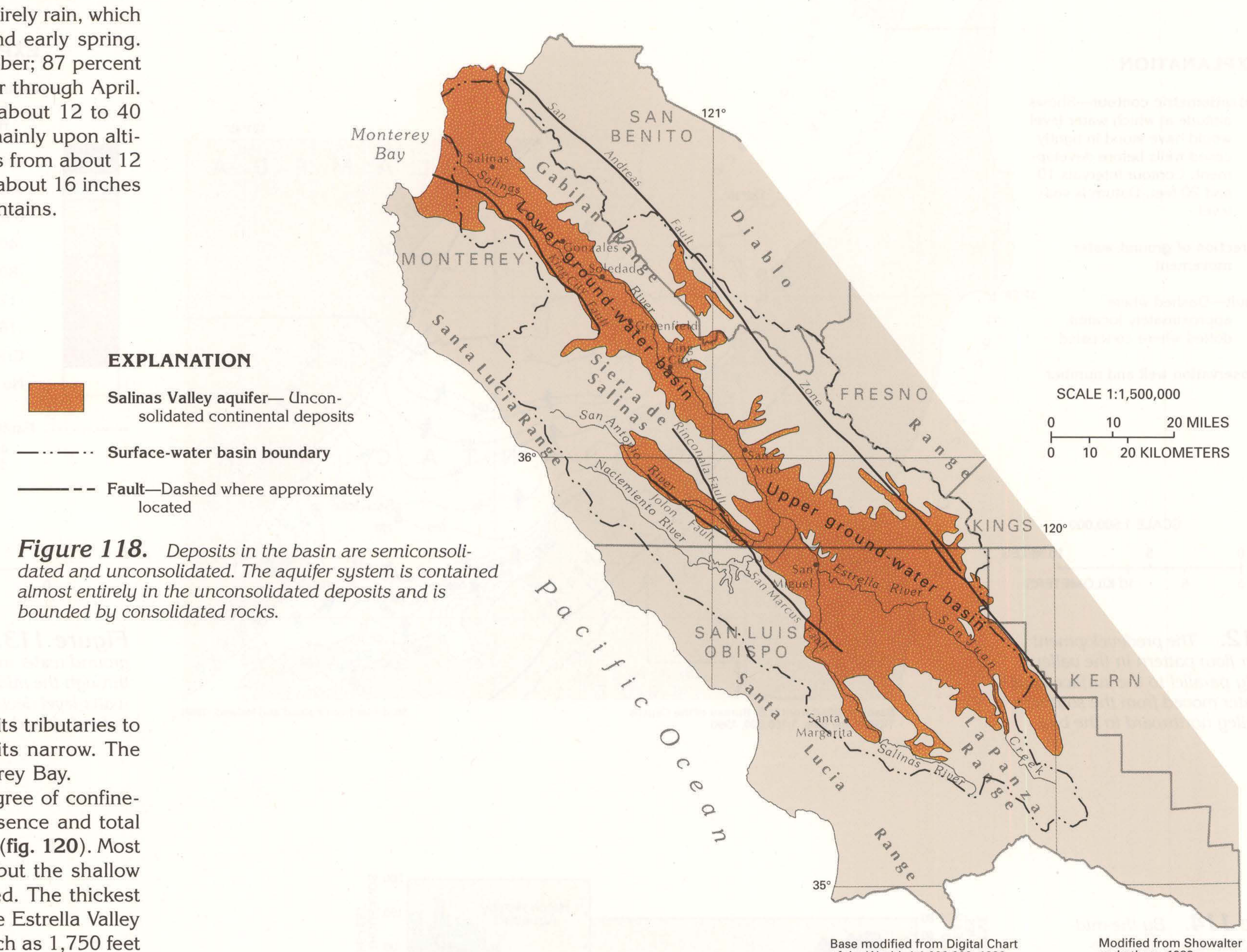


Figure 118. Deposits in the basin are semiconsolidated and unconsolidated. The aquifer system is contained almost entirely in the unconsolidated deposits and is bounded by consolidated rocks.

Aquifers and Confining Units

The Salinas Valley aquifer is contained within a structural trough that is underlain and bounded on the margins by a complex of igneous and metamorphic rocks of pre-Tertiary age. The crystalline rocks in the trough are overlain by consolidated sedimentary rocks of marine origin that yield only small volumes of water (**fig. 119**). The consolidated marine sedimentary rocks are in turn overlain by semiconsolidated deposits of marine origin. Unconsolidated continental deposits, which include the Paso Robles Formation and constitute the principal aquifer, are the uppermost deposits and fill the valley to depths of 1,000 feet or more.

Freshwater is contained mainly in the unconsolidated basin-fill deposits. In a few areas, sufficient water for domestic and stock use can be obtained from the semiconsolidated and consolidated rocks where they are fractured or weathered. The deeper unconsolidated deposits contain the largest amount of water in storage, but the shallower alluvial-fan and stream-valley deposits currently (1995) yield more water. Very permeable deposits of windblown sand are generally above the water table and, therefore, largely unsaturated; they do, however, form important recharge areas.

The Salinas Valley aquifer system is divisible into upper and lower ground-water basins. The upper basin extends from near the headwaters of the Salinas River and its tributaries to San Ardo, where the unconsolidated deposits narrow. The lower basin extends from San Ardo to Monterey Bay.

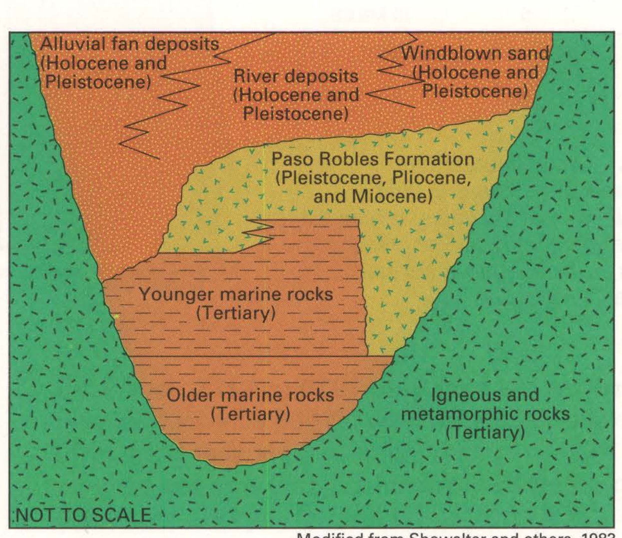
In the upper ground-water basin, the degree of confinement varies locally and depends on the presence and total thickness of deposits of fine-grained materials (**fig. 120**). Most ground water in deep deposits is confined, but the shallow ground water is, for the most part, unconfined. The thickest area of the aquifer in the upper basin is in the Estrella Valley where the unconsolidated deposits are as much as 1,750 feet thick. Recharge in the upper basin is from precipitation, infiltration from streams, and irrigation return flow. Ground-water discharge in the upper basin is by loss to streams, withdrawals by wells, and evapotranspiration. Nearly all the tributary flow to the Salinas River is in the upper basin.

Ground water in the lower basin is mostly under water-table conditions except on the northwest side of the valley from near Gonzales to Monterey Bay. In this area, a clay layer near the land surface provides varying degrees of confinement to water in the aquifers below. Infiltration from the Salinas River provides most of the recharge for aquifers in the lower basin. Nearly all the discharge in the lower basin is by withdrawals from wells.

Figure 119. The consolidated rocks that underlie the Salinas Valley have minimal permeability and are overlain by semiconsolidated marine deposits. The unconsolidated deposits that compose productive aquifers consist of the Paso Robles Formation and alluvium, which includes alluvial fan, river, and windblown sand deposits, shown conceptually in this diagrammatic hydrogeologic section.

EXPLANATION

- Principal aquifer—Unconsolidated deposits
- Minor aquifer—Semiconsolidated deposits
- Consolidated rocks
  - Marine rocks
  - Igneous and metamorphic rocks



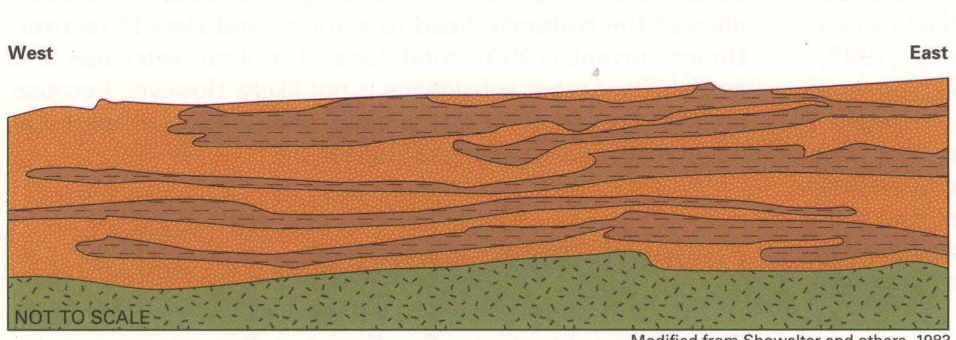


Figure 120. A diagrammatic hydrogeologic section illustrates the sequence of complexly interbedded aquifers and confining units in the northern end of the Salinas Valley.

EXPLANATION

- Principal aquifer—Sand and gravel
- Confining unit—Clay and silt
- Consolidated rocks

Ground-Water Flow System

Ground-water movement in most of the valley is in the direction of surface-water flow and follows the gradient of the land surface seaward (**fig. 121**). In dry years, withdrawals in the upper basin can disturb the natural ground-water flow patterns, but normally the flow direction approximates predevelopment conditions. In the lower basin, however, large withdrawals near Salinas have diverted the natural seaward ground-water flow, and much of the water now moves toward wells.

Much of the water that enters the upper basin from the surrounding mountains runs directly into the Salinas River and its tributary streams. The streams gain water by seepage from the aquifer system because the water table in the headwater area of the Salinas River is above the river level. From approximately San Miguel in the upper valley to Soledad, which is about 40 miles upriver from Monterey Bay, the water table in the vicinity of the river is approximately at the same altitude as the river level, so no water moves between the stream and the aquifer. At Soledad, the water-table altitude is lower than the river level, and the river loses water to the aquifer system.

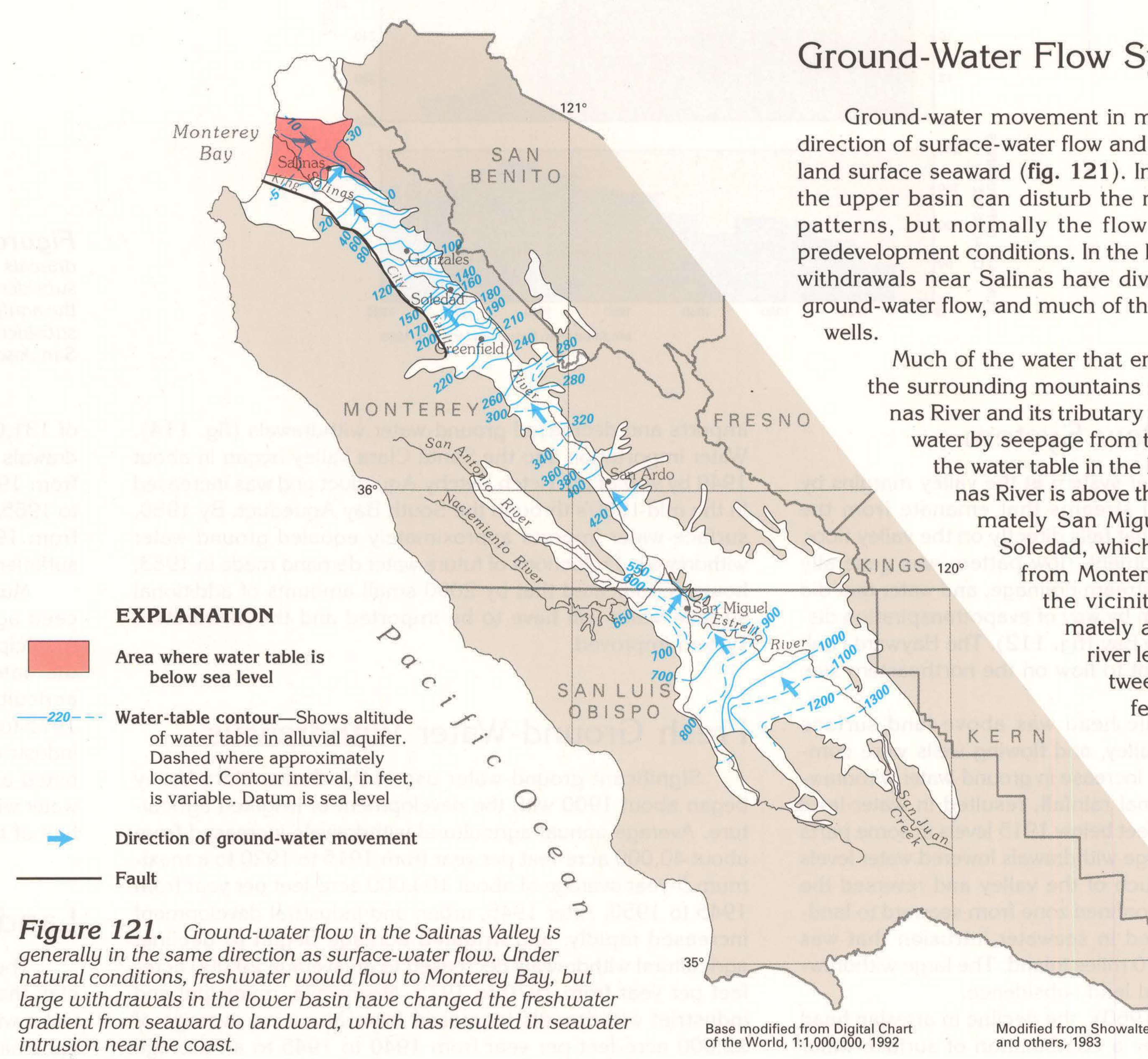


Figure 121. Ground-water flow in the Salinas Valley is generally in the same direction as surface-water flow. Under natural conditions, freshwater would flow to Monterey Bay, but large withdrawals in the lower basin have changed the freshwater gradient from seaward to landward, which has resulted in seawater intrusion near the coast.

