Evaluation of the Hydrologic System and Selected Water-Management Alternatives in the Owens Valley, California

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Prepared in cooperation
with Inyo County and the
Los Angeles Department
of Water and Power

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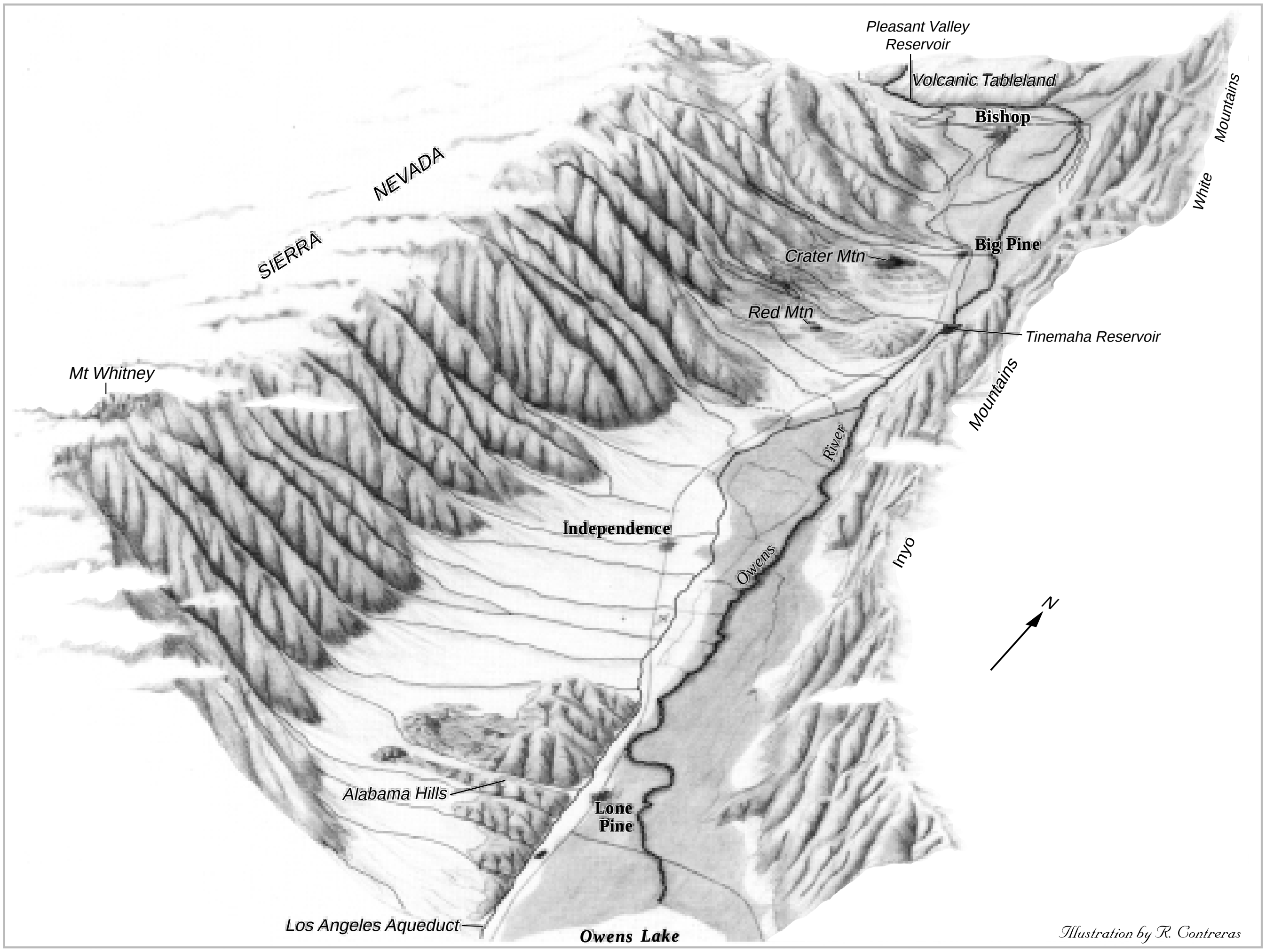
EVALUATION OF THE HYDROLOGIC SYSTEM AND SELECTED
WATER-MANAGEMENT ALTERNATIVES IN THE
OWENS VALLEY, CALIFORNIA



Frontispiece. Vertically exaggerated perspective and oblique view of the Owens Valley, California, showing the dramatic difference in topographic relief between the valley and the surrounding mountains.

Chapter H

Evaluation of the Hydrologic System and Selected Water-Management Alternatives in the Owens Valley, California

By WESLEY R. DANSKIN

Prepared in cooperation with Inyo County and the
Los Angeles Department of Water and Power

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HYDROLOGY AND SOIL-WATER-PLANT RELATIONS IN OWENS VALLEY, CALIFORNIA

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CONVERSION FACTORS

Multiply	By	To obtain
acre	0.405	square hectometer
acre-foot (acre-ft)	.001233	cubic hectometer
acre-foot per acre (acre-ft/acre)	.001233	cubic hectometer per hectometer
acre-foot per year (acre-ft/yr)	.001233	cubic hectometer per year
acre-foot per year per mile [(acre-ft/yr)/mi]	.0007663	cubic hectometer per year per kilometer
cubic foot (ft^3)	.02832	cubic meter
cubic foot per second (ft^3/s)	.02832	cubic meter per second
cubic foot per second per mile [(ft^3/s)/mi]	.0176	cubic meter per second per kilometer
foot (ft)	.3048	meter
foot per day (ft/d)	.3048	meter per day
foot per mile (ft/mi)	.1895	meter per kilometer
foot per second (ft/s)	.3048	meter per second
foot per year (ft/yr)	.3048	meter per year
foot squared per day (ft^2/d)	.0929	meter squared per day
gallon (gal)	3.785	liter
gallon per day per foot [(gal/d)/ft]	12.418	liter per day per meter
gallon per day per cubic foot [(gal/d)/ft^3]	.1072	liter per day per cubic meter
gallon per day per square foot [(gal/d)/ft^2]	.3516	liter per day per square meter
gallon per minute (gal/min)	.06308	liter per second
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	l.609	kilometer
mile per hour (mi/h)	.447	meter per second
pound per square foot (lb/ft^2)	16.01846	kilogram per square meter
pound per square inch (lb/in^2)	11.1239	kilogram per square centimeter
square foot (ft^2)	.09294	square meter
square mile (mi^2)	2.590	square kilometer

Temperature is given in degrees Fahrenheit (°F), which can be converted to degrees Celsius (°C) by the following equation:

$$\text{Temp. } ^\circ C = (\text{temp. } ^\circ F - 32) / 1.8$$

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.

ABBREVIATIONS AND DEFINITIONS

Abbreviations:

g/m^3	gram per cubic meter
m	meter
mg/L	milligram per liter
mL	milliliter
CEQA	California Environmental Quality Act
EIR	Environmental Impact Report
GIS	geographic information system
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator

Definitions:

Calendar year	January 1 through December 31
Runoff year	April 1 through March 31
Rain year	July 1 through June 30
Water year	October 1 through September 30

Evaluation of the Hydrologic System and Selected Water-Management Alternatives in the Owens Valley, California

By Wesley R. Danskin

"We shall not cease from exploration and the end of all our exploring will be to arrive where we started and know the place for the first time."

—T.S. Eliot

Abstract

The Owens Valley, a long, narrow valley along the east side of the Sierra Nevada in east-central California, is the main source of water for the city of Los Angeles. The city diverts most of the surface water in the valley into the Owens River–Los Angeles Aqueduct system, which transports the water more than 200 miles south to areas of distribution and use. Additionally, ground water is pumped or flows from wells to supplement the surface-water diversions to the river–aqueduct system. Pumpage from wells needed to supplement water export has increased since 1970, when a second aqueduct was put into service, and local residents have expressed concerns that the increased pumping may have a detrimental effect on the environment and the native vegetation (indigenous alkaline scrub and meadow plant communities) in the valley. Native vegetation on the valley floor depends on soil moisture derived from precipitation and from the unconfined part of a multilayered ground-water system. This report, which describes the evaluation of the hydrologic system and selected water-management alternatives, is one in a series designed to identify the effects that ground-water pumping has on native vegetation and evaluate alternative strategies to mitigate any adverse effects caused by pumping.

The hydrologic system of the Owens Valley can be conceptualized as having three parts: (1) an unsaturated zone affected by precipitation and evapotranspiration; (2) a surface-water system composed of the Owens River, the Los Angeles Aqueduct, tributary streams, canals, ditches, and ponds; and (3) a saturated ground-water system contained in the valley fill.

Analysis of the hydrologic system was aided by development of a ground-water flow model of the "aquifer system," which is defined as the most active part of the ground-water system and which includes nearly all of the Owens Valley except for the area surrounding the Owens Lake. The model was calibrated and verified for water years 1963–88 and used to evaluate general concepts of the hydrologic system and the effects of past water-management practices. The model also was used to evaluate the likely effects of selected water-management alternatives designed to lessen the adverse effects of ground-water pumping on native vegetation.

Results of the model simulations confirm that a major change in the hydrologic system was caused by the additional export of water from the valley beginning in 1970. Average ground-water pumpage increased by a factor of five, discharge from springs decreased almost to zero, reaches of the Owens River that previously had gained water from the aquifer system began losing water, and total evapotranspiration by native plants decreased by about 35 percent.

Water-management practices as of 1988 were defined and evaluted using the model. Simulation results indicate that increased ground-water pumpage since 1985 for enhancement and mitigation projects within the Owens Valley has further stressed the aquifer system and resulted in declines of the water table and reduced evapotranspiration. Most of the water-table declines are beneath the western alluvial fans and in the immediate vicinity of production wells. The water-table altitude beneath the valley floor has remained relatively constant over time because of hydrologic buffers, such as evapotranspiration, springs, and permanent surface-water features. These buffers adjust the quantity of water exchanged with the aquifer system and effectively minimize variations in water-table altitude. The widespread presence of hydrologic buffers is the primary reason the water-table altitude beneath the valley floor has remained relatively constant since 1970 despite major changes in the type and location of ground-water discharge.

Evaluation of selected water-management alternatives indicates that long-term variations in average runoff to the Owens Valley of as much as 10 percent will not have a significant effect on the water-table altitude. However, reductions in pumpage to an average annual value of about 75,000 acre-ft/yr are needed to maintain the water table at the same altitude as observed during water year 1984. A 9-year transient simulation of dry, average, and wet conditions indicates that the aquifer system takes several years to recover from increased pumping during a drought, even when followed by average and above-average runoff and recharge. Increasing recharge from selected tributary streams by additional diversion of high flows onto the alluvial fans, increasing artificial recharge near well fields, and allocating more pumpage to the Bishop area may be useful in mitigating the adverse effects on native vegetation caused by drought and short-term increases in pumpage.

Analysis of the optimal use of the existing well fields to minimize drawdown of the water table indicates no significant lessening of adverse effects on native vegetation at any of the well fields at the end of a 1-year simulation. Some improvement might result from pumping from a few high-capacity wells in a small area, such as the Thibaut–Sawmill well field; pumping from the upper elevations of alluvial fans, such as the Bishop well field; or pumping in an area surrounded by irrigated lands, such as the Big Pine well field. Use of these water-management techniques would provide some flexibility in management from one year to another, but would not solve the basic problem that increased ground-water pumpage causes decreases in evapotranspiration and in the biomass of native vegetation. Furthermore, the highly transmissive and narrow aquifer system will transmit the effects of pumping to other more sensitive areas of the valley within a couple of years.

Other possible changes in water management that might be useful in minimizing the short-term effects of pumping on native vegetation include sealing well perforations in the unconfined part of the aquifer system; rotating pumpage among well fields; continuing or renewing use of unlined surface-water features such as canals and ditches; developing recharge and extraction facilities in deeper volcanic deposits near Big Pine or in alluvial fan deposits along the east side of the valley; installing additional wells along the west side of the Owens Lake; and conjunctively using other ground-water basins between the Owens Valley and Los Angeles to store exported water for subsequent extraction and use during droughts.

INTRODUCTION

The Owens Valley, a long, narrow valley along the east flank of the Sierra Nevada in east-central California (fig. 1), is the main source of water for the city of Los Angeles. Precipitation in the Sierra Nevada and the Inyo and the White Mountains, which surround the valley, results in an abundance of water flowing into this high desert basin. Because the valley has no surface-water outlet, streams historically have flowed into the Owens Lake, a large saline body of water at the south end of the valley, and evaporated.

Figure 1. Drainage areas and physiographic and cultural features of the Owens Valley and the Mono Basin, California.

In 1913, the Los Angeles Department of Water and Power constructed a 233-mile-long aqueduct to divert surface water from the Owens River to the city of Los Angeles. This supply later was increased to an average export of 330,000 acre-ft/yr by adding diversions of surface water from the Mono Basin, which adjoins the northwestern side of the Owens Valley (fig. 1). The Owens River–Los Angeles Aqueduct system (subsequently referred to in this report as “the river–aqueduct system”) begins in the Mono Basin and extends southward through the Owens Valley.

In 1970, a second aqueduct to Los Angeles was completed, increasing the total maximum capacity to 565,000 acre-ft/yr. The average export subsequently increased to 482,000 acre-ft/yr. This additional supply was obtained by increasing surface-water diversions from the Owens Valley and the Mono Basin, by reducing the quantity of water supplied for irrigation on lands owned by the city of Los Angeles in Mono and Inyo Counties, and by pumping ground water from the Owens Valley into the river–aqueduct system. Ground-water pumpage in the Owens Valley for both export and local use has varied from year to year and is dependent on the availability of surface-water supplies.

Natural discharge of ground water also occurs in the Owens Valley. The principal mechanisms include transpiration by indigenous alkaline scrub and meadow plant communities (Sorenson and others, 1989, p. C2), evaporation from soil in shallow ground-water areas, including the Owens Lake playa, and discharge from springs. Approximately 73,000 acres of the valley floor is covered by alkaline plant communities that are dependent on ground water (Dileanis and Groeneveld, 1989, p. D2). These plant communities collectively are referred to in this report as “native vegetation.” Transpiration from native vegetation and evaporation from soil expend about 40 percent of the average annual recharge to the aquifer system (Hollett and others, 1991, p. B58). The “aquifer system” of the Owens Valley, as defined by Hollett and others (1991, fig. 17), includes nearly all the ground water flowing through the valley, except for lesser quantities flowing (1) beneath the Volcanic Tableland, (2) south of the Alabama Hills, and (3) at depths greater than 1,000 ft below land surface (fig. 1).

In the early 1970's, ground-water levels and the acreage covered by native vegetation were similar to the levels and acreage observed between 1912 and 1921 (Griepentrog and Groeneveld, 1981). Between 1970 and 1978, water levels in many wells declined, and in 1981, a loss of 20 to 100 percent of the plant cover on about 26,000 acres was noted (Griepentrog and Groeneveld, 1981). This reduction was postulated to be a response to increases in ground-water pumpage and changes in surface-water use. Residents of the valley and local businesses that depend on tourism became concerned that the additional export of water since 1970 by the Los Angeles Department of Water and Power was a cause of the degradation observed in the Owens Valley environment.

In addressing the concerns about water, officials of Inyo County filed a lawsuit claiming that the Los Angeles Department of Water and Power needed to prepare an Environmental Impact Report (EIR) on the effects of increased ground-water pumping. In 1970, the California Legislature had enacted the California Environmental Quality Act (CEQA), which required public decision-makers to document the environmental implications of their actions and to seek the reduction or avoidance of significant environmental damage. Although the second aqueduct was operational 6 months prior to the passage of CEQA, Inyo County argued for an injunction on water export until an EIR was prepared and approved. A sequence of litigation ensued (Los Angeles and Inyo County, 1990a, sec. 2.4), and litigation still is pending (1994).

The political impasse became more critical because of an impending reduction in one of the alternative sources of water available to Los Angeles. As a member of the Metropolitan Water District of Southern California, Los Angeles receives part of its water supply from the Colorado River. As a result of a U.S. Supreme Court decree, the allocation of water in the Colorado River was changed, effectively reducing the quantity of water available to Los Angeles. As the physical capability of the Central Arizona Water Project increases and the State of Arizona uses more of its allocation of the Colorado River, Los Angeles will be forced to rely more heavily on water imported from the Owens Valley and northern California (Los Angeles and Inyo County, 1990a, sec. 3.4).

The diversion of surface water from the Mono Basin to Los Angeles via the river–aqueduct system prompted a similar, but separate sequence of litigation. In 1979, the Audubon Society filed a lawsuit against Los Angeles, seeking to reduce the surface-water exports from the Mono Basin and contending that the exports, which had reduced water levels in Mono Lake, were harmful to the environment. This conflict resulted in hydrogeologic studies separate from those initiated in the Owens Valley (Los Angeles Department of Water and Power, 1984b, 1987).

The combination of increased demand for water, reduced regional supplies, and unresolved litigation emphasized the need to better understand the water resources of the Owens Valley. In 1982, the U.S. Geological Survey, in cooperation with Inyo County and the Los Angeles Department of Water and Power, began a series of comprehensive studies to evaluate the geology, water resources, and native vegetation of the Owens Valley. Extensive hydrologic field investigations and numerical ground-water flow modeling conducted over a 6-year period (1982–88) focused on determining the effect of ground-water withdrawals on native vegetation (fig. 2 and table 1). Results of these studies are being used by the Los Angeles Department of Water and Power and Inyo County in preparing the required EIR and in developing a joint ground-water-management plan for the valley (Los Angeles and Inyo County, 1990a, b, c). These studies and the related background materials are discussed more fully by Hollett (1987) and Danskin (1988).

Results of the studies, including a summary, are presented in a U.S. Geological Survey Water-Supply Paper series as the interpretive products become available. The series (Water-Supply Paper 2370), "Hydrology and Soil-Water-Plant Relations in Owens Valley, California," consists of eight chapters as follows:

A. A summary of the hydrologic system and soil-water-plant relations in the Owens Valley, California, 1982–88, with an evaluation of management alternatives;

B. Geology and water resources of the Owens Valley, California;

C. Estimating soil matric potential in the Owens Valley, California;

D. Osmotic potential and projected drought tolerance of four phreatophytic shrub species in the Owens Valley, California;

E. Estimates of evapotranspiration in alkaline scrub and meadow communities of the Owens Valley, California, using the Bowen-ratio, eddy-correlation, and Penman-combination methods;

F. Influence of changes in soil water and depth to ground water on transpiration and canopy of alkaline scrub communities in the Owens Valley, California;

G. Soil water and vegetation responses to precipitation and changes in depth to ground water in the Owens Valley, California; and

H. Evaluation of the hydrologic system and selected water-management alternatives in the Owens Valley, California (this report).

During about the same period as the U.S. Geological Survey studies, Inyo County and the Los Angeles Department of Water and Power conducted a separate cooperative vegetation study that focused on mapping vegetation over most of the valley floor and quantifying the response of native vegetation to changes in water availability (Blevins and others, 1984; Groeneveld and others, 1985). Synthesis of the data obtained from that study, the U.S. Geological Survey studies, and several smaller studies conducted primarily by universities has resulted in an improved understanding of the native vegetation and its dependence on ground water, the geologic setting and its effect on ground-water movement, and the interaction of surface water and ground water.

Purpose and Scope

This report describes the results of an evaluation of the hydrologic system of the Owens Valley, with an emphasis on simulating ground-water flow and predicting the effects of pumping on native vegetation. The development and wise use of water resources are best achieved through a comprehensive understanding of the hydrologic system and its interaction with the geologic setting, native vegetation, and human water-supply needs. This report provides the necessary integration of geologic, hydrologic, and vegetation studies to more fully understand the hydrologic system of the Owens Valley and to evaluate selected water-management alternatives. As such, it relies heavily on findings presented in the companion reports (chapters B, C, D, E, F, and G). A primary purpose of this report is to communicate the specific methods used to evaluate the effects of ground-water pumping on native vegetation and to serve as a guide and technical reference to aid the management of the hydrologic system in the Owens Valley.

The scope of this report includes a thorough literature search and compilation of published and unpublished geologic, hydrologic, and vegetative information. Data collected through September 1988 and reports published through December 1992 were used in preparation of this report, which was approved for publication in March 1995. Much of the vegetative information was collected as a part of a separate study by Inyo County and the Los Angeles Department of

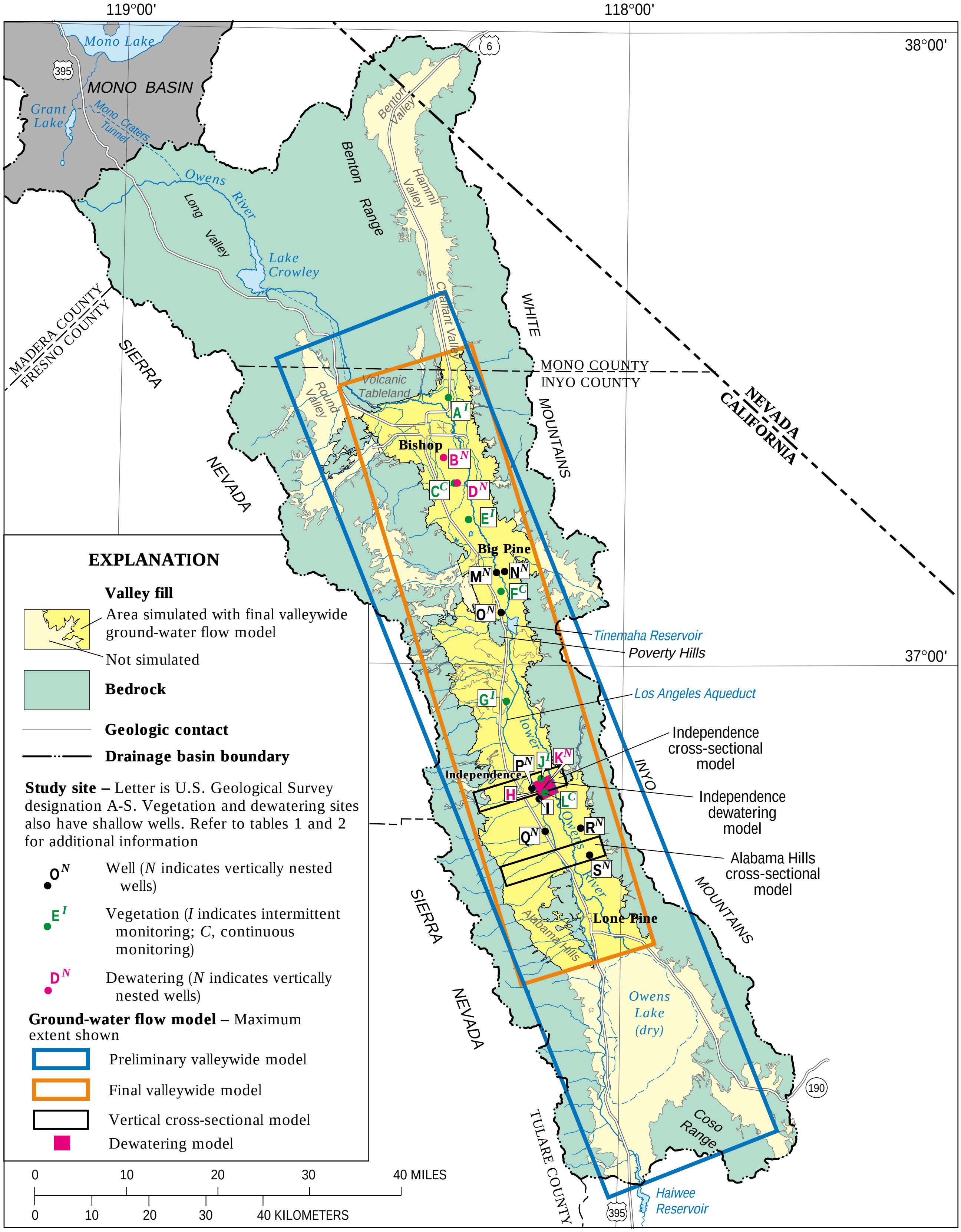

Figure 2. Location of detailed hydrologic investigations and ground-water flow models for the Owens Valley, California, 1982–88.

Table 1. Ground-water and vegetation study sites in the Owens Valley, California, 1982–88

[na, not applicable; nc, not collected; USGS, U.S. Geological Survey. Wells USGS 4 and USGS 11 dropped from study; USGS 9 selected for evapotranspiration monitoring, but used sparingly]

Site designation (figure 2)	Well number	Latitude (north)	Longitude (west)	Site name	Monitoring at site		
					Wells	Evapotrans-piration	Dewater-ing
A	USGS 1	37° 25' 06"	118° 21' 02"	Laws	Shallow	Intermittent	na.
B	USGS 12	37° 19' 25"	118° 21' 31"	Warm Springs slow site	Nested	nc	Slow.
C	USGS 2	37° 17' 02"	118° 20' 15"	Warm Springs weather site	Shallow	Continuous	na.
D	USGS 2A	37° 17' 00"	118° 20' 11"	Collins Road fast site	Nested	nc	Fast.
E	USGS 3	37° 25' 06"	118° 21' 02"	Klondike Lake site	Shallow	Intermittent	na.
F	USGS 5	37° 06' 48"	118° 14' 29"	Big Pine weather site	Shallow	Continuous	na.
G	USGS 6	36° 56' 23"	118° 13' 40"	Blackrock Spring site	Shallow	Intermittent	na.
H	USGS 13	36° 47' 57"	118° 09' 33"	Independence slow site	Shallow	nc	Slow.
I	USGS 9	36° 47' 11"	118° 09' 40"	South Independence site	Shallow	nc	na.
J	USGS 7	36° 49' 07"	118° 09' 28"	North Independence site	Shallow	Intermittent	na.
K	USGS 8	36° 48' 08"	118° 09' 11"	Independence fast site	Nested	nc	Fast.
L	USGS 10	36° 47' 45"	118° 09' 00"	Independence weather site	Shallow	Continuous	na.
M	USGS 14	37° 08' 35"	118° 15' 03"	Steward Lane west	Nested	nc	na.
N	USGS 16	37° 08' 41"	118° 14' 05"	Steward Lane east	Nested	nc	na.
O	USGS 17	37° 04' 47"	118° 14' 26"	Fish Springs	Nested	nc	na.
P	USGS 15	36° 48' 10"	118° 10' 32"	Independence spring field	Nested	nc	na.
Q	USGS 19	36° 44' 07"	118° 08' 55"	Manzanar airport	Nested	nc	na.
R	USGS 18	36° 44' 27"	118° 04' 44"	Reward Road east	Nested	nc	na.
S	USGS 20	36° 41' 54"	118° 03' 39"	Northeast of Alabama Gates	Nested	nc	na.

Water and Power. Additional background for the report included compilation and analysis of streamflow records, ground-water-level measurements, pumping and recharge data, aquifer-test data, drillers' logs, borehole geophysical logs, water-quality data, and reports from the cooperating agencies.

New field studies, which included test drilling, surface and borehole geophysical surveys, and reconnaissance geologic and hydrologic mapping, were used to refine the hydrogeologic knowledge of the valley. New ground-water-level data, particularly from multiple-depth wells, and pumping and aquifer-test data were used to improve the definition of the ground-water flow system. Preliminary ground-water flow models were used to evaluate the adequacy of background data, identify the most sensitive parts of the hydrologic system, and guide the design of the final, valleywide ground-water flow model. This detailed model, which is fully documented in this report, was used to confirm concepts of the surface-water and ground-water systems, identify historical changes in the systems, and evaluate selected water-management alternatives. Finally, this report identifies deficiencies in data and concepts that limit further improvements in the understanding and water management of the Owens Valley.

Previous Investigations

The geology and hydrology of the Owens Valley have been studied extensively since the late 1800's. Because of extensive faulting, glaciation, volcanism, and the occurrence of economic minerals and geothermal resources, the geologic history of the area has been a subject of continuing interest and debate.

Prior to 1900, investigations generally examined the geologic structure of the valley and proposed a geologic history for some of the major features (Walcott, 1897). At the turn of the century, the number of geologic investigations increased. These were related to quantification and understanding of mineral occurrence and to the regional geology (G.E. Bailey, 1902; Spurr, 1903; Trowbridge, 1911; Gale, 1915; Knopf, 1918; Hess and Larsen, 1921). As an economic resource, tungsten continued to be the subject of further geologic studies in the Bishop mining district from 1934 to 1950 (Lemmon, 1941; Bateman and others, 1950). During the late 1950's and early 1960's, there was a resurgence in both detailed and regional geologic investigations. These studies were aimed at further mineral assessment, understanding of crustal evolution and tectonics, and evaluation of geothermal resources along the eastern front of the Sierra Nevada. As a result of these numerous studies, geologic quadrangle maps were completed for nearly all parts of the Owens Valley drainage basin area. In addition, comprehensive regional structural and geophysical studies of the Owens Valley region (Pakiser and others, 1964) and the Bishop area and the Volcanic Tableland (Bateman, 1965) were conducted. Numerous small-scale, topical studies, primarily by universities, concerning geologic history and stratigraphy also have been completed. The geological investigations in the Owens Valley region generally have been supported by strong public interest in volcanic hazards and geothermal energy assessment, plate tectonic implications of the Sierra Nevada, recent volcanism, and seismicity. Selected discussions on regional tectonism in the Owens Valley region are given by Oliver (1977), Stewart (1978), Prodehl (1979), and Blakely and McKee (1985). A comprehensive review and compilation of previous geologic and geophysical studies are given by Hollett and others (1991, fig. 6).

Hydrologic investigations have paralleled geologic studies since the early 1900's because of the abundance of water in an otherwise arid region. Preliminary hydrologic investigations documented conditions in parts of the Owens Valley prior to the diversion of surface water to Los Angeles, which began in 1913 (W.T. Lee, 1906; C.H. Lee, 1912). On the basis of those investigations, the Owens Valley was divided into four ground-water regions: Long Valley, Bishop–Big Pine, Independence, and the Owens Lake (C.H. Lee, 1912, fig. 1). The exceptionally comprehensive and detailed study of the Independence area done by C.H. Lee (1912) included an analysis of both tributary streams and shallow ground water beneath the valley floor. Hydrologic investigations with comparable detail were not completed for other parts of the Owens Valley until after 1970. The availability and use of water in the Owens Valley and the Mono Basin to the north were summarized by Conkling (1921) as part of an evaluation of the potential export of water from the Mono Basin to the Owens Valley. Basic hydrogeologic concepts of the Owens Valley, including the hydrologic relation of ground-water flow from the alluvial fans to lacustrine deposits, the importance of buried members of the Bishop Tuff as water-bearing formations, and the differences in hydrogeologic character of the northern and southern parts of the Owens Valley, were described by Tolman (1937, p. 526).

As demand for water in Los Angeles increased, a more complete understanding of the hydrology of the Owens Valley was needed. Beginning during the drought of the early 1930's and continuing through 1988, large quantities of data on streamflow and ground-water pumpage were collected throughout much of the valley by the Los Angeles Department of Water and Power. Although most of these data have not been published, four summaries are available (Los Angeles Department of Water and Power, 1972, 1976, 1978, 1979). Various technical reports associated with the construction and maintenance of the aqueduct also are available (Los Angeles Board of Public Service Commissioners, 1916; C.H. Lee, 1932; Los Angeles Department of Water and Power, written commun., 1913–87). The quantity of water in the valley that could be used for various recreational uses was calculated by the California Department of Water Resources (1960). As part of the planning and permitting for construction of the second aqueduct and the proposed increase in exported water from the Owens Valley, the California Department of Water Resources (1965, 1966) again evaluated the availability of local water supplies for recreation and local use, and concluded that although considerable surface-water data were available, scant information was available on the occurrence and movement of ground water. Nevertheless, the California Water Rights Board (1963) and the California Department of Water Resources (1967b) concluded that surplus surface water and ground water were available for export.

Litigation that resulted from the additional export of water in the second aqueduct prompted nearly 20 years of investigations related to water use and the effects of increased water exports. The Los Angeles Department of Water and Power (1974b, 1975, 1976, 1978, and 1979) submitted three drafts and two final versions of an EIR although neither final version was accepted by the California Court of Appeals that had jurisdiction in the litigation. Simple regression models were used with some success to quantify the relation between ground-water pumpage, precipitation, and ground-water levels (P.B. Williams, 1978). The state of knowledge as of 1980 about the multi-layer ground-water system was summarized and some of the unresolved hydrogeologic questions were answered by Hardt (1980). Also, in a related study, the additional data required to develop a water-management plan were identified (California Department of Water Resources, 1980). The hydrology of the valley and the effects of ground-water-level declines on native vegetation were the focus of a comprehensive report for Inyo County by Griepentrog and Groeneveld (1981). These results were integrated into a draft EIR by the Inyo County Water Department (1982) and a response by the Los Angeles Department of Water and Power (1982).

Shortly after litigation was halted and the U.S. Geological Survey studies began in 1982, the Los Angeles Department of Water and Power summarized the ongoing investigations of ground water and native vegetation (Blevins and others, 1984) and concluded from a cursory analysis of pumpage and ground-water levels that conditions in 1984 were similar to those in 1970 (Los Angeles Department of Water and Power, 1984a). The importance of the water table in determining the health of native vegetation and the key factors controlling water-table fluctuations were evaluated (An, 1985; Nork, 1987). In a series of reports, the Inyo County Water Department, using regression analysis, correlated pumpage with valleywide runoff; updated surface-water and ground-water budgets; and evaluated storage changes in the river–aqueduct system (Hutchison, 1986a, b, c). The depositional history of the ground-water system near Independence was recognized as important in controlling the effect of pumping on nearby ground-water levels and native vegetation (Walti, 1987). As part of the U.S. Geological Survey studies, prior geologic information was synthesized, hydrogeologic boundary conditions of the ground-water flow system were defined, and recent water-budget data were summarized (Hollett and others, 1991).

Ground-water modeling studies of the Owens Valley began about 1970 with D.E. Williams (1969), who investigated methods for increasing ground-water storage and developed a single-layer ground-water flow model for the Independence region using boundaries defined by C.H. Lee (1912). Later, a deterministic-probabilistic analysis coupled to a ground-water flow model of the Independence area was used to evaluate the effect of uncertainty in model parameters on computed hydraulic heads (Yen, 1985; Guymon and Yen, 1988). In the Bishop area, a ground-water flow model for the period 1938–68 was attempted by the Los Angeles Department of Water and Power (M.L. Blevins, written commun., 1985). Although the ground-water flow model was never successfully calibrated, it did identify important deficiencies in the understanding of the ground-water system. The first valleywide ground-water flow model of the Owens Valley was developed by Danskin (1988), who identified the key hydrogeologic concepts and data that would be required for a more accurate simulation of the ground-water system. A more complete discussion of previous hydrogeologic investigations, as well as a preliminary evaluation of the hydrogeologic system prior to the U.S. Geological Survey studies, is given by Danskin (1988).

These prior geologic and hydrologic studies provided the basis for development of the detailed, valleywide ground-water flow model documented in this report. During the process of developing the final valleywide model, several smaller ground-water flow models of selected areas of the Owens Valley were developed by the Inyo County Water Department (Hutchison, 1988; Hutchison and Radell, 1988a, b; Radell, 1989), and by the Los Angeles Department of Water and Power (1988). More recently, Hutchison (1990) proposed concepts and plans for simulating the entire Los Angeles aqueduct system from the Mono Basin to Los Angeles, including runoff and pumpage contributions to the aqueduct from the Owens Valley.

Investigations of water quality have been included as sections in other reports, but they have not been as prominent as studies of water quantity. This lack of attention probably results because both the surface water and ground water are generally of good quality. Although routine sampling of selected surface-water and ground-water sites is done by the Los Angeles Department of Water and Power, the sampling focuses on constituents related to public health, and results are not published. Discharge from the Tinemaha Reservoir was sampled extensively during water years 1975–85 for chemical and biological constituents, and results were published in annual data reports (U.S. Geological Survey, 1976–82; Bowers and others, 1984, 1985a, 1985b, 1987). In studying the effects of well-field pumpage near the Tinemaha Reservoir, the Los Angeles Department of Water and Power (Roland Triay, Jr., written commun., 1973) recognized the possibility of ground water having different water-quality characteristics on the east and west sides of the valley. Hollett and others (1991) summarized surface-water and ground-water quality throughout the valley and noted the few exceptions of water not suitable for drinking or agricultural uses.

Previous investigations of native vegetation generally were made in conjunction with hydrologic studies (C.H. Lee, 1912; Griepentrog and Groeneveld, 1981; Los Angeles Department of Water and Power, 1972, 1976, 1978, 1979). More recently, however, native vegetation has been a primary subject of study. Rooting characteristics, transpiration processes, and steady-state conditions for shrubs and grasses dependent on shallow ground water have been quantified for the period 1983–86 (Groeneveld, 1986; Groeneveld and others, 1986a, 1986b). Vegetation in most parts of the valley, particularly on the valley floor, has been mapped in great detail using aerial photographs and site visits (R.H. Rawson, Los Angeles Department of Water and Power, written commun., 1988). Also, vegetation in most parts of the valley, particularly on the alluvial fans, has been mapped using remotely sensed multispectral images (M.O. Smith and others, 1990a, b).

Detailed estimates of evapotranspiration from native vegetation during 1984–85 were made using Bowen-ratio, eddy-correlation, and Penman-combination methods (Duell, 1990). The response of native vegetation to changes in water-table elevation was investigated using specially designed dewatering sites (fig. 2) (Dileanis and Groeneveld, 1989). From detailed data collected at these sites, plant stress caused by drought was correlated to osmotic potential within the plant, and the osmotic potential within the plant was correlated to pressure within the soil matrix (Sorenson and others, 1989). The response of different plant species to changes in precipitation and depth to ground water was measured and summarized by Sorenson and others (1991). These detailed field investigations made major contributions to understanding the responses of native vegetation to changes in its environment and the type of monitoring system needed to observe plant stress caused by droughts or ground-water pumpage.

In addition to a lengthy list of scientific investigations—the geology, water resources, vegetation, and political controversies of the Owens Valley have resulted in an abundance of field guides, handbooks, novels, films, and historical accounts describing this unique area. Some of the most comprehensive of these include works by Nadeau (1974), G.S. Smith (1978), Hoffmann (1981), Kahrl (1982), and Reisner (1986).

Methods of Investigation

This evaluation of the hydrologic system of the Owens Valley consists of a comprehensive review of published and unpublished geologic and hydrologic information, a synthesis of water-budget data for the surface-water and ground-water systems, an incorporation of recently developed information about the survivability and water use of native vegetation, and the development and use of a detailed, valleywide ground-water flow model.

A companion report by Hollett and others (1991) presents much of the geologic and hydrologic information that formed the basis of this investigation. Over the 6-year period of investigation, the two studies were highly interdependent and thus minor differences between this report and the companion report reflect knowledge gained since the earlier work was completed. Nearly continuous interaction also was maintained with the technical representatives of Inyo County and the Los Angeles Department of Water and Power. This interaction is most evident in the presence of similar concepts, data, and findings by the several individuals and agencies.

The methods of investigation for this study differ from those of most prior hydrologic investigations of the Owens Valley. Nearly all previous investigations were either site-specific studies, such as aquifer tests, or general studies used to assess the average hydrologic characteristics of the entire valley. Site-specific studies, including those in the Owens Valley, provide necessary local information, but results from different studies may not be hydrologically compatible. For example, a ground-water budget compiled for one part of the valley may not be consistent with the values and boundary conditions assumed in compiling a ground-water budget for an adjacent part. Each budget when viewed separately might seem reasonable, although the budgets are hydrologically incompatible and one of them must be wrong. In contrast, general studies can give insight into the overall effects of water-management decisions, but local effects cannot be determined. For example, a valleywide ground-water budget may be useful for general planning, but it cannot be used to identify the effects of changing pumpage in a small part of the valley.

To help overcome these deficiencies, a valley-wide ground-water flow model was developed. This type of model integrates site-specific data with general valleywide concepts and ensures that both are compatible. The valleywide model played a critical role in simulating the aquifer system, defining many of the surface-water/ground-water relations, and providing a consistent basis to quantify the valleywide hydrologic system. Although detailed discussion of the ground-water flow model is included in a separate section, results of the modeling effort are pervasive throughout this report.

Development of the valleywide ground-water flow model was based on several preliminary models developed by the author (fig. 2; Danskin, 1988) and on models of parts of the Owens Valley developed by others (D.E. Williams, 1969; Yen, 1985; Los Angeles Department of Water and Power, 1988; Hutchison, 1988; Hutchison and Radell, 1988a, b). These other researchers, except for D.E. Williams (1969), worked in separate, but related environments. Their models were based on the general concepts of the ground-water system discussed by Danskin (1988) and Hollett and others (1991), but most used different mathematical formulations or simplifying assumptions. The similarity of results from all the different modeling exercises helped to validate the hydrologic concepts and particular approximations used in the valleywide model. The use of the various ground-water flow models developed as part of the U.S. Geological Survey studies is described in table 2.

Table 2. Characteristics and purpose of ground-water flow models developed for the Owens Valley, California

Model	Characteristics	Purpose	Reference
Half-valley models of Bishop and Independence areas.	Finite-element code; 5 layers; includes Round Valley and Owens Lake.	Identify computer codes, appropriate discretization, and boundaries of ground-water flow system.	Danskin (1988).
Half-valley model of Independence area.	Finite-element code; 2 layers.	Identify the effect of parameter uncertainty on model results.	Yen (1985).
Valleywide (preliminary).	Finite-difference code; 2 layers; includes Round Valley and Owens Lake.	Confirm initial hydrogeologic concepts and ground-water budget. Identify necessary data and concepts.	Danskin (1988); figure 2.
Dewatering.	Variable grid spacing with minimum 10-foot by 10-foot cell; 3 layers.	Determine vertical hydraulic conductivity and leakance.	Figure 2.
Cross-sectional (vertical slice).	Vertical section along parallel ground-water flowlines.	Determine ground-water flow characteristics from alluvial fans to valley floor and effect of depositional facies.	Figure 2.
Valleywide (final).	Finite-difference code; 2 layers; detailed hydrogeology, recharge, and discharge.	Verify regional hydrologic concepts and ground-water budget. Evaluate historical conditions. Predict valleywide effects of possible changes in water management. Provide boundary conditions for well-field models.	Figure 2.
Well field..........	Fine spatial discretization; each model uses 2 or 3 layers and covers from 1/4 to 1/2 of Owens Valley.	Testing and prediction of localized effects.	Hutchison (1988); Hutchison and Radell (1988a); Radell (1989); Los Angeles Department of Water and Power (1988).
Regression........	Statistical regression equations.	Prediction of effects at specific wells; no testing of concepts.	Hutchison (1986d, 1991).

Additional methods of investigation used to evaluate individual hydrologic features include semi-quantitative mapping (depositional patterns, hydrogeologic units, model parameter zones), quantitative areal interpolation (transpiration by native vegetation), linear regression (precipitation, tributary stream recharge, pumpage), and probability analysis (valleywide runoff).

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DESCRIPTION OF STUDY AREA

The Owens Valley is within the Owens Valley drainage basin area (fig. 1) and occupies the western part of the Great Basin section of the Basin and Range Province (Fenneman, 1931; Fenneman and Johnson, 1946). The Great Basin section typically consists of linear, roughly parallel, north–south mountain ranges separated by valleys, most of which are closed drainage basins (Hunt, 1974). The Owens Valley drainage area, about 3,300 mi^2, includes the mountain areas that extend from the crest of the Sierra Nevada on the west to the crest of the Inyo and the White Mountains on the east. Also included are part of the Haiwee Reservoir and the crest of the Coso Range on the south and the crest of the volcanic hills and mountains that separate the Mono Basin and the Adobe Valley from the Long and the Chalfant Valleys and the Volcanic Tableland (fig. 1). The drainage area includes the Long Valley, the headwaters of the Owens River (fig. 1). The Owens Valley ground-water basin extends northward from the Haiwee Reservoir in the south to include Round, Chalfant, Hammil, and Benton Valleys (fig. 1). The Owens Valley aquifer system, defined by Hollett and others (1991) and discussed extensively in this report, includes the main part of the Owens Valley ground-water basin and extends from the south side of the Alabama Hills to the Volcanic Tableland.

Physiography

Physiographically, the Owens Valley contrasts sharply with the prominent, jagged mountains that surround it (fig. 3). These mountains—the Sierra Nevada on the west and the Inyo and the White Mountains on the east—rise more than 9,000 ft above the valley floor and include Mount Whitney, the highest mountain in the conterminous United States. The valley, characterized as high desert rangeland, ranges in altitude from about 4,500 ft north of Bishop to about 3,500 ft above sea level at the Owens Lake (dry).

The valley floor is incised by one major trunk stream, the Owens River, which meanders southward through the valley. Numerous tributaries that drain the east face of the Sierra Nevada have formed extensive coalesced alluvial fans along the west side of the valley. These fans form prominent alluvial aprons that extend eastward nearly to the center of the valley (fig. 3). In contrast, the tributary streams and related alluvial fans on the east side of the valley are solitary forms with no continuous apron. Consequently, the Inyo and the White Mountains rise abruptly from the valley floor. As a result of this asymmetrical alluvial fan configuration, the Owens River flows on the east side of the valley.

The Owens Valley is a closed drainage system. Prior to the construction of the Los Angeles Aqueduct, water that flowed from the mountains as a result of precipitation was transported by the tributary streams to the Owens River in both the Long and the Owens Valleys and then south to the Owens Lake, the natural terminus of the drainage system. The Coso Range, which has a poorly defined circular form, unlike the linear forms of the Sierra Nevada or the Inyo and the White Mountains (Duffield and others, 1980), forms a barrier at the south end of the Owens Valley (fig. 1). The Coso Range prevents downvalley streamflow at the Owens Lake (dry) and blocks any significant natural ground-water outflow from the lower end of the valley. Prior to 20th-century development in the Owens Valley, the Owens Lake was a large body of water that covered more than 100 mi^2 and exceeded a depth of 20 ft. Diversion of streamflow for irrigation uses in the early 1900's and to the river–aqueduct system after 1913, however, altered the water budget of the lake. Evaporation now exceeds inflow except in very wet years, and the lake is presently (1988) a playa.

The river–aqueduct system in the Owens Valley drainage area is defined for purposes of this report as: (1) the Owens River from its headwaters in the Long Valley to the intake of the Los Angeles Aqueduct; (2) the Mono Craters Tunnel and streamflow diverted from the Mono Basin; (3) the Los Angeles Aqueduct from the intake to the Haiwee Reservoir; and (4) all reservoirs along the defined system (fig. 1). The actual Owens River between the aqueduct intake and the Owens Lake (dry), a reach informally referred to as the “lower Owens River,” is not a part of the river–aqueduct system. Flow in the Owens River upstream from the aqueduct intake (fig. 1) is an integral part of the river–aqueduct system and is controlled by releases from Lake Crowley and the Tinemaha Reservoir (fig. 1). Flow in the lower Owens River is dependent on releases from the river–aqueduct system or discharge from the ground-water system.

Several reservoirs along the course of the river–aqueduct system, principally Grant Lake, Lake Crowley, and the Pleasant Valley, the Tinemaha, and the Haiwee Reservoirs (fig. 1), are used primarily to regulate flows and to store water for the river–aqueduct system. Secondary uses include recreation, fishing, and boating.

Geologic Setting

Two principal topographic features represent the surface expression of the geologic setting—the high, prominent mountains on the east and west sides of the valley and the long, narrow intermountain valley floor (fig. 3). The mountains are composed of sedimentary, metamorphic, and granitic rocks that are mantled in part by volcanic rocks and by glacial, talus, and fluvial deposits (fig. 4). The valley floor is underlain by valley fill that consists of unconsolidated to moderately consolidated alluvial fan, transition-zone, glacial and talus, and fluvial and lacustrine deposits (fig. 5). The valley fill also includes interlayered recent volcanic flows and pyroclastic rocks. The valley fill consists mostly of detritus eroded from the surrounding bedrock mountains.

The structure and configuration of the bedrock surface beneath the Owens Valley defines the areal extent and depth of the valley fill and therefore affects the movement and storage of ground water. The bedrock surface beneath the valley is a narrow, steep-sided graben, divided into two structural basins—the Bishop Basin in the north and the Owens Lake Basin in the south—as defined by Hollett and others (1991, fig. 11). The two basins are separated by east–west-trending normal faults, a block of bedrock material (Poverty Hills), and recent olivine basalt flows and cones (Big Pine volcanic field) (fig. 4). The combined effect of the bedrock high created by the normal faults, the upthrown block of the Poverty Hills, and the Pleistocene olivine basaltic rocks forms a “narrows,” which separates the sedimentary depositional systems of the two basins (fig. 4). The Bishop Basin includes Round, Chalfant, Hammil, and Benton Valleys, which are partly buried by the Volcanic Tableland, and extends south to the “narrows,” opposite the Poverty Hills. The deepest part of the bedrock surface in the Bishop Basin is about 4,000 ft below land surface between Bishop and Big Pine. To the south, the bedrock surface rises to approximately 1,000 to 1,500 ft below land surface in the “narrows.” From this saddle, the bedrock surface deepens southward to approximately 8,000 ft below land surface near the Owens Lake (dry). The bedrock of the Coso Mountains forms the south end of the Owens Lake Basin.

During deposition of the valley-fill deposits in the Quaternary Period, the Bishop and the Owens Lake Basins acted as independent loci of deposition, separated by the bedrock high at the “narrows” and, later, by basaltic flows and cones. Both basins supported ancient

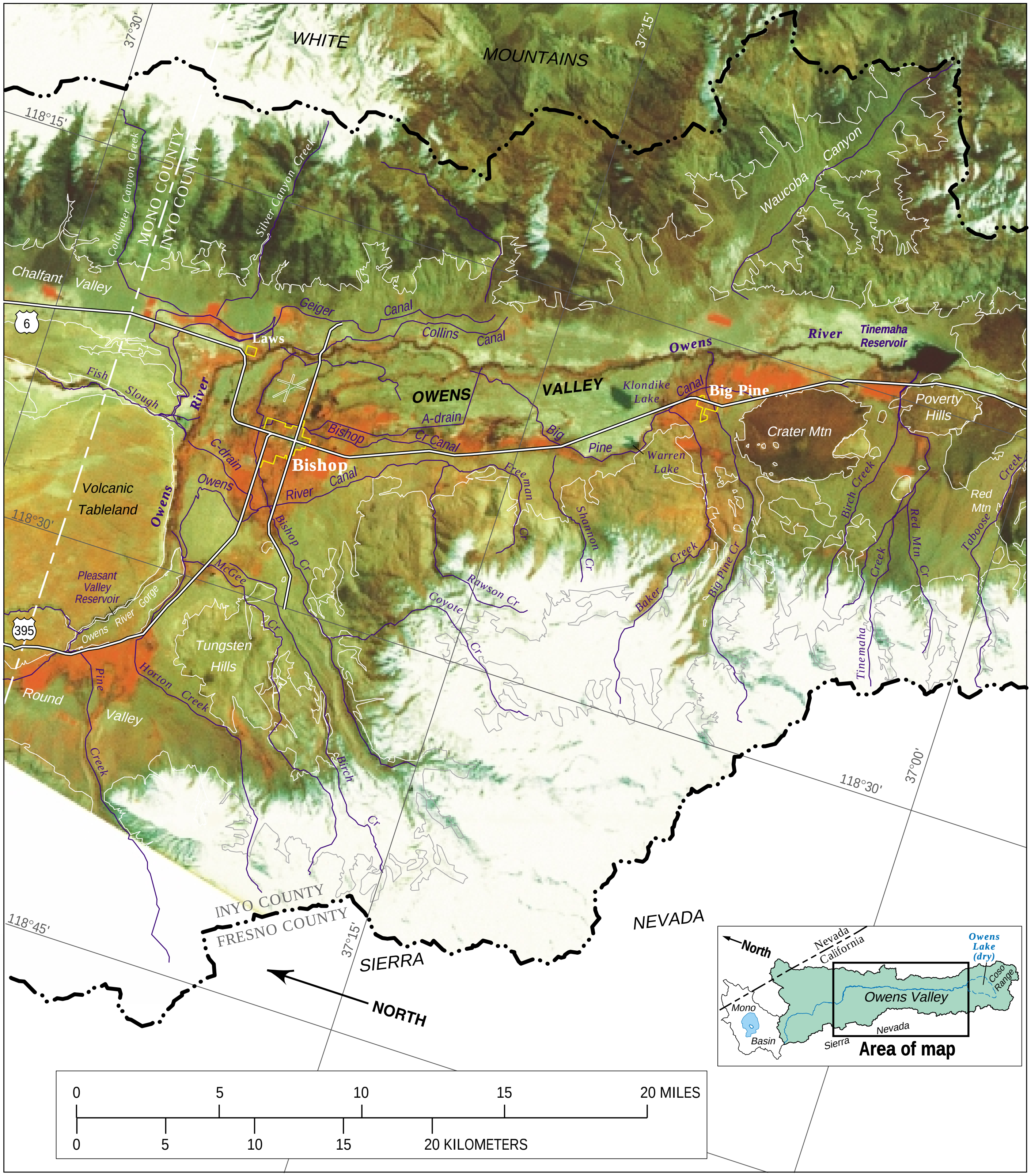


Figure 3. High-altitude infrared imagery showing major geologic, hydrologic, and cultural features of the Owens Valley, California. Image taken May 3, 1983, from Landsat by National Aeronautical and Space Administration. Processing and permission by EROS data center, Sioux Falls, South Dakota.

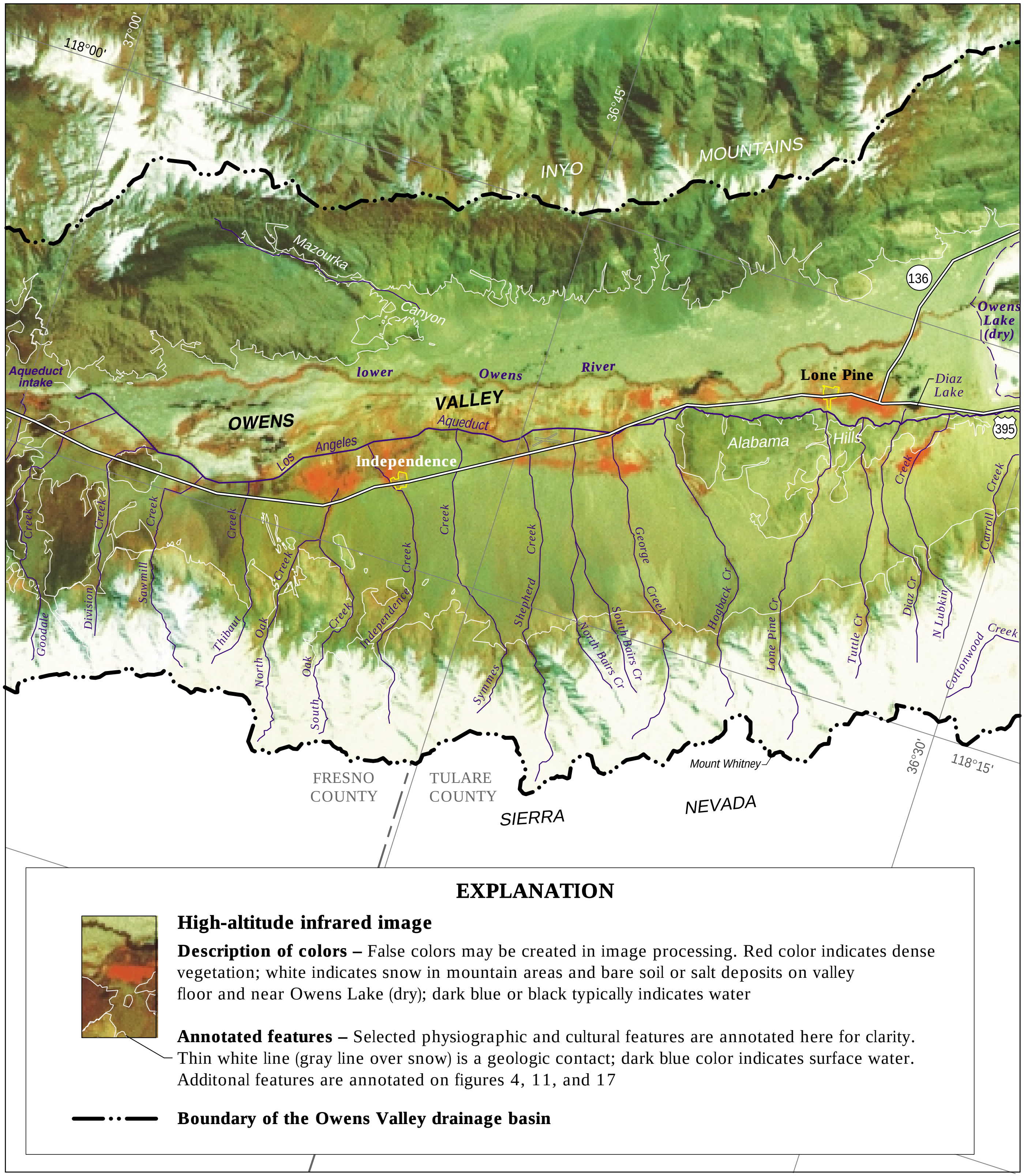


Figure 3. Continued.

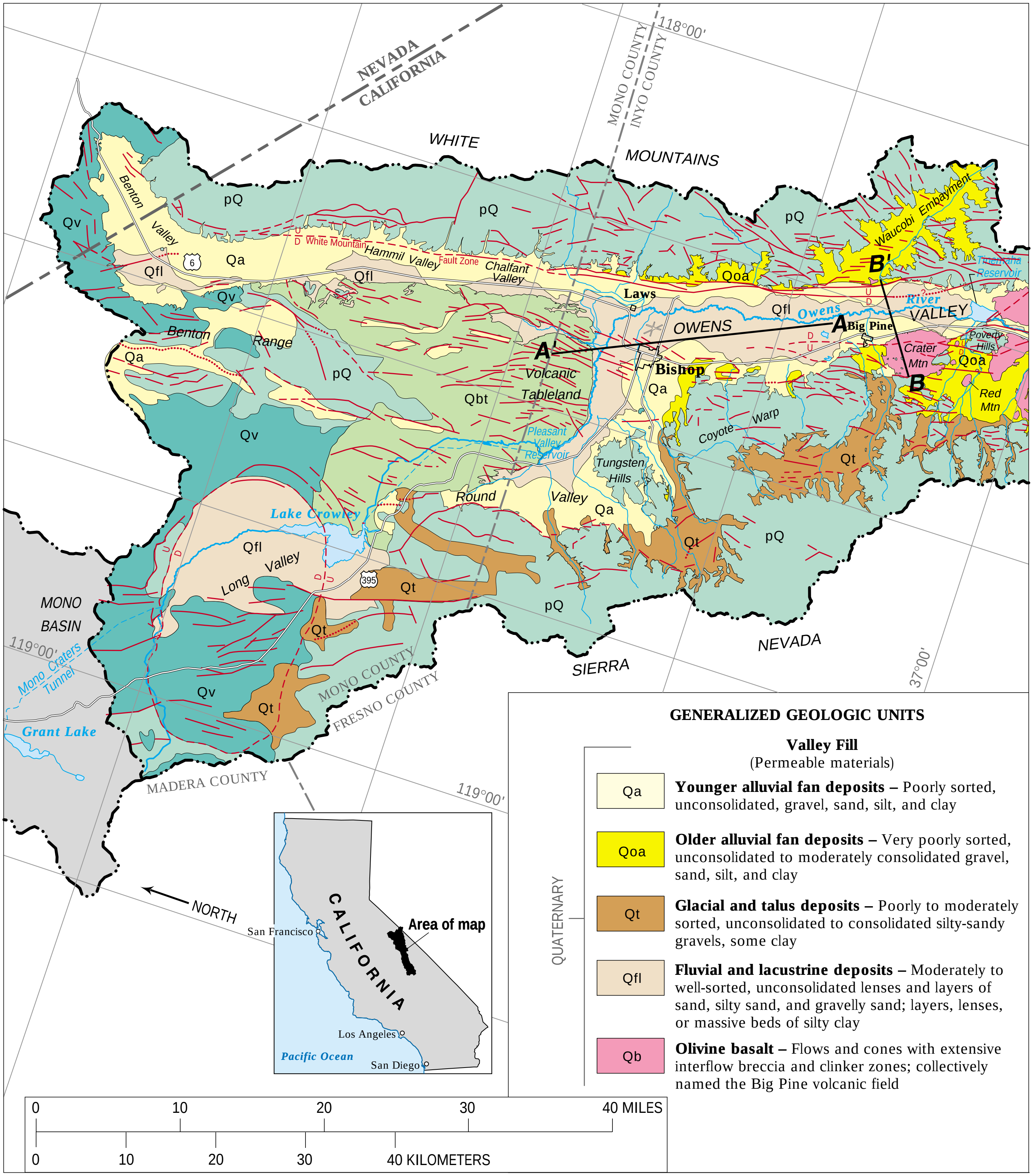
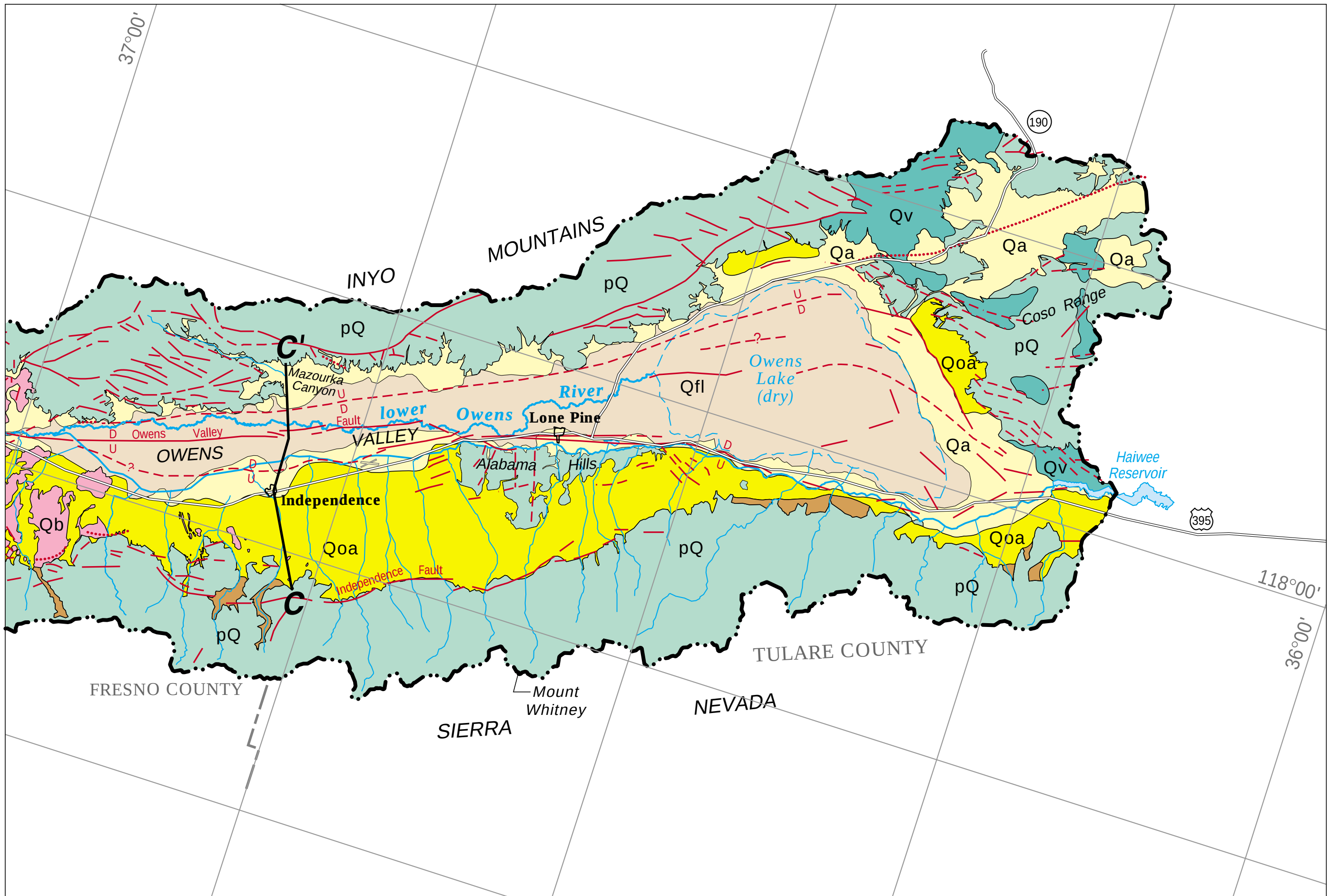


Figure 4. Generalized surficial geology of the Owens Valley drainage basin, California (modified from Hollett and others, 1991).



GENERALIZED GEOLOGIC UNITS

QUATERNARY

Bedrock
(Impermeable or poorly permeable materials, not part of the Owens Valley ground-water basin)

Qbt — **Bishop Tuff –** Bedrock member of the Bishop Tuff, commonly referred to as the Volcanic Tableland where exposed; composed of welded or agglutinated ash and tuff. Impermeable except where fractured; underlain by permeable members of the Bishop Tuff and valley-fill deposits

Qv — **Volcanic flows and pyroclastic rocks, undifferentiated –** Includes rocks of the Coso volcanic field. Storage and transmissive characteristics are largely unknown

PRE-QUATERNARY

pQ — **Undifferentiated sedimentary, metamorphic, and granitic rocks –** Consolidated and impermeable

Geologic contact

U D ?
Fault – Dashed where inferred, dotted where concealed, queried where uncertain. D, downthrown side; U, upthrown side; arrows indicate relative direction of lateral movement

A —— A' **Line of hydrogeologic section** (Shown in figure 5)

Boundary of the Owens Valley drainage basin

Figure 4. Continued.

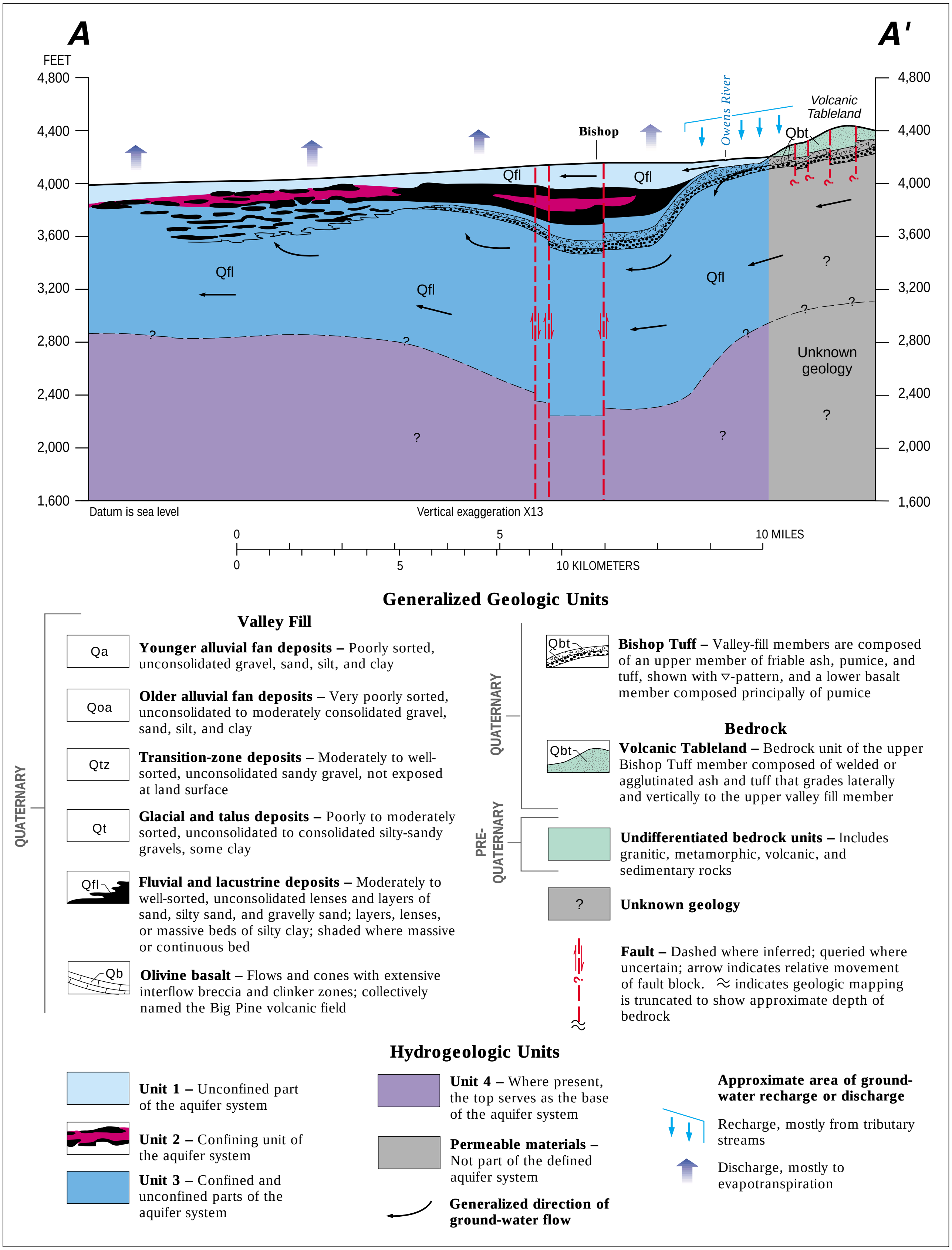


Figure 5. Typical hydrogeologic sections of the Owens Valley, California (modified from Hollett and others, 1991, plates 1 and 2). Sections located on figure 4.

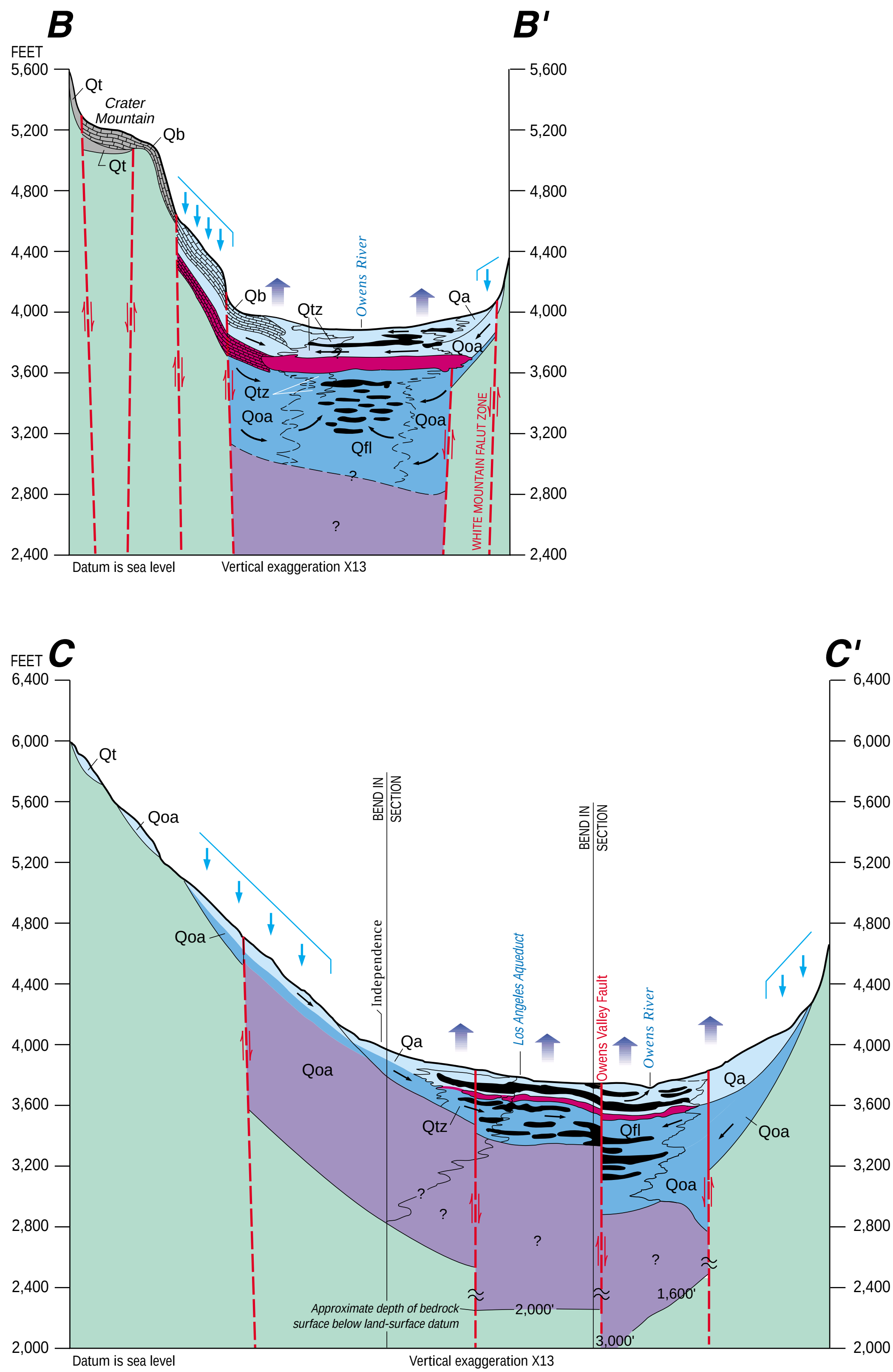


Figure 5. Continued.

shallow lake systems at different times during their geological evolution (Hollett and others, 1991). Lake sedimentation, as evidenced by lacustrine, deltaic, and beach deposits, is interrupted periodically in the geologic section of both basins by fluvial deposits (Hollett and others 1991, fig. 14). Coincident with deposition of lacustrian and fluvial deposits in the center of the basins was alluvial fan deposition and beach, bar, and stream deposition of the transition zones along the margins of each basin. As the mountain blocks were eroded and fronts receded, the alluvial fan deposits thickened. The fans are thicker and more extensive on the wetter, west side of the valley than on the east side and have displaced the Owens River eastward of the center of the valley (figs. 3 and 4).

The valley fill in both basins can be conceptualized by using three depositional models adapted by Hollett and others (1991, fig. 14) from general models suggested by Miall (1981, 1984). The three models are (1) alluvial fan to fluvial and lacustrine plain to trunk river, (2) alluvial fan to lake, and (3) alluvial fan to trunk river to lake margin with localized river-dominated delta. These models depict specific depositional patterns that interrelate and provide a means of subdividing the heterogeneous valley-fill sediments into generalized geologic units with similar lithologic characteristics (fig. 5). The geologic and geophysical signature of each depositional pattern aids in recognizing specific geologic units from field data, and with the aid of the depositional models, the probable occurrence of units can be inferred for parts of the valley were no data are available. The present condition in the Owens Valley is represented by model 1. A more extensive discussion of the geology of the Owens Valley and the surrounding area, as well as a detailed description of the depositional models, is given by Hollett and others (1991).

Climate

The climate in the Owens Valley is greatly influenced by the Sierra Nevada. Precipitation is derived chiefly from moisture-laden airmasses that originate over the Pacific Ocean and move eastward. Because of the orographic effect of the Sierra Nevada, a rain shadow is present east of the crest; precipitation on the valley floor and on the Inyo and the White Mountains and the Coso Range is appreciably less than that west of the crest (figs. 1 and 3). Average precipitation ranges from more than 30 in/yr at the crest of the Sierra Nevada, to about 7 to 14 in/yr in the Inyo and the White Mountains, to approximately 5 in/yr on the valley floor (Hollett and others, 1991, fig. 3). Consequently, the climate in the valley is semiarid to arid and is characterized by low precipitation, abundant sunshine, frequent winds, moderate to low humidity, and high potential evapotranspiration.

Air temperature in the valley also varies greatly. Continuous records from 1931 to 1985 at Bishop and Independence National Weather Bureau stations indicate that daily temperatures can fall to as low as –2°F in winter and can rise to as high as 107°F in summer; these conditions are typical of the semiarid to arid climate in high desert basins. Even within a single day, temperatures can span more than 50°F. Average monthly air temperature ranges from near freezing in winter to more than 80°F in summer. The average monthly air temperatures are generally 1 to 3°F lower in the Bishop area than in the Independence area, but the seasonal pattern and amplitudes are similar (Duell, 1990, fig. 4).

Wind direction, commonly westerly, can be variable depending on the type of storm and the amount of deflection caused by the surrounding mountains. Studies by Duell (1990) during the years 1984 through 1985 indicated that windspeeds in the valley ranged from zero to more than 30 mi/h. Windspeed was found to be highly variable, even within a single day, and no seasonal trend was evident. High windspeeds can occur any time during the year, but generally accompany a winter or a spring storm.

Relative humidity ranges from 6 to 100 percent and averages less than 30 percent during the summer months and more than 40 percent during the winter months (Duell, 1990). Actual water-vapor content in air can be expressed in terms of vapor density. In the Owens Valley, average vapor density in 1984 was about 4.5 g/m^3 and one-half-hour average vapor density ranged from 0.5 g/m^3 (during winter months) to 17.4 g/m^3 (in August) (Duell, 1990). Relative humidity and vapor density of the air are important factors not only in characterizing the climate of the Owens Valley, but also in transporting energy and in determining the type and health of native vegetation in the valley (Miller, 1981).

Vegetation

Vegetation in the Owens Valley is controlled largely by the arid to semiarid conditions, the high salinity of soil in many locations, and the presence of a shallow water table beneath the valley floor. Much of the native vegetation in the valley has been characterized as phreatophytes—defined by Meinzer (1923) as plants that regularly obtain water from the zone of saturation. Recent studies by Sorenson and others (1989, 1991) and Dileanis and Groeneveld (1989) suggest that use of water by "phreatophytes" in the Owens Valley may be more complex. The plants seem to preferentially use infiltration of direct precipitation, which is primarily rainfall. Then, if necessary, the plants use water from the lower part of the soil-moisture zone that is replenished by capillarity from the water table and recharge from overland flow, stream courses, or excess direct precipitation (Groeneveld and others, 1986a; Groeneveld, 1990; Sorenson and others, 1991). Some plants seem to be capable of subsisting on water in a soil-moisture zone that has been denied significant replenishment for as much as 2 or 3 years, including replenishment from the water table (Sorenson and others, 1991). In this way, the "phreatophytes" of the Owens Valley are similar to desert plants growing in xerophytic environments above a water table (Sorenson and others, 1991), and they do not follow the strict definition of a phreatophyte (Meinzer, 1923; Robinson, 1958).

