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-

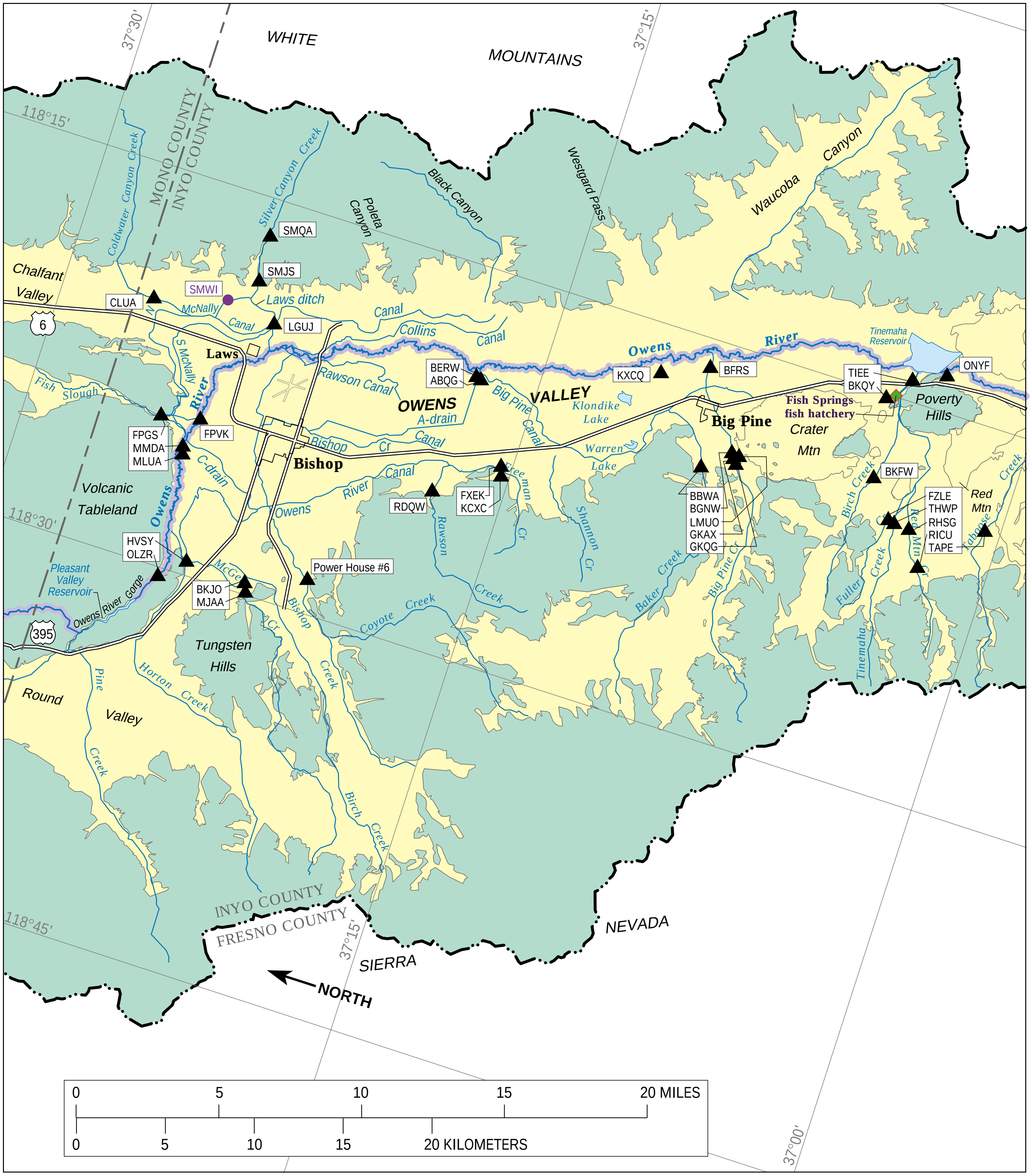


Figure 11. Location of the Owens River–Los Angeles Aqueduct system, the lower Owens River, tributary streams, lakes, reservoirs, spillgates, major gaging stations, and selected pumped wells in the Owens Valley, California.