Fresh Ground-Water Withdrawals

Water use in the valley has increased with a growth in agriculture and population. During 1985, total ground-water withdrawals approximately equaled the basinwide annual recharge of about 700,000 acre-feet. Water levels in the upper basin have shown little decline because of minimal ground-water development. Throughout the lower basin, however, agricultural and municipal withdrawals caused a general decline until the mid-1950's. In 1956, the flow of the Salinas River became perennial with the regulation of the Nacimiento River. Ground-water levels ceased to decline from San Ardo to Gonzalez because the increased streamflow maintained recharge to the ground-water system by seepage from the river. In 1967, a second dam was completed on the San Antonio River and helped to maintain the year-round flow of the river. Nonetheless, large and increasing withdrawals near Monterey Bay downstream from the city of Salinas have resulted in continued water-level declines, although availability of surface-water recharge has increased. Water levels in wells in this area have remained below sea level since the late 1940's and have resulted in saltwater encroachment from Monterey Bay.

Ground-Water Quality

Ground-water quality in the upper basin is generally acceptable for most uses, except in local areas. Dissolved-solids concentrations in the water range from about 200 to 700 milligrams per liter. The only major area of concern is the so-called Bitterwater area in the upper basin (**fig. 122**), where boron and arsenic that have been leached from aquifer materials and consolidated rocks can be at excessive levels. Despite the near absence of regional water-quality problems, agricultural and industrial activities have resulted in localized aquifer contamination.

Dissolution of gypsum beds in the deep unconsolidated sediments and in consolidated marine deposits on the east side of the valley causes large concentrations of sulfate in ground and surface waters along the Salinas River and San Lorenzo Creek (**fig. 122**). Dissolved-solids concentrations in ground water in this area are as much as 3,000 milligrams per liter. Because the ground-water system receives recharge from surface water in the lower basin, ground-water quality in areas without gypsum beds can be affected by infiltration from streams that drain areas with such beds. Water in streams on the southwest side of the valley is less mineralized and partly dilutes the highly mineralized water during the wet season.

Aquifers near the coast are subject to seawater contamination when ground-water withdrawals in the area exceed natural recharge. Large withdrawals for agricultural and municipal supplies have lowered the potentiometric surface east of the city of Salinas until it is considerably below sea level (**fig. 121**). As a result, the natural freshwater gradient has been reversed from seaward to landward, which allows saltwater to enter the aquifer system where it crops out on the sea floor. Saltwater intrusion was already a concern when monitoring began in 1943, and, as of 1995, the area affected has increased greatly in size. The contamination has resulted in the abandonment of some wells.

Another area of concern in the lower basin is on the east side of the Salinas River between Soledad and Salinas (**fig. 122**). Organic pollutants and excessive nitrate concentrations that result from industrial and agricultural activity are possible threats to ground-water quality in this area.

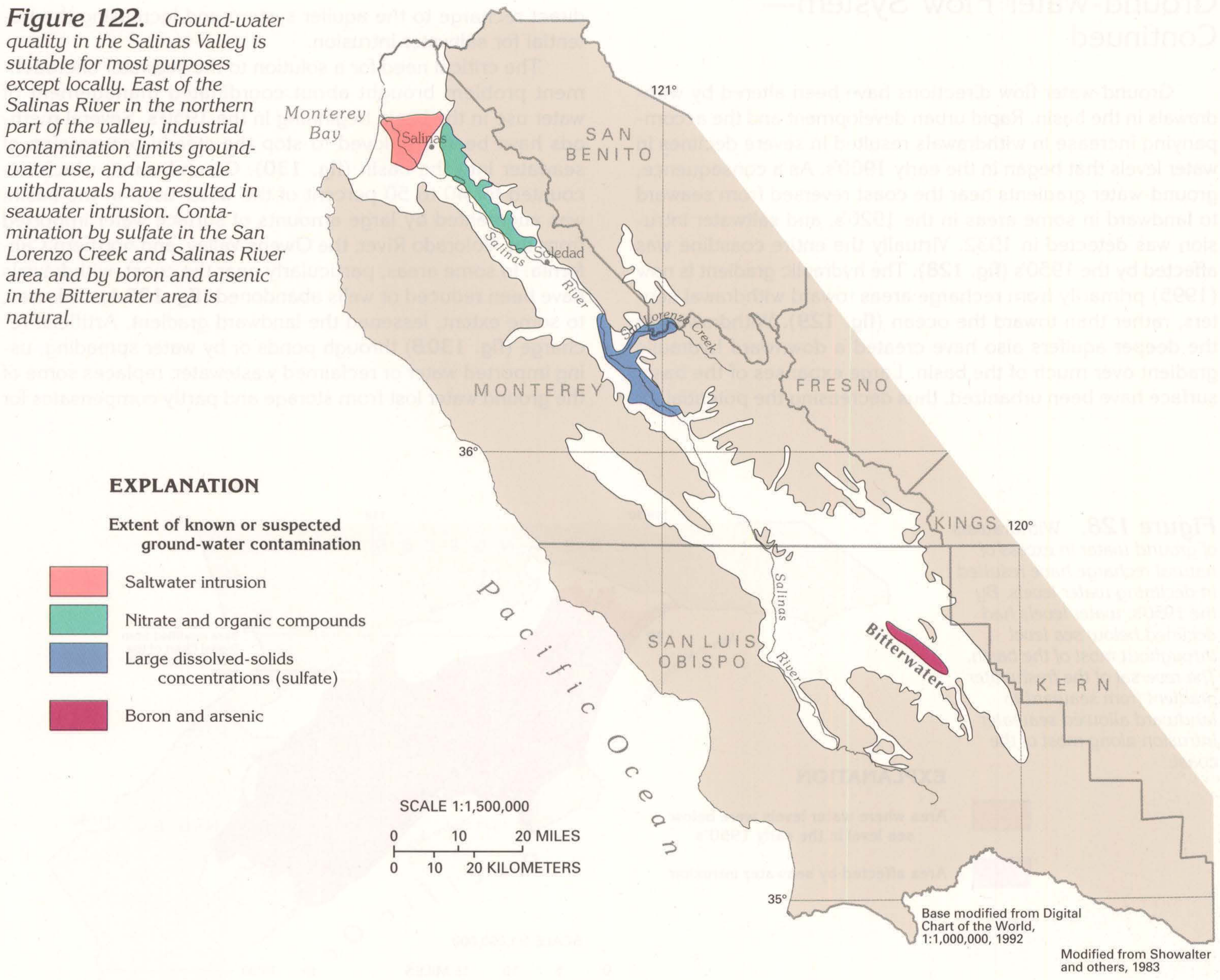


Figure 122. Ground-water quality in the Salinas Valley is suitable for most purposes except locally. East of the Salinas River in the northern part of the valley, industrial contamination limits ground-water use, and large-scale withdrawals have resulted in seawater intrusion. Contamination by sulfate in the San Lorenzo Creek and Salinas River area and by boron and arsenic in the Bitterwater area is natural.

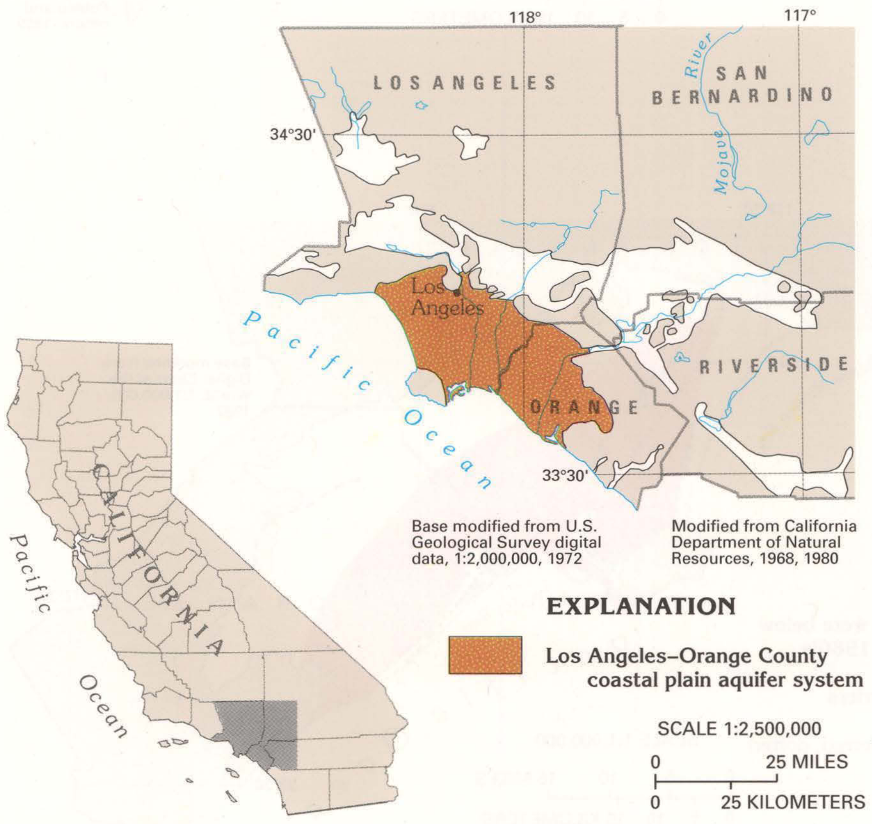


Figure 123. The Los Angeles–Orange County coastal plain aquifer system is located in southern California, and occupies most of coastal Los Angeles and Orange Counties.

Figure 124. The heavily populated Los Angeles area has an extremely large demand for water in this relatively water-poor area.

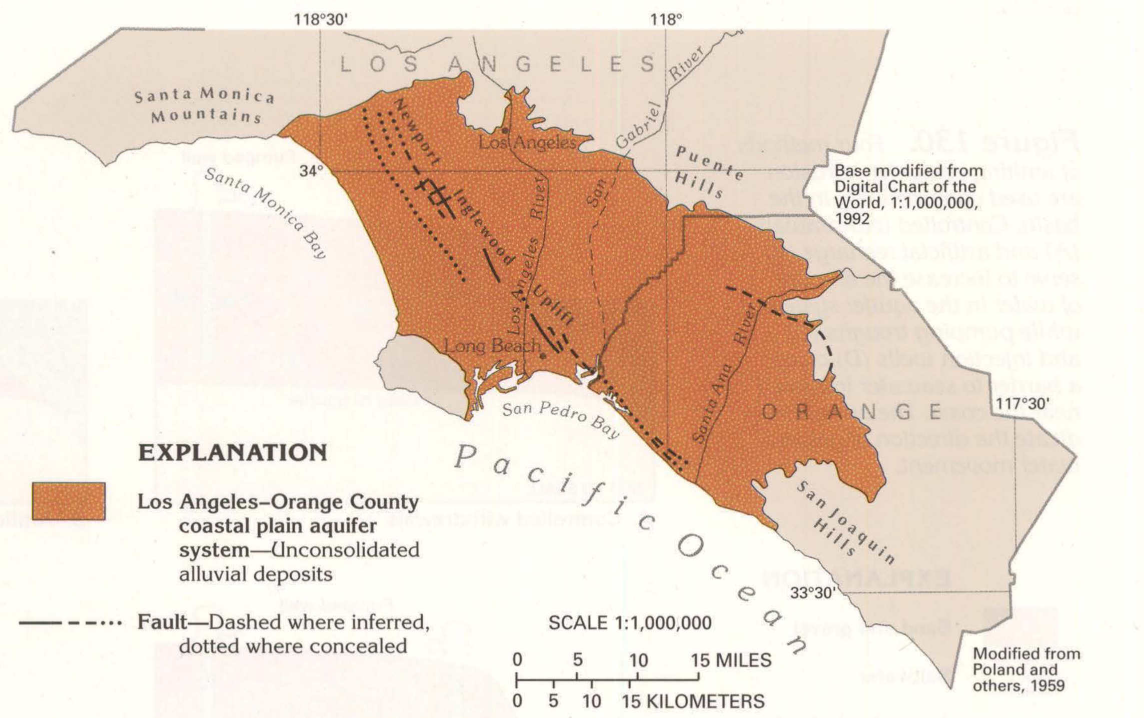
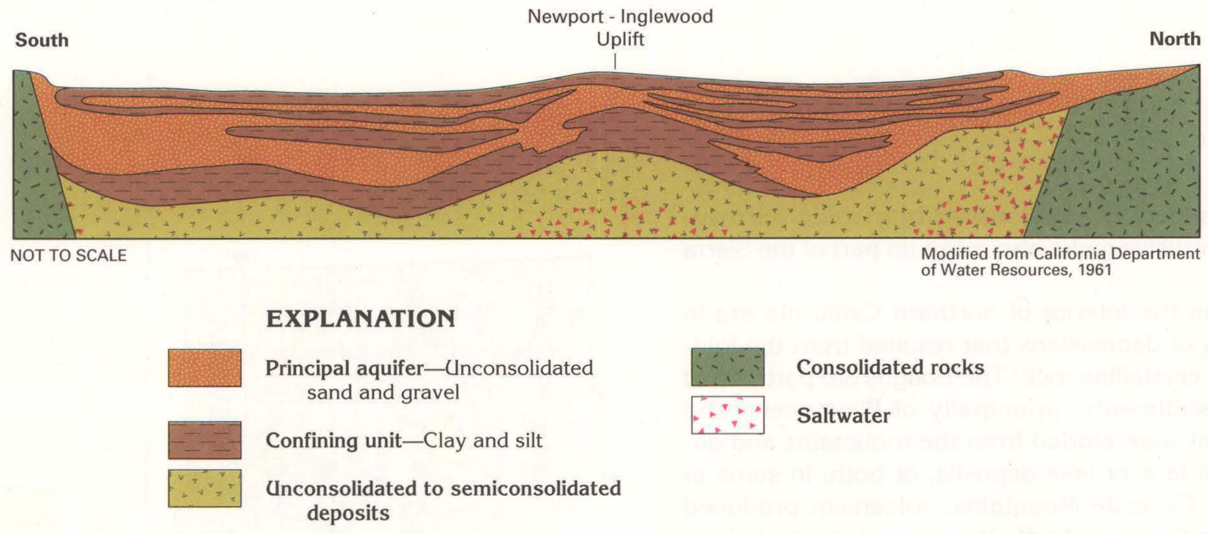


Figure 125. The Los Angeles–Orange County coastal plain basin is bounded on the west by the Pacific Ocean and on all other sides by mountains. The Newport–Inglewood Uplift, which is a prominent structural feature, extends nearly the length of the basin.