Many of the plants growing on the floor of the Owens Valley, however, do require occasional replenishment of soil moisture from the water table. Extensive field studies done as part of the overall investigation (Sorenson and others, 1991) included an artificial lowering of the water table and a detailed monitoring of the overlying vegetation at selected sites (table 1). Results of the monitoring showed that the native vegetation was affected adversely by the decline in water table. Most plants lost leaves, and some plants, in particular rubber rabbitbrush (*Chrysothamnus nauseosus*), died (Sorenson and others, 1991, p. G35).

Extensive mapping of vegetation during 1983–87 by the Los Angeles Department of Water and Power (R.H. Rawson, written commun., 1988) identified more than 300 plant species in the valley. The dominant species found on the valley floor include salt grass (*Distichlis spicata* var. *stricta*), Alkali sacaton (*Sporobolus airoides*), rubber rabbitbrush (*Chrysothamnus nauseosus*), greasewood (*Sarcobatus vermiculatus*), Nevada saltbush (*Atriplex torreyi*), big sagebrush (*Artemisia tridentata*) and shadscale (*Atriplex confertifolia*). Many of these plants display a high tolerance to salt and can extract soil moisture at osmotic pressures greater than 300 lb/in^2 (Branson and others, 1988). These and other valley-floor species have been grouped into one of four plant communities by Griepentrog and Groeneveld (1981). The groupings were based on the two dominant factors that control plant growth on the valley floor—soil water and salinity. A representative photograph of each of the four plant communities is shown in figure 6, and the main characteristics are listed in table 3. In addition to these general plant communities, many variations are present in different parts of the valley depending on local variations in the physical and chemical characteristics of the soil. The interaction of plants and soil water is described in detail by Kramer (1983) and Slatyer (1967).

As of 1988, a few irrigated fields of alfalfa are maintained on or near the valley floor—for example, in the Bishop area, south of Big Pine, and near Shepherd Creek south of Independence. Additional alfalfa fields are being planned by the Los Angeles Department of Water and Power and Inyo County near Independence in order to mitigate areas of native vegetation adversely affected by pumpage. In many areas of the valley floor, isolated stands of willows or saltcedar trees mark previous ranch houses or water courses. Some previously irrigated lands have reverted to an abundance of rubber rabbitbrush (*Chrysothamnus nauseosus*), an intrusive species (P. J. Novak, Los Angeles Department of Water and Power, oral commun., 1986).

On the sides of the valley, plants subsist solely on direct precipitation or percolation from overland flow or nearby stream courses. The water table in these areas, which are primarily alluvial fans, is many hundreds of feet below land surface and does not provide any water to plants. Large trees are present near the heads of the alluvial fans and along tributary stream channels, and large shrubs and grasses are present along depressions in the land surface that collect small quantities of runoff. Most of the volcanic deposits (fig. 4) are sparsely covered with vegetation that probably subsists solely on direct precipitation because few stream courses have eroded the recent flows. Meadow areas are found in isolated areas west of Crater Mountain and the Alabama Hills. Dense vegetation, shown in red in figure 3, is present along and downslope from springlines caused by faults.

Land and Water Use

Most of the land in the Owens Valley drainage basin area is owned by either the U.S. Government or the Los Angeles Department of Water and Power (Hollett and others, 1991, fig. 5). Considerably less land is owned by municipalities or private citizens.

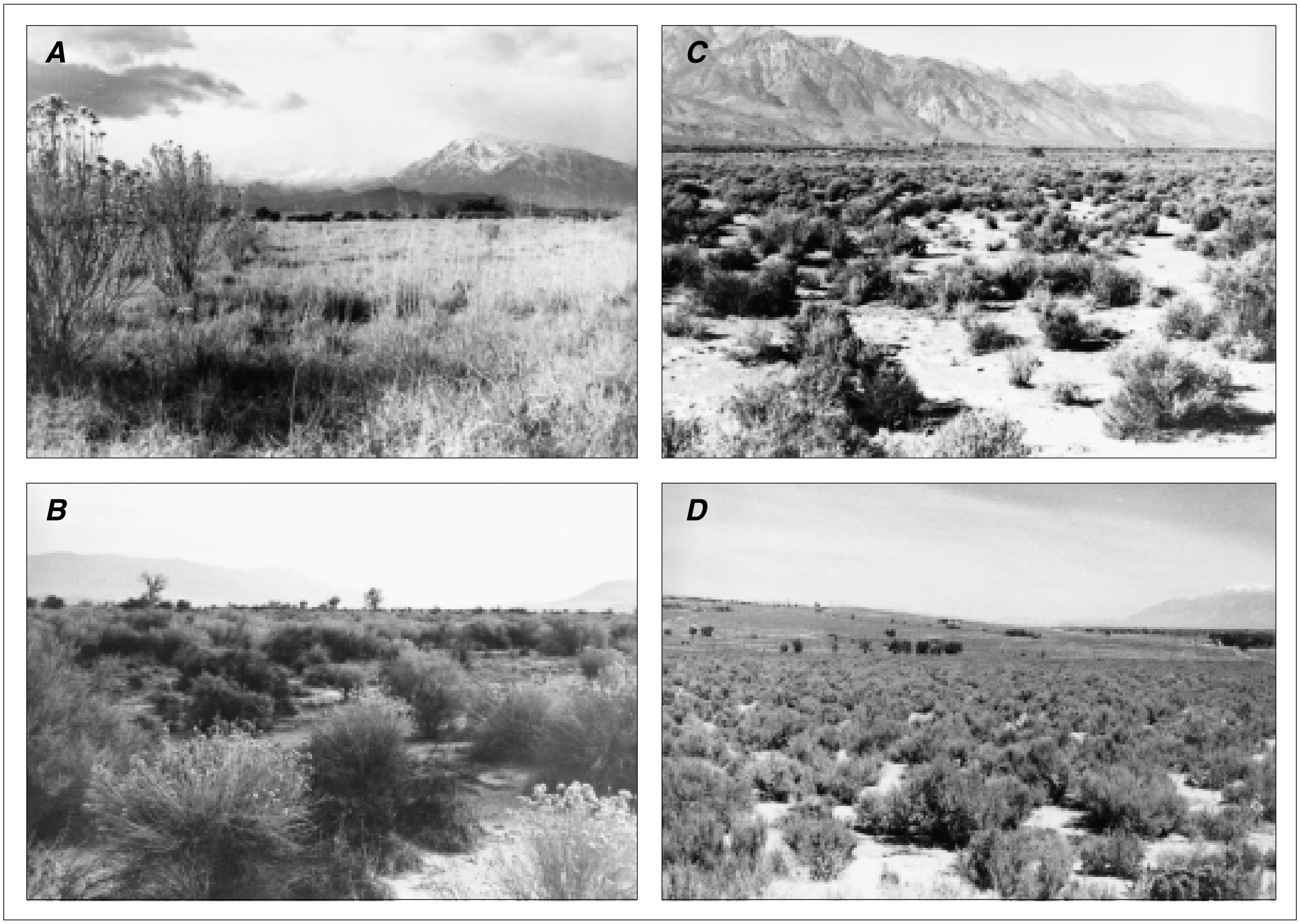


Figure 6. Native plant communities in the Owens Valley, California. ***A,*** High-ground-water alkaline meadow. ***B,*** High-ground-water alkaline scrub. ***C,*** Dryland alkaline scrub. ***D,*** Dryland nonalkaline scrub.

U.S. Government lands, either Forest Service or Bureau of Land Management, are located generally in the mountains and along the edge of the mountains or on the Volcanic Tableland. Of the 307,000 acres owned by the Los Angeles Department of Water and Power in the Owens Valley and the Mono Basin drainage basins, most of the land (240,000 acres) is located on the valley floor of the Owens Valley.

The main economic activities in the valley are livestock ranching and tourism. About 190,000 acres of the valley floor is leased by the Los Angeles Department of Water and Power to ranchers for grazing and about 12,400 additional acres is leased for growing alfalfa pasture. Access to most lands in the mountains and the valley is open to the public, and tens of thousands of people each year utilize the many recreational benefits such as hunting, fishing, skiing, and camping.

Since the early 1900's, water use in the Owens Valley has changed from meeting local needs, such as ranching and farming, to exporting some surface water, to exporting a greater quantity of both surface and ground water. The major historical periods with similar water use are summarized in table 4.

As of 1988, water use within the valley involves both surface-water diversions and ground-water pumping. About 1,200 to 2,000 acre-ft/yr of ground water is supplied to the four major towns in the valley—Bishop, population 10,352; Big Pine, population 1,610; Independence, population 655; and Lone Pine, population 2,062 (U.S. Department of Commerce, 1990). Other in-valley uses of water are for Indian reservations and for stockwater, irrigation of pastures, and cultivation of alfalfa. Fish Springs and Blackrock fish hatcheries rely on ground water, and the Mt. Whitney fish hatchery uses surface water diverted from tributary runoff from the Sierra Nevada. Numerous private wells in the valley, which are not maintained or monitored by the Los Angeles Department of Water and Power, are used mostly for domestic water supply, primarily at Mt. Whitney fish hatchery, on isolated ranches, in Bishop, and on the four small Indian reservations in the valley. The reservations are about 1 mi^2 or less in size and are

Table 3. Native plant communities in the Owens Valley, California

[Adapted from Sorenson and others, 1991]

Native plant community	Species name	Common name	Characteristics
High-ground-water alkaline meadow.	*Distichlis spicata* *Glycyrrhiza lepidota* *Juncus balticus* *Sida leprosa* *Sporobolus airoides*	Saltgrass Wild licorice Wire rush Alkali mallow Alkali sacaton	Vegetation is highly salt tolerant and grows in areas where the water table ranges from land surface to 4 feet below land surface most of the year. Site L (figure 2) is an example.
High-ground-water alkaline scrub.	*Atriplex torreyi* *Sarcobatus vermiculatus* *Chrysothamnus nauseosus* *Suaeda torreyana*	Nevada saltbush Greasewood Rubber rabbitbrush Inkweed	Vegetation is highly tolerant of alkalinity and salinity; generally found where the water table ranges from 3 to 10 feet below land surface. Predominant plant species are phreatophytic and require contact between the rooting zone and the water table. Community also may contain plant species characteristic of the high-ground-water alkaline meadow community. Sites B, H, and K (figure 2) are examples.
Dryland alkaline scrub	*Ambrosia dumosa* *Artemisia spinescens* *Atriplex confertifolia* *Atriplex polycarpa* *Ceratoides lanata* *Hymenoclea salsola* *Lycium cooperi* *Psorothamnus sp.* *Stephanomeria pauciflora*	Burrobush Bud sage Shadscale Allscale Winterfat Cheesebush Peach thorn Dalea Desert milkaster	Vegetation is found where there is no connection between the water table and the rooting zone. Soils are well drained and usually alkaline or saline. Site K (figure 2) has some of these species.
Dryland nonalkaline scrub	*Artemisia tridentata* *Chrysothamnus teretifolius* *Eriogonum fasciculatum* *Ephedra nevadensis* *Purshia glandulosa*	Big sagebrush Green rabbitbrush California buckwheat Nevada squawtea Desert bitterbrush	Vegetation generally is intolerant of high alkalinity or salinity. Found on coarse, well-drained soils, often on alluvial fans that border the valley.

Table 4. Historical periods of similar water use in the Owens Valley, California

Time period	Characteristics of water use
Pre-1913	Prior to the first export of water from the Owens Valley. Installation of canals to dewater the valley floor and supply water for farming and ranching.
1913–69	Export of surface water from the Owens Valley by diversion of the Owens River and tributary streams into the Los Angeles Aqueduct. General decrease of farming and ranching in the valley. Brief periods of pumping to augment local surface-water supplies.
1970–84	Export of some additional surface water. Beginning export of ground water with the addition of new wells and second aqueduct. Major fish hatcheries switch supply from surface water to ground water. Decrease in consumptive use of water by remaining ranches.
1985–88	Continued export of surface and ground water. Design of cooperative water-management plan between Inyo County and the Los Angeles Department of Water and Power. Installation and initial operation of enhancement and mitigation wells.

located near Bishop, near Big Pine, north of Independence, and near Lone Pine (Hollett and others, 1991, fig. 5).

HYDROLOGIC SYSTEM

The hydrologic system of the Owens Valley can be conceptualized as having three parts: (1) an unsaturated zone affected by precipitation and evapotranspiration; (2) a surface-water system composed of the Owens River, the Los Angeles Aqueduct, tributary streams, canals, ditches, and ponds; and (3) a saturated ground-water system contained in the valley fill.

The following evaluation identifies key components of the hydrologic system, describes their interaction, and quantifies their spatial and temporal variations. Discussion of the unsaturated zone is limited to precipitation and evapotranspiration. The evaluation also includes the interaction between the hydrologic system, much of which has been altered by human activity, and the native vegetation; this interaction is the subject of recent controversy and litigation.

For purposes of organization, the surface-water and ground-water systems are presented separately. For items that have both a surface-water and a ground-water component, such as the river–aqueduct system, the discussion is presented in the section entitled “Surface-Water System”; included in this convention is the quantification of ground-water recharge and discharge. All water-budget calculations are for the area defined by Hollett and others (1991) as the aquifer system (figs. 4 and 5). Three key periods—water years 1963–69, water years 1970–84, and water years 1985–88—were used to calculate historical water budgets, to calibrate the valleywide ground-water flow model, to verify performance of the model, and to evaluate past and possible future changes in the surface-water and ground-water systems (table 4). A complete description of the ground-water flow model is included in the section entitled “Ground-Water System.”

Precipitation and Evapotranspiration

Precipitation

The pattern of precipitation throughout the Owens Valley is strongly influenced by altitude, and precipitation varies in a predictable manner from approximately 4 to 6 in/yr on the valley floor to more than 30 in/yr at the crest of the Sierra Nevada on the west side of the valley (Groeneveld and others, 1986a, 1986b; Duell, 1990; Hollett and others, 1991, fig. 3). On the east side of the valley, precipitation follows a similar pattern, but with somewhat lower rates of 7 to 14 in/yr because of the lower altitude of the Inyo and the White Mountains and the rain-shadow effect caused by the Sierra Nevada. Snow, when present on the Sierra Nevada and the White Mountains, commonly is absent on the Inyo Mountains (fig. 3) and the Coso Range. Of the total average annual precipitation in the Owens Valley drainage area, about 60 to 80 percent falls as snow or rain in the Sierra Nevada, primarily during the period October to April. A lesser quantity falls during summer thunderstorms.

As shown in figure 7*A*, the pattern of average precipitation is well defined by the more than 20 precipitation and snow-survey stations that have been monitored routinely, many for more than 50 years (fig. 7*C*). Average precipitation tends to increase from south to north, much as does altitude of the land surface. The strong correlation between altitude and recent mean annual precipitation can be seen in figure 7*B* and can be described by the regression equation,

$$P_i^{RAVE} = 0.00245 \; LSD_i - 3.205 \;, \qquad (1)$$

where

P^{RAVE} is recent mean annual precipitation, in inches per year, on the basis of data for rain years 1963–84;

LSD is altitude of land surface, in feet above sea level; and

i is an index referring to location.

Regression equation 1 was fitted by hand from figure 7*B*, which is a graph of data presented in figure 7*C*, with an emphasis on data from the west side of the valley where the bulk of the more transmissive materials of the ground-water system are present (fig. 4). Predictably, the White Mountain Stations 1 and 2 (sites 19 and 20, fig. 7*B*) fall somewhat below the line. A similar relation that more accurately represents precipitation falling on the east side of the valley could be developed (Lopes, 1988, fig. 3). However, that relation would need to account for the difference between the quantity of precipitation falling on the White Mountains and farther south on the Inyo Mountains (fig. 3)—only part of which seems to be attributable to a difference in altitude of the two mountain ranges.

The time period (rain years 1963–84) used to develop equation 1 was chosen on the basis of two criteria: a nearly complete record for all 20 stations and symmetry with the period selected for calibration of the ground-water flow model. Because very little precipitation occurs in the Owens Valley during July through September, precipitation values for a rain year (July 1–June 30) are virtually identical to values for the corresponding water year (October 1–September 30), which is used to summarize streamflow and ground-water pumpage data. Equation 1 can be generalized for a much longer period of record using data for the U. S. Weather Bureau station at Independence (site 10, fig. 7*C*). Long-term mean annual precipitation at this station, for the 99-year period 1886–1985, is 5.10 in/yr (M.L. Blevins, Los Angeles Department of Water and Power, written commun., 1986)—in comparison with 5.98 in/yr for rain years 1963–84. Scaling equation 1 by the ratio 5.10/5.98 produces an estimate of the long-term mean annual precipitation (P^{LTAVE}) at any location along the west side of the valley. This relation is:

$$P_i^{LTAVE} = \frac{5.10}{5.98} P_i^{RAVE}, \qquad (2)$$

where units of both P^{LTAVE} and P^{RAVE} are inches per year. Precipitation $(P_{i,j}^{AN})$ for a particular year *(j)* can be estimated by using annual precipitation at the Independence station $(P_{Ind,j}^{AN})$ for that same year as a weighting factor:

$$P_{ij}^{AN} = P_i^{LTAVE}\left[\frac{P_{Ind,j}}{5.10}\right], \qquad (3)$$

where

P^{AN} is annual precipitation, in inches per year;

P^{LTAVE} is long-term mean annual precipitation, in inches per year; and

P_{Ind} is annual precipitation at the U.S. Weather Bureau station at Independence, in inches per year.

Estimates of precipitation based on equations 1, 2, and 3 for locations on the valley floor need to be used cautiously because of significant local variability in precipitation (fig. 7*B*).

Although the spatial distribution of mean annual precipitation is well documented and highly correlated with altitude (fig. 7*B*), the spatial distribution of precipitation during specific years is highly variable (Hollett and others, 1991, fig. 3). For example, annual precipitation at Bishop and at Independence was compared for rain years 1935–88 (fig. 8). On average, similar quantities of precipitation fall at Bishop and at Independence (sites 2 and 10, respectively, fig. 7*C*). This similarity occurs because both sites are located on the valley floor and differ in altitude by less than 160 ft. As shown in figure 8, however, it is not uncommon for either site to have more, sometimes much more, precipitation during a particular year. C.H. Lee (1912, p. 15) noted that the high variability in precipitation in the Owens Valley is the result of the three distinct types of storms that occur in the area: (1) north Pacific storms that dominate the rainy season and provide most of the precipitation both to the mountain areas and the valley floor, (2) south Pacific storms that migrate north up the valley (usually a few times each year) generating sporadic precipitation, but favoring neither the Sierra Nevada nor the Inyo Mountains, and (3) local storms which occur during summer and which are an important contributor to total precipitation on the east side of the valley. This annual and seasonal variability makes continued monitoring of precipitation at various sites throughout the valley important—especially because both the quantity and the timing of precipitation on the valley floor play a critical role in the water use and the health of native vegetation (Sorenson and others, 1991). Ground-water recharge from precipitation is highly dependent on the quantity of water used by the overlying vegetation and is discussed in the next section on evapotranspiration.

Evapotranspiration

Evapotranspiration by the dominant native vegetation of the valley had not been measured since the detailed lysimeter studies by C.H. Lee (1912) in the early 1900's. Instead, evapotranspiration was estimated as the residual, a very large residual, in numerous water-budget studies (California Department of Water Resources, 1960, 1965, 1966; Los Angeles Department of Water and Power, 1972, 1976, 1978, 1979; Danskin, 1988). A key element of the cooperative studies begun in 1982 by the U.S. Geological Survey, Inyo County, and the Los Angeles Department of Water and Power

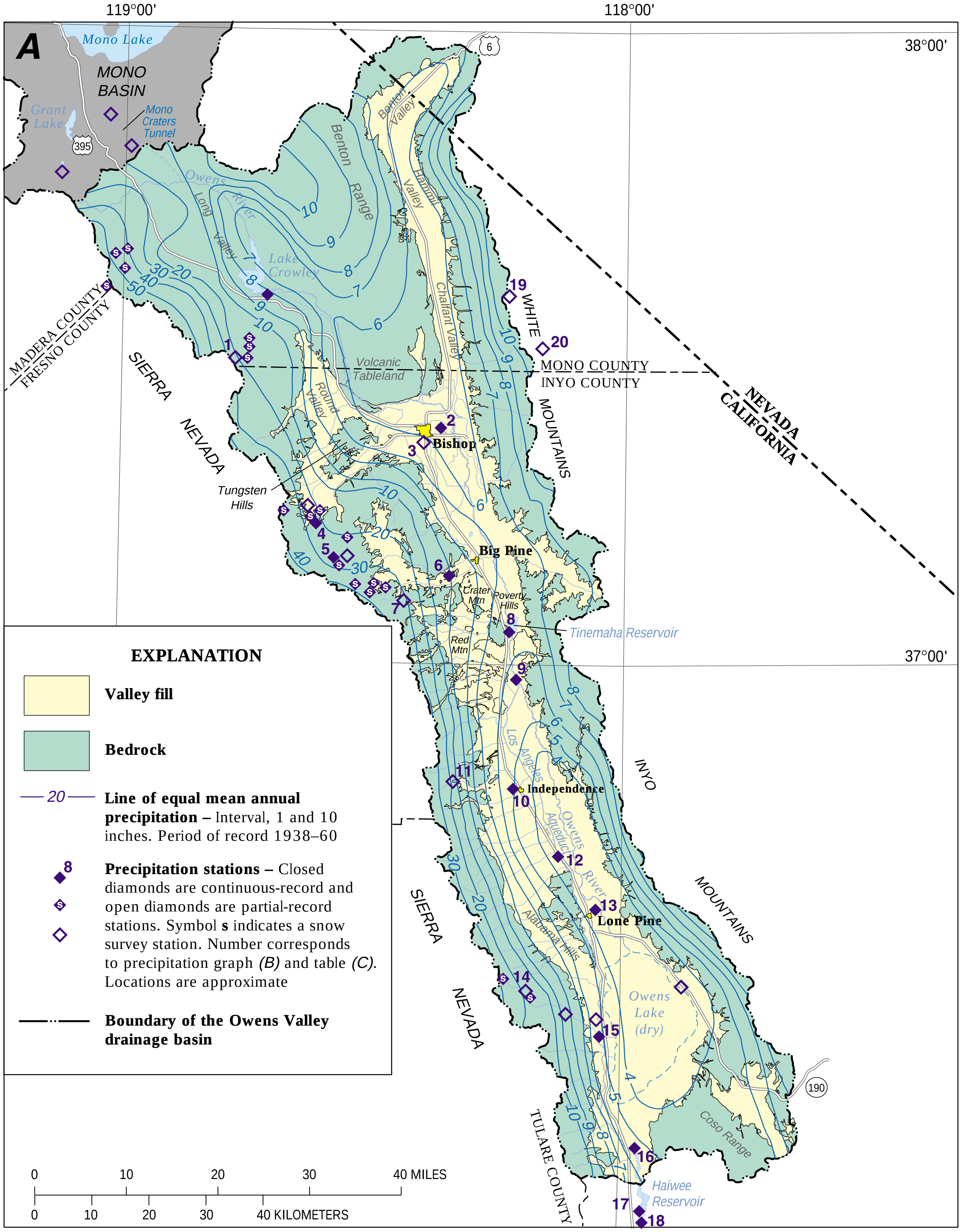
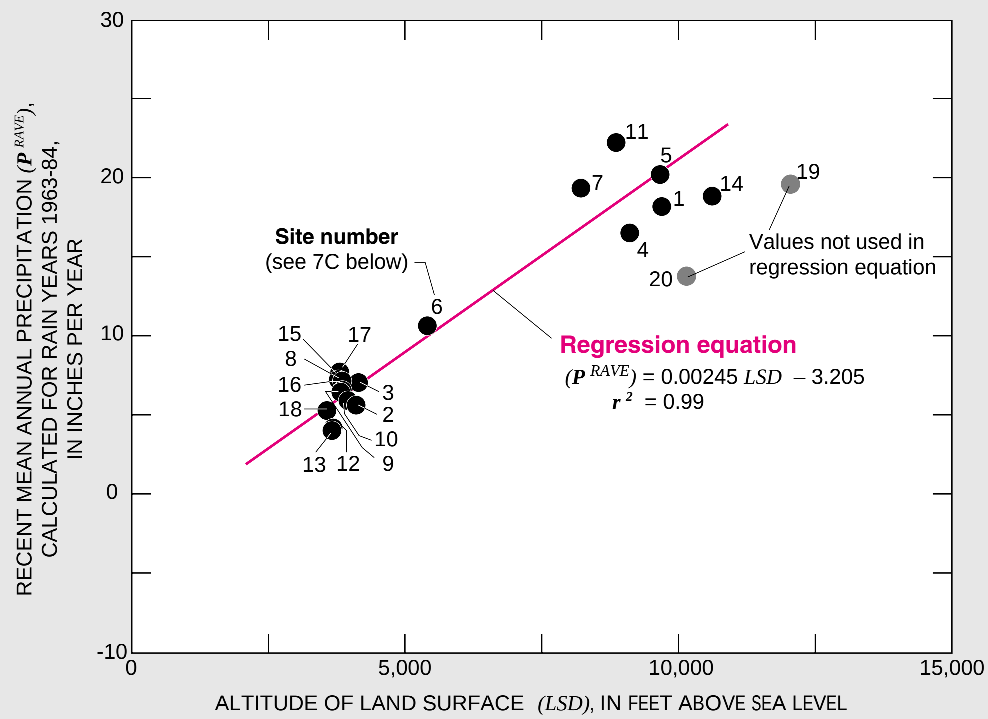


Figure 7. ***(A)*** Contours of mean annual precipitation; ***(B)*** relation between recent mean annual precipitation and altitude; and ***(C)*** data for selected precipitation stations in the Owens Valley, California. Data from E.L. Coufal, Los Angeles Department of Water and Power, written commun., 1986, and oral commun., 1989. Map modified from Stetson, Strauss, and Dresselhaus, consulting engineers, written commun., 1961.



C

Site no.	Station name	Recent mean annual precipitation for rain years 1963-84 (inches/year)	Altitude (feet)	Latitude (north)	Longitude (west)	Period of record (rain years)
1.	Rock Creek at store	18.30	9,700	37°27'	118°45'	1948-88
2.	U.S. Weather Bureau, Bishop	5.67	4,108	37°22'	118°22'	1931-88
3.	Bishop Yard	7.12	4,140	37°21'	118°24'	1931-88
4.	U.S. Weather Bureau, Lake Sabrina	16.56	9,100	37°13'	118°37'	1926-88
5.	U.S. Weather Bureau, South Lake	20.30	9,620	37°11'	118°34'	1926-88
6.	Big Pine Power House No. 3	10.72	5,400	37°08'	118°20'	1927-88
7.	Big Pine Creek at Glacier Lodge	19.45	8,200	37°06'	118°26'	1948-88
8.	Tinemaha Reservoir	7.20	3,850	37°04'	118°14'	1935-88
9.	Los Angeles Aqueduct at intake	6.49	3,825	36°58'	118°13'	1932-88
10.	U.S. Weather Bureau, Independence	5.98	3,950	36°48'	118°12'	1886-1988
11.	Onion Valley	[1]22.77	8,850	36°46'	118°20'	1950-88
12.	Los Angeles Aqueduct at Alabama Gates	4.24	3,675	36°41'	118°05'	1931-88
13.	Lone Pine	4.06	3,661	36°36'	118°04'	1919-88
14.	Cottonwood at Golden Trout Camp	[1]19.04	10,600	36°29'	118°11'	1948-81
15.	Cottonwood Gates	7.31	3,775	36°25'	118°02'	1928-88
16.	North Haiwee Reservoir	6.60	3,850	36°14'	117°58'	1931-88
17.	South Haiwee Reservoir	7.79	3,800	36°08'	117°57'	1924-88
18.	Haiwee Power House	[1]5.34	3,570	36°07'	117°57'	1930-75
19.	White Mountain No. 2	[1]19.73	12,070	37°35'	118°14'	1953-88
20.	White Mountain No. 1	[1]13.94	10,150	37°30'	118°10'	1950-77

[1] Short or discontinuous record.

Figure 7. Continued.

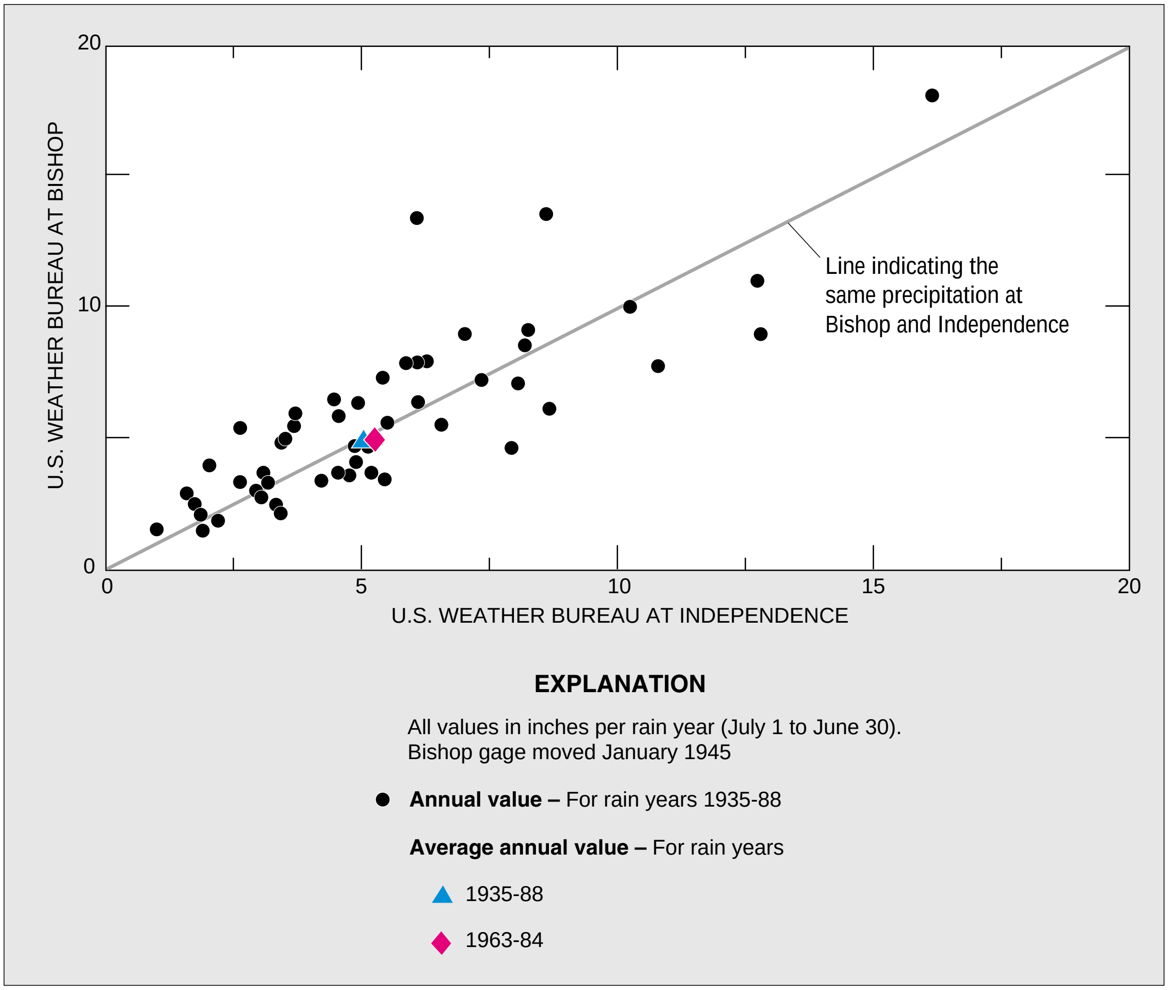


Figure 8. Annual precipitation as Bishop and Independence, California (sites 2 and 10, respectively, in figure 7).

was to measure evapotranspiration at representative vegetation study sites throughout the valley (fig. 2), to relate these data to soil and plant characteristics at the sites, to extend the relations to quantify evapotranspiration throughout the valley, and then to synthesize the results in an analysis of the overall hydrologic system.

As part of the studies of native vegetation, Duell (1990) used micrometeorologic equipment to collect detailed evapotranspiration measurements during 1984–85, a period of relatively abundant surface water and ground water in the valley. The results for high-ground-water alkali meadow and alkali scrub communities (fig. 6 and table 3), which are summarized in table 5, show that evapotranspiration rates on the valley floor ranged from about 12 in/yr to about 45 in/yr depending on the type and percentage of vegetative cover. Assuming that these rates are representative of average conditions on the valley floor where the depth to water is approximately 3 to 15 ft, then evapotranspiration is about 3 to 6 times greater than the quantity of precipitation that is available.

During the same period and at the same sites, Groeneveld and others (1986a, 1986b) collected transpiration measurements from native vegetation using a porometer, an instrument that encloses a few leaves of a plant and measures water-vapor flux (Beardsell and others, 1972). These measurements can be converted to transpiration from an entire site using measurements of total leaf area per plant and plant density per site. Results from Groeneveld and others (1986a, p.117) suggest that most of the evapotranspiration measured by Duell (1990) is transpiration from native vegetation.

Coincident monitoring of soil moisture at the same sites indicated that most of the transpired water came from the unsaturated zone, including that part just below the land surface. These findings indicate that the plants, although originally classified as phreatophytes, might be described more accurately as facultative phreatophytes (Sorenson and others, 1991). However, one common plant on the valley floor, *Atriplex torreyi* (Nevada saltbush) (tables 3 and 5), was found to be restricted to shallow-ground-water zones. The phenology, reproductive processes, and flooding tolerance of *Atriplex torreyi* suggests that it is an obligate

Table 5. Composition of native plant communities, ground-water-level and precipitation data, and range in evapotranspiration estimates at vegetation study sites in the Owens Valley, California

[nc, not collected; —, not available; USGS, U.S. Geological Survey. Vegetation data from the Los Angeles Department of Water and Power (R.H. Rawson, written commun., 1984, 1987); evapotranspiration estimates from Duell, 1990. Estimated annual evapotranspiration from the saturated ground-water system equals average annual evapotranspiration for 1984–85 minus annual precipitation for 1984]

Site designation (figure 2 and table 1)	Well number (table 1)	Native high-ground-water plant community (table 3)	Most common plant types		Total vegetative cover (percent)	Range of ground-water levels for 1984 (feet below land surface)	Annual precipitation for 1984 (inches)	Annual evapotranspiration for 1984–85 (inches)			Estimated annual evapotranspiration from the saturated ground-water system for 1984–85 (inches)
			Common name	Percentage of total vegetation				Maximum	Average	Minimum	
A	USGS 1	Alkaline meadow.	Alkali sacaton	43	42	10.5–15.5	nc	33.6	32.3	30.9	—
			Russian thistle	22							
C	USGS 2	Alkaline meadow.	Saltgrass	34	35	10.2–11.4	5.9	21.8	18.5	14.8	12.6
			Rubber rabbitbrush.	25							
E	USGS 3	Alkaline scrub.	Rubber rabbitbrush.	24	26	10.2–10.9	nc	23.6	23.6	23.5	—
			Alkali sacaton	23							
			Mormon tea	8							
F	USGS 5	Alkaline scrub.	Saltgrass	34	24	8.0–9.0	6.3	18.9	15.2	11.9	8.9
			Greasewood	27							
G	USGS 6	Alkaline meadow.	Saltgrass	30	33	7.1–8.9	nc	25.8	24.3	22.8	—
			Alkali sacaton	13							
			Rubber rabbitbrush.	9							
J	USGS 7	Alkaline meadow.	Nevada saltbush.	29	50	4.7–7.2	nc	33.0	32.0	31.0	—
			Alkali sacaton	21							
			Rubber rabbitbrush.	16							
L	USGS 10	Alkaline meadow.	Saltgrass	20	72	.1–3.9	3.1	44.8	40.5	33.1	37.4
			Alkali sacaton	17							
			Baltic rush	15							

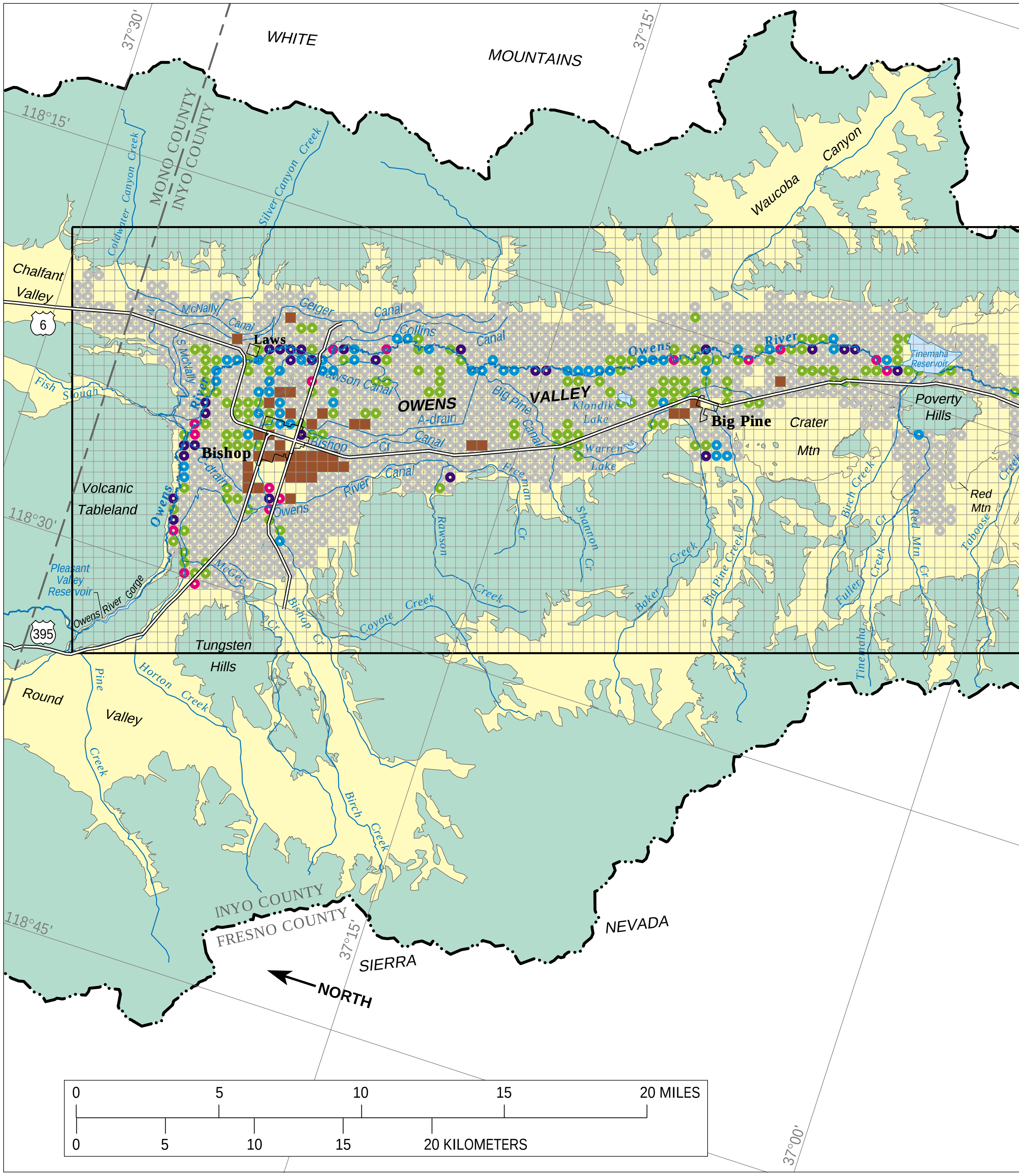


Figure 9. Estimated average annual transpiration by native vegetation during water years 1983–87 in the Owens Valley, California. Map values derived from more than 14,000 point estimates of average annual evapotranspiration obtained from the Los Angeles Department of Water and Power (R.H. Rawson, written commun., 1988).

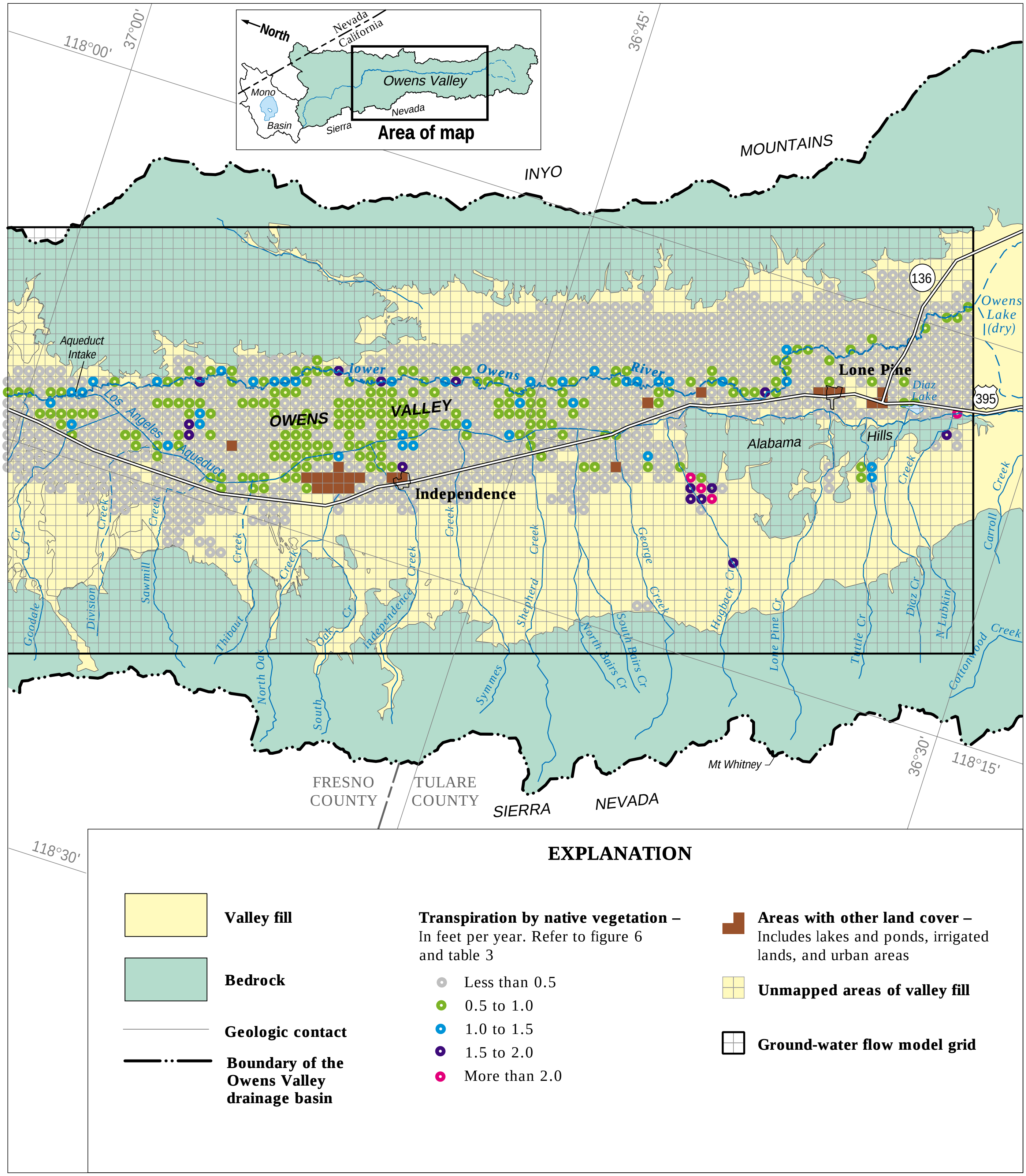


Figure 9. Continued.

phreatophyte in the Owens Valley (Groeneveld, 1985). This species also was found by Dileanis and Groeneveld (1989) to be among the most drought tolerant of the dominant species on the valley floor.

Soil-moisture monitoring also indicated that much of the precipitation that falls on the valley floor (fig. 7) percolates into the near-surface unsaturated zone and later is transpired by native vegetation (Sorenson and others, 1991). Except during brief periods of rainfall or snowmelt, or in areas where the water table is nearly at the land surface, evaporation is not a dominant part of evapotranspiration from the valley floor.

The findings of Duell (1990) and Groeneveld and others (1986a, 1986b; 1987) were combined with extensive mapping of vegetation by the Los Angeles Department of Water and Power (D.D. Buchholz, written commun., 1988) in order to produce an estimate of average annual transpiration from the valley floor (fig. 9). The mapping was done in the field using aerial photographs and land-use maps. Data collected for each mapped area (parcel) included information about plant communities, species composition, percentage of bare ground, and land use. The data were compiled on topographic maps at a scale of 1:24,000 and then digitized into data points every 250 m (820 ft) based on the Universal Transverse Mercator grid system (Synder, 1982, 1985, 1987; Newton, 1985). These individual data points of total evapotranspiration were combined with regressed values of precipitation (fig. 7) and averaged using the grid of the valleywide ground-water flow model. Evaporation from the water table was assumed to be negligible for most areas of native vegetation and to be of minor importance in the limited areas of riparian plants. To maintain consistency with analysis of the same data done by the Los Angeles Department of Water and Power (R.H. Rawson, written commun., 1988), about 50 percent of the precipitation on the valley floor was assumed to evaporate. This percentage is reasonable but has a high degree of uncertainty (D.N. Tillemans, Los Angeles Department of Water and Power, oral commun., 1987). The resulting transpiration values for native vegetation are summarized in figure 9.

Transpiration by native vegetation from most of the valley floor is less than 1.0 ft/yr, and transpiration from much of the valley floor, particularly along the east side of the valley, is less than 0.5 ft/yr. These estimates are generally lower than previous estimates of transpiration by native vegetation (R.H. Rawson, Los Angeles Department of Water and Power, written commun., 1986) and are lower than calculated values obtained by subtracting a percentage of precipitation from estimated evapotranspiration (Danskin, 1988; C.H. Lee, 1912). This reduction in transpiration is consistent with the lower values of valleywide evapotranspiration calculated by Hollett and others (1991, table 6) in comparison with values from prior studies (C.H. Lee, 1912; Los Angeles Department of Water and Power, 1974b, 1975, 1976, 1978, 1979; Danskin, 1988). These prior studies quantified transpiration or evapotranspiration for periods before the additional diversions of water from the valley in 1913 and 1970. The additional diversions reduced the quantity of water available for transpiration by native vegetation.

In a few areas of the valley floor, infiltration to the water table may occur during part of the year. For example, in meadow areas, such as east of Independence, the water table is nearly at the land surface in winter months and some precipitation likely percolates to the saturated ground-water system. However, the high annual evapotranspiration rates observed by Duell (1990) in those areas—for example, at site L (table 5 and fig. 2)—indicate that the meadow areas are net discharge points from the ground-water system. Any water that infiltrates in winter is removed in summer. In other parts of the valley floor, such as small alkali flats or patches that are almost devoid of vegetation (fig. 3), net infiltration may result during unusually wet periods when rainfall or local runoff exceeds evapotranspiration. The quantity of infiltration from such microplaya areas, however, is very small because of extremely slow infiltration rates through these characteristically fine-textured, deflocculated soils (Groeneveld and others, 1986a). As in the meadow areas, wet conditions generally are present only in winter, and all the water infiltrated (perhaps with some additional ground water) is removed in summer when evapotranspiration rates increase markedly (Duell, 1990, fig. 24). For the area of the valley fill simulated by the valleywide ground-water flow model (fig. 4), average net discharge by evapotranspiration from the saturated aquifer system was estimated to decrease from 112,000 acre-ft/yr for water years 1963–69 to 72,000 acre-ft/yr for water years 1970–84.

In the alluvial fan deposits and volcanic rocks, the depth to water ranges from many tens to many hundreds of feet. Extraction of water by plants from the saturated ground-water system is not possible, and the plants subsist on direct precipitation. Because the precipitation rates are higher than those on the valley floor (fig. 7), some recharge to the ground-water system may occur. However, the density of vegetation also is greater at the heads of fans and may balance the increased precipitation (M.O. Smith and others, 1990a, b). Any precipitation that does infiltrate past the root zone eventually recharges the saturated ground-water system, probably at a relatively uniform rate, and flows toward the center of the valley. About 16 percent of the direct precipitation on the alluvial fan areas was estimated to recharge the ground-water system (C.H. Lee, 1912). This percentage equates to about 1.25 to 2.75 in/yr of recharge. Ground-water simulation studies suggest that these rates may be too high and that maximum values of from 0.5 to 1.0 in/yr are more likely (Danskin, 1988; Hutchison, 1988; Hutchison and Radell, 1988a, b; Los Angeles Department of Water and Power, 1988). An investigation of recharge from precipitation in other arid regions indicated that recharge did not occur until precipitation rates exceeded about 8 in/yr (Mann, 1976, p. 368). The area of valley fill in the Owens Valley that has an average precipitation of more than 8 in/yr is limited to the higher attitudes, mostly along the western alluvial fans (fig. 7*A*). On the basis of these findings, equation 2 was used to calculate 5 percent of the average annual precipitation for values greater than 8 in/yr (fig. 7*A*). For the defined aquifer system (fig. 2), the total quantity of infiltration from direct precipitation, which occurs primarily on the alluvial fan deposits and volcanic rocks, averages approximately 2,000 acre-ft/yr. Detailed evapotranspiration data on the alluvial fans will help to confirm this approximation.

These conclusions about recharge from precipitation and discharge from evapotranspiration are in general agreement with the assumptions made in previous water-budget studies by C.H. Lee (1912), Los Angeles Department of Water and Power (1972, 1976, 1978, 1979), Hutchison (1986b), and Danskin (1988) and in soil-moisture studies by Groeneveld (1986), Groeneveld and others (1986a, 1986b), and Sorenson and others (1991). All the studies assume that a minimal quantity of recharge occurs from direct precipitation on the valley floor, generally less than 10 percent of the average precipitation rate, and that a somewhat greater potential for recharge from direct precipitation is present on the alluvial fan deposits and volcanic rocks.

An important difference between this study and those done prior to 1983, when the fieldwork and model simulations for this study were begun, is the assumption of a lower infiltration rate from direct precipitation on the alluvial fan and volcanic areas. The lower infiltration rate multiplied by the large size of the affected area results in a substantially lower value of recharge to the saturated ground-water system. This decrease in recharge is matched by a similar decrease in discharge by evapotranspiration from the valley floor. In general, average evapotranspiration rates measured by Duell (1990) and transpiration rates measured by Groeneveld and others (1986a, 1986b) are lower than previous estimates and support the assumption of lower recharge rates from direct precipitation. Because of the recent collection of detailed evapotranspiration data on the valley floor, recharge from direct precipitation on the alluvial fan deposits and volcanic rocks is now the least quantified part of a valleywide ground-water budget. Additional evapotranspiration measurements or soil-moisture studies in these areas would help to confirm present water-budget estimates.

Surface-Water System

The primary source of surface water in the Owens Valley is precipitation that falls on the slopes of the Sierra Nevada. Rivulets from the resulting runoff form tributary streams that flow down mountain canyons, across the alluvial fans, and out onto the valley floor. In the Bishop Basin, the tributary streams are captured by the trunk stream of the valley, the Owens River, which has its headwaters in the Long Valley (fig. 1). In the Owens Lake Basin, approximately 5 mi downstream (south) from the Tinemaha Reservoir, the Los Angeles Department of Water and Power diverts nearly all flow in the Owens River into the Los Angeles Aqueduct. The upstream end of the Los Angeles Aqueduct is referred to as the “intake” (fig. 1). Any water not diverted into the aqueduct continues to flow east of the aqueduct in the natural channel of the lower Owens River. South of the intake, additional tributary streams along the west side of the valley are diverted into the aqueduct. The combined flows of the river–aqueduct system and the diverted tributary streams are routed south out of the valley through the Haiwee Reservoir. Any water remaining in the lower Owens River flows into the Owens Lake (dry) and evaporates. The entire Owens Valley drainage basin area is shown in figure 1, and photographs of major surface-water features in the Owens Valley are shown in figure 10. The river–aqueduct system, major tributaries, and selected gages within the area of concentrated study are shown in figure 11.

Surface-water monitoring in the Owens Valley is much more complete than in most basins in the United States. More than 600 continuous gaging stations are monitored by the Los Angeles Department of Water and Power in order to measure inflow to the valley from tributary streams and to document water use within the valley. Most of the continuous gages monitor minor flows in canals and ditches in the Bishop area to ensure that sufficient water is delivered to ranching operations. Many of the gages are on the tributary streams and are used to monitor inflow to the valley and to schedule diversions to the river–aqueduct system.

Monitoring of the river–aqueduct system and the lower Owens River is less well documented. Discharge in the river–aqueduct system is gaged routinely at only three locations (the Pleasant Valley Reservoir, the Tinemaha Reservoir, and near the Alabama Hills); discharge in the lower Owens River is gaged routinely at only two locations (immediately below the intake to the aqueduct and at Keeler Bridge) (fig. 11). For other locations, "calculated" discharge values are made by using measured and estimated inflow, outflow, and water use. These calculated values are subject to a large roundoff error as a result of the addition and subtraction of many numbers.

Tributary Streams

Tributary streams provide nearly 50 percent of the surface-water inflow to the Owens Valley; the Owens River and ungaged runoff provide the rest (M.L. Blevins, Los Angeles Department of Water and Power, written commun., 1988; Hollett and others, 1991, tables 2 and 3). Many of the natural channels of tributary streams have been modified by the Los Angeles Department of Water and Power for operation of the river–aqueduct system. Diversion structures have been installed in nearly all streams, and the natural channels of some streams, such as Goodale Creek, have been straightened. Other streams, namely Bishop Creek, Thibaut Creek, Division Creek, and Coldwater Canyon Creek, are diverted to pipes for much of their length (fig. 11). In the Bishop Basin, most of the tributary streamflow that reaches the valley floor is diverted to canals that distribute water for agricultural uses, wildlife habitat, or ground-water recharge. Excess water is returned to the canals and eventually to the Owens River.

Since 1913, little or no tributary streamflow in the Owens Lake Basin has reached the lower Owens River in average-runoff years. During wet years when surface water is abundant, however, tributary streamflow exceeds the capacity of the river–aqueduct system, and some of the tributary streamflow either is diverted onto the alluvial fans to recharge the ground-water system or is conducted in pipes over the top of the aqueduct and then flows across the valley floor toward the lower Owens River.

Tributary streamflow in the Owens Valley is gaged continuously by the Los Angeles Department of Water and Power at more than 60 sites on 34 tributaries. The sites, many constructed originally during prior investigations by the U.S. Geological Survey in the early 1900's (W.T. Lee, 1906; C.H. Lee, 1912), are equipped with concrete channel controls, stilling wells, and automatic data recorders. On most of the tributaries, at least two sites are gaged. Typically, one gage is located near the base of the mountains, and the other is located close to the river–aqueduct system. The location of these gages is shown in figure 11. The station names and abbreviations are given in table 6. A complete record at the sites, except for occasional short gaps, is available for water years 1935–88 (M.L. Blevins, Los Angeles Department of Water and Power, written commun., 1988).

Mean annual discharge for tributaries measured at base-of-mountains gaging stations ranged from 51 to 67,748 acre-ft (Hollett and others, 1991, table 2). Tributaries having the greatest flow include Bishop, Big Pine, Cottonwood, Independence, and Lone Pine Creeks (fig. 11). Mean annual discharge for most streams was about 6,000 acre-ft. Annual flow is highly variable, and maximum and minimum mean annual discharge values for individual streams typically differ by a factor of 10 or more. Although useful as a guide, annual values (Hollett and others, 1991, table 2) tend to mask periods of even higher or lower flows occurring within a single year. Variability in streamflow among tributaries results from differences in size of the drainage basin, quantities of precipitation per basin, and

Figure 10. Major surface-water features in the Owens Valley, California. ***A,*** Owens River just north of Bishop looking west toward the Tungsten Hills and Round Valley (photograph taken winter 1988). ***B***, Los Angeles Aqueduct looking north toward the Sierra Nevada (photograph taken winter 1985). ***C,*** lower Owens River east of the Alabama Hills (photograph taken summer 1988). ***D,*** Owens Lake viewed from alluvial fan south of the Alabama Hills (photograph taken spring 1986).

rates of infiltration. In general, tributary streamflow increases from south to north much as precipitation does (fig. 7).

As expected from precipitation patterns (fig. 7*A*), discharge from tributary streams on the east side of the valley is much less than discharge on the west. Only two streams produce a reliable source of water each year—Coldwater Canyon and Silver Canyon Creeks (fig. 11), and these streams typically discharge less than 2,000 acre-ft/yr. Farther south, Mazourka Creek was monitored by the U.S. Geological Survey continuously during 1961–72 (Mazourka Creek near Independence, USGS station 10282480). Zero flow was recorded all days except during two brief periods in 1967 and 1969. During these periods, discharge peaked at more than 1,300 and 600 ft^3/s, respectively. This type of large, infrequent runoff is characteristic of other basin-and-range valleys (Fenneman, 1931, p. 329) and probably is typical of most stream drainages along the east side of the Owens Valley south of Silver Canyon Creek (fig. 11).

Percent Valleywide Runoff

Total runoff for the Owens Valley is highly correlated with flow in individual tributary streams and has been calculated by the Los Angeles Department of Water and Power (M.L. Blevins, written commun., 1988; table 5) for water years 1935–88. Total runoff is defined as the sum of inflow from the Owens River at the Pleasant Valley Reservoir, measured and estimated inflow from tributary streams, and estimated mountain-

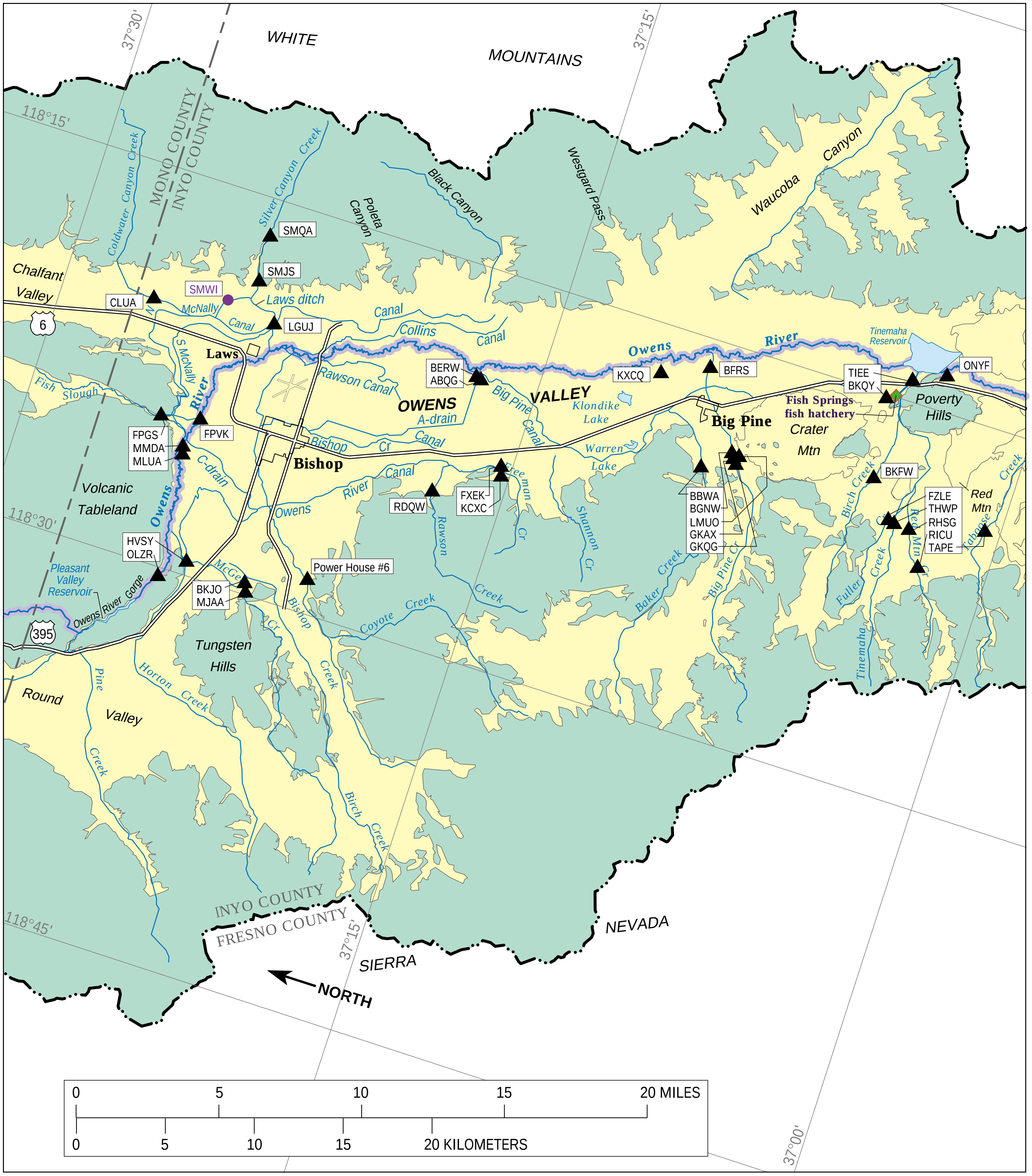


Figure 11. Location of the Owens River–Los Angeles Aqueduct system, the lower Owens River, tributary streams, lakes, reservoirs, spillgates, major gaging stations, and selected pumped wells in the Owens Valley, California.

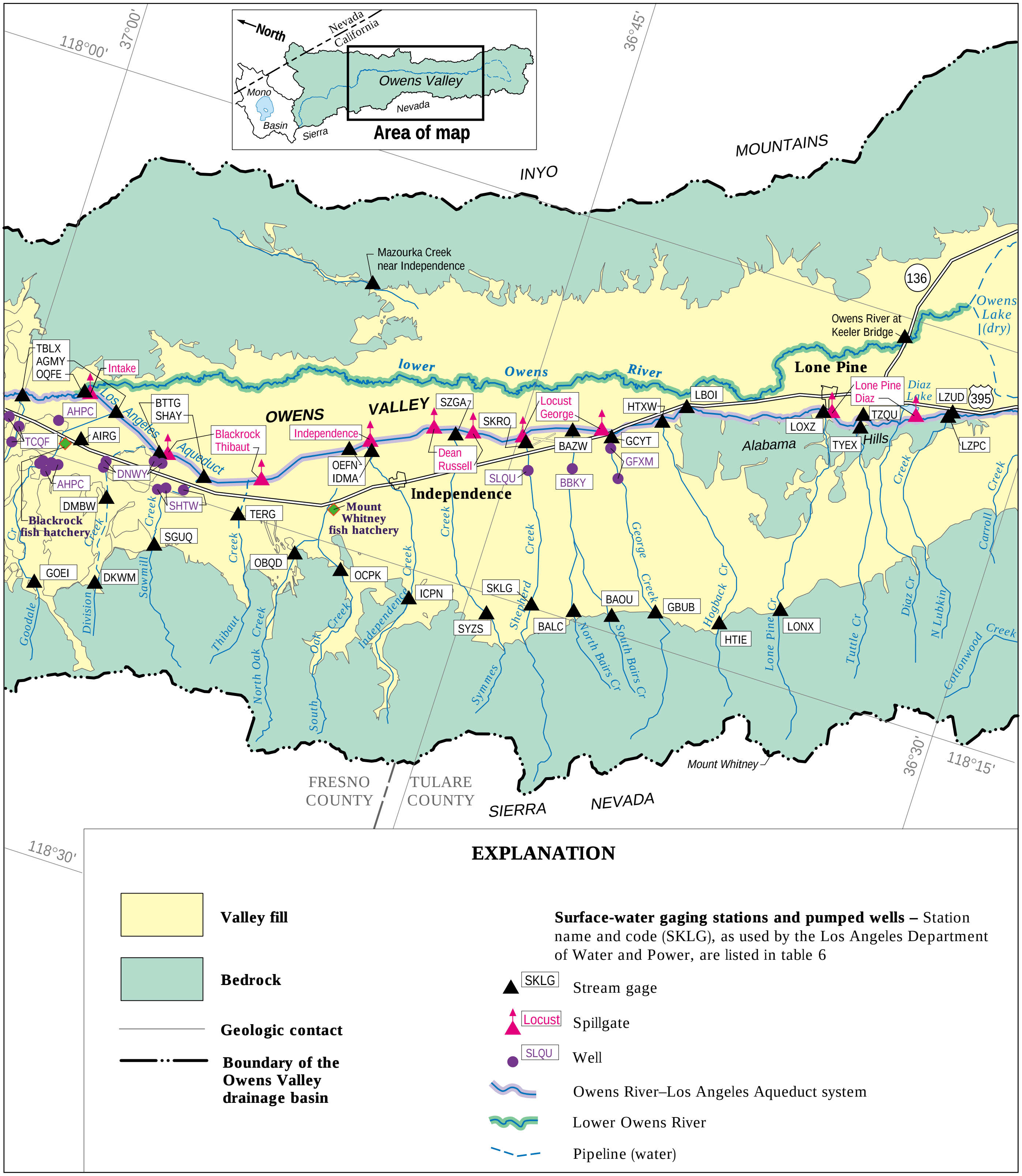


Figure 11. Continued.

front runoff between tributary streams. From annual values of total valleywide runoff, the percent of long-term average annual valleywide runoff for a specific year, referred to locally as the "percent runoff year," is calculated and used extensively by the Los Angeles Department of Water and Power to guide water-

Table 6. Selected surface-water gaging stations and pumped wells in the Owens Valley, California

[Station code and name used by the Los Angeles Department of Water and Power; pumped wells are assigned a station code if well discharge affects a surface-water discharge measurement]

Station code	Station name	Station code	Station name
ABQG	A Drain above Big Pine Canal.	LONX	Lone Pine Creek at base of mountains.
AGMY	Aberdeen Ditch at Los Angeles Aqueduct.	LOXZ	Lone Pine Creek at overhead no. 19.
AHPC	Aberdeen Ditch wells 106, 110–114, 355.	LZPC	Lubkin Creek at Los Angeles Aqueduct.
AIRG	Aberdeen–Blackrock bypass ditch at intake.	LZUD	Lubkin Creek over Los Angeles Aqueduct.
BALC	Bairs Creek (north fork) at base of mountains.	MJAA	McGee Creek at Aberlour Ranch.
BAOU	Bairs Creek (south fork) at base of mountains.	MLUA	South (lower) McNally Canal at O.V.P.A. (Owens Valley Protective Association).
BAZW	Bairs Creek at Los Angeles Aqueduct.	MMDA	North (upper) McNally Canal at O.V.P.A. (Owens Valley Protective Association).
BBKY	Bairs Creek well 353.	OBQD	Oak Creek (north fork) at base of mountains.
BBWA	Baker Creek at Los Angeles Aqueduct Station (4-foot flume).	OCPK	Oak Creek (south fork) at base of mountains.
BERW	Big Pine Canal at intake.	OEFN	Oak Creek at Los Angeles Aqueduct.
BFRS	Big Pine Creek at Cartmell well.	OLZR	Owens River at Pleasant Valley Reservoir, total.
BGNW	Big Pine Creek at U.S. Geological Survey.	ONYF	Owens River at Tinemaha Reservoir.
BKFW	Birch Creek above mill site.	OQFE	Owens River below intake spillgates.
BKJO	Birch Creek at Tungsten City Road.	OUKR	Owens Valley runoff.
BKQY	Birch Creek below highway.	PXHU	Owens River transit loss, Pleasant Valley Reservoir to Tinemaha Reservoir.
BTTG	Blackrock Ditch at Los Angeles Aqueduct.	RDQW	Rawson Creek at base of mountains.
CLUA	Coldwater Canyon Creek at end of pipeline.	RHSG	Red Mountain Creek at Forest Service boundary.
DKWM	Division Creek below intake (overflow).	RICU	Red Mountain Creek diversion above station.
DMBW	Division Creek powerhouse no. 1.	SGUQ	Sawmill Creek at base of mountains.
DNWY	Division Creek wells 108, 109, 351, 356.	SHAY	Sawmill Creek at Los Angeles Aqueduct.
FPGS	Fish Slough at Los Angeles station no. 2.	SHTW	Sawmill Creek wells 155, 159, 339.
FPVK	Fish Slough at Owens River.	SKLG	Shepherd Creek at base of mountains.
FXEK	Freeman Creek at Keough.	SKRO	Shepherd Creek at Los Angeles Aqueduct.
FZLE	Fuller Creek at Forest Service boundary.	SLQU	Shepherd Creek well 345.
GBUB	George Creek at base of mountains.	SMJS	Silver Canyon Creek at base of mountains.
GCYT	George Creek at Los Angeles Aqueduct.	SMQA	Silver Canyon Creek at base of mountains, site no. 2.
GFXM	George Creek wells 76, 343.	SMWI	Silver Canyon Creek at old Clark Ranch (at well 251).
GKAX	Giroux Ditch (lower).	SYZS	Symmes Creek at base of mountains.
GKQG	Giroux Ditch (upper).	SZGA	Symmes Creek at Los Angeles Aqueduct.
GOEI	Goodale Creek at base of mountains.	TAPE	Taboose Creek at base of mountains.
HCKU	North Haiwee Reservoir inflow.	TBLX	Taboose Creek at Owens River.
HTIE	Hogback Creek at base of mountains.	TCQF	Taboose Creek wells 116, 342, 347.
HTXW	Hogback Creek at Los Angeles Aqueduct.	TERG	Thibaut Creek at intake.
HVSY	Horton Creek above Owens River Canal.	THWP	Tinemaha Creek at Forest Service boundary.
ICPN	Independence Creek at Junction Station.	TIEE	Tinemaha Creek at railroad crossing.
IDMA	Independence Creek at Los Angeles Aqueduct	TLRC	Tinemaha Reservoir evaporation, including precipitation.
KCXC	Keough Hot Springs above diversions.	TLYR	Tinemaha Reservoir evaporation pan.
KXCQ	Klondike Drain at Owens River.	TYEX	Tuttle Creek at Canyon Road.
LBOI	Los Angeles Aqueduct at Alabama Gates.	TZQU	Tuttle Creek flow into Los Angeles Aqueduct.
LGUJ	Laws Ditch at railroad.		
LMUO	Little Pine Creek at McMurray Meadows Road.		

management decisions. Values for water years 1935–88 are given in table 7.

Using the percent runoff year for various analyses has two major advantages over other methods: (1) it provides a simple, unifying theme to many complex calculations, and (2) it is relatively independent of the specific method and values used by different individuals and agencies to calculate valleywide runoff. As a result, this key parameter was used extensively in this study, particularly in the analysis of recharge from tributary streams and in the evaluation of selected water-management alternatives.

The probability distribution of the percent runoff year for the Owens Valley for water years 1935–84 is shown in figure 12. This graph and the related best-fit line identify the likely occurrence of a particular percent runoff year. For example, a runoff year having 70 percent or less of the average annual runoff (a 70-percent runoff year) will occur about 15 percent of the time, or about 1 out of 7 years. Water years 1976 and 1977 fall into this category.

The method of developing the probability plot uses the technique of Weibull (1939), as described by Chow (1964, p. 8–28). The 50 annual values for water years 1935–84 (table 7) were assumed to be independent and follow a lognormal distribution. The values were ranked in order (r) and plotted on lognormal probability paper using the relation r/(n + 1), where in this case n equals 50. A general trend line was fitted by hand. Although skewness in the data was recognized (mean equals 100, median equals 94), no other evaluation of the probability distribution was made.

Runoff during the detailed period of analysis chosen for this study, water years 1963–88, slightly exceeded (106 percent) the long-term average runoff. Thus, despite two periods of exceptionally dry conditions (1976–77 and 1987–88) (table 7), the overall period was wetter than normal. In addition, unusually high runoff years—1967, 1969, 1978, 1980, 1982, and 1983—all occurred during this period (fig. 12).

Table 7. Percent of long-term average annual runoff for the Owens Valley, California, water years 1935–88

[Data for station OUKR (table 6) (M.L. Blevins, Los Angeles Department of Water and Power, written commun., 1988). Average runoff (469,604 acre-feet per year equals 100 percent) was calculated for base period, water years 1935–84]

Water year	Percent of average annual runoff	Water year	Percent of average annual runoff
1935	78	1962	94
1936	94	1963	107
1937	110	1964	69
1938	156	1965	96
1939	92	1966	73
1940	94	1967	141
1941	131	1968	80
1942	114	1969	196
1943	108	1970	99
1944	89	1971	79
1945	114	1972	69
1946	111	1973	106
1947	86	1974	107
1948	67	1975	88
1949	70	1976	64
1950	72	1977	55
1951	80	1978	134
1952	132	1979	98
1953	82	1980	142
1954	80	1981	89
1955	77	1982	143
1956	115	1983	189
1957	91	1984	132
1958	122	1985	98
1959	74	1986	158
1960	58	1987	78
1961	53	1988	68

Tributary Stream Recharge

Tributary streams generally lose water as a result of streambed leakage, diversions of streamflow onto the alluvial fans, and, to a lesser extent, evapotranspiration from areas along the stream channel. Several streams also receive water from pumped wells just upstream from the river–aqueduct site (fig. 11), and a few streams receive water from springs, canals, or diversions from other streams. Some streams may gain water in lower reaches because of local seepage of ground water caused by faults, shallow bedrock, or changes in the hydraulic characteristics of the depositional material. Although discharge at the base-of-mountains and river–aqueduct sites is gaged continuously and pumpage from wells is metered, other gains to or losses from tributary streams generally are not measured or are not measured continuously.

The basic technique used to estimate tributary stream recharge is similar to that of C.H. Lee (1912) and uses the following general equation:

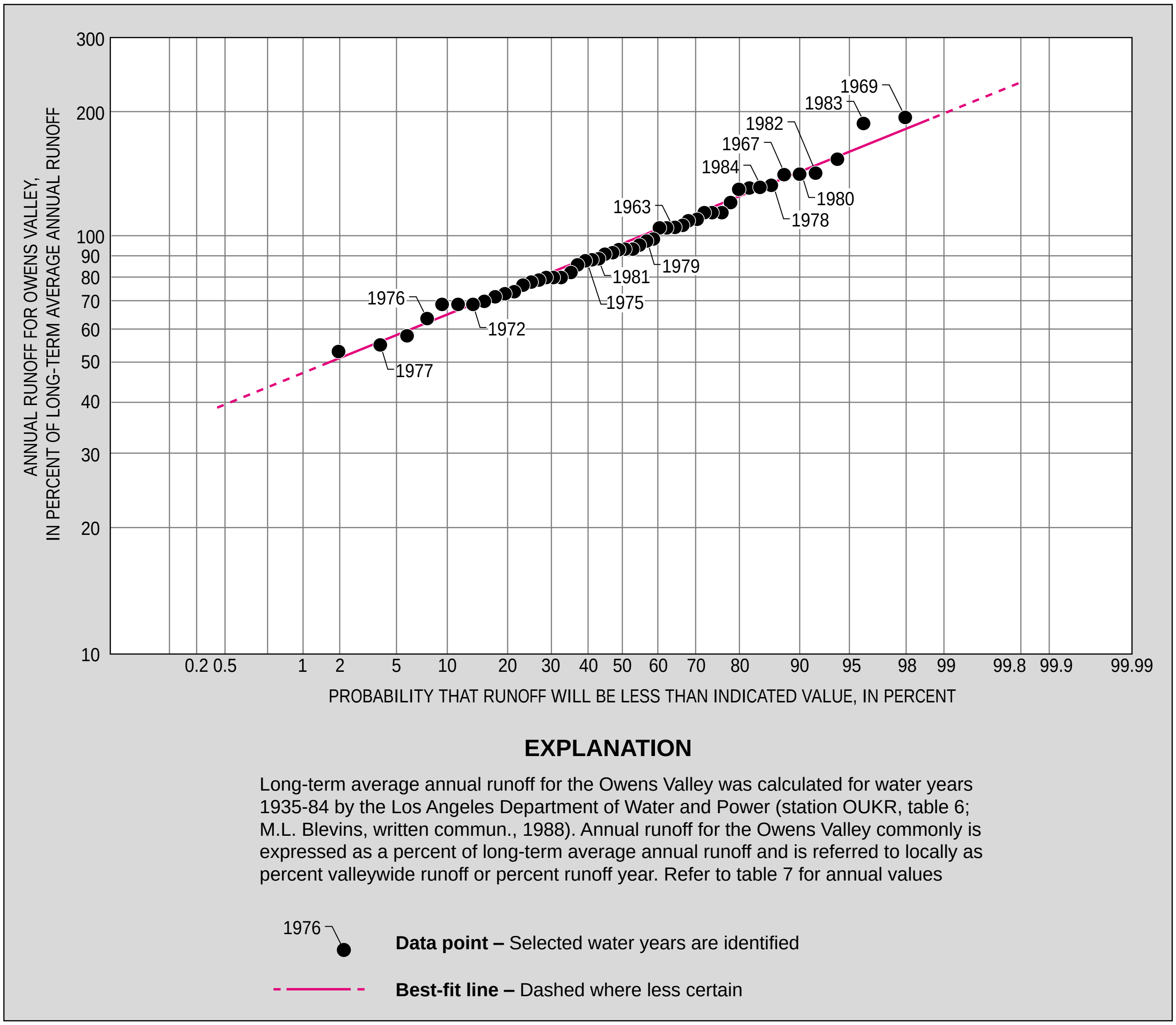


Figure 12. Annual-runoff probability for the Owens Valley, California.

$$R^G = (S^{BM} - S^{RA}) + W^G - ET^G \,, \qquad (4)$$

where

R^G is stream recharge to the aquifer system for the reach between the base-of-mountains and river–aqueduct gages, in acre-feet per year;

S^{BM} is measured stream discharge at the base-of-mountains gage, in acre-feet per year;

S^{RA} is measured stream discharge at the river–aqueduct gage, in acre-feet per year;

W^G is measured well discharge that flows into the stream between the base-of-mountains and river–aqueduct gages, in acre-feet per year; and

ET^G is the estimated evapotranspiration between the two gages in the immediate vicinity of the stream channel, in acre-feet per year.