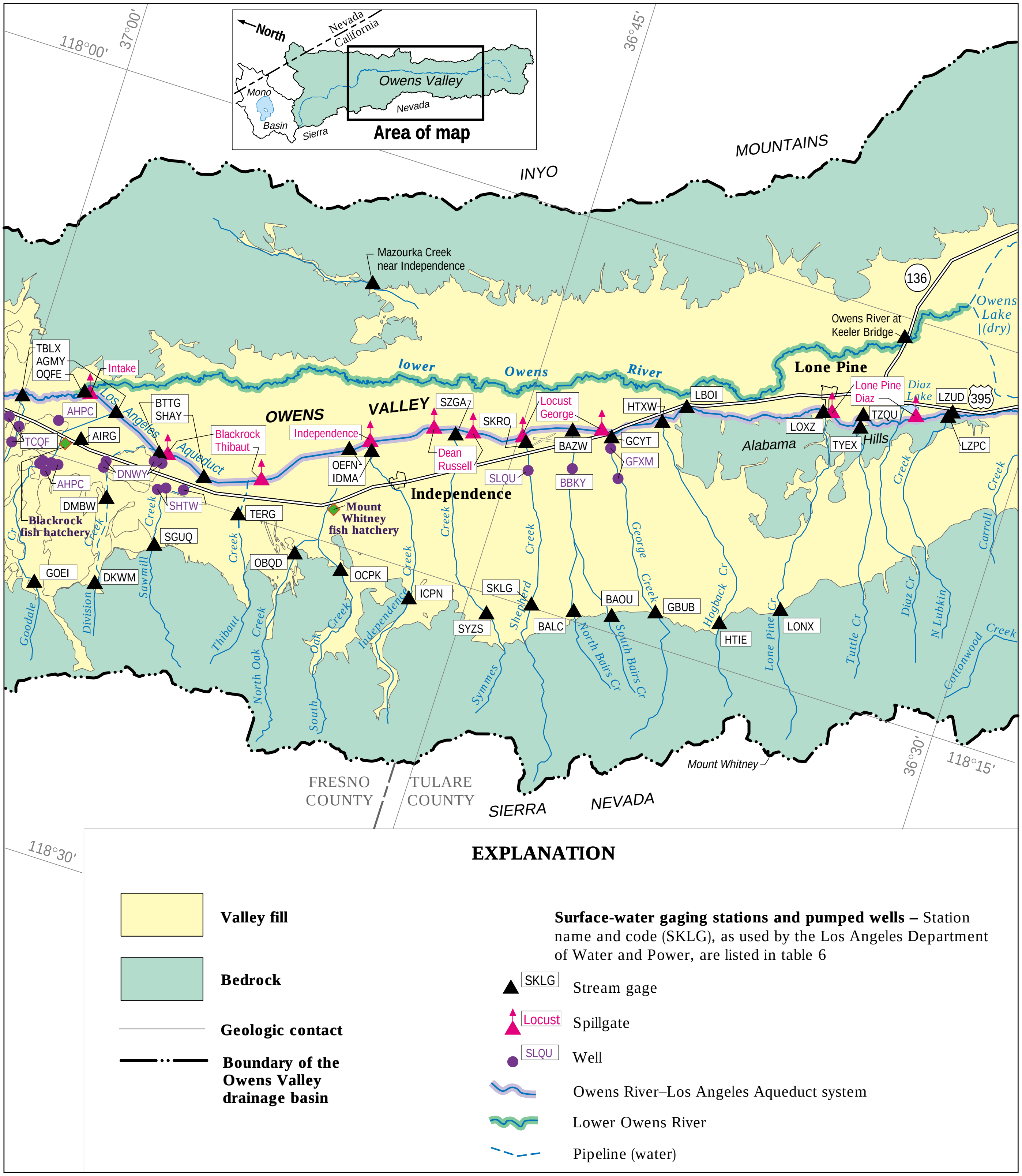


Figure 11. Continued.

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:

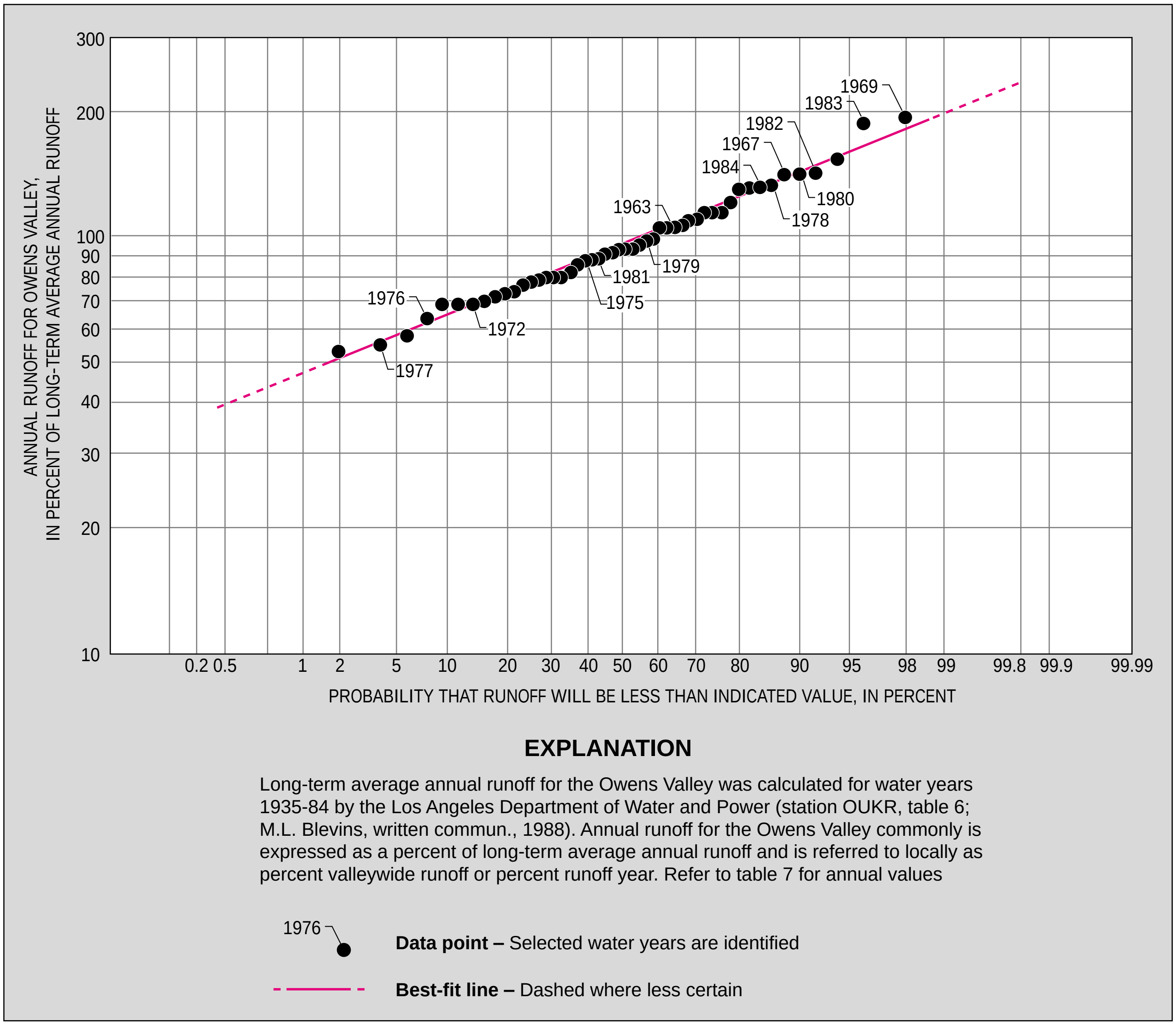


Figure 12. Annual-runoff probability for the Owens Valley, California.