Figure 126. A diagrammatic hydrogeologic section shows that the aquifer system consists of alternating beds of permeable sediments, which are primarily sand and gravel, and beds of less permeable sediments, such as clay and silt. Structural features, such as anticlines, are common in the basin and affect ground-water movement.



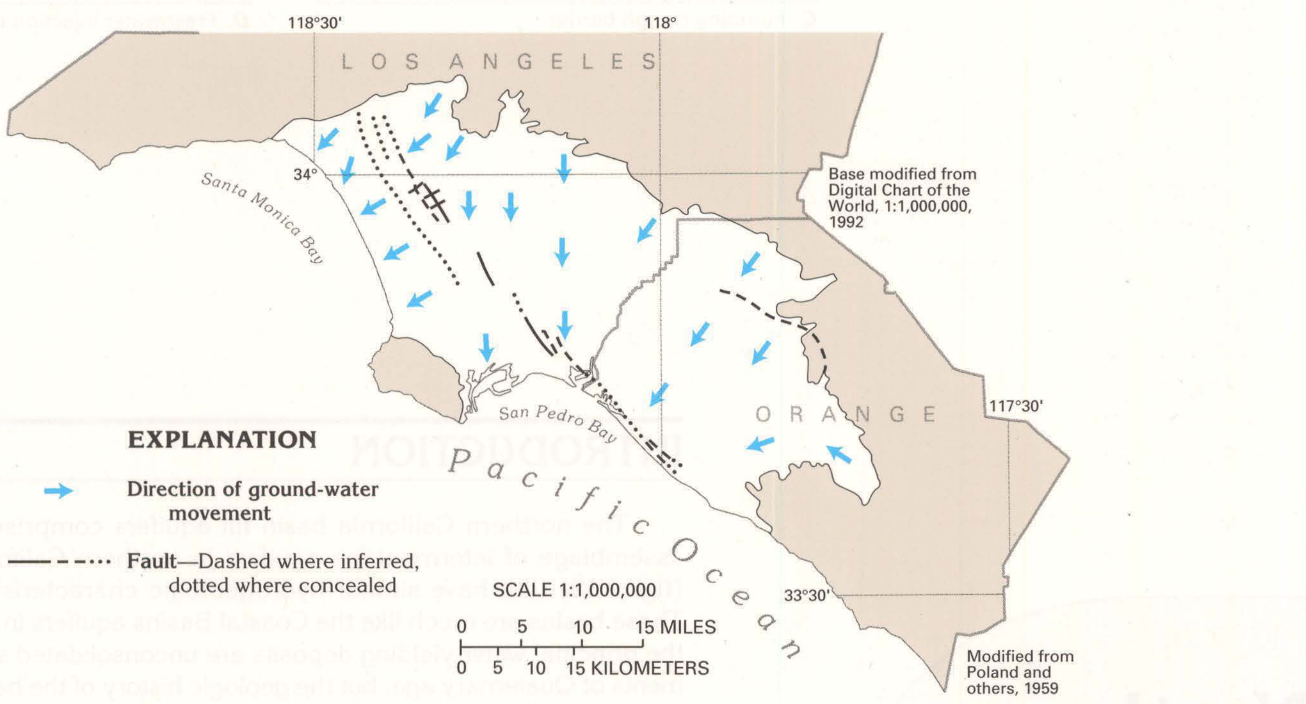


Figure 127. Ground water moved toward and discharged into the Pacific Ocean before development of the aquifer system.

LOS ANGELES–ORANGE COUNTY COASTAL PLAIN AQUIFER SYSTEM

The Los Angeles–Orange County coastal plain aquifer system is located in southern California and is contained in a coastal plain basin that extends over an area of approximately 860 square miles (**fig. 123**). Ground-water development began in the basin in the 1870's, when the demands of irrigated agriculture began to exceed surface-water supplies; however, urbanization subsequently displaced most of the agriculture in the basin, and today the predominant use of water is for public supply. Because metropolitan Los Angeles and the surrounding area is one of the largest population centers in the world (**fig. 124**), the demand for water is great. In addition to local ground-water sources, water is imported from the Colorado River, the Owens Valley, and northern California by an aqueduct system. Also, reclaimed wastewater is spread in recharge areas for ground-water replenishment and is pumped into the aquifer system near the coast to prevent seawater intrusion.

The Los Angeles–Orange County coastal plain basin is bounded on the north and east by the Santa Monica Mountains and the Puente Hills, on the south by the San Joaquin Hills, and on the west by the Pacific Ocean (**fig. 125**). The mountains are underlain by consolidated rocks of igneous, metamorphic, and marine-sedimentary origin. These consolidated rocks surround and underlie thick unconsolidated alluvial deposits. The major drainages in the basin are the Los Angeles, the San Gabriel, and the Santa Ana Rivers, all of which have headwaters outside the basin.

Marine sediments deposited during periodic encroachment of the sea and alluvium derived from weathering and erosion of the rocks in the surrounding mountains have filled the basin with a thick sequence of deposits. The surface of the basin is relatively flat, but upwarping along the Newport–Inglewood Uplift (**fig. 125**) has formed hills that rise in places as much as 400 feet above the surrounding coastal plain. Also, along the coast from just north of Long Beach southward to the San Joaquin Mountains, resistant sediments of late Pleistocene age underlie several mesas. The mesas are separated by erosional gaps through which the major drainages either now flow or have flowed historically.

Climate in the basin is Mediterranean, characterized by warm summers, cool winters, and markedly seasonal rainfall. Nearly all rain falls from late autumn to early spring; virtually no precipitation falls during the summer. The average annual rainfall in Los Angeles is about 15 inches. Potential evapotranspiration in the coastal plain exceeds precipitation on an annual basis, and, under natural conditions, the lower reaches of rivers that drain the basin are dry in summer.

Aquifers and Confining Units

The Los Angeles–Orange County coastal plain basin is a structural basin formed by folding of the consolidated sedimentary, igneous, and metamorphic rocks that underlie the basin at great depths. Although the subsurface structure of the basin is complex, two major northwest-trending troughs (**fig. 126**), which are separated for most of their length by an uplifted and faulted structural zone, contain the sediments that compose the aquifer system. These sediments are as thick as 30,000 feet in some areas.

The coastal plain aquifer system is made up of as many as 11 locally named aquifers. Each consists of a distinct layer of water-yielding sand and gravel usually separated from other sand and gravel beds by clay and silt confining units (**fig. 126**). In many places, however, either the water-yielding sediments are in direct hydraulic contact or the intervening confining units contain sufficient sand and gravel to allow water to pass between adjacent aquifers.

A layer of clay and silty clay of marine and continental origin, which is at or near the land surface over most of the basin, is a competent confining unit where it does not contain large amounts of sand and gravel. This confining unit ranges from less than 1 foot to about 180 feet in thickness. Near Santa Monica and San Pedro Bays, the confining unit is not present, and ground water is under unconfined, or water-table, conditions.

Freshwater is contained within deposits that range in age from Holocene to late Pliocene. The main freshwater body extends from depths of less than 100 to about 4,000 feet. At greater depths, the water is saline and unpotable. The freshwater body is thickest near the axis of the troughs where water-yielding sediments reach their greatest thickness and thinnest where these sediments overlie anticlines or become thin at the margins of the aquifer system.

Ground-Water Flow System

Before development, ground water in the basin flowed generally toward the Pacific Ocean (**fig. 127**). Natural recharge, which is virtually all from precipitation, entered the aquifer system at the basin margins as runoff from the mountains, losses along stream channels, subsurface flow from adjacent basins to the north, and precipitation that fell directly on the basin floor. Where aquifers are hydraulically connected and sufficient differences in hydraulic head existed, some water doubtless flowed from one aquifer to another.

Structural features, such as faults and anticlines, alter or restrict ground-water flow at several places in the Los Angeles–Orange County coastal plain basin. The most prominent structural zone is the Newport–Inglewood Uplift (**figs. 125 and 126**), which trends northwestward, extends virtually the entire length of the basin, and is approximately perpendicular to the direction of natural ground-water flow. The aquifers might be interrupted by faults or thinned near the upwarped structural zone, but, for the most part, such restrictions are not complete barriers to ground-water flow. The sediments that form the mesas along much of the coast have minimal permeability and also impede ground-water flow; however, erosion formed gaps in the mesas, which subsequently filled with alluvial deposits; these gaps allow water to move between the inland aquifers and the sea.

Ground-Water Flow System—Continued

Ground-water flow directions have been altered by withdrawals in the basin. Rapid urban development and the accompanying increase in withdrawals resulted in severe declines in water levels that began in the early 1900's. As a consequence, ground-water gradients near the coast reversed from seaward to landward in some areas in the 1920's, and saltwater intrusion was detected in 1932. Virtually the entire coastline was affected by the 1950's (**fig. 128**). The hydraulic gradient is now (1995) primarily from recharge areas toward withdrawal centers, rather than toward the ocean (**fig. 129**). Withdrawals in the deeper aquifers also have created a downward hydraulic gradient over much of the basin. Large expanses of the basin surface have been urbanized, thus decreasing the potential for direct recharge to the aquifer system and increasing the potential for saltwater intrusion.

The critical need for a solution to the seawater encroachment problem brought about coordinated management of water use in the basin beginning in the 1950's. Several methods have been employed to stop the steady progression of seawater into the basin (**fig. 130**). Ground water, which accounted for 40 to 50 percent of the water used in the basin, was augmented by large amounts of surface water imported from the Colorado River, the Owens Valley, and northern California. In some areas, particularly near the coast, withdrawals have been reduced or wells abandoned (**fig. 130*A***). This has, to some extent, lessened the landward gradient. Artificial recharge (**fig. 130*B***) through ponds or by water spreading, using imported water or reclaimed wastewater, replaces some of the ground water lost from storage and partly compensates for the loss of recharge potential that results from urbanization. Three barriers have been constructed near the coast in areas where seawater was encroaching into the freshwater aquifer system. The barriers consist of a series of either pumping wells that will remove saltwater from the aquifer and form a trough barrier (**fig. 130*C***) or injection wells that pump reclaimed waste water into the permeable sediments, and thus establish a narrow zone in which the freshwater gradient is seaward (**fig. 130*D***). In some places, wells that withdraw saline water from the aquifer system on the seaward side of the injection wells are part of the barrier. To date (1995), the combination of methods has been successful in halting seawater intrusion and also reducing the area of the basin with ground-water levels below sea level (**fig. 131**).

Ground-Water Quality

The quality of water in the confined aquifers in the basin is generally suitable for most uses. Dissolved-solids concentrations in the water are generally less than 500 milligrams per liter and concentrations of chloride do not exceed drinking-water standards recommended by the U.S. Environmental Protection Agency. Water imported from the Owens Valley and the Colorado River for recharge has larger concentrations of dissolved solids, chloride, and sulfate than the ground water, but the quality of the mixed native ground water and imported water is within State and Federal standards for drinking water.