Streamflow data for a 50-year period, water years 1935–84, were used to determine the loss for each tributary stream, defined as the sum of R^G and ET^G. Because all other values in equation 4 are

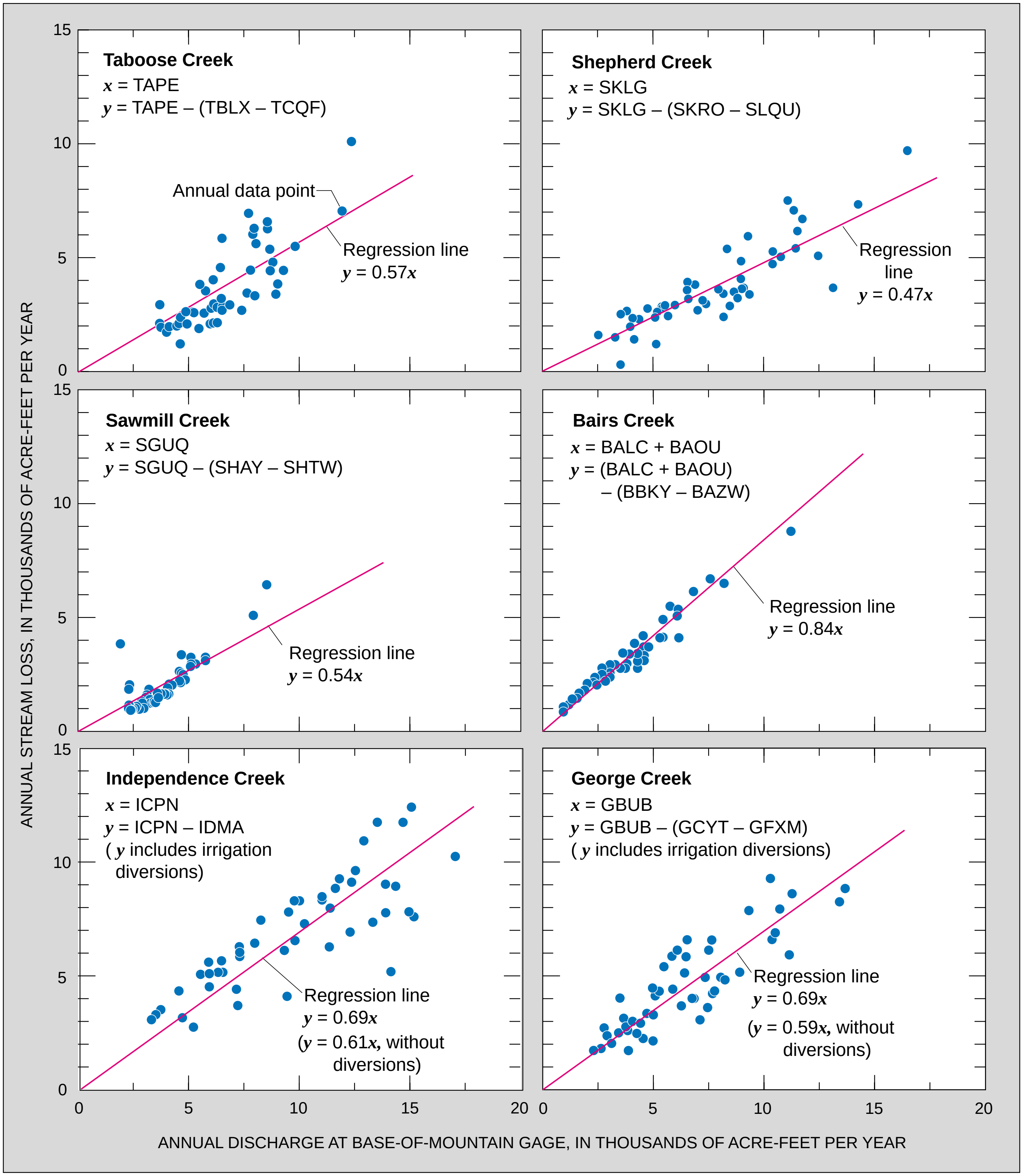


Figure 13. Streamflow relations for selected tributary streams in the Owens Valley, California. Annual data are for water years 1935–84. Station codes, such as TAPE, are shown in figure 11 and described in table 6.

measured, the quantity of stream loss between the base-of-mountains and river–aqueduct gages is well documented. As shown in figure 13, stream loss for each stream is fairly predictable if the quantity of discharge at the base-of-mountains gage (S^{BM}) is known. From the regression equation for each stream (fig. 13), the quantity of stream loss between the gages can be calculated for any known or estimated discharge at the base-of-mountains gage. Similar graphical relations were evaluated, and linear regression equations were developed, for each of the 34 tributary streams using data from the discharge gages identified in figure 11 and listed in table 6.

The average stream loss rates (coefficient *a* in the regression equations in figure 13 with the general form $y = ax$) calculated from the 50 years of discharge data generally are higher than those reported by C.H. Lee (1912, pl. 9), who used about 4 years of record. The cause of the increase is not known, but it may result from the slightly greater length of the gaged section, additional diversions of water from the streams, or changes to the channels.

Tributary stream recharge between the gages (R^G) was calculated from stream loss by estimating evapotranspiration for each stream using the equation,

$$ET^G = \frac{ET^O SL_i^G SW^G SV^G}{43,560}, \qquad (5)$$

where

ET^G is estimated evapotranspiration between the two gages in the immediate vicinity of the stream channel, in acre-feet per year;

ET^O is the average annual evapotranspiration rate for high-water-use species, in feet per year;

SL^G is the length of the stream channel between the two gages, in feet;

SW^G is the width of vegetation near the stream channel, in feet; and

SV^G is the percent of vegetative cover near the stream, expressed as a decimal fraction.

Because detailed data were not available for most variables in equation 5, estimates were made on the basis of limited field observations of Bishop, Independence, Oak, Taboose, and Lone Pine Creeks, and measurements of vegetative conditions on the valley floor (table 5) (D.P. Groeneveld, Inyo County Water Department, written commun., 1986; Duell, 1990). Constant values were chosen for SW^G (50 ft), ET^O (47 in/yr), and SV^G (0.30). Stream length was measured by digitizing 1:24,000-scale topographic maps. For each of the tributary streams, evapotranspiration was found to be minimal, ranging from about 10 to less than 100 acre-ft/yr (Hollett and others, 1991, table 8). This quantity generally is less than about 2 percent of the discharge at the base-of-mountains gage and less than about 5 percent of the estimated recharge between the two gages.

For selected water years, such as the ground-water simulation period (water years 1963–88), annual discharge at each base-of-mountains gage was estimated by multiplying the 50-year average discharge at the base-of-mountains gage (water years 1935–84) by the percent runoff year for individual years (table 7). Recharge above or below the gaged section of the stream was determined from gaged records of diversions and by comparing respective lengths of stream channels in the gaged and ungaged sections. The relation for total recharge for a stream *(i)* in water year *(j)* can be expressed as:

$$R_{ij}^T = R_{ij}^G + R_{ij}^A + R_{ij}^B, \qquad (6)$$

where

R^T is the total stream recharge between the surrounding bedrock and the river–aqueduct system, in acre-feet per year;

R^G is stream recharge that occurs between the base-of-mountains and river–aqueduct gages, in acre-feet per year;

R^A is the stream recharge that occurs above the base-of-mountains gage, in acre-feet per year; and

R^B is the stream recharge that occurs below the river–aqueduct gage, in acre-feet per year.

Within the gaged section of a specific stream (*i*), stream loss during a particular year (*j*) can be estimated as,

$$SLQ_{ij}^G = SLR_i^G [S_i^{BM} RO_j], \qquad (7a)$$

and stream recharge estimated as,

$$R_{ij}^G = SL_{ij}^G - ET_i^G, \qquad (7b)$$

where

SLQ^G is the quantity of water lost from the stream between the base-of-mountains and river–aqueduct gages, in acre-feet per year;

SLR^G is the average loss rate (a), determined from the regression equation $y = ax$ (fig. 13) expressed as a decimal fraction;

S^{BM} is the long-term mean annual discharge at the base-of-mountains gage (Hollett and others, 1991, table 2), in acre-feet per year;

RO is the percent runoff year (table 7), expressed as a decimal fraction; and

ET^G is estimated evapotranspiration between the two gages in the immediate vicinity of the stream channel, in acre-feet per year.

For most streams with standard channels,

$$R_{ij}^{A} = R_{ij}^{G}\left[\frac{SL_i^A}{SL_i^G}\right], \qquad (8a)$$

and

$$R_{ij}^{B} = R_{ij}^{G}\left[\frac{SL_i^B}{SL_i^G}\right], \qquad (8b)$$

where

SL^A is stream length above the base-of-mountains gage, in feet;

SL^G is the stream length between the base-of-mountains and river–aqueduct gages, in feet; and

SL^B is stream length below the river–aqueduct gage, in feet.

From these relations, total recharge for each stream can be estimated both for historical periods and for hypothetical situations, such as those evaluated as possible water-management alternatives.

Several of the tributary streams could not be evaluated using this approach because only a single gaging station was operated on the stream, because unquantified diversions were made from one stream to another, or because a spring between the two gages added an unknown quantity of water to the stream. In these cases, an average recharge rate per foot of stream channel was calculated for streams with two gages (Hollett and others, 1991, table 8). These recharge rates were applied to streams that have similar annual discharge rates and that flow over similar types of materials.

For a few streams, the long length of channel above the base-of-mountains gage *(SL^A)*, such as for Independence Creek (fig. 11), produced an unrealistically high quantity of recharge, indicating that the stream may have been flowing on top of a narrow, fully saturated, alluvial fan or glacial deposit that was not capable of receiving additional water from the stream. For these sections of streams, recharge estimates were scaled downward on the basis of a shorter recharge length for the stream and on recharge values for similar nearby streams. Diversion of flow from Big Pine Creek and Oak Creek for domestic use and irrigation on nearby Indian reservations decreased recharge rates for those streams in comparison with the total loss rate calculated from equation 4. Using these methods, the average annual recharge for all tributary streams within the area of the defined aquifer system (fig. 2) was estimated to be 106,000 acre-ft/yr for water years 1963–69 and 103,000 acre-ft/yr for water years 1970–84.

Ungaged Runoff

Mountain-Front Runoff Between Tributary Streams

Most runoff from precipitation falling on the mountains surrounding the Owens Valley is measured at the base-of-mountains gaging stations on the major tributary streams (fig. 11). Some runoff, however, occurs from precipitation falling on ungaged drainage areas between gaged tributary streams. Precipitation in these small, triangular-shaped areas—commonly referred to as intermountain slopes (C.H. Lee, 1912)—runs off as sheet flow, in rivulets, or in small intermittently flowing streams. The intermountain slopes along the southwest side of the basin were mapped and described by C.H. Lee (1912, p. 13 and pl. 1). Most of the runoff from these areas disappears into the alluvial fans a short distance from the edge of the mountains. This water, referred to as “hidden recharge” by Feth (1964a) because it is not measured, either is transpired by nearby plants or contributes recharge to the ground-water system. The increase in vegetation along the upper part of the alluvial fans observed by M.O. Smith and others (1990a, b) may result not only from increased precipitation, related to the increase in altitude (fig. 7*B*), but also from runoff between tributary streams.

The abundance of springs in many bedrock areas along both sides of the valley (shown on USGS 1:62,500-scale topographic maps) indicates that the quantity of water contributed to the basin might be significant. For example, discharge from Scotty Springs near Division Creek (Mt. Pinchot quadrangle) has been measured at greater than 2 ft^3/s (C.H. Lee, 1912, p. 44). Except for spring discharge, the total quantity of ungaged surface-water inflow is difficult or impossible to measure.

Instead, estimates of the quantity of ungaged surface-water inflow and resulting ground-water recharge typically are made using precipitation records, runoff coefficients calculated for gaged drainage areas, and assumptions about the percentage of runoff that percolates to the ground-water system. Using this approach in the southwestern part of the Owens Valley, C.H. Lee (1912, p. 66–67 and table 61) estimated that as much as 75 percent of the total volume of precipitation on the ungaged drainage areas recharged the ground-water system. Lee noted that the high rate resulted from steep mountain slopes and rapid melting of snow, both of which minimize losses from evapotranspiration and percolation through the extremely transmissive alluvial fan deposits.

In the present study, recharge for each of the ungaged drainage areas was estimated in a similar manner, but using different percolation rates depending on the part of the valley being analyzed. Recharge for each area along the southwest side of the valley was calculated using the average annual precipitation from figure 7 and the 75-percent percolation rate suggested by C.H. Lee (1912). Recharge for areas along the northwest side of the valley was somewhat less because of smaller drainage areas, lower precipitation values, or an abundance of mountain meadows that discharge the ungaged water as evapotranspiration before it can reach the valley ground-water system. Recharge for the Volcanic Tableland was significantly less than for areas on the west side of the valley because precipitation rates are much lower (fig. 7), potential evaporation is much higher because of the higher average temperature, and percolation is restricted by the impermeable capping member of the Bishop Tuff (figs. 4 and 5). Recharge for areas on the east side of the basin was almost zero because virtually no runoff has been observed between the intermittently flowing tributary streams, particularly those south of Coldwater Canyon Creek (figs. 3 and 11).

A few of the larger ungaged streams flow far enough down the alluvial fans to join a major tributary stream below the base-of-mountains gage (fig. 3). This addition of water to the gaged tributaries is not accounted for in the estimates of tributary streamflow or tributary stream recharge described earlier in the section “Tributary Streams.” This recharge, however, is accounted for using the method described above for ungaged runoff.

Recharge to the defined aquifer system (fig. 2) contributed from all ungaged areas was estimated to average approximately 26,000 acre-ft/yr for both water years 1963–69 and water years 1970–84. In order to estimate ungaged recharge for different water years, the long-term average recharge rates were multiplied by the annual percent of valleywide runoff (table 7). Although a high degree of uncertainty is associated with the values of recharge between tributary streams, recharge from ungaged areas for most of the valley is a relatively small component of the ground-water budget. Significant refinement in the quantity of runoff or ground-water recharge is unlikely because of the difficulty of measurement. However, a comprehensive surface-water/ground-water budget for the entire valley, as suggested by Danskin (1988), might improve the confidence limits for ungaged runoff and the related ground-water recharge.

Runoff from Bedrock Outcrops Within the Valley Fill

A small quantity of precipitation falls on the bedrock outcrops within the valley fill, in particular on the Tungsten Hills, the Poverty Hills, and the Alabama Hills (fig. 7). Most of the precipitation probably is evaporated or transpired by the sparse native vegetation covering the hills. Some runoff can occur during longer duration, high-intensity storms. This quantity is not important either for local uses or for export from the valley.

Springs visible on the north and west sides of the Alabama Hills (Lone Pine and Union Wash quadrangles, USGS 1:24,000-scale topographic maps) indicate that precipitation does exceed evapotranspiration and that some local infiltration occurs into the soil and fractured rocks. During longer duration storms, some recharge to the ground-water system in the immediate vicinity of the bedrock outcrops probably occurs. Also, some additional recharge probably occurs from the minor spring discharges along the sides of the bedrock outcrops. A likely range of recharge values was determined using estimates of average precipitation (fig. 7) and a range of possible runoff coefficients (C.H. Lee, 1912). The total quantity of recharge to the aquifer system (fig. 2) from runoff from bedrock outcrops for average conditions of precipitation and evaporation probably is less than 1,000 acre-ft/yr.

Table 8. Mean annual discharge at selected gaging stations on the Owens River–Los Angeles Aqueduct system in the Owens Valley, California.

[—, not available. Measured discharge data in acre-feet per year from the Los Angeles Department of Water and Power (M.L. Belvins, written commun., 1988). Values for the Los Angeles Aqueduct at the North Haiwee Reservoir are estimates]

Station name	Station code (table 6)	Water years			
		1935–69	1945–69	1953–69	1970–84
Owens River at the Pleasant Valley Reservoir.	OLZR	250,000	260,000	260,000	330,000
Owens River at the Tinemaha Reservoir.	ONYF	—	—	320,000	390,000
Los Angeles Aqueduct at the Alabama Gates.	LBOI	—	320,000	330,000	450,000
Los Angeles Aqueduct at the North Haiwee Reservoir.	HCKU	320,000	340,000	350,000	480,000

Owens River and the Los Angeles Aqueduct

The river–aqueduct system within the study area extends from the Mono Basin to the Haiwee Reservoir (fig. 1). At the northernmost point of the river–aqueduct system in the Mono Basin, streams flowing out of the Sierra Nevada are diverted into a concrete-box conduit. The diverted water is routed to Grant Lake in the Mono Basin and eventually is conveyed to the Owens River in the Long Valley through the 11.3-mile-long Mono Craters Tunnel (fig. 1). The mean annual discharge through the tunnel is about 72,000 acre-ft. At the end of the Mono Craters Tunnel, water from the Mono Basin joins the upper reach of the Owens River and together flows about 12 mi to Lake Crowley, also known as the Long Valley Reservoir. Lake Crowley, which is the largest reservoir in the river–aqueduct system, regulates the flow of water through a 96- to 108-inch pipeline (penstock) that connects Lake Crowley in the Long Valley with the Pleasant Valley Reservoir in the Owens Valley. The natural channel of the Owens River through the Volcanic Tableland is used infrequently to convey floodwaters or to divert water during maintenance of the pipeline. Three hydroelectric plants located along the pipeline generate electricity as a result of a drop in altitude of about 1,600 ft from the Long Valley to the Owens Valley. The mean annual discharge of the Owens River at the Pleasant Valley Reservoir increased from about 250,000 acre-ft for water years 1935–69 to about 330,000 acre-ft for water years 1970–84 (table 8). This increase resulted from additional diversion of water from the Mono Basin, as well as from greater runoff during the latter, wetter period (106 percent runoff in comparison with 97 percent).

The Pleasant Valley Reservoir regulates flow to the natural channel of the Owens River downstream from the outlet tower at the Pleasant Valley Dam. Between the Pleasant Valley Reservoir and the Haiwee Reservoir at the south end of the Owens Valley, discharge in the river–aqueduct system is constantly altered by gains of water from streams, springs, pumped wells, flowing wells, and seepage from the ground-water system, as well as by losses of water to irrigation and to the ground-water system. Emerging from the Pleasant Valley Reservoir, the Owens River continues south, gaining water primarily from tributary streams and from pumped and flowing wells before discharging into the Tinemaha Reservoir at the south end of the Bishop Basin. A photograph (fig. 10*A*) taken just north of Bishop near the Five Bridges area (Fish Slough quadrangle, USGS 1:24,000-scale topographic map) shows the general character of the Owens River in the Bishop Basin. The natural, meandering channel of the Owens River is generally about 20 to 50 ft wide and about 3 to 6 ft deep, and has a silt, sand, and clay bottom. The mean annual discharge of the Owens River at the Tinemaha Reservoir was about 390,000 acre-ft for water years 1970–84, or about 60,000 acre-ft/yr greater than the discharge at the north end of the Bishop Basin at the Pleasant Valley Reservoir (table 8).

Flow in the Owens River resumes south of the Tinemaha Reservoir and continues for approximately 5 mi until virtually all water is diverted into the unlined, trapezoidal channel of the Los Angeles Aqueduct (fig. 10*B*). Flowing along the toes of the western alluvial fans, the aqueduct gains additional water from streams and wells. In the Owens Lake Basin, tributary streams are generally smaller, although more numerous than in the Bishop Basin, and there are fewer diversions for agricultural uses. At the Alabama Gates (fig. 11), on the north side of the Alabama Hills, the aqueduct changes to a concrete-lined channel. The mean annual discharge at the Alabama Gates was about 450,000 acre-ft for water years 1970–84, or about 60,000 acre-ft/yr greater than the discharge at the Tinemaha Reservoir (table 8). At the Haiwee Reservoir at the southern boundary of the study area, mean annual discharge is about 1.5 times mean annual discharge at the Pleasant Valley Reservoir (table 8). The Haiwee Reservoir regulates and temporarily stores water before releasing it into the two channels of the dual-aqueduct system that conveys the water to the Los Angeles area. After completion of the second aqueduct, discharge to Los Angeles increased approximately 160,000 acre-ft/yr both as a result of changes in management practices and greater average runoff (tables 4, 7, and 8).

Since the early 1900's, successive changes in water management have altered the role of the Owens River in the Owens Valley hydrologic system. Prior to development of the river–aqueduct system, the natural channel of the Owens River was the primary drain of both the surface-water and ground-water systems. Tributary streams flowed across the valley floor to merge with the river, and ground water flowed upward under pressure to augment discharge in the perennially flowing Owens River. After operation of the Los Angeles Aqueduct was begun in 1913, the hydrologic system of the valley remained dominated by the Owens River in the Bishop Basin, but the system became dominated by the Los Angeles Aqueduct in the Owens Lake Basin. The diversion of tributary streams at the edge of alluvial fans into the aqueduct prevented the lower Owens River from acting as a major surface-water collector. The river–aqueduct system drained the surface-water system, and the Owens River in the Bishop Basin and the lower Owens River in the Owens Lake Basin drained the ground-water system.

After 1970, increased ground-water pumping began to change these conditions. What had been a relatively simple hydrologic system began the transition to a more complex system with dynamically changing surface-water/ground-water interactions. In at least one area of the valley near Big Pine, the Owens River began losing water to the ground-water system. Water-level data collected from nearby wells show a hydraulic gradient from the Owens River to production wells along the edge of Crater Mountain (fig. 11). In other parts of the valley with high ground-water pumpage, such as near Laws, the quantity of water gained by the Owens River from the ground-water system probably was reduced.

The Los Angeles Aqueduct, because it is elevated topographically above the center line of the valley, never acted as a major ground-water collector. However, for most of its unlined length, the aqueduct is at an altitude at which it can exchange water readily with the ground-water system. The local hydraulic gradient between the aqueduct and the ground-water system, as described above for the Owens River, determines the direction and rate of flow. Hydrogeologic sections developed by Hollett and others (1991, pl. 2), Griepentrog and Groeneveld (1981), and the Los Angeles Department of Water and Power (1978) indicate the general areas where the aqueduct gains or loses water for different ground-water conditions. Under average conditions, most sections of the aqueduct continue to gain water from the ground-water system. However, during periods of significant ground-water withdrawals, such as 1971–74, ground-water levels near the aqueduct decline and the rate of gain decreases; the decline can be sufficient to change the direction of flow, resulting in a loss of water from the aqueduct. This condition likely occurred in areas with numerous production wells, such as between Taboose and Thibaut Creeks (fig. 11). South of George Creek, the altitude of the aqueduct is generally above even the highest ground-water levels; therefore, the aqueduct loses water to the ground-water system. The concrete-lined section of the aqueduct adjacent to the Alabama Hills also is elevated above the nearby ground-water system and has the potential to lose water; however, the loss through the concrete and related joints probably is minimal.

Estimates of the quantity of loss (or gain) for the river–aqueduct system typically are calculated as the residual of a mass balance for a gaged section of the stream. This is the same method used to calculate recharge for the tributary streams. When the loss is a small fraction of the measured flows, however, large residual errors can result, masking the actual loss or gain. For this reason, estimates of the likely range of loss or gain for the river and aqueduct were developed using loss studies on canals that flow over similar materials, but have a much smaller discharge.

Analysis of several canals in the Laws area indicates that a 15-foot-wide canal with a mean discharge of 2 to 10 ft^3/s typically loses 0.3 to

1.1 (ft^3/s)/mi (R.H. Rawson, Los Angeles Department of Water and Power, oral commun., 1988). Similar loss rates were calculated for tributary streams (Hollett and others, 1991, table 8). If vertical conductivity for the canals, river, and aqueduct are similar, then these rates equate to approximately 1 to 3 (ft^3/s)/mi for the wider Owens River or the Los Angeles Aqueduct. Because the rate of exchange (either loss or gain) between the river or aqueduct and the ground-water system is dependent on the physical characteristics of the stream channel, which are fairly constant, and on the local hydraulic gradient between the stream and the ground-water system, which generally varies over a small range of values, the exchange rates probably are similar for both the gaining and losing reaches of the river and aqueduct.

If bed material of the river–aqueduct system is finer grained than bed material of the tributary streams and selected canals, the exchange rates probably are less for the river–aqueduct than for streams or canals. To accommodate this uncertainty, ground-water recharge or discharge (river–aqueduct loss or gain) was determined by applying a range of estimated rates of gain or loss to the respective gaining or losing sections of the river–aqueduct system and then comparing these values with results from the valleywide ground-water flow model. For the area of the aquifer system (fig. 4), the river–aqueduct system during water years 1963–69 and water years 1970–84 was estimated to gain approximately 16,000 acre-ft/yr and 3,000 acre-ft/yr, respectively.

As part of an extensive surface-water monitoring network, the Los Angeles Department of Water and Power computes mass balances for various sections of the river–aqueduct system. These calculations are given stations identifiers, such as those in table 6, and are listed in a monthly report, “Uses and Losses” (L. Lund, Los Angeles Department of Water and Power, written commun., 1988). The mass-balance values for several years suggest that the Owens River gains about 33,000 acre-ft/yr from the ground-water system between the Pleasant Valley Reservoir and the Tinemaha Reservoir (station PXHU, table 6). This value is equivalent to a rate of gain of about 1.5 (ft^3/s)/mi of river channel. Although this value is physically realistic, the calculated gain for the river–aqueduct system in this reach is much higher than the values estimated using the technique described above or values derived from the ground-water flow model described later. A detailed water budget linking the surface-water and ground-water systems as suggested by Danskin (1988), or development of a surface-water/ground-water model, might help solve this discrepancy.

The specific interactions of the river–aqueduct system with the ground-water system are difficult to measure or estimate. Further improvements in knowledge may require taking advantage of water-quality and temperature measurements of the river–aqueduct and of ground water. These analyses may be useful in confirming concepts and quantities of interactions that are less clearly defined by water-use calculations and water-level mapping, particularly in the complex water-distribution area near Bishop (fig. 3).

Spillgates.—Ten spillgates are located along the aqueduct and are used at various times throughout the year to clean the aqueduct of debris and, during high-runoff years, to discharge excess water onto the valley floor. Discharge from the spillgates is measured and is relatively constant in average-runoff years. During most years, total discharge from the 10 spillgates averages about 22,000 acre-ft/yr, but during high-runoff years such as 1967, 1969, and 1983 (fig. 12), total discharge can be several times that quantity. Nine spillgates are shown in figure 11; an additional spillgate is located near Cottonwood Creek, just south of the focused area of study. The Cottonwood spillgate was not included in the analysis presented in this report.

Some ground-water recharge occurs as a result of discharge from the spillgates. Although the quantity of discharge is measured, the quantity that infiltrates to the ground-water system is not known. Some of the discharge, especially in high-runoff years, may flow across the valley floor to the channel of the lower Owens River. In a regression analysis of discharge in the lower Owens River, Hutchison (1986d) attributed much of the measured discharge in the lower Owens River at Keeler Bridge (fig. 11) to releases from the spillgates.

Discharge of surface water from the spillgates is limited to some extent by litigation (*Natural Soda Products Co.* v. *Los Angeles*, 23 California 193) that restricts discharge to the Owens Lake (dry). Occasional wetting of the dry lakebed is believed to contribute to air-quality degradation in the valley caused by dust storms (Saint-Amand and others, 1986; Lopes, 1988). In high-runoff years, these restrictions are difficult or impossible to meet because of the large quantity of water in the valley and the limited capacity of the river–aqueduct system. For example, in the exceptionally wet water years 1969 and 1983 (fig. 12), there was water, quite literally, everywhere in the valley and the spillgates were used extensively. Surface water that could not be exported out of the valley was diverted onto the valley floor, primarily through the Blackrock spillgate (fig. 11).

During such exceptionally-high-runoff years, infiltration into the unsaturated zone and recharge to the underlying water table may be so great that the infiltration restores the unsaturated zone to field capacity and the recharge reequilibrates shallow ground-water levels from any previous decline caused by nearby pumping or drought. Massive releases from the several spillgates likely play an important role in doing this. Areas of the valley that historically have been inundated with water during high-runoff years are shown on maps compiled by Boyle Engineering and by the Los Angeles Department of Water and Power (M.L. Blevins, written commun., 1986) for 1952, 1967, and 1969.

In this present study, the quantity of infiltration from spillgates was estimated by subtracting the likely losses from evapotranspiration and an estimate of the return flow to the lower Owens River from the measured discharge. Because the discharge channels were observed to have a greater abundance of vegetation than nearby areas on the valley floor, a relatively high evapotranspiration rate of 40 in/yr (Duell, 1990) was used in the calculations. The total recharge to the defined aquifer system (fig. 4) from spillgates was estimated to average approximately 6,000 acre-ft/yr.

Lower Owens River

Prior to substantial surface-water diversions in 1913, both surface and ground water migrated to the lower Owens River and eventually discharged into the Owens Lake. As of 1988, nearly all water flowing out of the Tinemaha Reservoir is diverted into the river–aqueduct system, and the lower Owens River has become relatively isolated from other surface-water features of the valley. A photograph of the lower Owens River (fig. 10*C*) taken in summer 1988 shows an abundance of riparian vegetation, especially bulrush and cattails, within the river channel. Typically, the riverbed itself is moist almost to the land surface. Although in some places the lower Owens River has flowing water that continues for several hundred feet, most of the river channel is occupied by this type of riparian vegetation (fig. 3).

In average-runoff years, most discharge reaching the Owens Lake (dry) via the lower Owens River is surface water returned to the river from ditches and undiverted tributary streamflow or ground water that seeps into the river channel (Hutchison, 1986d). During extremely wet years, runoff exceeds the capacity of the river–aqueduct system and not all flow in the Owens River is diverted into the Los Angeles Aqueduct. For example, annual discharge in the lower Owens River measured just below the aqueduct intake (station OQFE, table 6; fig. 11) for water years 1945–84 was typically 0 acre-ft, but annual discharge for water years 1969 and 1983 exceeded 75,000 acre-ft (L. Lund, Los Angeles Department of Water and Power, written commun., 1988).

Discharge in the lower Owens River also is measured continuously at the Keeler Bridge east of Lone Pine (fig. 11). For water years 1927–86, mean annual discharge was about 17,000 acre-ft (Hollett and others, 1991, table 3). Using regression techniques, Hutchison (1986d) evaluated the river-discharge record at the Keeler Bridge for runoff years 1946–86 and concluded that most streamflow at the bridge resulted either from operational releases to the river from the river–aqueduct system or from ground-water discharge. He noted that ground-water discharge in the lower Owens River was affected significantly by bank storage. Sediment along the bank of the river becomes saturated with river water as stage of the river rises, and the stored water then is gradually released back to the river as stage of the river falls. This hydraulic buffering dampens fluctuations in stage and discharge. By separating the various components of discharge, Hutchison (1986d) estimated that the ground-water contributions to the lower Owens River for runoff years 1946–86 ranged from 3,000 to 11,000 acre-ft/yr and averaged about 3,600 acre-ft/yr.

In years of much greater than average runoff (fig. 12 and table 7), the lower Owens River probably changes from a gaining stream to a losing stream, thereby recharging the nearby ground-water system, particularly on the east side of the valley. This change is most likely a temporary one; water that is lost will be regained by the river over the next few months or couple of years as the stage in the river channel returns to almost zero. This is essentially the same bank-storage process noted by Hutchison (1986d).

In order to more accurately identify interaction of the lower Owens River with the ground-water system, the Los Angeles Department of Water and

Power measured instantaneous discharge during 1986–87 at 10 sites along the river from the aqueduct intake to the Keeler Bridge (Hollett and others, 1991, fig. 22). River reaches between the measurement sites were defined as either gaining- or losing-water reaches—although only three of the reaches were found to act in a consistent manner during the period of observations. The first section, a few miles south of the aqueduct intake (Hollett and others, 1991, fig. 22), generally lost water to the ground-water system. As discussed in later sections of this report, this loss may correlate with pumpage from wells between Taboose and Thibaut Creeks (fig. 11). Gaining reaches near Independence and Lone Pine may result from abundant recharge in the vicinity of Oak Creek, discharge from spillgates (fig. 11), and a fining of aquifer materials near Lone Pine. Some of the water gained by the river is discharged as evapotranspiration by the abundant riparian vegetation in the natural channel of the lower Owens River (fig. 10*C*).

Areas surrounding the lower Owens River are shown as having transpiration values ranging from about 0.5 to 1.5 ft/yr (fig. 9). These intermediate values are attributed to transpiration by riparian vegetation that has high transpiration rates, often exceeding 3.5 ft/yr (D.P. Groeneveld, Inyo County Water Department, written commun., 1984), mixed with other native vegetation that has lower rates (table 5). In the immediate vicinity of the lower Owens River, transpiration from dense riparian vegetation, such as occupies the river channel (figs. 3 and 10*C*), probably consumes much of the rising ground water that would otherwise flow down the river.

Reservoirs and Small Lakes

Reservoirs

The Pleasant Valley and the Tinemaha Reservoirs are impounded by earth-filled dams and are used to regulate flow in the river–aqueduct system (fig. 11). The Pleasant Valley Reservoir is at the mouth of the Owens River gorge, which cuts deeply through the Volcanic Tableland. Nearly all water that normally flowed through the gorge has been diverted into a 96- to 108-inch pipeline (penstock) that passes through three power-generation plants. Water is discharged from the third power plant into the adjacent reservoir, which is about 20 ft deep and covers about 1,700 acres. The reservoir is used primarily as an afterbay for the power-generation facilities and to stabilize flow into the Owens River. Since 1970, when the additional diversions of water from the Mono Basin began, annual inflow to the Pleasant Valley Reservoir has increased by more than 60,000 acre-ft (table 8).

Seepage through the earthen dam that impounds the Pleasant Valley Reservoir undoubtedly occurs although the rate is not known. Any seepage through the dam probably is regained by the Owens River a short distance downstream from the dam. More important, the bottom of the reservoir may contact the more transmissive members of the Bishop Tuff (fig. 5; Hollett and others, 1991). If this contact is present and the normal siltation in the reservoir has not restricted direct hydraulic connection between reservoir water and these well-sorted sands, then significant seepage may occur from the reservoir to the ground-water system.

The Tinemaha Reservoir is at the south end of the Bishop Basin, about 5 mi upstream from the intake to the aqueduct (fig. 11). The reservoir, which was built in 1929, covers between 0 and 16,000 acres depending on runoff during the particular year (table 7) and is less than 25 ft deep. The reservoir is underlain by moderately transmissive fluvial deposits composed primarily of silt, clay, and sand (fig. 4).

Mass-balance calculations for the Tinemaha Reservoir are made each day using gaged outflow (station ONYF, table 6; fig. 11) and nearby measurements of pan evaporation. Evaporation from the reservoir in excess of precipitation for water years 1945–84 was estimated to be about 300 acre-ft/yr (station TLRC, table 6). Mean annual pan evaporation for the same period was 92.6 in. (station TLYR, table 6). Measurements were not made that permit a calculation of ground-water recharge from the reservoir. This recharge is caused by the elevated stage of the reservoir in comparison with nearby ground-water levels. Some of the recharge, particularly seepage through the face of the earthen dam, may be gained back into the Owens River just downstream (south) of the reservoir, as in the case of the Pleasant Valley Reservoir. Because of the large values of river inflow and outflow (about 450 ft^3/s), any value of ground-water recharge calculated as a residual in a mass-balance equation has a high degree of uncertainty.

To gain a better understanding of the interaction of reservoirs with the ground-water system, detailed maps of surface-water and ground-water contours near each reservoir were developed. Water-level data for 1984 were plotted at a scale of 1:62,500 using a 10-foot contour interval. In the area near the Pleasant Valley Reservoir, few ground-water-level data points were available and, therefore, the contouring was inconclusive. The elevated stage of the reservoir, however, indicates that it was recharging the nearby ground-water system. In the area surrounding the Tinemaha Reservoir, the water-level data clearly indicate a hydraulic gradient from the Owens River, and possibly from the northern part of the Tinemaha Reservoir, to the northwest toward production wells along the edge of Crater Mountain (fig. 1). This gradient indicates that, as suggested by T.E. Griepentrog (Buckhorn Geotech, written commun., 1985), surface water from the reservoir was moving into and through the ground-water system in a northwest direction. This direction of movement is just opposite of the natural flow direction prior to increased pumpage in the Big Pine area. Although qualitatively helpful, the contouring methods did not yield reliable estimates of the quantity of recharge.

Water quality of outflow from the Tinemaha Reservoir was sampled bimonthly during 1974–85 as part of the USGS National Stream Quality Accounting Network. The principal ions found in the samples were calcium (the predominant cation), sodium, bicarbonate (the predominant anion), and sulfate. Total concentration of dissolved solids ranged from 66 to 274 mg/L, with a mean of 181 mg/L (Hollett and others, 1991, table 4). This particular sampling point indicates the quality of water emanating from the reservoir and may reflect some changes in chemical and physical properties because of residence time in the reservoir. Comparison of these data with data from nearby ground water may aid in understanding the dynamics of flow between the reservoir and the ground-water system. However, it is likely that additional surface-water and ground-water samples would be needed for the comparison. A similar analysis of water quality in and around the Pleasant Valley Reservoir would help answer similar questions of seepage rates and flow directions in that area.

Small Lakes

Several small lakes, including Klondike, Warren, and Diaz Lakes (figs. 3 and 11), are present in the Owens Valley. Diaz Lake and, more recently, Klondike Lake have been used for recreation, including fishing and the use of motor boats. To accommodate this usage, water levels in Klondike and Diaz Lakes have been maintained within a fairly narrow range by the diversion of water from nearby tributary streams and canals.

Prior to being used and managed for recreation in 1986, Klondike Lake functioned much as does Warren Lake. Under unmanaged conditions, water levels in both lakes fluctuate markedly from one season to another and from one year to another depending on the quantity of runoff and the altitude of nearby ground-water levels. During above-average runoff years (fig. 12 and table 7), the lakes fill; during drier periods, the lakes empty as a result of local withdrawals and evapotranspiration.

Because the lakes are topographically low points, they most likely are natural ground-water discharge areas under unmanaged conditions. During wet periods, the lakes receive an influx of water and probably act as localized recharge points to the ground-water system. In general, this type of recharge will be temporary—as the water level in the lake falls, the hydraulic gradient from the ground-water system to the lake is reestablished, and the ground-water system resumes draining. This cyclical process is similar to that observed for the lower Owens River.

Detailed analysis of the small lakes and the surrounding ground-water system is beyond the scope of the present study. However, as an aid in determining local recharge and discharge relations, water-level data were plotted at a scale of 1:62,500 using a 10-foot contour interval as was done in analyzing the reservoirs. No indications of recharge from or discharge to the lakes were evident. The absence of a noticeable hydraulic gradient suggests that the rates of exchange with the ground-water system probably are small and localized in comparison with the more dominant controls on ground-water flow, such as recharge from tributary streams and discharge to the Owens River.

Although the small lakes do not seem to have a major effect on the valleywide hydrologic system, they can be locally important. For example, Klondike Lake is north of production wells near Big Pine and may buffer the effects of pumping, much as the Tinemaha Reservoir does to the south. As pumpage increases and ground-water levels decline, additional recharge will be induced from Klondike Lake, thereby minimizing ground-water-level declines and increasing recharge to the ground-water system. The presence of fine-grained, lake-bottom sediment will inhibit, but not prevent, recharge. Similarly, Diaz Lake may provide an important source of ground-water recharge for the Lone Pine area, including the Lone Pine town-supply wells.

Canals, Ditches, and Ponds

Canals and Ditches

A complex network of canals and ditches, particularly near Bishop, have been used to convey water for irrigation, livestock, and ground-water recharge (figs. 3 and 11). The canals and ditches range in length from tens of feet to tens of miles and, although some channels are lined with broken rock or concrete, most have sides and bottom composed of native earth. The original purpose of many of the ditches in the Bishop area was to drain the soil so that the land could be farmed. Agricultural activities, begun in the late 1800's, increased rapidly and by 1920 there were about 24,000 acres of cultivated crop land and 51,000 acres of flood-irrigated pasture land (D.E. Babb, Los Angeles Department of Water and Power, written commun., 1988).

By 1978, irrigated farmlands had declined to about 17,000 acres, largely as a result of land purchases by the Los Angeles Department of Water and Power and subsequent retirement of land from irrigated use. Over the past 75 years in the Owens Valley, the net result of many separate changes in land use has been a general shift toward less local consumption of water (table 4; Hollett and others, 1991, fig. 5).

Changes in land use, beginning about 1968, affected the operation of canals and ditches. Although less land was being farmed, the allocation of water to the remaining farms and ranches was more certain. The few canals and ditches that remained in operation had a more constant flow rate during each year, and from year to year (R.H. Rawson, Los Angeles Department of Water and Power, oral commun., 1988). With more uniform conditions, recharge from the canals and ditches to the ground-water system probably also was more uniform.

As of 1988, most of the canals and ditches in the Owens Valley are used conjunctively for purposes of flood control, irrigation, stockwater, recreation, wildlife habitats, and spreading of water for recharge. The Bishop area has the highest density of canals and ditches, and most of the larger ones are operated during most of the year (fig. 11). South of Bishop, canals and ditches are concentrated in agricultural areas near the towns of Big Pine and Lone Pine, and in the vicinity of Oak Creek near Independence (fig. 3).

Parts of the Owens Valley that no longer have active farms or ranches, such as east of Independence, still have remnant canals and ditches. Some of the canals and ditches are marked by occasional trees. The ditches typically are the lowest point of the local land surface and determine the highest altitude of ground-water levels. Ground water rising to a higher altitude is drained. In extremely-high-runoff years, such as 1969 and 1983 (table 7), dormant canals and ditches in the areas south of Bishop and east of Independence are used by the Los Angeles Department of Water and Power to disperse excess surface water.

The complex and confusing array of canals and ditches in the Bishop area (fig. 3) makes detailed analysis difficult. Computations of surface-water and ground-water budgets are probably less reliable than those made for other parts of the valley. To help overcome this complexity, the Los Angeles Department of Water and Power maintains more than 500 continuously recording gaging stations on the canal and ditch system. The stations generally are equipped with a Parshall flume and recording float (R.H. Rawson, Los Angeles Department of Water and Power, oral commun., 1987). Most of the stations are used to document the quantity of water delivered to individuals who lease lands from the Los Angeles Department of Water and Power.

The specific interaction of each canal and ditch with the ground-water system is not documented, but estimates can be made by comparing measurements of discharge at the different gages and subtracting estimates of water use between the gages. Using this approach, the Los Angeles Department of Water and Power (R.H. Rawson, written commun., 1988) concluded that most of the canals lose water to the ground-water system. This interaction is just the opposite from that observed when the valley was first developed for farming in the late 1800's, when many of the canals were built to drain the soil. Some localized sections of canals, particularly in the Bishop area, may still operate as drainage ditches.

The quantity of ground-water recharge from canals and ditches varies from one year to the next depending on operating conditions. Data for the larger canals and ditches, such as the North (upper) McNally and the Big Pine Canals (fig. 11), indicate that loss rates of as much as 1.1 (ft^3/s)/mi can be sustained over a period of several months. These larger conveyances typically have water flowing in them continuously except for brief periods of maintenance. Most of the water flowing in them and the related recharge is from diversions of tributary streams and the Owens River.

However, during some periods, ground-water pumpage is the only source of water routed into some sections of the canals. Recharge under these conditions is a localized recycling of ground water. This condition is most common for the South (lower) McNally Canal, which has a series of wells spaced along its banks (fig. 11).

Riparian vegetation growing in and along the canals and ditches withdraws water from the soil-moisture zone and reduces the quantity of seepage that actually enters the ground-water system. This reduction in actual recharge was found to be minimal [less than 0.02 (ft^3/s)/mi] using calculations based on estimates of the width of vegetation (5 to 20 ft), percentage of vegetation cover (30 to 100 percent), and evapotranspiration (40 to 60 in/yr).

An estimate of recharge was made for each of the 19 larger canals and ditches, which have individual names such as the Owens River Canal. The largest of these are shown in figure 11; all 19 canals and ditches are shown on USGS 1:24,000-scale topographic maps compiled by the Los Angeles Department of Water and Power (R.H. Rawson, written commun., 1987). Recharge was calculated using measured and estimated loss rates, the measured length of the channel, and the average period of operation. Typically, the canals and ditches lost about 0.7 (ft^3/s)/mi and were operated all year. Total recharge from the named canals and ditches within the defined aquifer system (fig. 4) was estimated to average about 20,000 acre-ft/yr.

Many smaller, unnamed canals and ditches have a lower loss rate because of a smaller wetted perimeter and lesser depth of water. The recharge from these conveyances was lumped into the values of ground-water recharge from irrigation and watering of livestock discussed in later sections of this report.

The effect on native vegetation from operation of the canals and ditches is not well documented. In general, however, when a canal or ditch is taken out of service, as was the Owens River Canal (fig. 11) after 1969, recharge to the ground-water system is reduced and the quantity of water available for evapotranspiration in the immediate vicinity of the canal is less. This change may be visible as a reduction in the quantity of leaves or possibly the number of plants (Groeneveld and others, 1986b) in the immediate vicinity of the canal or ditch. If the canal or ditch is elevated above the water table, then similar effects can be expected to occur toward the center of the valley where the water table is closer to the rooting depth of native vegetation.

Ponds

Several ponds are operated in the valley, usually in conjunction with canals and ditches, for wildlife habitat and as areas to contain operational releases of surface water or to purposefully recharge the ground-water system. Some of the pond-like areas are referred to as sloughs, although the distinction generally is not important. Sloughs, which are referred to as ponds in this report, tend to be areas with a more undulating topography and a less-well-defined shoreline. The primary areas of ponds are Farmer's Ponds north of Bishop; Buckley Ponds, Arkansas Flats, Runkle Slough, and Partridge Slough south of Bishop; Thibaut Ponds near Thibaut Creek; Calvert Slough near Taboose Creek; and Billy Lake east of Independence. The location of these areas is shown on USGS 1:24,000-scale topographic maps and on land-use maps compiled by the Los Angeles Department of Water and Power (R.H. Rawson, written commun., 1987). The quantity of discharge to these areas varies with the quantity of runoff in the valley (table 7). In years with below-normal runoff, little or no water is diverted except to the few migratory-bird habitat areas, such as Farmer's Ponds. In years with unusually high quantities of runoff, the ponds are flooded with tens of thousands of acre-feet of water.

After operation of the second aqueduct was begun in 1970, purposeful recharge operations were emphasized in order to help balance the increased quantity of ground water pumped. Whenever extra surface water is available, in excess of the demands for wildlife habitat, it is diverted to areas with the most favorable ground-water-recharge characteristics. During high-runoff years, such as 1978, just the purposeful ground-water recharge from those areas has been estimated to be as much as 25,000 acre-ft (R.H. Rawson, Los Angeles Department of Water and Power, written commun., 1988). During average and below-average runoff years (fig. 12 and table 7), the total quantity of recharge from ponds is much less.

Annual recharge from each pond was estimated from an annual water-use summary obtained from the Los Angeles Department of Water and Power (R.H. Rawson, written commun., 1988). In this unpublished summary, water use is tabulated by area of the basin (Laws, Bishop, Big Pine, Tinemaha–Haiwee) and by category of water use (operational, ground-water recharge, recreation and wildlife, enhancement and mitigation). In general, operational use is defined as water that is released from the river–aqueduct system for safety or maintenance reasons; ground-water recharge is defined as water used to purposefully maximize recharge of the aquifer system; recreation and wildlife is defined as surface water released to meet the needs of wildlife, primarily birds; enhancement and mitigation is defined as water designed to meet the needs of vegetation in selected areas.

With the considerable aid of R.H. Rawson, percentages were chosen to split the summary values for each area into values for individual ponds (or pond-like areas). For example, water used in the Laws area for operational purposes is distributed to three ponds: south of the North (upper) McNally Canal, south of the South (lower) McNally Canal, and near the Laws Ditch (fig. 11). The average percentage distribution to each pond was estimated to be 40 percent, 40 percent, and 20 percent, respectively.

Also with the aid of R.H. Rawson, a recharge rate was estimated for each pond and use of water. For example, recharge from an operational release of water to the pond near the Laws Ditch was estimated to be about 20 percent of the total water released. In contrast, recharge from water designated as ground-water recharge in the same pond was estimated to be about 75 percent. This large difference in recharge rates for the same physical area results from the specific conditions, timing, and volume of the release of water. The extensive gaging-station records maintained by the Los Angeles Department of Water and Power aided in confirming the reasonableness of the estimates for water distribution and recharge. From these estimates, annual recharge was calculated for 28 different combinations of ponds and water use for water years 1970–88.

Tabulated summaries for years prior to 1970 were not available from the Los Angeles Department of Water and Power. Therefore, correlations between the 1970–88 data and the percent valleywide runoff were used to determine values of water distribution and recharge for water years 1963–69. Because changes in definitions and categories occurred during the period 1970–88, such as between “operational releases” and “ground-water recharge,” some judgement was required in assigning the earlier values. Average recharge from all ponds within the defined aquifer system (fig. 4) was estimated to be 12,000 acre-ft/yr during water years 1963–69 and 11,000 acre-ft/yr during water years 1970–84.

Owens Lake

The Owens Lake is the terminus for the natural surface-water system (figs. 1, 3, 10*D*, and 11). Runoff that is not diverted into the Los Angeles Aqueduct, recharged to the ground-water system, or evapotranspired eventually flows onto the Owens Lake playa and is evaporated.

Historically, the Owens Lake was as much as 20 ft deep, and steam-powered ferry boats crossed it. As of 1988, the lake was dry, except for a small area near the northwestern side. Spring discharge into the lake is visible along the northwestern shore—presumably ground-water discharge from the area west of the Alabama Hills. During the high-runoff year of 1983 (fig. 12), the lake occupied nearly the entire area of the playa shown in figures 1 and 10*D*, but it evaporated almost entirely within a single year. Not surprisingly, lake water and nearby ground water have exceptionally high concentrations of dissolved solids (Hollett and others, 1991; Lopes, 1988).

Although not a part of the detailed study area for this investigation, the Owens Lake remains a major factor in water-management operations within the Owens Valley. The restriction on the Los Angeles Department of Water and Power from discharging water into the lake and the occurrence of huge dust storms, which are believed to be related to rewetting of the playa and which occasionally extend from the area of the Owens Lake to north of Independence, are ongoing topics of investigation (Saint-Amand and others, 1986; Lopes, 1988).

Ground-Water System

The ground-water system of the Owens Valley is unusual in comparison with that of other basin-and-range valleys in eastern California. The abundant precipitation in the Sierra Nevada and resulting runoff fills the basin to nearly overflowing each year. Historically, this abundance of water has eroded the surrounding mountains, filled the graben with highly transmissive deposits, and created a shallow water table beneath much of the valley, a water table which in turn supports a great density of native vegetation not found in other similarly formed basins. In nearby basin-and-range valleys, such as Indian Wells Valley to the south (Dutcher and Moyle, 1973) and Death Valley to the southeast (Hunt and others, 1966), the quantity of runoff is much less and most of the sparse native vegetation must subsist solely on precipitation.

As a result of the abundant runoff into the Owens Valley, the surface-water and ground-water systems are strongly linked. Much of the valley floor is characterized by surface-water conveyances that are in contact with the ground-water system (figs. 3 and 10), and this connection facilitates a ready exchange of water. Native vegetation on the valley floor is dependent on a combination of water obtained from precipitation, subirrigation from surface-water conveyances, and ground water. Since 1970, when export of water from the valley was expanded to include ground water, the two systems have become linked even more closely politically as well as physically. Water management of one system typically has a noticeable effect on the other.

The following sections describe the hydrogeologic framework of the ground-water system; the hydraulic characteristics of the hydrogeologic units that compose the system; the source, occurrence, and movement of water through the system; and the valleywide ground-water flow model used to simulate the system and evaluate selected water-management alternatives. The hydrogeologic history of the ground-water system and related aquifer materials is described in detail by Hollett and others (1991). Many of the major components of the ground-water system are strongly linked to a surface-water feature, such as the river–aqueduct system. For these components, the primary description, including quantification of ground-water recharge and discharge, is presented in an earlier section entitled “Surface-Water System.”

Geometry and Boundary Conditions

Nearly all the recoverable ground water in the valley is in the unconsolidated to moderately consolidated sedimentary deposits and intercalated volcanic flows and pyroclastic rocks that fill the basin. Where saturated, these sedimentary deposits and volcanic rocks make up the ground-water system. The primary part of the ground-water system, defined by Hollett and others (1991) as the “aquifer system,” is capable of yielding significant quantities of ground water to wells (Lohman and others, 1972). The defined aquifer system delineated in figure 14 is also the part of the ground-water system that was simulated with the valleywide ground-water flow model documented later in this report.

The aquifer system is a three-dimensional body of valley fill that is saturated with ground water. This saturated volume of valley fill is bounded on all sides by a “boundary surface” (Franke and others, 1987). The boundary surface allows water to either flow in or out of the system, such as at the water table, or acts as a flow barrier, which allows little or no water to enter or leave the system across the boundary surface, such as at a bedrock contact.

The upper boundary surface of the aquifer system is the water table and the lower surface is either a bedrock contact, the top of moderately consolidated valley fill, or an arbitrary depth based on the depth of pumped wells. The sides of the aquifer system are either bedrock or a part of a lateral boundary surface that allows ground water to flow in or out of the aquifer system, termed a “flow boundary.” Thus, water can flow in (recharge) or out (discharge) of the aquifer system only through a flow boundary.

Flow also occurs into or out of the Owens Valley aquifer system at wells, springs, rivers, or as underflow through a cross section of the aquifer system. Lateral inflow boundaries (underflow) include sections along the southeast end of Round Valley, south end of Chalfant Valley, and that part of the two valleys overlain by the Volcanic Tableland (figs. 4, 5, and 14). Underflow also enters the aquifer system from the drainages of Bishop and Big Pine Creeks and from Waucoba Canyon. The lateral outflow boundary from the system is a section that crosses the valley approximately east to west at the south end of the Alabama Hills.

Hydrogeologic Units and Subunits

The hydrogeologic framework of the aquifer system controls the vertical and horizontal flow of ground water in the system. The complex framework of the actual system was simplified by Hollett and others (1991) into a vertical series of units that represent either ground-water-producing zones or major zones of confinement to vertical flow. These units are referred to as “hydrogeologic units” and are numbered 1 to 3, from top to bottom in the aquifer system. Saturated valley fill that lies below the defined aquifer system and in contact with the bedrock is referred to as hydrogeologic unit 4 and is not part of the aquifer system. The primary purpose for simplifying the heterogeneous sedimentary and volcanic materials into hydrogeologic units was to be able to discretize the aquifer system for the three-dimensional, ground-water flow model. Shown in figure 5 are typical hydrogeologic sections representing the major structural and depositional areas of the aquifer system and the division into hydrogeologic units. Additional sections and descriptions are presented by Pakiser and others (1964), Bateman (1965), Griepentrog and Groeneveld (1981), and Hollett and others (1991).

The criteria for dividing the aquifer system into hydrogeologic units are described in detail by Hollett and others (1991); only a summary is presented here. The first criterion used to divide the aquifer system is a method that defines the hydrogeologic units on the basis of uniform hydraulic properties, commonly represented by geologic or stratigraphic units. This method worked well for some parts of the aquifer system, such as the thick clay beds near Big Pine (section *B–B′*, fig. 5), but not for most of it. The second criterion defines hydrogeologic units on the basis of the distribution of vertical head. This method enabled the definition of units in the thick sequences of valley fill where interfingering and lateral discontinuity cause complex heterogeneity, such as beneath much of the valley floor. The third criterion defines hydrogeologic units on the basis of the depth at which significant recharge or discharge can occur. In areas of the Owens Lake Basin where little information is present to differentiate between hydrogeologic units 3 and 4 (section *C–C′*, fig. 5), the base of hydrogeologic unit 3 was chosen arbitrarily at 1.5 times the depth of the deepest production well in the area. The following is a brief description of the geologic, stratigraphic, and hydraulic characteristics of each of the hydrogeologic units.

Hydrogeologic Unit 1.—Hydrogeologic unit 1 represents the unconfined part of the aquifer system and includes the water table as the upper boundary surface. Unconfined conditions are areally pervasive throughout the aquifer system, although the depth of significant confinement varies with local conditions. Typically, the upper 100 ft of saturated deposits displays minimal restriction to the vertical movement of water, and differences in hydraulic head usually are less than 2 to 3 ft. In some parts of the aquifer system, confined conditions near the water table can be created by the less transmissive layers of the olivine basalt flows or by a fine-grained fluvial or lacustrine deposit (figs. 4 and 14). This type of local confinement near the land surface is not typical of most conditions in the valley, and hydrogeologic unit 1 can be considered generally to have a saturated thickness of about 100 ft.

Hydrogeologic Unit 2.—Hydrogeologic unit 2 is the material, where present, that separates hydrogeologic unit 1 from hydrogeologic unit 3. In the middle of the valley, this material typically consists of fine-grained silt and clay beds that restrict the vertical movement of ground water. Near Big Pine, hydrogeologic unit 2 is composed of a massive, readily identifiable clay bed with a total thickness of more than 80 ft—referred to as the “blue-green clay” by Hollett and others (1991, p. 31 and fig. 12). Vertical groundwater flow also is restricted by the volcanic materials of the Big Pine volcanic field even though they are depositionally much different from the fine-grained silt and clay beds. The volcanic material in the aquifer system near Bishop, in contrast, consists mostly of unconsolidated pumice (the lower member of the Bishop Tuff), which has hydraulic properties similar to sand and offers minimal restriction to vertical flow. Along the margins of the valley, the alluvial fan deposits are relatively homogeneous, displaying no dominant horizontal layering. In these areas, hydrogeologic unit 2 is virtually absent.

Hydrogeologic Unit 3.—Several confined zones that are present in the aquifer system have been combined into hydrogeologic unit 3. The confined part of the aquifer system generally extends from the toes of the alluvial fans along the Sierra Nevada to the toes of the alluvial fans along the Inyo and the White Mountains and extends along nearly the full length of the valley (fig. 14). Confinement is created by a number of lenticular-to-continuous, flat-lying fluvial and lacustrine clay and silty-clay beds (hydrogeologic unit 2). Confinement also can be created by fine-grained material deposited by mudflows. These confining beds thin to extinction along the margins of the valley. Additional areas of confinement may be formed by the upper member of the Bishop Tuff, where present (fig. 5), and by volcanic flows of the Big Pine volcanic field (fig. 4), but an absence of data in these areas prevents a more detailed analysis. Saturated thickness of hydrogeologic unit 3 ranges from tens of feet along the margins of the basin to about 500 ft beneath most of the valley floor.

Hydrogeologic Unit 4.—Although not part of the defined aquifer system, hydrogeologic unit 4 occupies a large part of the valley fill (fig. 5). Despite its large volume, the quantity of ground water flowing through or extractable from hydrogeologic unit 4 probably is minimal. Deep test drilling during 1988 by the Los Angeles Department of Water and Power (E.L. Coufal, oral commun., 1988) showed that most materials at depths greater than about 700 ft do not yield significant quantities of water to wells, generally less than 0.2 ft^3/s. Deep volcanic deposits penetrated by drilling near Taboose Creek (fig. 14) may yield greater quantities, although no aquifer testing was done. Except at the location of these deep test borings and a

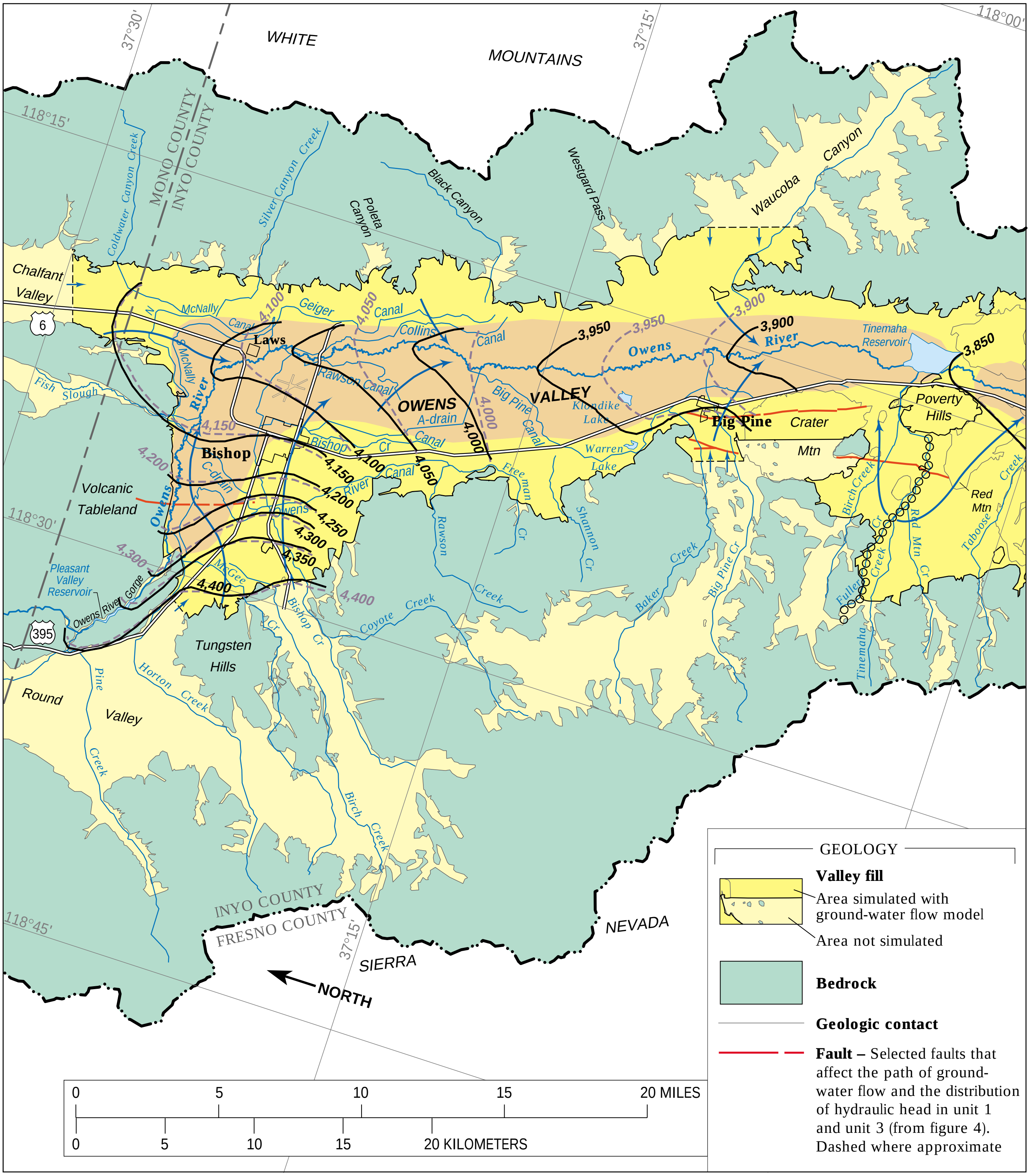
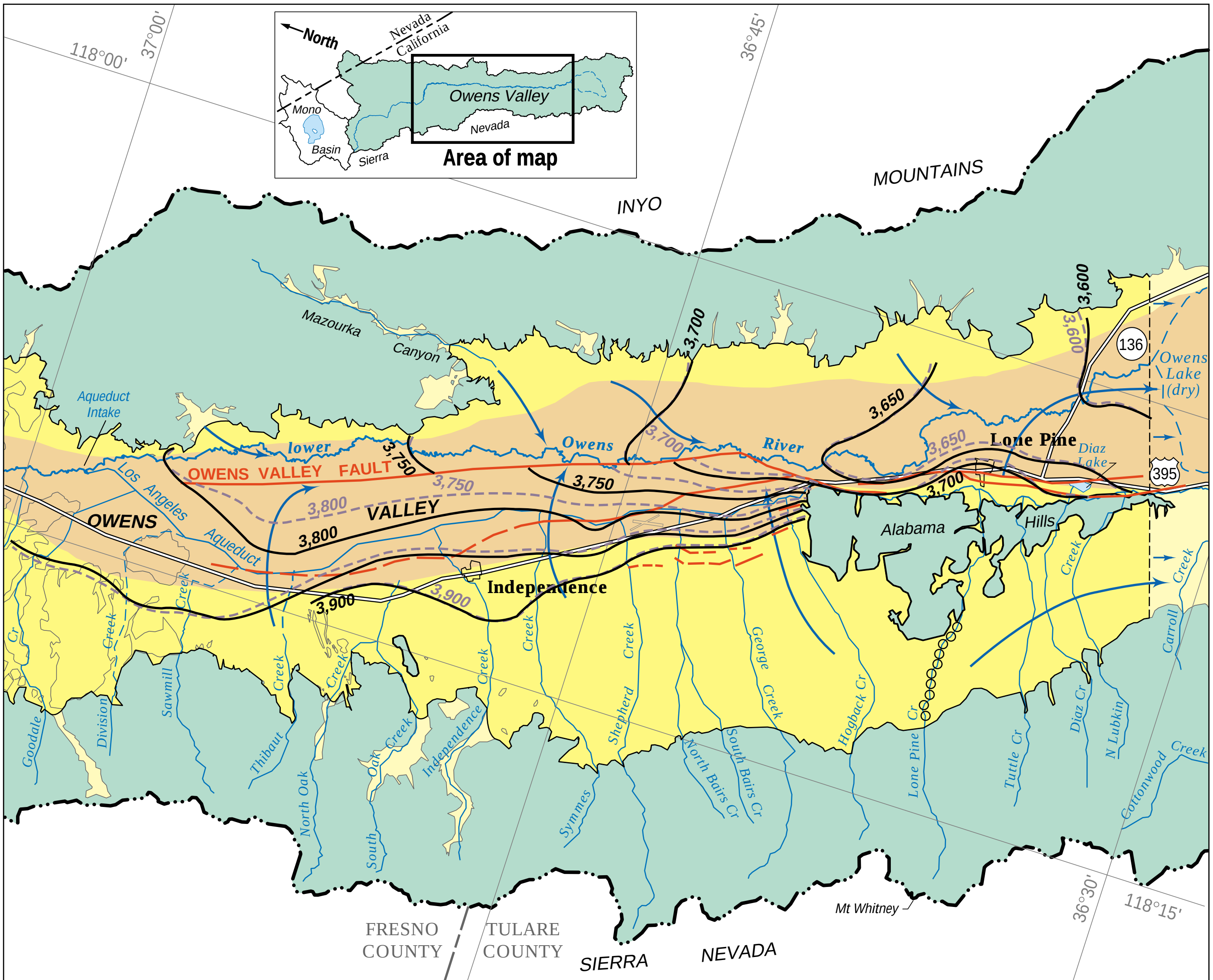


Figure 14. Ground-water conditions in the defined aquifer system of the Owens Valley, California, spring 1984. Shown area areal extent of the defined aquifer system, occurrence of unconfined and confined conditions, boundary conditions, configuration of potentiometric surface in hydrogeologic units 1 and 3, and generalized direction of ground-water flow (from Hollett and others, 1991, fig. 17).



EXPLANATION

HYDROLOGY

Approximate extent of the confined part of the aquifer

Potentiometric contour – Shows approximate altitude of the water table in hydrogeologic unit 1, represented by the upper layer of the ground-water flow model, spring 1984. Contour interval 50 feet. Datum is sea level

Potentiometric contour – Shows approximate altitude of the hydraulic head in hydrogeologic unit 3, represented by the lower layer of the ground-water flow model, spring 1984. Contour interval 50 feet. Datum is sea level

Generalized direction of ground-water flow – Combined direction of ground-water flow in hydrogeologic units 1 and 3

Ground-water divide – Approximately located

Boundary of the aquifer system – As defined in this report. Arrows indicate the direction of ground-water flow to or from adjacent permeable materials

Boundary of the Owens Valley drainage basin

Figure 14. Continued.

few previously drilled deep wells, the chemical and hydraulic characters of hydrogeologic unit 4 are largely undocumented.

Hollett and others (1991) further divided the hydrogeologic units into subunits on the basis of the type of geologic deposit (fig. 4). For example, hydrogeologic unit 1 in section *C–C′* (fig. 5) has subunits 1a representing alluvial fan deposits and 1c representing undifferentiated fluvial deposits. Hydrogeologic unit 3 in the same section has subunit 3a representing alluvial fan deposits; subunit 3t representing transition-zone deposits; and subunit 3c representing undifferentiated fluvial deposits. Additional subunits were defined for volcanic deposits and massive clay-bed deposits (figs. 4 and 5). The combination of hydrogeologic units and subunits formed the basis of ground-water “model zones” discussed later.

Hydraulic Characteristics

The hydraulic characteristics of the aquifer system—transmissivity, saturated thickness, horizontal and vertical hydraulic conductivities, specific yield, and storage coefficient—were estimated from pumped-well and aquifer tests, drill-hole data, and geophysical data. Detailed descriptions of the methods used to define the hydraulic characteristics and a general range of horizontal hydraulic conductivity and specific yield for different types of aquifer materials in the Owens Valley are presented by Hollett and others (1991, table 1). Additional confirmation of these values was obtained from preliminary ground-water flow models (Yen, 1985; Danskin, 1988; Hutchison, 1988; Hutchison and Radell, 1988a, b; Los Angeles Department of Water and Power, 1988) and from development and calibration of the final valleywide ground-water flow model documented in this report.

The areal distribution of aquifer characteristics was determined by analyses of all known pumped-well and aquifer tests, at more than 130 wells, in the valley. A complete list of the transmissivity, average horizontal hydraulic conductivity, and storage coefficient obtained from these analyses and the method of calculation (aquifer-test method) are given in table 9 (p. 155). In some cases, several calculations were made for a single well. Values calculated by the Los Angeles Department of Water and Power (M.L. Blevins, written commun., 1984–87) for some wells also were obtained. The values given in table 9 are those most representative of transmissivity unaffected by leakance and of a longer-term storage coefficient that reflects drainage of the aquifer system. These criteria were chosen in part to ensure consistency with the valleywide ground-water flow model. Leakance, if not taken into account in aquifer-test analysis, will tend to increase calculated transmissivity values. Storage coefficient, which is specific yield for water-table conditions, was difficult to calculate from the available tests. None of the values reach the 0.10–0.15 range that is characteristic of a true specific yield of these aquifer materials (Hollett and others, 1991; S.N. Davis, 1969). Much longer aquifer tests probably are required to achieve more representative values of specific yield. Calculation of storage coefficients for confined conditions was somewhat more successful; values typically ranged from 0.0005 to 0.005. Average horizontal hydraulic conductivity was calculated using an estimate of the total saturated thickness of transmissive deposits affected by the well—calculated as the depth of the well below the water table minus the total thickness of clay layers or, if data were available, as the total length of perforations.

The areal distributions of transmissivity and average horizontal hydraulic conductivity are shown in figures 15 and 16, respectively. Both sets of values are well correlated with the distribution of depositional materials (figs. 4 and 5). Values for many of the wells near the Los Angeles Aqueduct in the Owens Lake Basin reflect the buried, more transmissive, transition zone deposits (fig. 5) rather than the overlying, less transmissive, alluvial fan deposits.

In some cases, the transmissivity values in figure 15 and table 9 represent only a part of the transmissivity of the aquifer system. Some wells are not open to all of the transmissive aquifer materials, especially shallow materials, or the wells may not penetrate the entire depth of the aquifer system, especially in the volcanic areas. For these reasons, extrapolation of transmissivity values to the entire aquifer needs to be done cautiously. Alternatively, average horizontal hydraulic conductivity values (fig. 16) multiplied by an estimate of the saturated thickness of the aquifer system may yield more reliable values of transmissivity. Gross estimates of saturated thickness in the center of the valley are 100 ft and 500 ft for hydrogeologic units 1 and 3, respectively. The thickness of hydrogeologic unit 2 is minimal, generally less than 15 ft, except near Big Pine.

Movement of Ground Water

Virtually all the ground water in the Owens Valley aquifer system is derived from precipitation that falls within the Owens Valley drainage basin area (fig. 1). Ground-water recharge (deep infiltration) occurs primarily through the alluvial fans as water runs off the Sierra Nevada as a result of snowmelt or rainfall. Most of the runoff infiltrates through the heads of the alluvial fans and through the tributary stream channels. Lesser quantities of recharge result from seepage of water flowing in canals and ditches, from direct precipitation on the sparsely vegetated volcanic rocks, from runoff from bedrock areas within the valley fill, by leakage from the river–aqueduct system, and as underflow from Chalfant and Round Valleys. Underflow to the Bishop Basin from Chalfant Valley also includes water moving south from Hammil and Benton Valleys. Most of the ground water from Chalfant, Hammil, and Benton Valleys is believed to enter the Bishop Basin near Fish Slough beneath the southeastern part of the Volcanic Tableland (Hollett and others, 1991, p. 63). Recharge to the aquifer system is minimal from percolation of water that moves through fractures in the surrounding bedrock to the zone of saturation or, because of the high evapotranspiration, from water that percolates directly to the water table from rainfall on the valley floor.

Ground water moves along permeable zones of the ground-water system from areas of higher head to areas of lower head. The direction of ground-water flow is approximately perpendicular to lines of equal head. The areal pattern of ground-water flow in the valley is shown in figure 14. The vertical flow directions in hydrogeologic units 1, 2, and 3 are shown in figure 5 and can be inferred from the relative position of equal-head contours for hydrogeologic units 1 and 3 in figure 14. The Darcian rate of flow along the illustrated flow paths is determined by the hydraulic gradient, the hydraulic conductivity, and the cross-sectional area of flow. Typical rates in the valley range from less than a foot per year in clay and silt to hundreds of feet per year in the more permeable basalt. Rates of horizontal flow of water in hydrogeologic units 1 and 3 generally range from 50 to 200 ft/yr. Additional studies of ground-water quality, particularly the analysis of hydrogen and oxygen isotopes, which can be used to determine the relative age of water, would help to confirm these rates of flow.

Ground water flows from areas of recharge to areas of discharge. Discharge can be from springs, wells, evapotranspiration, or seepage to the river–aqueduct system and the lower Owens River. In general, ground-water flow is from the margins of the valley, mainly the west margin, toward the center of the valley and then southward toward the Owens Lake (fig. 14). As ground water flows downgradient to the toes of the alluvial fans and the transition-zone deposits, the flow is primarily horizontal rather than vertical (fig. 5). This horizontal flow of ground water is split by the confining beds of hydrogeologic unit 2 that interfinger with the alluvial fan and the transition-zone deposits and direct the flow of water into hydrogeologic units 1 and 3. Discharge from hydrogeologic unit 3 is generally upward through hydrogeologic unit 2 to unit 1, from pumped or flowing wells, or through the valley fill to the south end of the valley. Discharge from hydrogeologic unit 1 is principally to evapotranspiration, pumped wells, springs, the river–aqueduct system, and the lower Owens River.

In the Bishop Basin, ground water that originates as underflow from Round and Chalfant Valleys and as underflow from the lower member of the Bishop Tuff enters hydrogeologic units 1 and 3. This water mixes with water recharged through alluvial fans and through the Big Pine volcanic rocks and moves southward along the center line of the valley (fig. 14). In the Big Pine area, however, the direction of ground-water flow has changed, at least during some periods, since 1970. Increased pumpage from wells near Crater Mountain has shifted the ground-water gradient and caused ground water to flow northwest from the Tinemaha Reservoir and west from the section of the Owens River just north of the reservoir toward Crater Mountain.