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

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

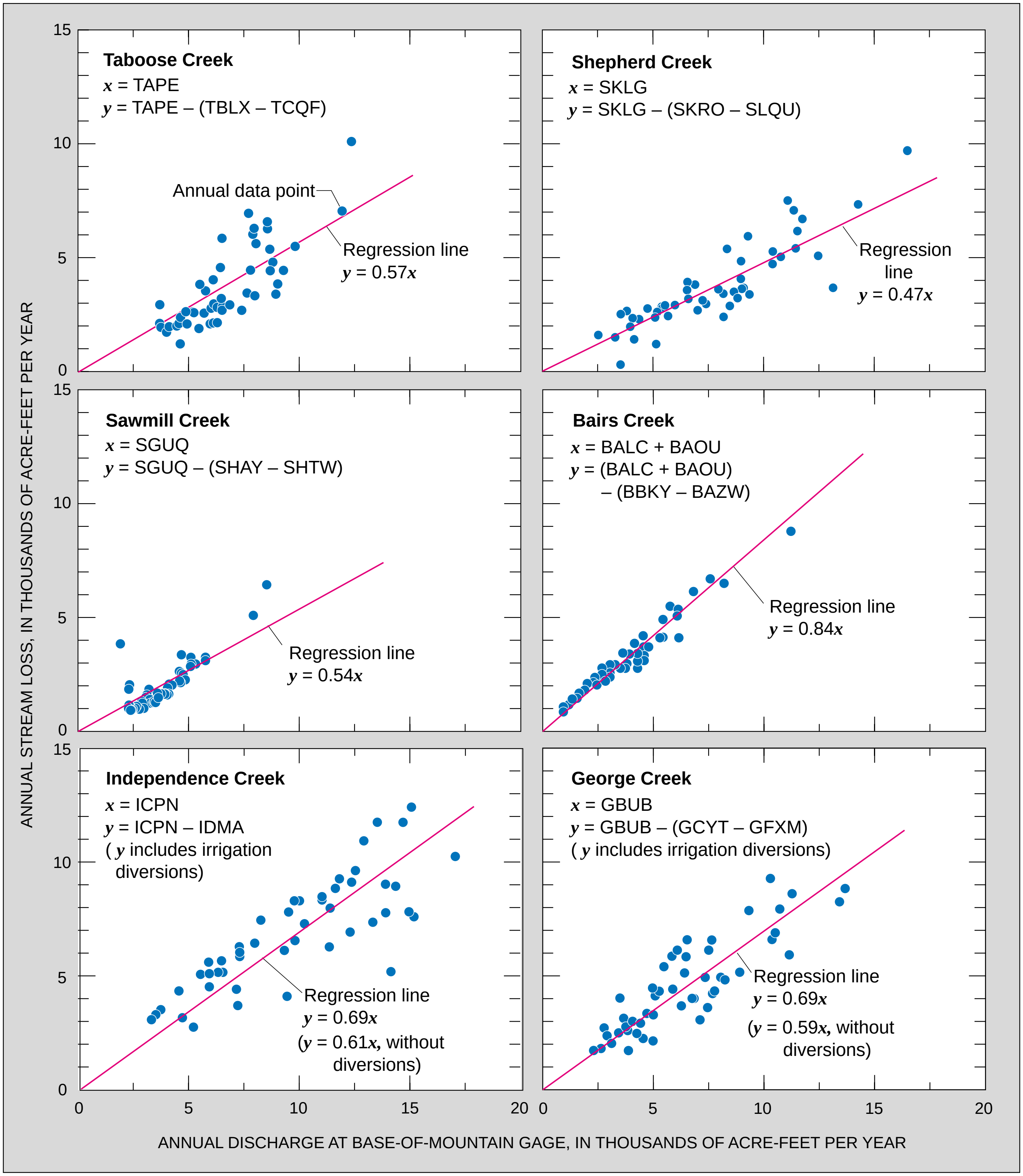


Figure 13. Streamflow relations for selected tributary streams in the Owens Valley, California. Annual data are for water years 1935–84. Station codes, such as TAPE, are shown in figure 11 and described in table 6.

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,

$$R^A_{ij} = R^G_{ij} \left[\frac{SL^A_i}{SL^G_i} \right], \qquad (8a)$$

and

$$R^B_{ij} = R^G_{ij} \left[\frac{SL^B_i}{SL^G_i} \right], \qquad (8b)$$

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 ground-water 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