Figure 128. *Withdrawals of ground water in excess of natural recharge have resulted in declining water levels. By the 1950's, water levels had declined below sea level throughout most of the basin. The reversal of the freshwater gradient from seaward to landward allowed seawater intrusion along most of the coast.*

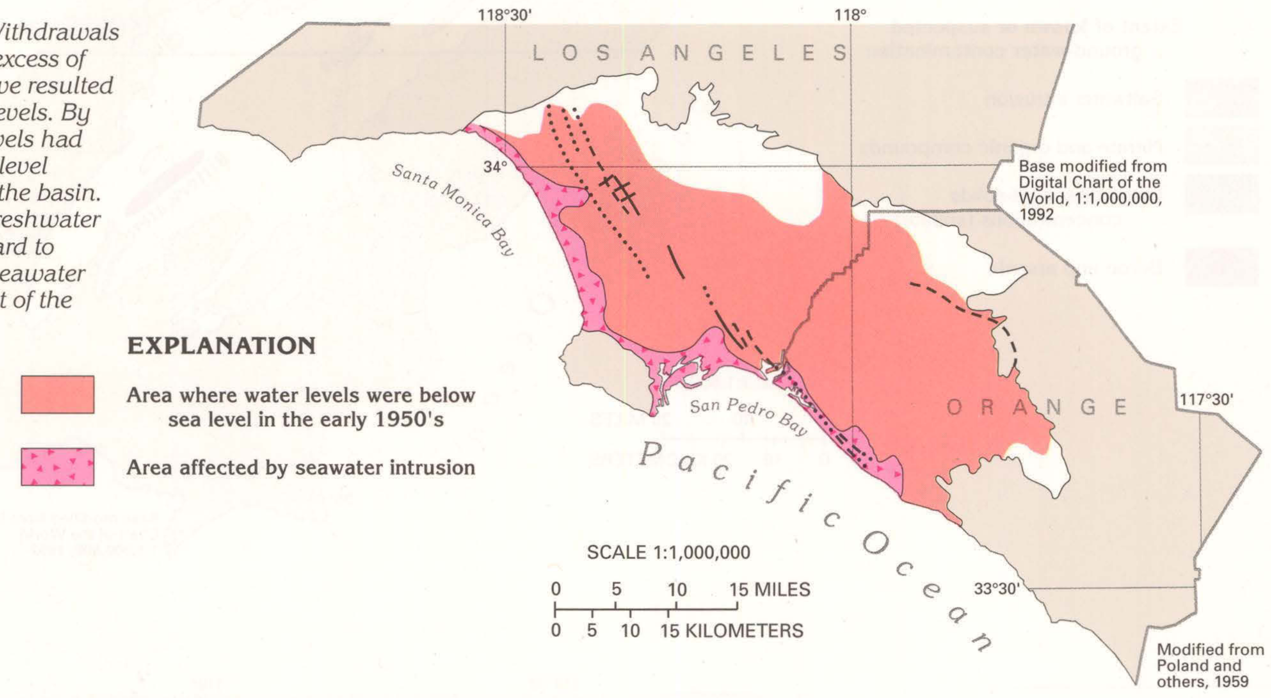


Figure 129. *After development, ground water moved primarily from recharge areas toward withdrawal centers instead of toward the ocean. Most ground water that enters the basin is removed by wells; thus, little reaches the ocean.*

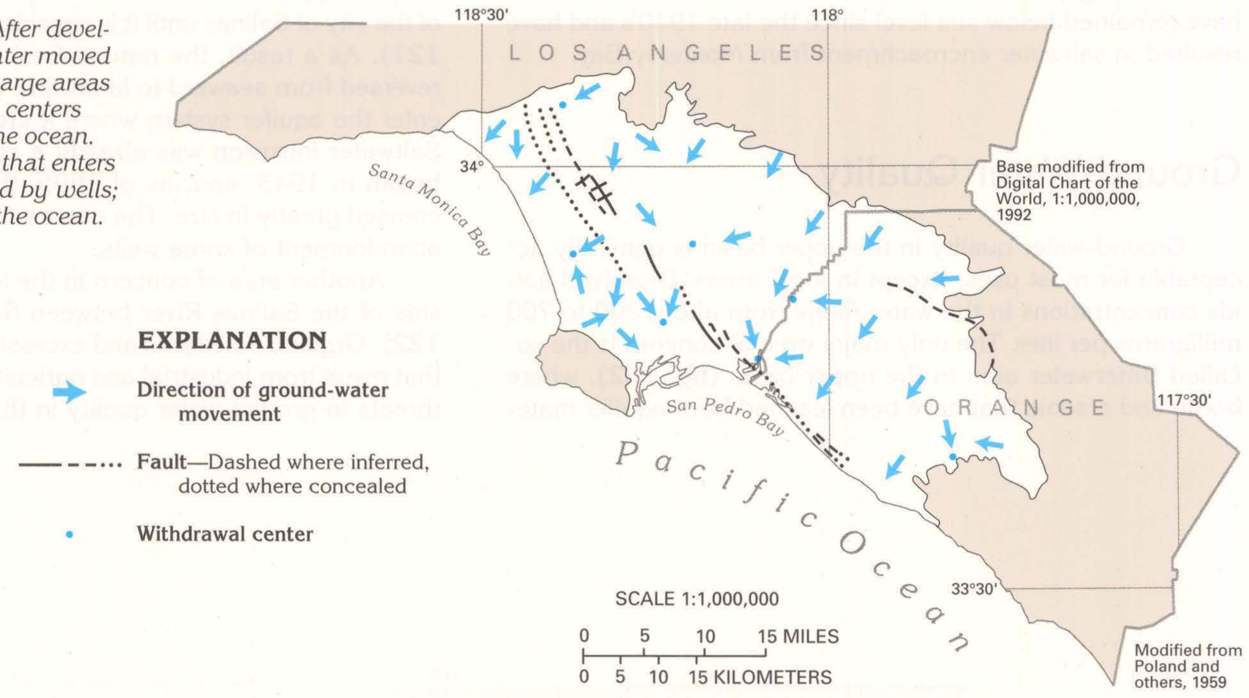


Figure 130. *Four methods of limiting seawater intrusion are used conjunctively in the basin. Controlled withdrawals (A) and artificial recharge (B) serve to increase the amount of water in the aquifer system, while pumping troughs (C) and injection wells (D) create a barrier to seawater intrusion near the coast. The arrows indicate the direction of ground-water movement.*

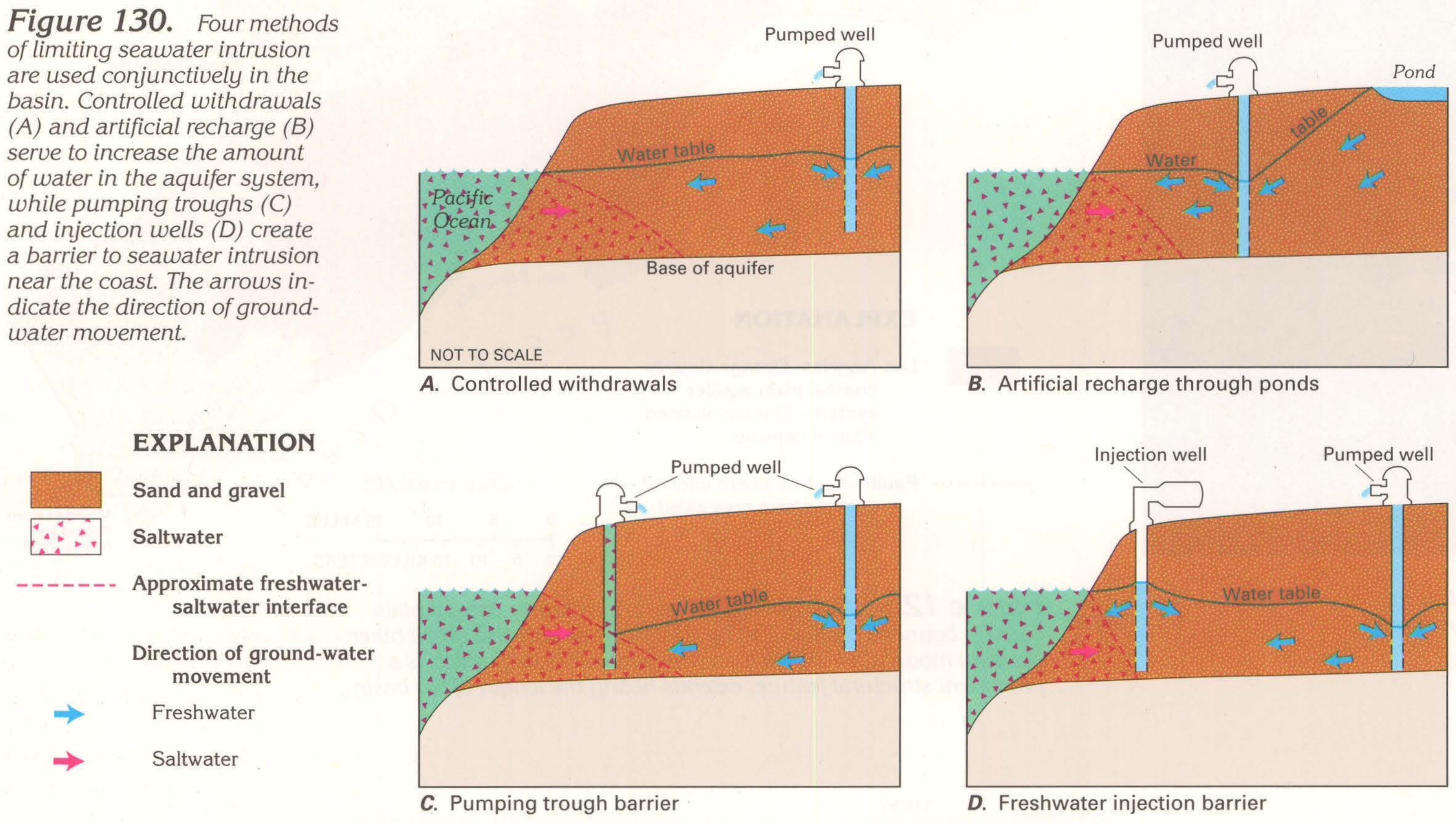
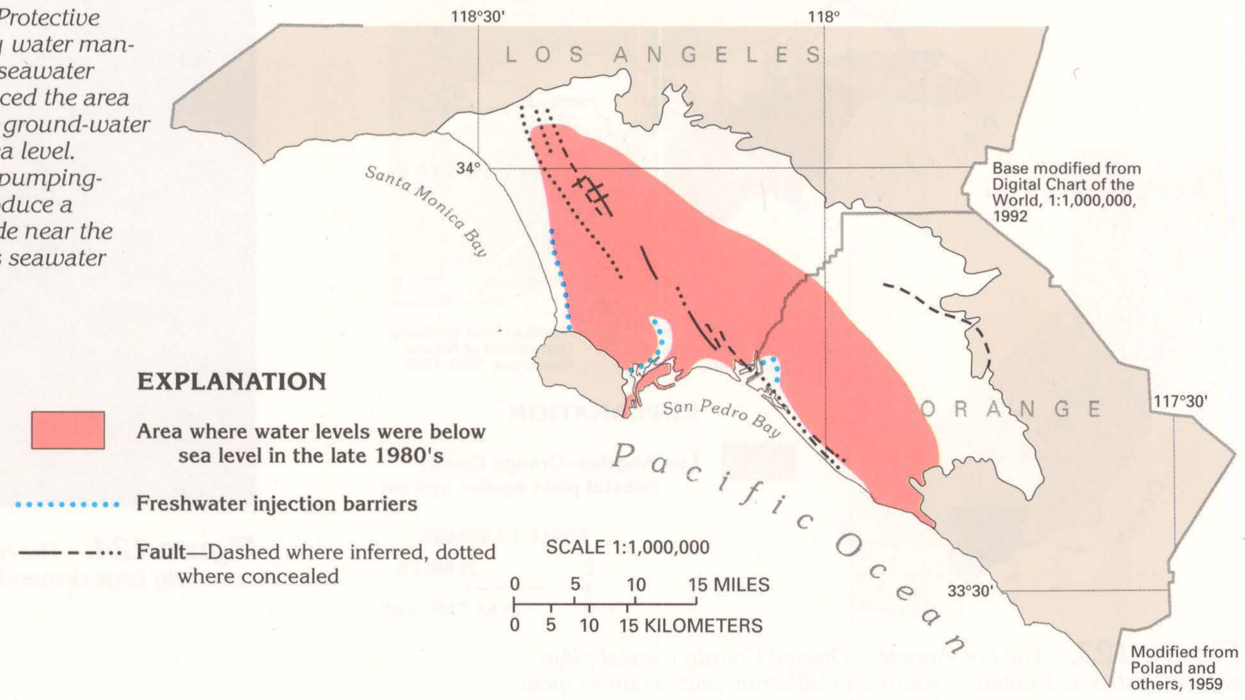


Figure 131. *Protective measures taken by water managers have halted seawater intrusion and reduced the area of the basin where ground-water levels are below sea level. Injection-well and pumping-trough barriers produce a ground-water divide near the coast that prevents seawater encroachment.*



Northern California basin-fill aquifers

INTRODUCTION

The northern California basin-fill aquifers comprise an assemblage of intermontane aquifers in northern California (**fig. 132**) that have similar hydrogeologic characteristics. These basins are much like the Coastal Basins aquifers in that the principal water-yielding deposits are unconsolidated sediments of Quaternary age, but the geologic history of the basin-fill aquifers is different.

The valleys are located mostly in the Cascade Mountains, the northern Sierra Nevada, and the Modoc Plateau. All the valleys are drained by tributaries or the main stems of the Klamath and the Sacramento Rivers. The principal land uses in these sparsely populated valleys are agriculture and grazing; some land is devoted to timber.

Climate among the valleys varies with altitude and distance from the Pacific Ocean. Generally, the valleys nearest the ocean and at lower altitudes have a moderate climate. Precipitation amounts vary with altitude and local physiography. The average annual precipitation ranges from less than 20 inches in Butte Valley near the Oregon border to as much as 80 inches in some valleys of the Sierra Nevada.

The most common use of water withdrawn from the northern California alluvial-valley aquifers is irrigated agriculture. Surface water provides the largest source of supply, but ground water is a significant percentage of the total water withdrawn, especially in dry years. Municipal and industrial supplies in most of the valleys depend primarily on ground water. Because ground-water withdrawals currently (1995) do not exceed natural recharge in these valleys, additional development is possible.

The complex geologic history of northern California is characterized by extreme tectonic and volcanic activity. The oldest exposed rocks date from the middle part of the Paleozoic Era and are in the Salmon and the Cascade Mountains and the Sierra Nevada. Mesozoic marine rocks also are in these mountains; for the most part, these rocks are metamorphosed sedimentary and volcanic rocks. The lithology of the rocks in these areas provides evidence of an ocean that once extended much farther inland than does the modern Pacific Ocean and a subduction zone that was located as far east as the Sierra Nevada, which predominately consists of granitic intrusive rocks. Mesozoic intrusive rocks also make up part of the Sierra Nevada.