In the Owens Lake Basin, water that enters the aquifer system as underflow through the narrows or as recharge through the alluvial fans moves south to the Owens Lake (dry). Most of the water is discharged to evapotranspiration, wells, or the lower Owens River. What happens to the remaining ground water that reaches the south end of the ground-water system at the Owens Lake (dry), however, is not known with certainty. The bulk of the ground water probably flows vertically upward and is discharged as evaporation from the dry lake. Minor quantities of water may flow at depth through the fractured bedrock beneath the Haiwee Reservoir to Rose Valley, which is south of the Owens Valley. Berenbrock and Martin (1991) estimated total underflow from Rose Valley south to Indian

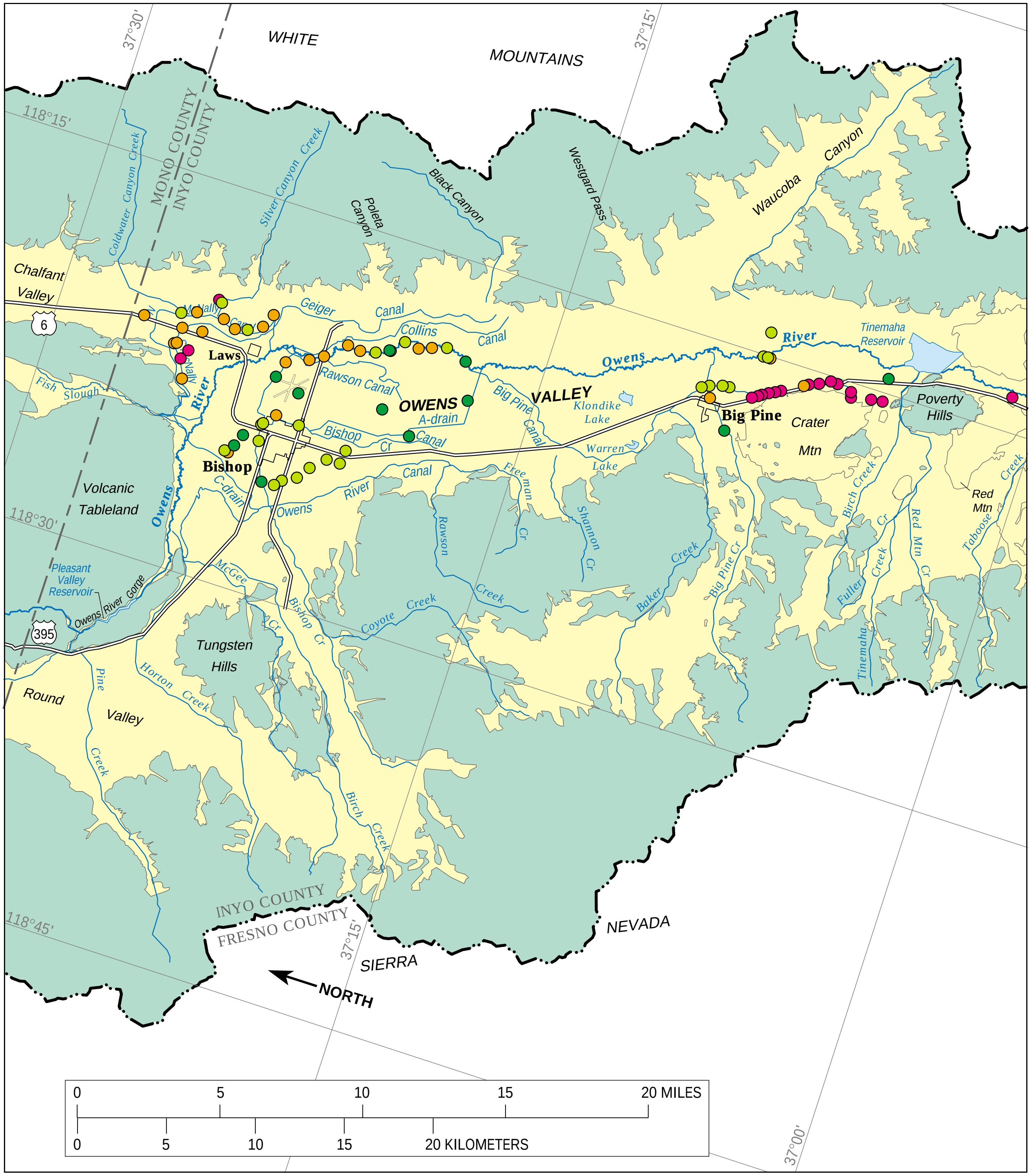


Figure 15. Transmissivity of valley-fill deposits as determined from aquifer tests in the Owens Valley, California.

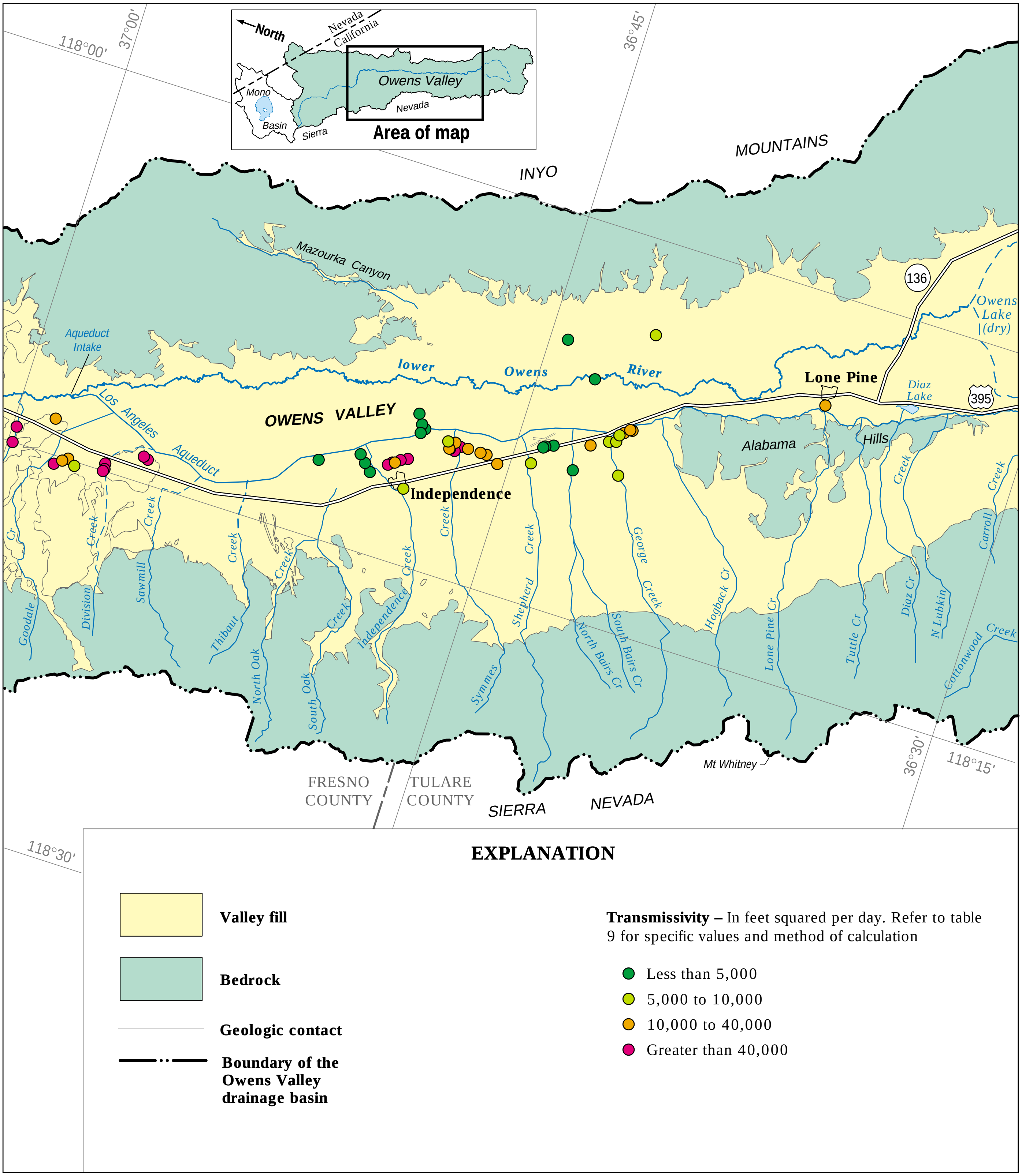


Figure 15. Continued.

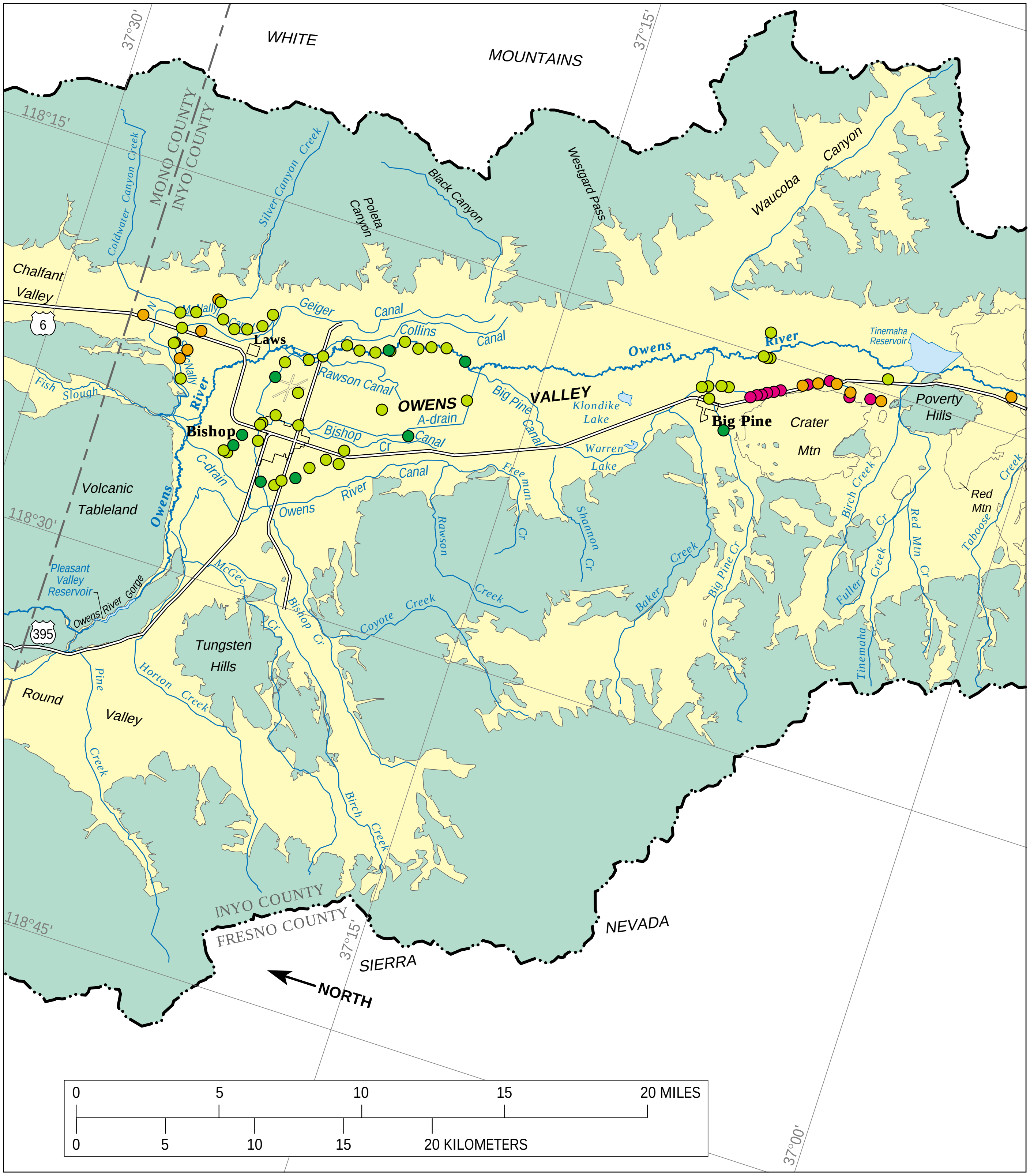


Figure 16. Average horizontal hydraulic conductivity of valley-fill deposits in the Owens Valley, California.

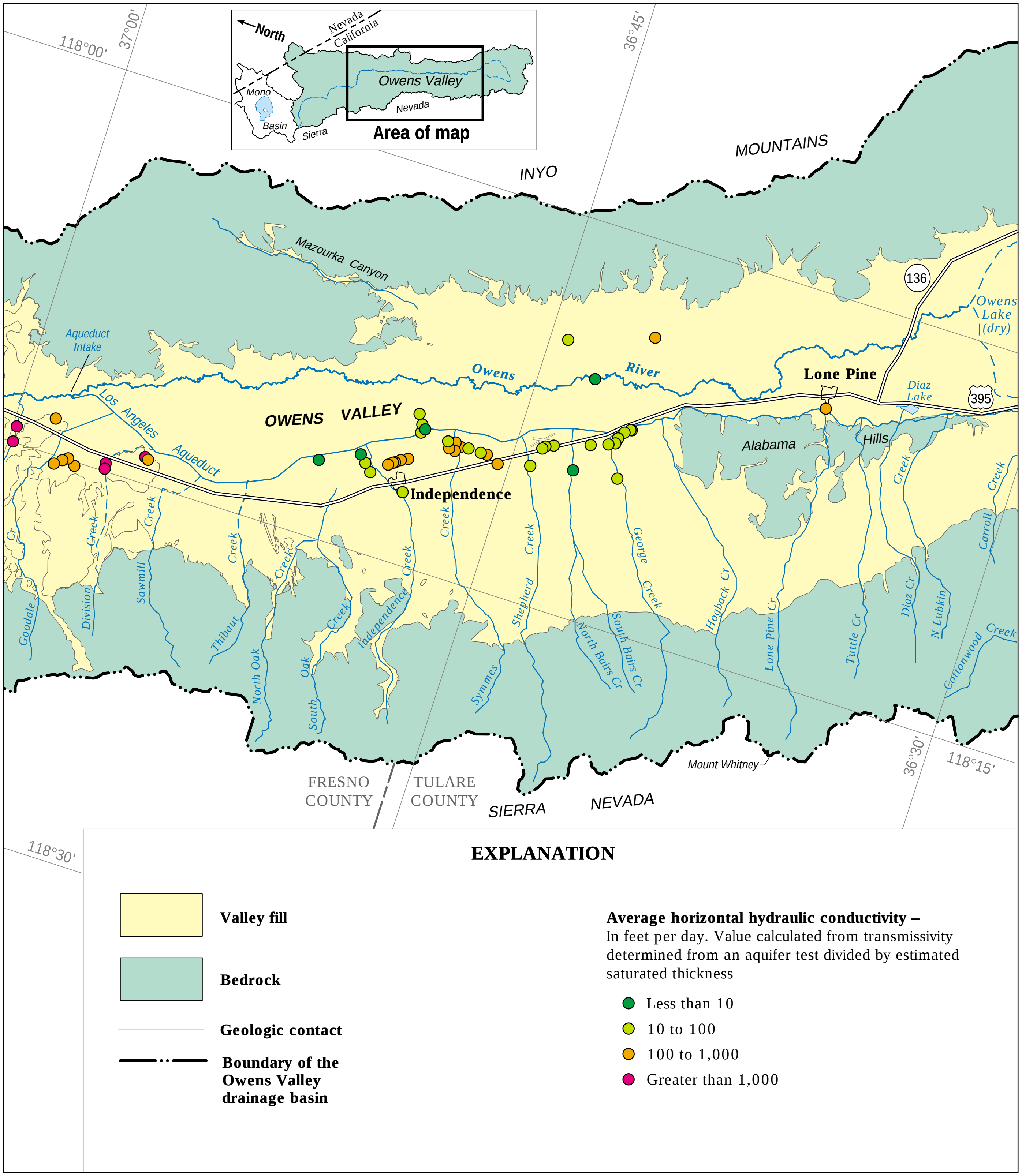


Figure 16. Continued.

Wells Valley to be less than 50 acre-ft/yr, part of which is seepage from the Haiwee Reservoir (Danskin, 1988).

The presence of faults within the aquifer system (fig. 4) may affect the movement of ground water, depending on the transmissive characteristics of the individual faults. The physical and chemical processes that cause one fault to retard ground-water movement more than another are discussed by Schaefer (1978), Freeze and Cherry (1979, p. 474) and Hollett and others (1991). Some faults in the Owens Valley, most notably the Owens Valley Fault (figs. 4 and 14), significantly retard and deflect ground-water movement. For example, the Owens Valley Fault effectively splits the Owens Lake Basin into two halves. Most ground water flows southward down the west side of the fault; lesser quantities slowly seep over and through the fault to the east side of the basin. The effects of both recharge and pumping on the west side of the basin are isolated to a large extent from the east side of the basin—except in the northern part of the Owens Lake Basin, where the Owens Valley Fault does not appear to impede ground-water movement (compare figs. 4 and 14).

Other faults that have a significant regional effect on ground-water flow were noted by Hollett and others (1991, p. 74). Additional water-retarding faults identified since that study was completed include a fault through Red Mountain (figs. 3 and 14), en echelon sliver faults near Lone Pine (figs. 4 and 14), and a probable, unexposed fault in the vicinity of west Bishop (figs. 4 and 14).

Northwest-trending faults along the east side of Crater Mountain (Hollett and others, 1991, fig.15) have created additional fractures in the highly transmissive volcanic deposits. Calibration of the ground-water flow model required much higher transmissivities in this area than for other volcanic deposits in order to maintain the unusually flat water table along the edge of Crater Mountain. These fracture conduits appear to provide an enhanced pathway for ground water recharged in the Big Pine Creek drainage to move southward through Crater Mountain to the vicinity of Fish Springs.

Some of the water-retarding faults force ground water to rise to land surface, producing noticeable seeps and springlines. Many of these features can be identified readily by an increase in vegetation (Meinzer, 1927) and are indicated by linear red zones (false color) in figure 3. An excellent example is the sequence of faults just north of the Alabama Hills (figs. 3, 4, and 14) described by D.E. Williams (1970).

In some parts of the Owens Valley, water-retarding en echelon faults have created flow compartments that are relatively isolated from the rest of the aquifer system. Areas with closely spaced faults near Lone Pine and just north of the Alabama Hills are typical of this phenomenon (fig. 4). Recharge to the compartments typically is localized, such as from a stream. Discharge may be to a spring or well. Underflow into and out of the compartment depends on the retarding effect of the fault, which may vary with depth. Simulation of these areas, as discussed later, was difficult and not particularly successful.

Hollett and others (1991, fig. 6) mapped numerous other fault traces, some of which may be locally important in affecting ground-water movement. Additional site-specific aquifer tests could be used to detect any significant retardation of ground-water flow caused by known or suspected faults in the Owens Valley. Ground-water-level data from an aquifer test show an unexpected change in the rate of drawdown if a flow-retarding fault is within the area of influence of the pumped well (Driscoll, 1986, p. 562).

The movement of ground water in the Owens Valley is controlled to a large extent by springs, seeps, evapotranspiration by native vegetation, and seepage to the river–aqueduct system and the lower Owens River. Each of these features acts as a "hydraulic buffer" on nearby ground-water levels in hydrogeologic unit 1. As the altitude of the water table increases, discharge from the springs and seeps, by native vegetation, and to the river–aqueduct system and the lower Owens River increases, thereby restricting the rise in water-table altitude. As the water table declines, discharge from each feature is reduced, thereby reducing the decline in water-table altitude. Without the broad areal distribution of these hydraulic buffers, which cover most of the valley floor, fluctuations in ground-water levels in response to changes in recharge and discharge would be much greater. The action of hydraulic buffers on ground-water levels and on recharge to and discharge from the aquifer system is a recurring theme that is exceptionally important in understanding the operation of the hydrologic system in the Owens Valley and in evaluating the effect of different water-management alternatives.

Ground-Water Budget

A ground-water budget is an accounting of the inflow to and outflow from a ground-water system (in this case, the defined aquifer system) and the changes in the volume of ground water in storage. If inflow equals outflow and if the change in the volume of ground water is zero, then the aquifer is in equilibrium or a steady-state condition. Equilibrium is reflected by nearly constant ground-water levels or by even fluctuations of levels with no long-term rise or decline. If total inflow does not equal total outflow, then the aquifer is in nonequilibrium or a transient condition, and the change in the volume of ground water in storage is reflected in the changing ground-water levels.

In several previous investigations, water budgets have been summarized for the whole hydrologic system in the Owens Valley. The investigators include C.H. Lee (1912), Conkling (1921), California Department of Water Resources (1960), D.E. Williams (1969), Los Angeles Department of Water and Power (1972, 1974b, 1975, 1976, 1978, and 1979), Griepentrog and Groeneveld (1981), and Hutchison (1986b).

Each of the water budgets, except that of Hutchison (1986b), was reviewed by Danskin (1988). In comparing the respective components of inflow and outflow, he noted that comparisons were difficult because each of the studies covered different areas or different periods of time. In addition, some of the water budgets used the same components of inflow and outflow, but with different definitions. A complete analysis of the hydrologic system of the Owens Valley, he concluded, would require at least three interrelated water budgets for the valley-fill part of the drainage basin area—a total budget for both saturated and unsaturated materials, including all precipitation and evapotranspiration; a budget for the surface-water system; and a budget for the ground-water system. To facilitate verification and comparisons, the budgets would need to cover the same area and time period and use similarly defined components.

The synthesis of three complex, interrelated water budgets was outside the scope of this study; however, significant progress in that direction has been made by development of a detailed ground-water budget (tables 10 and 11) [table 11 in pocket]. In addition, data have been collected and summarized and predictive relations have been developed for precipitation, evapotranspiration, and tributary streamflow. Eventual development of the three interrelated budgets would be needed to further refine the ground-water budget presented in this report.

The ground-water budget for the defined aquifer system shown in figure 14 is summarized in table 10. Each component of the ground-water budget is defined and discussed more fully by Hollett and others (1991). The values in table 10 are revised slightly from those presented by Hollett and others (1991, table 6), but they were developed using identical concepts and methods. Development of the ground-water budget involved using data from previous studies, new evapotranspiration and stream-loss data collected during this 6-year study, and results of simulation of the aquifer system described later in this report.

Average values for each component are given in table 10 for two time periods, water years 1963–69 and water years 1970–84. The first period represents average conditions in the aquifer system prior to increased pumpage and additional export of water from the valley (table 4). The second period represents conditions after pumpage and exports increased. The uncertainty of each value for the second period was estimated, and the likely range of values is given.

Ground-water budgets, such as the two given in table 10, can be useful in making semi-quantitative evaluations of an aquifer system, but budgets can be misinterpreted or misused quite easily (Bredehoeft and others, 1982). For example, the approximation of equilibrium is rarely satisfied over an entire system that has been modified by human activity. Localized areas in the Owens Valley likely will be undergoing change for years or decades as a result of human intervention. Changes in recharge or discharge, such as occurred in 1913 and 1970, are reflected in changes in the magnitude of several different components of the water budget (compare tables 4 and 10). In general, the interaction between the components is complex and the magnitude of the changes to the hydrologic system cannot be estimated from the budget alone. For this reason, numerical simulation is a critical part of understanding the operation of the aquifer system and the potential effects of water-management decisions.

The following components of the ground-water budget are not linked to a specific surface-water feature and were not discussed in previous sections of this report.

Discharge from Pumped and Flowing Wells

Discharge from wells includes discharge from both pumped and flowing wells, although the quantity from flowing wells is much less and is limited to a few wells along the Owens River south of Bishop and a few

Table 10. Ground-water budget for the aquifer system of the Owens Valley, California [1]

[Values in acre-feet per year. Positive numbers indicate recharge to the aquifer system; negative numbers ( ) indicate discharge from the aquifer system]

Component	Average values		Likely range of average values for water years 1970–84	
	Water years 1963–69	Water years 1970–84	Minimum	Maximum
Precipitation	2,000	2,000	0	5,000
Evapotranspiration	(112,000)	(72,000)	(50,000)	(90,000)
Tributary streams	106,000	103,000	90,000	115,000
Mountain-front recharge between tributary streams	26,000	26,000	15,000	35,000
Runoff from bedrock outcrops within the valley fill	1,000	1,000	0	2,000
Owens River and Los Angeles Aqueduct system:				
Channel seepage	(16,000)	(3,000)	0	(20,000)
Spillgates	6,000	6,000	3,000	10,000
Lower Owens River	(5,000)	(3,000)	(1,000)	(8,000)
Reservoirs and small lakes	1,000	1,000	(5,000)	5,000
Canals, ditches, and ponds	32,000	31,000	15,000	60,000
Irrigation and watering of livestock	18,000	10,000	5,000	20,000
Pumped and flowing wells	(20,000)	(98,000)	(90,000)	(110,000)
Springs and seeps	(26,000)	(6,000)	(4,000)	(10,000)
Underflow:				
Into the aquifer system	4,000	4,000	3,000	10,000
Out of the aquifer system	(10,000)	(10,000)	(5,000)	(20,000)
Total recharge	196,000	184,000	170,000	210,000
Total discharge	(189,000)	(192,000)	(175,000)	(225,000)
Change in ground-water storage[2]	7,000	(8,000)	(5,000)	(15,000)

[1] Values of water-budget components for individual years may vary considerably from the average values presented in this table. Uncertainties in the measurement and estimation of each water-budget component for water years 1970–84 are reflected in the likely range of average values. The likely ranges for total recharge, total discharge, and change in ground-water storage are estimated separately for the overall aquifer system and are somewhat less than what would be computed by summing the individual ranges for respective water-budget components.

[2] Positive change in storage indicates water going into ground-water storage; negative ( ) change in storage indicates water coming out of ground-water storage.

wells in the Independence area near the aqueduct. Several of the flowing wells also are equipped with pumps, and thus discharge sometimes is free-flowing ground water and sometimes is pumped ground water. In this report, all discharge from pumped and flowing wells is referred to informally as “ground-water pumpage.”

Nearly all ground-water pumpage is from production wells owned and operated by the Los Angeles Department of Water and Power. Most of these wells provide water for export; a few wells supply water for ranching operations and to the four major towns; and four large-capacity wells supply water to two fish hatcheries. Some additional pumpage is from private domestic and agricultural wells. Distribution of the wells (fig. 17) generally follows the river–aqueduct system. In fact, a few of the present production wells were installed in the early 1900's for dewatering and water supply during construction of the first aqueduct. Division of the wells into well fields shown in figure 17 was done on the basis of general location of the wells and included all wells with production during water years 1963–88, as reported by the Los Angeles Department of Water and Power (M.L. Blevins, written commun., 1988; table 11). The well fields identified in figure 17 and used elsewhere in this report are similar to those defined by the Los Angeles Department of

Water and Power (1979, fig. 4-4; Hollett and others, 1991, fig. 18).

Annual pumpage for individual wells for water years 1963 through 1988 was obtained from the Los Angeles Department of Water and Power (M.L. Blevins, written commun., 1988). Pumpage for water years 1963–69 was copied from typed summary sheets of well discharge per month. Pumpage for water years 1970–71 was estimated by interpolating between instantaneous discharge readings for each well. Pumpage for water years 1972–88 was obtained directly from computerized files.

Average pumpage in most areas of the Owens Valley changed dramatically after 1970, as shown by the inset graphs of well-field discharge in figure 17. Within the defined aquifer system (fig. 14), total pumpage averaged about 20,000 acre-ft/yr during water years 1963–69 and about 98,000 acre-ft/yr during water years 1970–84 (table 10). Much of this increase was caused by the switching from surface to ground water by two major fish hatcheries. The fish hatcheries, Fish Springs and Blackrock, are located near Fish Springs and Big Blackrock Springs, respectively (fig. 17). Average pumpage changed again in 1987 with the addition of new “enhancement and mitigation” wells, which were used to provide water for selected recreation and wildlife projects throughout the Owens Valley (table 4; Los Angeles and Inyo County, 1990a, p. 5–20).

The total quantity of ground-water pumpage varies each year with the quantity of runoff. In years of greater runoff, less pumpage is required for in-valley uses or for export. Pumpage also depends on the quantity of runoff in the preceding year, as shown in figure 18. When antecedent conditions are wet, the river–aqueduct system is full, and pumpage is less.

Discharge from different hydrogeologic units was investigated by analyzing each well. The first significant clay layer, as identified from the lithologic well log, was used to mark the separation between hydrogeologic units 1 and 3. Discharge from each well then was apportioned as withdrawal from hydrogeologic units 1 and 3 (upper and lower model layers) on the basis of length of perforations and estimated hydraulic conductivity of the adjacent material in hydrogeologic units 1 and 3, respectively. In most parts of the valley, well withdrawals are primarily from hydrogeologic unit 3 (fig. 17). Near the Big Pine volcanic field, many wells tend to be shallow, and most water is withdrawn from the highly transmissive volcanic deposits near the land surface (figs. 4 and 5).

Springs and Seeps

Most springs in the Owens Valley are near the toes of alluvial fans and along the edge of volcanic deposits near the Poverty Hills (fig. 17). A few springs are caused by faulting as indicated by an obvious surface trace (fig. 3; Hollett and others, 1991, fig. 15). Historically, springs have discharged a large quantity of water, most of which eventually flowed into the river–aqueduct system. For example, Fish Springs near Crater Mountain discharged as much as 22 ft^3/s prior to 1970. When ground-water pumpage increased in 1970, discharge at springs dropped dramatically, to zero at some. Average discharge from major springs within the defined aquifer system was about 33,000 acre-ft/yr during water years 1963–69 and about 8,000 acre-ft/yr during water years 1970–84. About 20 percent of this discharge was estimated to return to the aquifer system as recharge in the immediate vicinity of the springs (Hollett and others, 1991). Net discharge from the aquifer system was about 26,000 and 6,000 acre-ft/yr for the two periods, respectively (table 10).

Seeps occur along some faults where ground-water flow is forced to the land surface and along the toes of alluvial fans where ground water flows out onto the valley floor. The major seeps (shown in figures 3 and 17) discharge an unknown quantity of water, nearly all of which is evapotranspired by nearby vegetation.

Springs and to a lesser extent seeps, such as the Independence “springfield” (fig. 17), act as hydraulic buffers and exert a strong local influence on the aquifer system. The maximum altitude of the water table, particularly near the Poverty Hills, is controlled by the altitude of nearby springs and the transmissive properties of the adjacent deposits (figs. 14, 15, and 17). Fish Springs, for example, prior to an increase in nearby pumpage in 1970, was exceptionally effective at dampening fluctuations in nearby ground-water levels [well 224, pl. 1 (in pocket)]. In the Big Pine area, an increase in recharge to the aquifer resulted in an increase in discharge from Fish Springs and only a minimal rise in ground-water levels near the spring; a decrease in recharge to the aquifer resulted in a decrease in discharge from Fish Springs and only a minimal decline in ground-water levels near the spring. After 1970, the buffering effect of springs near the Poverty Hills (fig. 17) was reduced, and changes in

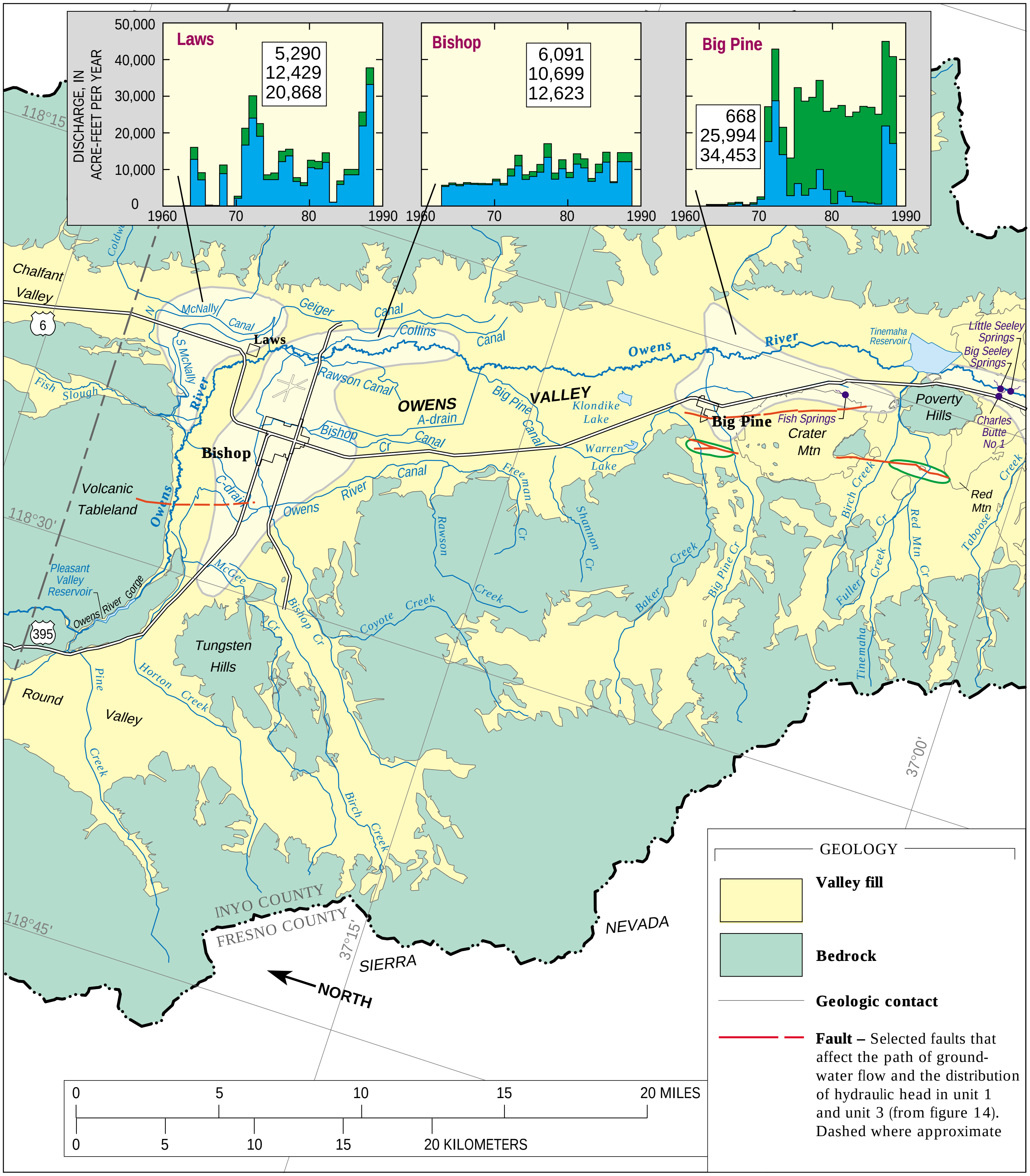


Figure 17. Location of springs, seeps, pumped or flowing wells, and approximate area of well fields in the Owens Valley, California. Inset graphs show annual discharge from each well field for water years 1963–88.

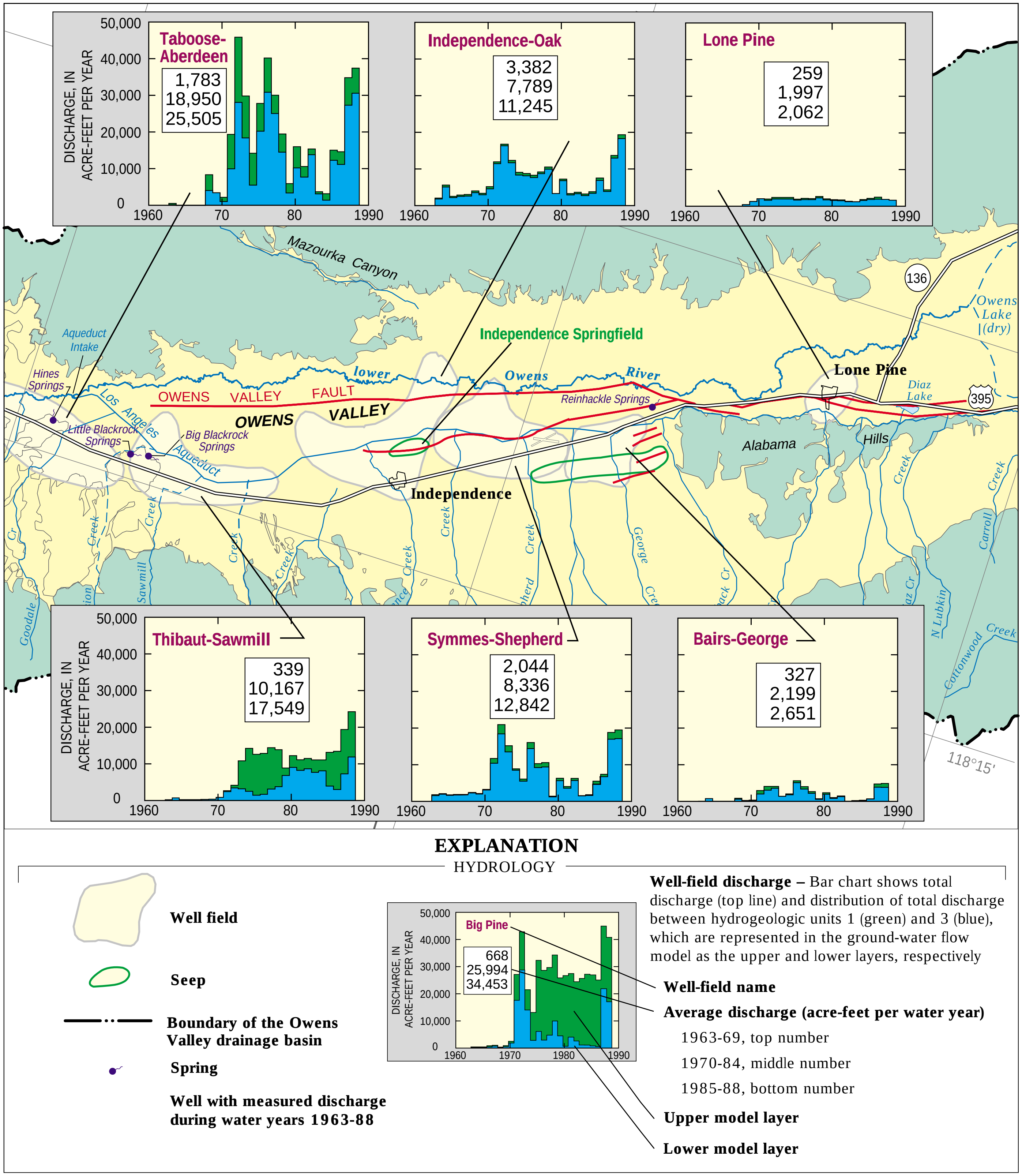


Figure 17. Continued.

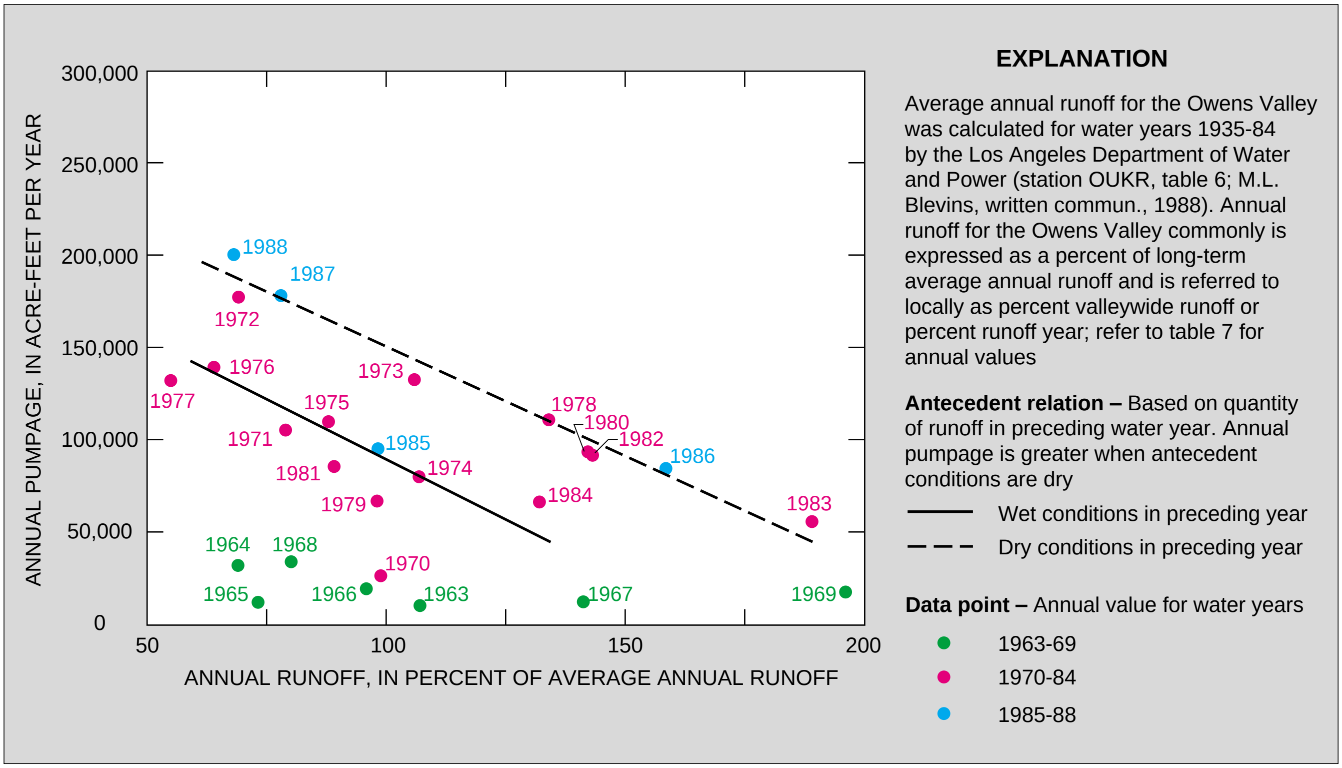


Figure 18. Relation between annual pumpage and annual runoff for the Owens Valley, California.

aquifer recharge and discharge resulted in greater fluctuations in ground-water levels.

Underflow

Underflow into and out of the aquifer system occurs at several locations shown in figure 14. Underflow from three drainages (Bishop and Big Pine Creeks and Waucoba Canyon) originates as recharge from tributary streams outside the aquifer system. For that reason, the quantity of underflow from those areas, totaling about 500 acre-ft/yr, is included for water-budget purposes as part of tributary stream recharge (table 10).

The quantity of underflow from Round Valley, the Volcanic Tableland, and Chalfant Valley is much greater and was estimated to average about 4,000 acre-ft/yr (table 10). Prior estimates of underflow from these areas were significantly higher, totaling as much as 25,000 acre-ft/yr. These estimates were based on Darcy's law (Los Angeles Department of Water and Power 1972, 1976, 1978, 1979) and on steady-state ground-water-model simulations (Danskin, 1988). As shown in table 10, the quantity of underflow into the aquifer system is not known with certainty. However, the present estimates, which are consistent with results from several different ground-water flow models developed during the cooperative USGS studies, probably are more accurate than previous estimates. The models also are based on Darcy's law, but they have additional advantages; these include incorporating nearby ground-water recharge and discharge, accounting for changes in ground-water storage, and matching various historical conditions (calibration).

Underflow out of the aquifer system occurs only across an arbitrary east–west line south of Lone Pine. In the area east of the Alabama Hills, most ground water flows out of the aquifer system through hydrogeologic unit 3, which is thicker and more transmissive than hydrogeologic unit 1. In the area west of the Alabama Hills, hydrogeologic units 1 and 3 act together, and there is no clear distinction between the two units, or indication of the relative quantity of underflow from each. Total underflow from both areas was estimated to be about 10,000 acre-ft/yr. This estimate is based on calibration of the valleywide ground-water flow model and on a water-budget analysis of the Owens Lake area by Lopes (1988). No difference in the quantity of underflow before and after 1970 was detected (table 10).

Irrigation and Watering of Livestock

Irrigation of agricultural and pasture land is still (1988) prevalent in the Owens Valley (fig. 3), although the total acreage of irrigated lands and the quantity of water applied to irrigated lands is much less than in previous years (D.E. Babb and R.H. Rawson, Los Angeles Department of Water and Power, written commun., 1988). The most recent change in water-management practices in the Owens Valley occurred in about 1968 in anticipation of providing sufficient water to fill the second aqueduct (table 4). Some land was taken out of production. Historical agricultural practices that resulted in an excessive application of water, such as using flood irrigation, were discouraged. Fields were leveled and irrigation sprinklers were installed. Water supplied by the Los Angeles Department of Water and Power to lessees was reduced from about 6 acre-ft/acre to about 5 acre-ft/acre. Watering of livestock, which typically involves diverting surface water from a canal or ditch and flooding a small area of the land surface, continued, but to a lesser degree. As a result, the total recharge from both irrigation and stock watering decreased, and the salvaged water was available for export.

Recharge to the aquifer system from irrigation and watering of livestock was estimated from maps of land use compiled by the Los Angeles Department of Water and Power (R.H. Rawson, written commun., 1988). Digitized map information was combined with assumptions about the quantity of water supplied and used per acre and the likely recharge rates on different types of soils. For years prior to 1970, water applied on volcanic materials was assumed to recharge at a rate of 24 in/yr, and water applied on other permeable materials, at a rate of 12 in/yr. For 1970–84, these rates were reduced to 12 in/yr and 6 in/yr, respectively. On the basis of these assumptions, the average recharge from irrigation and watering of livestock within the aquifer system (fig. 14) was estimated to be about 18,000 acre-ft/yr in water years 1963–69 and about 10,000 acre-ft/yr in water years 1970–84 (table 10).

Ground-Water Quality

Ground water in most parts of the Owens Valley has a preponderance of calcium and bicarbonate ions, and the range of concentrations for dissolved constituents is small (Hollett and others, 1991, fig. 21). Concentrations of dissolved solids are generally less than 300 mg/L. However, at the extreme southern end of the basin near the Owens Lake, ground-water quality is much different. A well named “Dirty Socks” (Hollett and others, 1991, fig. 18) was found to have markedly different water quality—mostly sodium, chloride, and bicarbonate ions and a concentration of dissolved solids greater than 5,000 mg/L.

In 1973–74, the Los Angeles Department of Water and Power (1974a) conducted an areally extensive study of ground-water quality that included samples from selected wells in each well field (fig. 17). Although the study focused primarily on drinking-water standards (California Department of Health Services, 1983; U.S. Environmental Protection Agency, 1977a, b, 1986), results did not reflect any major differences in ground-water quality throughout most of the valley. It was also concluded in the study that no significant changes have occurred in ground-water quality in the valley during the past 10 to 35 years.

One area of exception was noted, however. On the basis of earlier data, ground-water quality just south of the Tinemaha Reservoir seemed to be different and possibly changing from 1972 to 1973 (Roland Triay, Jr., Los Angeles Department of Water and Power, written commun., 1973). Alkalinity for wells near the Taboose–Aberdeen well field (table 9, wells 118, 349, and 116) increased between June 1972 and April 1973 by as much as 90 percent. One possible explanation is that the extensive pumping from 1970 to 1973 (fig. 17) induced movement of water from the east side of the valley toward the Taboose–Aberdeen well field. Ground water in contact with sedimentary and metamorphic rocks along the east side of the valley likely has a higher concentration of dissolved solids and a higher alkalinity than does ground water in contact with granitic rocks and near the dominant recharge areas on the west side of the valley. The significant drawdown observed at nearby wells (pl. 1, wells 362 and 347), a steep hydraulic gradient from east to west, and a pattern of increasing dissolved-solids concentration from west to east lend credibility to this explanation.

Another possible explanation is that dissolution and mobilization of soluble minerals in nearby fine-grained deposits caused the observed changes in ground-water quality (Roland Triay, Jr., Los Angeles Department of Water and Power, written commun., 1973). Also, the increased hydraulic gradient may have induced vertical movement of ground water of different quality from an adjacent part of the aquifer. Additional localized water-quality studies would help in identifying the specific flow paths of ground-water movement, particularly as influenced by pumping and artificial recharge.

More generally, a complete inventory of ground-water quality in the Owens Valley is needed to confirm ground-water concepts presented in this report and by Hollett and others (1991). Many of the older wells are open to a combination of hydrogeologic units 1, 2, and 3. Water-quality data from these wells are ambiguous and difficult to interpret. Recently installed production and observation wells that are open only to specific strata offer the opportunity to sample ground-water quality for specific hydrogeologic units of the aquifer system. Also, some of the new wells are located near and some far from areas of recharge and discharge. Water-quality information from these new wells could aid considerably in confirming the areal and vertical ground-water flow paths (fig. 14), and in identifying likely changes in flow paths. The water-quality characteristics of interest are major and minor ions; trace metals; nitrate and nitrite; hydrogen, oxygen, and carbon isotopes to date the water and identify different sources of recharge; and possibly pesticides or organic contaminants to document issues of public health.

Studies of oxygen- and hydrogen-isotope concentrations across much of southern California by Gleason and others (1994) revealed strong regional differences. Ground water from eight wells in the Owens Valley had less deuterium (that is, was much “lighter” in hydrogen isotopes) than did ground water in basins to the east and south. This trend implies that the dominant recharge to the Owens Valley ground-water basin comes from precipitation from storms that are moving westward. No trend within the Owens Valley could be detected from the scant number of samples. Although storm cells originating to the south may be important in providing water for native vegetation, the quantity of recharge to the ground-water system from such storms is much less than the quantity of recharge resulting from runoff from the Sierra Nevada.

Ground-Water Flow Model

A valleywide ground-water flow model was developed to integrate and test the concepts about the structure and physical properties of the aquifer system, the quantity of recharge and discharge, and the likely effects of water-management decisions. A numerical ground-water flow model, such as the valleywide model, is a group of mathematical equations that describe the flow of water through an aquifer. Variables (parameters) in the equations include hydraulic heads, transmissive characteristics, storage characteristics, and the rates of inflow and outflow. Different values for each variable, such as transmissivity or pumpage, can be distributed throughout the area being modeled in order to simulate observed spatial and temporal variations. This general technique is referred to as a distributed-parameter approach in contrast to a lumped approach, which uses a single value for each type of parameter.

Even when using a distributed-parameter approach, however, not all characteristics of the actual aquifer system can be included in the ground-water flow model. Simplifying assumptions are required to make the modeling effort manageable. Many of the assumptions used in developing the Owens Valley ground-water flow model are characteristic of most numerical ground-water flow models. Explanations of these assumptions are given by Remson and others (1971), Durbin (1978), Freeze and Cherry (1979), Wang and Anderson (1982), and Franke and others (1987). Assumptions underlying the particular computer program used in this study are described by McDonald and Harbaugh (1988). Additional assumptions made in the application of the computer program to the Owens Valley aquifer system are discussed in the next sections of this report.

For purposes of clarity in this report, hydraulic head (head) is used when referring to simulated hydraulic potential, which is well defined and has a precise x–y–z location. Ground-water level (level) is used when referring to general concepts of ground-water flow and to measured data, which are less well defined vertically and often represent a composite hydraulic potential.

Although a simulation model is only an approximation of the real world, it can be extremely useful in gaining an improved understanding of a complex system—in this case, a ground-water system interacting with many surface-water features. A ground-water flow model assures that estimates of local aquifer characteristics, the water budget, and hydraulic heads all are compatible. It is this attribute that gives additional confidence in the concepts and quantities presented in this report and in those described by Hollett and others (1991). In areas where data are sparse or uncertain, the ground-water flow model can be used to test the reasonableness of assumed values. Finally, a calibrated model—one for which all the parameter values are acceptable—can be used to compare the likely effects of different water-management alternatives.

General Characteristics

The computer program developed by McDonald and Harbaugh (1988) uses standard finite-difference techniques to approximate the partial differential equations that describe saturated ground-water flow. General characteristics of the numerical code include division of a ground-water system into finite-difference cells, each with uniform hydraulic properties. Multiple layers can be identified and linked with Darcy's law. A variety of different types of recharge and discharge can be simulated with constant-head, head-dependent, or specified-flux terms. Transmissivity can be constant or calculated as the product of hydraulic conductivity and saturated thickness. Both steady-state and transient conditions can be simulated, each with its own formulation. Several solvers are available, including those provided by Hill (1990a,b) and Kuiper (1987a,b) that constrain convergence of the solution using both head and mass-balance terms. The computer code is stable and flexible, and it is widely used in the public and private sectors.

Application of the numerical code to the aquifer system of the Owens Valley involved the use of two model layers. Flow between the layers was approximated by a relation that uses calculated head in vertically adjacent cells and an estimate of “vertical conductance” between the cells. Vertical conductance is calculated from vertical hydraulic conductivity, thickness between the layers, and horizontal area of the cell (McDonald and Harbaugh, 1988, p. 5–11). Transmissivity was varied between groups of model cells (model zones), but was assumed to remain constant over time. Specified flux terms were used to approximate discharge from wells and recharge from precipitation, tributary streams, canals, and ditches. Head-dependent relations were used to simulate springs, evapotranspiration, and interaction of the aquifer system with the river–aqueduct system and the lower Owens River. A 26-year simulation period included water years 1963–88 and used annual approximations of recharge and discharge.

A geographic information system (GIS) was developed to ensure an accurate spatial control of physical features and the finite-difference model grid. This accuracy was critical in linking map information, such as the vegetative mapping by the Los Angeles Department of Water and Power (fig. 9), the valleywide ground-water flow model, and the several more detailed ground-water flow models developed by Inyo County and the Los Angeles Department of Water and Power (table 2). The original digitizing of geologic and hydrologic information was done in latitude and longitude coordinates, using the North American Datum 1929, from maps with scales of 1:24,000 and 1:62,500. Replotting was done using a Universal Transverse Mercator (UTM) projection (Newton, 1985). This GIS methodology was used for all map illustrations in this report and in Hollett and others (1991). Because of the accuracy of the GIS method, subsequent computer scanning of the map illustrations should produce an accuracy of approximately 0.01 in. and permit registration with other maps drawn from a UTM projection. Detailed information on GIS and UTM mapping systems is given by J.P. Snyder (1982, 1985, 1987) and Newton (1985).

As part of the GIS system, the finite-difference model grid was linked mathematically to latitude and longitude and the UTM coordinate system. Coordinates of the finite-difference model grid are given in table 12. Projection and translation of coordinate systems (latitude-longitude, UTM, model) were done using computer programs based on those developed by Newton (1985). Use of the coordinates in table 12 and similar computer projection programs will enable future investigators to reproduce the model locations precisely. Use of this technique reduces any differences caused solely by spatial discretization and aids in duplicating specific results presented in this report.

Representation of the Aquifer System

Boundaries of the ground-water flow model conform to the physical boundaries of the Owens Valley aquifer system as shown in figure 14 and as described by Hollett and others (1991). Lateral underflow boundaries are present in eight locations: Chalfant Valley, the edge of the Volcanic Tableland, Round Valley, Bishop Creek, Big Pine Creek, Waucoba Canyon, and east and west of the Alabama Hills. All other boundaries of the aquifer system were assumed to be impermeable and were simulated with no-flow boundary conditions. The top of the aquifer system is the water table, and the bottom is either bedrock, the top of a partly consolidated unit, or an arbitrary depth based on the depth of production wells. Hydrogeologic unit 4 (fig. 5) lies below the aquifer system in the center of the valley and is a poorly transmissive part of the ground-water system. Simulation studies by Danskin (1988) concluded that this unit could be eliminated

Table 12. Map coordinates for the ground-water flow model of the aquifer system of the Owens Valley, California

[Coordinates are calculated at the outside edge of the finite-difference model grid]

Corner of model grid	Map coordinates				
	Model grid (row, column)	Latitude (north) (decimal value in parentheses)	Longitude (west) (decimal value in parentheses)	Universal Transverse Mercator (UTM) coordinates, zone 11, in meters	
Northwest	(0.0, 0.0)	37° 26' 14" (37.4371)	118° 34' 12" (118.5700)	361,101	4,144,319
Northeast	(0.0, 40.0)	37° 30' 16" (37.5044)	118° 18' 27" (118.3076)	384,423	4,151,436
Southwest	(180.0, 0.0)	36° 29' 44" (36.4955)	118° 11' 36" (118.1933)	393,126	4,039,368
Southeast	(180.0, 40.0)	36° 33' 43" (36.5619)	117° 56' 01" (117.9337)	416,449	4,046,485

from future ground-water flow models with little loss of accuracy in the upper 1,000 ft of more transmissive materials. Round Valley and the Owens Lake area also were excluded as suggested by Danskin (1988), primarily for computational reasons and because the areas were peripheral to the specific objectives of this study. Future simulation studies with more powerful computer capabilities may find that including both areas is an advantage in analyzing some water-management questions as well as in eliminating the use of specified-flux boundary conditions.

Division of the aquifer system into hydrogeologic units and model layers is more complex and somewhat more arbitrary than the selection of boundary conditions. For this study, the aquifer system was simulated using two model layers. The upper model layer (layer 1) represents hydrogeologic unit 1, the unconfined part of the aquifer system. The lower model layer (layer 2) represents hydrogeologic unit 3, the confined part of the aquifer system. Each model layer is composed of 7,200 cells created by 180 rows and 40 columns (pl. 2, in pocket). The active area of ground-water flow (active model cells) is the same in both model layers.

This division of the aquifer system permits simulation of the measured ground-water levels, which generally are either for shallow wells that monitor unconfined conditions or for deeper wells that monitor a composite confined zone. The use of two layers is consistent with the assumption that both unconfined and confined storage conditions are present in some parts of the valley (fig. 14).

To test the value of additional model layers, a smaller, more detailed ground-water flow model was developed to simulate conditions in the Big Pine area (P.D. Rogalsky, Los Angeles Department of Water and Power, written commun., 1988). Although three layers were used in the model in order to more closely approximate the complex layering of volcanic and fluvial deposits described by Hollett and others (1991), results from the more detailed model were not significantly different from results obtained using the valleywide model.

Hydrogeologic unit 2, as defined by Hollett and others (1991), usually represents either a massive clay bed, such as the blue-green clay near Big Pine (fig. 5, section *B–B'*), or overlapping lenses or beds, which are more typical of the valley fill. The Darcian relation that simulates vertical flow between the model layers was used to approximate the vertically transmissive properties of hydrogeologic unit 2. Storage characteristics of hydrogeologic unit 2 were included in the storage coefficients of the surrounding model layers. This formulation is typical of most models used to simulate ground-water movement in unconsolidated, poorly stratified deposits, such as those in the Owens Valley (Hanson and others, 1990; Berenbrock and Martin, 1991; and Londquist and Martin, 1991).

Along the edge of the basin, the clay beds thin, and hydrogeologic unit 2 virtually disappears (fig. 5, section *C–C'*). In these areas, a high value of vertical conductance was used, allowing water to move between the model layers with minimal resistance. The spatial distribution of vertical conductance and its relation to hydrogeologic model zones are shown on plate 2.

In some parts of the valley, hydrogeologic unit 2 represents volcanic deposits, such as those near Big Pine (section *B–B'* in fig. 5). The volcanic deposits have a high transmissivity but can restrict the vertical movement of water as a result of the depositional layering of individual volcanic flows. Where faulted or highly brecciated, the volcanic deposits of hydrogeologic unit 2 were represented by a high value of vertical conductance. As with other deposits represented by hydrogeologic unit 2, the transmissivity of the volcanic deposits was included in the model layer that best approximates the storage properties of the deposit—usually the upper model layer, which represents unconfined conditions.

To facilitate modeling, the aquifer system was divided into model zones, each representing part of a hydrogeologic unit or subunit (Hollett and others, 1991, pl. 2). This technique was shown to be effective in preliminary model evaluations (Danskin, 1988), although the use of additional model zones was suggested in order to simulate key areas of the basin, such as along the toes of alluvial fans. Therefore, development of the valleywide model included additional model zones—specifically, zones to represent the transition-zone deposits. Each model zone represents similar geologic materials that have fairly uniform hydraulic properties. In the volcanic areas of the basin, maintaining this uniformity was not possible. Instead, a single model zone included highly transmissive volcanic deposits along with other much less transmissive fluvial deposits (fig. 5). For these zones, the presence of volcanic deposits dominated the hydraulic properties. Outcrops of volcanic flows and cinder cones on the land surface identified likely locations of volcanic deposits in the subsurface. The actual presence of volcanic deposits was confirmed using lithologic information from well logs wherever possible. Calibration of the model was necessary to refine the locations and hydraulic properties of the volcanic zones.

A likely range of transmissivity for each model zone was determined by using the values given in table 9 and the distribution shown in figure 15. In some areas of the basin, however, little or no data were available. In these areas, the depositional models described by Hollett and others (1991, fig. 14) were used to extrapolate data and concepts. This technique based on general depositional models with specific data points throughout the aquifer system worked surprisingly well. Values of average horizontal hydraulic conductivity (fig. 16) times estimated saturated thickness were compared with estimated transmissivity values in each zone in order to ensure consistency of hydraulic conductivity, saturated thickness, and transmissivity. Other methods of interpolating transmissivity, such as kriging (Journel and Huijbregts, 1978; Sampson, 1978, 1988; Yeh, 1986), were evaluated and found to be of little use in the faulted, complex structure of the Owens Valley (figs. 4 and 5).

The transmissivity of volcanic areas was determined by means of arithmetic weighting of the estimated hydraulic conductivity and thickness of volcanic deposits with that of the surrounding sand, gravel, and silt deposits. Not surprisingly, the exceptionally transmissive volcanic deposits dominated the value of all zones where they were present (pl. 2). Only a few electric logs were available, but lithologic well logs were of great value in identifying the general type of depositional material and its appropriate zone.

Transmissivity in all areas of the model was assumed to remain constant over time (pl. 2). This assumption implies that saturated thickness of the model layer—particularly the upper, water-table layer—does not change significantly during model simulations. Changes in saturated thickness may result in differences in computed heads as a result of a mathematical nonlinearity in the ground-water-flow equations (Bear, 1979, p. 308). Because of the relative thinness of hydrogeologic unit 1, a 20-foot change in saturated thickness of unit 1 produces a 10-percent greater fluctuation in nearby water-table altitude than that predicted by the model. The modeling option to vary transmissivity over time (McDonald and Harbaugh, 1988, p. 5–10), however, creates its own set of problems. These problems include the need for significantly more detailed data for model construction and the conversion from active to inactive model cells when dewatered conditions are simulated. For the Owens valleywide model, these problems outweighed the benefits gained by varying transmissivity over time.

Vertical conductance between the two model layers was estimated from aquifer tests, development of preliminary dewatering and cross-sectional models (fig. 2), and calibration of the final valleywide model. A high correlation was found between the value of vertical conductance and the type of material in the lower model layer. In most instances, the thicker lower model layer contributed most of the impediment to vertical ground-water flow. As a result, the values of vertical conductance were keyed to the model zones representing the lower model layer (pl. 2).

Faults that restrict ground-water movement (fig. 14) were represented by lower values of transmissivity in model cells. The ratio of reduced transmissivity caused by the fault to transmissivity of adjacent aquifer materials is noted on plate 2. For example, a section of the Owens Valley Fault (F20) was determined to reduce transmissivity of the aquifer materials for that zone by a factor of 20—from 80,000 to 4,000 (gal/d)/ft.

Approximation of Recharge and Discharge

The physical characteristics of recharge to and discharge from the aquifer system are described in detail in earlier sections of this report, specifically in the sections entitled “Surface-Water System” and “Ground-Water Budget.” The following discussion describes only the approximations of ground-water recharge and discharge that were made in order to simulate these processes in the ground-water flow model. The type of boundary condition and method of approximation for each recharge and discharge component are given in table 13. Annual values for each component for water years 1963–88 are given in table 11, along with the derivation of the value (measured, estimated, or calculated by the model). The areal distribution of each recharge or discharge component in the model and the average values for each model cell for water years 1970–84 are shown on plate 3 (in pocket).

Well package.—Most of the recharge and discharge components were simulated using the well package of McDonald and Harbaugh (1988, p. 8–1). This package simulates extraction of a defined quantity of water from a specific cell in the ground-water flow model. Annual estimates for several recharge and discharge components (table 13) were combined in a pre-processing program, and the net result was used as input for the well package. In most areas of the model, only a few values in the well package represent actual discharge from wells (pl. 3*F*). Estimated flux for individual items, such as for a stream or an area of ground-water recharge, was distributed uniformly to all model cells related to that item. For example, recharge for a specific stream was the same for each model cell along its length. The individual items are listed in table 11. A few components (precipitation, spillways, and underflow) were assumed to have a virtually constant recharge or discharge rate from one year to another, and were simulated with a constant value for water

Table 13. Recharge and discharge approximations for the ground-water flow model of the aquifer system of the Owens Valley, California

[Type of boundary condition: Franke and others (1987). Ground-water flow model approximation: McDonald and Harbaugh (1988). Recharge and discharge components defined in text. Temporal variation in stress: A, annually varying rate; C, constant rate; $\overline{C}$, constant rate for several years]

Type of boundary condition	Ground-water flow model approximation	Recharge (R) or discharge (D) component	Temporal variation in stress
Specified flux	Well package	Precipitation (R)	C
		Spillgate releases (R)	C
		Underflow (R,D)	C
		Canals and ditches (R)	$\overline{C}$
		Irrigation (R)	$\overline{C}$
		Watering of livestock (R)	$\overline{C}$
		Tributary streams (R)	A
		Miscellaneous water use (R)	A
		Mountain-front runoff (R)	A
		Pumpage (D)	A
		Runoff from bedrock within the valley (R)	A
Head-dependent flux	River package	Lakes (R,D)	A
		Lower Owens River (R,D)	A
		River–aqueduct system (R,D)	A
		Sewage ponds (R,D)	A
		Tinemaha Reservoir (R,D)	A
Head-dependent flux	Evapotranspiration package	Evapotranspiration (D)	A
Head-dependent flux	Drain package	Springs and seeps (D)	A

years 1963–88. Recharge from irrigation and watering of livestock was simulated as having a constant rate for each of two periods, water years 1963–69 and 1970–88. All other components were simulated as having different annual values. Any major changes that were made to initial estimates of recharge and discharge components simulated by the well package are described below.

Some canals, ditches, and ponds probably gain water from the aquifer system, at times, instead of acting as recharge components (table 13). To attempt to account for this dual character, a head-dependent relation (in particular, the river package described below) was used to approximate some of the larger canals during development of the detailed ground-water flow model of the Bishop area (Hutchison, 1988). This technique, however, was found to dampen fluctuations in ground-water levels too severely, and it was abandoned.

Estimates of recharge from ponds were not changed, except for an initial estimate of a 90-percent percolation rate for purposeful ground-water recharge in the Laws area. This rate produced poor model results, and it was reduced during calibration to 75 percent.

Pumpage for each well was assigned to individual model cells using the map-projection and translation programs described in the previous "General Characteristics" section of this report and the well-location information given in table 9. Distribution of average measured pumpage from both model layers is shown on plate 3*F*.

Underflow was approximated, at first, using Darcy's law. The calculated quantities of underflow were distributed along the flow boundary on the basis of estimated transmissivities. These initial estimates of underflow had a high degree of uncertainty associated with them, and they did not work well in the model; subsequently, they were reduced significantly during calibration (pl. 3*G*).

River package.—Permanent surface-water bodies exchange water with the aquifer system—gaining water if nearby ground-water levels are higher than the surface-water stage, and loosing water if nearby levels are lower. A head-dependent relation, referred to as "the river package" by McDonald and Harbaugh (1988, p. 6–1), permits simulation of this type of interaction. The quantity of water exchanged is calculated by the model from the average stage of the stream, altitude of the bottom of the streambed, transmissive properties of the streambed, and model-calculated head for the upper model layer.

In order to simulate different surface-water features (table 13), the average stage and altitude of the bottom of the streambed (or equivalent riverbed or lakebed) were estimated for each model cell from values of land-surface datum obtained from 1:62,500-scale USGS topographic maps. For the Owens River, the Los Angeles Aqueduct, and the lower Owens River, the slope of the river stage from upstream to downstream model cells was checked to ensure that the slope was relatively smooth and uniformly downhill. The concrete-lined, nearly impermeable section of the Los Angeles Aqueduct near the Alabama Hills was not included in the model.

A "conductance" term is used in the river package to incorporate both the transmissive properties of the streambed and the wetted area of the surface-water feature. The transmissive properties of the streambed (bottom sediment) for each feature were estimated from typical values for valley-fill deposits (table 9; Hollett and others, 1991, table 1) and later were modified during calibration. For example, values of conductance for the lower Owens River were decreased somewhat from values for the Owens River in the Bishop Basin because deposits near the river in the Owens Lake Basin are characteristically finer and less transmissive. The wetted area of each feature was estimated from topographic maps, photographs, and field reconnaissance.

The Pleasant Valley Reservoir was not simulated explicitly in the model, although recharge from the reservoir was considered in selecting values of underflow and in evaluating the simulated gain of water by the Owens River immediately downstream from the reservoir. Use of the river package to simulate sewage ponds near the four major towns was physically realistic, but the parameters and results are highly uncertain.

Evapotranspiration package.—Evapotranspiration was calculated in the model from a piecewise-linear relation, a series of connected straight-line segments, that is based on depth of the water table below land surface (McDonald and Harbaugh, 1988, p. 10–3). An assumption was made that evapotranspiration ceases when the water table is more than 15 ft below land surface (Groeneveld and others, 1986a; Sorenson and others, 1991). When the water table is at land surface, a maximum evapotranspiration rate is reached. At intermediate depths, the evapotranspiration rate linearly decreases from the maximum rate to zero.

The average maximum evapotranspiration rate for vegetation on the valley floor was estimated to be 24 in/yr for the period prior to 1978. This estimate is based on measured evapotranspiration (table 5), results from previous modeling (Danskin, 1988), and measurements of transpiration by Groeneveld and others (1986a, p. 120). The dramatic increase in average pumping after 1970 and the drought of 1976–77 were assumed to permanently decrease the maximum vegetative cover on the valley floor. As a result, the maximum evapotranspiration rate was reduced by 25 percent from 24 in/yr to 18 in/yr for the period after 1977. This reduction was based on the reduced quantity of water available for evapotranspiration (table 10), on the variability of maximum evapotranspiration rates (table 5), and on the observed response to decreased water availability (Sorenson and others, 1991).

The maximum evapotranspiration rates used in the ground-water flow model (28 or 24 in/yr) were chosen to represent the broad areas of native vegetation covering most of the valley floor. These rates tend to underestimate evapotranspiration from riparian vegetation, for which evapotranspiration exceeds 40 to 60 in/yr (D.P. Groeneveld, Inyo County Water Department, written commun., 1984; Duell, 1990). In particular, along the lower Owens River, evapotranspiration is influenced greatly by an abundance of high-water-use cattails (fig. 10*C*). As a result, evapotranspiration calculated by the model underestimates the actual evapotranspiration near the lower Owens River, possibly by as much as 2,000 acre-ft/yr. Most of this extra discharge, however, is simulated by the river package as a gain to the lower Owens River. The net effect on the aquifer system is the same although the accounting is different. This artifact of the model is recognized as potentially confusing, but it does not alter any of the basic conclusions presented in this report.

Drain package.—Springs and seeps were simulated with the head-dependent relation referred to as “the drain package” by McDonald and Harbaugh (1988, p. 9–1). This relation uses a value of the transmissive properties (conductance) of the spring and the simulated model head to compute a discharge—if the model head is higher than a specified drain altitude. If the model head is lower, discharge is zero. The drain altitudes were chosen on the basis of a leveling survey of each spring (R.H. Rawson, Los Angeles Department of Water and Power, written commun., 1988), or on a value of land surface obtained from 1:62,500-scale USGS topographic maps.

Simulation Periods

Simulation periods were chosen to calibrate and verify the ground-water flow model, to evaluate past water-management practices, and to predict the likely condition of the aquifer system after 1988. Historical periods of similar water use, as summarized in table 4, were used as an aid in selecting simulation periods that capture the main elements of water management in the Owens Valley and rigorously test the model.

Water year 1963 was chosen to calibrate the ground-water flow model under equilibrium or steady-state conditions. This particular period was chosen for three reasons. First, ground-water levels did not seem to change significantly during water year 1963, a prerequisite for a steady-state analysis. Second, the percent of valleywide runoff for water year 1963 was about average (107 percent of normal). Third, although water year 1963 was preceded by a short-term increase in ground-water pumpage, the year was sufficiently isolated from major runoff or pumping effects that the aquifer system was assumed to be in a quasi-steady-state condition—that is, sufficiently stable to begin a transient simulation.

Water years 1963–84 were chosen to calibrate the ground-water flow model under nonequilibrium or transient conditions. Stable initial conditions were ensured by beginning the transient simulation with results from the steady-state simulation of water year 1963. The first part of this period, water years 1963–69, represents conditions in the valley prior to completion of the second aqueduct (table 4). The Los Angeles Department of Water and Power (1972) showed that the valleywide system was in approximate equilibrium for water years 1935–69 and, except for brief periods of heavy pumping during the 1930's and early 1960's, probably in near-equilibrium for most of the period between the completion of the first aqueduct in 1913 and the second in 1970. Therefore, the first part of the calibration period, water years 1963–69, was assumed to be fairly analogous to the entire period prior to operation of the second aqueduct.

The second part of the calibration period, water years 1970–84, represents the significantly different conditions in the valley after completion of the second aqueduct and the related changes in water use (table 4). This second period was a time of significantly increased pumpage, a decrease in water supplied for agricultural and ranching operations, a severe drought (1976–77), and extremely wet conditions following the drought. The ability of the model to simulate such diversity of conditions within the same calibration period reflects on its appropriate design and helps to confirm that the model is a fairly complete representation of the actual aquifer system.

Water years 1985–88 were chosen to verify that the ground-water flow model was not uniquely tuned to the calibration period and could be used to evaluate non-calibration periods. The verification period, although short, is a good test of the calibrated ground-water flow model because there are significant fluctuations in runoff and pumpage. Also, new high-production "enhancement and mitigation" wells were put into service. The verification period was simulated after calibration of the model was complete. Recharge and discharge components required for the verification period were calculated in the same way as for the calibration period. No changes were made to recharge, discharge, or other parameters in the ground-water flow model. In fact, as it turned out, all model simulations for the verification period were completed prior to obtaining and reviewing measured ground-water-level data for the period—a rather unnerving, if somewhat fortuitous sequence for verification.

A final simulation period was defined to represent "1988 steady-state conditions"—that is, the equilibrium that the aquifer system would reach if operations as of 1988 were continued well into the future. Preliminary evaluation at the beginning of the cooperative studies identified water year 1984 as a likely period that could be used to simulate average present conditions. Subsequent analysis, however, determined that the Owens Valley was in the midst of significant vegetation and hydrologic changes and that stable quasi-steady-state conditions did not exist in 1984. Therefore, a more generalized steady-state simulation was designed, taking into account long-term average runoff and new enhancement and mitigation wells that were installed after 1984. This simulation and the related assumptions and approximations are described later in this report in a section entitled "Alternative 1: Continue 1988 Operations."

Calibration

Calibration of the ground-water flow model involved a trial-and-error adjustment of model parameters representing aquifer characteristics and certain recharge and discharge components in order to obtain an acceptable match between measured ground-water levels and computed heads and between estimated and computed recharge and discharge. For example, more than 200 hydrographs displaying levels and heads were reviewed throughout the calibration process; 67 of these hydrographs for 56 model cells are shown on plate 1. Also, simulated recharge and discharge were reviewed extensively on a "cell-by-cell" basis (McDonald and Harbaugh, 1988, p. 4–15) to ensure that the magnitude and distribution of computed ground-water flows (fluxes) were appropriate. The calibration process was continued until further changes in the ground-water flow model did not significantly improve the results and until the model parameters, inflows and outflows, and heads were within the uncertainty of historical data.

The philosophy of model development and calibration was to use general relations for as many components of the model as possible. These relations, or conceptual themes, permit an improved understanding of the overall model and its more than 100,000 parameters. For example, the hydraulic characteristics of the model were based on hydrogeologic subunits (model zones), each with uniform hydraulic properties. Reductions in transmissivity caused by faults were calculated as a percentage of the transmissivity of the faulted material (pl. 2). Recharge and discharge commonly were related to a more general concept, such as the percent of average valleywide runoff. Detailed, site-specific adjustment of parameters or relations was done rarely, if at all. Because of the way it was calibrated, the model is most useful for evaluating valleywide conditions, not for predicting small-scale effects covering a few model cells. Site-specific ground-water flow models or multivariate regression models, such as developed by P.B. Williams (1978) and Hutchison (1991), can give more accurate predictions at selected sites. However, these models in turn are less useful for evaluating valleywide hydrogeologic concepts or predicting valleywide results of water-management decisions.

The calibration procedure first involved estimating initial values of inflow and outflow to the aquifer system for the steady-state period, water year 1963. Many of the estimates were obtained from preliminary work by Danskin (1988). Adjustments were made in some of the initial estimates in order to ensure a balance of inflow and outflow as well as to match the distribution of measured ground-water levels. An assumption in the calibration of steady-state conditions was that ground-water levels in 1963 were similar to those in 1984 for most parts of the basin (fig. 14). This assumption was necessary because of the absence of virtually any ground-water-level data prior to 1974 for hydrogeologic unit 1.

The bulk of the calibration involved making adjustments to the model that are based on the transient behavior of the aquifer system during the 22-year period, water years 1963–84. To ensure stable initial conditions, the steady-state period was resimulated each time changes were made to the model. Also, the distribution of head and the pattern of ground-water flow were reevaluated for each steady-state simulation to ensure that they remained conceptually valid and similar to those shown in figure 14.

Transmissivity values were adjusted within the general range indicated by aquifer tests (fig. 15 and table 9) and related studies (Hollett and others, 1991; Berenbrock and Martin, 1991). Calibrated values of transmissivity were slightly higher than initial estimates for highly transmissive volcanic deposits, especially in the area of Crater Mountain near Fish Springs (fig. 15 and pl. 2).

Values of vertical conductance were constrained to approximately the same values derived from the preliminary models (fig. 2) and from aquifer tests described by Hollett and others (1991). Values were adjusted until simulated heads in the upper and lower model layers matched measured ground-water levels indicated on contour maps (fig. 14) and on hydrographs (pl. 1). For most of the area covered by alluvial fan deposits, measured levels were not available. In these areas, values of vertical conductance were adjusted so that simulated heads in the two layers differed by less than 1 ft.

Storage coefficients were held constant at 0.1 and 0.001 for the upper and lower model layers, respectively. For the upper model layer, the storage coefficient is virtually equivalent to specific yield. Values determined from aquifer tests (table 9), as expected, were lower than model values. Aquifer tests, even those extending several days, are affected most by the compressive response of the aquifer and expansion of ground water and are affected very little by actual drainage of the aquifer materials. This drainage, which accounts for nearly all of the specific-yield value, is delayed and occurs slowly over a period of weeks, months, or years. As a result, storage coefficients obtained from model calibration of long-term conditions usually are much more indicative of actual values than are those calculated from aquifer tests. Attempts at specifying unique storage coefficients for each hydrogeologic unit proved to be tediously unproductive.

All recharge and discharge components had conceptual or semi-quantitative bounds associated with them. These bounds (which are discussed in greater detail in other sections of this report, including "Surface-Water System" and "Ground-Water Budget") restricted model calibration in much the same way as did measured ground-water levels (pl. 1). Some recharge and discharge components (recharge from precipitation, recharge from spillgates, and underflow) were assigned constant rates on the basis of their uniform characteristics from one year to another (tables 11 and 13). All other components were varied annually on the basis of a general concept such as percent annual runoff.

Most recharge and discharge components did require some degree of adjustment, often minor, during calibration. This adjustment was needed not only to match measured conditions, but also to ensure that a consistency between different recharge and discharge components was maintained. For example, changing recharge from a narrow canal on the valley floor required re-evaluating the quantity of recharge from narrow tributary streams on alluvial fans and from broad river channels on the valley floor. The philosophy of calibration did not permit adjusting values in individual model cells in order to match historical conditions.