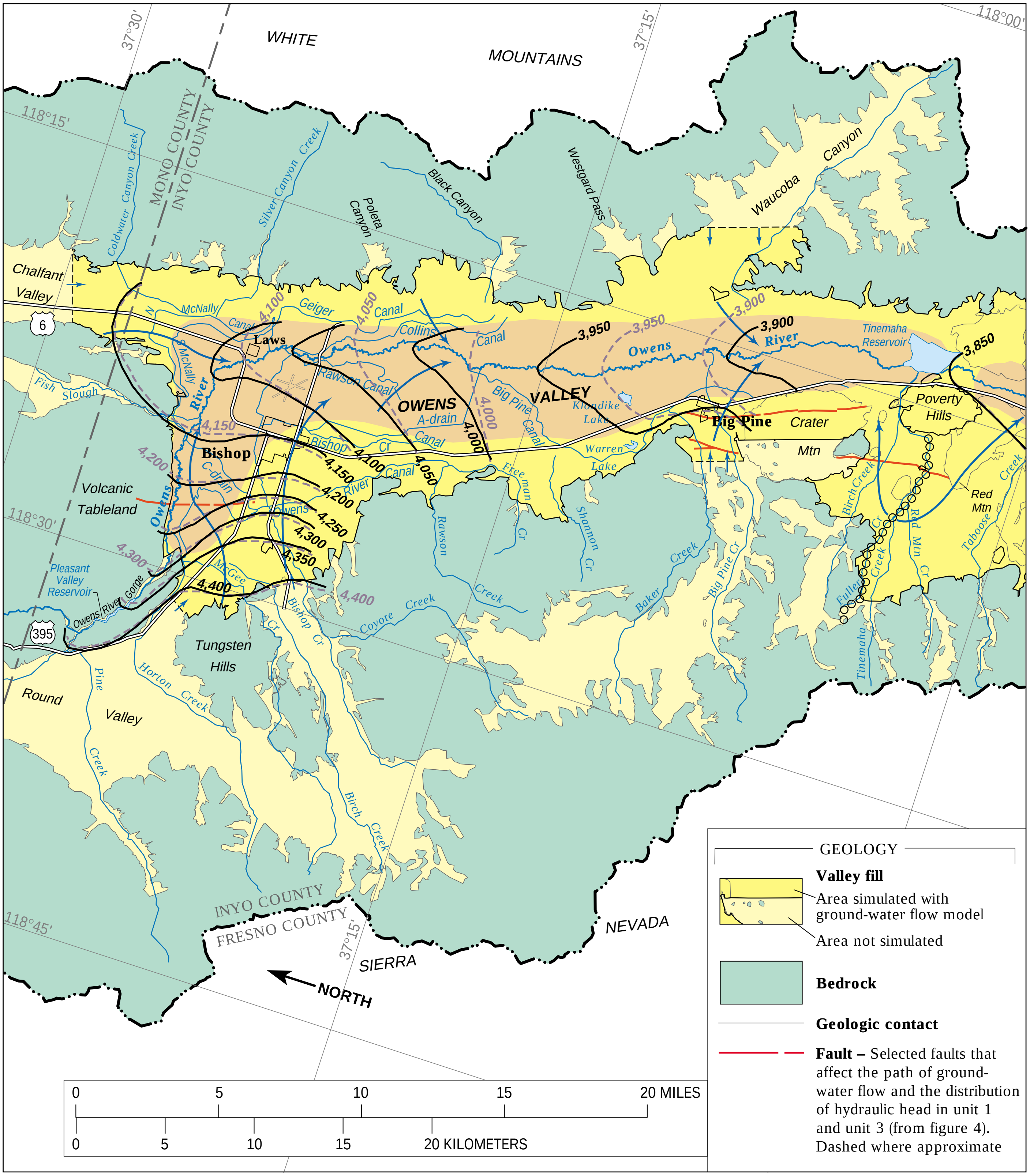
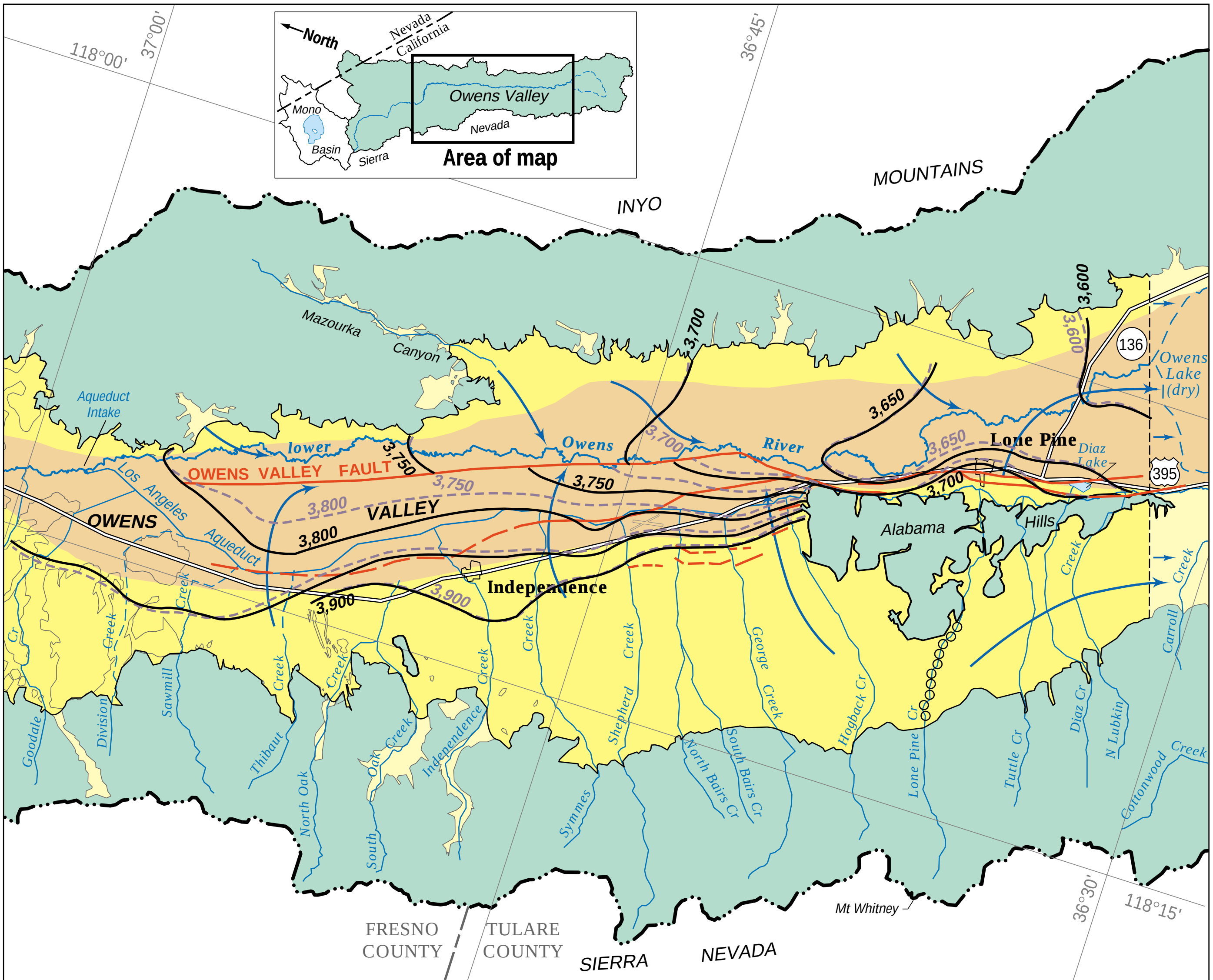


Figure 14. Ground-water conditions in the defined aquifer system of the Owens Valley, California, spring 1984. Shown area areal extent of the defined aquifer system, occurrence of unconfined and confined conditions, boundary conditions, configuration of potentiometric surface in hydrogeologic units 1 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 (symbol: 3,900 solid line)

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 (symbol: 3,900 dashed line)