The valleys in the interior of northern California are in structural troughs or depressions that resulted from the folding and faulting of crystalline rock. The troughs are partly filled with permeable sediments, principally of Pleistocene and Holocene age, that were eroded from the mountains and deposited as alluvial fans or lake deposits, or both. In some of the basins in the Cascade Mountains, volcanism produced basalt, pyroclastic flows, and tuffs that were deposited along with the basin-fill sediments. These volcanic and pyroclastic rocks were subsequently covered with alluvial material. The maximum thickness of unconsolidated permeable deposits in the valleys ranges from approximately 300 to 1,700 feet.

Ground water in the valleys is contained mostly in the alluvial-fan and lake deposits that fill the basins. Small to large amounts of ground water are stored in fractures and joints of volcanic rocks. In some basins, however, volcanic rocks store, transmit, and yield large amounts of water. Whether the ground water is under unconfined to confined conditions depends upon depth and the amount of fine-grained materials.

The aquifers are recharged by runoff from the surrounding mountains, seepage from streams, precipitation on the valley floor, irrigation return, or subsurface flow through fractured crystalline rocks. Ground water leaves the valleys by evapotranspiration, as stream discharge in the valleys that are drained by rivers, and, in some cases, by subsurface flow through permeable bedrock.

Well depths vary among the valleys, but most wells are from 50 to 500 feet deep; those completed in volcanic rock, however, can exceed 1,300 feet in depth. Well yields vary widely, and depend on the permeablilty of the water-yielding material in which the well is completed. Yields range from less than 100 gallons per minute in alluvial-fan and lake deposits to as much as 5,000 gallons per minute in intensely fractured volcanic rocks.

Although isolated areas have highly mineralized water, ground water suitable for most uses is widely available in these valleys. Locally, some of the water contains objectionable quantities of sodium or sulfate.

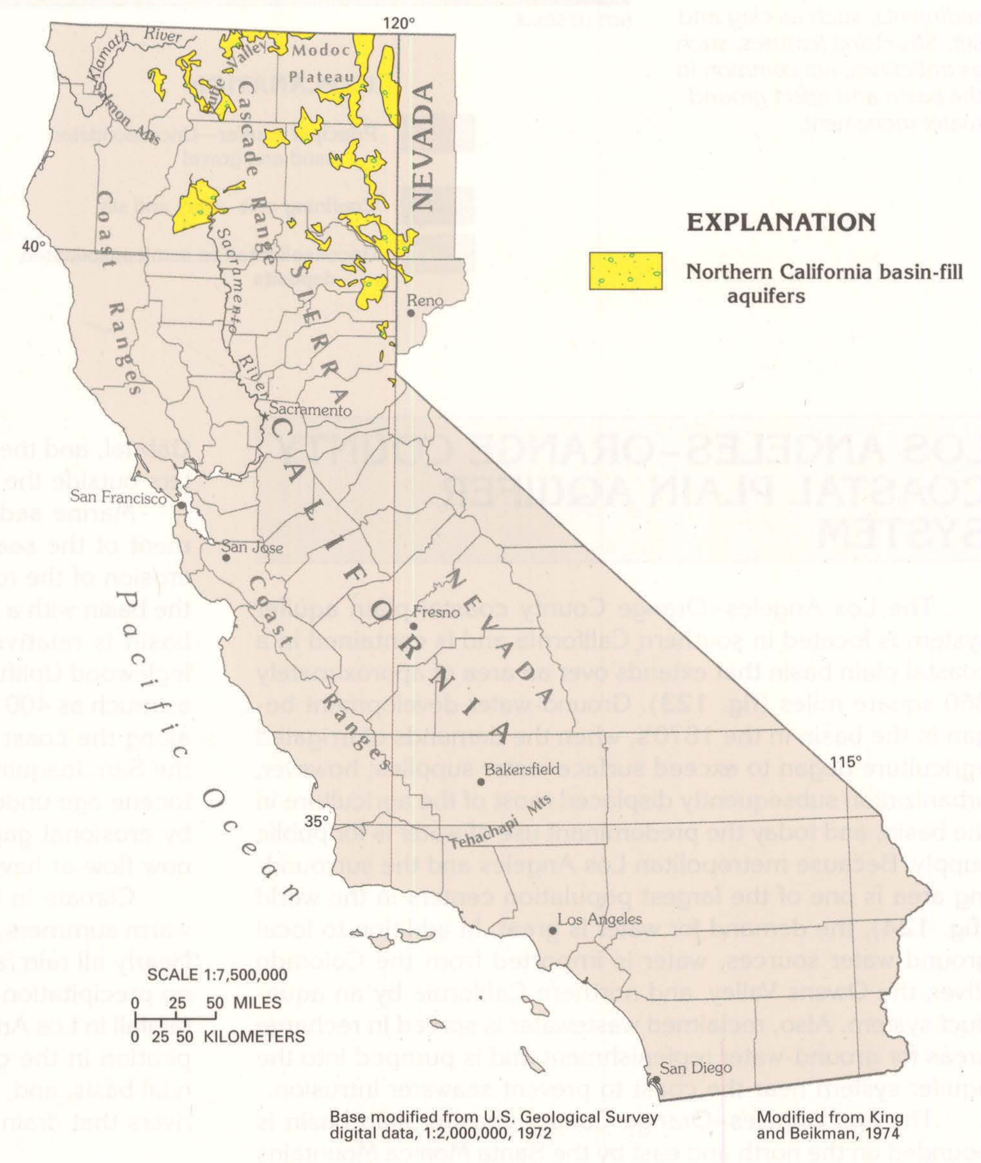


Figure 132. *The northern California basin-fill aquifers are primarily in the larger valleys of the Cascade Mountains, the Sierra Nevada, and the Modoc Plateau. Butte Valley in Siskiyou County is an example of these aquifers.*

BUTTE VALLEY

Butte Valley, which contains one of the more intensively developed aquifers of the northern California basin-fill aquifers, is located in north-central California just south of the Oregon border (**fig. 132**). The valley is one of several intermontane basins in northern California that is filled with alluvial deposits or lake deposits, which are a major source of ground water. However, Butte Valley is unique in that fractured volcanic rocks that underlie the basin fill and basalt interbedded with the basin fill also are major sources of water. Population in the valley is small, and irrigated agriculture accounts for most ground-water use.

Butte Valley, which was formed by faulting, is a closed basin approximately 18 miles long from north to south and has a maximum width of 13 miles (**fig. 133**). The valley floor is an ancestral lake bed that encompasses an area of about 130 square miles. Volcanic rocks surround the valley and underlie it at depths of about 400 to 1,500 feet (**fig. 134**). Streams drain into the valley from the west, and the water either infiltrates permeable deposits or flows into Meiss Lake (**fig. 133**), which is a small remnant of the large lake that once filled the valley. Discharge from the valley is by subsurface flow through fractured volcanic rocks to adjacent basins.

The valley floor receives approximately 12 inches of precipitation annually as rain or snow, mostly from October to June. The basinwide average is about 18 inches, but as much as 40 inches falls at the higher altitudes. Summers in the valley are warm and dry, and winters are cool and humid.

Aquifers and Confining Units

The major rocks and deposits that yield water to wells in the valley are the Butte Valley Basalt, fractured volcanic rocks, and coarse-grained lake deposits (**fig. 133**). Ground water is generally under unconfined, or water-table, conditions except in the volcanic rocks that underlie the lake deposits and in the Butte Valley Basalt where it is overlain by clayey lake deposits (**fig. 134**). Feeder dikes within the volcanic rocks may be barriers to water movement.

The permeability of the Butte Valley Basalt and the volcanic rocks is directly related to the thickness of the individual flows that compose the formations and to the number of individual flows. The thinner flows usually have higher permeability because they cooled more rapidly; thus, fracture and shrinkage joints that result from the cooling are common. Contacts between individual flows are rough, fractured, and porous; more such contacts are in a given thickness of rock that contains numerous flows than one that contains only a few thick flows.

The Butte Valley Basalt is a highly productive, though relatively thin, formation. The thickness of the basalt ranges from 6 feet to slightly more than 100 feet and averages about 40 feet. Individual basalt flows that compose the formation are thin and average only about 12 feet in thickness in one well. The contacts of the flow units are rough and broken and transmit water freely. The thinness of the flow units resulted in vertical fracturing that permits water to move between the flow contacts.

Individual flows in the volcanic rocks of the Cascade Mountains are usually thicker than those in the Butte Valley Basalt, and connections between flows are not as common. However, the volcanic rocks are a dependable source of water, and their large extent provides a vast source. Wells that penetrate several flow contacts can yield large volumes of water.

Local pyroclastic rocks (**fig. 133**) are as much as 400 feet thick and are moderately to highly permeable. Some of these rocks are above the water table and, therefore, are unsaturated. Where saturated, however, the pyroclastic rocks can yield large volumes of water.

Wells in the eastern and southern parts of the valley obtain large yields from the sand and gravel that compose the upper part of the lake deposits. In the area underlain by the Butte Valley Basalt, wells are commonly screened in the basalt and the underlying sands and gravels of the lake deposits. Lake deposits in the northern, central, and northwestern parts of the valley, however, are not a good source of ground water because of the predominance of clay and silt in those areas.

Alluvium, alluvial-fan deposits, talus, and dune sands in the valley are commonly permeable but usually are unsaturated. Although these deposits are recharge areas for underlying formations, they are not sources of water for wells.

Ground-Water Flow

Recharge to the aquifer is primarily by infiltration from perennial streams and percolation of precipitation through the lake and alluvial deposits. Some recharge percolates through unconsolidated deposits that overlie the lake beds where the deposits are above the water table. Small amounts of recharge also are by irrigation return flow and subsurface inflow from aquifers outside the basin. Ground water discharges from the aquifer by subsurface flow to the east, ground-water withdrawals, and evapotranspiration.

The major source of recharge to the unconfined part of the aquifer in the southern part of the valley is infiltration of streamflow from Prather and Butte Creeks. Water enters the aquifer as leakage from natural channels, unlined diversion canals, and two small storage reservoirs. Another recharge source for the southern end of the valley is subsurface inflow from the west and south. Minor amounts of recharge are from infiltration of precipitation and irrigation return flow. In other parts of the valley, the unconfined part of the aquifer is recharged by direct precipitation, subsurface inflow, and irrigation return flow. The confined part of the aquifer is recharged almost entirely by subsurface inflow from the north, west, and south.

Flow in the unconfined part of the aquifer is generally from west to east (**fig. 135**), whereas flow in the volcanic rocks that contain water under confined conditions is toward the center of the valley from the north, south, and west and then toward the east (**fig. 136**). The potentiometric surfaces shown in **figures 135 and 136** indicate that the hydraulic head of the unconfined part of the aquifer is higher than that of the confined part at Mahogany Mountain, which is the eastern boundary of the valley. Because this is not a major recharge area, the downward hydraulic gradient and west-to-east flow in the valley suggest that ground water leaves the valley as flow through the volcanic rocks beneath Mahogany Mountain and flows toward Klamath Lake and the Klamath River in the adjacent valley to the east.

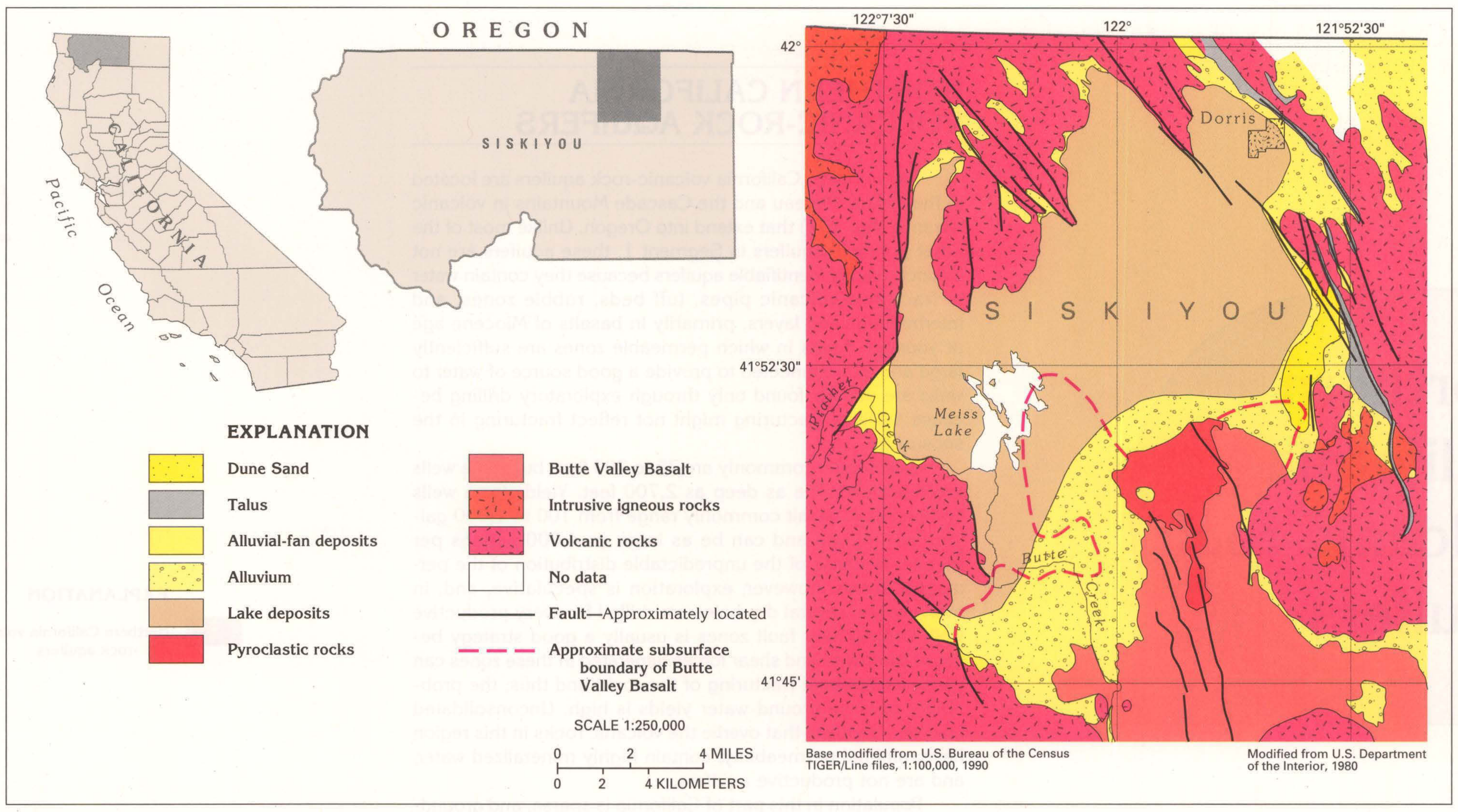


Figure 133. Butte Valley is surrounded and underlain at depth predominately by volcanic rocks of the Cascade Mountains. The valley is filled mostly with sediments deposited in a small remnant of a lake that occupied the valley during Pleistocene to Holocene time. The Butte Valley Basalt is interbedded with the lake sediments.