The location and type of model boundaries were assumed to be known and were not varied. The quantity of underflow, however, was reduced considerably from previous estimates by Danskin (1988) and the Los Angeles Department of Water and Power (1976). Recharge from canals was slightly less than original estimates. Recharge from purposeful water-spreading operations was about two-thirds of the initial estimate. Conductance of both the river–aqueduct and the lower Owens River were increased during calibration, thereby increasing ground-water recharge to or discharge from them. The quantity of evapotranspiration was less than original estimates. Pumpage was assumed to be known and was not changed.

Land-surface datum was used in many parts of the model, particularly in defining head-dependent relations and estimating precipitation (fig. 7*B*). Attempts at computing land-surface values from 1:250,000-scale AMS (Army Mapping Service) point data sets obtained from R.J. Blakely (U.S. Geological Survey, written commun., 1986) required fitting a surface to the point data; results were not satisfactory, especially in areas of abrupt change in slope of the land surface, such as near the Tinemaha Reservoir. Therefore, the values were interpolated by hand from 1:62,500-scale USGS topographic maps and held constant during calibration.

Results of the model calibration are displayed in figures 19 and 20, which show comparisons of measured ground-water levels and simulated heads during spring 1984 for the upper and lower model layers, respectively. This was a time when levels were higher than they had been for several years, dormant springs had resumed some discharge, and the basin was assumed to be in a nearly full condition (Hollett and others, 1991). The match between measured levels and simulated heads for both the upper and the lower model layers seems to be quite good for most parts of the basin. A notable exception is the area west of Bishop near the Tungsten Hills.

Measured water levels and simulated heads for individual wells are compared on plate 1. Although more than 200 wells were used extensively in the calibration process, only 67 wells are included on plate 1. The 67 wells were selected to represent different well fields, different model layers, and different hydrogeologic subunits (model zones). Some wells were included on plate 1 to illustrate those parts of the valley where the ability of the model to simulate actual conditions is not as good as in other locations—for example, well 278 near Bishop and well 172 near Lone Pine (pl. 1).

Precise tracking of the measured and simulated hydrographs (pl. 1) was not deemed necessary, and might not be desirable or correct depending on the characteristics of the well, the surrounding aquifer material, and the model cell approximating the well. Of primary importance was that the measured and simulated hydrographs be of the same general shape and trend. Shape of a hydrograph is influenced by aquifer characteristics, recharge, and discharge; trend is influenced most by change in aquifer storage. The magnitude of vertical deflection likely will be different for measured and simulated hydrographs because of spatial discretization required for the model. The ratio of vertical deflections between the two hydrographs, however, should remain similar over time. Vertical offsets might or might not be important depending on the specific well. For example, an acceptable vertical offset can result when a well is located away from the center of a model cell; this type of offset is particularly noticeable in areas of steep hydraulic gradients, such as on the alluvial fans.

During calibration of the valleywide model, the comparison between estimated and simulated recharge and discharge was as important as the comparison between measured ground-water levels and simulated heads. Recharge and discharge components that act as hydraulic buffers respond to changes in other model parameters and reflect the dynamics of the aquifer system—sometimes much better than do changes in head. The simulated recharge and discharge for the dominant fluxes in the model after calibration are shown in figure 21.

As an aid in using and extending the work presented in this report, simulated values for each component of recharge and discharge in the ground-water flow model are given in table 11. The individual values are important aids in compiling water budgets for specific parts of the valley; developing linked water budgets for the surface-water and ground-water systems; defining the relative degree of confidence to be placed in model results in different parts of the valley; identifying how to revise and improve the model; and making local water-management decisions.

In places where concepts or data were uncertain, the ground-water flow model was not calibrated forcibly to produce a match between simulated heads and measured levels. For example, in the area north of Laws, something is missing in the ground-water flow model. Simulated heads in layer 1 do not recover after 1974 as fully as do the measured levels (well 107T, pl. 1). The actual recovery could be caused by any of several processes—increased underflow during the drawdown period, induced flow of water from Fish Slough or the Bishop Tuff, increased percolation of operational spreading of surface water, or changes in the operation of nearby canals. Without a valid reason to pick one process rather than another, none was altered during calibration—thus highlighting an area of uncertainty and an area where further work is necessary. This approach was a major philosophy of the modeling study and the rationale for including some of the hydrographs shown on plate 1.

Verification

Water years 1985–88 were used to verify that the calibrated ground-water flow model will duplicate measured data for a non-calibration period. The 4-year verification period included significant stress on the aquifer system because of unusually wet and dry

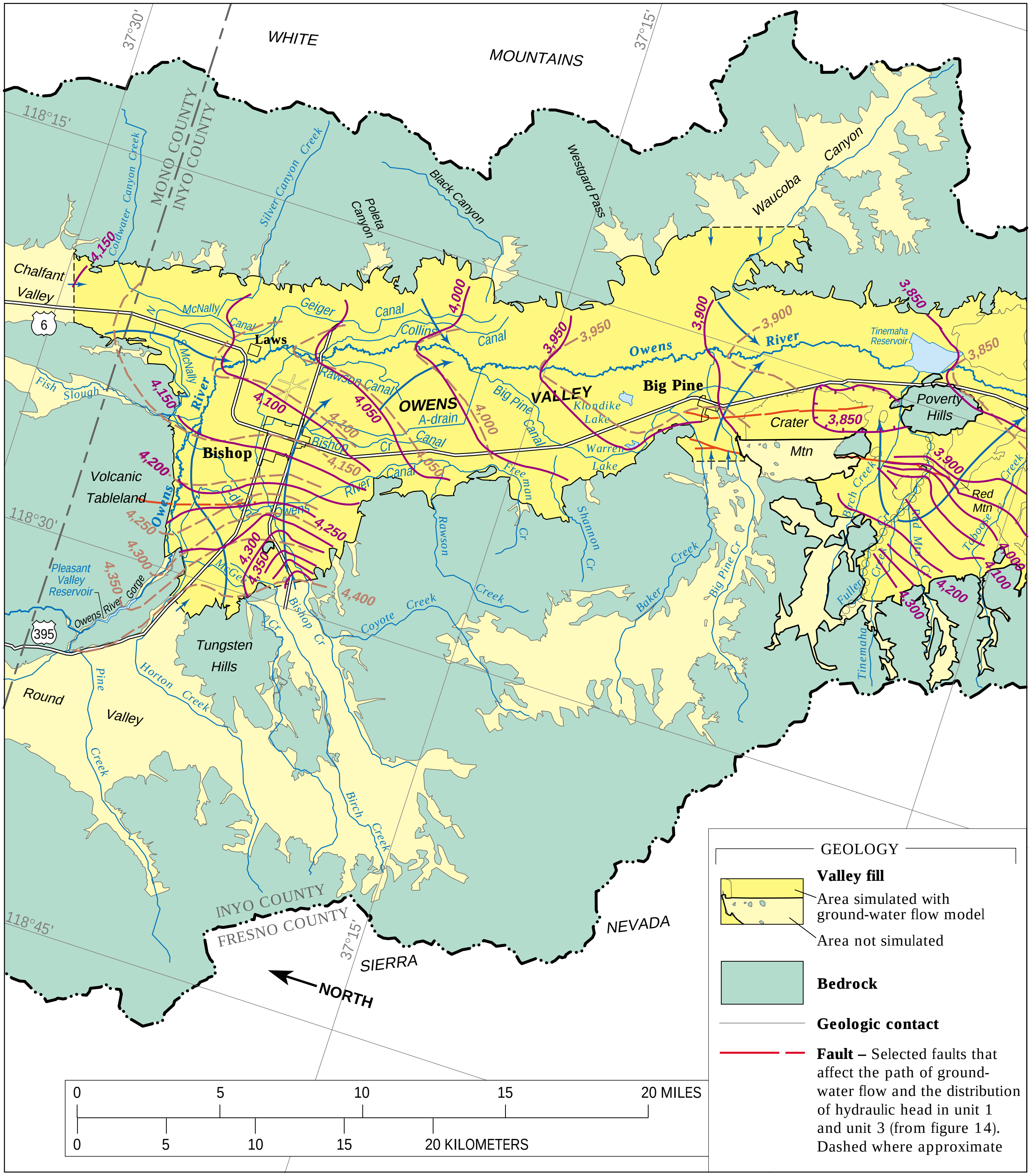
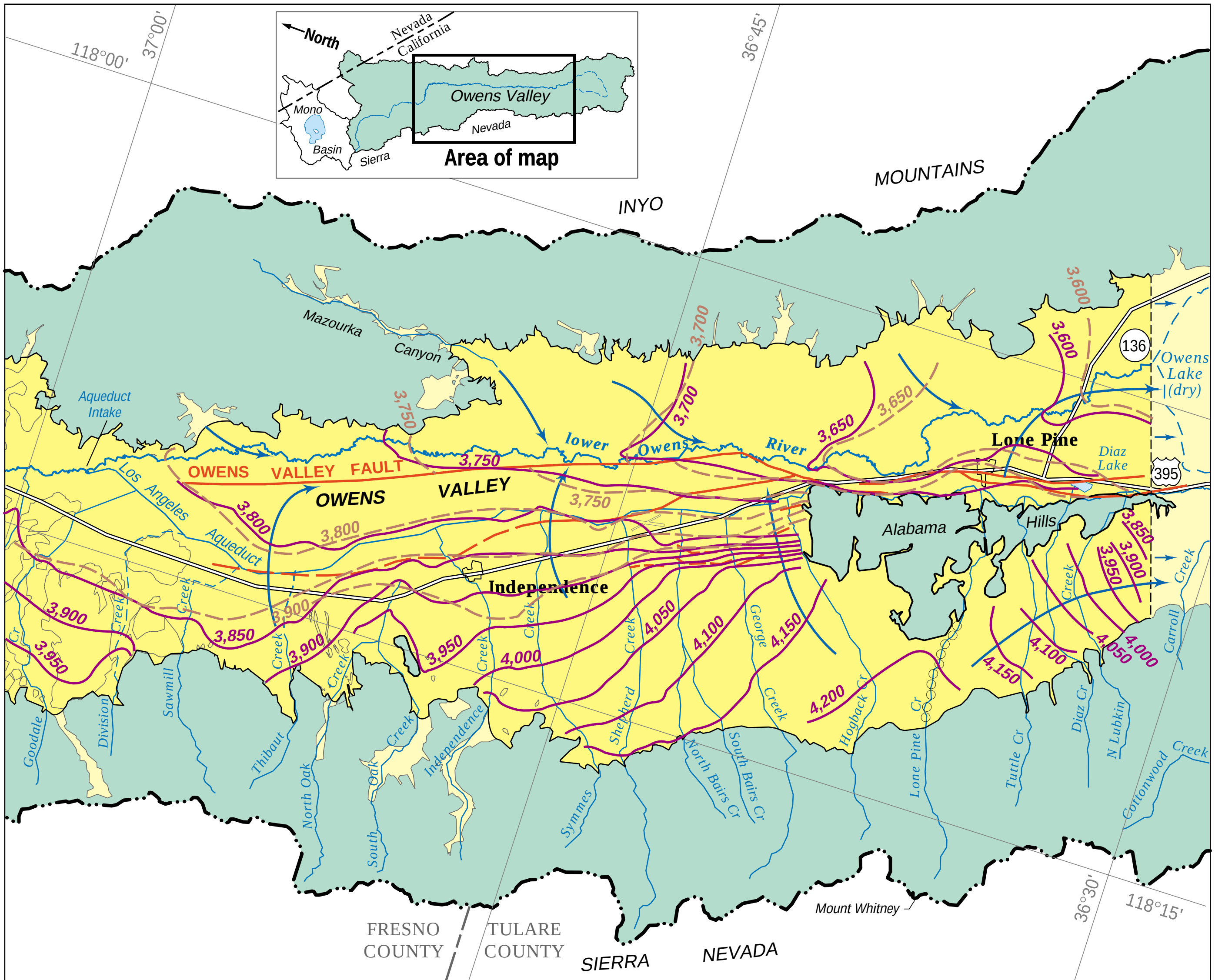


Figure 19. Measured and simulated potentiometric surfaces for hydrogeologic unit 1 (upper model layer) in the Owens Valley, California, spring 1984.



EXPLANATION

HYDROLOGY

3,900 Measured — **Potentiometric contour –** Shows approximate altitude of the water table in hydrogeologic unit 1, represented by the upper layer of the ground-water flow model, spring 1984. Contour interval 50 feet. Datum is sea level

3,900 Simulated

Generalized direction of ground-water flow – Combined direction of ground-water flow in hydrogeologic units 1 and 3

Ground-water divide – Approximately located

Boundary of the aquifer system – As defined in this report. Arrows indicate the direction of ground-water flow to or from adjacent permeable materials

Boundary of the Owens Valley drainage basin

Figure 19. Continued.

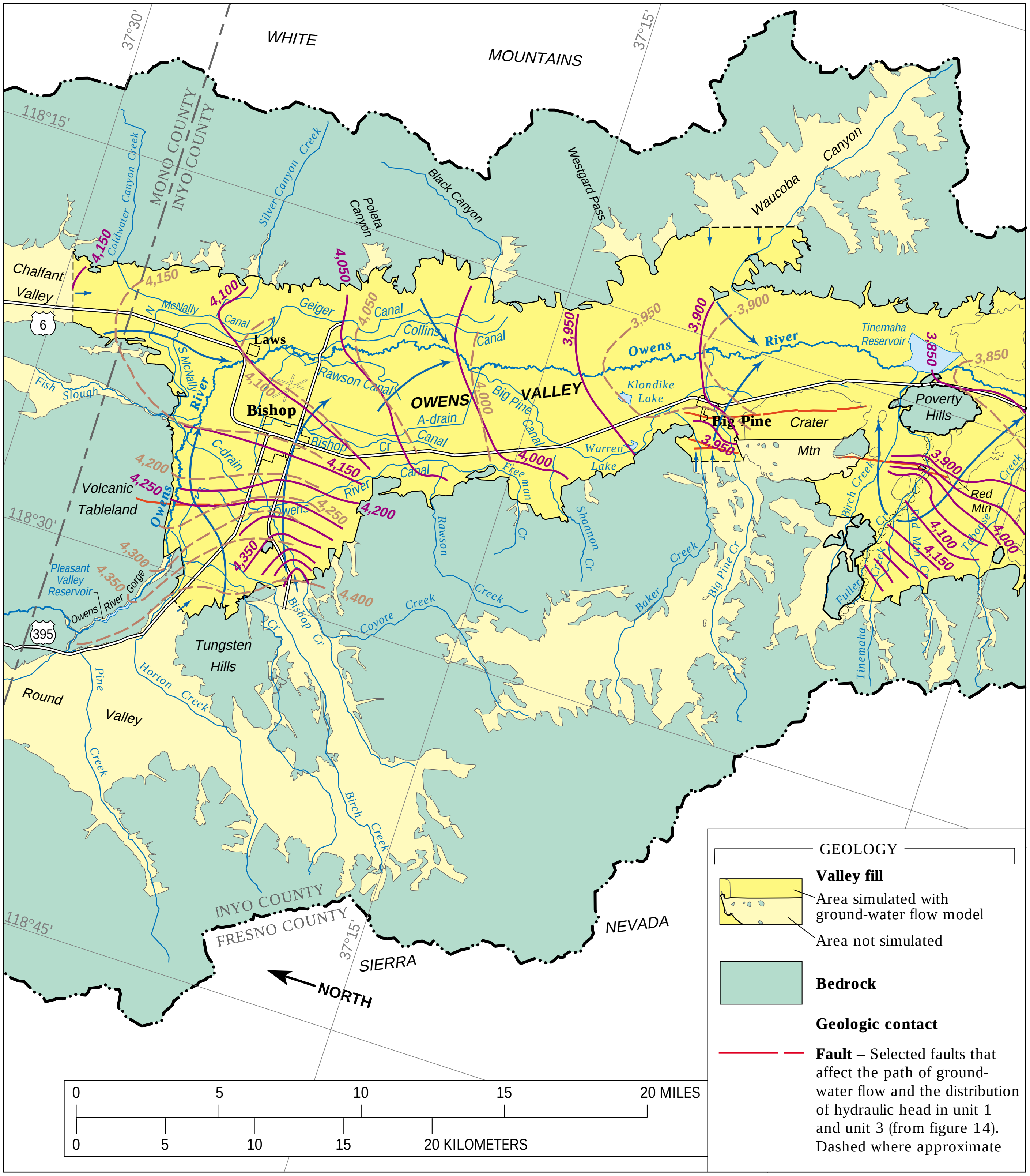
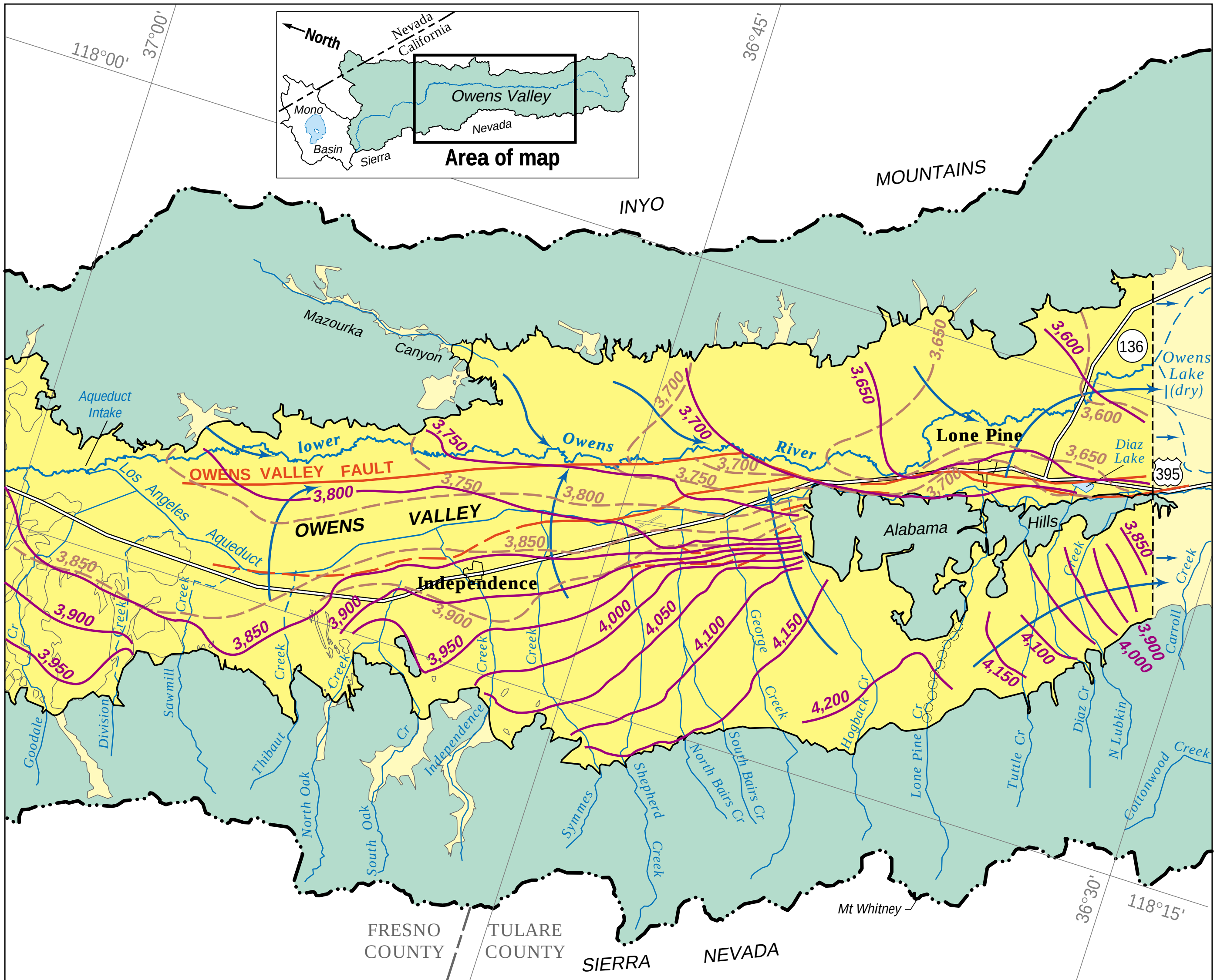


Figure 20. Measured and simulated potentiometric surfaces for hydrogeologic unit 3 (lower model layer) in the Owens Valley, California, spring 1984.



EXPLANATION

HYDROLOGY

3,900 — Measured; 3,900 — Simulated: **Potentiometric contour –** Shows approximate altitude of the hydraulic head in hydrogeologic unit 3, represented by the lower layer of the ground-water flow model, spring 1984. Contour interval 50 feet. Datum is sea level

Generalized direction of ground-water flow – Combined direction of ground-water flow in hydrogeologic units 1 and 3

Ground-water divide – Approximately located

Boundary of the aquifer system – As defined in this report. Arrows indicate the direction of ground-water flow to or from adjacent permeable materials

Boundary of the Owens Valley drainage basin

Figure 20. Continued.

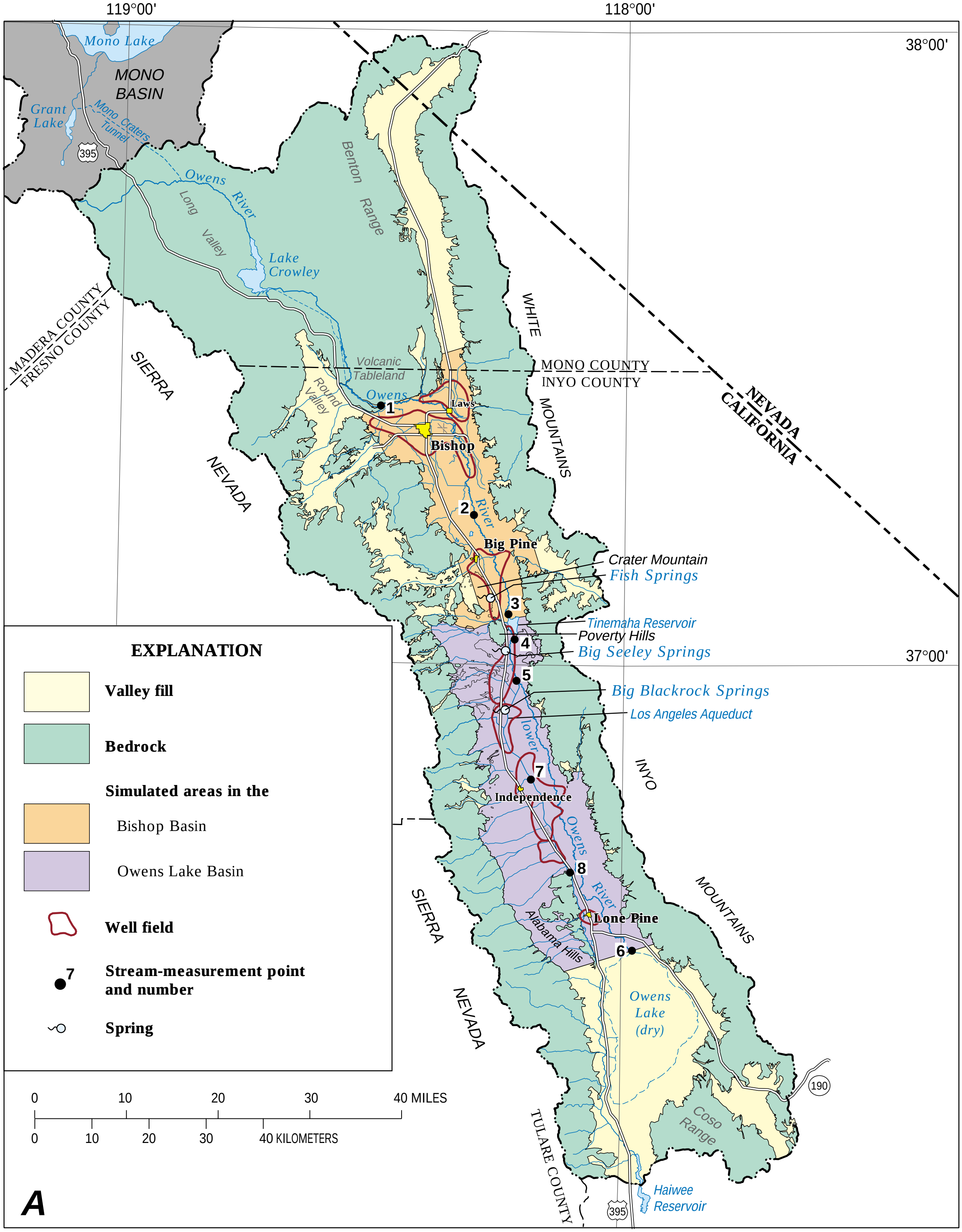
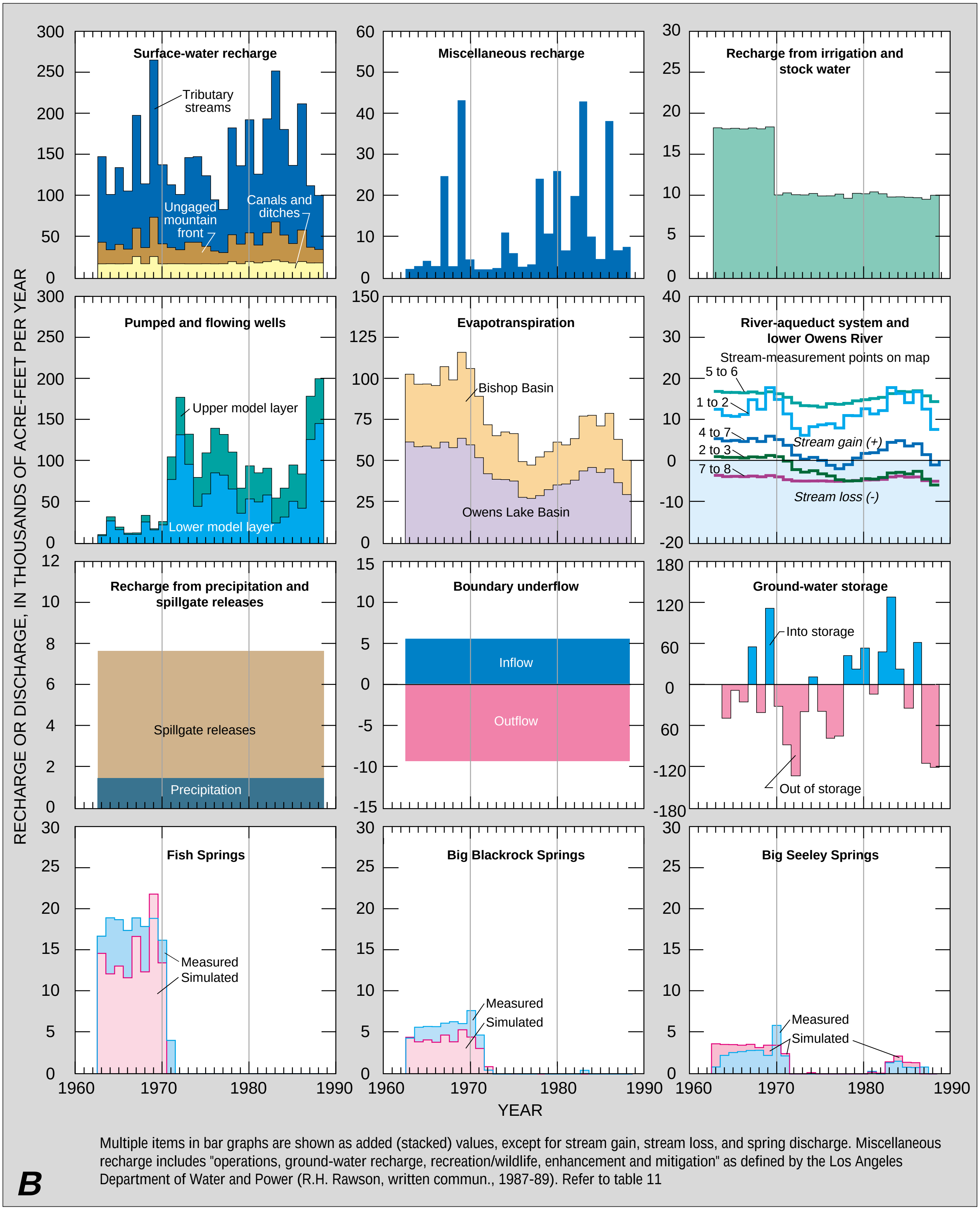


Figure 21. Simulated ground-water recharge and discharge during water years 1963–88 in the Owens Valley, California. Values for each water-budget component are given in table 11.



Multiple items in bar graphs are shown as added (stacked) values, except for stream gain, stream loss, and spring discharge. Miscellaneous recharge includes "operations, ground-water recharge, recreation/wildlife, enhancement and mitigation" as defined by the Los Angeles Department of Water and Power (R.H. Rawson, written commun., 1987-89). Refer to table 11

Figure 21. Continued.

conditions. Valleywide runoff varied from 158 to 68 percent of normal (table 7). In addition, new enhancement and mitigation wells were put into production in various locations throughout the valley (tables 9 and 11). Initial conditions for the verification were simulated heads for water year 1984 at the end of the calibration period. Recharge and discharge data were developed for the ground-water flow model in exactly the same way and using the same relations as had been done for the calibration.

A comparison of measured ground-water levels and simulated heads during the verification period is shown on plate 1. In general, the match is very good, particularly in the Laws area where the aquifer was highly stressed. The model also simulates the return of spring discharge during the period (fig. 21). The close agreement between measured ground-water levels and simulated heads and between measured and simulated spring-discharge rates was achieved without any adjustment of model parameters. This ability to reasonably match data from another time period suggests that the ground-water flow model can be used to predict results from stresses that are similar in type and magnitude, but not exactly the same as those used during calibration—a prerequisite for a predictive model.

Sensitivity Analysis

Sensitivity analysis is a procedure to determine how sensitive the model solution is to a change in each model parameter, including transmissivity, vertical conductance, storage coefficients, and inflow and outflow rates. As is always the case with numerical models, not all parameters of the model were known completely. Because some uncertainty is present in each parameter, there is some uncertainty in the model solution. This uncertainty is reflected in heads and inflow and outflow rates that are somewhat in error. A sensitivity analysis identifies which parameters exert the most control over the model solution and, therefore, have the potential to generate the largest errors. An improved understanding of those parts of the aquifer system represented by the most sensitive parameters yields the greatest improvement in the ground-water flow model.

One of the sensitivity tests that was most illuminating is presented in figure 22. For the test, water years 1963–88 were resimulated with slight modifications in recharge and discharge. For the first part of the test (fig. 22*A*), recharge from tributary streams, recharge from ungaged areas between tributary streams, and recharge from runoff from bedrock outcrops within the valley fill were held constant at 100 percent of long-term average conditions (100-percent runoff year). In the second part of the test (fig. 22*B*), calibration values were used for everything except ground-water pumpage, which was held constant at the values for water year 1963. Effects from each test were observed at wells in recharge areas, near well fields, and away from both recharge areas and well fields. As expected, the effects in recharge areas are most dependent on recharge, and the effects near well fields are most dependent on pumpage. Away from either area, heads are relatively unaffected by changes in either recharge or pumpage, probably as a result of the many hydraulic buffers in the aquifer system. What is somewhat surprising is the degree to which both recharge areas and well fields are affected by pumpage. Clearly, pumpage plays the dominant role in affecting heads (ground-water levels) in the valley.

For the rest of the sensitivity analysis, each of the model parameters was altered by a certain amount from the calibrated values. The amount of the alteration was determined by estimates of the likely range of the data (Hollett and others, 1991, table 1) (figs. 15 and 16; tables 9, 10, and 11). To simplify the analysis, similar variables, such as transmissivity on the alluvial fans, were altered together. The variables associated with the most change in the model solution were identified as the most sensitive. Similar sensitivity analyses were done using a ground-water flow model of the Bishop Basin (Radell, 1989) and a model of the Owens Lake Basin (Yen, 1985). Those analyses are presented graphically for several of the model parameters and depict results similar to those discussed here for the valleywide model.

Although useful, this method of testing sensitivity is subject to a potentially significant flaw. Because each variable in the model is tested separately, the additive effects of changes in more than one variable are not considered. For example, the simultaneous overestimation of both recharge and evapotranspiration in the model would tend to be self-correcting. However, overestimating recharge and underestimating evapotranspiration would produce a considerably different model solution. If neither recharge nor evapotranspiration by itself were a sensitive part of the model, the conclusion from a routine sensitivity analysis would be that additional refinement of these rates is unnecessary. Nevertheless, the additive effects of errors in recharge and evapotranspiration might produce significantly erroneous results in some simulations of the aquifer system.

This type of error can be prevented by means of a more subjective analysis of sensitivity during development and calibration of the ground-water flow model. The modeling technique chosen for the valleywide model took advantage of this method. Those characteristics of the aquifer system believed to be most important were analyzed first using different-scale models (fig. 2). Then, the valleywide model was developed by adding sequentially greater complexity to the model—one recharge or discharge component, or one additional model zone at a time. In this way, during model development and calibration, the sensitivity of each model parameter could be identified more easily. These observations, which are as valuable as a post-calibration sensitivity analysis, also are included in the following discussion of the sensitivity of each parameter.

Transmissivity.—The areal distribution of transmissivity in the valley is based on scattered data (fig. 15) and an assumption of uniformity within each model zone (pl. 2). Model errors can be associated with the values of transmissivity chosen for an individual zone and with the choice of zone boundaries. The sensitivity of the model to the locations of the zone boundaries is best evaluated by altering the locations, recalibrating the model, and observing the differences. Although this time-consuming process was not part of this investigation, the location of the transition zone was found, during model development, to be a sensitive parameter. Equally sensitive was the location and, in particular, the continuity of volcanic deposits near the Taboose–Aberdeen and the Thibaut–Sawmill well fields (fig. 17).

Variations in the value of transmissivity within a model zone produced less effect on heads and ground-water discharge than was hypothesized initially. An exception to this was the area of highly transmissive volcanic materials between Big Pine and Fish Springs (pl. 2). Lower values of transmissivity produced much lower discharge from Fish Springs and unrealistically steep gradients from north to south along the edge of Crater Mountain. From a valleywide perspective, the addition of the more transmissive model zones representing transition-zone and volcanic deposits produced a much greater effect on heads than did variations of transmissivity within individual zones.

Vertical conductance.—Calibrated values of vertical conductance (the model equivalent of vertical hydraulic conductivity) were based on sparse field data and model calibration. To test a wide range of possible values, vertical conductance in each hydrogeologic area was varied by two orders of magnitude. However, the effect on heads was not as pronounced as was expected. In fact, the model seemed to be rather insensitive to changes in vertical conductance (Radell, 1989, fig. 6.4). Part of the reason for this may be the relatively large size of the model cells and use of an annual approximation of recharge and discharge. Both of these model characteristics, which require averaging simulated recharge and discharge over space or time, result in less change in simulated ground-water levels for a given recharge or discharge than would occur in the actual aquifer system. A greater sensitivity in vertical conductance might be expected in an analysis using smaller distances and shorter timeframes, similar to those used to analyze an aquifer test. During calibration, the value of vertical conductance was noted as being closely tied to the rate of evapotranspiration, which tends to dampen changes in heads near the valley floor. Lower values of vertical conductance result in less flow from the lower model layer to the upper, which in turn results in less water available for evapotranspiration. This spatial correlation between vertical conductance and evapotranspiration can be seen by comparing the vertical difference in head (figs. 19 and 20) with evapotranspiration rates (pl. 3*A*)

Storage coefficient.—Storage coefficient was determined to be one of the least sensitive variables. This result corresponds to similar findings by Yen (1985, p.150). Sensitivity analysis showed that storage coefficients higher than the calibrated values did not change heads significantly, but values less than about 0.0001 for the lower model layer (hydrogeologic unit 3) produced unrealistic variations in heads at many locations in the basin.

Precipitation.—Precipitation records for the Owens Valley, in general, are very good, except for an absence of precipitation stations on the east side of the valley (fig. 7*A*). Nearly all precipitation falling on the valley floor is assumed to be used by native vegetation, and recent monitoring of the unsaturated zone tends to confirm this assumption (Groeneveld and others, 1986a; Sorenson and others, 1991). Therefore, the effect of recharge from precipitation falling on the valley floor was not tested in the sensitivity analysis.

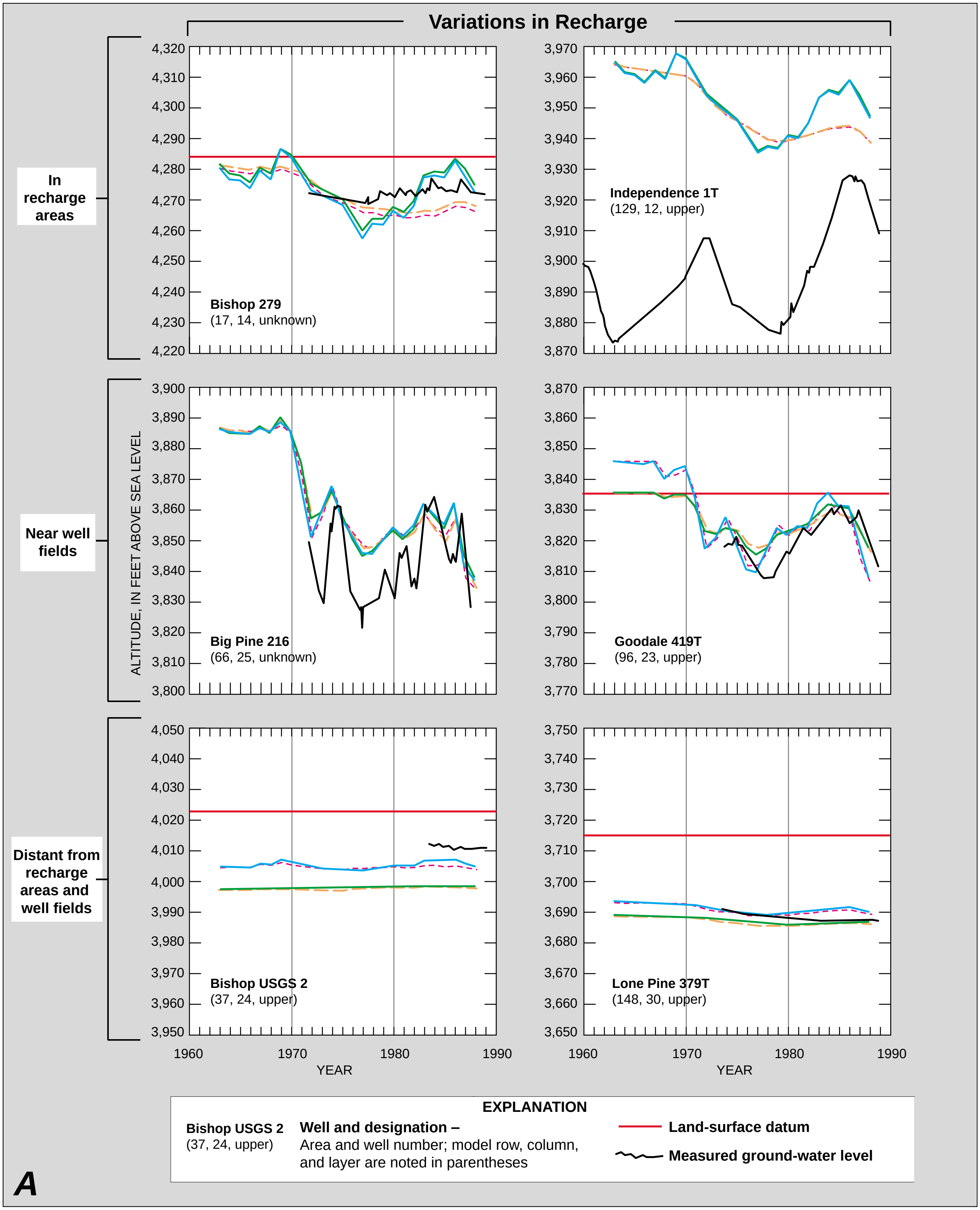


Figure 22. Sensitivity of simulated hydraulic heads in the Owens Valley, California, to variations in recharge ***(A)*** and pumpage ***(B)*** at wells in recharge areas, near well fields, and distant from both. Method of variation is described in text. Well locations are shown on plate 1.

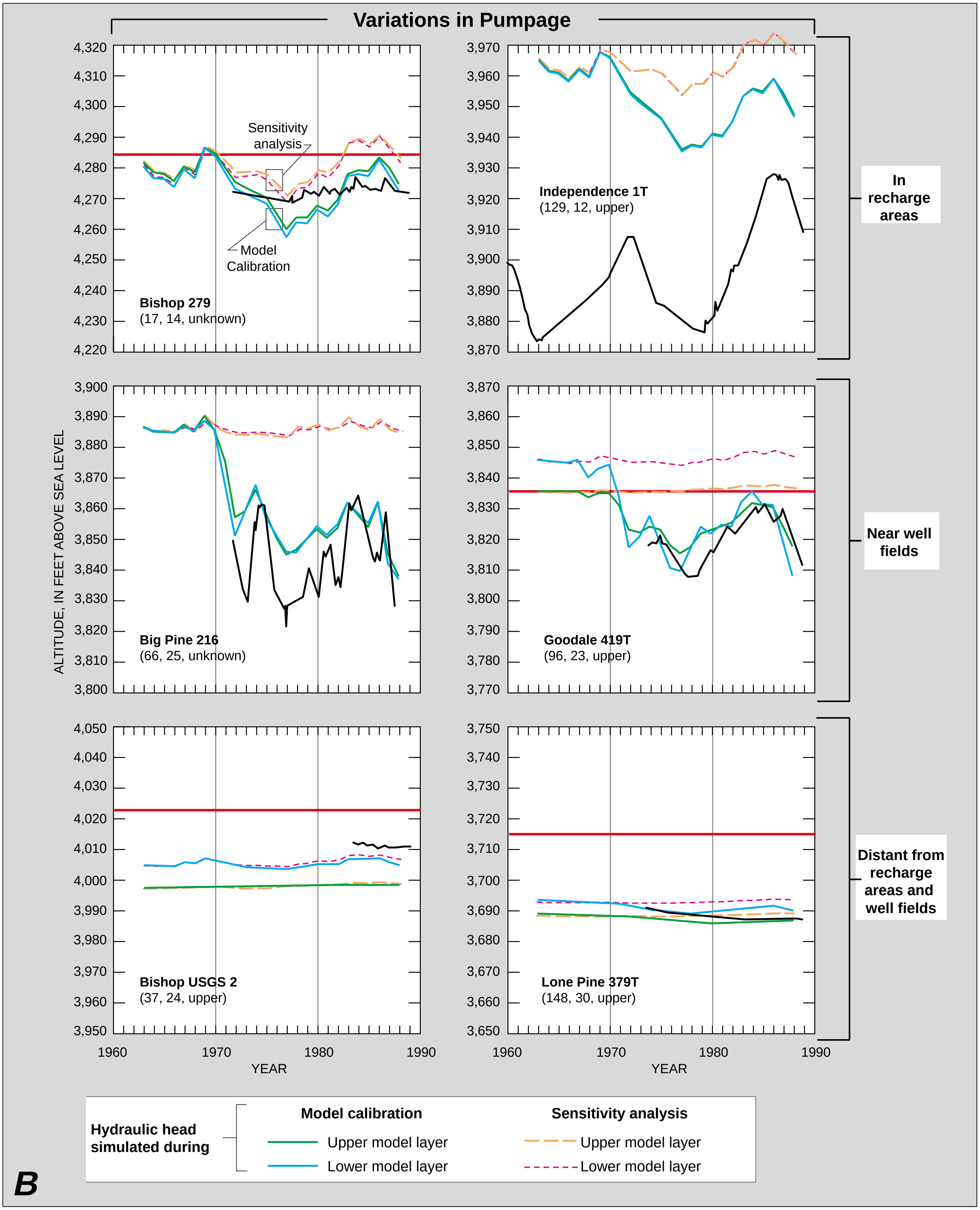


Figure 22. Continued.

In contrast, recharge from precipitation is assumed to occur along the mountain fronts, but the quantity is completely unknown. The present assumption is that about 95 percent of precipitation is evapotranspired, and 5 percent, or about 2,000 acre-ft/yr, is recharged (table 10). Variations of 3 to 4 times this value produced minor effects on model simulations, primarily increasing evapotranspiration from the valley floor and gains of water by the river–aqueduct system. Similar results were found by Radell (1989, fig. 6.10). If the present assumption is largely incorrect, then recharge from precipitation could be a sensitive model parameter with respect to ground-water flow rates as found by Danskin (1988). However, a large increase in recharge from precipitation probably would require a similar decrease in mountain-front recharge between tributary streams (tables 10 and 11) in order to maintain a calibrated model.

Tributary stream recharge.—Measurements of tributary stream discharge are among the most complete and most accurate hydrologic measurements in the valley. Because most tributary streams are measured at both a base-of-mountains gage and a river–aqueduct gage (fig. 11), estimates of tributary stream recharge do not vary greatly. An increase of 10 to 20 percent in tributary stream recharge for streams in the Owens Lake Basin resulted in moderate to significant changes—generally, higher heads on the fans and a greater gain of water by the river–aqueduct system. Heads and evapotranspiration rates on the valley floor showed much less effect. In the Bishop Basin, particularly near Big Pine, accounting for each stream is more difficult, and the uncertainty in recharge estimates is greater than in the Owens Lake Basin. Variations of as much as 50 percent in tributary stream recharge near Big Pine and Taboose Creeks resulted in a minimal change in heads in this area of high transmissivities, but an important change in the discharge of nearby springs (fig. 17).

Mountain-front recharge.—Mountain-front recharge between tributary streams is a large, poorly quantified component of the ground-water budget (table 10). Sensitivity analysis of this item included variations of a 50-percent increase or decrease and resulted in significantly different heads and ground-water fluxes along the west side of the basin. Results are similar to a 15-percent error in recharge from all tributary streams. The lack of measured data suggests that errors in estimating mountain-front recharge are more likely than for most other components of the ground-water flow model. This large degree of uncertainty makes the high sensitivity of this component even more important. During calibration of the Bishop area, an inverse correlation was observed between the quantity of mountain-front recharge and the quantity of recharge from canals and ditches; an increase in recharge for one component probably requires a decrease in recharge for the other.

Evapotranspiration.—Evapotranspiration data are sparse, even in the most intensively studied parts of the valley (fig. 2). Correlations of selected evapotranspiration data with extensive mapping of vegetation has permitted a far more detailed examination of evapotranspiration than was possible a few years ago. Even so, valleywide evapotranspiration remains a largely unquantified, highly variable component of the ground-water flow model. Given this uncertainty, variations of as much as 25 percent were investigated during the sensitivity analysis. Not surprisingly, these variations produced the greatest overall variations in heads, inflows, and outflows of any parameter in the ground-water flow model. This effect results primarily from the large role that evapotranspiration plays in the ground-water budget and from its broad areal distribution. Changes in evapotranspiration rates were most evident in the simulated gain of water by the river– aqueduct system and the lower Owens River.

Variations in the maximum evapotranspiration rate for the head-dependent evapotranspiration relation (McDonald and Harbaugh, 1988, p. 10–1) produced most of the change in the model. Variations in the depth below land surface at which evapotranspiration was assumed to be zero did not significantly affect the model solution—except that the solution became numerically less stable for depths less than 10 ft.

Underflow.—The quantity of underflow is relatively small in comparison with that of other components of the ground-water budget, but unlike many components, underflow in the model is concentrated in areas of limited extent. Variations in the quantity of underflow from Round Valley (fig. 14) significantly affected heads in that part of the basin. Variations in the quantity of underflow from the Chalfant Valley resulted in slightly different quantities of evapotranspiration near Bishop and some gain or loss of water by the Owens River near Laws. Variations in the quantity of underflow along the Volcanic Tableland made little difference in either nearby heads or gains by the Owens River.

Variations in the quantity of underflow south to the Owens Lake area produced a significant change in heads west of the Alabama Hills and relatively little change in heads east of the Alabama Hills. Much of the potential change in heads east of the Alabama Hills was dampened by changes in gains to the lower Owens River. Values of underflow near Bishop and Big Pine Creeks and near the Waucoba Canyon were locally less important and were not varied as part of the sensitivity analysis.

As was typical of much of the sensitivity analysis, changes in the quantity of underflow were not as evident in heads as in the distribution and quantity of other inflow and outflow components. The hydraulic buffering of heads by evapotranspiration, springs, and surface-water features was repeatedly demonstrated in the sensitivity testing. An analysis of sensitivity of the valleywide model, or similar models (Yen, 1985; Hutchison, 1988; Los Angeles Department of Water and Power, 1988; Radell, 1989), with respect only to changes in head would miss much of the response of the model.

Pumped and flowing wells.—Discharge from pumped and flowing wells was assumed to be known and was not varied as a part of the sensitivity analysis. The effect of withdrawing water from different model layers, however, was investigated. Initially during model development, all water was withdrawn from the lower model layer, and the model matched measured ground-water levels surprisingly well. Subsequently, discharge for each well was split between the upper and lower model layers on the basis of the length of perforations and the estimated hydraulic conductivity of adjacent aquifer materials. The match with measured data did not improve significantly. This is a curious result for a topic that has been thought to be critical in isolating the water table and native vegetation from the effects of pumping. The case of withdrawing all pumpage from the upper model layer was deemed physically impossible and was not simulated.

The causes of the lack of model sensitivity to the vertical distribution of pumpage may be the same as those suggested for the lack of sensitivity to changes in vertical conductance—that is, model cells are large in comparison with individual wells and the simulation period is long. A preliminary simulation model of the Independence fast-drawdown site (fig. 2; tables 1 and 2) used model cells as small as 10 ft on a side and simulated a time period of a few weeks. Results indicated that the smaller model was highly sensitive to changes in the pumpage distribution between layers. Similar results have been suggested by the Inyo County Water Department (W.R. Hutchison, oral commun., 1989).

The lack of sensitivity also may result from the proximity of many production wells to the edge of the confining unit (compare figs. 14 and 17). Over a longer timeframe, the pumping influence reaches the vertically transmissive alluvial fans and is transmitted vertically to both model layers. The confining clay layers are effectively short-circuited because of the geometry of the aquifer and the location of the production wells.

Surface water.—The head-dependent method of simulating the interaction of the aquifer system with the Owens River, the Los Angeles Aqueduct, and the Tinemaha Reservoir allows for adjustments in the prescribed stream stage, altitude of the bottom of the streambed, and conductance of the streambed. Stream stage and altitude of the bottom of the streambed were assumed to be known and were not varied. Variations in streambed conductance identified this parameter as important and narrowly defined. Increasing or decreasing streambed conductance resulted in significantly different gains to or losses from the aquifer system. This response implies that the head-dependent surface-water features exert a strong control on the simulated aquifer system, but do not act as constant heads (McDonald and Harbaugh, 1988, p. 3–16; Franke and others, 1987; S.A. Leake, U.S. Geological Survey, oral commun., 1989).

Springs.—Springs are simulated in the model using the drain package (table 13). Spring discharge is controlled mostly by a conductance term representing the transmissive properties of the spring conduit, such as fractured lava or lava tubes, and by nearby recharge or discharge. A decrease in the conductance of individual springs produced remarkable, although somewhat localized, results. Much of this sensitivity results from the high natural discharges for several springs (fig. 21). In contrast, increases in the conductance of individual springs produced much less effect. These results indicate that the transmissive properties of the spring conduits are much greater than those of the surrounding aquifer materials.

Use, Limitations, and Future Revisions

The valleywide ground-water flow model is best used to help answer questions of regional water use, ground-water flow, and surface-water/ground-water interaction. The conceptualization of the aquifer system described by Hollett and others (1991) provided the basis for a consistent, logical model for nearly the entire basin. This translation from qualitative concepts to quantitative testing was a major purpose for constructing the valleywide model and remains an important use of the model. Additional or alternative concepts of the aquifer system can be tested using the model as presently constructed or using the model as a skeleton for a somewhat different model. If changes to the present model are significant—for example, change in number of model zones, in transmissivities, or in areal extent—then recalibration will be required.

The philosophy and methodology of developing the valleywide model indicate its strengths and possible uses. The modeling technique used in this study was the development of successively more complex models to simulate the aquifer system. The initial model resembled that documented by Danskin (1988). Subsequent site-specific models (fig. 2) were developed to investigate specific questions about the aquifer system (table 2), and information gained from these smaller models was incorporated in the design of the valleywide model. Final refinements in the valleywide model were critiqued in concert with ongoing modeling studies by Inyo County and the Los Angeles Department of Water and Power. In this way, important information was obtained at several different scales and from several different viewpoints. As a result, the valleywide model reflects this technical and numerical consensus. During the cooperative studies, the model played an important role as a neutral, technical arbitrator in answering complex and often volatile water-use questions. Future beneficial use of the model may be in a similar way.

Valuable information gained from design, development, calibration, and sensitivity analysis of the ground-water flow model is not complete. Additional information and insight certainly can be obtained without any new model simulations simply by additional review of model data and results presented in this report. Additional sensitivity analysis may be helpful in identifying which new data are most beneficial in answering water-management questions. Although regional by design, the valleywide model does include many small-scale features and site-specific data and concepts. Future analysis of these smaller-scale features or issues—such as a volcanic deposit, a facies change, or a question of local water use—might best be done by use of smaller-scale models or field studies, in combination with simulations from the valleywide model.

The most appropriate use of the valleywide model is best illustrated by the results presented in this report. The goal in designing both water-management alternatives and figures was to maintain the “regional” character of the model, focusing on larger issues, over longer periods of time. Results are presented precisely (table 11) in order that they can be duplicated and extended; however, use of model results needs to be more schematic—for example, more change occurs in this part of the basin, less in that part. The specific value of drawdown at a well (pl. 1) or for an area of the basin (fig. 23) is far less important than the relative value (more drawdown or less drawdown) in comparison with other areas of the basin. Use of the model in this way will maximize its utility and minimize the limitations.

The primary limitation of the valleywide ground-water flow model is that it is regional in nature. Interpreting results at a scale of less than about 1 mi^2 is inappropriate. The model also is “regional” with respect to the time scale that was chosen for calibration. Interpreting results at a scale of less than a single year is inappropriate. Many limitations of the valleywide model are common to all numerical models and are described by Remson and others (1971), Durbin (1978), Wang and Anderson (1982), Franke and others (1987), and McDonald and Harbaugh (1988). Despite these general limitations of modeling and the specific limitations of the valleywide model of the Owens Valley, as described below, no other methodology provides such a complete testing of ground-water concepts and data.

Interpretation of model results in selected areas of the basin requires special caution. In particular, the area west of Bishop and the area near Lone Pine are simulated poorly. The area west of Bishop has a combination of faults, buried Bishop Tuff, terrace gravel deposits, and abundant recharge. The measured levels and simulated heads (figs. 19 and 20; pl. 1) do not match well, indicating that the model does not

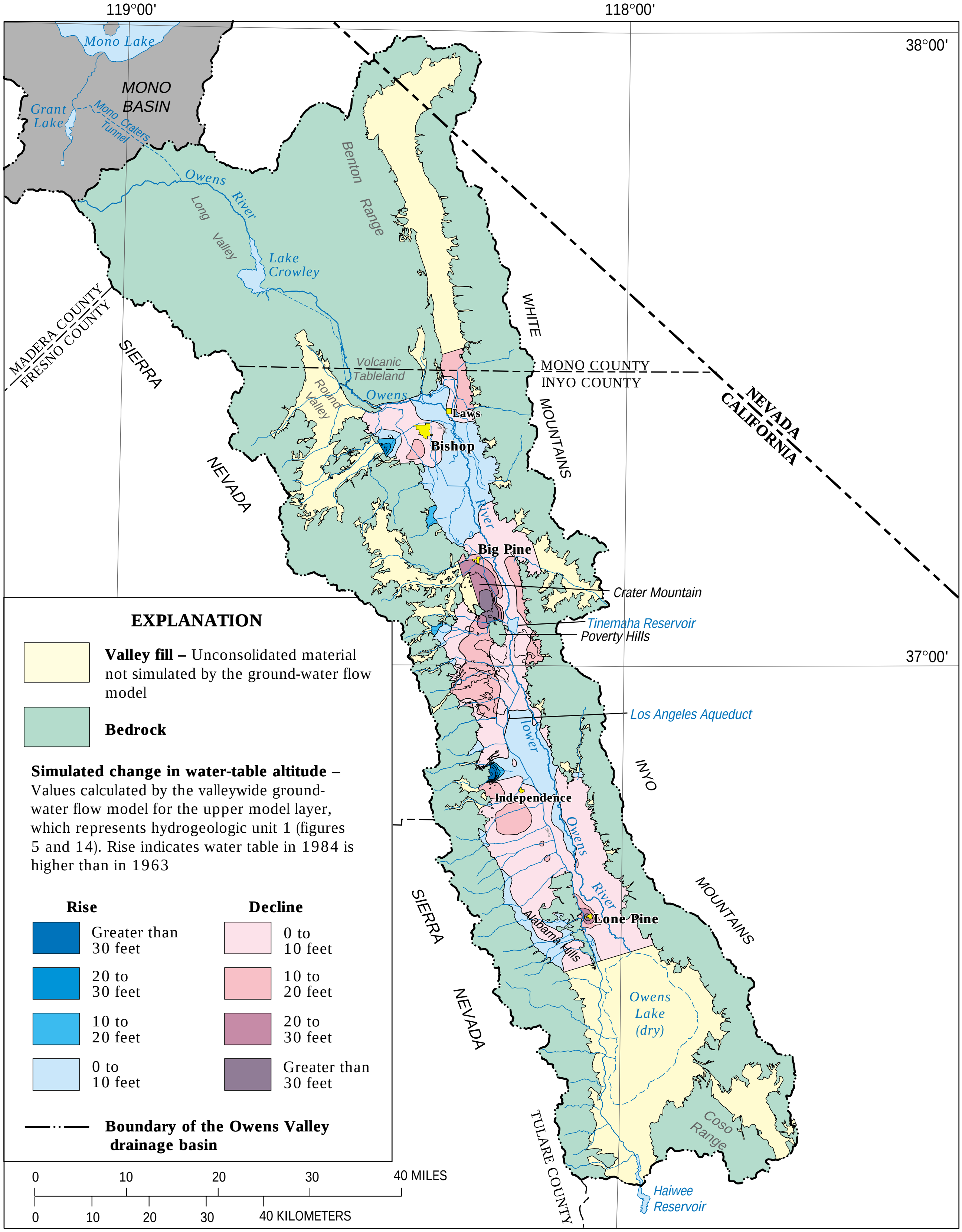


Figure 23. Simulated change in water-table altitude in the Owens Valley, California, between water years 1963 and 1984.

represent actual conditions. It is not clear at this point whether a more detailed simulation of the complex geometry of the Bishop Basin described by Hollett and others (1991) is needed, or if refinement of present hydrogeologic concepts is necessary.

The area around Lone Pine also is simulated poorly. Any number of changes in the model—in the location or hydraulic properties of nearby en echelon faults, in underflow rates, or in recharge from Lone Pine Creek—did little to improve the match for wells in the immediate area, such as well 172 (pl. 1). A basic problem may be that the wells are in small, isolated compartments created by the en echelon faulting. This same phenomenon probably is present north of the Alabama Hills near well 363T (pl. 1). These wells do not interact with the rest of the aquifer system in a way readily approximated by this model. The complex hydrogeology of the areas requires extensive data collection in order to provide the concepts, spatial definition, and parameters necessary to design and calibrate a more accurate numerical model. An alternative method for predicting local ground-water-level changes is to use a simple regression model that avoids many of the spatial and conceptual issues. However, as noted by Hodgson (1978), use of a regression model does not obviate the need for a more rigorous ground-water flow model, at least at a regional scale.

In some parts of the valley, critical hydrologic features are located within a few thousand feet of each other. In the Independence area, for example, the aqueduct, pumped wells, changes in transmissivity and vertical conductance, and changes in vegetation from dryland sagebrush to valley-floor phreatophytes (xerophytes) all are present within about 3,000 ft of each other. Abrupt changes, such as these, result in differences between measured ground-water levels and simulated heads (figs. 19 and 20). From a regional perspective, the differences are acceptable; however, an evaluation of specific local conditions may require a better match.

In the area north of Laws, measured ground-water levels in the immediate vicinity of the boundary of the aquifer system (wells 107T and 252, pl. 1) recover more rapidly than do heads predicted by the model. Although noted, this discrepancy does not affect model simulations or the related results significantly. Simulation of the western alluvial fans and the area east of the Owens River produced reasonable results that seem to validate the basic hydrogeologic concepts about each area; however, an absence of measured data in each area suggests that results in these areas should be interpreted cautiously.

Some of the chosen methods for approximating the aquifer system may produce undesirable effects in some parts of the basin under some conditions. The choice of simulating a constant saturated thickness for hydrogeologic unit 1 may lead to differences in drawdown near sites of significant recharge or pumpage when compared with simulated results that account for changes in saturated thickness. Simulation of canals and ditches only as sources of recharge underestimate their capacity to drain the aquifer system during extended periods of high runoff. The simulation of underflow as a specified, constant rate limits the accuracy of the model for predicting effects of recharge or discharge near a flow boundary, such as north of Laws.

The valleywide model, which simulates the saturated aquifer system, does not incorporate the complex process of vegetative growth and water use as explicit variables, nor does the model simulate the unsaturated soil-moisture zone. Vertical one-dimensional models with these capabilities were developed for selected areas of the valley (table 1 and fig. 2) as a related part of the comprehensive studies of the Owens Valley (Welch, 1988). Incorporating these features in a valleywide model would make it numerically far too large to be useful. The ground-water flow model, however, does simulate changes in the water table and extraction of water from hydrogeologic unit 1 by various processes, including evapotranspiration. With these capabilities, the model can be used to predict areas of the valley where hydrologic stress, such as a decline in the water table or a decrease in ground-water flow rates or discharge, probably will occur.

A key assumption in using the saturated ground-water flow model to evaluate likely effects on native vegetation is that areas of significant hydrologic stress correspond to areas of vegetative stress. In related studies, researchers found that a significant decline in the water table corresponded to a significant stress on native vegetation, particularly rubber rabbitbrush (*Chrysothamnus nauseosus*) (Dileanis and Groeneveld, 1989; Sorenson and others, 1991). Other factors, including alkalinity and salinity (table 3), are acknowledged to play an important role in the health of native plant communities (fig. 6). Therefore, results from the ground-water flow model should be viewed in general terms as areas of the valley where stress on native vegetation is likely.

A simplification of how the ground-water flow model simulates water use by plants may contribute to an underestimation of water-table recovery during wet periods immediately following dry conditions. During a drought, plants drop leaves in order to limit transpiration and loss of water. During the year following a drought, use of water by plants is restricted (because number of leaves is fewer) until more leaves can be grown. If abundant precipitation falls during this time when the plants have fewer leaves, then the precipitation may satisfy the bulk of the water needs of the plants. Relatively little ground water will be transpired even though ground-water levels are rising because of increased recharge. The ground-water flow model assumes that higher ground-water levels always result in higher evapotranspiration from the ground-water system. This feature may overestimate evapotranspiration during some wet years, and may not allow the simulated water table to recover as rapidly as measured data indicate.

During development of the valleywide model, the simulation of evapotranspiration by native vegetation was studied extensively. Several different approaches were tested, including use of a piecewise-linear, head-dependent relation with a fixed maximum evapotranspiration rate, as described for the final calibrated model; the same relation with a spatially varying maximum evapotranspiration rate based on mapped native vegetation; an evapotranspiration rate based on a separate soil-moisture-box accounting; and an evapotranspiration rate related to precipitation. Each method had its own advantages and disadvantages but yielded surprisingly similar results. This unanticipated conclusion probably stems from the annual approximation of recharge and discharge, the long simulation period, and the regional character of the model. In order to better simulate some transient conditions, future revisions of the valleywide model may consider use of a more complex evapotranspiration package with spatially varying parameters to simulate direct precipitation on the valley floor, antecedent soil moisture, and vegetative growth and water use.

Spatial and temporal discretization of the valleywide model generally does not adversely affect the simulation of regional or subregional water-management issues. The two-layer approximation of the aquifer system produced good results in nearly all areas of the valley. However, a three- or four-layer approximation of the Big Pine and the Taboose–Aberdeen areas, paralleling the conceptualization documented by Hollett and others (1991), would yield a more physically based and possibly more reliable model. Addition of more layers to the model allows a better spatial representation of the complex geometry between pumped volcanic deposits and nearby fluvial and lacustrine deposits, and might result in a more accurate simulation of pumping effects on different parts of the aquifer system. The approximation of numerous individual clay layers by a single confining layer, such as for the fluvial and lacustrine deposits (figs. 4 and 5), yielded good results and does not need to be changed in future revisions of the valleywide model. The present approximation of the massive blue-green clay near Big Pine with a simple Darcian relation is likely to result in inaccurate results for some simulations that are sensitive to the transient propagation of hydraulic head through the thick clay and the concurrent release of ground water from storage in the clay.

The use of model zones to group areas with similar geologic materials (hydrogeologic subunits) was a simple technique that produced good results. Identifying transition-zone deposits as a unique hydrogeologic unit (fig. 5) and incorporating the unit as a separate model zone, as suggested by Danskin (1988), substantially improved simulation along the toes of the western alluvial fans. Additional drilling east of the Owens River would help to confirm the presence and configuration of hydrogeologic subunits and related model zones in that area (pl. 2). A more detailed definition of the hydrogeology of the area west of Bishop is needed and might prompt a redefinition of model zones in that area.

One method of solving some limitations of the valleywide model is to decrease the size of the model grid. A finer grid-spacing facilitates a more gradual change in hydraulic parameters, which produces a better simulation of the aquifer system. Microcomputer capabilities as of 1988 permit design of a valleywide model with three or possibly four layers using a uniform grid size of 1,000 ft on a side. Use of finite-element techniques facilitates increased spatial resolution in key areas (Danskin, 1988). However, prior to redesigning the present model, certain questions about hydrogeologic concepts need to be answered or the increased numerical resolution will not be accompanied by a commensurate increase in reliability. These questions are itemized in a later section entitled "Need for Further Studies."

Another method of improving the predictive capability of the valleywide model in selected areas of the basin is to use smaller, more detailed models, such as those developed by Inyo County and the Los Angeles Department of Water and Power (table 2). An important caveat in the use of this type of model became apparent during the cooperative studies when a detailed model of the Thibaut–Sawmill area was developed by Inyo County (Hutchison and Radell, 1988a, b). Although the boundary conditions of the smaller model were chosen carefully, the model could not be successfully calibrated. Inspection of the valleywide model revealed that the boundaries of the smaller model, although reasonable under steady-state conditions, were too dynamic under transient conditions to be simulated using the standard modeling techniques described by McDonald and Harbaugh (1988). Only transient specified-flux boundary conditions obtained from the valleywide model were sufficient to achieve a reliable transient simulation. Thus, use of more detailed models may offer advantages, particularly near well fields or spatially complex areas, but the models need to incorporate boundary conditions from a valleywide model.

Both the spatial distribution and method of simulating stream recharge worked well. Although ground-water-level data are sparse for the upper slopes of alluvial fans, the general distribution of recharge along individual streams produced reasonably good results in areas of known levels (figs. 19 and 20; pl. 1). Because of the considerable distance between land surface on the alluvial fans and the underlying water table, a noticeable lag may occur between a measured loss of water in a stream and the resulting response of the aquifer system (well 1T, pl. 1). Although recognized, this lag did not affect simulation results significantly. Future revisions that use stress periods of 6 months or less may need to account for this time lag.

The addition of spring discharge to the model, in comparison with previous modeling efforts by Danskin (1988), produced major improvements in simulating areas along the toes of alluvial fans and edges of volcanic deposits. These areas also are characterized by a relative abundance of water and native vegetation (fig. 3), which might indicate that evapotranspiration rates are higher than in most other parts of the valley. Simulation of these areas might be improved further by locally increasing the maximum evapotranspiration rate.

Future modeling also might benefit from a more detailed simulation of the interaction between the major surface-water bodies and the aquifer system. A variety of physically based relations are available that incorporate the wetted surface area of the interface, the hydraulic conductivity of intervening materials, and temporal variability in the hydraulic head of the surface-water body (Durbin and others, 1978; Yates, 1985; Prudic, 1989). Use of an explicit surface-water model linked to the ground-water flow model would allow more detailed mass balancing of the surface-water system than was possible in this study and would facilitate the development of integrated surface-water/ground-water budgets as suggested by Danskin (1988).

Discussion of Simulated Results, Water Years 1963–88

Calibration and verification of the ground-water flow model for water years 1963–88 enabled both a critique of model performance and an analysis of a critical period of basin operation—in particular, the conditions before and after the second aqueduct was put into operation. Because measured ground-water levels for hydrogeologic unit 1 (upper model layer) were collected at only a few sites prior to 1974, a quantitative analysis of the period requires the use of simulated results.

The simulated change in water-table altitude between water years 1963 and 1984, both times of a relatively "full basin," is shown in figure 23. Simulated conditions for water year 1963 generally reflect average conditions prior to 1970 (table 4). In some parts of the valley, antecedent pumping seems to have affected measured ground-water levels (pl. 1). Because this antecedent pumpage is not included in the model, simulated heads for water year 1963 may be slightly higher than measured levels in those areas. Simulated conditions for water year 1984 also reflect a nearly full basin, but one after the substantive changes in basin management that occurred in 1970.

Major changes in the simulated water table between water years 1963 and 1984 are obvious in the Laws and the Big Pine areas (fig. 23), and are visible in measured levels (pl. 1). Equally major changes also are suggested beneath western alluvial fans, particularly near the Taboose–Aberdeen well field (fig. 17). Because no measured levels are available in the fan areas, this simulated result is less certain. However, the result is consistent with the large increase in pumpage from the Taboose–Aberdeen and the Thibaut–Sawmill well fields (fig. 17), the decrease in discharge from nearby springs (fig. 21), and the reasonable simulation by the model of other conditions during water years 1963–88.

The relatively wet conditions in 1984 are reflected by the blue areas in figure 23, indicating a rise in the simulated water table. It is important to note that many areas of the valley floor had a rise in the simulated water table between water years 1963 and 1984—even though elsewhere in the valley, the simulated water table declined. This duality of response is typical of the complexity observed in the valleywide system.

One of the primary questions at the beginning of the study was, "What effect does pumping have on ground-water levels and native vegetation in the middle of the valley?" The ground-water flow model was used to investigate this question for the Independence area, an area of intensive monitoring and modeling during the USGS studies (fig. 2 and table 1). Shown in figure 24 are simulation results from the valleywide model for water years 1963–88 at the Independence fast-drawdown site (site K, fig. 2; table 1). Values of ground-water-flow vectors for two periods, water years 1963–69 and water years 1970–84, are shown in figure 24*A*.

The principal components of the vectors show that the dominant ground-water flow direction is horizontal and generally eastward, although there is a significant southward component in hydrogeologic unit 3. These results are comparable to those depicted in figures 14, 19, and 20. As is typical of a layered aquifer, vertical flow rates are significantly less than the total horizontal flow rate in either unit. The difference in flow rates between the two periods is most evident as a decrease in the vertical flow rate, decrease in the evapotranspiration rate, and increase in the southward flow rate in hydrogeologic unit 3.

It is important to note that the vertical flow rate, and the related decrease in vertical flow rate, is a larger percentage of flow in hydrogeologic unit 1 than it is in hydrogeologic unit 3. Pumping may produce relatively minor effects in hydrogeologic unit 3, and at the same time, have a much greater effect on flow rates into and evapotranspiration from hydrogeologic unit 1. Native vegetation depends on the continuous flow of water into hydrogeologic unit 1 and is affected by a change in flow rates. Shown in figure 24*B* is the simulated change in flow rates and evapotranspiration for water years 1963–88. The effect of pumping is clearly evident, beginning in 1970, in simulated flow rates and evapotranspiration at the Independence fast-drawdown site.

The importance of maintaining an adequate ground-water flow rate into hydrogeologic unit 1 also is illustrated in figure 25, which shows a schematic east– west section in the same general area of Independence shown in figure 24. Two conditions are shown in the section (fig. 25)—ground-water levels with and without ground-water pumping. With no pumping, ground-water levels are fairly static. Ground water recharges hydrogeologic units 1 and 3 from the western alluvial fans in proportion to the saturated thickness of each unit. With pumping, the saturated thickness of hydrogeologic unit 1 is decreased, which in turn decreases the quantity of ground water flowing into hydrogeologic unit 1.

Eventually, this decrease will reduce the rate of evapotranspiration from the middle of the valley (fig. 24). This aspect of a fluctuating saturated thickness (time-variant transmissivity) was not simulated by the ground-water flow model; as a result, changes in actual ground-water flow rates into hydrogeologic unit 1 may be somewhat greater than those shown in figure 24.

In summary, the aquifer system, particularly the discharge components, changed significantly with the increase in pumping and export of ground water after 1970. Although changes in water use and distribution of surface water also were made in 1970, most of the changes in the aquifer system resulted primarily from increased ground-water pumpage. The increased efforts at ground-water recharge after 1970 did not compensate for the increased pumpage (table 10).

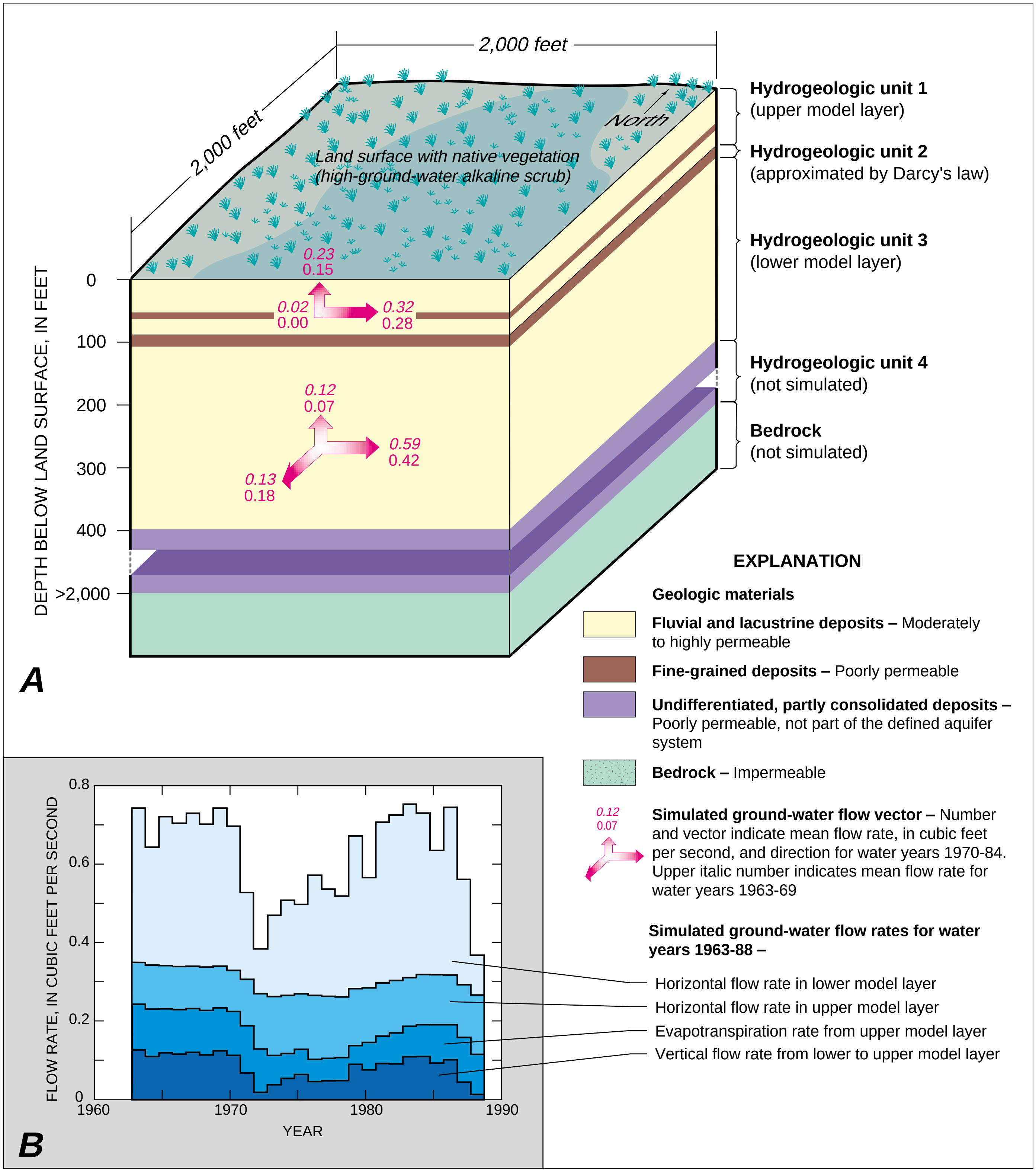
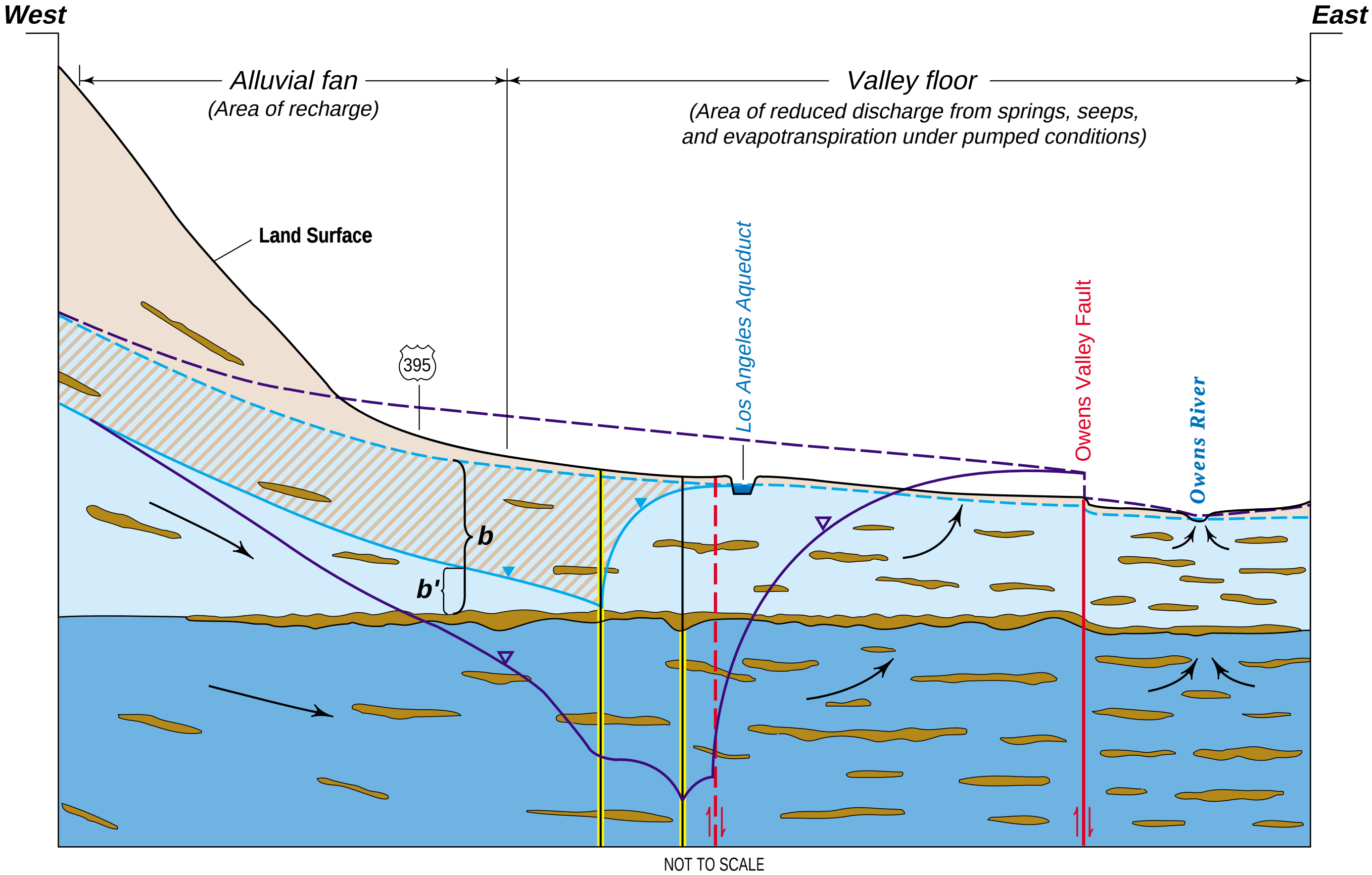


Figure 24. Simulated ground-water flow rates near the fast-drawdown site at Independence, California (figure 2, site K; table 1). ***A,*** average flow vectors for water years 1963–69 and 1970–84 for the ground-water model cell (row 128, column 23) that represents the area surrounding site K. Also refer to section ***C–C'*** (figure 5). ***B,*** annual flow rates for water years 1963–88.