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

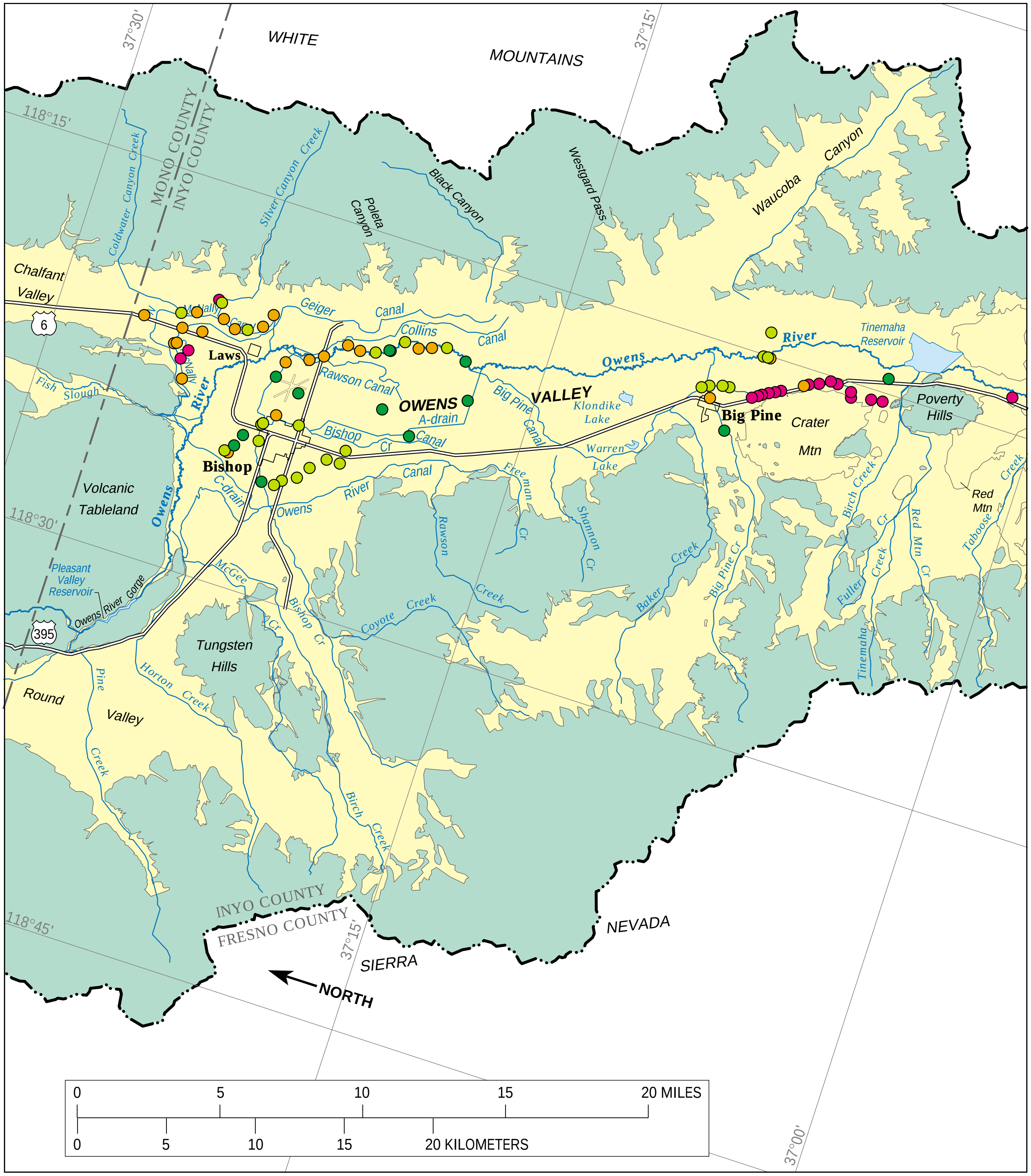


Figure 15. Transmissivity of valley-fill deposits as determined from aquifer tests in the Owens Valley, California.

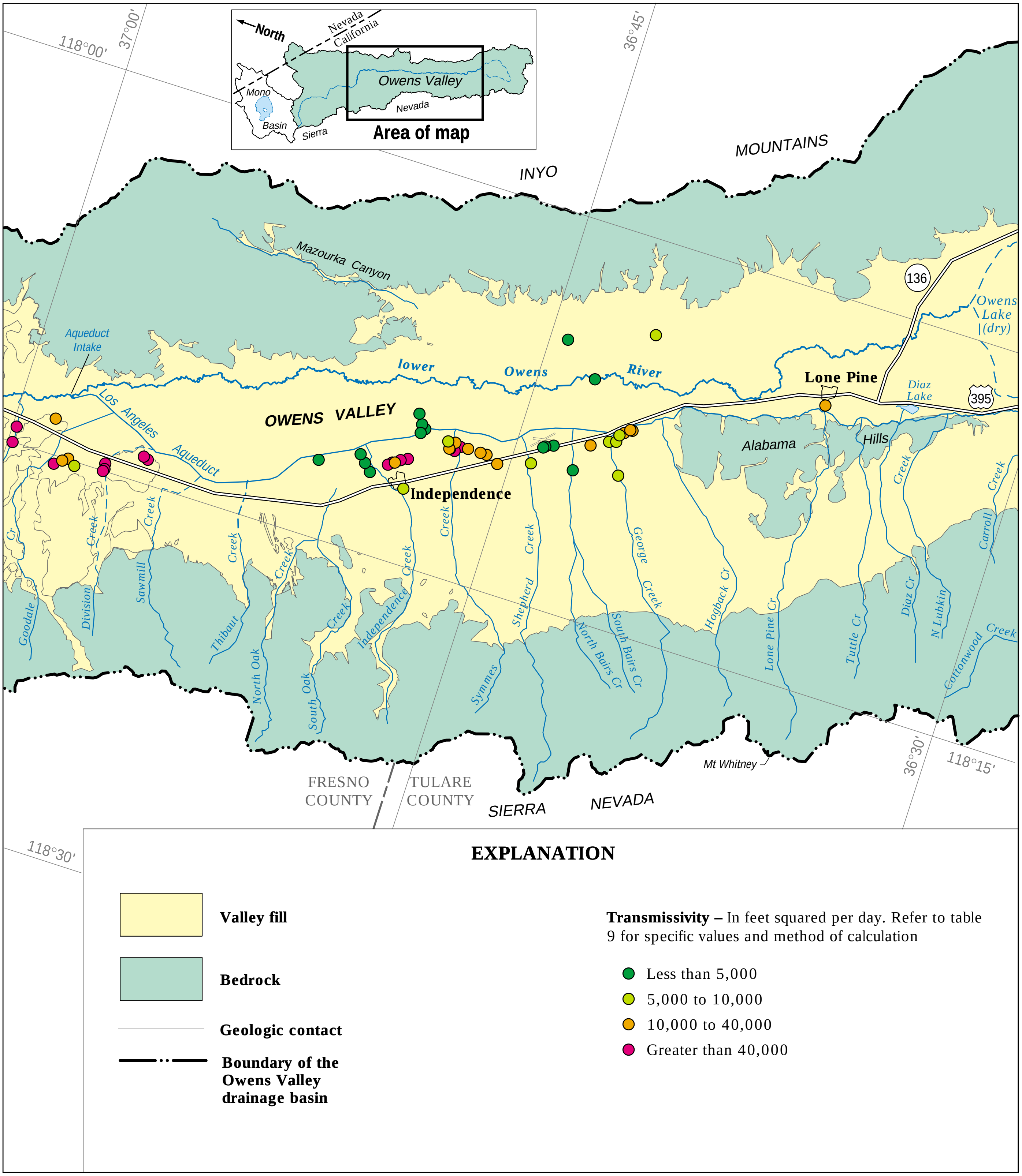


Figure 15. Continued.