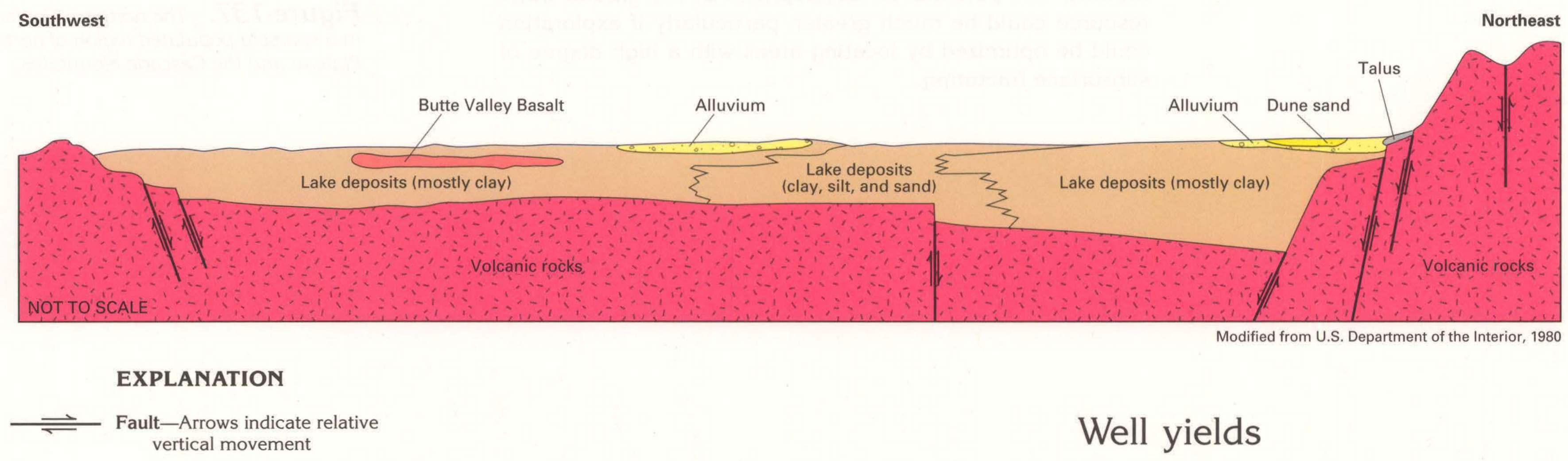


Figure 134. A diagrammatic hydrogeologic section shows that Butte Valley is a structural depression formed by faulting in volcanic rocks. The lake deposits that fill the valley grade mostly from fine grained in the north and west to coarse grained in the east and south. The Butte Valley Basalt flowed into the lake late in the valley's history and is near the surface of the lake deposits.

Figure 135. Ground-water flow in the unconfined part of the aquifer is generally from west to east. The water leaves the valley as flow under Mahogany Mountain.

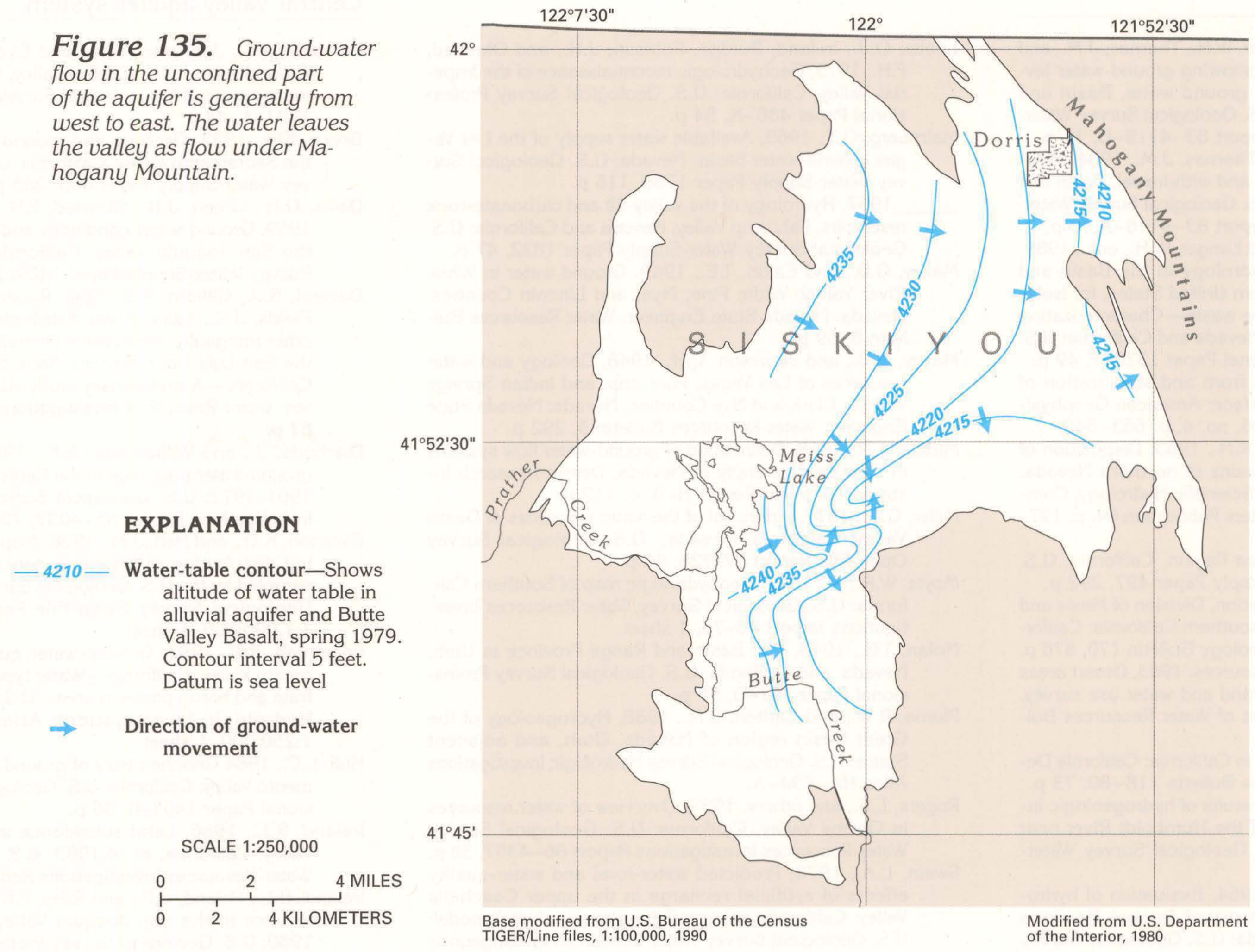
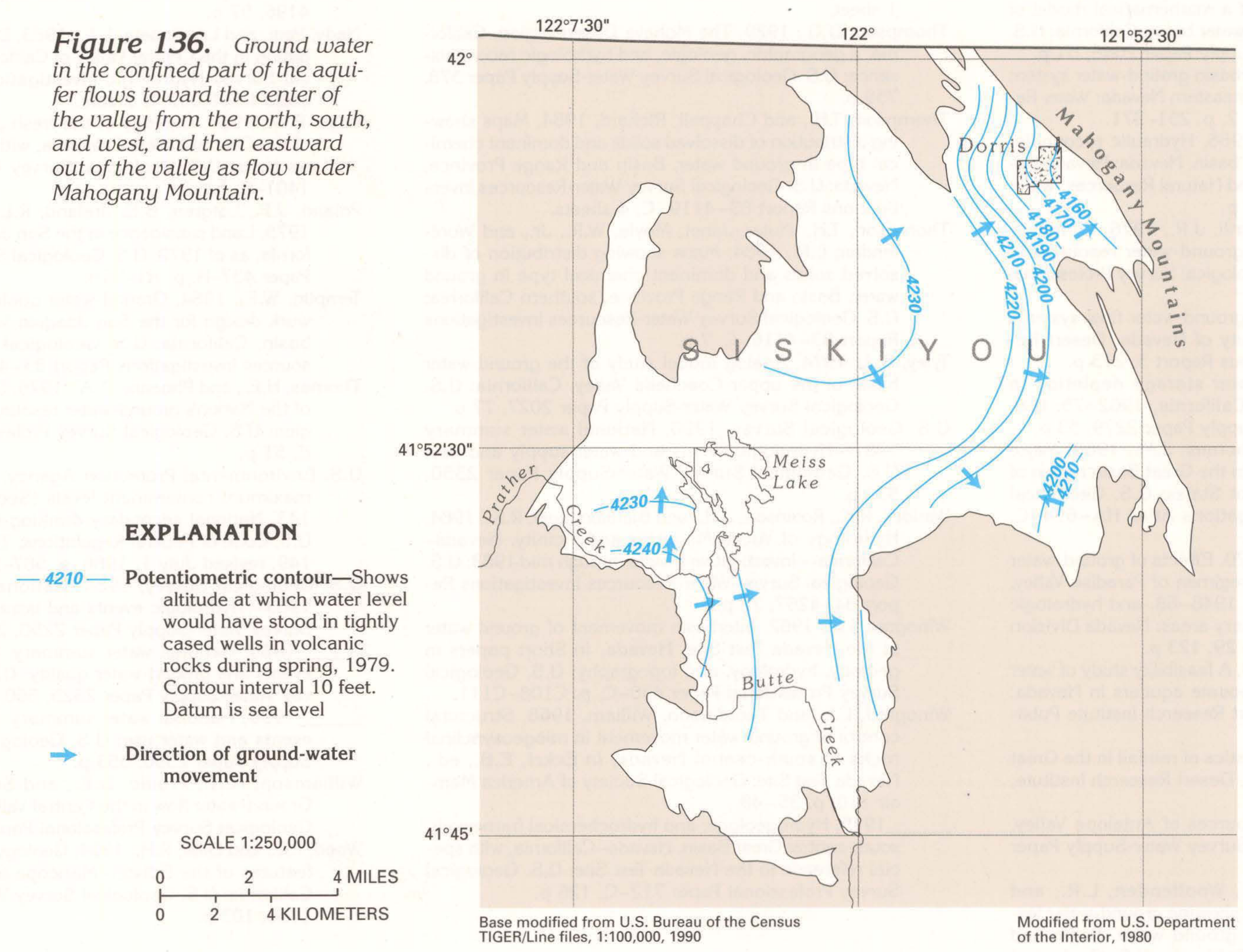


Figure 136. Ground water in the confined part of the aquifer flows toward the center of the valley from the north, south, and west, and then eastward out of the valley as flow under Mahogany Mountain.



Well yields

Well yields in Butte Valley are highly variable because of the permeability differences in the rocks and deposits. Yields vary greatly in the volcanic rocks and the Butte Valley Basalt because permeability depends on the thickness of the flow units and the degree of fracturing within the flows. Wells that penetrate such rocks in areas where flows are thin and contacts between flows are numerous generally have large yields. Yields of wells completed in the lake deposits likewise vary with location. The predominance of fine-grained lake sediments in the northern, northwestern, and central parts of the valley preclude large yields. Conversely, numerous wells are completed in large sand and gravel beds in the lake deposits on the eastern and southern sides of the valley.

Yields of wells completed in the lake deposits and pyroclastic rocks range from 1,500 to 4,000 gallons per minute. Specific capacities of individual wells range from 16 to 97 gallons per minute per foot of drawdown. Wells completed in the Butte Valley Basalt yield from 1,000 to more than 4,000 gallons per minute. Yields from wells completed in the volcanic rocks are highly variable and range from 700 to 5,000 gallons per minute.

Fresh Ground-Water Withdrawals

Estimates of ground-water withdrawals in Butte Valley during 1979 range from 62,000 to 72,000 acre-feet per year. Surface-water use accounted for another 10,000 to 20,000 acre-feet of the approximate total of 82,000 acre-feet of water used. Agricultural use far exceeded urban use, which was only about 700 acre-feet. According to a 1976 study, gross water demand for agriculture will eventually reach 162,000 acre-feet annually in Butte Valley.

In 1980, 40,000 acre-feet per year of ground water was estimated to have left the valley as subsurface outflow, most of which cannot be recovered. Ground-water withdrawals during that same year were conservatively estimated to be 62,000 acre-feet per year. Thus, the maximum amount of ground water available in the valley for annual use is approximately 102,000 acre-feet. Most of the land available for future development is in the northern end of the valley where surface soils and subsoils consist of fine-grained lake deposits that do not allow irrigation return flow to reach the aquifer. Therefore, unless surface water is imported to augment natural recharge, the amount of water available for agriculture appears to be much less than the projected demand.