EXPLANATION

Hydrogeologic unit 1 – Unconfined zone with water-table surface. Light brown area is unsaturated. Cross-hatched area is desaturated by pumping and no longer capable of transporting ground water toward the valley floor

No pumping

Pumping

Hydrogeologic unit 3 – Composite confined zone with potentiometric surface

No pumping

Pumping

Fine-grained, less permeable deposit – Mostly silt and clay

Saturated thickness of hydrogeologic unit 1 – Under different pumping conditions

b no pumping
b' pumping

Generalized direction of ground-water flow

Well – Yellow color indicates interval open to the aquifer

Fault – Dashed where inferred. Arrows indicate direction of movement

Figure 25. Schematic section across the Owens Valley near Independence, California, showing ground-water flow under different pumping conditions. Saturated thickness of hydrogeologic unit 1 beneath the alluvial fans may decrease markedly (from ***b*** to ***b'***) during pumping and result in significantly less ground-water flow toward the valley flow.

EVALUATION OF SELECTED WATER-MANAGEMENT ALTERNATIVES

An evaluation of alternative methods of water management involves an appraisal of the present (1988) operating conditions and the physical and social constraints that restrict changes in operations. This evaluation recognizes the social constraints, but focuses on the hydrologic constraints, recognizing that although social constraints might seem to be more encumbering, they often are far less static than the physical constraints presented by precipitation, streamflows, and the aquifer system. Much of the evaluation relies on simulation results from the valleywide ground-water flow model to quantify the likely effects of different management alternatives.

General Water-Management Considerations

Water management of the Owens Valley involves a complex array of conflicting needs and desires. The residents of the Owens Valley need water for local uses such as ranching and domestic supply. Many of the residents desire that water be used for the aesthetic aspects of the valley such as flowing streams and to provide the water needs of native vegetation. The Los Angeles Department of Water and Power, although recognizing these local needs and desires, has continuing needs to export water to Los Angeles. As regional water supplies dwindle and the population of southern California increases, Los Angeles may desire to export additional high-quality water from the Owens Valley. In the difficult task of balancing conflicting needs and desires, the emotional side of water-management issues often tends to take precedence over otherwise purely technical issues.

The goals of water management in the Owens Valley consist of fulfilling both needs and desires. The primary goals include supplying sufficient water for local domestic, ranching, and municipal uses; for native vegetation and aesthetics; and for export to Los Angeles. Secondary goals include mitigation of pumping effects on native vegetation in the immediate area of wells and enhancement of selected areas of the valley. Inherent in achieving these secondary goals, if other water-management practices are continued, is an acceptance of a likely overall decrease in the quantity of native vegetation in other areas of the valley. An ongoing management goal since 1970 has been to decrease consumptive use of water on ranches and lands leased by the Los Angeles Department of Water and Power and to use water more efficiently throughout the valley. Achievement of each of these goals is limited by a variety of considerations that constrain water management in the Owens Valley. The major considerations are described below.

Regional water supplies.—The Owens Valley is part of a much larger network of water supplies, transport, and use. In southern California, water is obtained from a limited number of sources, primarily from northern California, the Colorado River, and the Owens Valley. The use and export of water from the Owens Valley must be viewed within the larger issues of water supply and demand within the arid Southwest, particularly southern California.

Export of surface and ground water.—Water-gathering activities along the aqueduct, primarily north of the Owens Valley in the Mono Basin and the Long Valley, contribute to the total export of water to Los Angeles. A series of reservoirs and ground-water basins along the aqueduct system between the Mono Basin and Los Angeles are used to regulate flow and to store water from one year to the next. Because these storage capacities, in general, are limited, a nearly constant export of water from the Owens Valley is desired. Since 1970, ground-water withdrawals from the Owens Valley have been used to augment surface-water diversions. In an average-runoff year, some ground water typically is exported; however, in a below-average runoff year, the quantity of ground-water exported out of the valley is increased significantly to make up for the shortage in surface water.

Antecedent conditions from the previous water year affect the quantity of export desired by the Los Angeles Department of Water and Power. If antecedent conditions are dry, then less water is stored in reservoirs and ground-water basins along the aqueduct system, and more water is needed from the Owens Valley. As shown in figure 18, the antecedent conditions in turn affect the quantity of ground water that is pumped. If the preceding year has had average or above-average runoff, then ground-water pumpage is less.

The exportation of water from the Owens Valley to Los Angeles has been the subject of many controversies and lawsuits. Historically, California water law has been interpreted to require maximum beneficial use of water (State of California, 1992). In the early 1900's, beneficial use was nearly synonymous with reclamation of the land for farming and for industrial and municipal use. Since about 1970, the historical beneficial uses of water have been constrained by various environmental issues, such as preservation of phreatophytic vegetation in the Owens Valley and the maintenance of lake levels in the Mono Basin for wildlife habitat. Complying with environmental constraints and satisfying requirements of the California Environmental Quality Act (CEQA) play an increasingly critical role in the export of water from the Owens Valley.

Local use of water.—Water use within the Owens Valley includes commitments of water to each of the four major towns, four Indian reservations, three fish hatcheries, and many ranches (fig. 1, pl. 3, and table 11; Hollett and others, 1991, fig. 5). More recently, additional surface and ground water has been committed to maintain several enhancement and mitigation projects. These relatively high-water-use projects are scattered throughout the valley and provide maintenance of pastureland, wildlife habitat, and riparian vegetation.

Water management in the Owens Valley also has been affected by litigation, particularly the "Hillside Decree" (Los Angeles and Inyo County, 1990a, p. 5–16). This legal injunction required that ground-water pumpage in the Bishop area be used locally within an area extending from north of Bishop to just north of Klondike Lake (fig. 11). Within this area, which is referred to as the "Hillside area" or "Bishop Cone," no ground-water pumpage can be exported to other areas of the valley, or out of the valley to Los Angeles. Although the injunction protects the Bishop area, it severely constrains water-management options for the valley as a whole. The Bishop area has the most abundant native water supplies of any area of the valley as indicated by the large discharge of Bishop Creek (average annual discharge is more than 90 ft^3/s). Even if local residents, the Inyo County water managers, and the Los Angeles Department of Water and Power should agree on extracting additional ground water from the Bishop area to compensate for reducing ground-water pumpage from another area of the valley, the injunction prevents this reallocation of water.

Hydrologic considerations.—Water management within the Owens Valley also is constrained by physical limitations. Streamflow varies within each year, as well as from year to year. During some high-flow periods, not all streamflow can be captured for export or recharged to the ground-water system. During drier periods, minimum flows in the tributary streams may be required to maintain fish populations, and ground-water-recharge operations may be restricted. Some tributary streams, such as Oak Creek, have a large discharge, but a relatively small alluvial fan to be used for ground-water recharge. Other streams, such as Shepherd Creek, have a small discharge and a large alluvial fan.

Antecedent conditions affect the saturated ground-water system. As much as a 3- to 12-month delay occurs in the effect of an above-average runoff year on ground-water levels and discharge rates (well 1T, pl. 1; spring discharge, fig. 21). This means that above-average runoff will mitigate some of the adverse effects of a drought that occurs the following year. Ground-water levels beneath the valley floor will tend to rise at the same time as there is a need for additional ground water by native vegetation. The adverse effects of an extended dry period, however, will not be counteracted immediately by an above-average runoff year; the delay in recharge essentially extends the drought for an additional 3 to 12 months.

Antecedent conditions for the unsaturated zone are equally important in water management, as determined during the cooperative vegetation studies (Groeneveld and others, 1986a). In particular, the quantity of water in the unsaturated zone that is carried over from one year to the next is a primary indicator of whether native vegetation will remain healthy (Groeneveld and others, 1986b; Sorenson and others, 1991). As a result of this finding, past water-management practices may need to be altered. For example, ground-water pumpage could be restricted whenever antecedent soil-moisture conditions are too dry.

Simulation of Selected Water-Management Alternatives

The valleywide ground-water flow model was used to evaluate selected water-management alternatives for the Owens Valley. The specific alternatives described in table 14 were chosen after discussion with the technical staffs of Inyo County and the Los Angeles Department of Water and Power. The primary items of concern to valley residents and water managers were the long-term effects of continuing present (1988) operations (alternative 1); the effects of less runoff resulting from long-term climatic cycles or change in climate (alternative 2); the effects of long-term variations in average pumpage (alternative 3); and the ways to mitigate effects of a severe drought and to take

Table 14. Simulated water-management alternatives for the Owens Valley, California

[na, not applicable, because the solution does not depend on initial head]

Simulated water-management alternative	Description	Type of simulation	Initial conditions	Related figures (number)
1	Continue 1988 operations	Steady state.................	na	26 and 27
2	Continue 1988 operations with variations in recharge of plus or minus 10 percent of the 1988 steady-state value. Simulates long-term change in climatic conditions.	Steady state.................	na	28
3	Continue 1988 operations with variations in pumpage from 0 to 125 percent of the 1988 steady-state value.	Steady state.................	na	29
4	A 9-year sequence consisting of: 3 years of drought 3 years of average conditions 3 years of wet conditions.	Transient (9 years).	Results for water-management alternative 1.	30, 31, 32, and 33

advantage of unusually wet conditions (alternative 4). The first three alternatives were simulated with steady-state conditions; the fourth alternative was a 9-year transient simulation.

Because water management in the Owens Valley is exceptionally intricate—involving more than 40 streams, 30 canals, 600 gaging stations, and 200 production wells—the alternatives were designed to simulate general valleywide conditions in order to illustrate how the overall system responds. More detailed site-specific investigations, such as predicting the effects of managing selected wells or streams, are being conducted as part of ongoing water-management activities by Inyo County and the Los Angeles Department of Water and Power.

Alternative 1: Continue 1988 Operations

Alternative 1 addresses the question, “What will happen if present (1988) operations are continued?” That is, what will be the average condition (steady state) of the aquifer system if operations as of 1988 are continued for a long time, probably tens of years? To aid in defining 1988 operations and in evaluating the difference between present and past water-management practices, general water use in the Owens Valley since about 1900 was summarized. Periods with relatively similar characteristics of water use, and therefore relatively similar operation of the surface-water and ground-water systems, were identified (table 4). Results of this analysis were used in selecting appropriate time periods to calibrate and verify the ground-water flow model, as well as in identifying how 1988 conditions were different from past operations, even those as recent as the early 1980's.

Changes in water-management operations undoubtedly will be made as the hydrologic system and native vegetation of the Owens Valley are more fully understood. An important caveat in viewing the “1988 conditions,” as defined in this report, is that the study period was a time of considerable change, or proposed change, in water-management practices. Wide-ranging discussions between Inyo County and the Los Angeles Department of Water and Power typify the process of developing a joint water-management plan for the valley. Possible changes in water management being discussed include discharging a small quantity of water down the lower Owens River to maintain wildlife habitats along the river; installing new wells or using surface-water diversions to provide water for additional enhancement and mitigation sites; and installing new production wells with perforations only in the lower zones of the aquifer system (hydrogeologic unit 3)—not in hydrogeologic unit 1 where effects on the water table and native vegetation are more direct. Additional pumpage for enhancement and mitigation projects may prompt a reduction in pumpage for other uses, including export. Thus, the 1988 conditions as defined in this report likely will evolve over time as understanding of the hydrology of the Owens Valley improves and negotiations between Inyo County and the Los Angeles

Department of Water and Power continue. Nevertheless, the 1988 conditions as defined in this report represent the best estimates of future operations based on information available in 1988, and most results based on this definition will not be changed significantly by minor changes in local operations.

Average 1988 conditions in the Owens Valley were defined using a combination of long-term historical data (water years 1935–84) and selected recent data (water years 1985–88) that reflect recent water-management practices (tables 4 and 11). The selection of specific values for the ground-water flow model can be grouped into four categories depending on how static each item has been.

Long-term average relations.—A long-term average period, water years 1935–84, was used to define average-runoff conditions. The relations of runoff to ground-water recharge for tributary streams (fig. 13) and for ungaged areas (table 11), both of which were used to simulate ground-water conditions during water years 1963–88, were assumed to remain valid for future conditions.

Long-term constant values.—Underflow and recharge from precipitation were held constant as they had been during simulation of water years 1963–88 (table 11).

Recent constant values.—Recharge from irrigated areas was the same as the constant values used during simulation of water years 1970–88. This period reflects the change in water use that occurred about 1970 (table 4). The maximum evapotranspiration rate was the same as that used to simulate water years 1978–88.

Recent average values.—A recent period (water years 1985, 1986, and 1988) was selected to represent average conditions for those items that were recently added or changed. The selection of these specific years included an evaluation of the probability of different percent-runoff years (fig. 12) and of the effect of antecedent conditions on pumpage (fig. 18). The selected period includes a wet water year (1986), an average water year (1985), and a dry water year (1988). This period was used to determine recharge from miscellaneous operations, recharge from water use on Indian lands, recharge from canals and ditches, and discharge from pumping. Pumpage from enhancement and mitigation wells, which were being installed during water years 1985–88, was planned to provide a virtually constant supply regardless of runoff conditions (R.G. Wilson, Los Angeles Department of Water and Power, oral commun., 1988). As a result, average pumpage for enhancement and mitigation wells was defined as the values for water year 1988. An important assumption regarding pumpage was that average pumpage for enhancement and mitigation projects was in addition to average pumpage for export.

These values of recharge and discharge defined for average 1988 conditions were used in the calibrated ground-water flow model to determine a steady-state solution of simulated heads, recharge, and discharge (table 11). The simulated change in water-table altitude between water year 1984 (fig. 19 and pl. 1) and 1988 steady-state conditions is shown in figure 26. Water year 1984 was chosen for comparison because ground-water levels were relatively high over most of the basin, most springs had resumed some discharge, and the ground-water basin was nearly as “full” as it had been prior to 1970 (Hollett and others, 1991). A comparison of water-budget components for the 1988 steady-state period with those for water years 1963–69 and water years 1970–84 is shown in figure 27. These three periods represent the main changes in the Owens Valley hydrologic system (table 4) since the early 1900's.

On the basis of the model simulations, changes in the 1984 water-table altitude and in recharge and discharge will occur if the 1988 operating conditions, as defined above, are continued. Most of the predicted water-table changes occur in the alluvial fan areas, particularly in the Taboose–Aberdeen and Independence areas (sections *C–C'* and *D–D'*, fig. 26). A large difference also is predicted in the Laws area and near Big Pine. The valley floor exhibits somewhat less change in the water table, as expected because of hydraulic buffers. Decreases in evapotranspiration and changes in the ground-water flow rate to or from the river–aqueduct system and the lower Owens River tend to minimize fluctuations in heads. On the valley floor, changes are characterized primarily by differences in recharge and discharge, as indicated by the simulated decrease in evapotranspiration (fig. 27 and table 11). Interestingly, total ground-water inflow is greater in the 1988 simulation (fig. 27) because a lower water table induces additional recharge from surface-water features. On the basis of observations made during calibration and verification of the ground-water flow model and during testing of water-management alternative 4, described later, reaching new steady-state conditions may require as much as from 10 to 20 years of similar operations (fig. 21 and pl. 1).

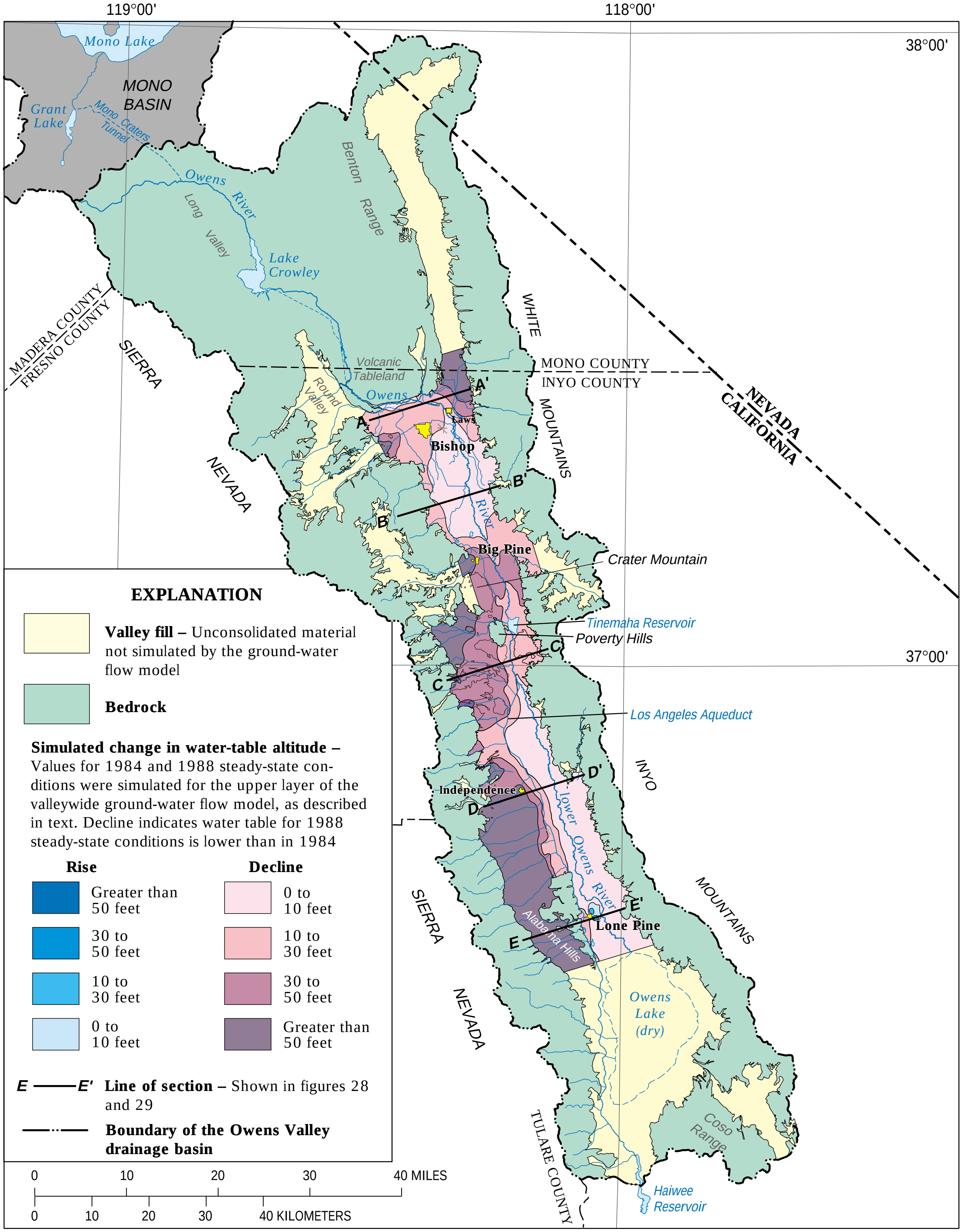


Figure 26. Simulated change in water-table altitude in the Owens Valley, California, between water year 1984 conditions and 1988 steady-state conditions.

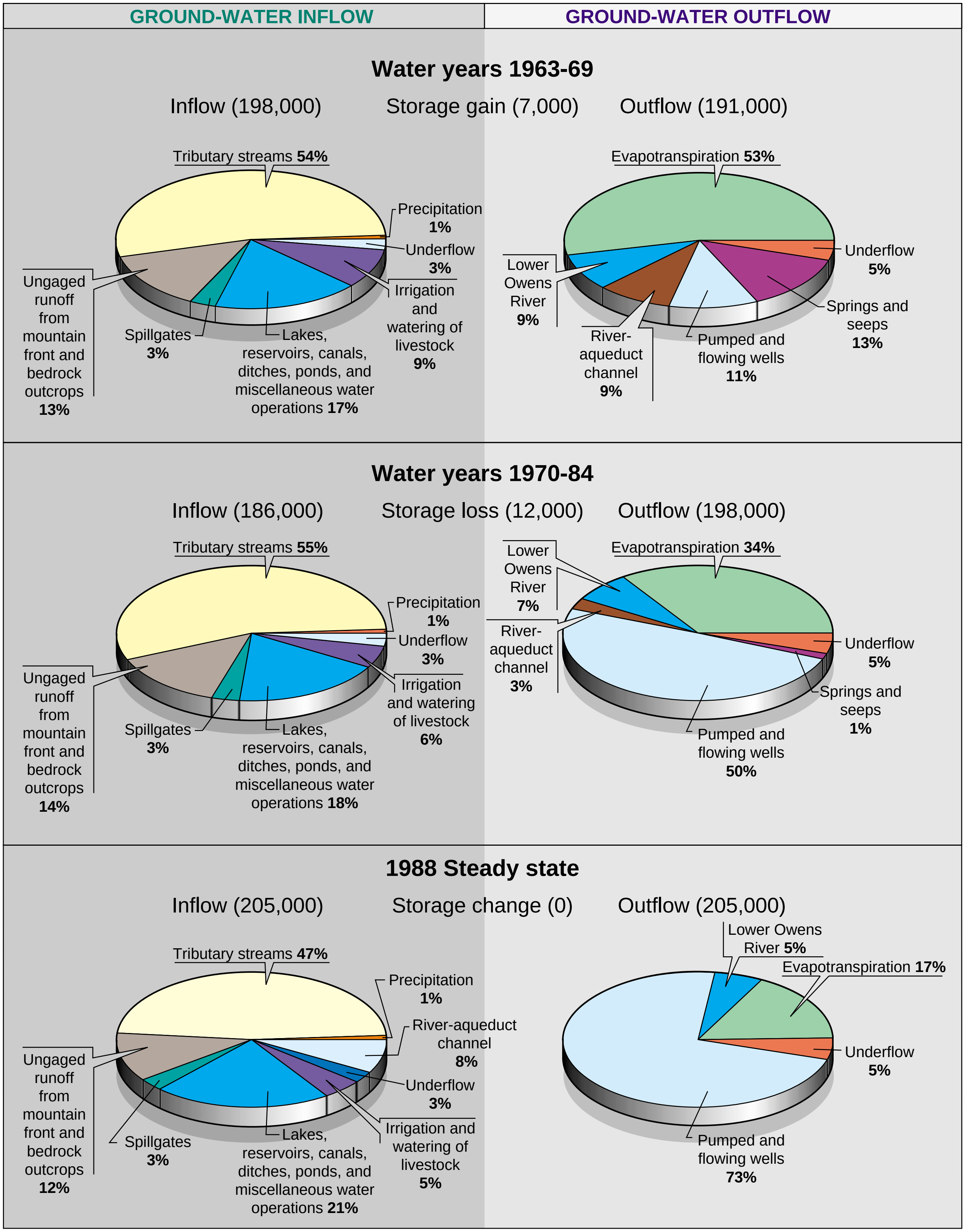


Figure 27. Simulated ground-water budgets for the aquifer system of the Owens Valley, California, for water years 1963–69, water years 1970–84, and 1988 steady-state conditions. Average inflow, outflow, and change in storage are expressed in acre-feet per year. Refer to text for model assumptions and to table 11 for precise values.

Table 15. Average pumpage from well fields in the Owens Valley, California

[ns, not simulated; wy, water years. Values in acre-feet per year. Values for 1-year responses are in excess of 1988 steady-state pumpage]

Time period	Well fields (figure 17)										
						Independence South					
	Laws	Bishop	Big Pine	Taboose–Aberdeen	Thibaut–Sawmill	Indepen-dence–Oak	Symmes–Shepherd	Bairs–George	Subtotal	Lone Pine	Total
1963–88 wy...	11,805	9,754	20,477	15,336	8,657	7,134	7,335	1,765	16,234	1,539	83,802
1963–69 wy...	5,290	6,091	668	1,783	339	3,382	2,044	327	5,753	259	20,182
1970–84 wy...	12,429	10,699	25,994	18,950	10,167	7,789	8,336	2,199	18,324	1,997	98,559
1985–88 wy...	20,868	12,623	34,453	25,505	17,549	11,245	12,842	2,651	26,738	2,062	139,798
1988 steady state.	29,391	11,962	37,113	22,386	21,169	11,497	11,500	1,952	24,949	2,305	149,275
1-year unit response (figure 34).	10,000	10,000	10,000	10,000	10,000	4,608	4,609	783	10,000	ns	60,000
1-year response (figure 35).	10,280	5,518	14,873	16,894	4,427	9,412	10,140	3,408	22,960	2,018	76,970

Although some uncertainty is present in the assumptions of this simulated steady-state condition, the general conclusions are not altered by slightly different assumptions about specific recharge or discharge components. The main difference between the 1988 steady-state values of recharge and discharge and previous values is the marked increase in ground-water pumpage, especially pumpage from enhancement and mitigation wells (table 11). An additional difference is that the long-term average runoff (100 percent of average runoff) assumed for the 1988 steady-state period is somewhat lower than that during water years 1963–84 (107 percent of average runoff).

The large increase in pumpage that occurred during water years 1970–84 was offset partially by a decrease in springflow, which helped to minimize changes in the water-table altitude. By 1984, total spring discharge was significantly less than it was prior to 1970, and the buffering effect on the water table was largely gone (fig. 21 and table 11). The further increase in pumpage assumed for the 1988 steady-state period combined with the slight decrease in average runoff resulted in a further decline of the water table in comparison with 1984 conditions (fig. 26).

During the initial part of this study, the 1984 water year was perceived to represent a return to relatively average conditions—water levels had returned to near the 1970 levels in most parts of the valley. However, this condition was highly contingent on the large runoff quantities of the late 1970's and early 1980's (fig. 12 and table 7) and the relatively lower pumpage (fig. 18). In contrast, the 1988 steady-state conditions assume long-term average runoff and a much higher quantity of average pumpage (table 15), albeit for various uses other than export out of the valley. If these assumptions remain valid, then the basin, as of 1988, is in the midst of another transition, one prompted largely by the increased pumpage from the enhancement and mitigation wells (table 11).

In general, the water-table decline is greatest in the alluvial fans, and least in the areas of seeps, drains, and surface-water bodies (hydraulic buffers) that are in contact with the ground-water system. The significant water-table decline in the alluvial fans will have no effect on overlying vegetation because the water table is many tens or hundreds of feet beneath the land surface of the fans, except in highly faulted areas, such as near Red Mountain or immediately north of the Alabama Hills (figs. 3 and 14). The water-table decline in the alluvial fans, however, will reduce the ground-water flow rate toward the valley floor, which in turn will reduce ground-water discharge, primarily transpiration from native vegetation on the valley floor. Plant stress similar to that observed by Sorenson and others (1991) can be expected to occur in areas near the toes of the fans and in parts of the valley floor near Big Pine and Laws if 1988 conditions are continued. It is important to note that there may be only a slight change in water-table altitude beneath these plants as a result of changes in plant transpiration and changes in flow to nearby seeps, drains, and surface-water bodies. This is a characteristic response of a ground-water system modulated by hydraulic buffers.

Changes in water management can offset some of the adverse effects implied in figure 26. Increased recharge of surface water during wet years, especially in or upgradient from areas likely to have decreased transpiration by native vegetation, would help to minimize a long-term reduction in native vegetation on the valley floor. In contrast to other nearby basins, however, the recharged water is not retained for an extended period of time (Danskin, 1990). The relatively high transmissivity of sand and gravel deposits and the exceptionally high transmissivity of volcanic materials tend to dissipate recharged water relatively fast (within a few years). In order to successfully mitigate the effects implied in figure 26, recharge needs to be increased above historical averages (figs. 21 and 27; tables 10 and 11) and pumpage probably needs to be decreased in selected areas where recharge cannot be increased.

Alternative 2: Continue 1988 Operations with Long-Term Changes in Climate

Alternative 2 addresses the question, "What if climatic cycles or long-term climatic change cause average basinwide runoff to be slightly less, or more?" The time period, water years 1935–84, that was used to analyze the surface-water system and develop runoff-recharge relations (fig. 13 and table 11), despite being 50 years long, may not be representative of average-runoff conditions for the next 25 to 50 years. Normal variations in climate could produce a change of a few percent in long-term average runoff. In addition, possible climatic change caused by human activities, although a highly controversial and largely unresearched topic (Danskin, 1990), is a recent global concern. The specific effects of induced climatic change are unknown; however, changes in the average annual runoff in basins in the Southwestern United States, including the Owens Valley, have been suggested (Revelle and Waggoner, 1983; Lins and others, 1988; Lettenmaier and Sheer, 1991). It also is possible that an induced climatic change may alter runoff conditions even more within individual years (Wigley and Jones, 1985; Moss and Lins, 1989), but this highly speculative aspect was not addressed in this study.

Simulation of alternative 2 used the 1988 steady-state conditions (alternative 1) with variations of plus or minus 10 percent in the average percent of runoff. This relatively small deviation reflects the generally well-known and stable condition of long-term average runoff. Also, the runoff-recharge relations are likely to remain valid for small changes in runoff. Analysis of a greater change in average runoff, which might result from more substantial changes in climate, would require a reinterpretation of precipitation patterns and amounts (fig. 7) and streamflow relations (fig. 13). In the present analysis, the quantities of ground-water recharge affected by the change in percent runoff include recharge from tributary streams, from mountain-front runoff between tributary streams, and from local runoff from bedrock outcrops within the valley fill (table 10). Recharge from precipitation was assumed to occur primarily during extremely wet years and was not changed. All other quantities of ground-water recharge and discharge were the same as those defined for alternative 1.

Results from alternative 2 are shown in figure 28 for representative sections across the valley. Sections *B–B′*, *C–C′*, *D–D′*, and *E–E′* in figure 28 correspond closely with hydrogeologic sections *B–B′*, *D–D′*, *E–E′*, and *F–F′*, respectively, of Hollett and others (1991, pl. 1 and 2). Also shown on the sections in figure 28 are simulated water tables for water year 1984 and for average runoff conditions (1988 steady-state simulation, fig. 26) and the range in simulated water tables for water years 1963–88. Only the simulated heads for the upper model layer (water table) are shown because they are most important in predicting effects on native vegetation; simulated heads for the lower model layer show a similar pattern, but with some vertical offset from heads for the upper model layer.

Most obvious in figure 28 is the difference between simulated steady-state conditions for 1988 (100 percent runoff) and simulated conditions for water years 1963–88. By comparison, variations of 10 percent in average basinwide runoff produced less difference in the water table in most areas of the basin, except along the western edge of the valley from Independence to Lone Pine (sections *D–D′* and *E–E′* in fig. 28). As expected, water-table differences resulting from variations in runoff are most pronounced in the

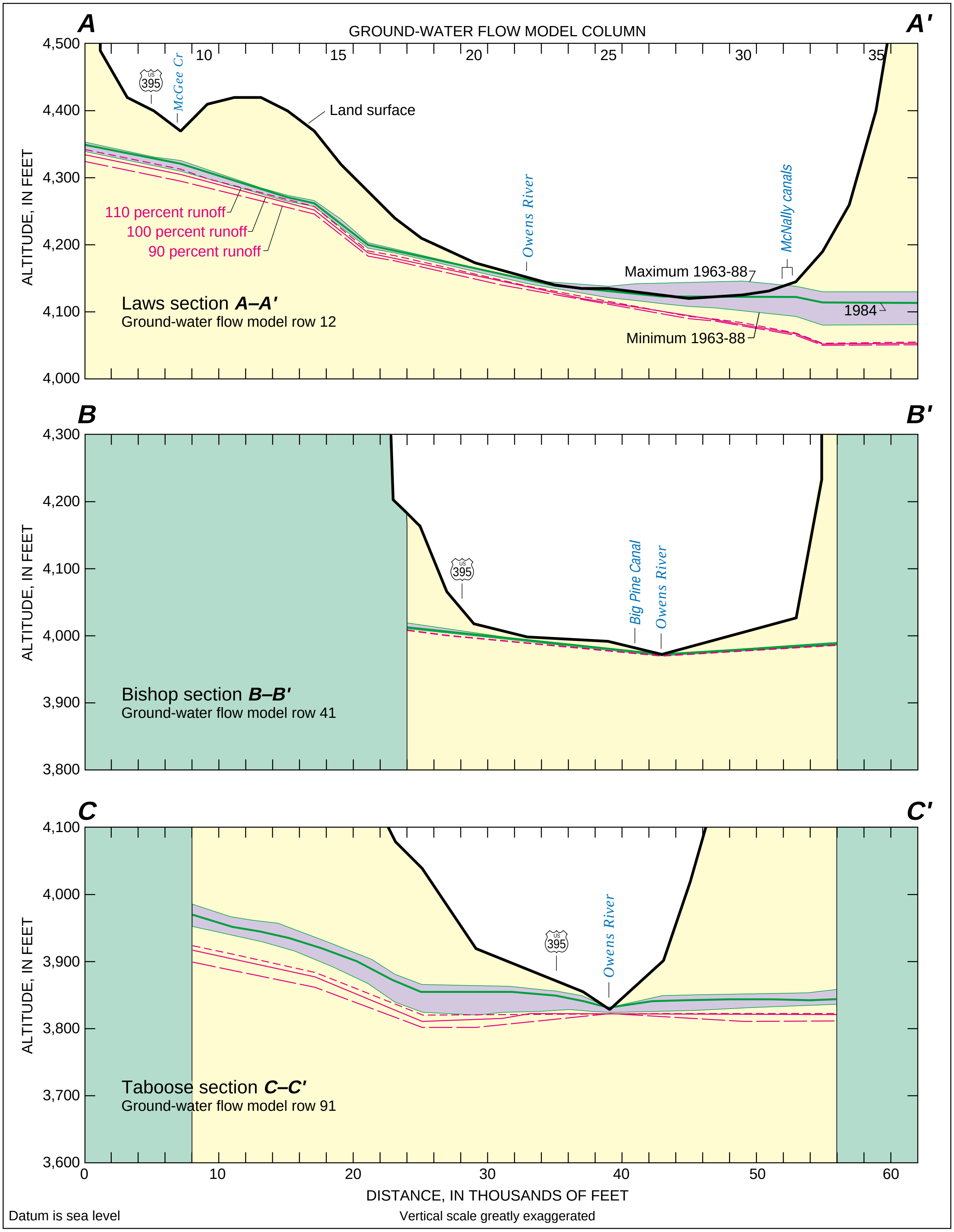


Figure 28. Sections showing the simulated water table in the Owens Valley, California, for 1998 steady-state conditions with different quantities of runoff. Line of sections shown in figure 26.

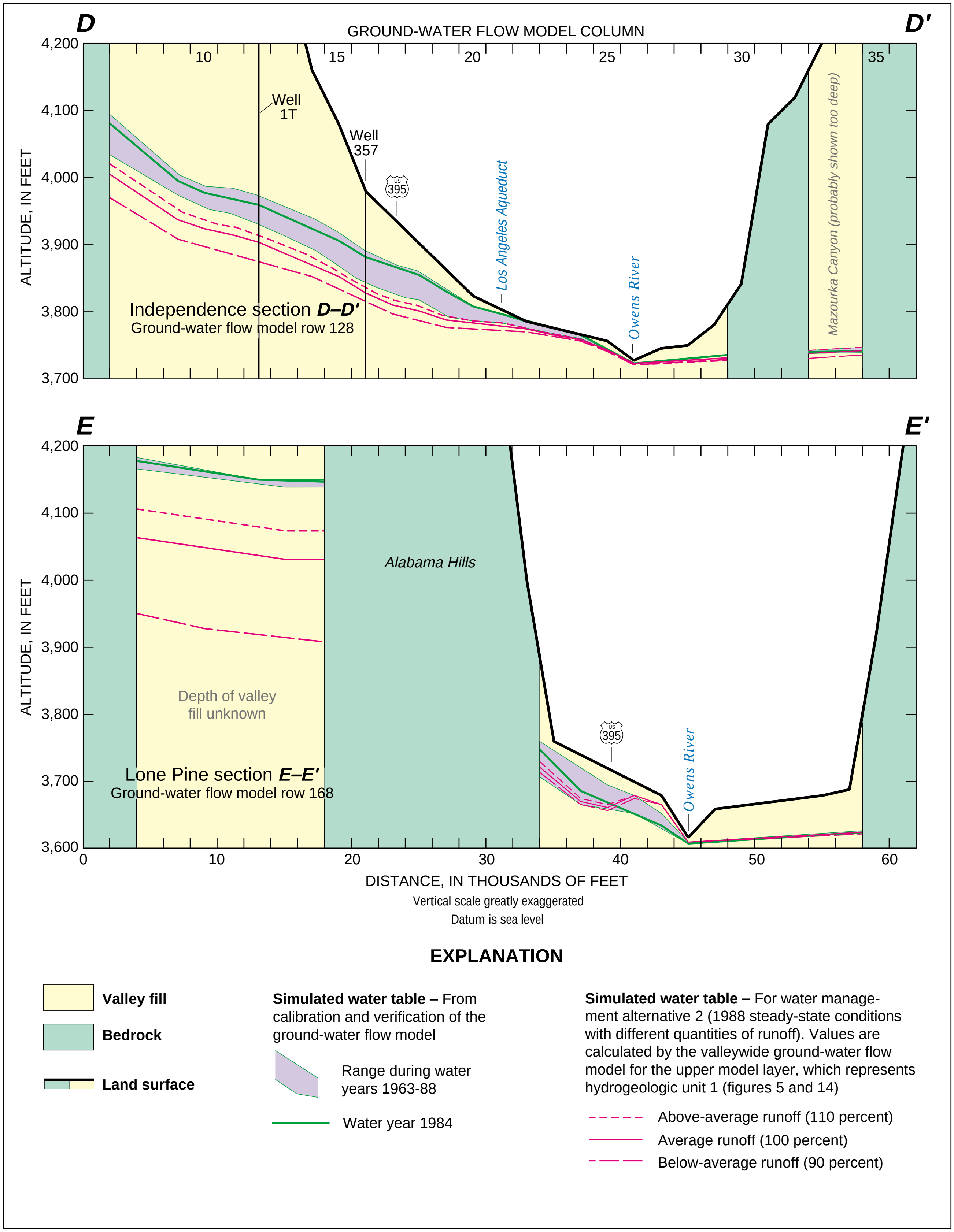


Figure 28. Continued.

recharge areas, particularly under the western alluvial fans. The river–aqueduct system, the lower Owens River, and native vegetation act as hydraulic buffers and help to reduce water-table changes near the valley floor.

Variations in runoff have less effect in the Bishop and the Laws areas than in the Taboose and the Independence areas. In the Lone Pine area, the marked change in the water table west of the Alabama Hills is largely a result of low transmissivities associated with the thin alluvial fan deposits and probably is not a major concern. The Alabama Hills effectively isolates the fan area to the west from the valley floor and related native vegetation to the east. In the Taboose and the Independence areas, however, the change in the water table beneath the alluvial fans translates to a significant decrease in the rate of ground-water movement toward the valley floor and a consequent decrease in evapotranspiration from the valley floor. Long-term monitoring of ground-water levels beneath the alluvial fans and valley floor and of evapotranspiration by native vegetation on the valley floor would identify such a long-term trend. In the Lone Pine area just west of the Owens River, the simulated water table for 1988 is higher than that for 1984 because of additional recharge from a new enhancement and mitigation project started in 1988.

Also of importance in figure 28 is a change in the river–aqueduct system in section *C–C′*. Simulation of 1988 steady-state conditions and variations in runoff of 10 percent indicate that under these conditions the river–aqueduct loses water to the Taboose–Aberdeen well field to the west. This change in flow direction could be verified with detailed water-level monitoring and water-quality sampling of the river–aqueduct and aquifer systems.

One management technique to minimize the effect of a long-term decrease in runoff is to increase the recharge from streams that have relatively low loss rates (fig. 13 and table 11). These streams include Bishop, Big Pine, Birch, Shepherd, and Lone Pine Creeks. Indeed, on the basis of results from alternative 1, increasing the recharge from streams is indicated even if long-term runoff does not decrease. Because past management efforts have pursued this option, it is unclear how much more water can be recharged on the alluvial fans in the critical areas of Taboose and Independence. An alternative management technique is to selectively decrease pumpage in sensitive areas.

The effects of a slightly different long-term average runoff, such as might occur as a result of climatic variations in precipitation, are less than those induced by human water-management decisions. Long-term variations in climate that produce slightly different annual quantities of runoff, assuming that stream-loss relations (fig. 13) continue to be valid, will not markedly affect the valley.

Alternative 3: Increase or Decrease Long-Term Average Pumpage

Alternative 3 addresses the question, “What will happen if average pumpage is increased or decreased from 1988 steady-state conditions?” One of the few aspects of the hydrologic system of the Owens Valley that can be altered readily is the quantity of pumpage. Over the past 20 years, pumpage has increased (fig. 17; tables 10 and 15) and has been the primary cause of change in the Owens Valley aquifer system during that time. Alternative 3 simulates scaling average annual basinwide pumpage up or down.

The design of alternative 3 was similar to that of alternative 2. Steady-state conditions for 1988 were assumed for all ground-water recharge and discharge, except pumpage. The value of pumpage at each well was scaled to 25, 50, 75, 100, and 125 percent of the 1988 steady-state value (table 9). The 100-percent pumpage simulation is identical to the 100-percent runoff simulation (alternative 2), which is identical to the 1988 steady-state simulation (alternative 1).

Although future pumpage in the valley is likely to be somewhat different from past pumpage because old wells occasionally are replaced with new wells, this difference is probably minimal for steady-state conditions, such as those simulated in alternative 3. Replacement wells usually are right next to the original well and are designed to extract water directly from hydrogeologic unit 3 (lower model layer) in order to delay the effects of pumpage on the water table. Given sufficient time, however, these effects will be transmitted to hydrogeologic unit 1 (upper model layer). The change in well design is recognized as an important management technique for shorter time periods, but it will become less valuable over time as the entire aquifer system equilibrates. Also, the valleywide ground-water flow model, as demonstrated during calibration, is relatively insensitive to withdrawing a greater percentage of pumpage from the lower layer.

Results from simulating alternative 3 are shown in figure 29 for the same sections shown in figure 28. The variations in pumpage are shown in 25-percent increments of the assumed 1988 steady-state pumpage. The increments are arbitrary, but they are within the confidence limits of the calibration model. Also shown is the simulated water table for water year 1984 in order to aid in correlating with figure 28 and plate 1.

As was true of figure 28, the most notable feature shown in figure 29 is the significant difference between the simulated water table for water year 1984 and that for 1988 steady-state conditions (100 percent pumpage) (fig. 26). This difference illustrates the large quantity of pumpage assumed for 1988 steady-state conditions—a quantity that combines average pumpage for export and new pumpage for enhancement and mitigation projects. In order to approximate the 1984 levels, average pumpage needs to be decreased significantly, to about 50 percent of the value assumed for the 1988 steady-state conditions, or to about 75,000 acre-ft/yr (fig. 29 and table 15).

The general linearity of pumpage effects is shown by an approximately even change in water-table altitude for each 25-percent increment. This feature is to be expected for a model using constant transmissivities and operating within the linear range of head-dependent recharge and discharge relations (table 13). A marked change in water-table altitude, however, is visible in the Taboose area (section *C–C′* in fig. 29) for the 125-percent increment. This result indicates that the simulated water table in the surrounding area has dropped below the zone of linearity of the head-dependent evapotranspiration and stream-recharge relations (refer to McDonald and Harbaugh, 1988, p. 10–3 and 6–9). When this occurs, the hydraulic buffering action is no longer effective, and the water table declines at a more rapid rate.

Different parts of the basin respond very differently to reductions in pumpage. The greatest change in the water table occurs near pumped wells, near bedrock boundaries, and away from head-dependent sources of recharge, such as the river–aqueduct system. As a result, a large change in the water table occurs on the west side of the valley, and relatively little change occurs on the east side of the valley across the Owens Valley Fault where there are few pumped wells (figs. 14 and 17). As noted in the discussion of alternative 2, wide variations in water-table altitude beneath the alluvial fans (such as those shown in section *D–D’* in fig. 28) do not affect overlying vegetation but do change the hydraulic gradient toward the discharge areas, and thereby decrease evapotranspiration rates for native vegetation some distance away on the valley floor.

Changes in the water table in the Bishop Basin occur mostly in the Laws area (section *A–A′* in fig. 29). Because head-dependent recharge along the eastern edge of the basin near Laws is minimal, no additional source of water is available except ground-water storage, and the simulated water table rises and falls dramatically with changes in pumpage. A similar response has been observed in measured ground-water levels (pl. 1). If some sources of recharge in the Laws area, such as the McNally Canals (figs. 11 and 29), act in a head-dependent way rather than as defined quantities of recharge as simulated in the model, then the use of head-dependent relations (table 13) to simulate these features will lessen the simulated fluctuations in the water table near Laws (fig. 29). Gaging of discharge in the canals and ditches, in addition to monitoring local ground-water levels, will aid in better defining these surface-water/ground-water relations.

The simulated water table in the area just south of Bishop is as unaffected by changes in pumpage as by changes in recharge (compare figs. 28 and 29). This lack of response results primarily because the area historically has had little recharge or pumpage, and, therefore, little was simulated in the model. A similarly static response was found in measured ground-water levels for well 335T (pl. 1) during water years 1963–88, a period of large variations in pumpage and recharge.

A decrease in evapotranspiration from the valley floor in the area south of Bishop may occur, however, even when the water table changes as little as 2 to 3 ft (Sorenson and others, 1991, p. G33). This decrease in evapotranspiration coincides with a decrease in the biomass of the native vegetation, as noted by Griepentrog and Groeneveld (1981, map 2) and by Sorenson and others (1991, fig. 24). Therefore, caution is required in interpreting simulation results even in areas that appear to have a minimal change in water-table altitude.

In the Owens Lake Basin, the primary effects of simulated changes in pumpage occur between Taboose and Independence Creeks (fig. 29). There is an

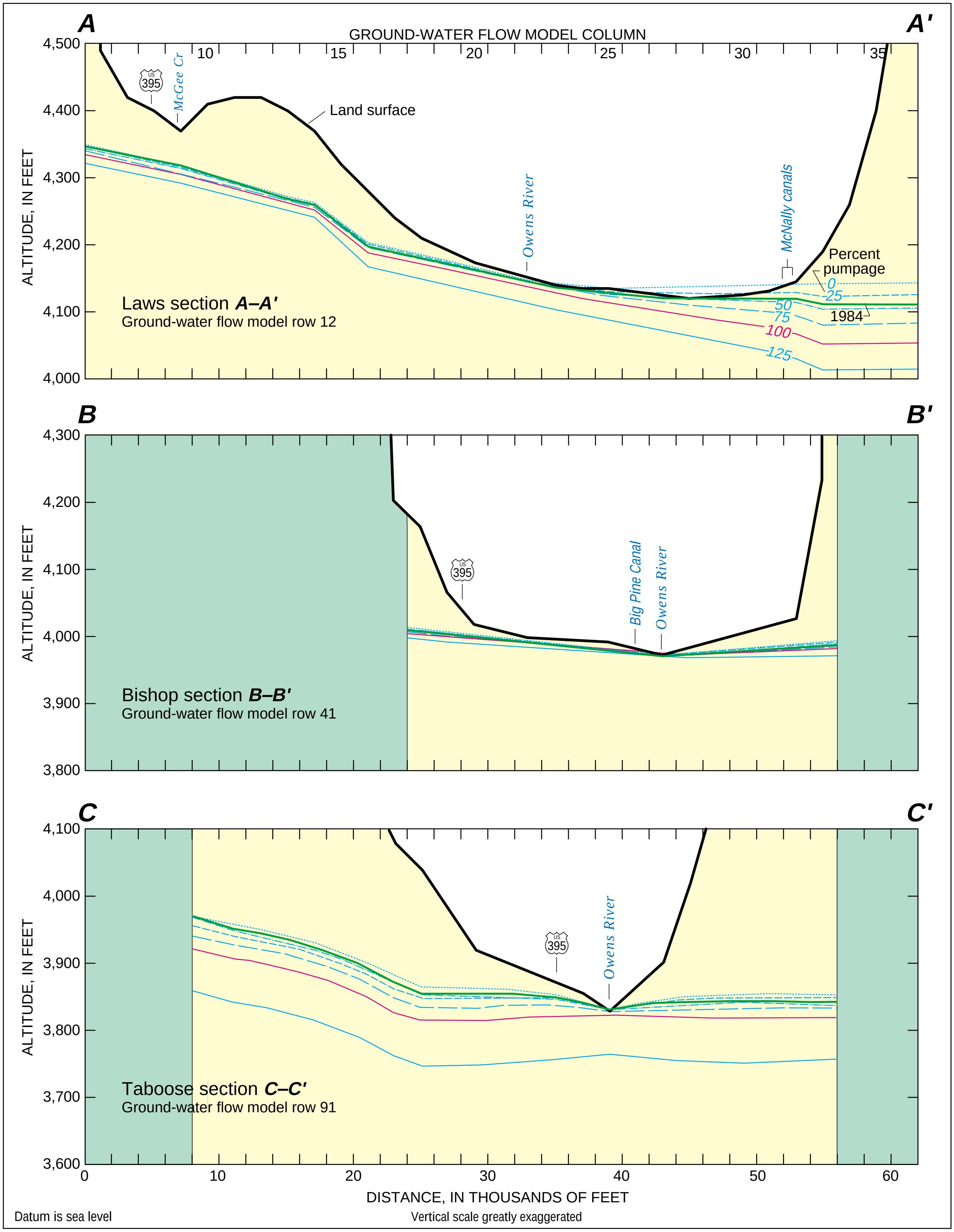


Figure 29. Sections showing the simulated water table in the Owens Valley, California, for 1988 steady-state conditions with different quantities of pumpage. Line of sections shown in figure 26.

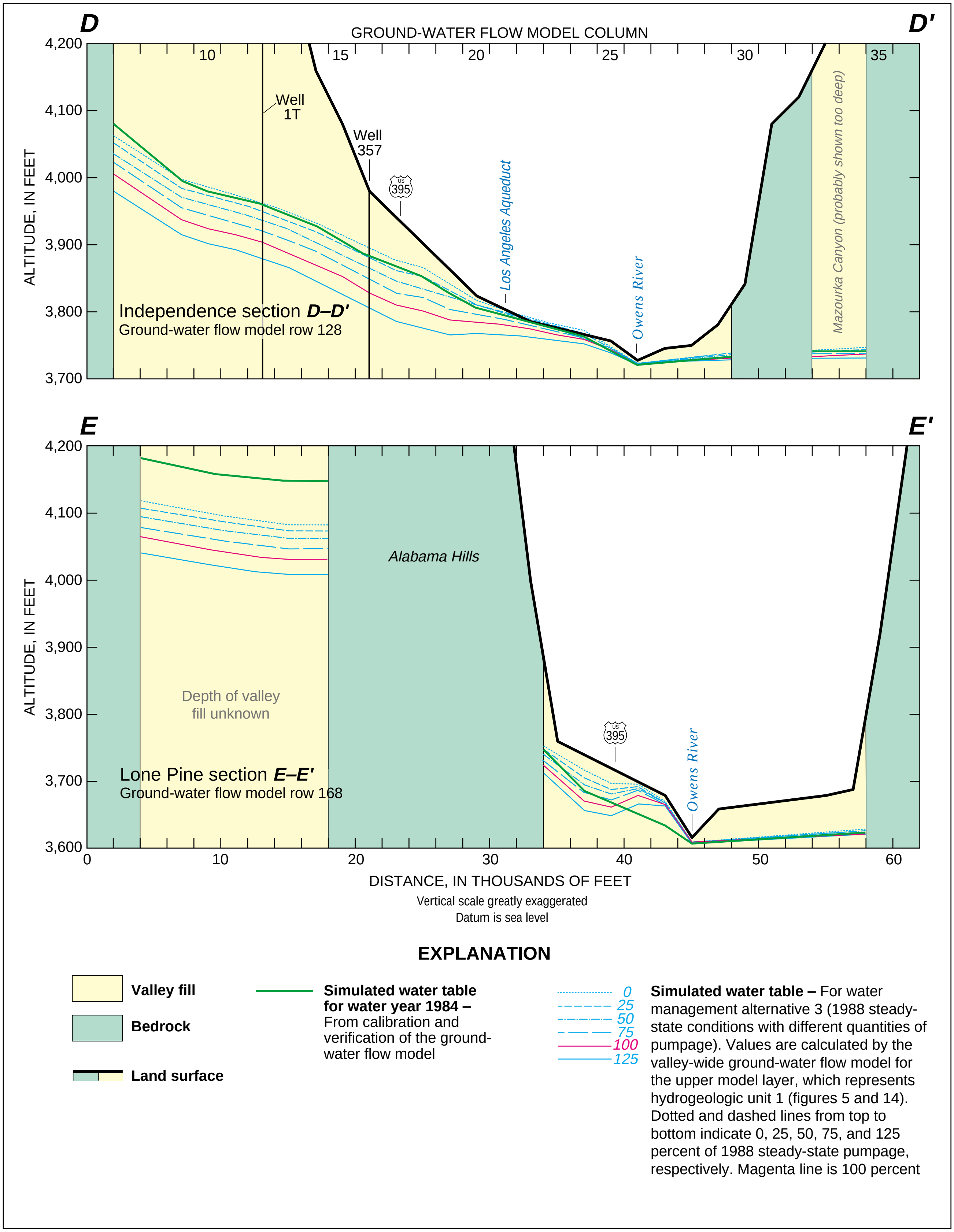


Figure 29. Continued.

indication in the Taboose area, as well as in the Laws area (section *A*–*A'* in fig. 29), that pumpage in excess of the 1988 steady-state quantity may cause hydraulic separation of the Owens River from the adjacent water table, creating a partially saturated zone beneath the river. This separation as simulated in the model causes a precipitous lowering of the water table, as discussed previously and as shown by the 125-percent increment.

In summary, results of model simulations suggest that the water table will continue to decline for some time if recharge and pumpage remain at the assumed 1988 steady-state values. This water-table decline will result in a decrease in evapotranspiration and a decrease in the biomass of native vegetation. Results of simulations indicate that to maintain the water table at an altitude similar to that of 1984, total pumpage needs to be about 75,000 acre-ft/yr, or about 50 percent of the assumed 1988 steady-state value.

Alternative 4: Manage Periodic Variations in Runoff and Pumpage

Alternative 4 addresses the question, “How can a sequence of dry and wet years be managed?” For example, which areas of the valley are likely to be affected most by a severe drought, which least, and how fast do the different areas recover? Which areas need help in recovering to pre-drought conditions? The Owens Valley hydrologic system historically has cycled between droughts and periods of abundant water (table 7). Because of the multiplicity of and constant change in water-management operations, such as during water years 1970–88, it is difficult to identify the effects of a typical cycle using historical data. Simulation of alternative 4 attempts to clarify these effects with a simple, but typical, management scenario.

A schematic of the 9-year transient simulation used for alternative 4 is shown in figure 30. The 9-year simulation period has similarities to drought, average-runoff, and above-average-runoff conditions experienced during the 1970's and 80's. Initial conditions for alternative 4 were assumed to be alternative 1 (1988 steady-state) conditions. The first 3-year period (I) represents drought conditions and simulates 70 percent of average runoff and maximum pumpage. Maximum pumpage is defined as the maximum annual pumpage recorded at each well during water years 1985–88; maximum pumpage for enhancement and mitigation wells is the value recorded for water year 1988 (table 11). The implicit water-management goal during the first 3-year period is to maximize export of ground water to compensate for decreased export of surface water. The second 3-year simulation period (II) represents a return to average conditions and simulates 100 percent of average runoff and the same value of pumpage as the initial (1988 steady-state) conditions. The management question during the second period is, “How fast does the system return to normal?” The third 3-year simulation period (III) represents wet conditions and simulates 130 percent of average runoff and the same average pumpage as during the second 3-year period. Actual pumpage during a wet cycle most likely will be somewhat less than average, particularly after a couple of wet years (fig. 18). This decrease, however, is poorly quantified for future conditions and was not incorporated in the simulation. Results from the third period identify areas of the valley in which the simulated heads have not recovered to initial conditions even after 3 years of average conditions and 3 years of wet conditions. Specific values of recharge and discharge are given in table 11.

The simulated change in water-table altitude at the end of each 3-year period (drought, average, and wet) with respect to initial conditions is shown in figures 31, 32, and 33, respectively. Because no site-specific water-management techniques were incorporated in the simulation, the results identify those stressed areas of the valley that require additional monitoring and possibly additional manipulations of ground-water recharge and discharge.

The areas of the valley that show the greatest effects at the end of a 3-year drought marked by lesser runoff and greater pumpage are identified in figure 31. Clearly, the effect of drought is widespread. Much of the decline in the water table occurs beneath the alluvial fans and volcanic deposits, as in other simulations (figs. 23, 26, 28, and 29). Areas with the most dramatic changes are those in abundant recharge areas (Bishop and Oak Creeks). Other areas with significant water-table decline are near the well fields (Laws, Big Pine, Taboose–Aberdeen, and Independence–Oak) (fig. 17). As determined during sensitivity analysis of the ground-water flow model, the effect of lower runoff near well fields is minimal in comparison with the effect of nearby pumping.

Some areas on the valley floor that have a simulated decline in water-table altitude greater than 10 ft are areas that are covered with native vegetation identified as susceptible to stress from pumping (R.H. Rawson, Los Angeles Department of Water and Power, written commun., 1988; Sorenson and others, 1991). The significant water-table decline in these areas decreases evapotranspiration, prompts native vegetation to drop leaves, and reduces total biomass on the valley floor. Some species, such as rabbitbrush

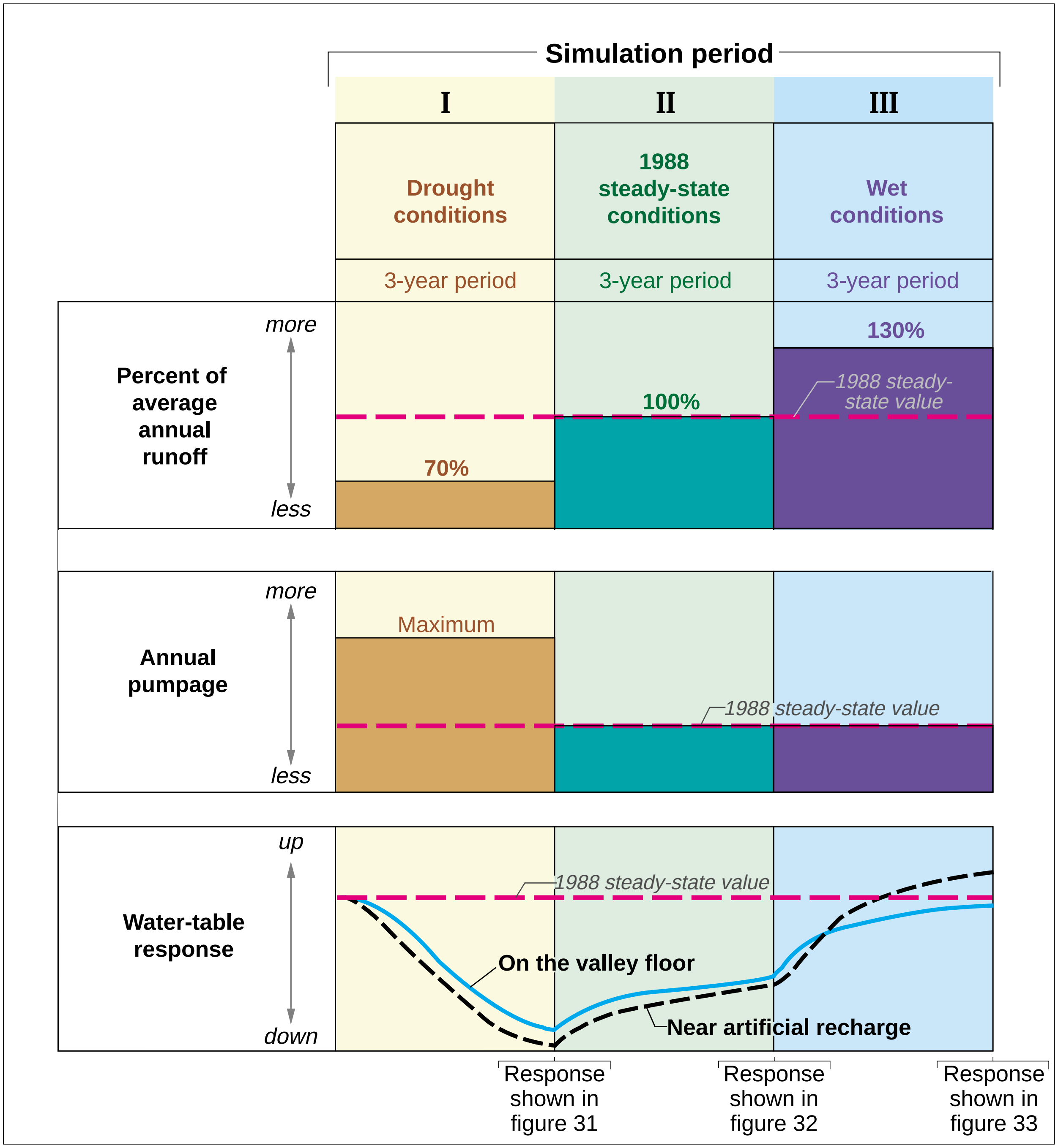


Figure 30. Diagram of water-management alternative 4 for the Owens Valley, California. Shown are changes in percent of average annual runoff, annual pumpage, and water-table response at typical locations in the valley during the 9-year simulation period. Results at the end of each 3-year period are displayed in figures 31–33.

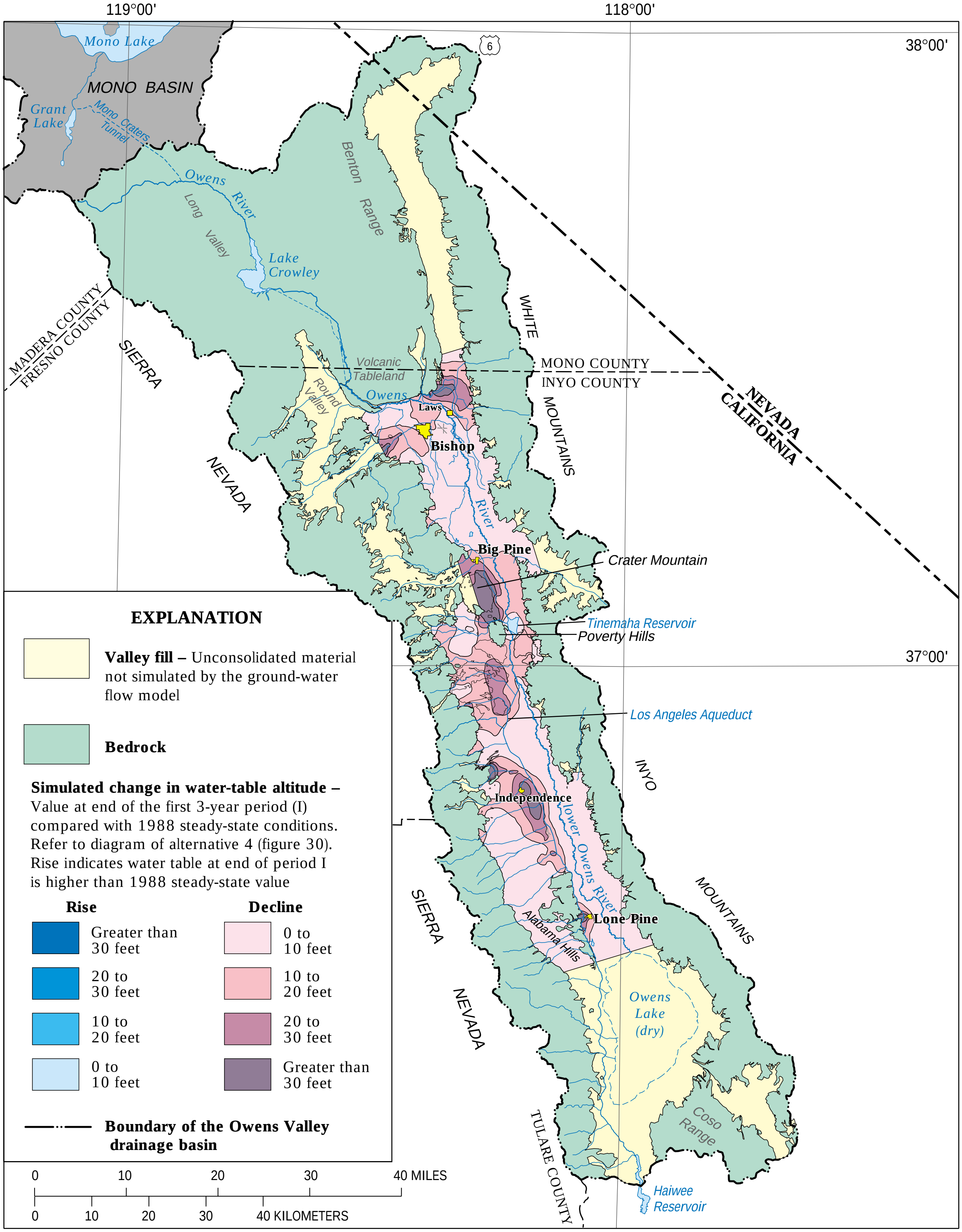


Figure 31. Simulated change in water-table altitude in the Owens Valley, California, for water-management alternative 4 at the end of period I, representing 3 years of drought.

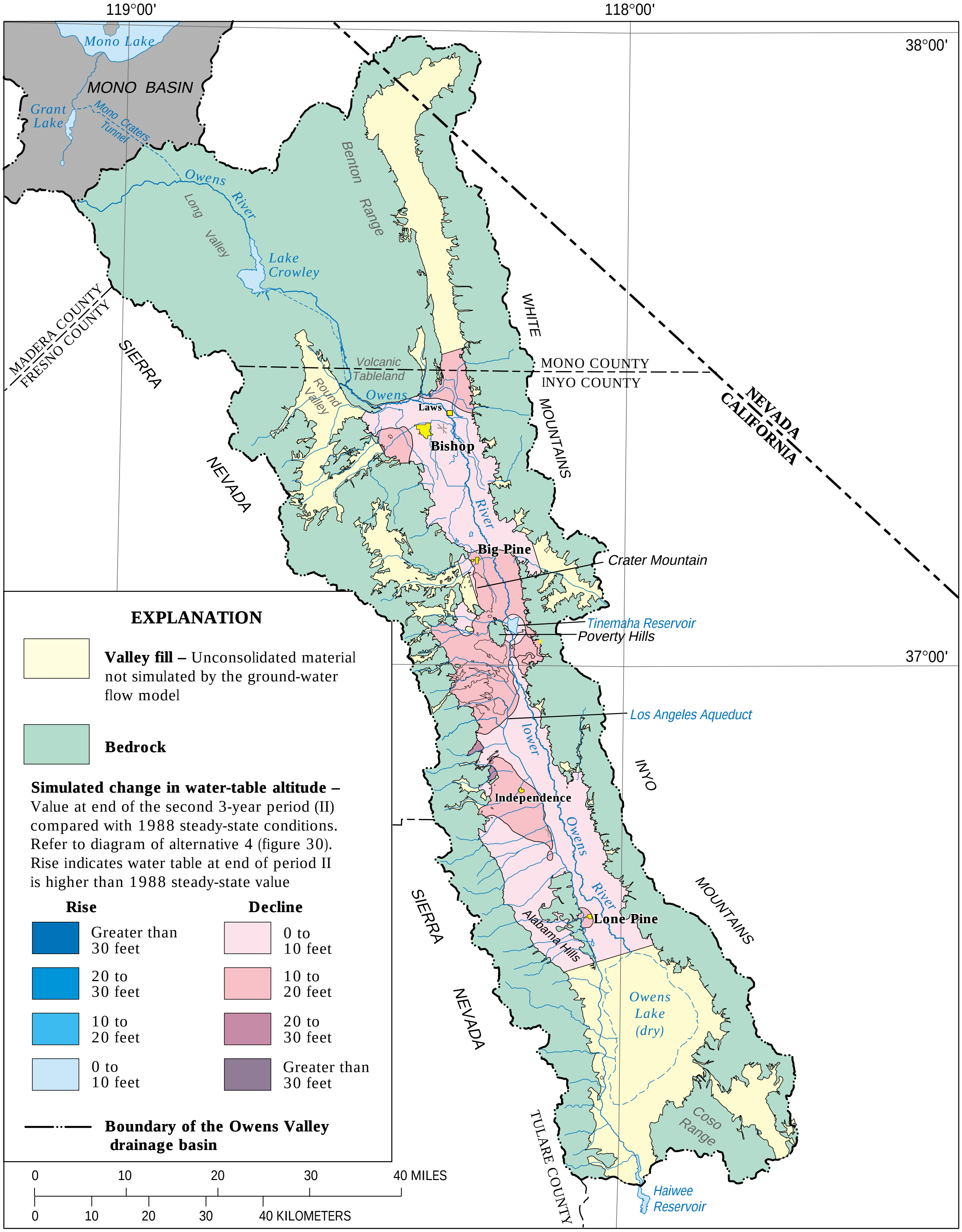


Figure 32. Simulated change in water-table altitude in the Owens Valley, California, for water-management alternative 4 at the end of period II, representing 3 years of recovery.

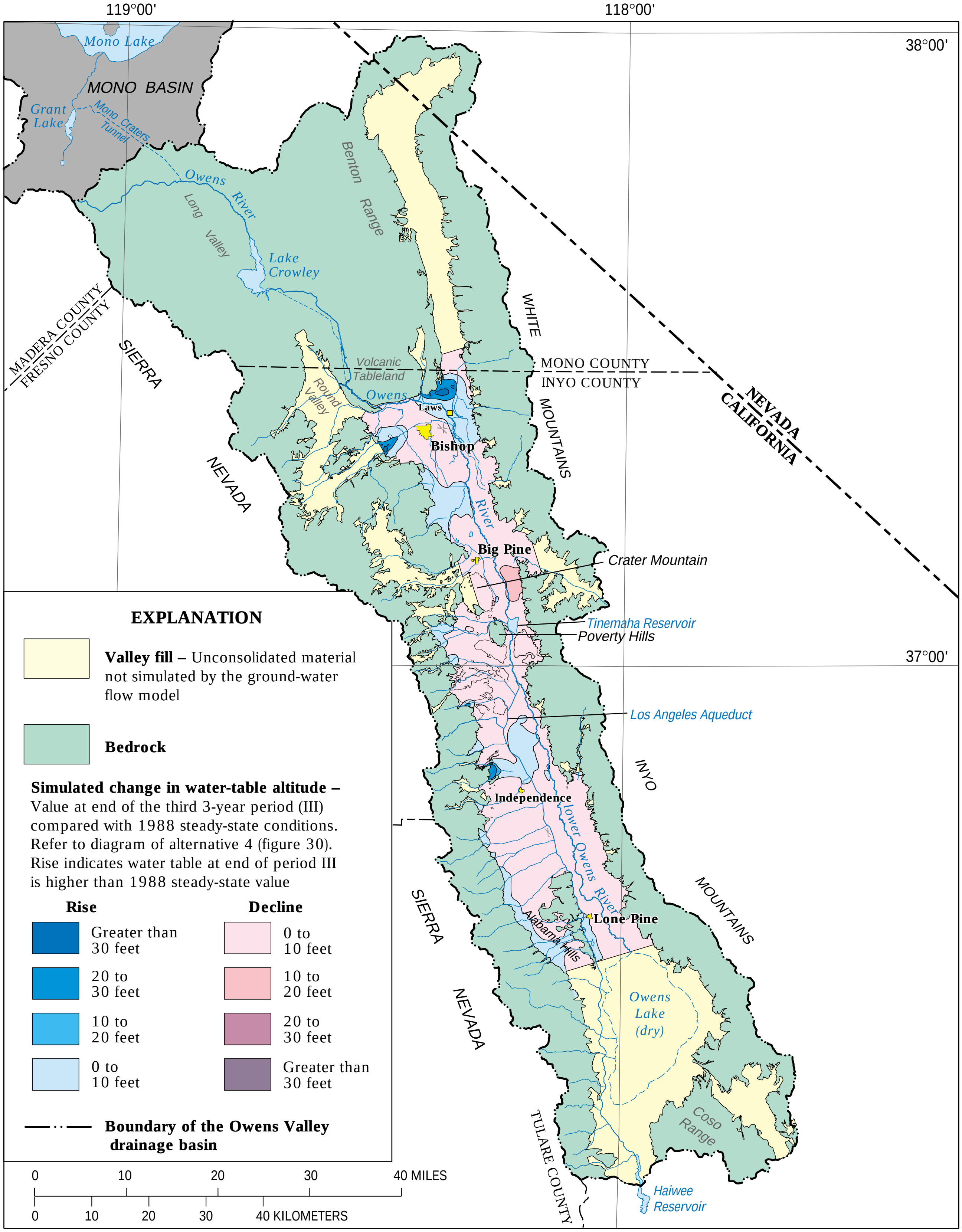


Figure 33. Simulated change in water-table altitude in the Owens Valley, California, for water-management alternative 4 at the end of period III, representing 3 years of wet conditions.

(Sorenson and others, 1991, p. G35) may die during a 3-year drought if the plants cannot grow additional roots deep enough and fast enough.

Areas of the valley floor that are isolated from recharge and pumping effects, such as between Bishop and Big Pine and east of the Owens River, have a simulated decline in water-table altitude of only a foot or two. Although some decrease in evapotranspiration is likely, the effects on native vegetation are much less than effects near recharge areas and well fields. Because these isolated areas have few monitoring wells, simulation results need to be viewed cautiously.

The Taboose–Aberdeen area exhibits a broad areal change in water-table altitude, broader than in most other areas of the valley. The many springs in the area historically acted as hydraulic buffers and dampened the effects of pumping on water-table fluctuations. That capacity, however, now is largely gone (figs. 17 and 21), and, with changes in pumpage, the water-table fluctuations are greater (pl. 1). Neither the Owens Valley Fault nor the unnamed fault near the aqueduct (fig. 14) is an effective barrier to ground-water flow in this part of the Owens Lake Basin. Cones of depression in the water table created by pumping in well fields (fig. 17) propagate unimpeded eastward across the valley.

In the southern part of the Bishop Basin, cones of depression are transmitted even more effectively through hydrogeologic unit 3 to the east side of the valley because of the presence of the relatively impermeable blue-green clay (Hollett and others, 1991, pl. 1). This thick clay layer effectively restricts the vertical flow of water from hydrogeologic unit 1 to hydrogeologic unit 3 in the center of the valley. Release of water from hydrogeologic unit 3 is derived mostly from elastic expansion of water and compression of the aquifer, which results in a storage coefficient that is much smaller than specific yield. As a result of these conditions, the cone of depression expands to cover a large area. The highly transmissive sand and gravel beds in hydrogeologic unit 3 aid in propagating the cone of depression horizontally. On the east side of the valley, the alluvial fan deposits have a greater vertical hydraulic conductivity than does the blue-green clay, and ground water can readily flow from hydrogeologic unit 1 to hydrogeologic unit 3. In this way, the water table along the east side of the valley responds to pumping on the west side. The net result is that most of the nearby area north and south of the Tinemaha Reservoir exhibits a significant decline in the simulated water table. Associated adverse effects on nearby native vegetation are likely, particularly in areas distant from surface-water features, which are a source of recharge.