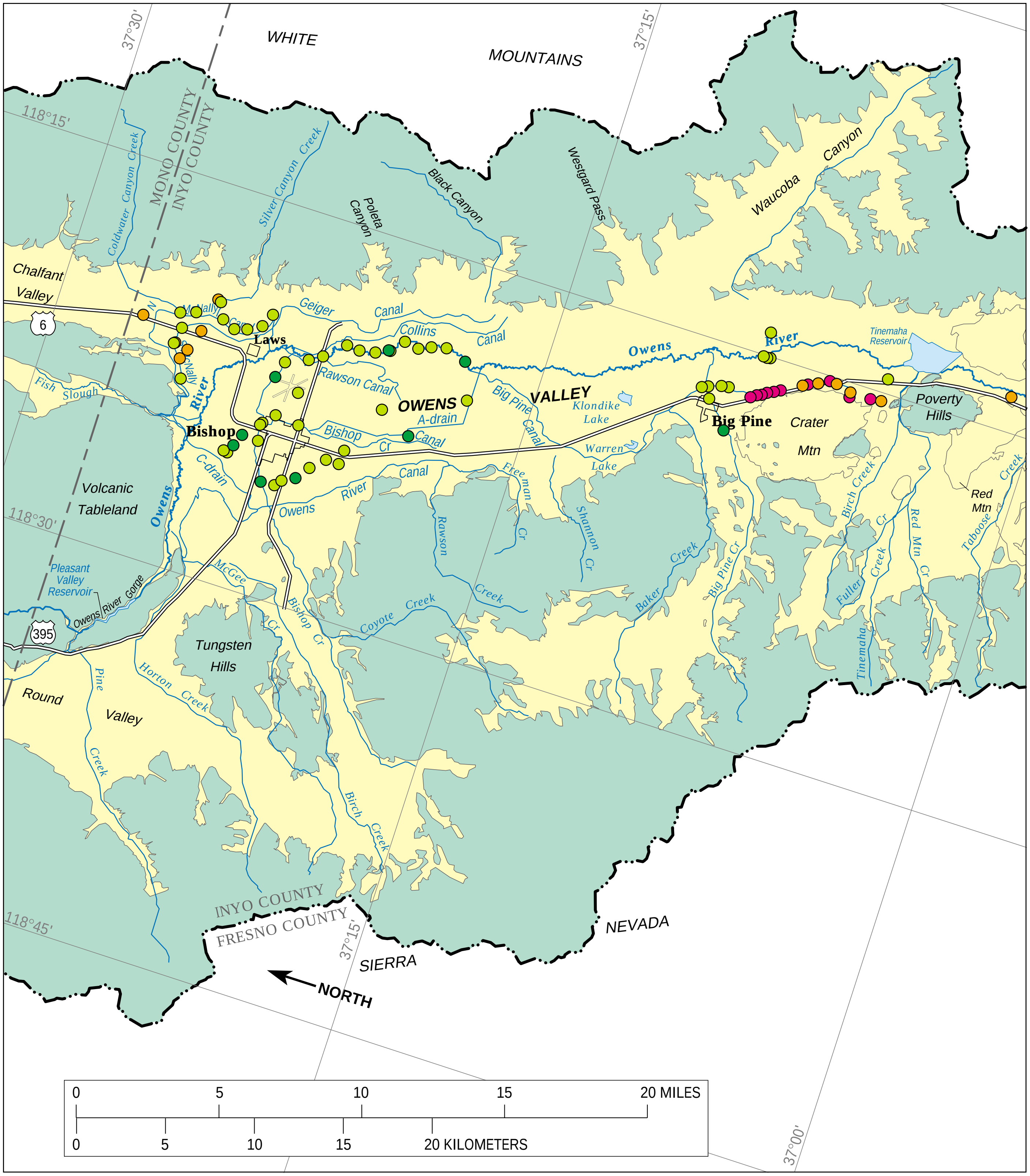


Figure 16. Average horizontal hydraulic conductivity of valley-fill deposits in the Owens Valley, California.