Current (1995) usage is less than the amount of ground water available. Water levels might fluctuate as a result of annual precipitation and withdrawal cycles but are essentially unchanged in the long term. However, because of the limited storage capacity of the Butte Valley Basalt and the large volume of withdrawals from that formation, water-level decline is sufficient to cause some wells to go dry during the withdrawal season. Water levels recover, however, when withdrawals cease after the growing season. Deepening wells so that they penetrate the underlying sand and gravel of the lake deposits or the volcanic rocks could alleviate this seasonal situation.

Ground-Water Quality

The quality of ground water in Butte Valley is generally suitable for most uses. Dissolved-solids concentrations in the water rarely exceed 500 milligrams per liter. However, owners of a few wells completed in the volcanic rocks report that the water has a sulfur odor, and sodium concentrations exceed 50 milligrams per liter in water from a few wells completed in these rocks. Shallow wells completed in the lake deposits about 4 miles southwest of Dorris produce highly mineralized water that exceeds 500 milligrams per liter dissolved-solids concentrations probably because the water that recharges the aquifer in that area becomes mineralized while percolating through the overlying playa deposits.

Northern California volcanic-rock aquifers

NORTHERN CALIFORNIA VOLCANIC-ROCK AQUIFERS

The northern California volcanic-rock aquifers are located in the Modoc Plateau and the Cascade Mountains in volcanic terranes (**fig. 137**) that extend into Oregon. Unlike most of the other principal aquifers in Segment 1, these aquifers are not distinct, readily identifiable aquifers because they contain water in fractures, volcanic pipes, tuff beds, rubble zones, and interbedded sand layers, primarily in basalts of Miocene age or younger. Areas in which permeable zones are sufficiently large and interconnected to provide a good source of water to wells are usually found only through exploratory drilling because surficial fracturing might not reflect fracturing in the subsurface.

Well depths commonly are 75 to 200 feet, but some wells are reported to be as deep as 2,700 feet. Yields from wells completed in basalt commonly range from 100 to 1,000 gallons per minute and can be as large as 4,000 gallons per minute. Because of the unpredictable distribution of the permeable zones, however, exploration is speculative, and, in many cases, several dry holes are drilled for every productive well. Drilling near fault zones is usually a good strategy because the stress and shear forces generated in these zones can cause exceptional fracturing of the rock, and thus, the probability of large ground-water yields is high. Unconsolidated lake-bed deposits that overlie the volcanic rocks in this region have minimal permeability, contain highly mineralized water, and are not productive aquifers.

Population in this part of California is sparse, and ground-water use is minimal; recharge to the aquifers exceeds withdrawals. The potential for development of the ground-water resource could be much greater, particularly if exploration could be optimized by locating areas with a high degree of subsurface fracturing.

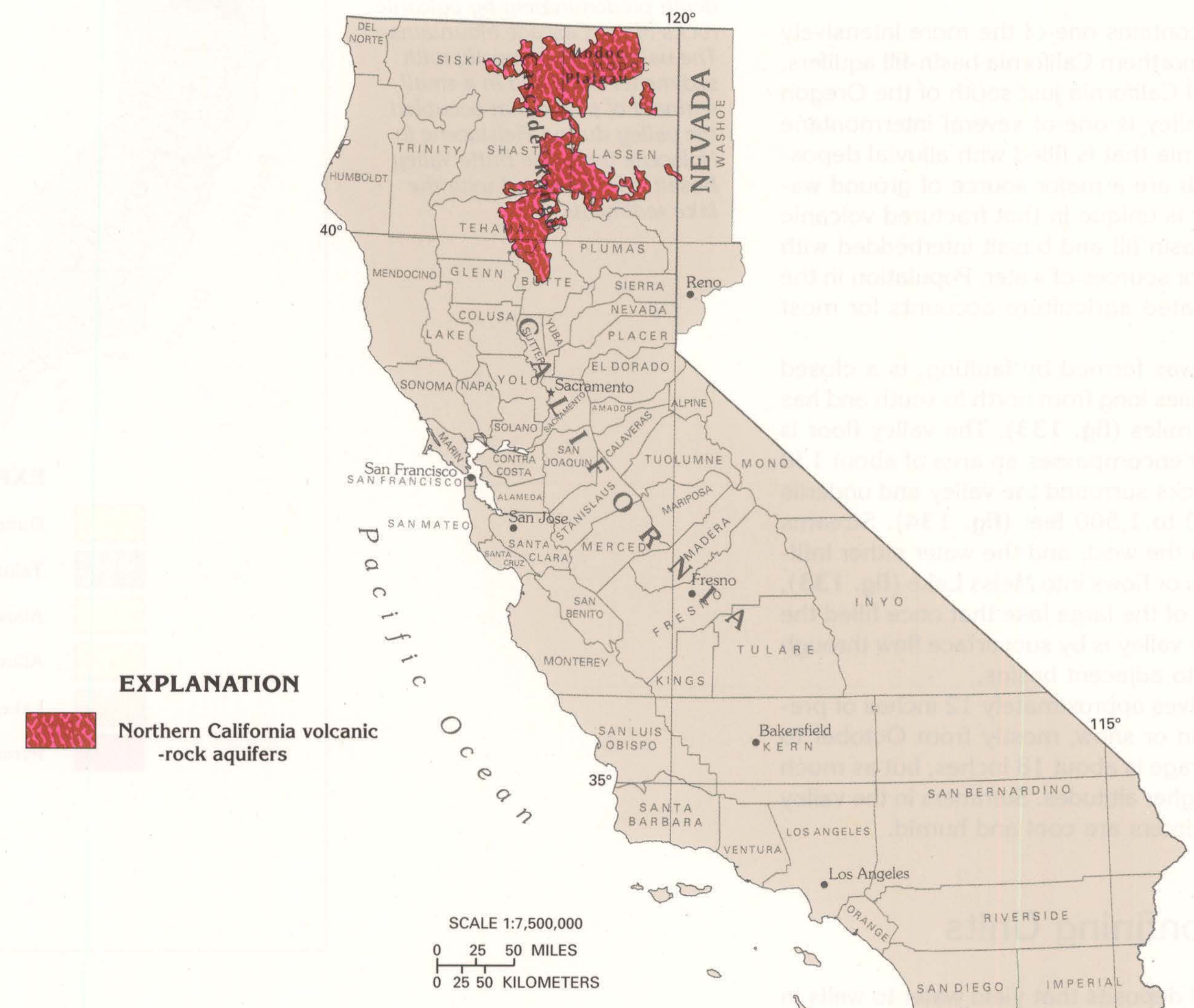


Figure 137. The northern California volcanic-rock aquifers are in a sparsely populated region of northern California in the Modoc Plateau and the Cascade Mountains.

Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972

Modified from King and Beikman, 1974

References

Regional summary

Bertoldi, G.L., Johnston, R.H., and Evenson, K.D., 1991, Ground water in the Central Valley, California—A summary report: U.S. Geological Survey Professional Paper 1401–A, 44 p.

California Department of Water Resources, 1980, Ground water basins in California: California Department of Water Resources Bulletin 118–80, 73 p.

Dunbar, C.O., 1966, Historical geology: New York, John Wiley and Sons, Inc., 500 p.

Fenneman, N.M., and Johnson, D.W., 1946, Physical divisions of the United States: U.S. Geological Survey, scale 1:7,000,000, 1 sheet.

Gebert, W.A., Graczyk, D.J., and Krug, W.R., 1987, Average annual runoff in the United States, 1951–80: U.S. Geological Survey Hydrologic Investigations Atlas HA–710, scale 1:7,500,000, 1 sheet.

King, P.B., and Beikman, H.M., 1974, Geologic map of the United States: U.S. Geological Survey, scale 1:2,500,00, 3 sheets.

Plume, R.W., and Carlton, S.M., 1988, Hydrogeology of the Great Basin region of Nevada, Utah, and adjacent States: U.S. Geological Survey Hydrologic Investigations Atlas HA–694–A.

Snyder, C.T., Hardman, George, and Zdenek, F.E., 1964, Pleistocene lake in the Great Basin: U.S. Geological Survey Miscellaneous Geologic Investigations Map I–416, scale 1:1,000,000, 1 sheet.

Thomas, H.E., and Phoenix, D.A., 1976, Summary appraisals of the Nation's ground-water resources—California region: U.S. Geological Survey Professional Paper 813–E, 51 p.

Thelin, G.P., and Pike, R.J., 1990, Digital shaded relief map of the conterminous United States: Menlo Park, California, U.S. Geological Survey digital image processing, scale 1:3,500,000

Trewartha, G.T., 1968, An introduction to climate (4th ed.): New York, McGraw-Hill, 408 p.

U.S. Geological Survey, 1986, National water summary 1985—Hydrologic events and surface-water resources: U.S. Geological Survey Water-Supply Paper 2300, 506 p.

U.S. Geological Survey, 1984, National water summary 1983—Hydrologic events and issues: U.S. Geological Survey Water-Supply Paper 2250, 243 p.

______1990, National water summary 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, 553 p.

______1993, National water summary 1990–91—Hydrologic events and stream water quality: U.S. Geological Survey Water Supply Paper 2400, 590 p.

Basin and Range aquifers

Bedinger, M.S., Harrill, J.R., Langer, W.H., Thomas, J.M., and Mulvihill, D.A.,1984, Maps showing ground-water levels, springs, and depth to ground water, Basin and Range Province, Nevada: U.S. Geological Survey Water-Resources Investigations Report 83–4119–B, 11 p.

Bedinger, M.S., Harrill, J.R., and Thomas, J.M., 1984, Maps showing ground-water units and withdrawal, Basin and Range Province, Nevada: U.S. Geological Survey Water-Resources Investigations Report 83–4116–A,10 p.

Bedinger, M.S., Sargent, K.A., and Langer, W.H., eds., 1989, Studies of geology and hydrology in the Basin and Range Province, southwestern United States, for isolation of high-level radioactive waste—Characterization of the Death Valley region, Nevada and California: U.S. Geological Survey Professional Paper 1370–F, 49 p.

Blaney, H.F., 1955, Evaporation from and stabilization of Salton Sea (Calif.) water surface: American Geophysical Union Transactions, v. 36, no. 4, p. 663–640.

Bredehoeft, J.D., and Farvolden, R.N., 1963, Disposition of aquifers in intermontane basins of northern Nevada: International Association of Scientific Hydrology, Commission of Subterranean Waters Publication 64, p. 197–212.

Brown, J.S., 1923, The Salton Sea Region, California: U.S. Geological Survey Water-Supply Paper 497, 292 p.

California Department of Conservation, Division of Mines and Geology, 1954, Geology of southern California: California Division of Mines and Geology Bulletin 170, 878 p.

California Department of Water Resources, 1963, Desert areas of southeastern California, land and water use survey, 1958: California Department of Water Resources Bulletin 101, 74 p.

______1980, Ground water basins in California: California Department of Water Resources Bulletin 118–80, 73 p.

Cohen, Philip, 1964, Preliminary results of hydrogeologic investigations in the valley of the Humboldt River near Winnemucca, Nevada: U.S. Geological Survey Water-Supply Paper 1754, 59 p.

Cohen, Philip, and Loeltz, O.J., 1964, Evaluation of hydrogeology and hydrogeochemistry of Truckee Meadows area, Washoe County, Nevada: U.S. Geological Survey Water-Supply Paper 1779–S, p. S6–S62.

Dettinger, M.D., 1989, Distribution of carbonate-rock aquifers in southern Nevada and the potential for their development—Summary of findings, 1985–88: University of Nevada, Desert Research Institute Report 1, 37 p.

Durbin, T.J., 1978, Calibration of a mathematical model of the Antelope Valley ground-water basin, California: U.S. Geological Survey Water-Supply Paper 2046, 51 p.

Eakin, T.E., 1966, A regional interbasin ground-water system in the White River area, southeastern Nevada: Water Resources Research, v. 2, no. 2, p. 251–271.

Eakin, T.E., and Lamke, R.D., 1966, Hydraulic reconnaissance of the Humboldt River basin, Nevada: Nevada Department of Conservation and Natural Resources, Water Resources Bulletin 32, 107 p.

Eakin, T.E., Price, Don, and Harrill, J.R., 1976, Summary appraisals of the Nation's ground-water resources—Great Basin region: U.S. Geological Survey Professional Paper 813–G, 37 p.

Fiero, G.W., Jr., 1968, Regional ground-water flow systems of central Nevada: University of Nevada, Desert Research Institute Miscellaneous Report 5, 213 p.

Harrill, J.R., 1986, Ground-water storage depletion in Pahrump Valley, Nevada–California, 1962–75: U.S. Geological Survey Water-Supply Paper 2279, 53 p.

Harrill, J.R., Gates, J.S., and Thomas, J.M., 1988, Major ground-water flow systems in the Great Basin region of Nevada, Utah, and adjacent States: U.S. Geological Survey Hydrologic Investigations Atlas HA–694–C, scale 1:1,000,000, 1 sheet.

Harrill, J.R., and Moore, D.O., 1970, Effects of ground-water development on the water regimen of Paradise Valley, Humboldt County, Nevada, 1948–68, and hydrologic reconnaissance of the tributary areas: Nevada Division of Water Resources Bulletin 29, 123 p.

Hess, J.W., and Mifflin, M.D., 1978, A feasibility study of water production from deep carbonate aquifers in Nevada: University of Nevada, Desert Research Institute Publication 41054, 125 p.

Houghton, J.G., 1967, Characteristics of rainfall in the Great Basin: University of Nevada, Desert Research Institute, 205 p.