Historical water-management operations in the Owens Valley have tended to create feast or famine conditions for native vegetation. For example, the recent (1984) rise in the water table near Laws and Independence (fig. 23) resulted from an abundance of recharge in these areas, primarily as a result of water-spreading activities by the Los Angeles Department of Water and Power (pls. 1 and 3; table 11), and from a temporary reduction in pumpage (fig. 17). Native vegetation responds to increased water availability by increasing leaf growth or plant density, which results in a commensurate increase in evapotranspiration (Groeneveld and others, 1987). A subsequent period of drought and increased pumpage, such as during water years 1987–88 (pl. 1) or as simulated during the first 3-year period of alternative 4 (figs. 30 and 31), results in a declining water table and a decrease in plant leaf area and evapotranspiration. The declining water table then prompts a water-management decision to decrease pumpage and implement water-spreading efforts to increase recharge when water is again abundant. This cyclic pattern of response by the aquifer system and native vegetation to alternating drought and high runoff, accentuated by water-management decisions that increase pumpage during droughts and then increase artificial recharge during periods of high runoff, typifies a more highly managed Owens Valley.

One attribute of a more highly managed aquifer system is that native vegetation will be less evenly distributed. The natural flow of the aquifer system tends to smooth out ground-water levels, recharge, and discharge. Human changes in the aquifer system tend to focus recharge and discharge into smaller areas. As the valley becomes more controlled, it will become more pod-like, with pods of thriving vegetation near enhancement and mitigation projects and pods of highly stressed vegetation near wells. In between, native vegetation will be using less water than it had been using prior to the increase in water development.

A water-management goal for most ground-water basins is the same as for a surface-water reservoir. Empty the reservoir when water is scarce; fill it when water is plentiful. The paradox in managing the Owens Valley is that if the water table beneath the valley floor fluctuates too much, native vegetation is adversely affected. Therefore, the reservoir must be kept virtually full.

Alternative water-management techniques to lessen the effect of pumping on the water table and nearby native vegetation are limited in many ways, as discussed in the section “General Water-Management Considerations.” From a long-term, valleywide perspective, the water table is affected most by the quantity of water pumped, not by the particular location of pumping in the valley (fig. 26). Nevertheless, locations with pumped wells have greater fluctuations in the water table and a greater likelihood of having native vegetation adversely affected by water-table fluctuations (compare figs. 17 and 31). Locating pumping on alluvial fans away from the valley floor will lessen the decline of the water table near sensitive vegetation. Pumping from high on the western alluvial fans, in particular in areas of abundant recharge, will lessen the immediate effects on the valley floor.

However, past experiences of drilling on the western alluvial fans (well 1T, pl. 1) showed that installation of wells has been difficult or nearly impossible because of massive rock and boulders (M.L. Blevins, Los Angeles Department of Water and Power, oral commun., 1987). Also, transmissivities of the alluvial fans and related well yields are significantly less than in transition-zone or volcanic deposits (fig. 15). Electrical usage is higher in order to lift water the greater distance to land surface. Similar difficulties might be encountered in installing new wells on the eastern alluvial fans. In addition, the eastern alluvial fans are areas of limited recharge and, possibly, poorer quality ground water with a higher concentration of dissolved solids.

Pumping from high on the Bishop Creek alluvial fan (Bishop Cone), although now limited by the Hillside Decree, probably would produce minimal effects on the valley floor, especially if pumping were limited to short-term supply during a drought. This broad, gently sloping fan is characterized by abundant recharge from Bishop Creek. The fan has additional recharge potential through the use of spreading basins, and it might be easier to drill through this fan than through the steep, rocky fans near Independence.

Much of the valley floor in the Bishop and Big Pine areas is urban or irrigated land that is not affected by a decline in the water table. Additional pumping from within these areas probably will have less effect on native vegetation than pumping from other areas of the valley floor.

Pumping only from lower zones of the aquifer system, beneath hydrogeologic unit 1, reduces the immediate decline of the water table. The amount of this reduction is unknown, but it could be approximated using detailed, site-specific ground-water flow models of individual well fields, or possibly by field testing a single pumped well surrounded by several, multiple-depth monitoring wells (Driscoll, 1986, p. 719–728). The benefit of pumping from lower zones, however, decreases the longer the wells are pumped continuously. Hydrogeologic boundary conditions and vertical leakage through hydrogeologic unit 2 and alluvial fan deposits eventually will transmit the effects of pumping from lower zones to hydrogeologic unit 1, lowering the water table and decreasing evapotranspiration from areas where the water table is within 15 ft of land surface (table 5).

Differences in the simulated water-table altitude following 3 years of drought and 3 years of average conditions are shown in figure 32. The areas of residual decline in the water table are similar to those in figure 31, but the magnitude is less. Areas where the decline is greater than 10 ft indicate locations in the valley that need careful monitoring of the water table, soil-moisture zone, and native vegetation. Results from simulating alternative 4 also suggest that monitoring the effects of a drought need to be continued for several years following the end of the drought—much longer than previously thought necessary.

Differences in the simulated water-table altitude following 3 years of drought, 3 years of average conditions, and 3 years of 130-percent runoff are shown in figure 33. As expected, recharge areas show a considerable rise in the water table, as do areas of focused artificial recharge, such as near Laws and Independence (fig. 33 and pl. 3). Somewhat surprising, however, is that 6 years after a drought and immediately following 3 years of above-average runoff, the water table in many areas of the valley still shows signs of the drought and coincident pumpage. Minor residual drawdown is present over most of the valley floor, and an isolated area of declines greater than 10 ft still is present beneath the alluvial fans east of Big Pine. This result demonstrates the slowness of recovery in areas away from abundant recharge.

The period of recovery for the water table is much longer than was hypothesized at the beginning of the modeling studies. This characteristic of the aquifer system, however, agrees well with the tentative conclusion that the aquifer system and native vegetation were still in transition in the mid-1980's from the effects of increased pumping in the early 1970's and the drought conditions in 1976–77.

The water-table decline simulated in alternative 4 can be reduced by focusing artificial-recharge efforts in areas of greatest decline and concentrated pumping (figs. 17 and 31). Localized recharge efforts may need to be continued for as long as 6 years after the end of a 3-year drought in order to compensate for the decline in water table. Areas of abundant water and lush vegetation induced by artificial recharge likely will become areas of stressed vegetation in future drought conditions (compare figs. 31 and 33).

Because of the limitations associated with the valleywide ground-water flow model and the unique characteristics of a particular drought, ongoing monitoring of the aquifer system, soil-moisture zone, and native vegetation needs to be continued, particularly in areas simulated in alternative 4 as having water-table declines greater than 10 ft (figs. 31, 32, and 33).

Optimal Operation of Well Fields

An extensive body of literature deals with the general topic of mathematical optimization of physical systems (Gorelick, 1983; Rogers and Fiering, 1986), and a few applications have been made to combined surface-water and ground-water systems (Young and Bredehoeft, 1972; Bredehoeft and Young, 1970, 1983; Danskin and Gorelick, 1985). Although use of these techniques was proposed initially as a promising method of evaluating water management in the Owens Valley, detailed appraisals during the 6-year study identified several numerical limitations. The mathematical dimensions ($m \times n$ matrix) required by a realistic optimization model for the Owens Valley are very large. There are more than 40 streams, 9 well fields, 200 production wells, 800 observation wells, and 600 surface-water gaging stations—as well as a multitude of decision points in the basin, such as whether or not to divert a stream. Also, the optimization problem is moderately nonlinear as a result of the piecewise-linear relations used to approximate some recharge and discharge components in the ground-water flow model (table 13). The large dimensionality and nonlinearities would require considerable computer time to solve even a relatively simple problem in a mathematically rigorous way. As computer capabilities increase and costs diminish, a basinwide optimization study may prove to be more tractable. The approach presented in this report uses the basics of the mathematical optimization techniques and could serve as the foundation of a simple optimization model.

The actual operation of individual well fields is a complex and iterative process, dependent on many factors—including those general concerns presented in the section entitled "General Water-Management Considerations," as well as day-to-day concerns of mechanical efficiency, repair and maintenance, and personnel requirements. Optimal operation probably involves meeting several different objectives, which makes the mathematical problem even more complex and makes a simple, instructive version of the water-management system difficult to define.

For this evaluation, however, optimal operation of well fields was defined in a semi-quantitative way to be the most pumpage for the least adverse effect on native vegetation. The ground-water flow model was used to determine the effect of pumpage from each well field. The model response, referred to in optimization literature as a "response function," is the change in head, recharge, and discharge in response to a defined increase in pumpage. A unit increase in pumpage produces a "unit response." Those well fields that produce the least adverse effects on native vegetation (least water-table decline under vegetation that relies on ground water) are considered the optimal well fields to use. Well fields with a greater water-table decline are less desirable, or less optimal.

Two similar analyses were done to determine the effect of pumpage from each well field. Each analysis involved simulating the response to pumpage at individual well fields. The simulation timeframe was 1 year with constant stresses. Initial conditions for each simulation were the 1988 steady-state conditions (alternative 1). To simplify the analysis, the Independence–Oak, the Symmes–Shepherd, and the Bairs–George well fields (fig. 17) were grouped together and are referred to as the "Independence south" well field. The Lone Pine well field was not included in the first analysis because of its limited capacity, the presence near the well field of relatively fine-grained and less transmissive aquifer materials (figs. 15 and 16), and the abundance of nearby en echelon faults that limit production (fig. 4).

The first analysis involved increasing pumpage at each well field (tables 11 and 15) by 10,000 acre-ft/yr more than the 1988 steady-state simulation (alternative 1). Pumpage for an individual well was increased in proportion to its 1988 steady-state value (table 11). After 1 year of simulation, the decline in water-table altitude was noted and is shown in figure 34. From this analysis, the well field having the greatest effect on native vegetation is readily discernible as the one producing the greatest water-table decline under the largest area of native vegetation

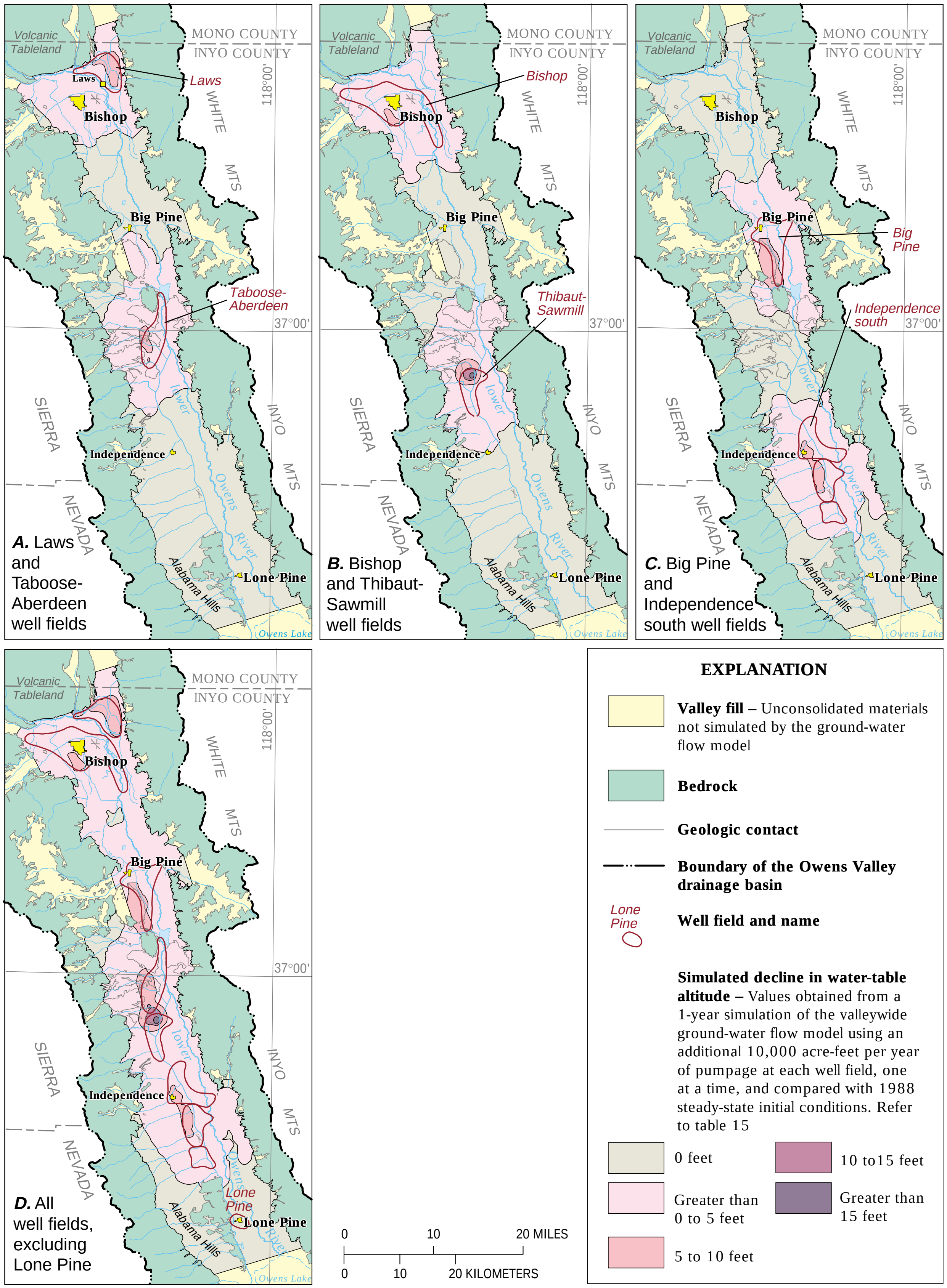


Figure 34. Simulated decline in water-table altitude in the Owens Valley, California, resulting from a unit increase in pumpage at each well field.

dependent on the water table. This technique of using a unit stress (10,000 acre-ft/yr of pumpage) to observe the "unit response" (drawdown surrounding each well field) is a dominant feature in most hydraulic optimization techniques (Gorelick, 1983). For comparison, the combined effect of 10,000 acre-ft of additional pumpage at each of the six well fields is shown in figure 34*D*.

The approximate area of native vegetation dependent on the water table is indicated by the boundary of alluvial fans (compare figs. 4 and 34). Detailed mapping by the Los Angeles Department of Water and Power (R.H. Rawson, written commun., 1988) identified a few isolated parts of the valley floor, primarily east of the lower Owens River, where native vegetation may not be dependent on ground water. Vegetation in these areas of the valley floor presumably is isolated from the effects of pumpage.

All well fields produce approximately the same areal effect (fig. 34). Cones of depression in the water table extend to the edge of the Owens Valley aquifer system, even within a single year. The cones of depression extend somewhat farther up and down the valley because of boundary effects along the edges of the valley and the linearity of hydrogeologic units (fig. 5). All well fields except the Bishop produce greater than 5 ft of drawdown beneath the valley floor, but the magnitude of drawdown is somewhat more concentrated in well fields that have fewer, higher production wells, such as the Big Pine and the Thibaut–Sawmill well fields. The combined pumpage of an additional 60,000 acre-ft/yr (fig. 34*D*) indicates that cones of depression from individual well fields merge and extend over most of the valley.

The most surprising result of this first "unit response" analysis is the similarity of response from each of the well fields. No obviously better place to extract water is evident despite the spatial differences in hydraulic properties of the aquifer system, the distribution of wells, the locations of surface-water features, or the presence of faults that retard ground-water movement. The Bishop well field probably produces the least effect on native vegetation, but water from this well field cannot be used for export, as stipulated by the Hillside Decree. The optimal management of well fields favors producing a large volume of water from a small area, such as from the Thibaut–Sawmill well field. The resulting drawdown is greater, but the area of significant drawdown is more localized.

Extraction of water from the large alluvial fan near Bishop in lieu of other areas of the valley is a favorable management alternative, as discussed in the preceding section (p. 122), except for the restrictions imposed by the Hillside Decree. Vegetation covering most of the fan is not dependent on ground water because the water table is tens or hundreds of feet beneath land surface. The present distribution of wells (fig. 17) indicates that the fan is not used extensively for production. Increasing production uniformly (fig. 34*B*) produces a small area with greater than 5 ft of drawdown near the edge of the fan. By distributing production farther up the fan, the area of greatest drawdown will be reduced in size, and any increased drawdown will occur beneath vegetation that does not subsist on ground water. An important caveat, however, is that sustained pumping from alluvial fan areas eventually decreases ground-water flow rates toward the valley floor area and will cause some change in native vegetation, even if the water table beneath the valley floor remains relatively unaffected. Although pumping from other alluvial fans will yield similar beneficial results, the benefits will be limited by problems of lesser recharge and technical difficulties in installing wells.

The second analysis involved increasing 1988 steady-state pumpage at each well field to the maximum annual value measured at each well during water years 1985–88 (tables 11 and 15). This analysis is designed to optimally distribute present pumping capacity in excess of the 1988 steady-state quantity (alternative 1). Water-table decline after the 1-year simulation is shown in figure 35. For some well fields, the increase is approximately 10,000 acre-ft/yr and the drawdown in figure 35 resembles that in figure 34.

Most of the pumpage from the Bishop and the Thibaut–Sawmill well fields is used for ongoing commitments of water (fig. 17 and table 11), and little pumping capacity above the 1988 steady-state values is available (table 15). Some flexibility exists in managing pumpage from Laws, Big Pine, Taboose, and Independence south well fields. None of these well fields, however, creates a pattern of drawdown that is markedly better with respect to native vegetation than the others (figs. 34 and 35). An ideal pattern from the simulation is zero drawdown beneath native vegetation on the valley floor. The area surrounding the Big Pine well field, because of the large area of irrigated lands and sparsely vegetated volcanic flows, is probably least affected and closest to the ideal. The Laws well field, because of its great distance from a large alluvial fan that acts as a storage reservoir, seems to affect the

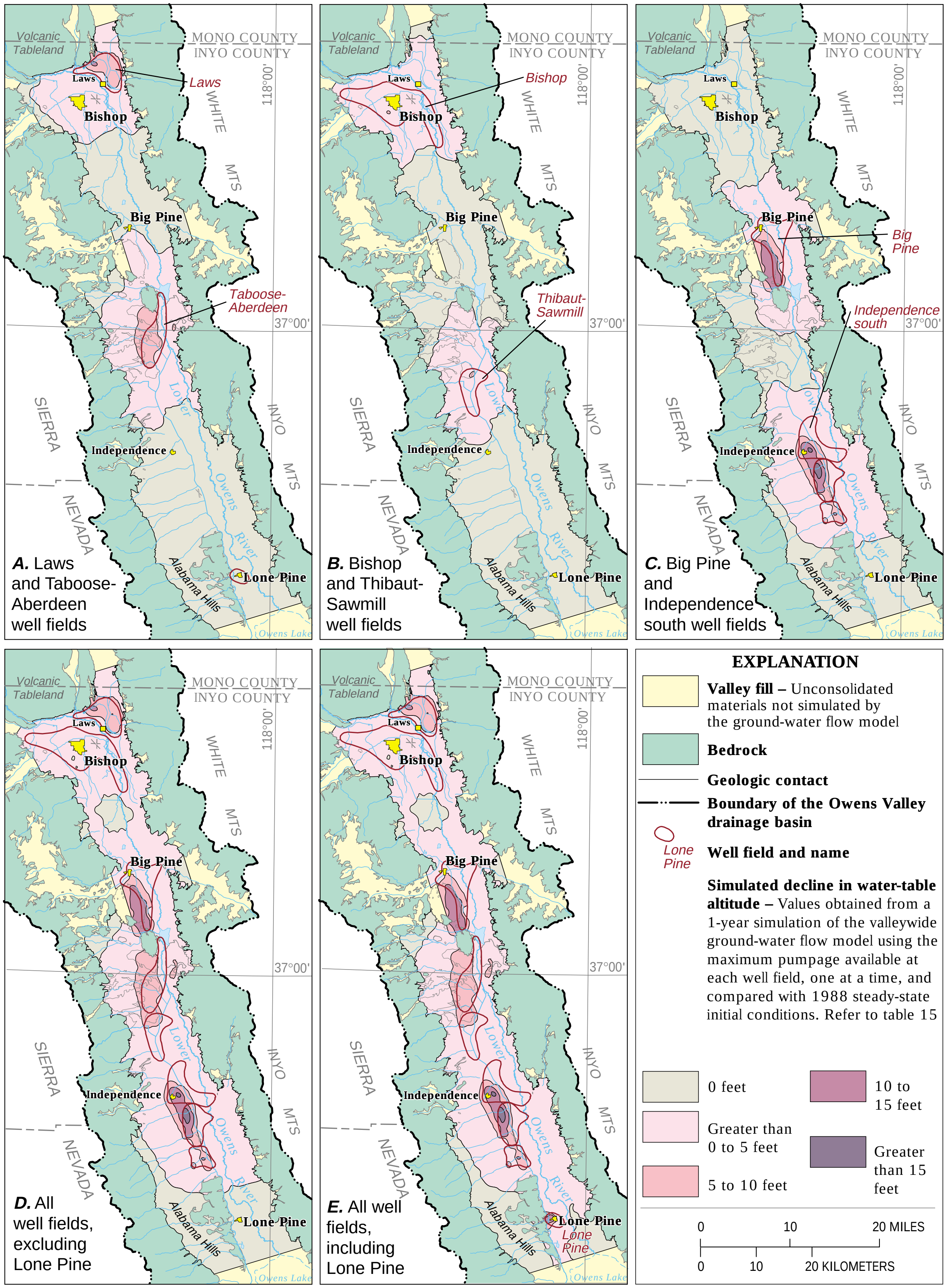


Figure 35. Simulated decline in water-table altitude in the Owens Valley, California, resulting from maximum pumpage at each well field.

largest area of the valley floor and is the poorest choice. Consequently, mitigation measures need to be more intensive in that area—as they have been in recent years—than in other parts of the valley.

The simulated water-table decline after 1 year of maximum pumpage at the six well fields, in comparison with 1988 steady-state conditions, is shown in figure 35*D*. As with the simulation of unit responses (fig. 34*D*), the cones of depression from the individual well fields overlap, but not to a significant degree. Pumping from the small Lone Pine well field, which has limited extra capacity (table 15), has a minimal effect on the rest of the valley (fig. 35*E*).

One feature that is interesting to note is an unaffected area south of Bishop. This area, near Collins Road and vegetation sites C and D (fig. 2), shows no decline in the simulated water table after 1 year of maximum pumpage (fig. 35*E*). Coincidentally, native vegetation in that area was observed to remain greener than in other parts of the valley during 1982–88, a period of wide variations in precipitation, recharge, and pumpage. This observation, paired with the simulated results presented in figures 34*D*, 35*D*, and 35*E*, helps to confirm the reasonableness of the ground-water flow model in that part of the valley. The primary reasons the area remains unaffected by changes elsewhere in the valley are the lack of nearby pumping (fig. 17) and the effectiveness of hydraulic buffering of the water table by native vegetation and the Owens River.

In summary, optimal water management of the well fields—with the objective of minimizing declines in the water table—is relatively insensitive to pumpage from a specific well field. The areal extent of greatest drawdown in the water table is similar for each of the six well fields, both from the standpoint of installing new production wells (fig. 34) and of using existing capacity (fig. 35). If pumpage can be increased at one or two well fields for only a single year or part of a year, then drawdown and any adverse effects on native vegetation will be restricted to a small, more manageable area. Rotating pumpage from one well field to another may facilitate this result, and may be an optimal way to manage the well fields during times of below-average runoff.

Reliability of Results

The reliability of this evaluation of water management in the Owens Valley depends on three critical assumptions: first, that the aquifer system and native vegetation are conceptualized correctly; second, that the aquifer system is numerically approximated with only minor, recognized errors; and third, that the selected water-management alternatives are a realistic representation of possible future conditions.

The conceptualization of the aquifer system and native vegetation was the focus of related studies by Groeneveld and others (1985, 1986a); Hutchison (1986b); Dileanis and Groeneveld (1989); Sorenson and others (1989, 1991), Duell (1990), and Hollett and others (1991). Although not all aspects of the aquifer system and native vegetation are well understood, the important role of the aquifer system in providing water for the long-term health of native vegetation on the valley floor is well documented. The primary difficulty in predicting the response of native vegetation to a change in water availability is that a decline in the water table does not always result in an immediate adverse effect on native vegetation (Sorenson and others, 1991, p. G35). For example, if precipitation on the valley floor is well above average, native vegetation can survive, even prosper, for 1 to 3 years with no water supplied via capillarity from hydrogeologic unit 1.

Because precipitation on the valley floor and valleywide runoff from the surrounding mountains are not well correlated, it is possible to have precipitation on the valley floor and thus an increase in soil moisture, which promotes additional plant growth, and at the same time have reduced runoff from the mountains, which prompts an increase in pumpage and results in a lowering of the water table. Under these conditions, the native vegetation remains healthy, but the water table declines. However, if the extra pumpage continues through a period of below-average precipitation on the valley floor, then plants will begin dropping leaves to conserve water and the overall health of native vegetation is jeopardized. During the evaluation of different water-management alternatives, this variability of response was recognized, but an assumption was made that the plants were not aided by a short-term increase in precipitation.

The numerical approximation of the aquifer system was made using a ground-water flow model that incorporates most of the major concepts of the aquifer system as well as the use of ground water by native vegetation. The limitations of ground-water flow models in general, and the valleywide model in particular, are discussed extensively in a previous section, entitled “Use, Limitations, and Future Revisions.” The reliability of the ground-water flow model is affected most by those limitations. For example, two areas of the basin—west of Bishop and near Lone Pine—are either poorly understood or poorly simulated. Results in these areas are less reliable than those in other parts of the basin. During development of the valleywide model, several other ground-water flow models of parts of the Owens Valley were developed by a number of different organizations and individual researchers (fig. 2; table 2). Each of the models tends to show similar results. Although it is possible that all the models are incorrect, this uniformity gives additional credibility to the modeling approach and results.

Use of the ground-water flow model to identify areas where native vegetation is likely to be affected adversely by pumping is based on the assumption that a hydraulic stress (decline in water-table altitude) equates to a vegetative stress (decrease in biomass). As discussed above, this is not always true. For longer periods of time, however, such as the period of steady-state conditions simulated in three of the four alternatives evaluated, the assumption becomes more reliable. The benefits of a short-term increase in precipitation on the valley floor are outweighed by long-term water requirements for transpiration. More reliable results might be produced by using another type of model that explicitly incorporates vegetative growth, precipitation, and use of ground water and is linked to a valleywide ground-water flow model. For the present study, however, such a model was deemed to be numerically too large and to have too many poorly quantified parameters.

Changes in simulated recharge and discharge in the valleywide ground-water flow model that were required to evaluate different water-management alternatives were well within the range of values used during calibration and verification of the model. This minimal modification of the model increases the reliability of results—particularly, if the results are viewed in a general, semi-quantitative way. In analyzing the different water-management alternatives, the simulated drawdown seems to be somewhat greater than what might actually occur. A simulated 30-ft decline might represent an actual decline of 20 ft; a simulated 10-ft decline, an actual decline of 6 ft; and so forth. The reason for the deviation is not known, but it may result from greater delayed drainage of hydrogeologic unit 1 or more effective action of hydraulic buffers, such as evapotranspiration. Because the ground-water flow model uses generalized model zones of aquifer properties and localized recharge and discharge, the spatial pattern and relative magnitude of drawdown probably are more reliable than the specific value of drawdown.

The selection of water-management alternatives was based on what was considered a realistic representation of possible future conditions. Because of the extremely wide-ranging nature of negotiations between Inyo County and the Los Angeles Department of Water and Power in designing a water-management plan for the Owens Valley, the definition of realistic is somewhat subjective. For example, the assumption that 1988 steady-state pumpage is the sum of average historical pumpage and new enhancement and mitigation pumpage was an arbitrary choice reflecting one possible agreement. The choice of some lesser quantity of pumpage would have been an equally valid assumption. Choice of a greater quantity of pumpage did not seem politically plausible. The use of 0, 25, 50, 75, 100, and 125 percent of 1988 steady-state pumpage for alternative 3 brackets the range of what was deemed realistic.

Many of the choices in defining future conditions were much less subjective. Several were based on long-term hydrologic conditions, such as runoff for water years 1935–84 or land use for water years 1970–88. Values of recharge and discharge based on past long-term conditions are probably reliable indicators of future long-term conditions.

Only a few choices were based on recent changes in water management, primarily the addition of enhancement and mitigation pumpage and related recharge. Both hydrologically and politically, the recently altered recharge and discharge are much less certain than long-term values. Additional changes in water management, such as reestablishing the lower Owens River as a perennial stream or establishing alfalfa fields near well fields, seem likely and will affect localized areas of the valley. The evolving water management of the Owens Valley prompted by the requirement of a court-accepted EIR and joint water-management plan for the valley creates the greatest uncertainty in future conditions and is probably the most important caveat in assessing the reliability of results presented in this report.

Potential Changes in Operation

The following is a summary of potential changes in water-management operations designed to protect native vegetation as well as to provide water for export to Los Angeles. The options involve changes in recharge, changes in pumpage, and changes in mitigation measures.

Increase tributary stream recharge.—An increase in recharge from tributary streams is limited by the timing and quantity of runoff from the Sierra Nevada. Some tributary streams have a lower loss rate (fig. 13 and table 9) than others, depending on characteristics of the surficial deposits and length of the stream channel. Estimates of evapotranspiration for vegetation along tributary stream channels indicate that most of the loss actually seeps into the ground and recharges the aquifer system. An increase in the recharge rate of selected streams, therefore, can compensate for an increase in ground-water pumpage, depending on the timing of recharge and pumping.

Most tributary streamflow that does not seep into the ground is exported out of the valley. Increasing the recharge rate in years of average or below-average runoff probably is not productive, as a reduction in streamflow means that additional ground water likely will be pumped from other parts of the valley to make up the difference. If the total quantity of water exported in average-runoff years could be reduced, then increasing recharge from some tributary streams, in particular Taboose and Bishop Creeks, can provide additional ground water in future years. A further increase in recharge for these or other tributary streams may be possible through modifications of the diversion operations near the base of the mountains or use of a different configuration of diversion channels on the alluvial fans. Increasing recharge during years of above-average runoff may be advantageous, but this general operating policy has been in effect since the early 1970's. Also, some of the recharge, particularly during wet periods, will be lost to increased evapotranspiration and gain of water by the river–aqueduct system.

Increase artificial recharge on the valley floor.—Artificial recharge of surface water on the valley floor is being done in the Bishop and the Laws areas, and to a lesser extent, in the Big Pine area (table 11 and pl. 3). The purpose of the recharge is to replenish ground-water storage that has been depleted by pumping and to enhance recovery of the water table in order to protect native vegetation. Expansion of these efforts may be possible to further reduce the adverse effects of pumping on native vegetation.

Artificial recharge in most parts of the valley floor is limited by the presence of fine-grained deposits and the horizontal layering of the aquifer system (figs. 5 and 14). Although unlined surface-water features are an important source of local recharge, direct irrigation of the native vegetation has been discounted as an option because of likely problems with salinity and disruption of the soil horizon (D.P. Groeneveld, Inyo County Water Department, oral commun., 1987). Direct recharge through wells, however, may be a water-management option—particularly, as new wells are installed with perforations only in the lower zones. Use of recharge wells can help repressurize the production zone after large extractions have been made, such as during a drought, or whenever extra surface water is available. Repressurizing a confined zone results in a moderate increase in ground-water storage—much less than if the zone is unconfined—and an important recovery of ground-water levels and gradients. Evaluation of the likely changes in ground-water quality resulting from direct recharge of surface water will require additional water-quality data.

Recharge surface water on the east side of the valley.—Artificial-recharge efforts on the east side of the valley during periods of above-average runoff will provide some additional storage of ground water. Because natural runoff on the east side of the valley is scant, recharge efforts probably will require diversion of surface water from the river–aqueduct system into those areas. As indicated by simulations using the valleywide ground-water flow model (figs. 34 and 35), drawdown cones from well fields reach to the bedrock sides of the valley. Recharge along the sides of the valley, even the east side, will help to reduce the effects of pumping. However, recharged water that is not captured by pumping may eventually seep into the river–aqueduct system or the lower Owens River, and may induce more growth of vegetation between the recharge and discharge points.

Recharge on the east side of the Bishop Basin, particularly east of the Big Pine well field, might help minimize the areal effects of pumping in the Big Pine area, as well as provide some additional ground-water storage, particularly beneath the blue-green clay. In contrast, recharge east of the Owens Valley Fault in the Owens Lake Basin has little effect on the western well fields. The Owens Valley Fault tends to channel recharge water down the east side of the basin, allowing only small quantities of flow westward across the fault.

Extract ground water from the Bishop Creek alluvial fan.—Extraction of water in the Owens Valley is a highly charged topic that does not lend itself to purely scientific assessments. Nevertheless, one of the premier places to extract water and have little effect on native vegetation seems to be near Bishop, particularly the Bishop Creek alluvial fan (Bishop Cone). The great depth to water over much of the fan, abundance of recharge, prevalence of urban land and irrigated vegetation, and large number of canals and ditches crisscrossing the fan make it an area with higher recharge and production potential and fewer adverse effects on native vegetation than most other areas of the valley. Uncertainties about the aquifer system west of Bishop do not alter this conclusion. However, additional understanding of how the Bishop Tuff, the Coyote Warp, and valley-fill faults (fig. 4) affect the aquifer system will be most helpful in planning any changes in water management.

Extract ground water from the Owens Lake area.—Additional extraction of ground water from the area south of the Alabama Hills and surrounding the Owens Lake may be possible. Although drilling and lithologic data are sparse for that part of the valley, depositional concepts indicate that the alluvial fan deposits along the western side of the basin probably grade into a narrow band of moderately transmissive transition-zone deposits. Extraction of a significant quantity of ground water near the Owens Lake probably will require additional recharge in order to minimize the migration of poorer quality (higher dissolved-solids concentration) ground water from beneath the lakebed toward the production wells. South of the valleywide model area, Cottonwood Creek (Hollett and others, 1991, fig. 16) has a greater discharge than any other tributary stream in the Owens Valley except Bishop and Big Pine Creeks. If recharge from Cottonwood Creek could be increased, especially by utilizing its large alluvial fan, then additional ground-water extractions from that area might increase water-management flexibility. Ground-water pumpage in that area likely will affect a narrow band of native vegetation near the springline and edge of the lakebed (figs. 1 and 3). Additional drilling, aquifer tests, water-level and water-quality monitoring, and possibly small-scale simulation studies will be required to further document and evaluate this option.

Extract ground water from the east side of the Owens Valley.—Extraction from the east side of the Owens Valley is not as efficient as extraction from the west side. Aquifer materials on the east side are finer and probably less transmissive. If the depositional models are correct for that side of the basin, then a narrow band of transition-zone deposits should be present as suggested on plate 2. The most transmissive deposits and greatest quantity of transition-zone deposits probably are near the alluvial fans of Waucoba and Mazourka Canyons (fig. 4). Because of the apparent symmetry of the basin and aquifer materials, the pattern and extent of drawdown from pumping on the east side of the valley probably will be similar to that of drawdown from pumping on the west side of the valley (fig. 34).

A major limitation of pumpage from the east side of the basin is the meager quantity of natural recharge. Without additional recharge near proposed wells, ground-water storage will be depleted rapidly. This depletion is accentuated by the restriction to ground-water flow caused by the Owens Valley Fault. Both the quality of ground water along the eastern side of the basin and the probable changes in ground-water quality resulting from recharge and extraction in that area are unknown. Despite these considerable limitations, extraction from the east side of the valley should be hydrogeologically feasible and might offer some flexibility in future water management.

Extract ground water from the Lone Pine area.—The Lone Pine area is characterized by finer-grained materials, lower transmissivities, more en echelon faulting, and possibly poorer water quality than in many other parts of the basin. These characteristics alone do not make it a particularly desirable place to develop additional well production. A more complete assessment requires a better understanding and simulation of ground-water flow in that part of the valley.

Pump from selected well fields.—A shift of pumping to selected well fields may provide protection for native vegetation in other areas. For example, the prevalence of irrigated lands near the Big Pine well field makes widespread, adverse effects on native vegetation less likely than at other well fields such as the Taboose–Aberdeen or the Independence–Oak (fig. 17). Also, localized pumping from highly transmissive volcanic deposits at the Thibaut–Sawmill well field restricts the areal extent of the adverse effects on native vegetation (fig. 34). Extraction from similar well fields or parts of the valley will require less mitigation for native vegetation than will extraction at other locations.

Rotate pumpage among well fields.—As indicated in figures 25, 34, and 35, rotational pumpage may have some advantage over continual extraction from a single well field. A key to the health of native vegetation is the water availability within the rooting zone of the plants (Groeneveld, 1986; Sorenson and others, 1991). Cycling pumpage from one well field to another can enable the water table near the wells to recover and soil moisture in the overlying unsaturated zone to be replenished via capillarity. Although recovery of the water table occurs fairly rapidly, replenishment of soil moisture is much slower (Groeneveld and others, 1986a, 1986b). Field data and modeling results suggest that a few weeks or months are needed to replenish soil moisture (Groeneveld and others, 1986a, p. 86; Welch, 1988). Although the valleywide model can give some semi-quantitative guidance, water management using rotational pumpage needs to rely on monitoring of multiple-depth wells and soil-moisture sites in the vicinity of well fields, and possibly on results from unsaturated-saturated flow models.

Seal upper perforations of existing wells.—Sealing of perforations adjacent to the unconfined zone in existing production wells was investigated during this study and was found to be marginally successful. Continuation of this effort will limit the immediate effect of production wells on the unconfined zone and the related adverse effects on nearby native vegetation (fig. 25). Sealing of abandoned wells limits the short-circuiting of flow that occurs through a casing that is open to multiple strata. Installation of new production wells with perforations only in the lower zones (hydrogeologic unit 3) of the aquifer system will reduce the effects of pumping on the water table and native vegetation. Adverse effects on native vegetation, however, still will occur if a large quantity of water is pumped for an extended period of time, possibly 1 to 3 years (fig. 25; Sorenson and others, 1991, p. G35).

Utilize other ground-water basins.—Additional recharge and extraction facilities in other basins along the route of the dual-aqueduct system might provide additional flexibility in the water management of the Owens Valley (Danskin, 1990). For example, the Indian Wells Valley, just south of the Owens Valley, is having ground-water storage depletion and related ground-water-quality problems (Berenbrock and Martin, 1991; Berenbrock and Schroeder, 1994) that might be mitigated by additional recharge. During periods of above-average runoff in the Sierra Nevada or during a period of lesser demand in Los Angeles for water from the Owens Valley, surplus water could be conveyed via the Los Angeles Aqueduct to the Indian Wells Valley, and recharged there. Conversely, during drier periods, ground-water production from the Indian Wells Valley could be increased to augment flow in the Los Angeles Aqueduct, thereby reducing the quantity of water needed from the Owens Valley. Other desert basins between the Owens Valley and Los Angeles, such as in the Mojave Desert, the Antelope Valley, and the Coachella Valley, have a large potential for ground-water storage (California Department of Water Resources, 1964, 1967a; the Antelope Valley–East Kern Water Agency, 1965; Reichard and Meadows, 1992). These basins, which are connected to the extensive system of water delivery in southern California (California Department of Water Resources, 1987), could provide additional water-banking opportunities.

NEED FOR FURTHER STUDIES

This evaluation of the hydrologic system in the Owens Valley has resulted in the following suggestions for further studies. The items are listed in their approximate order of importance within each topic.

Aquifer System

Improved understanding of the aquifer system west of Bishop.—Conceptual understanding and simulation of the area west of Bishop need improvement. The geologic structure, aquifer materials, and effect of faulting on ground-water movement in that area are unclear.

Detailed mapping of the Bishop Tuff.—The Bishop Tuff includes both permeable layers that enhance horizontal flow and nearly impermeable layers that restrict vertical flow. Detailed mapping of individual layers throughout the Bishop Basin will permit an improved conceptualization and simulation of the aquifer system in that area.

Improved understanding of the aquifer system near Lone Pine.—A better understanding of ground-water flow near Lone Pine is needed. This area is difficult to simulate because of the several en echelon faults, the abrupt change in ground-water gradient near Lone Pine, and the unknown rate of underflow from the aquifer system to the Owens Lake. Installing monitoring wells east of Lone Pine and north of the Owens Lake to confirm lithology, aquifer characteristics, and ground-water gradients will aid in a needed reevaluation of data and concepts.

Aquifer characteristics east of the Owens River.—Aquifer characteristics have been defined for most parts of the valley, except east of the Owens River. Additional wells and aquifer tests in this area will be helpful in confirming assumptions made in this study and in the related study by Hollett and others (1991).

Numerical model of the depositional evolution of the Owens Valley.—The general depositional character of the basin is well documented, but mapping of individual deposits is limited by the sparse lithologic data and by the complexity of the depositional environment. Linking lithologic data to depositional concepts and numerically extrapolating them throughout the basin in the manner of Koltermann and Gorelick (1992) will aid in being able to predict the three-dimensional location of different types of deposits within the aquifer system and their hydraulic importance in controlling ground-water flow.

Ground-Water Flow

Survey of ground-water quality.—A survey of ground-water quality from different locations and depths throughout the Owens Valley ground-water system will aid in confirming concepts and results of this study and related work by Hollett and others (1991). In particular, isotopic analyses of ground water from different depths in the aquifer system will aid in defining ground-water flow paths and rates of movement (Alley, 1993).

Detailed mapping of volcanic deposits in the Big Pine volcanic field.—A more detailed spatial definition of basalt flows, particularly ones deeper than 300 ft below land surface, will help to identify important ground-water flow paths in the area extending from Big Pine to Oak Creek.

Discharge measurements of the Owens River.—Additional discharge measurements are needed along the Owens River, especially near the Laws and the Big Pine well fields, to better identify gaining and losing reaches of the river. The temporal variability of flow in each reach also is important.

Improved understanding of underflow from the Chalfant Valley.—A difference between simulated heads and measured ground-water levels was noted near the boundary of the aquifer system north of Laws. An improved understanding and simulation of underflow in this area will lend additional credibility to results from the valleywide model in the vicinity of Laws.

Surface-Water Flow

Use of a streamflow-routing simulator.—Use of a streamflow-routing simulator, such as that by Prudic (1989), in conjunction with the ground-water flow model will enhance simulation of extremely wet or extremely dry conditions and will aid in developing an integrated surface-water and ground-water budget.

Water Budgets

Set of consistent water budgets.—A set of consistent and interrelated water budgets is needed, including a surface-water budget, a ground-water budget, and a budget for the entire valley. Ideally, the same components would be used in each budget to ensure consistency and facilitate comparisons with numerical models of either the surface-water or ground-water system. The valleywide budget will need to include all precipitation falling on, and all evapotranspiration from, the valley-fill deposits. As part of the present study, a detailed ground-water budget has been provided along with descriptions of key hydrologic processes and some of the relations needed to develop the related water budgets. This information needs to be expanded to include surface-water and valleywide water budgets.

Improved estimates of ungaged runoff and recharge.—Items with a high degree of uncertainty in the present study are ungaged mountain-front runoff between tributary streams and related ground-water recharge. Additional verification of ungaged drainage areas north of Taboose Creek, likely runoff, and resulting ground-water recharge will help to confirm water-budget estimates in the Bishop area.

Measurements of recharge from direct precipitation on alluvial fans.—The quantity of ground-water recharge from direct precipitation on the alluvial fans is virtually unknown. Some field measurements of precipitation, evapotranspiration, and soil-moisture content, such as those made on the valley floor, will help to verify the assumption used in this study that nearly all precipitation on alluvial fans is evaporated or transpired.

Native Vegetation

Precipitation measurements.—Although some predictive relations have been developed from past precipitation measurements (figs. 7 and 8), the great variability of precipitation on the valley floor and its importance in the health of native vegetation requires that precipitation measurements be continued. Additional precipitation measurements near established vegetation study sites (table 1 and fig. 2) will continue to be useful in determining the response of native vegetation to changes in water availability and in understanding the role that other factors play in the health of native vegetation (tables 3 and 5).

Valleywide evapotranspiration measurements.—Valleywide measurements of evapotranspiration will aid in detecting changes in native vegetation and in correlating field data with model results. The detailed mapping of native vegetation done by the Los Angeles Department of Water and Power during 1984–88 provides an excellent basis for analysis. However, continued valleywide data collection is needed to aid in evaluating the 1984–88 data set and to detect temporal changes. Remote-sensing techniques may provide a reasonably accurate method of correlating valleywide coverage to site-specific measurements of evapotranspiration and plant density (Jackson, 1985; Reginato and others, 1985).

Further understanding of native vegetation.—Continued investigation is needed of the physiology of native vegetation, in particular how water availability and biochemical factors affect plant growth, vegetative stress, and recovery from stress.

Water Management

Monitoring of native vegetation near production wells.—Monitoring of native vegetation, soil moisture, and ground-water levels near production wells and in areas of the valley most susceptible to hydrologic stress (figs. 26, 31, 32, and 33) is needed to aid in making water-management decisions that are based on actual field data.

Investigation of the ground-water system in the Owens Lake area.—Future water-management issues, such as rotational ground-water pumpage, probably will involve the Owens Lake area (E.L. Coufal, Los Angeles Department of Water and Water, oral commun., 1992). Prior to additional pumping near the Owens Lake, the area needs to be studied to determine the feasibility of pumping freshwater near a saline lake and the effects of such pumping on native vegetation and on desiccation of the lakebed. The investigation will need to include installation of new wells, logging of lithology and ground-water quality, testing of aquifer characteristics, and monitoring of ground-water levels in different zones of the ground-water system.

Use of site-specific ground-water flow models.—Site-specific ground-water flow models, when used in conjunction with information from the valley-wide ground-water flow model, can be extremely useful in efficient testing of hydrologic concepts and possible water-management options. Suggested areas for site-specific models include west of Bishop, near Big Pine, east of Lone Pine, and near Cottonwood Creek. Some site-specific models could take advantage of additional model layers to more accurately represent the hydrogeologic units in the aquifer system.

Include Round Valley in the water-management analysis.—As knowledge about the area west of Bishop is improved, it may be advantageous to include Round Valley in future simulations of the Owens Valley ground-water system. Inclusion of Round Valley in the valleywide model will help to confirm underflow rates from Round Valley and the Bishop Tuff and will aid in evaluating any water-management options that include Round Valley.

More detailed valleywide ground-water flow model.—Detailed simulations of ground-water flow in complicated areas, such as the Big Pine volcanic and massive lacustrine deposits, may require additional layers in the valleywide model or development of a site-specific model. Updating the valleywide model with improvements in concepts and inevitable changes in recharge and discharge will be necessary at some point after water year 1988 in order to evaluate other water-management alternatives.

SUMMARY AND CONCLUSIONS

The Owens Valley, a long, narrow valley along the east side of the Sierra Nevada in east-central California, is the main source of water for the city of Los Angeles. The city diverts most of the surface water in the valley into the Owens River–Los Angeles Aqueduct system, which transports the water more than 200 mi south to areas of distribution and use. Additionally, ground water is pumped or flows from wells to supplement the surface-water diversions to the river–aqueduct system. Pumpage from wells used to supplement water export has increased since 1970, when a second aqueduct from the Owens Valley was put into service, and local residents have expressed concerns that the increased pumping may have a detrimental effect on native vegetation consisting of indigenous alkaline scrub and meadow plant communities. This native vegetation on the valley floor depends on soil moisture supplied by precipitation and a relatively shallow water table.

A comprehensive series of studies by Inyo County, the Los Angeles Department of Water and Power, and the USGS was done to determine the effects of ground-water pumping on the survivability of scrub and meadow plant communities and to evaluate alternative methods of water management. Findings from the USGS studies are presented in a series of reports designated Water-Supply Paper 2370 A–H.

This report (Water-Supply Paper 2370-H), as part of that series, integrates findings from the individual studies, which focused on the geology, water resources, and native vegetation of the Owens Valley. This particular study included defining the hydrologic system of the Owens Valley and evaluating the major components of the system and historical changes that have occurred, primarily through use of a valleywide ground-water flow model. The model, which simulates the aquifer system as defined in a companion report by Hollett and others (1991), was calibrated for water years 1963–84 and verified for water years 1985–88. Possible changes in future water management of the Owens Valley, including four general water-management alternatives, were evaluated with the aid of the ground-water flow model.

Major conclusions that resulted from integration of the related studies and from evaluation of the hydrologic system and selected water-management alternatives are summarized below, grouped by general topic.

Hydrologic System.—The hydrologic system of the Owens Valley can be conceptualized as having three parts: (1) an unsaturated zone affected by precipitation and evapotranspiration; (2) a surface-water system composed of the Owens River, the Los Angeles Aqueduct, tributary streams, canals, ditches, and ponds; and (3) a saturated ground-water system contained in the valley fill. Since 1913, the hydrologic system in the Owens Valley has been changed substantially by human activities—first by export of large quantities of surface water (virtually the entire flow of the Owens River) via the Los Angeles Aqueduct and later, beginning in 1970, by the additional extraction and export of ground water. Present (1988) water-management practices, which emphasize localized ground-water extractions and artificial recharge, will cause additional, though less extensive changes to the hydrologic system and native vegetation.

Precipitation, Evapotranspiration, and Native Vegetation.—Precipitation patterns are influenced primarily by the rain-shadow effects of the Sierra Nevada. As a result, most precipitation from storms falls on the Sierra Nevada; much less falls on the Inyo and the White Mountains farther to the east. As summarized on an equal precipitation map for the Owens Valley drainage area, average precipitation ranges from more than 30 in/yr along the crest of the Sierra Nevada, to less than 6 in/yr on the valley floor, to about 10 in/yr in the White Mountains. A linear relation between altitude and average annual precipitation can be used with measured precipitation at Independence to predict annual precipitation at any location on the valley floor and along the west side of the valley. Although precipitation on the valley floor depends primarily on altitude, precipitation within an individual year can vary widely. Part of this variation is caused by the three different types of storms that move across the valley from different directions and during different times of the year.

Native vegetation covering most of the valley floor depends on soil moisture replenished by both precipitation and the shallow water table. The native vegetation, originally characterized as phreatophytic, has been found to be highly xerophytic and capable of surviving for as much as 2 years or more on soil moisture provided by precipitation. An extended decline in the shallow water table, however, caused by nearby ground-water pumping can cause a substantial loss of leaves and the eventual death of individual plants. These conditions are accentuated during times of drought.

The quantity of evapotranspiration by native vegetation is directly related to the amount of transpiring surface (leaf area) and evaporating surface (bare soil). Less evapotranspiration implies fewer leaves and less total vegetative biomass. Less evapotranspiration, however, does not necessarily imply fewer plants.

By 1984, average annual evapotranspiration from the valley floor was about 35 percent less than prior to 1970. This reduction implies a substantial decrease in transpiration from native plants, and possibly a slight increase in evaporation from bare soil. The reduction in evapotranspiration resulted primarily from increased ground-water pumpage after 1970. Pumping causes a decline of the water table, which reduces replenishment of soil moisture to the overlying unsaturated zone and effectively reduces the quantity of water available to plants for transpiration. Decreases in transpiration and the related decrease in biomass of native vegetation have been greatest close to production wells, but moderate decreases probably have occurred at some distance from the well fields. Changes in the water-table altitude caused by pumping are greatest near the pumped well, but effects of pumping can be communicated over distances of as much as several miles by a slight decrease in ground-water levels. This change in levels (gradient) reduces ground-water flow rates to other parts of the valley as a result of the diversion of ground water to pumped wells.

The infiltration of precipitation to and evapotranspiration from the unsaturated zone are the primary hydrologic processes related to the health of native vegetation. Other biochemical processes probably are important, particularly when water availability is restricted, but knowledge about the effects of such processes on native vegetation in the Owens Valley is meager.

Surface Water.—The abundant precipitation that falls, mostly as snow, in the Owens Valley drainage area provides abundant runoff into more than 40 streams that are tributary to the Owens River, the trunk stream of the valley. More than 600 gaging stations are operated by the Los Angeles Department of Water and Power in order to measure runoff into the valley, to allocate water within the valley, and to export water out of the valley to Los Angeles.

The Owens River–Los Angeles Aqueduct system extends from the Mono Basin and the headwaters of the Owens River in the Long Valley, to the outflow point from the Owens Valley at the Haiwee Reservoir and includes several small reservoirs to store and balance flow. More than 100 wells in the Owens Valley pump ground water into the river–aqueduct system to augment flow. Total inflow to the Owens Valley at the Pleasant Valley Reservoir historically has averaged between 250,000 and 330,000 acre-ft/yr, depending on runoff and water-management activities in the Long Valley and the Mono Basin to the north. Export to Los Angeles, which averaged 320,000 acre-ft/yr for water years 1935–69, increased by about 50 percent to an average of 480,000 acre-ft/yr for water years 1970–84.

Annual runoff within the Owens Valley drainage basin ranges from about 50 to 200 percent of the average for water years 1935–84. On the basis of these 50 years of record, a probability distribution was developed to define the likelihood of different quantities of annual valleywide runoff. This distribution can be used to define the statistical significance of a particular “wet” or “dry” year.

Tributary streams in the Owens Valley lose between 35 and 99 percent of their annual discharge while flowing over the alluvial fan and volcanic deposits. Most of this loss recharges the ground-water system; much less is evapotranspired. The seepage rate for a stream typically decreases with increasing discharge; however, in the Owens Valley, the diversion of high flows onto alluvial fans to enhance recharge has resulted in a fairly constant seepage rate for individual streams. Linear runoff-recharge relations that were developed for each tributary stream using these seepage rates can be used to predict likely ground-water recharge for different quantities of valleywide runoff.

The Owens River gains water from ground-water seepage along most of its length in the Owens Valley. Since about 1970, however, the river has begun losing water to the aquifer system near the Big Pine well field. A similar condition may soon occur near the Laws well field. Surface water probably also seeps into the ground beneath the Tinemaha Reservoir. The lower Owens River gains water from the aquifer system, but much of this water is used to support riparian vegetation covering most of the nearly dry river channel. The Los Angeles Aqueduct, an unlined channel through much of the Owens Valley, gains water from the aquifer system, except where the aqueduct rises from the valley floor south of Independence. Between Independence and the Alabama Hills, the aqueduct loses water to the aquifer system. From the Alabama Hills to the Haiwee Reservoir, a concrete liner restricts any significant interaction between the aqueduct and the aquifer system.

Structure of the Aquifer System.—The ground-water system of the Owens Valley includes all permeable valley-fill deposits within the Owens Valley graben and is bounded by the welded members of the Bishop Tuff on the north and by the impermeable metamorphic and igneous rocks of the Sierra Nevada on the west, the White and the Inyo Mountains on the east, and the Coso Range on the south. The ground-water system is composed of two structurally separated depositional basins—the Bishop Basin to the north and the Owens Lake Basin to the south. The two basins are joined just south of Big Pine. This juncture is formed by a structural offset in graben-bounding faults, by a gentle rise in the underlying bedrock, by an upthrown piece of bedrock (Poverty Hills), and by the presence of volcanic deposits that intermittently have blocked the downvalley flow of water and sediment. Just north of the juncture, an 80-ft thick, tight blue-green clay identified by test drilling indicates that a lake was present at the south end of the Bishop Basin during some period(s) of accumulation of valley-fill sediment.

The aquifer system is defined as the most active part of the ground-water system and includes an unconfined member (hydrogeologic unit 1), a confining member (hydrogeologic unit 2), and a composite confined member (hydrogeologic unit 3). The aquifer system extends from the south side of the Volcanic Tableland to the north side of the Owens Lake. Below the aquifer system are poorly transmissive unconsolidated deposits (hydrogeologic unit 4).

The aquifer system was conceptualized with the aid of depositional models that defined the type and location of deposits within the basin. Previously unidentified transition-zone deposits, which are not present at land surface, were suggested by the depositional models and were found to play a dominant role in ground-water movement. The depositional models were aided by the discovery of lake deposits (blue-green clay) in the Bishop Basin and were especially useful in extending data and concepts to areas with sparse or missing data.

Faulting throughout the Owens Valley is important in controlling ground-water movement. The Owens Valley Fault restricts flow from west to east across the fault; thus, flow on either side of the fault is channeled south toward the Owens Lake. A previously unidentified fault adjacent and roughly parallel to the aqueduct in the Owens Lake Basin also restricts movement of ground water from west to east. More ground water is stored in alluvial fan deposits to the west because of this restriction. On the north side of the Alabama Hills, faults and a shallow depth to bedrock restrict ground-water movement. As a result, ground water in the vicinity of the Alabama Hills is forced to flow as far north as Independence before reaching the valley floor.

Faults near Big Pine are related to major structural movement. A fault whose primary trace crosses Crater Mountain and the alluvial deposits of Big Pine Creek restricts ground-water movement in the alluvial deposits, but it produces an extremely transmissive fracture zone in the volcanic deposits of Crater Mountain. Several other minor faults that restrict ground-water movement have been identified throughout the valley, and the major structural movement that formed the Owens Valley undoubtedly created many other faults that are hidden from view. The installation and operation of future monitoring and production wells, particularly west of Bishop and near Lone Pine, may identify additional faulting that affects ground-water flow.

Ground-Water Recharge and Discharge.—Ground-water recharge to the aquifer system occurs primarily from tributary streams; mountain-front runoff between tributary streams; canals, ditches, and ponds; and irrigation and watering of livestock. Lesser quantities of recharge occur from spillgate releases, underflow, and direct precipitation. Ground-water discharge occurs primarily from pumped and flowing wells; evapotranspiration; and underflow out of the aquifer system. Lesser quantities of discharge occur from springs and seeps and from channel seepage to the river–aqueduct system and the lower Owens River.

Both underflow into the aquifer system from Round and Chalfant Valleys and underflow out of the aquifer system into the Owens Lake area are significantly less than prior estimates. Ground-water flow through the permeable layers of the Bishop Tuff and into the aquifer system is minimal. Ground-water flow into the aquifer system from the north is limited by the small quantity of recharge that is available and by the moderately transmissive deposits near the boundaries. Ground water that flows out of the aquifer system to the south crosses the boundary of the aquifer system and eventually is discharged by flowing upward through many fine clay and silt layers in the Owens Lake bed or by flowing from springs and seeps along the toes of alluvial fans bordering the Owens Lake.

In 1970, pumpage was increased from an average of about 20,000 acre-ft/yr to more than 98,000 acre-ft/yr in order to provide water for export in the second aqueduct. Pumpage commonly exceeded 130,000 acre-ft/yr, and in water year 1972, pumpage exceeded 175,000 acre-ft/yr. Also in about 1970, the allocation of water for irrigation and livestock in the valley was decreased, resulting in less recharge from those operations. The combination of these changes in water use caused significant changes in other components of ground-water recharge and discharge. Evapotranspiration decreased from about 112,000 acre-ft/yr during water years 1963–69 to 72,000 acre-ft/yr during water years 1970–84; discharge from springs and seeps decreased from about 26,000 acre-ft/yr to 6,000 acre-ft/yr; ground-water discharge to the river–aqueduct system decreased from about 16,000 acre-ft/yr to 3,000 acre-ft/yr; and storage in the aquifer system was depleted by about 8,000 acre-ft/yr.

Detailed measurements of evapotranspiration, transpiration, and leaf area were made at several study sites throughout the Owens Valley. These data confirm that transpiration by native vegetation is proportional to the quantity of vegetative biomass (leaf area). The data also show that evapotranspiration consists primarily of transpiration by native vegetation. Therefore, the substantial change in evapotranspiration that occurred from about 1970 to 1984 reflects a nearly equivalent change in the quantity of native vegetation. Changes in native vegetation induced by increased pumping beginning in 1970 probably were accentuated by the drought of 1976–77. At some point between 1970 and 1978, water use per acre of native vegetation decreased about 25 percent.

By 1988, pumping capacity was increased again, this time to provide water to enhance or mitigate selected sites where native vegetation was adversely affected by previous increases in pumping. In water years 1987–88, total pumpage—for in-valley uses, export, and enhancement and mitigation—exceeded 175,000 acre-ft/yr. This increase in total pumpage, whether for export or mitigation, will further decrease total evapotranspiration and the total biomass of native vegetation in the Owens Valley.

The successful extraction of ground water from the Owens Valley has been aided by locating the wells in transition-zone and volcanic deposits. Pumping within the transition zone causes water to be withdrawn from western alluvial fans, which have a large areal extent and high specific yield and serve as extremely useful underground reservoirs. Well yields commonly exceed 6 ft^3/s from the highly transmissive (21,000 ft^2/d) transition-zone deposits and 15 ft^3/s from the exceptionally transmissive (greater than 200,000 ft^2/d) volcanic deposits. The large capacity of many production wells in the Owens Valley makes them comparable in size (volume of flow) with the smaller streams in the valley and accentuates their effect on the aquifer system.

Ground-Water Movement.—Ground water moves from areas of recharge to areas of discharge. In the Owens Valley, ground water generally moves from the sides of the valley toward the center, and from north to south. Pumping from several well fields in the valley captures some of the ground water before it reaches the center of the valley. Most ground water that is not captured by the well fields is discharged as evapotranspiration or flows into the river–aqueduct system or the lower Owens River. Ground water that is recharged on the sides of the valley moves vertically down through moderately transmissive deposits, and then horizontally into either the unconfined member (hydrogeologic unit 1) or the composite confined member (hydrogeologic unit 3) of the aquifer system. Along the sides of the valley, the vertical hydraulic gradient is downward; in the center of the valley, the vertical hydraulic gradient is upward, with a head difference of as much as 30 ft.

Along the sides of the valley, horizontal hydraulic gradients are steep and ground water flows rapidly through the alluvial fan or volcanic deposits. Beneath the valley floor, horizontal ground-water gradients are exceptionally flat, except near pumped wells, and ground water moves slowly toward discharge locations. Flow from hydrogeologic unit 3 to hydrogeologic unit 1, or vice versa, occurs very slowly through confining clay layers (hydrogeologic unit 2), or more rapidly through the gravel pack or casing of unpumped wells.

The water table beneath the valley floor is maintained at a nearly constant altitude. Native vegetation, springs, and surface-water bodies on the valley floor act as hydraulic buffers to minimize changes in water-table altitude through changes in recharge and discharge. A small rise in the water table results in increased discharge to evapotranspiration by native vegetation, to springs, and to surface-water bodies. A small decline in the water table results in decreased discharge and, in areas where ground water drops below the level of surface-water bodies, to increased recharge from the surface-water bodies. In contrast, the water table beneath the alluvial fans fluctuates markedly from one year to another as a result of changes in the quantity of recharge and pumpage; the hydraulic buffers on the valley floor are too distant to make a noticeable difference.

As a result of hydraulic buffering, the water table beneath the valley floor was at approximately the same altitude in 1984 as it was prior to 1970 except in two locations—near Big Pine and near Laws. In those areas, large quantities of pumpage resulted in a water-table decline of as much as 20 ft. This decline was greater than the effective range of buffering by nearby spring discharge and evapotranspiration. It was mistakenly assumed at the outset of the cooperative studies that a similar water-table altitude implies a similar condition of the aquifer system. However, the results of this study show that the same, or nearly the same, water-table altitude is possible with two substantially different combinations of recharge and discharge. In the Owens Valley, changes in vegetative cover, evapotranspiration, discharge from springs and seeps, and recharge from the river–aqueduct system and the lower Owens River have compensated for changes in water-table altitude.

Although ground-water levels are relatively flat over much of the valley floor, drawdown cones do form near the well fields. Typically, the cones elongate up and down the transition-zone deposits, broaden up the alluvial fans, and steepen toward the valley floor. This asymmetric shape is caused by the linearity of the transition-zone deposits combined with the high storage of the alluvial fans and the less transmissive deposits and faults toward the center of the valley. In the southern part of the Owens Lake Basin, drawdown cones near well fields are even more severely deformed by the presence of a barrier fault near the aqueduct.

If pumping rates are sufficiently high from a line of wells in the transition-zone or volcanic deposits, then a pumping trough is formed that limits or prevents ground water from flowing into hydrogeologic unit 1, which is an important source of water for native vegetation. Under more moderate pumping conditions, drawdown cones still extend up into the western alluvial fans and decrease the quantity of ground water flowing horizontally into hydrogeologic units 1 and 3 beneath the valley floor. Drawdown cones produced on the west side of the Bishop Basin and northern part of the Owens Lake Basin extend beneath confining clay layers and induce ground-water movement from alluvial fans on the east side of the valley. This effect is most evident near Big Pine because of the extraction of an exceptionally large quantity of ground water and the presence of the 80-ft-thick blue-green clay layer overlying the pumped zone.

Ground-Water Flow Model.—Development and calibration of the valleywide ground-water flow model confirmed the general conceptualization of the aquifer system as presented by Hollett and others (1991). Use of the model also confirmed that the Owens Valley aquifer system has been in a transition caused by increased pumping and changes in water use that were prompted by increased water exports beginning in 1970. Model simulations suggest that as of 1988 the transition is not complete.

Design of the valleywide model, which simulates the aquifer system, includes two layers, a finite-difference grid consisting of 180 rows and 40 columns, and uniform square model cells with a dimension of 2,000 ft on each side. Transmissivity is temporally constant and is spatially defined by about 20 model zones; storage coefficients are temporally and spatially constant. The model zones are based on hydrogeologic units and subunits. The model uses annual stress periods with many discrete recharge and discharge components—some simulated as specified fluxes, and some simulated as head-dependent relations. The model was calibrated for water years 1963–84 and verified for water years 1985–88. Four additional simulations were based on hypothetical future conditions and were used to evaluate selected water-management alternatives.

Prior to development of the valleywide model, several preliminary models with different scales and levels of complexity were developed to test particular questions about the aquifer system or about methods of simulating the aquifer system. This modeling approach proved to be most valuable. Understanding of both the model and the aquifer system was greatly improved and a more accurate and useful valleywide model was obtained.

An important benefit of using the valleywide ground-water flow model is that it can be used to calculate an annual value for hydrologic components (such as valleywide evapotranspiration from the aquifer system, streamflow gains and losses, and change in ground-water storage) that either are not measured routinely or are extremely difficult to measure. The model also enables the separation of multiple coincident stresses on the system, such as extremely high runoff occurring in 1969 at nearly the same time as the significant increase in valleywide pumpage in 1970. Analysis of how recharge and discharge components of the aquifer system changed from 1963 to 1988 provided as much insight into the operation of the aquifer system as did the concurrent analysis of measured ground-water levels and computed heads.

Sensitivity analysis of the ground-water model showed that pumpage is the dominant stress in the aquifer system both near well fields and in recharge areas. Away from recharge areas and well fields, such as in the area between Bishop and Big Pine, neither recharge nor pumpage has a significant effect on simulated heads. Surprisingly, the model was not sensitive to the vertical distribution of pumped water. The match with measured ground-water-level data when all the pumpage was from the lower model layer was similar to the match when pumpage was divided between the layers. During short-term aquifer tests, the vertical distribution of pumpage has been shown to be important; however, this lack of sensitivity shown by the model indicates that over a longer period of time the quantity of pumpage is more important than the design or location of wells.

Results from the simulations indicate that since 1963 the water table has declined beneath much of the western alluvial fans, particularly in the Taboose–Aberdeen area. Only a couple of monitoring wells, however, are present on the fans to confirm this result. In the Taboose–Aberdeen area, model simulations indicate that the water table beneath the alluvial fans has declined as a result of increased ground-water pumping, even though the water table beneath the valley floor has changed very little. This decline in water-table altitude beneath the fans results in a decrease in evapotranspiration by native vegetation on the valley floor and implies that a reduction in the biomass of native vegetation in the area is occurring now (1988), or will occur soon.

Water Management.—In many ways, the water management of the Owens Valley has been optimized over time. Purposeful diversion of tributary streams on the alluvial fans has enhanced natural recharge. Siting wells in the most transmissive deposits in the valley and near the dominant sources of recharge has increased management flexibility. The quick and easy answers to improved water management are largely gone.

Present water-management considerations in the Owens Valley include both the needs and desires of residents of the valley, and of Inyo County and the Los Angeles Department of Water and Power. Water operations are constrained by water-supply needs both in the valley and in Los Angeles and by variations in water-supply availability both in the valley and throughout much of the Southwestern United States. Native vegetation is resilient to short-term changes in the availability of water but requires a replenishment of soil moisture at least every 2 years, commonly by capillarity from the saturated aquifer system. Recharge of the aquifer system is constrained by the physical capacity to transport surface water and by the transmissivity of the surficial materials. The control and distribution of excess surface water also is constrained by air-quality restrictions related to the desiccation of the Owens Lake bed.

Selected water-management alternatives for the Owens Valley were analyzed both with the aid of hydrologic data and interpretations gained during the cooperative studies and with simulations using the valleywide ground-water flow model. Four water-management alternatives simulated with the model were: (1) a steady-state simulation of conditions in 1988; (2) the same steady-state simulation as alternative 1, but with variations in recharge of plus or minus 10 percent; (3) the same steady-state simulation as alternative 1, but with variations in pumpage using 25-percent increments of average pumpage; and (4) a 9-year transient simulation using 3 sequential years each of drought, average, and wet conditions.

Results from the simulations indicate that significant changes in water-table altitude and evapotranspiration will result if average pumpage exceeds about 75,000 acre-ft/yr. If increased pumpage is distributed to existing wells, changes in water-table altitude will occur in nearly all areas of the valley except in the unstressed area between Bishop and Big Pine and east of the Owens River. Long-term variations in recharge of plus or minus 10 percent have relatively little effect in comparison with variations in pumpage. These minor variations in long-term recharge were used to evaluate the effects of climatic cycles or changes in climate.

The results of alternative 4 were instructive for several reasons. Not surprisingly, the simulated effects of a 3-year drought are propagated to all areas of the aquifer system. Water-table declines are greatest near well fields, in particular Big Pine, Independence–Oak, and Laws. What is surprising is how long these changes in the water-table altitude persist. Significant drawdown in the water table continues through 3 years of average conditions, and some drawdown continues through 3 subsequent years of above-average recharge. These results imply that changes in native vegetation (water use and biomass) still may be occurring several years after a significant water-table decline caused by drought or pumping.

The transient simulation also indicated areas of the valley (Laws, Taboose–Aberdeen, and Independence–Oak well fields) where alterations in recharge and pumping could minimize the adverse effects of water-table decline. These areas have native vegetation and significant water-table fluctuations; either pumping would need to be reduced or recharge would need to be increased if a long-term reduction in native vegetation is to be avoided.

Alternative methods of water management that can minimize the adverse effects of pumping on native vegetation are limited to a few choices. In general, the alternative methods will be most effective in providing short-term benefits and increased flexibility in water management. Some alternative methods may create a localized benefit, but they may adversely affect native vegetation in other areas of the valley.

Storing additional ground water beneath the alluvial fans and volcanic flows will provide additional water in subsequent years; however, the higher ground-water levels will induce increased discharge of ground water from springs and seeps and from native vegetation as evapotranspiration. Increasing recharge for tributary streams that presently have low recharge rates may be possible. Volcanic deposits present opportunities for exceptionally high recharge and pumping rates, but the high transmissivities and low storage of the volcanic flows tend to limit their usefulness for long-term water management. The volcanic zones fill fast, but also drain fast. By recharging more water, higher on the alluvial fans, the time lag between ground-water recharge and discharge can be increased.

Siting new production wells on the alluvial fans or volcanic deposits will limit the short-term effects of pumping on native vegetation. Over time, however, as drawdown cones extend toward the valley floor, native vegetation may be affected by the decline in ground-water levels several thousand feet away. Drilling on alluvial fans may be difficult and well yields will be less than for comparable wells in more transmissive deposits.

The most promising long-term water-management alternative for the Owens Valley—one that provides ground water for export and minimizes adverse effects on native vegetation—is increasing extractions from the Bishop Creek alluvial fan (Bishop Cone). Land on the valley floor near the Bishop Cone either is urban or is manipulated with water-spreading and canals. However, as of 1988, export of ground water from the Bishop Cone is not permitted as a result of the Hillside Decree. This legal decision requires that ground-water extractions from the Bishop Cone be used in the immediate area and not be exported to other areas of the Owens Valley or out of the valley to Los Angeles.

The potential for development of a well field south of Bishop and north of Big Pine is promising. Highly transmissive transition-zone deposits may be present along the western side, and possibly eastern side, of the valley. However, the lack of significant recharge may limit production and accentuate drawdowns. The absence of horizontally extensive fine-grained deposits in the area will cause more rapid decline of the water table and probably greater adverse effects on native vegetation than would occur in most other areas of the valley.

Additional water development in the Laws area is limited by the minimal quantity of local recharge and by the absence of horizontally extensive fine-grained deposits. In this and other areas of the valley, unlined surface-water features, such as canals and ditches, provide an important source of local recharge; continued use of them will minimize adverse effects on native vegetation. Additional pumpage from the Big Pine well field is limited by natural inflow. Deeper wells might tap previously unknown volcanic deposits and derive water from storage; the pumped water could be replaced in years of above-average runoff using the abundant flow of Big Pine Creek and the highly transmissive volcanic deposits. Ground-water pumpage on the east side of the lower Owens River may be possible, but long-term yield is dependent on additional artificial recharge. Potentially poor ground-water quality also is a concern. Development of a well field near the Lone Pine area is limited by the presence of abundant fine-grained deposits and the lack of recharge. Development of some well production south of Lone Pine may be possible hydraulically, especially if transition-zone deposits are present beneath alluvial fans on the west side of the Owens Lake, but excessive pumpage likely will induce the migration of poor-quality water from the lake.

Development of new production facilities or further use of artificial recharge in the Owens Valley will increase water-management options and may provide a means of mitigating the adverse effects of pumping on native vegetation. However, one attribute of a more intensively managed aquifer system is that the distribution of native vegetation will be less even. The natural flow of the aquifer system tends to smooth out ground-water levels, recharge, and discharge. Human changes to the aquifer system tend to focus recharge and discharge into smaller areas. As the valley becomes more actively managed, it will become more pod-like, with pods of thriving vegetation near enhancement and mitigation projects and pods of highly stressed vegetation near wells. In between, less water will be available to native vegetation than was available prior to the increase in water development.

Rotation of pumpage among the several well fields is one method of optimal water management that facilitates the local recovery of the aquifer system. As a drought continues, a couple of weeks or months of replenishment of soil moisture may be extremely important in maintaining the health of native vegetation. Rotational pumpage, which allows recovery of the water table and replenishment of soil moisture in the root zone, probably is the most promising short-term water-management technique.

The most innovative water-management options for the Owens Valley may include conjunctive operations with other ground-water basins between the Owens Valley and Los Angeles. Water-banking along the aqueduct may be one way to capture water during periods of above-average runoff, save it for drier periods, and limit the adverse effects of pumping on native vegetation in the Owens Valley.