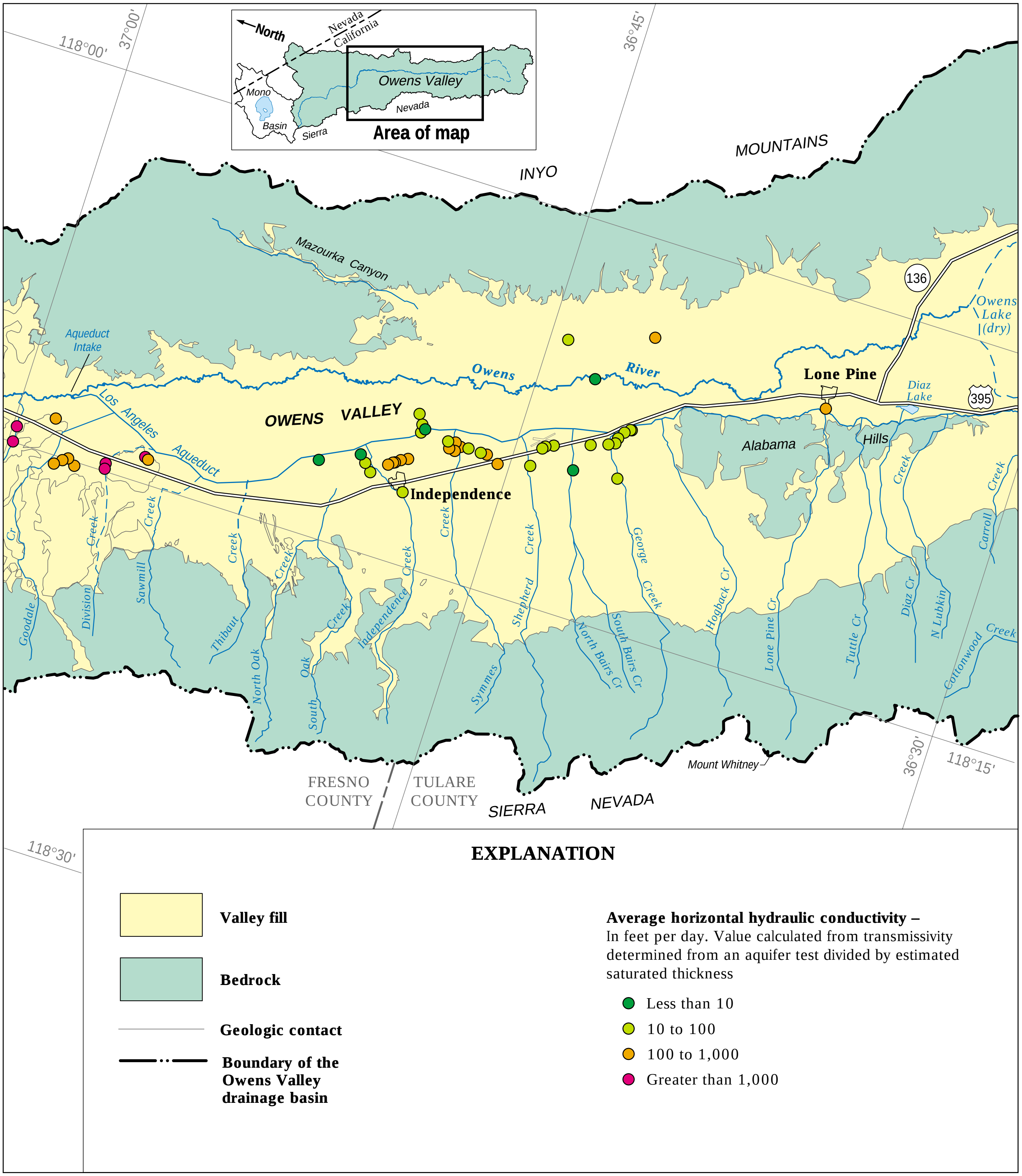


Figure 16. Continued.

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

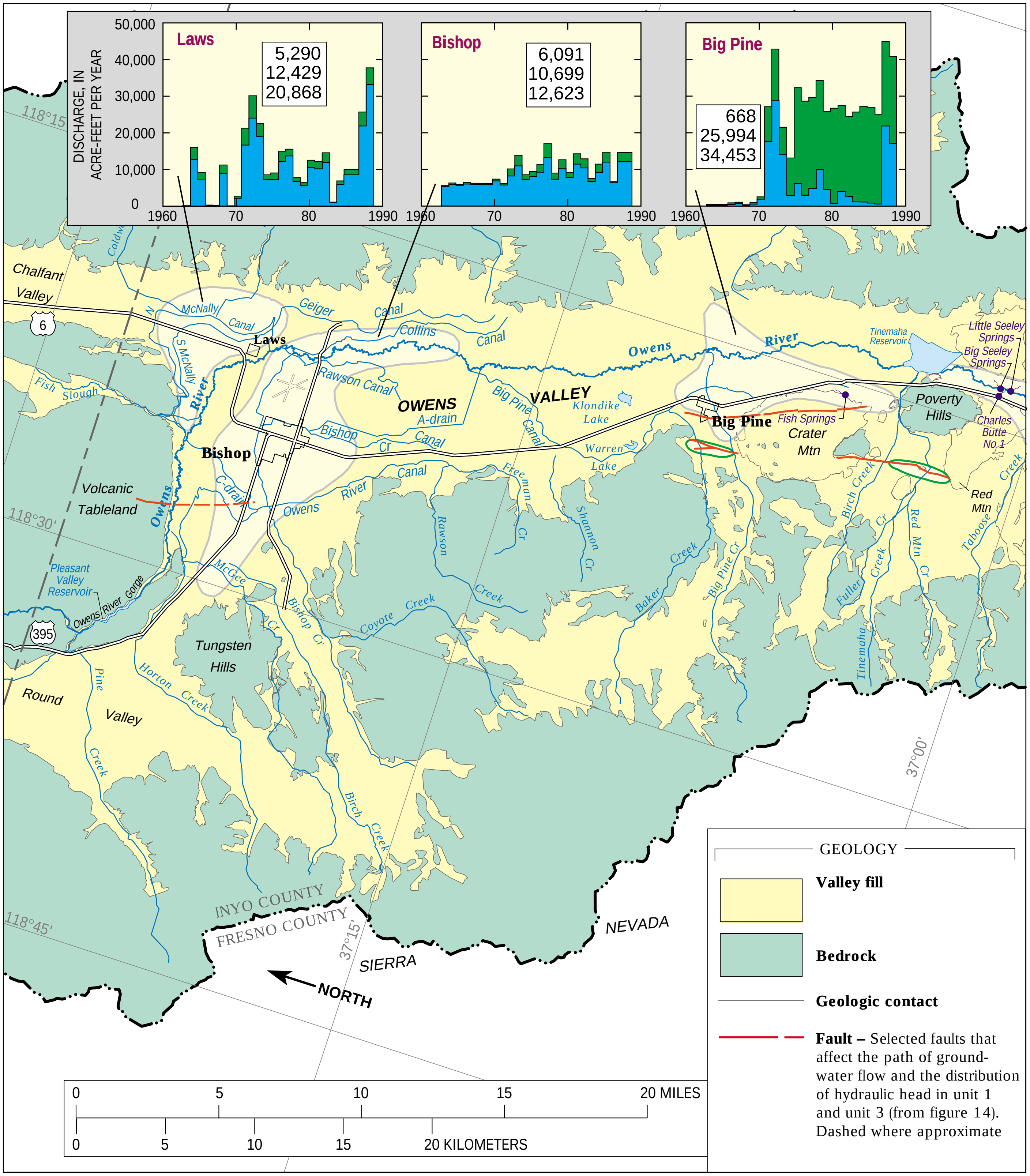


Figure 17. Location of springs, seeps, pumped or flowing wells, and approximate area of well fields in the Owens Valley, California. Inset graphs show annual discharge from each well field for water years 1963–88.