Johnson, H.R., 1911, Water resources of Antelope Valley, California: U.S. Geological Survey Water-Supply Paper 278, 92 p.

Langer, W.H., Moyle, W.R., Jr., Woolfenden, L.R., and Mulvilhill, D.A., 1984, Maps showing ground-water levels, springs, and depth to ground water, Basin and Range Province, southern California: U.S. Geological Survey Water-Resources Investigations Report 83–4116–B, 6 sheets.

Loeltz, O.J., Ireland, Burdge, Robison, J.H., and Olmsted, F.H., 1975, Geohydrologic reconnaissance of the Imperial Valley, California: U.S. Geological Survey Professional Paper 486–K, 54 p.

Malmberg, G.T., 1965, Available water supply of the Las Vegas ground-water basin, Nevada: U.S. Geological Survey Water-Supply Paper 1780, 116 p.

______1967, Hydrology of the valley-fill and carbonate-rock reservoirs, Pahrump Valley, Nevada and California: U.S. Geological Survey Water-Supply Paper 1832, 47 p.

Maxey, G.B., and Eakin, T.E., 1949, Ground water in White River Valley, White Pine, Nye, and Lincoln Counties, Nevada: Nevada State Engineer, Water Resources Bulletin 8, 59 p.

Maxey, G.B., and Jameson, C.H., 1948, Geology and water resources of Las Vegas, Pahrump, and Indian Springs Valleys, Clark and Nye Counties, Nevada: Nevada State Engineer, Water-Resources Bulletin 5, 292 p.

Mifflin, M.D., 1968, Delineation of ground-water flow systems in Nevada: University of Nevada, Desert Research Institute Technical Report H–W 4, 112 p.

Miller, G.A., 1977, Appraisal of the water resources of Death Valley, California–Nevada: U.S. Geological Survey Open-File Report 77–728, 68 p.

Moyle, W.R., Jr., 1974, Geohydrologic map of Southern California: U.S. Geological Survey Water-Resources Investigations Report 48–73, 1 sheet.

Nolan, T.B., 1943, The Basin and Range Province in Utah, Nevada, and California: U.S. Geological Survey Professional Paper 197–D, 55 p.

Plume, R.W., and Carlton, S.M., 1988, Hydrogeology of the Great Basin region of Nevada, Utah, and adjacent States: U.S. Geological Survey Hydrologic Investigations Atlas HA–694–A.

Rogers, L.S., and others, 1987, Overview of water resources in Owens Valley, California: U.S. Geological Survey Water-Resources Investigations Report 86–4357, 38 p.

Swain, L.A., 1978, Predicted water-level and water-quality effects of artificial recharge in the upper Coachella Valley, California, using a finite-element digital model: U.S. Geological Survey Water-Resources Investigations Report 77–29, 54 p.

Thomas, J.M., Mason, J.L., and Crabtree, J.D., 1986, Ground-water levels in the Great Basin of Nevada, Utah, and adjacent States: U.S. Geological Survey Hydrologic Investigations Atlas HA–694–B, scale 1:1,000,000, 1 sheet.

Thompson, D.G., 1929, The Mohave Desert region, California, a geographic, geologic, and hydrologic reconnaissance: U.S. Geological Survey Water-Supply Paper 578, 759 p.

Thompson, T.H., and Chappell, Richard, 1984, Maps showing distribution of dissolved solids and dominant chemical type in ground water, Basin and Range Province, Nevada: U.S. Geological Survey Water-Resources Investigations Report 83–4119–C, 4 sheets.

Thompson, T.H., Nuter, Janet, Moyle, W.R., Jr., and Woolfenden, L.R., 1984, Maps showing distribution of dissolved solids and dominant chemical type in ground water, Basin and Range Province, southern California: U.S. Geological Survey Water-Resources Investigations Report 83–4116–C, 7 p.

Tyley, S.J., 1974, Analog model study of the ground-water basin of the upper Coachella Valley, California: U.S. Geological Survey Water-Supply Paper 2027, 77 p.

U.S. Geological Survey, 1990, National water summary 1987—Hydrologic events and water supply and use: U.S. Geological Survey Water-Supply Paper 2350, 553 p.

Waddell, R.K., Robinson, J.H., and Blankennagel, R.K., 1984, Hydrology of Yucca Mountain and vicinity, Nevada–California—Investigative results through mid-1983: U.S. Geological Survey Water-Resources Investigations Report 84–4267, 72 p.

Winograd, I.J., 1962, Interbasin movement of ground water at the Nevada Test Site, Nevada, *in* Short papers in geology, hydrology, and topography: U.S. Geological Survey Professional Paper 450–C, p. C108–C111.

Winograd, I.J., and Thordarson, William, 1968, Structural control of ground-water movement in miogeosynclinal rocks of south-central Nevada, *in* Eckel, E.B., ed., Nevada Test Site: Geological Society of America Memoir 110, p. 35–48.

______1975, Hydrogeologic and hydrochemical framework, south-central Great Basin, Nevada–California, with special reference to the Nevada Test Site: U.S. Geological Survey Professional Paper 712–C, 126 p.

Central Valley aquifer system

Bertoldi, G.L., Johnston, R.H., and Evenson, K.D., 1991, Ground water in the Central Valley, California—A summary report: U.S. Geological Survey Professional Paper 1401–A, 44 p.

Bryan, Kirk, 1923, Geology and ground-water resources of the Sacramento Valley, California: U.S. Geological Survey Water-Supply Paper 495, 285 p.

Davis, G.H., Green, J.H., Olmsted, F.H., and Brown, D.W., 1959, Ground-water conditions and storage capacity in the San Joaquin Valley, California: U.S. Geological Survey Water-Supply Paper 1469, 287 p.

Deverel, S.J., Gilliom, R.J., Fujii, Roger, Izbicki, J.A., and Fields, J.C., 1984, Areal distribution of selenium and other inorganic constituents in shallow ground water of the San Luis Drain Service Area, San Joaquin Valley, California—A preliminary study: U.S. Geological Survey Water-Resources Investigations Report 84–4319, 67 p.

Diamond, J., and Williamson, A.K., 1983, A summary of ground-water pumpage in the Central Valley, California, 1961–1977: U.S. Geological Survey Water-Resources Investigations Report 83–4037, 70 p.

Evenson, K.D., and Neil, J.M., 1986, Map of California showing distribution of selenium concentrations in wells sampled by the U.S. Geological Survey, 1975–85: U.S. Geological Survey Open-File Report 86–72, scale 1:1,000,000, 1 sheet.

Fogelman, R.P., 1983, Ground-water quality in the Sacramento Valley, California—Water types and potential nitrate and boron problem areas: U.S. Geological Survey Hydrologic Investigations Atlas HA–651, scale 1:250,000, 1 sheet.

Hull, L.C., 1984 Geochemistry of ground water in the Sacramento Valley, California: U.S. Geological Survey Professional Paper 1401–B, 36 p.

Ireland, R.L., 1986, Land subsidence in the San Joaquin Valley, California, as of 1983: U.S. Geological Survey Water-Resources Investigations Report 85–4196, 50 p.

Ireland, R.L., Poland, J.F., and Riley, F.S., 1984, Land subsidence in the San Joaquin Valley, California, as of 1980: U.S. Geological Survey Professional Paper 437–I, p. I1–I93.

Mandle, R.J., and Kontis, A.L., 1986, Directions and rates of ground-water movement in the vicinity of Kesterson Reservoir, San Joaquin Valley, California: U.S. Geological Survey Water-Resources Investigations Report 86–4196, 57 p.

Nady, Paul, and Larragueta, L.L., 1983, Development of irrigation in the Central Valley of California: U.S. Geological Survey Hydrologic Investigation Atlas HA–649, scale 1:500,000, 2 sheets.

Page, R.W., 1986, Geology of the fresh ground-water basin of the Central Valley, California, with texture maps and sections: U.S. Geological Survey Professional Paper 1401–C, 54 p.

Poland, J.F., Lofgren, B.E., Ireland, R.L., and Pugh, A.G., 1975, Land subsidence in the San Joaquin Valley, California, as of 1972: U.S. Geological Survey Professional Paper 437–H, p. H1–H78.

Templin, W.E., 1984, Ground-water quality monitoring network design for the San Joaquin Valley ground-water basin, California: U.S. Geological Survey Water-Resources Investigations Report 83–4080, 133 p.

Thomas, H.E., and Phoenix, D.A., 1976, Summary appraisal of the Nation's ground-water resources—California region: U.S. Geological Survey Professional Paper 813–E, 51 p.

U.S. Environmental Protection Agency, 1986, Secondary maximum contaminant levels (Section 143.3 of part 143, National secondary drinking-water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100–149, revised July 1, 1986, p. 587–590.

U.S. Geological Survey, 1984, National water summary 1983—Hydrologic events and issues: U.S. Geological Survey Water-Supply Paper 2250, 243 p.

______1988, National water summary 1986—Hydrologic events and ground-water quality: U.S. Geological Survey Water-Supply Paper 2325, 560 p.

______1990, National water summary 1987—Hydrologic events and water use: U.S. Geological Survey Water-Supply Paper 2350, 553 p.

Williamson, A.K., Prudic, D.E., and Swain, L.A., 1989, Ground-water flow in the Central Valley, California: U.S. Geological Survey Professional Paper 1401–D, 127 p.

Wood, P.R., and Dale, R.H., 1964, Geology and ground-water features of the Edison–Maricopa area, Kern County, California: U.S. Geological Survey Water-Supply Paper 1656, 103 p.

Coastal Basins aquifers

California Department of Water Resources, 1961, Planned utilization of the ground water basins of the coastal plain of Los Angeles County: California Department of Water Resources Bulletin 104, Appendix A, 181 p.

______1968, Planned utilization of ground water basins—Coastal plain of Los Angeles County: California Department of Water Resources Bulletin 104, 25 p.

______1975, Sea-water intrusion in California—Inventory of coastal ground water basins: California Department of Water Resources Bulletin 63–5, 394 p.

______1980, California's ground water: California Department of Water Resources Bulletin 118, 135 p.

______1980, Ground water basins in California: California Department of Water Resources Bulletin 118–80, 73 p.

______1981, South Santa Clara County area, volume 4 *of* Evaluation of ground water resources south of San Francisco Bay: California Department of Water Resources Bulletin 118–1, 143 p.

______1982a, Santa Rosa Plain, volume 2 *of* Evaluation of ground water resources; Sonoma County: California Department of Water Resources Bulletin 118–4, 107 p.

______1982b, Petaluma Valley, volume 3 *of* Evaluation of ground water resources; Sonoma County, California Department of Water Resources Bulletin 118–4, 91 p.

______1982c, Sonoma Valley, volume 4 *of* Evaluation of ground water resources; Sonoma County: California Department of Water Resources Bulletin 118–4, 78 p.

______1988, Southern California, volume 5 *of* Hydrologic Data 1985: California Department of Water Resources Bulletin 130–85, 208 p.

Cardwell, G.T., 1958, Geology and ground water, Santa Rosa and Petaluma Valleys, California: U.S. Geological Survey Water-Supply Paper 1427, 273 p.

Clark, W.O., 1924, Ground water in Santa Clara Valley, California: U.S. Geological Survey Water-Supply Paper 519, 209 p.

Durham, D.L., 1974, Geology of the Southern Salinas Valley area, California: U.S. Geological Survey Professional Paper 819, 111 p.

Evenson, R.E., 1959, Geology and ground-water features of the Eureka area, Humboldt County, California: U.S. Geological Survey Water-Supply Paper 1470, 80 p.

Kunkel, F., and Upson, J.E., 1960, Geology and ground water in Napa and Sonoma Counties, California: U.S. Geological Survey Water-Supply Paper 1495, 252 p.

Piper, A.M., Garrett, A.A., and others, 1953, Native and contaminated ground waters in the Long Beach–Santa Ana area, California: U.S. Geological Survey Water-Supply Paper 1136, 320 p.

Poland, J.F., 1959, Hydrology of the Long Beach–Santa Ana area, California, with special reference to the water tightness of the Newport–Inglewood structural zone: U.S. Geological Survey Water-Supply Paper 1471, 257 p.

Poland, J.F., Garrett, A.A., and Sinnott, Albert, 1959, Geology, hydrology, and chemical character of ground waters in the Torrance–Santa Monica area, California: U.S. Geological Survey Water-Supply Paper 1461, 425 p.

Poland, J.F., and Ireland, R.L., 1988, Land subsidence in the Santa Clara Valley, California, as of 1982: U.S. Geological Survey Professional Paper 497–F, 61 p.

Showalter, P.E., Akers, J.P., and Swain, L.A., 1983, Design of a ground-water monitoring network for the Salinas River Basin, California: U.S. Geological Survey Water-Resources Investigations Report 83–4049, 74 p.

Thomasson, H.G., Olmsted, F.H., Jr., and LeRoux, E.F., 1960, Geology, water resources and usable ground-water storage capacity of part of Solano County, California: U.S. Geological Survey Water-Supply Paper 1464, 693 p.

Northern California basin-fill aquifers

California Department of Water Resources, 1964, Shasta Valley Investigation: California Department of Water Resources Bulletin 87, 170 p.

U.S. Department of the Interior, 1980, Klamath project, Butte Valley division: U.S. Department of Interior, Water and Power Resources Service, Feasibility, ground-water geology and resources appendix, 50 p.

Wood, P.R., 1960, Geology and ground-water features of the Butte Valley Region, Siskiyou County, California: U.S. Geological Survey Water-Supply Paper 1491, 150 p.

Northern California volcanic-rock aquifers

U.S. Geological Survey, 1985, National water summary 1984—Hydrologic events, selected water-quality trends, and ground-water resources: U.S. Geological Survey Water-Supply Paper 2275, 467 p.