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— TABLE 9 —

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California

[ft, foot; ft/d, foot per day; ft^2/d, foot squared per day; m, meter; —, not available. Table includes all wells owned or operated, as of 1988, by the Los Angeles Department of Water and Power or the U.S. Geological Survey (USGS); some additional low-capacity agricultural or domestic wells are present in the Owens Valley. Aquifer-test methods are described in text and include distance drawdown (DD); Jacob-Cooper (JC); leaky aquifer (LK); modified Hantush (MH); Neuman (N); specific capacity (SC); and Theis (T). These aquifer-test methods are described in Bear (1979), Driscoll (1986), Hantush (1960), Lohman (1979), Neuman (1975), and Neuman and Witherspoon (1971)]

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmis-sivity (ft^2/d)	Average hori-zontal hydraulic conduc-tivity (ft/d)	Storage coefficient	Aqui-fer test meth-od	Comments
			East	North	Row	Col-umn						
1	36°47'49"	118°09'41"	396,385	4,072,776	130	22	314	1,300	4	—	SC	—
2	36°47'55"	118°09'51"	396,140	4,072,964	129	21	502	3,000	12	—	SC	—
3	36°48'10"	118°09'57"	395,997	4,073,428	128	21	272	—	—	—	—	—
5	36°48'18"	118°10'10"	395,678	4,073,679	128	21	146	—	—	—	—	—
7	36°48'53"	118°10'34"	395,096	4,074,765	126	21	504	—	—	—	—	—
9	36°49'16"	118°10'46"	394,808	4,075,477	125	20	378	—	—	—	—	—
11	36°42'28"	118°07'10"	400,012	4,062,840	147	23	301	—	—	—	—	—
12	36°41'45"	118°06'31"	400,964	4,061,504	150	23	485	—	—	—	—	—
13	36°40'41"	118°05'42"	402,158	4,059,518	153	24	330	—	—	—	—	—
14	36°49'02"	118°11'54"	393,118	4,075,067	124	18	231	3,100	14	—	SC	—
15	36°49'16"	118°11'37"	393,544	4,075,493	124	18	225	4,300	16	—	SC	—
16	36°49'29"	118°11'21"	393,946	4,075,888	124	19	343	2,400	7	—	SC	—
17	36°47'19"	118°09'27"	396,721	4,071,848	131	22	399	—	—	—	—	—
18	36°46'39"	118°09'21"	396,855	4,070,613	133	21	287	—	—	—	—	—
20	36°47'05"	118°09'20"	396,890	4,071,414	132	22	485	—	—	—	—	—
21	36°42'59"	118°07'42"	399,229	4,063,805	145	22	177	—	—	—	—	—
22	36°47'58"	118°09'55"	396,042	4,073,058	129	21	161	—	—	—	—	—
23	36°49'22"	118°11'29"	393,745	4,075,675	124	19	336	—	—	—	—	—
24	36°46'53"	118°09'21"	396,860	4,071,045	133	22	368	—	—	—	—	—
25	36°46'45"	118°09'21"	396,857	4,070,798	133	21	308	—	—	—	—	—
26	36°48'05"	118°10'10"	395,673	4,073,278	129	21	332	—	—	—	—	—
27	36°46'23"	118°09'19"	396,899	4,070,120	134	21	310	—	—	—	—	—
28	36°48'09"	118°10'22"	395,377	4,073,405	128	20	140	—	—	—	—	—
29	36°49'36"	118°11'32"	393,676	4,076,107	123	19	352	—	—	—	—	—
30	36°48'12"	118°10'29"	395,205	4,073,500	128	20	220	—	—	—	—	—
31	36°46'32"	118°09'20"	396,877	4,070,397	134	21	458	—	—	—	—	—
32	36°46'10"	118°09'15"	396,993	4,069,718	135	21	365	—	—	—	—	—
33	36°48'20"	118°10'45"	394,811	4,073,751	127	20	370	—	—	—	—	—
34	36°45'51"	118°09'13"	397,036	4,069,132	136	21	121	—	—	—	—	—
35	36°48'31"	118°10'55"	394,568	4,074,093	127	19	230	—	—	—	—	—
36	36°49'46"	118°11'30"	393,729	4,076,415	123	19	458	—	—	—	—	—
37	36°45'40"	118°09'16"	396,957	4,068,794	136	21	201	—	—	—	—	—
38	36°45'50"	118°09'14"	397,010	4,069,101	136	21	342	—	—	—	—	—
39	36°49'59"	118°11'31"	393,709	4,076,816	122	19	603	—	—	—	—	—
40	36°50'13"	118°11'34"	393,640	4,077,248	121	19	480	—	—	—	—	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmis-sivity (ft^2/d)	Average hori-zontal hydraulic conduc-tivity (ft/d)	Storage coefficient	Aqui-fer test meth-od	Comments
			East	North	Row	Col-umn						
41	36°45'24"	118°09'16"	396,951	4,068,301	137	20	130	—	—	—	—	—
42	36°45'15"	118°09'12"	397,047	4,068,022	137	20	214	—	—	—	—	—
43	36°45'26"	118°09'18"	396,902	4,068,363	137	20	272	—	—	—	—	—
44	36°50'26"	118°11'41"	393,472	4,077,651	121	19	500	—	—	—	—	—
44A	36°47'29"	118°08'06"	398,733	4,072,132	132	25	—	—	—	—	—	—
45	36°45'04"	118°09'01"	397,316	4,067,680	138	21	330	—	—	—	—	—
45A	36°48'05"	118°08'26"	398,250	4,073,247	130	25	—	—	—	—	—	—
46	36°50'27"	118°12'01"	392,977	4,077,688	120	19	476	—	—	—	—	—
47	37°14'22"	118°18'29"	383,975	4,122,036	46	26	703	—	—	—	—	—
48	36°50'40"	118°12'03"	392,932	4,078,089	120	19	381	770	2	—	SC	
49	36°52'23"	118°13'45"	390,477	4,081,295	113	16	150	—	—	—	—	—
52	36°52'13"	118°13'39"	390,592	4,080,985	114	16	126	—	—	—	—	—
53	36°52'38"	118°13'57"	390,156	4,081,761	113	16	159	—	—	—	—	—
54	36°52'50"	118°14'01"	390,062	4,082,132	112	16	234	—	—	—	—	—
55	36°52'07"	118°13'35"	390,688	4,080,799	114	17	183	—	—	—	—	—
56	36°48'28"	118°11'17"	394,021	4,074,007	127	18	89	91,000	530	0.047	JC	—
57	36°48'15"	118°11'06"	394,289	4,073,603	127	19	347	47,000	144	.0011	JC	—
58	36°53'03"	118°14'02"	390,042	4,082,533	111	16	237	—	—	—	—	—
59	36°48'35"	118°11'25"	393,826	4,074,226	126	18	277	46,000	180	.0006	JC	—
60	36°48'03"	118°10'58"	394,483	4,073,231	128	19	275	44,000	180	.0005	JC	—
61	36°48'44"	118°11'34"	393,606	4,074,506	126	18	196	—	—	—	—	—
63	36°47'51"	118°10'28"	395,221	4,072,852	129	20	442	—	—	—	—	—
65	36°48'24"	118°11'15"	394,069	4,073,883	127	19	345	39,000	120	—	JC	—
66	36°46'48"	118°09'49"	396,164	4,070,899	132	20	310	35,000	120	—	JC	—
67	36°46'35"	118°09'49"	396,159	4,070,498	133	20	312	—	—	—	—	—
68	36°47'02"	118°09'52"	396,095	4,071,331	132	20	378	10,000	29	—	JC	—
69	36°46'45"	118°10'08"	395,692	4,070,812	132	20	324	45,000	170	—	JC	—
70	36°44'37"	118°09'25"	396,711	4,066,855	139	19	161	—	—	—	—	—
72	36°44'10"	118°08'58"	397,370	4,066,015	141	20	301	3,000	46	—	MH	—
73	36°46'22"	118°09'53"	396,055	4,070,099	134	20	314	20,000	75	—	SC	—
74	36°46'12"	118°09'54"	396,027	4,069,791	134	20	250	—	—	—	—	—
75	36°43'53"	118°08'47"	397,637	4,065,488	142	20	287	3,600	14	—	SC	—
76	36°42'17"	118°08'06"	398,619	4,062,518	147	20	174	5,100	34	—	JC	—
77	36°49'00"	118°11'36"	393,563	4,074,999	125	18	271	—	—	—	—	—
80	36°43'56"	118°08'13"	398,481	4,065,570	142	21	443	—	—	—	—	—
81	36°49'33"	118°12'42"	391,940	4,076,037	122	16	57	—	—	—	—	—
82	36°42'03"	118°07'46"	399,110	4,062,080	148	21	268	7,400	28	.0003	JC	—
83	36°42'34"	118°07'52"	398,972	4,063,037	146	21	317	—	—	—	—	—
84	36°44'17"	118°08'45"	397,695	4,066,227	141	21	312	—	—	—	—	—
85	36°49'32"	118°12'11"	392,708	4,075,996	123	17	261	—	—	—	—	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmissivity (ft²/d)	Average horizontal hydraulic conductivity (ft/d)	Storage coefficient	Aquifer test method	Comments
			East	North	Row	Column						
86	36°42'51"	118°08'04"	398,681	4,063,565	145	21	302	—	—	—	—	—
87	36°41'55"	118°07'29"	399,529	4,061,829	148	21	195	11,000	63	0.0003	JC	—
88	36°50'25"	118°12'53"	391,688	4,077,643	120	17	509	—	—	—	—	—
89	36°41'45"	118°07'19"	399,773	4,061,518	149	22	347	14,000	44	.002	JC	—
90	36°43'12"	118°08'19"	398,316	4,064,216	144	21	321	—	—	—	—	—
92	36°45'46"	118°09'54"	396,017	4,068,990	135	19	332	37,000	130	.00082	JC	—
95	36°42'05"	118°07'59"	398,788	4,062,146	147	20	375	7,500	30	.0003	JC	—
96	36°45'58"	118°09'54"	396,022	4,069,360	135	19	378	23,000	67	—	JC	—
97	36°42'48"	118°08'20"	398,283	4,063,477	145	20	319	24,000	80	.0009	JC	—
98	36°43'03"	118°08'16"	398,387	4,063,938	144	21	330	—	—	—	—	—
99	36°45'22"	118°10'07"	395,686	4,068,254	136	18	275	32,000	130	—	JC	—
103	36°53'23"	118°14'24"	389,505	4,083,157	110	16	260	—	—	—	—	—
104	36°53'12"	118°14'19"	389,625	4,082,816	111	16	226	—	—	—	—	—
105	36°53'26"	118°14'24"	389,507	4,083,249	110	16	199	—	—	—	—	—
106	36°58'04"	118°14'56"	388,827	4,091,826	96	19	145	22,000	260	—	SC	—
108	36°56'53"	118°14'54"	388,848	4,089,638	100	18	108	47,000	1,000	.050	DD	—
109	36°56'55"	118°14'41"	389,170	4,089,695	100	18	136	320,000	3,600	.11	DD	—
110	36°58'13"	118°15'04"	388,633	4,092,106	96	19	174	37,000	370	—	SC	—
111	36°58'26"	118°15'18"	388,292	4,092,511	95	18	125	48,000	570	—	SC	—
112	36°58'27"	118°14'52"	388,935	4,092,534	95	19	111	—	—	—	—	—
113	36°58'43"	118°14'56"	388,842	4,093,028	94	19	107	—	—	—	—	—
114	36°58'42"	118°15'10"	388,496	4,093,002	94	19	92	—	—	—	—	—
115	36°58'34"	118°14'53"	388,913	4,092,750	95	19	—	—	—	—	—	Never drilled.
116	37°00'19"	118°14'06"	390,117	4,095,970	90	23	103	—	—	—	—	—
117	36°57'49"	118°15'08"	388,524	4,091,368	97	18	108	5,000	108	—	SC	—
118	37°03'16"	118°13'37"	390,904	4,101,416	82	27	156	—	—	—	—	—
121	37°17'25"	118°18'46"	383,634	4,127,681	37	28	521	3,100	6	—	SC	—
122	37°18'06"	118°18'29"	384,070	4,128,939	36	29	532	5,100	10	—	SC	—
123	37°18'56"	118°18'50"	383,575	4,130,487	33	29	564	14,000	24	—	SC	—
124	37°19'46"	118°19'15"	382,981	4,132,037	30	29	634	2,200	3	—	SC	—
125	37°21'03"	118°19'34"	382,546	4,134,416	26	29	611	17,000	28	—	SC	—
126	37°20'38"	118°19'36"	382,486	4,133,646	27	29	581	13,000	24	—	SC	—
127	37°20'09"	118°19'29"	382,646	4,132,750	29	29	591	10,000	17	—	SC	—
128	37°19'22"	118°18'45"	383,709	4,131,287	32	30	597	7,800	13	—	SC	—
129	37°18'33"	118°18'39"	383,836	4,129,774	34	29	599	11,000	19	—	SC	—
130	37°19'44"	118°19'15"	382,980	4,131,975	30	29	716	17,000	24	—	SC	—
131	37°21'21"	118°19'53"	382,087	4,134,977	25	29	616	—	—	—	SC	—
132	37°21'39"	118°20'15"	381,553	4,135,540	24	28	602	17,000	28	—	SC	—
133	37°22'03"	118°20'33"	381,121	4,136,286	23	28	490	15,000	31	—	SC	—
134	37°22'25"	118°20'29"	381,229	4,136,962	22	29	692	—	—	—	—	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmissivity (ft²/d)	Average horizontal hydraulic conductivity (ft/d)	Storage coefficient	Aquifer test method	Comments
			East	North	Row	Column						
135	37°22'52"	118°21'35"	379,618	4,137,818	20	26	662	4,300	7	—	SC	—
136	37°22'43"	118°20'55"	380,598	4,137,526	20	28	647	13,000	20	—	SC	—
137	37°21'17"	118°25'03"	374,458	4,134,965	22	17	632	5,000	9	—	JC	—
138	37°21'00"	118°24'32"	375,213	4,134,430	23	18	584	5,100	10	—	JC	—
139	37°20'36"	118°24'02"	375,940	4,133,679	24	19	593	8,900	15	—	SC	—
140	37°20'11"	118°24'02"	375,929	4,132,909	26	18	632	6,800	12	—	JC	—
141	37°20'08"	118°23'29"	376,740	4,132,804	26	20	636	5,900	10	—	JC	—
145	37°18'23"	118°22'11"	378,612	4,129,540	32	21	1,187	4,000	1	—	SC	—
147	37°21'42"	118°25'20"	374,052	4,135,742	20	17	484	8,700	18	—	SC	—
148	37°21'52"	118°25'36"	373,663	4,136,056	19	16	353	7,900	23	—	SC	—
149	37°22'18"	118°25'37"	373,650	4,136,858	18	17	656	2,400	4	—	SC	—
150	36°58'48"	118°15'08"	388,548	4,093,186	94	19	—	—	—	—	—	—
151	36°58'35"	118°14'52"	388,938	4,092,780	95	20	89	—	—	—	—	—
154	36°57'50"	118°15'25"	388,104	4,091,404	96	18	81	—	—	—	—	—
155	36°54'59"	118°15'01"	388,628	4,086,127	105	16	259	—	—	—	—	—
156	36°54'50"	118°15'01"	388,625	4,085,850	105	16	—	—	—	—	—	—
157	36°54'39"	118°15'02"	388,595	4,085,511	106	15	—	—	—	—	—	—
158	36°54'29"	118°14'59"	388,666	4,085,202	106	15	173	—	—	—	—	—
159	36°54'14"	118°14'45"	389,006	4,084,735	107	16	435	—	—	—	—	—
160	36°58'16"	118°14'40"	389,227	4,092,191	96	20	113	—	—	—	—	—
161	36°50'00"	118°12'05"	392,867	4,076,857	122	18	—	—	—	—	—	—
164	36°46'26"	118°09'58"	395,933	4,070,224	133	20	88	—	—	—	—	—
165	36°46'56"	118°10'06"	395,746	4,071,151	132	20	96	39,000	790	0.0074	JC	—
166	36°46'54"	118°10'06"	395,745	4,071,089	132	20	87	120,000	3,300	.046	JC	—
169	36°43'49"	118°09'24"	396,717	4,065,376	141	19	215	—	—	—	—	—
170	36°46'17"	118°09'58"	395,930	4,069,947	134	20	90	—	—	—	—	—
172	36°36'14"	118°03'14"	405,741	4,051,250	168	26	59	—	—	—	—	—
175	36°46'37"	118°09'55"	396,012	4,070,562	133	20	109	94,000	960	.0042	JC	—
201	37°21'43"	118°23'06"	377,349	4,135,724	22	22	144	8,700	63	—	SC	—
202	37°22'09"	118°23'06"	377,360	4,136,525	21	22	544	—	—	—	—	—
203	37°09'25"	118°16'36"	386,636	4,112,845	62	25	228	8,200	46	—	SC	—
204	37°09'04"	118°16'34"	386,676	4,112,197	63	25	206	—	—	—	—	—
205	37°09'52"	118°16'40"	386,548	4,113,678	61	26	350	—	—	—	—	—
206	37°04'46"	118°15'19"	388,421	4,104,222	76	24	58	52,000	540	—	SC	—
207	37°22'30"	118°22'59"	377,542	4,137,170	20	23	174	20,000	27	—	JC	—
208	37°22'49"	118°23'26"	376,886	4,137,765	18	22	292	10,000	37	.00073	JC	—
210	37°10'13"	118°16'54"	386,212	4,114,330	60	26	352	6,300	15	—	SC	—
211	37°10'02"	118°16'48"	386,355	4,113,989	60	26	416	5,900	16	—	SC	—
212	37°09'37"	118°16'38"	386,591	4,113,216	62	26	221	6,800	38	—	SC	—
216	37°08'12"	118°16'22"	386,951	4,110,591	66	25	112	270,000	5,400	.062	JC	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmis-sivity (ft^2/d)	Average hori-zontal hydraulic conduc-tivity (ft/d)	Storage coefficient	Aqui-fer test meth-od	Comments
			East	North	Row	Col-umn						
217	37°07'51"	118°16'07"	387,312	4,109,939	67	25	78	290,000	6,000	0.062	JC	—
218	37°04'31"	118°15'24"	388,292	4,103,761	77	24	168	—	—	—	—	—
219	37°05'07"	118°15'22"	388,356	4,104,870	75	24	225	1,100,000	7,300	.0027	JC	—
220	37°08'39"	118°16'43"	386,444	4,111,430	64	25	152	76,000	2,100	—	SC	—
221	37°07'27"	118°15'49"	387,747	4,109,193	68	25	78	—	—	—	—	—
222	37°07'06"	118°15'34"	388,108	4,108,541	70	26	90	160,000	3,800	—	SC	—
223	37°06'40"	118°15'18"	388,493	4,107,735	71	26	159	—	—	—	—	—
224	37°06'15"	118°15'12"	388,630	4,106,962	72	26	322	230,000	800	.0028	JC	—
227	37°08'29"	118°16'34"	386,662	4,111,119	65	25	110	190,000	3,800	.013	JC	—
228	37°08'22"	118°16'29"	386,782	4,110,901	65	25	106	240,000	15,000	.041	JC	—
229	37°08'01"	118°16'14"	387,144	4,110,249	66	25	127	1,000,000	12,000	—	JC	—
230	37°07'40"	118°15'59"	387,505	4,109,597	68	25	139	—	—	—	—	—
231	37°07'14"	118°15'40"	387,963	4,108,790	69	26	120	23,000	360	—	SC	—
232	37°06'48"	118°15'24"	388,348	4,107,983	71	26	140	82,000	870	—	SC	—
233	37°06'28"	118°15'11"	388,660	4,107,363	72	26	49	210,000	2,000	.0019	JC	—
234	37°23'17"	118°24'07"	375,891	4,138,643	16	21	648	3,200	5	—	SC	—
235	37°22'46"	118°24'08"	375,852	4,137,688	18	20	264	10,000	39	—	JC	—
236	37°24'57"	118°20'04"	381,910	4,141,638	15	32	498	34,000	77	—	SC	—
237	37°23'27"	118°24'36"	375,182	4,138,962	16	20	518	2,500	5	—	SC	—
238	37°23'41"	118°24'54"	374,746	4,139,400	15	20	616	10,000	18	—	T	—
239	37°24'32"	118°20'18"	381,555	4,140,872	16	31	424	12,000	33	—	SC	—
240	37°24'08"	118°20'10"	381,741	4,140,130	17	31	609	5,500	10	—	SC	—
241	37°23'44"	118°19'52"	382,174	4,139,384	18	31	604	17,000	31	—	JC	—
242	37°23'31"	118°19'19"	382,979	4,138,972	19	32	438	12,000	33	—	SC	—
243	37°25'20"	118°19'54"	382,166	4,142,343	14	33	504	—	—	—	—	—
244	37°25'48"	118°20'07"	381,859	4,143,211	12	33	548	20,000	41	—	SC	—
245	37°26'16"	118°20'20"	381,552	4,144,078	11	32	324	7,200	25	—	JC	—
246	37°26'05"	118°20'52"	380,760	4,143,750	11	31	399	12,000	32	.002	JC	—
247	37°26'11"	118°21'32"	379,780	4,143,949	10	30	378	23,000	65	—	DD	—
248	37°25'51"	118°22'02"	379,034	4,143,344	11	28	602	98,000	169	.002	DD	—
249	37°25'38"	118°22'45"	377,971	4,142,958	11	26	500	22,000	47	—	SC	—
250	37°24'01"	118°20'31"	381,222	4,139,922	17	30	112	—	—	—	—	—
251	37°25'16"	118°19'24"	382,902	4,142,210	14	34	178	59,000	613	.0026	DD	—
252	37°27'20"	118°20'51"	380,818	4,146,061	7	32	192	30,000	215	—	SC	—
253	37°27'08"	118°20'44"	380,985	4,145,689	8	32	97	—	—	—	—	—
255	36°35'54"	118°04'10"	404,343	4,050,649	168	23	129	—	—	—	—	—
256	36°36'57"	118°04'20"	404,116	4,052,593	165	24	41	—	—	—	—	—
257	36°45'59"	118°10'32"	395,080	4,069,402	134	18	95	—	—	—	—	—
258	36°38'53"	118°05'05"	403,039	4,056,180	159	24	141	—	—	—	—	—
259	36°57'02"	118°14'52"	388,901	4,089,914	99	18	113	—	—	—	—	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmis-sivity (ft^2/d)	Average hori-zontal hydraulic conduc-tivity (ft/d)	Storage coefficient	Aqui-fer test meth-od	Comments
			East	North	Row	Col-umn						
260	37°03'56"	118°14'12"	390,056	4,102,659	80	26	110	—	—	—	—	—
262	37°26'43"	118°20'47"	380,900	4,144,920	9	32	97	—	—	—	—	—
265	37°27'44"	118°20'51"	380,829	4,146,801	6	33	95	—	—	—	—	—
266	37°27'35"	118°20'56"	380,702	4,146,525	6	32	53	—	—	—	—	—
269	37°26'07"	118°21'30"	379,827	4,143,825	10	30	100	28,000	374	0.006	LK	—
270	37°26'00"	118°20'16"	381,643	4,143,584	11	32	104	—	—	—	—	—
271	37°25'28"	118°20'46"	380,892	4,142,608	13	31	113	32,000	353	.00036	JC	—
272	37°25'13"	118°19'36"	382,606	4,142,121	14	33	76	—	—	—	—	—
274	37°28'09"	118°21'04"	380,520	4,147,576	5	33	250	—	—	—	—	—
275	37°26'39"	118°20'52"	380,775	4,144,798	9	32	98	—	—	—	—	—
276	37°27'41"	118°20'45"	380,975	4,146,707	6	33	79	—	—	—	—	—
277	37°22'26"	118°29'21"	368,144	4,137,189	15	8	365	—	—	—	—	—
278	37°22'56"	118°29'48"	367,495	4,138,124	13	8	488	—	—	—	—	—
279	37°22'35"	118°26'40"	372,109	4,137,405	17	14	536	—	—	—	—	—
280	37°22'05"	118°27'41"	370,594	4,136,504	17	12	513	—	—	—	—	—
281	37°23'07"	118°28'13"	369,836	4,138,427	14	11	—	—	—	—	—	—
282	37°22'04"	118°27'52"	370,323	4,136,477	17	11	—	—	—	—	—	—
284	37°29'58"	118°20'49"	380,937	4,150,930	1	35	—	—	—	—	—	—
286	37°26'17"	118°20'25"	381,429	4,144,111	11	32	122	—	—	—	—	—
287	37°16'26"	118°21'55"	378,954	4,125,929	38	20	69	—	—	—	—	—
288	37°23'42"	118°19'42"	382,419	4,139,319	19	32	101	—	—	—	—	—
289	37°26'10"	118°22'54"	377,764	4,143,948	9	26	64	—	—	—	—	—
290	37°25'42"	118°21'38"	379,620	4,143,058	11	29	147	74,000	561	.001	DD	—
291	37°28'55"	118°21'19"	380,172	4,148,999	2	33	—	—	—	—	—	—
292	37°20'01"	118°22'35"	378,065	4,132,569	27	21	500	—	—	—	—	—
294	37°05'06"	118°15'12"	388,602	4,104,836	76	25	181	—	—	—	—	—
295	37°10'15"	118°16'21"	387,026	4,114,381	60	27	618	—	—	—	—	—
296	37°12'58"	118°19'14"	382,830	4,119,463	50	23	351	—	—	—	—	—
297	37°09'30"	118°17'33"	385,232	4,113,018	61	23	70	—	—	—	—	—
298	37°11'19"	118°19'22"	382,590	4,116,414	55	21	224	—	—	—	—	—
299	37°09'21"	118°17'17"	385,623	4,112,736	62	24	111	—	—	—	—	—
304	36°59'58"	118°12'31"	392,457	4,095,293	92	26	—	—	—	—	—	—
316	37°18'26"	118°18'38"	383,857	4,129,558.	35	29	—	—	—	—	—	—
324	37°22'03"	118°21'55"	379,104	4,136,315	22	25	157	4,800	36	—	SC	—
327	36°48'19"	118°07'04"	400,287	4,073,654	130	28	101	—	—	—	—	—
328	36°48'01"	118°08'10"	398,645	4,073,119	130	25	79	—	—	—	—	—
329	37°05'50"	118°15'28"	388,225	4,106,197	73	25	100	—	—	—	—	—
330	37°05'45"	118°15'35"	388,050	4,106,045	73	24	198	—	—	—	—	—
331	37°05'46"	118°15'21"	388,396	4,106,072	74	25	303	230,000	850	—	JC	—
332	37°05'44"	118°15'32"	388,124	4,106,013	74	25	117	1,200,000	19,000	—	JC	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmissivity (ft^2/d)	Average horizontal hydraulic conductivity (ft/d)	Storage coefficient	Aquifer test method	Comments
			East	North	Row	Column						
333	36°50'13"	118°13'29"	390,792	4,077,284	120	15	219	—	—	—	—	—
339	36°55'09"	118°15'07"	388,484	4,086,437	104	16	140	—	—	—	—	—
341	37°09'09"	118°18'14"	384,212	4,112,385	62	21	695	540	1	—	JC	—
342	36°59'52"	118°14'22"	389,711	4,095,143	91	22	239	540,000	3,200	—	JC	—
343	36°41'42"	118°09'15"	396,894	4,061,460	148	17	531	5,300	10	—	JC	—
344	36°36'16"	118°04'09"	404,375	4,051,326	167	24	354	28,000	100	0.00001	T	—
345	36°44'23"	118°09'48"	396,135	4,066,431	139	18	386	5,300	15	—	JC	—
346	36°36'17"	118°04'06"	404,450	4,051,356	167	24	430	—	—	—	—	—
347	36°59'51"	118°14'58"	388,821	4,095,124	91	20	226	170,000	1,200	—	SC	—
348	36°41'46"	118°07'19"	399,774	4,061,549	149	22	429	13,000	33	—	JC	—
349	37°00'59"	118°13'38"	390,825	4,097,194	89	25	144	78,000	670	—	JC	—
351	36°55'42"	118°14'03"	390,081	4,087,433	104	19	115	56,000	940	—	SC	—
352	37°09'53"	118°17'14"	385,710	4,113,721	60	24	596	26,000	51	—	JC	—
353	36°43'05"	118°09'28"	396,602	4,064,021	143	18	570	2,700	5	.0004	JC	—
354	37°24'11"	118°20'36"	381,104	4,140,231	16	30	200	—	—	—	—	—
355	36°58'48"	118°13'37"	390,798	4,093,157	95	23	194	33,000	193		JC	—
356	36°55'49"	118°13'59"	390,182	4,087,648	103	19	158	280,000	2,600	—	JC	—
357	36°47'54"	118°12'15"	392,571	4,072,978	128	16	598	7,900	16	—	JC	—
362	37°00'25"	118°13'45"	390,639	4,096,148	90	24	162	—	—	—	—	—
363	37°02'34"	118°12'50"	392,049	4,100,106	85	28	53	—	—	—	—	—
364	37°01'43"	118°13'08"	391,584	4,098,540	87	26	60	—	—	—	—	—
365	37°25'10"	118°19'28"	382,801	4,142,026	14	33	388	10,000	34	—	JC	—
366	36°55'37"	118°12'38"	392,182	4,087,252	105	22	210	—	—	—	—	—
367	36°51'29"	118°10'54"	394,660	4,079,578	118	22	210	—	—	—	—	—
368	36°46'12"	118°07'30"	399,597	4,069,749	136	25	202	—	—	—	—	—
369	36°43'17"	118°05'52"	401,965	4,064,328	146	26	204	170	1	—	SC	—
370	36°56'55"	118°14'59"	388,725	4,089,701	99	18	266	33,000	—	—	DD	—
371	37°22'51"	118°23'31"	376,764	4,137,828	18	22	229	7,100	32	—	JC	—
374	37°08'40"	118°15'03"	388,912	4,111,428	65	28	—	9,800	24	—	JC	—
375EM	37°08'29"	118°15'02"	388,932	4,111,088	66	28	—	11,000	25	—	JC	—
376EM	37°23'29"	118°19'47"	382,290	4,138,920	19	31	—	—	—	—	—	—
377EM	37°23'16"	118°19'36"	382,555	4,138,516	20	31	—	—	—	—	—	—
378EM	37°10'31"	118°17'16"	385,677	4,114,892	58	25	—	—	—	—	—	—
379EM	37°10'28"	118°17'10"	385,823	4,114,798	59	25	—	—	—	—	—	—
380EM	36°55'32"	118°13'33"	390,819	4,087,116	104	20	—	—	—	—	—	—
381EM	36°55'23"	118°13'27"	390,964	4,086,836	105	20	—	—	—	—	—	—
382EM	36°52'15"	118°13'31"	390,790	4,081,044	114	17	—	—	—	—	—	—
383EM	36°48'27"	118°11'44"	393,352	4,073,985	126	17	—	—	—	—	—	—
384EM	36°47'59"	118°11'24"	393,837	4,073,116	128	18	—	—	—	—	—	—
385EM	37°25'07"	118°24'06"	375,966	4,142,032	11	23	—	—	—	—	—	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmissivity (ft^2/d)	Average horizontal hydraulic conductivity (ft/d)	Storage coefficient	Aquifer test method	Comments
			East	North	Row	Column						
386EM	37°25'02"	118°24'06"	375,964	4,141,878	11	23	—	—	—	—	—	—
387EM	37°26'25"	118°20'24"	381,457	4,144,357	10	32	—	—	—	—	—	—
388EM	37°26'11"	118°20'22"	381,500	4,143,925	11	32	—	—	—	—	—	—
389EM	37°10'34"	118°17'23"	385,505	4,114,987	58	25	—	—	—	—	—	—
390EM	36°36'07"	118°03'08"	405,888	4,051,032	168	26	—	—	—	—	—	—
1T	36°46'55"	118°13'34"	390,590	4,071,184	129	12	914	—	—	—	—	—
4T	36°51'02"	118°12'02"	392,966	4,078,767	119	19	—	—	—	—	—	—
23T	36°49'26"	118°11'26"	393,820	4,075,797	124	19	13	—	—	—	—	—
24T	36°46'48"	118°09'15"	397,007	4,070,889	133	22	13	—	—	—	—	—
52T	36°52'14"	118°13'36"	390,666	4,081,015	114	17	14	—	—	—	—	—
107T	37°27'19"	118°21'36"	379,712	4,146,047	7	31	39	—	—	—	—	Reconstructed 1961.
108T	37°22'35"	118°25'47"	373,412	4,137,385	17	16	9	—	—	—	—	—
110T	37°24'30"	118°25'47"	373,466	4,140,929	12	18	23	—	—	—	—	—
110AT	37°24'30"	118°25'47"	373,466	4,140,929	12	18	53	—	—	—	—	—
136AT	36°44'07"	118°08'54"	397,468	4,065,921	141	20	19	—	—	—	—	—
232T	37°10'10"	118°16'19"	387,074	4,114,226	60	27	8	—	—	—	—	—
276T	37°28'11"	118°21'54"	379,293	4,147,656	4	31	6	—	—	—	—	—
302T	37°05'53"	118°15'27"	388,251	4,106,289	73	25	31	—	—	—	—	—
304T	37°22'26"	118°22'59"	377,540	4,137,046	20	23	7	—	—	—	—	Destroyed.
305AT	37°22'44"	118°23'27"	376,860	4,137,611	19	22	7	—	—	—	—	—
306AT	37°22'39"	118°24'11"	375,775	4,137,473	18	20	8	—	—	—	—	—
307T	37°23'15"	118°24'07"	375,890	4,138,581	17	21	7	—	—	—	—	Destroyed 1976.
308T	37°23'27"	118°24'33"	375,256	4,138,960	16	20	6	—	—	—	—	—
309T	37°23'43"	118°24'58"	374,649	4,139,463	15	19	23	—	—	—	—	—
310T	37°25'36"	118°22'50"	377,847	4,142,899	11	26	10	—	—	—	—	Destroyed 1976.
311T	37°25'52"	118°22'07"	378,911	4,143,376	11	28	29	—	—	—	—	Destroyed 1981.
312AT	37°26'12"	118°21'31"	379,805	4,143,980	10	30	7	—	—	—	—	—
313T	37°26'04"	118°20'57"	380,637	4,143,721	11	31	14	—	—	—	—	—
314T	37°17'19"	118°18'53"	383,459	4,127,499	38	28	4	—	—	—	—	—
315T	37°17'59"	118°18'29"	384,067	4,128,723	36	29	8	—	—	—	—	—
316T	37°18'28"	118°18'37"	383,883	4,129,620	34	29	8	—	—	—	—	Destroyed 1975.
317T	37°18'53"	118°18'51"	383,549	4,130,395	33	29	9	—	—	—	—	—
319T	37°19'40"	118°19'23"	382,781	4,131,854	30	29	12	—	—	—	—	—
320T	37°20'04"	118°19'28"	382,669	4,132,596	29	29	7	—	—	—	—	—
321T	37°20'35"	118°19'35"	382,510	4,133,554	28	29	9	—	—	—	—	—
322T	37°20'59"	118°19'34"	382,545	4,134,293	26	29	7	—	—	—	—	—
323T	37°21'18"	118°19'52"	382,110	4,134,885	25	29	5	—	—	—	—	—
324T	37°21'36"	118°20'14"	381,577	4,135,447	24	28	8	—	—	—	—	—
325T	37°22'00"	118°20'33"	381,120	4,136,193	23	28	5	—	—	—	—	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m) East	Universal Transverse Mercator (UTM) coordinates (m) North	Ground-water flow model Row	Ground-water flow model Column	Most recent well depth (ft)	Transmissivity (ft^2/d)	Average horizontal hydraulic conductivity (ft/d)	Storage coefficient	Aquifer test method	Comments
326T	37°22'23"	118°20'23"	381,376	4,136,899	22	29	4	—	—	—	—	—
328T	37°28'44"	118°21'49"	379,430	4,148,671	2	31	22	—	—	—	—	—
329T	37°22'53"	118°21'39"	379,520	4,137,850	19	26	—	—	—	—	—	Destroyed.
330T	37°22'46"	118°20'50"	380,722	4,137,617	20	28	6	—	—	—	—	—
333T	37°21'46"	118°25'23"	373,980	4,135,866	20	17	12	—	—	—	—	Destroyed.
333AT	37°21'46"	118°25'23"	373,980	4,135,866	20	17	—	—	—	—	—	—
334T	37°21'15"	118°24'59"	374,556	4,134,902	22	17	7	—	—	—	—	—
335T	37°18'23"	118°22'04"	378,784	4,129,538	32	21	10	—	—	—	—	—
336T	37°20'58"	118°24'24"	375,409	4,134,365	23	18	8	—	—	—	—	—
337T	37°21'54"	118°25'30"	373,811	4,136,115	19	17	4	—	—	—	—	—
338T	37°22'21"	118°25'41"	373,553	4,136,952	18	17	2	—	—	—	—	—
345T	36°48'18"	118°07'14"	400,039	4,073,627	130	28	—	—	—	—	—	—
346T	36°48'05"	118°08'01"	398,870	4,073,240	130	26	—	—	—	—	—	—
347T	36°32'06"	118°01'57"	407,572	4,043,587	181	25	22	—	—	—	—	—
348T	36°32'28"	118°01'08"	408,798	4,044,252	180	27	810	—	—	—	—	Refer Meyer well log.
360T	36°36'20"	118°04'13"	404,277	4,051,451	167	24	106	—	—	—	—	—
361T	36°36'14"	118°04'11"	404,325	4,051,265	167	24	45	—	—	—	—	—
362T	36°41'49"	118°09'03"	397,194	4,061,672	147	18	80	—	—	—	—	—
363T	36°41'49"	118°09'08"	397,070	4,061,673	147	17	80	—	—	—	—	—
364T	36°43'52"	118°09'22"	396,768	4,065,468	141	19	150	—	—	—	—	—
365T	36°44'23"	118°09'54"	395,986	4,066,432	139	18	—	—	—	—	—	Destroyed.
372T	37°23'46"	118°24'59"	374,626	4,139,556	14	19	77	—	—	—	—	—
373T	37°23'44"	118°25'02"	374,551	4,139,495	15	19	53	—	—	—	—	—
374T	36°50'26"	118°09'34"	396,618	4,077,612	122	24	63	—	—	—	—	—
375T	36°50'26"	118°09'25"	396,841	4,077,609	122	25	53	—	—	—	—	—
376T	36°55'44"	118°12'05"	393,001	4,087,458	105	23	64	—	—	—	—	—
377T	36°55'45"	118°11'48"	393,422	4,087,483	105	24	53	—	—	—	—	—
378T	36°37'30"	118°01'24"	408,499	4,053,562	166	31	37	—	—	—	—	—
379T	36°42'51"	118°04'05"	404,610	4,063,497	148	30	74	—	—	—	—	—
380T	36°55'45"	118°12'08"	392,927	4,087,489	105	23	42	—	—	—	—	—
381T	36°55'45"	118°11'43"	393,546	4,087,482	105	24	52	—	—	—	—	—
382T	36°50'26"	118°09'40"	396,469	4,077,614	122	24	73	—	—	—	—	—
383T	36°50'26"	118°09'18"	397,014	4,077,607	122	25	65	—	—	—	—	—
384T	37°23'27"	118°25'02"	374,543	4,138,971	15	19	79	—	—	—	—	—
385T	37°23'36"	118°24'56"	374,695	4,139,246	15	19	191	12,000	72	—	T	—
386T	37°19'58"	118°23'40"	376,464	4,132,500	26	19	98	—	—	—	—	—
387T	37°21'08"	118°24'37"	375,094	4,134,678	22	18	198	—	—	—	—	—
388T	37°21'00"	118°24'33"	375,188	4,134,430	23	18	145	—	—	—	—	—
389T	37°21'14"	118°25'14"	374,186	4,134,877	22	17	81	—	—	—	—	—
390T	37°21'45"	118°25'48"	373,364	4,135,845	20	16	80	—	—	—	—	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmis-sivity (ft^2/d)	Average hori-zontal hydraulic conduc-tivity (ft/d)	Storage coefficient	Aqui-fer test meth-od	Comments
			East	North	Row	Col-umn						
391T	37˚22'10"	118˚26'40"	372,097	4,136,635	18	14	70	—	—	—	—	—
392T	37˚22'40"	118˚24'39"	375,087	4,137,514	18	19	111	—	—	—	—	—
393T	36˚39'24"	118˚05'31"	402,404	4,057,142	157	24	49	—	—	—	—	Skinner #4.
394T	36˚39'18"	118˚05'29"	402,451	4,056,957	157	24	62	—	—	—	—	Skinner #3.
395T	36˚39'20"	118˚05'33"	402,353	4,057,019	157	23	72	—	—	—	—	Skinner #2.
396T	36˚39'22"	118˚05'28"	402,478	4,057,080	157	24	70	—	—	—	—	Skinner #1.
398T	36˚42'11"	118˚07'30"	399,510	4,062,322	148	22	20	—	—	—	—	—
399T	36˚42'11"	118˚07'13"	399,932	4,062,317	148	22	20	—	—	—	—	—
400T	36˚42'34"	118˚06'58"	400,312	4,063,022	147	23	21	—	—	—	—	—
401T	36˚44'09"	118˚08'55"	397,444	4,065,983	141	20	21	—	—	—	—	Deepened to 42 ft in 1977.
402T	36˚43'56"	118˚08'01"	398,779	4,065,567	142	22	20	—	—	—	—	Deepened to 42 ft in 1977.
403T	36˚44'55"	118˚09'04"	397,238	4,067,404	138	20	21	—	—	—	—	Deepened to 42 ft in 1977.
404T	36˚45'16"	118˚09'14"	396,998	4,068,054	137	20	20	—	—	—	—	—
405T	36˚47'54"	118˚08'55"	397,527	4,072,917	130	23	20	—	—	—	—	—
406T	36˚48'03"	118˚08'25"	398,274	4,073,185	130	25	21	—	—	—	—	—
407T	36˚47'54"	118˚09'47"	396,239	4,072,932	129	21	20	—	—	—	—	Deepened to 42 ft in 1977.
408T	36˚48'41"	118˚10'28"	395,240	4,074,393	127	21	21	—	—	—	—	—
409T	36˚48'34"	118˚10'46"	394,792	4,074,183	127	20	21	—	—	—	—	Deepened to 42 ft in 1977.
410T	36˚48'18"	118˚11'26"	393,794	4,073,702	127	18	21	—	—	—	—	—
411T	36˚50'05"	118˚11'31"	393,712	4,077,001	122	19	20	—	—	—	—	—
412T	36˚49'45"	118˚11'27"	393,803	4,076,383	123	19	20	—	—	—	—	—
413T	36˚53'05"	118˚14'04"	389,993	4,082,596	111	16	20	—	—	—	—	Deepened to 42 ft in 1977.
414T	36˚53'07"	118˚14'07"	389,920	4,082,658	111	16	20	—	—	—	—	—
415T	36˚55'29"	118˚13'51"	390,372	4,087,029	104	19	21	—	—	—	—	Deepened to 42 ft in 1977.
416T	36˚55'44"	118˚13'44"	390,552	4,087,489	104	19	20	—	—	—	—	Deepened to 23 ft in 1977.
417T	36˚56'51"	118˚14'12"	389,886	4,089,563	100	19	21	—	—	—	—	Deepened to 63 ft in 1977.
418T	36˚58'26"	118˚13'02"	391,654	4,092,468	96	24	21	—	—	—	—	Deepened to 42 ft in 1977.
419T	36˚58'26"	118˚13'21"	391,185	4,092,474	96	23	24	—	—	—	—	Deepened to 29 ft in 1977.
420T	37˚00'03"	118˚13'12"	391,445	4,095,460	92	25	20	—	—	—	—	—
421T	37˚00'33"	118˚13'49"	390,543	4,096,396	90	24	21	—	—	—	—	Deepened to 65 ft in 1977.
422T	37˚05'40"	118˚14'43"	389,332	4,105,874	74	26	20	—	—	—	—	—
423T	37˚05'26"	118˚14'26"	389,746	4,105,437	75	27	21	—	—	—	—	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmissivity (ft^2/d)	Average horizontal hydraulic conductivity (ft/d)	Storage coefficient	Aquifer test method	Comments
			East	North	Row	Column						
424T	37°05'17"	118°14'09"	390,162	4,105,155	76	27	20	—	—	—	—	—
425T	37°06'32"	118°14'55"	389,057	4,107,481	72	27	21	—	—	—	—	Deepened to 42 ft in 1977.
426T	37°06'51"	118°14'34"	389,583	4,108,059	71	28	21	—	—	—	—	—
427T	37°07'11"	118°14'12"	390,134	4,108,669	70	29	21	—	—	—	—	—
428T	37°10'16"	118°16'03"	387,471	4,114,406	60	28	21	—	—	—	—	Deepened to 41 ft in 1977.
429T	37°10'20"	118°15'44"	387,941	4,114,523	60	28	21	—	—	—	—	—
430T	37°20'08"	118°23'29"	376,740	4,132,804	26	20	22	—	—	—	—	Deepened to 42 ft in 1977.
431T	37°20'14"	118°24'00"	375,979	4,133,000	25	18	21	—	—	—	—	Deepened to 26 ft in 1977.
431AT	37°20'14"	118°24'00"	375,979	4,133,000	25	18	—	—	—	—	—	—
432T	37°21'46"	118°22'58"	377,547	4,135,813	22	22	21	—	—	—	—	—
433T	37°23'50"	118°21'17"	380,086	4,139,599	17	28	21	—	—	—	—	—
433AT	37°23'50"	118°21'17"	380,086	4,139,599	17	28	—	—	—	—	—	—
434T	37°23'52"	118°21'07"	380,333	4,139,657	17	28	21	—	—	—	—	—
435T	37°25'03"	118°21'36"	379,651	4,141,855	13	28	21	—	—	—	—	Deepened to 54 ft in 1977.
436T	37°24'56"	118°21'38"	379,599	4,141,640	14	28	21	—	—	—	—	—
437T	37°24'47"	118°21'41"	379,521	4,141,364	14	28	21	—	—	—	—	Deepened to 53 ft in 1978.
438T	37°25'12"	118°23'19"	377,124	4,142,169	12	25	21	—	—	—	—	—
439T	37°25'08"	118°23'37"	376,679	4,142,053	12	24	10	—	—	—	—	—
440T	36°46'59"	118°08'43"	397,804	4,071,218	133	23	21	—	—	—	—	—
441T	36°46'14"	118°08'30"	398,110	4,069,828	135	23	21	—	—	—	—	—
442T	36°44'23"	118°06'41"	400,773	4,066,376	142	25	21	—	—	—	—	Deepened to 42 ft in 1977.
443T	36°44'23"	118°07'48"	399,111	4,066,395	141	23	21	—	—	—	—	—
444T	36°42'32"	118°06'08"	401,552	4,062,946	148	25	21	—	—	—	—	—
445T	36°40'38"	118°05'36"	402,306	4,059,424	153	25	21	—	—	—	—	—
446T	36°39'01"	118°04'51"	403,389	4,056,422	159	25	21	—	—	—	—	—
447T	36°47'04"	118°09'48"	396,195	4,071,392	132	21	21	—	—	—	—	Deepened to 63 ft in 1977.
448T	36°47'51"	118°07'57"	398,964	4,072,807	131	26	21	—	—	—	—	—
449T	36°45'55"	118°07'26"	399,690	4,069,224	137	25	20	—	—	—	—	Deepened to 42 ft in 1977.
450T	36°49'38"	118°08'58"	397,492	4,076,122	125	25	21	—	—	—	—	—
451T	36°49'21"	118°09'34"	396,593	4,075,609	125	23	20	—	—	—	—	—
452T	36°49'53"	118°12'19"	392,518	4,076,646	122	17	21	—	—	—	—	—
453T	36°50'56"	118°12'27"	392,344	4,078,590	119	18	21	—	—	—	—	—
454T	36°53'58"	118°14'04"	390,014	4,084,229	109	17	21	—	—	—	—	—
455T	36°57'16"	118°12'53"	391,849	4,090,308	100	23	21	—	—	—	—	—
456T	36°57'36"	118°12'03"	393,094	4,090,908	100	25	21	—	—	—	—	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmis-sivity (ft^2/d)	Average hori-zontal hydraulic conduc-tivity (ft/d)	Storage coefficient	Aqui-fer test meth-od	Comments
			East	North	Row	Col-umn						
457T	36°56'17"	118°11'37"	393,706	4,088,466	104	25	21	—	—	—	—	Deepened to 32 ft in 1977.
458T	36°54'57"	118°11'46"	393,453	4,086,003	107	23	20	—	—	—	—	—
459T	36°53'15"	118°12'03"	392,993	4,082,866	112	21	21	—	—	—	—	—
460T	36°53'19"	118°12'57"	391,657	4,083,006	111	19	21	—	—	—	—	Deepened to 42 ft in 1977.
461T	36°52'35"	118°12'20"	392,556	4,081,638	114	20	21	—	—	—	—	—
462T	36°53'05"	118°11'12"	394,251	4,082,542	113	23	21	—	—	—	—	—
463T	36°53'04"	118°10'14"	395,687	4,082,493	114	25	21	—	—	—	—	—
464T	36°51'50"	118°10'13"	395,683	4,080,212	118	24	20	—	—	—	—	—
465T	36°51'29"	118°11'11"	394,239	4,079,583	118	21	20	—	—	—	—	—
466T	36°53'54"	118°10'45"	394,938	4,084,043	111	25	21	—	—	—	—	Deepened to 42 ft in 1977.
467T	36°56'05"	118°10'51"	394,840	4,088,082	105	27	21	—	—	—	—	Deepened to 42 ft in 1977.
468T	37°07'29"	118°14'18"	389,993	4,109,225	69	29	21	—	—	—	—	—
469T	37°09'39"	118°15'49"	387,801	4,113,261	62	28	21	—	—	—	—	Deepened to 42 ft in 1977.
470T	37°11'09"	118°18'11"	384,336	4,116,082	56	23	21	—	—	—	—	—
471T	37°24'37"	118°21'55"	379,173	4,141,061	14	27	21	—	—	—	—	—
472T	37°12'16"	118°18'34"	383,798	4,118,155	52	24	21	—	—	—	—	—
473T	37°12'51"	118°17'39"	385,168	4,119,215	51	26	21	—	—	—	—	—
474T	37°13'41"	118°18'05"	384,549	4,120,764	49	26	21	—	—	—	—	—
475T	37°13'01"	118°19'11"	382,905	4,119,554	50	23	21	—	—	—	—	Deepened to 42 ft in 1977.
476T	37°13'46"	118°20'36"	380,830	4,120,970	47	20	21	—	—	—	—	—
477T	37°12'15"	118°20'17"	381,258	4,118,159	51	20	21	—	—	—	—	—
478T	37°14'32"	118°20'00"	381,737	4,122,375	45	22	20	—	—	—	—	—
479T	37°15'12"	118°18'59"	383,257	4,123,587	44	25	20	—	—	—	—	—
480T	37°16'56"	118°20'09"	381,578	4,126,816	38	24	21	—	—	—	—	—
481T	37°18'24"	118°19'51"	382,059	4,129,522	34	26	21	—	—	—	—	—
482T	37°16'27"	118°21'47"	379,151	4,125,957	38	20	21	—	—	—	—	—
483T	37°18'23"	118°22'46"	377,750	4,129,553	32	20	21	—	—	—	—	Deepened to 42 ft in 1977.
484T	37°19'33"	118°21'55"	379,037	4,131,692	29	23	21	—	—	—	—	—
485T	37°19'33"	118°20'51"	380,612	4,131,669	30	25	21	—	—	—	—	—
486T	37°16'56"	118°18'33"	383,942	4,126,783	39	28	21	—	—	—	—	—
487T	37°18'02"	118°18'14"	384,438	4,128,811	36	30	21	—	—	—	—	—
488T	37°19'58"	118°18'36"	383,946	4,132,393	30	31	21	—	—	—	—	Deepened to 42 ft in 1977.
489T	37°21'43"	118°19'45"	382,293	4,135,653	24	30	21	—	—	—	—	—
490T	37°22'54"	118°19'45"	382,324	4,137,841	21	31	21	—	—	—	—	Deepened to 42 ft in 1977.

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmis-sivity (ft^2/d)	Average hori-zontal hydraulic conduc-tivity (ft/d)	Storage coefficient	Aqui-fer test meth-od	Comments
			East	North	Row	Col-umn						
491T	37°23'20"	118°19'18"	382,999	4,138,633	20	32	21	—	—	—	—	Deepened to 53 ft in 1977.
492T	37°24'48"	118°20'32"	381,218	4,141,370	15	31	21	—	—	—	—	Deepened to 63 ft in 1977.
493T	37°25'43"	118°20'30"	381,291	4,143,065	12	32	21	—	—	—	—	Deepened to 64 ft in 1977.
494T	37°26'07"	118°20'58"	380,614	4,143,814	11	31	21	—	—	—	—	—
495T	37°25'49"	118°22'07"	378,910	4,143,284	11	28	21	—	—	—	—	—
496T	37°23'51"	118°20'50"	380,750	4,139,620	17	29	21	—	—	—	—	Deepened to 42 ft in 1977.
497T	37°23'54"	118°22'15"	378,662	4,139,743	16	26	21	—	—	—	—	Deepened to 31 ft in 1977.
498T	37°23'53"	118°23'25"	376,940	4,139,737	15	23	21	—	—	—	—	—
499T	37°20'47"	118°22'00"	378,947	4,133,974	25	24	21	—	—	—	—	—
500T	37°20'51"	118°20'28"	381,213	4,134,065	26	27	20	—	—	—	—	Deepened to 43 ft in 1977.
501T	37°22'11"	118°21'56"	379,083	4,136,562	21	25	21	—	—	—	—	Deepened to 42 ft in 1977.
502T	37°01'45"	118°13'11"	391,510	4,098,603	87	26	18	—	—	—	—	—
503T	37°24'07"	118°21'06"	380,364	4,140,119	16	29	52	—	—	—	—	—
504T	36°58'53"	118°13'29"	390,997	4,093,308	95	23	35	—	—	—	—	—
505T	36°57'30"	118°14'00"	390,198	4,090,760	98	21	53	—	—	—	—	—
506T	36°56'17"	118°13'59"	390,194	4,088,511	102	19	42	—	—	—	—	—
507T	36°55'08"	118°12'57"	391,700	4,086,365	106	21	52	—	—	—	—	—
508T	36°51'28"	118°10'02"	395,947	4,079,531	119	24	21	—	—	—	—	—
509T	36°47'54"	118°09'29"	396,685	4,072,927	130	22	31	—	—	—	—	—
510T	36°44'35"	118°08'16"	398,421	4,066,773	140	22	55	—	—	—	—	—
511T	36°46'35"	118°09'16"	396,978	4,070,489	134	21	42	—	—	—	—	—
512T	37°23'39"	118°29'45"	367,590	4,139,448	11	8	20	—	—	—	—	—
513T	37°21'44"	118°22'55"	377,620	4,135,751	22	22	19	—	—	—	—	—
514T	37°21'44"	118°22'58"	377,546	4,135,752	22	22	18	—	—	—	—	—
515T	37°21'44"	118°23'01"	377,472	4,135,753	22	22	21	—	—	—	—	—
516T	37°21'44"	118°23'04"	377,398	4,135,754	22	22	21	—	—	—	—	—
517T	37°21'44"	118°23'07"	377,324	4,135,755	22	22	20	—	—	—	—	—
518T	37°16'26"	118°21'41"	379,299	4,125,924	38	20	21	—	—	—	—	—
519T	37°16'27"	118°21'43"	379,250	4,125,955	38	20	21	—	—	—	—	—
520T	37°16'28"	118°21'46"	379,177	4,125,987	38	20	21	—	—	—	—	—
521T	37°16'29"	118°21'48"	379,128	4,126,019	38	20	21	—	—	—	—	—
522T	37°16'30"	118°21'50"	379,079	4,126,050	38	20	21	—	—	—	—	—
546T	36°49'26"	118°11'24"	393,870	4,075,797	124	19	20	—	—	—	—	—
547T	36°47'24"	118°09'54"	396,054	4,072,010	131	21	—	—	—	—	—	—
548T	36°47'57"	118°10'15"	395,546	4,073,033	129	20	—	—	—	—	—	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmis-sivity (ft^2/d)	Average hori-zontal hydraulic conduc-tivity (ft/d)	Storage coefficient	Aqui-fer test meth-od	Comments
			East	North	Row	Col-umn						
549T	36˚48'29"	118˚11'11"	394,170	4,074,036	127	19	—	—	—	—	—	—
550T	36˚48'29"	118˚10'15"	395,558	4,074,019	127	21	—	—	—	—	—	—
551T	36˚48'19"	118˚11'36"	393,547	4,073,736	127	18	—	—	—	—	—	—
552T	36˚48'35"	118˚10'56"	394,544	4,074,217	127	19	—	—	—	—	—	—
553T	36˚48'47"	118˚12'14"	392,616	4,074,611	125	17	—	—	—	—	—	—
554T	36˚49'33"	118˚11'08"	394,269	4,076,008	124	20	—	—	—	—	—	—
555T	36˚48'01"	118˚10'18"	395,473	4,073,157	129	20	—	—	—	—	—	—
556T	36˚47'59"	118˚10'35"	395,051	4,073,101	128	20	—	—	—	—	—	—
557T	36˚48'23"	118˚10'48"	394,738	4,073,844	127	20	—	—	—	—	—	—
558T	36˚48'12"	118˚10'35"	395,056	4,073,501	128	20	—	—	—	—	—	—
559T	36˚45'22"	118˚09'49"	396,132	4,068,249	137	19	—	—	—	—	—	—
560T	36˚45'10"	118˚09'55"	395,979	4,067,881	137	19	—	—	—	—	—	—
561T	36˚45'07"	118˚09'38"	396,399	4,067,783	137	19	—	—	—	—	—	—
562T	36˚44'44"	118˚09'20"	396,837	4,067,069	139	20	—	—	—	—	—	—
563T	36˚36'18"	118˚04'00"	404,600	4,051,385	167	24	—	—	—	—	—	—
564T	36˚36'27"	118˚03'33"	405,273	4,051,655	167	25	—	—	—	—	—	—
565T	37˚04'24"	118˚14'42"	389,326	4,103,532	78	25	—	—	—	—	—	—
566T	37˚06'05"	118˚14'56"	389,021	4,106,649	73	26	—	—	—	—	—	—
567T	37˚07'23"	118˚15'04"	388,856	4,109,055	69	27	—	—	—	—	—	—
568T	37˚07'53"	118˚15'06"	388,818	4,109,980	68	28	—	—	—	—	—	—
569T	37˚08'26"	118˚15'33"	388,166	4,111,006	66	27	—	—	—	—	—	—
570T	37˚08'43"	118˚16'04"	387,408	4,111,540	65	26	—	—	—	—	—	—
571T	37˚09'34"	118˚16'07"	387,355	4,113,113	62	27	—	—	—	—	—	—
572T	37˚10'21"	118˚16'33"	386,733	4,114,570	59	26	—	—	—	—	—	—
573T	37˚23'11"	118˚19'50"	382,208	4,138,366	20	31	—	—	—	—	—	—
574T	37˚23'32"	118˚20'29"	381,259	4,139,027	18	30	—	—	—	—	—	—
575T	37˚24'00"	118˚20'57"	380,582	4,139,900	17	29	—	—	—	—	—	—
576T	37˚25'00"	118˚22'45"	377,954	4,141,787	13	26	—	—	—	—	—	—
577T	37˚25'55"	118˚21'32"	379,773	4,143,456	11	29	—	—	—	—	—	—
578T	37˚26'29"	118˚21'34"	379,739	4,144,505	9	30	—	—	—	—	—	—
579T	37˚27'22"	118˚20'30"	381,335	4,146,116	7	33	—	—	—	—	—	—
580T	37˚24'30"	118˚20'53"	380,694	4,140,823	15	30	—	—	—	—	—	—
581T	36˚53'28"	118˚14'08"	389,903	4,083,306	110	16	—	—	—	—	—	—
582T	36˚54'27"	118˚13'57"	390,199	4,085,120	107	18	—	—	—	—	—	—
583T	36˚55'00"	118˚13'49"	390,410	4,086,135	106	19	—	—	—	—	—	—
584T	36˚55'35"	118˚12'56"	391,736	4,087,196	105	21	—	—	—	—	—	—
585T	36˚57'42"	118˚13'35"	390,821	4,091,122	98	22	—	—	—	—	—	—
586T	36˚58'53"	118˚13'06"	391,566	4,093,301	95	24	—	—	—	—	—	—
587T	37˚02'36"	118˚13'25"	391,185	4,100,179	84	27	—	—	—	—	—	—
588T	36˚35'25"	118˚03'21"	405,551	4,049,742	170	25	—	—	—	—	—	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmissivity (ft²/d)	Average horizontal hydraulic conductivity (ft/d)	Storage coefficient	Aquifer test method	Comments
			East	North	Row	Column						
589T	36˚35'46"	118˚03'55"	404,713	4,050,398	169	24	—	—	—	—	—	—
590T	36˚36'08"	118˚03'33"	405,267	4,051,070	168	25	—	—	—	—	—	—
591T	36˚36'05"	118˚03'40"	405,092	4,050,979	168	25	—	—	—	—	—	—
592T	36˚36'17"	118˚03'15"	405,717	4,051,342	168	26	—	—	—	—	—	—
593T	36˚36'57"	118˚03'30"	405,358	4,052,579	166	26	—	—	—	—	—	—
594T	36˚38'52"	118˚04'55"	403,287	4,056,146	159	24	—	—	—	—	—	—
596T	36˚41'57"	118˚07'41"	399,232	4,061,894	148	21	—	—	—	—	—	—
597T	36˚41'56"	118˚06'59"	400,274	4,061,851	149	22	—	—	—	—	—	—
598T	36˚42'24"	118˚07'51"	398,993	4,062,729	147	21	—	—	—	—	—	—
599T	36˚43'13"	118˚08'18"	398,341	4,064,247	144	21	—	—	—	—	—	—
600T	36˚43'26"	118˚07'21"	399,760	4,064,631	144	23	—	—	—	—	—	—
601T	36˚44'07"	118˚08'24"	398,212	4,065,913	141	21	—	—	—	—	—	—
602T	36˚44'21"	118˚08'37"	397,895	4,066,348	140	21	—	—	—	—	—	—
603T	36˚55'42"	118˚12'40"	392,134	4,087,407	105	22	—	—	—	—	—	—
604T	36˚51'24"	118˚11'05"	394,386	4,079,427	118	22	—	—	—	—	—	—
627T	37˚10'26"	118˚17'12"	385,773	4,114,737	59	25	—	—	—	—	—	—
628T	36˚55'30"	118˚13'29"	390,917	4,087,053	105	20	—	—	—	—	—	—
629T	36˚55'30"	118˚13'29"	390,917	4,087,053	105	20	—	—	—	—	—	—
630T	36˚55'23"	118˚13'27"	390,964	4,086,836	105	20	—	—	—	—	—	—
631T	36˚55'23"	118˚13'27"	390,964	4,086,836	105	20	—	—	—	—	—	—
632T	36˚48'28"	118˚11'40"	393,451	4,074,014	126	18	—	—	—	—	—	—
633T	36˚48'01"	118˚11'27"	393,763	4,073,178	128	18	—	—	—	—	—	—
641T	36˚44'40"	118˚09'23"	396,761	4,066,947	139	19	—	—	—	—	—	—
642T	36˚45'28"	118˚10'05"	395,738	4,068,439	136	19	—	—	—	—	—	—
643T	36˚46'00"	118˚10'26"	395,229	4,069,431	134	18	—	—	—	—	—	—
644T	36˚45'45"	118˚09'51"	396,091	4,068,958	135	19	—	—	—	—	—	—
645T	36˚46'31"	118˚09'54"	396,034	4,070,377	133	20	—	—	—	—	—	—
646T	36˚46'28"	118˚09'33"	396,554	4,070,278	134	21	—	—	—	—	—	—
647T	36˚45'44"	118˚09'15"	396,983	4,068,917	136	21	—	—	—	—	—	—
648T	36˚46'48"	118˚09'47"	396,214	4,070,898	133	20	—	—	—	—	—	—
649T	36˚46'51"	118˚09'27"	396,711	4,070,985	133	21	—	—	—	—	—	—
650T	36˚47'57"	118˚11'23"	393,861	4,073,054	128	18	—	—	—	—	—	—
651T	36˚48'27"	118˚11'48"	393,253	4,073,986	126	17	—	—	—	—	—	—
652T	36˚41'50"	118˚07'22"	399,701	4,061,673	149	21	—	—	—	—	—	—
653T	36˚41'54"	118˚07'47"	399,082	4,061,803	148	21	—	—	—	—	—	—
654T	36˚42'20"	118˚08'01"	398,744	4,062,609	147	20	—	—	—	—	—	—
655T	36˚52'41"	118˚13'59"	390,108	4,081,854	112	16	—	—	—	—	—	—
656T	36˚52'56"	118˚14'03"	390,014	4,082,318	112	16	—	—	—	—	—	—
658T	36˚53'17"	118˚14'18"	389,652	4,082,970	110	16	—	—	—	—	—	—
659T	36˚53'26"	118˚14'24"	389,507	4,083,249	110	16	—	—	—	—	—	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmissivity (ft^2/d)	Average horizontal hydraulic conductivity (ft/d)	Storage coefficient	Aquifer test method	Comments
			East	North	Row	Column						
660T	36°54'19"	118°14'39"	389,157	4,084,887	107	16	—	—	—	—	—	—
661T	36°54'58"	118°14'57"	388,727	4,086,095	105	16	—	—	—	—	—	—
662T	36°57'08"	118°14'55"	388,829	4,090,100	99	18	—	—	—	—	—	—
663T	36°57'55"	118°14'49"	388,996	4,091,547	97	19	—	—	—	—	—	—
664T	36°58'16"	118°14'38"	389,277	4,092,190	96	20	—	—	—	—	—	—
665T	36°58'10"	118°15'02"	388,681	4,092,013	96	19	—	—	—	—	—	—
666T	36°58'23"	118°15'14"	388,389	4,092,418	95	18	—	—	—	—	—	—
667T	36°58'42"	118°15'05"	388,620	4,093,000	94	19	—	—	—	—	—	—
668T	37°03'11"	118°13'34"	390,976	4,101,260	82	27	—	—	—	—	—	—
669T	37°00'55"	118°13'34"	390,922	4,097,069	89	25	—	—	—	—	—	—
670T	37°00'25"	118°13'40"	390,762	4,096,147	90	24	—	—	—	—	—	—
671T	37°00'15"	118°14'06"	390,115	4,095,847	90	23	—	—	—	—	—	—
672T	36°59'54"	118°14'06"	390,107	4,095,200	91	22	—	—	—	—	—	—
673T	36°55'29"	118°13'32"	390,842	4,087,023	105	20	—	—	—	—	—	—
674T	36°55'23"	118°13'31"	390,865	4,086,838	105	20	—	—	—	—	—	—
675T	36°59'57"	118°15'06"	388,625	4,095,312	91	20	—	—	—	—	—	—
676T	36°52'13"	118°13'28"	390,864	4,080,982	114	17	—	—	—	—	—	—
677T	37°04'37"	118°15'24"	388,294	4,103,946	77	24	—	—	—	—	—	—
678T	37°05'06"	118°15'18"	388,454	4,104,838	76	25	—	—	—	—	—	—
679T	37°05'52"	118°15'19"	388,448	4,106,256	73	25	—	—	—	—	—	—
680T	37°06'20"	118°15'08"	388,731	4,107,115	72	26	—	—	—	—	—	—
681T	37°06'40"	118°15'12"	388,641	4,107,733	71	26	—	—	—	—	—	—
682T	37°07'22"	118°15'42"	387,917	4,109,037	69	26	—	—	—	—	—	—
683T	37°08'01"	118°16'10"	387,242	4,110,248	66	25	—	—	—	—	—	—
684T	37°08'37"	118°16'36"	386,616	4,111,366	64	25	—	—	—	—	—	—
685T	37°09'02"	118°16'31"	386,750	4,112,135	63	25	—	—	—	—	—	—
686T	37°09'17"	118°17'10"	385,794	4,112,610	62	24	—	—	—	—	—	—
687T	37°09'37"	118°16'33"	386,715	4,113,214	62	26	—	—	—	—	—	—
688T	37°10'14"	118°16'51"	386,286	4,114,360	60	26	—	—	—	—	—	—
689T	37°10'30"	118°17'18"	385,627	4,114,862	58	25	—	—	—	—	—	—
690T	37°10'25"	118°17'08"	385,871	4,114,705	59	25	—	—	—	—	—	—
691T	37°09'55"	118°17'11"	385,785	4,113,781	60	25	—	—	—	—	—	—
692T	36°36'07"	118°03'11"	405,813	4,051,033	168	26	—	—	—	—	—	—
693T	36°36'05"	118°03'15"	405,713	4,050,972	168	26	—	—	—	—	—	—
694T	36°36'22"	118°03'49"	404,874	4,051,506	167	25	—	—	—	—	—	—
695T	37°02'30"	118°13'50"	390,565	4,100,002	84	26	—	—	—	—	—	—
696T	37°02'28"	118°13'49"	390,589	4,099,940	84	26	—	—	—	—	—	—
697T	37°02'29"	118°13'47"	390,638	4,099,970	84	26	—	—	—	—	—	—
698T	37°27'04"	118°20'48"	380,885	4,145,567	8	32	—	—	—	—	—	—
699T	37°26'41"	118°20'56"	380,678	4,144,861	9	31	—	—	—	—	—	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmissivity (ft^2/d)	Average horizontal hydraulic conductivity (ft/d)	Storage coefficient	Aquifer test method	Comments
			East	North	Row	Column						
700T	37°26'21"	118°20'23"	381,480	4,144,233	10	32	—	—	—	—	—	—
701T	37°26'07"	118°20'20"	381,548	4,143,801	11	32	—	—	—	—	—	—
702T	37°25'45"	118°21'42"	379,523	4,143,152	11	29	—	—	—	—	—	—
703T	37°25'04"	118°24'07"	375,940	4,141,940	11	23	—	—	—	—	—	—
704T	37°24'59"	118°24'05"	375,987	4,141,786	12	23	—	—	—	—	—	—
705T	37°24'59"	118°21'42"	379,502	4,141,734	13	28	—	—	—	—	—	—
707T	37°23'41"	118°19'51"	382,197	4,139,291	18	31	—	—	—	—	—	—
708T	37°23'25"	118°19'46"	382,313	4,138,796	19	31	—	—	—	—	—	—
709T	37°23'20"	118°19'36"	382,557	4,138,639	20	31	—	—	—	—	—	—
710T	37°23'53"	118°27'22"	371,113	4,139,825	12	14	—	—	—	—	—	—
711T	37°23'51"	118°27'24"	371,062	4,139,764	12	14	—	—	—	—	—	—
712T	37°23'51"	118°27'20"	371,161	4,139,763	12	14	—	—	—	—	—	—
713T	37°13'52"	118°17'03"	386,081	4,121,082	49	29	—	—	—	—	—	—
714T	37°13'52"	118°16'59"	386,180	4,121,081	49	29	—	—	—	—	—	—
715T	37°13'49"	118°17'00"	386,154	4,120,989	49	29	—	—	—	—	—	—
716T	37°09'47"	118°16'36"	386,645	4,113,523	61	26	—	—	—	—	—	—
717T	37°09'48"	118°16'32"	386,744	4,113,553	61	26	—	—	—	—	—	—
718T	37°09'45"	118°16'34"	386,693	4,113,461	61	26	—	—	—	—	—	—
719T	37°07'07"	118°13'05"	391,786	4,108,524	71	32	—	—	—	—	—	—
720T	37°07'08"	118°13'02"	391,860	4,108,554	71	32	—	—	—	—	—	—
721T	37°07'06"	118°13'02"	391,860	4,108,492	71	32	—	—	—	—	—	—
722T	36°44'20"	118°05'42"	402,235	4,066,266	143	28	—	—	—	—	—	—
723T	36°44'18"	118°05'40"	402,284	4,066,204	143	28	—	—	—	—	—	—
724T	36°44'18"	118°05'44"	402,185	4,066,205	143	28	—	—	—	—	—	—
725T	36°32'48"	118°01'28"	408,307	4,044,874	179	27	—	—	—	—	—	—
726T	36°32'46"	118°01'26"	408,356	4,044,811	179	27	—	—	—	—	—	—
727T	36°32'46"	118°01'29"	408,282	4,044,812	179	27	—	—	—	—	—	—
728T	36°52'18"	118°13'31"	390,792	4,081,137	114	17	—	—	—	—	—	—
729T	36°52'11"	118°13'31"	390,789	4,080,921	114	17	—	—	—	—	—	—
736T	37°10'32"	118°17'23"	385,504	4,114,926	58	25	—	—	—	—	—	—
1N	36°36'09"	118°04'08"	404,398	4,051,110	167	24	—	—	—	—	—	—
2N	37°10'32"	118°14'04"	390,412	4,114,860	61	32	—	—	—	—	—	—
3N	37°04'35"	118°15'10"	388,639	4,103,880	77	24	—	—	—	—	—	—
5N	37°09'45"	118°17'54"	384,720	4,113,488	60	23	—	—	—	—	—	—
6N	36°59'50"	118°14'04"	390,155	4,095,076	92	23	—	—	—	—	—	—
7N	36°58'40"	118°15'16"	388,347	4,092,942	94	19	—	—	—	—	—	—
8N	36°59'59"	118°12'29"	392,507	4,095,323	92	26	—	—	—	—	—	—
9N	36°56'46"	118°14'13"	389,859	4,089,409	100	19	—	—	—	—	—	—
11N	37°10'59"	118°15'38"	388,105	4,115,723	58	29	—	—	—	—	—	—
12N	37°03'11"	118°13'42"	390,779	4,101,263	82	26	—	—	—	—	—	—

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmissivity (ft^2/d)	Average horizontal hydraulic conductivity (ft/d)	Storage coefficient	Aquifer test method	Comments
			East	North	Row	Column						
13N	37°10'23"	118°17'39"	385,106	4,114,654	59	24	—	—	—	—	—	—
14N	36°35'19"	118°03'21"	405,549	4,049,557	170	25	—	—	—	—	—	—
15N	36°35'14"	118°03'21"	405,547	4,049,403	171	25	—	—	—	—	—	—
16N	37°22'19"	118°23'30"	376,774	4,136,842	20	22	—	—	—	—	—	—
17N	37°05'02"	118°15'09"	388,675	4,104,712	76	25	—	—	—	—	—	—
18N	36°43'37"	118°08'42"	397,755	4,064,993	143	20	—	—	—	—	—	—
19N	36°36'10"	118°04'08"	404,398	4,051,141	167	24	—	—	—	—	—	—
20N	37°21'36"	118°25'52"	373,262	4,135,569	20	15	—	—	—	—	—	—
22N	37°09'28"	118°17'24"	385,453	4,112,954	61	23	—	—	—	—	—	—
25N	37°09'30"	118°17'03"	385,972	4,113,008	62	25	—	—	—	—	—	—
83-1	37°25'06"	118°21'02"	380,489	4,141,936	14	30	—	—	—	—	—	USGS well.
83-2	37°17'02"	118°20'15"	381,433	4,127,003	37	24	—	—	—	—	—	USGS well.
83-2A	37°17'00"	118°20'11"	381,530	4,126,940	38	24	—	4,700	53	—	DD	USGS well.
83-2K	37°17'00"	118°20'11"	381,530	4,126,940	38	24	—	2,800	68	—	JC	USGS well.
83-3	37°13'40"	118°18'15"	384,302	4,120,737	49	26	—	—	—	—	—	USGS well.
83-4	37°11'24"	118°17'54"	384,762	4,116,538	55	24	—	—	—	—	—	USGS well.
85-5	37°06'48"	118°14'29"	389,705	4,107,965	71	28	—	—	—	—	—	USGS well.
83-6	36°56'23"	118°13'40"	390,666	4,088,689	102	20	—	—	—	—	—	USGS well.
83-7	36°49'07"	118°09'28"	396,737	4,075,176	126	23	—	—	—	—	—	USGS well.
83-7A	36°49'38"	118°09'44"	396,352	4,076,136	124	23	—	—	—	—	—	USGS well.
83-8N	36°48'08"	118°09'11"	397,136	4,073,353	129	23	—	540	12	—	JC	USGS well.
83-8P	36°48'08"	118°09'11"	397,136	4,073,353	129	23	—	900	45	—	JC	USGS well.
83-9	36°47'11"	118°09'40"	396,396	4,071,605	131	21	—	—	—	—	—	USGS well.
83-10	36°47'45"	118°09'00"	397,400.	4,072,641	130	23	—	—	—	—	—	USGS well.
83-11	36°45'28"	118°09'41"	396,333	4,068,431	136	19	—	—	—	—	—	USGS well.
83-12G	37°19'25"	118°21'31"	379,624	4,131,437	30	23	—	2,800	60	—	N	USGS well.
83-12N	37°19'25"	118°21'31"	379,624	4,131,437	30	23	—	1,200	31	—	JC	USGS well.
83-13A	36°47'57"	118°09'33"	396,587	4,073,020	129	22	—	1,200	33	—	JC	USGS well.
83-13G	36°47'57"	118°09'33"	396,587	4,073,020	129	22	—	—	—	—	—	USGS well.
83-14A	37°08'35"	118°15'03"	388,909	4,111,274	66	28	—	9,700	24	—	JC	USGS well.
83-14B	37°08'35"	118°15'03"	388,909	4,111,274	66	28	—	—	—	—	—	USGS well.
83-14C	37°08'35"	118°15'03"	388,909	4,111,274	66	28	—	—	—	—	—	USGS well.
83-15A	36°48'10"	118°10'32"	395,130	4,073,439	128	20	—	—	—	—	—	USGS well.
83-15B	36°48'10"	118°10'32"	395,130	4,073,439	128	20	—	—	—	—	—	USGS well.
83-15C	36°48'10"	118°10'32"	395,130	4,073,439	128	20	—	—	—	—	—	USGS well.
84-16A	37°08'41"	118°14'05"	390,343	4,111,440	66	31	—	6,100	68	—	JC	USGS well.
84-16B	37°08'41"	118°14'05"	390,343	4,111,440	66	31	—	—	—	—	—	USGS well.
84-17A	37°04'47"	118°14'26"	389,731	4,104,236	77	26	—	800	11	—	JC	USGS well.
84-17B	37°04'47"	118°14'26"	389,731	4,104,236	77	26	—	—	—	—	—	USGS well.
84-17C	37°04'47"	118°14'26"	389,731	4,104,236	77	26	—	—	—	—	—	USGS well.

Table 9. Location of wells and values from aquifer tests in the Owens Valley, California—continued

Well number	Latitude (north)	Longitude (west)	Universal Transverse Mercator (UTM) coordinates (m)		Ground-water flow model		Most recent well depth (ft)	Transmis-sivity (ft^2/d)	Average hori-zontal hydraulic conduc-tivity (ft/d)	Storage coefficient	Aqui-fer test meth-od	Comments
			East	North	Row	Col-umn						
84-18A	36˚44'27"	118˚04'44"	403,676	4,066,466	143	30	—	1,000	26	—	JC	USGS well.
84-18B	36˚44'27"	118˚04'44"	403,676	4,066,466	143	30	—	—	—	—	—	USGS well.
84-18C	36˚44'27"	118˚04'44"	403,676	4,066,466	143	30	—	—	—	—	—	USGS well.
84-19A	36˚44'07"	118˚08'55"	397,443	4,065,922	141	20	—	2,600	62	—	JC	USGS well.
84-19B	36˚44'07"	118˚08'55"	397,443	4,065,922	141	20	—	—	—	—	—	USGS well.
84-20A	36˚41'54"	118˚03'39"	405,236	4,061,733	151	30	—	5,000	126	—	JC	USGS well.
84-20B	36˚41'54"	118˚03'39"	405,236	4,061,733	151	30	—	—	—	—	—	USGS well.
84-20C	36˚41'54"	118˚03'39"	405,236	4,061,733	151	30	—	—	—	—	—	USGS well.
BTWN2	37˚21'52"	118˚23'47"	376,344	4,136,016	21	20	—	—	—	—	—	Bishop town well #2.
BTWN4	37˚21'41"	118˚26'23"	372,501	4,135,735	19	14	—	—	—	—	—	Bishop town well #4.
DOW	36˚36'09"	118˚04'10"	404,348	4,051,111	167	24	—	—	—	—	—	Dow well.
LPSTA	36˚37'10"	118˚02'24"	407,002	4,052,962	166	29	—	—	—	—	—	Lone Pine Station well.
MEYER	36˚35'18"	118˚03'22"	405,523	4,049,526	170	25	—	—	—	—	—	Meyer well.
MT.WH	36˚49'53"	118˚14'39"	389,050	4,076,690	120	12	—	—	—	—	—	Mt. Whitney Fish Hatchery well.