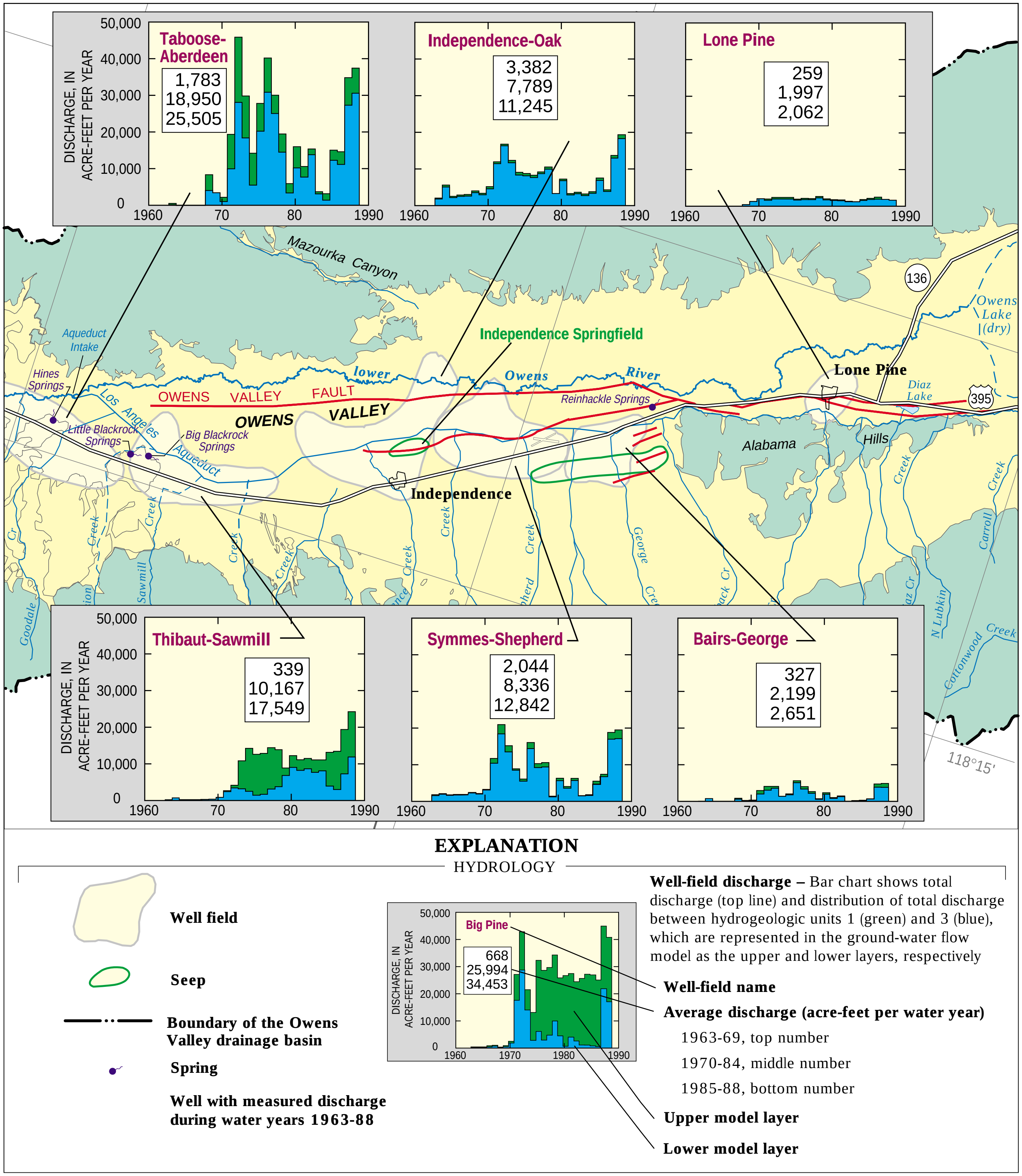


Figure 17. Continued.

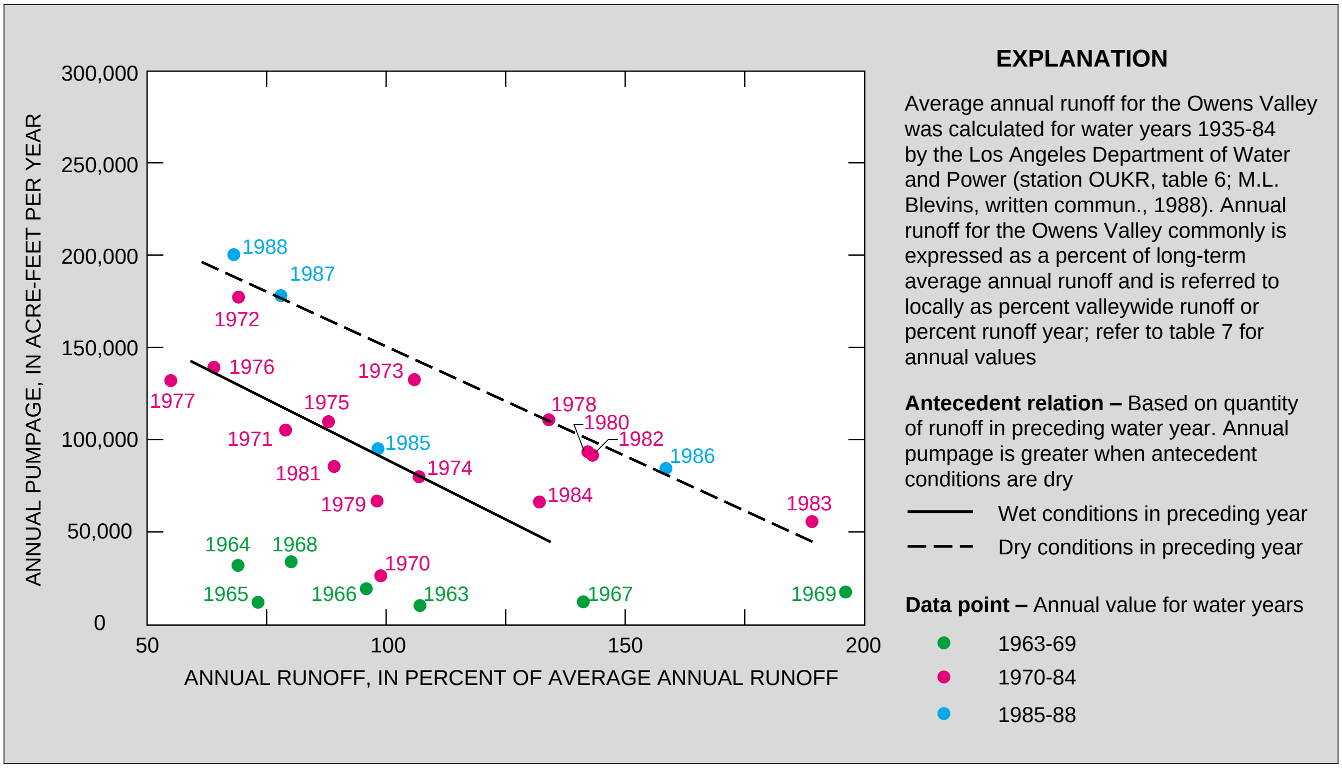


Figure 18. Relation between annual pumpage and annual runoff for the Owens Valley, California.

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