Hydrogeology and Simulated Effects of Urban Development on Water Resources of Spanish Springs Valley, Washoe County, West-Central Nevada

By David L. Berger, Wyn C. Ross, Carl E. Thodal, and Armando R. Robledo

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED UNITS

Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per mile (ft/mi)	0.1894	meter per kilometer
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	25.40	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Temperature: Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = [1.8(°C)]+32. Degrees Fahrenheit can be converted to degrees Celsius by using the formula °C = 0.556(°F-32).

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

Metric water-quality and geophysical units:

g/cm^3 (gram per cubic centimeter)
μm (micrometer)
permil (part per thousand)
pg/L (picogram per liter)
mGal (milliGal)
μS/cm (microsiemens per centimeter at 25° C)
nT (nanotesla)
mg/L (milligram per liter)
mL (milliliter)
pCi/L (picocurie per liter)

Northeastward photographic views of irrigated lands in southern part of Spanish Springs Valley in (***A***) 1967 and (***B***) 1996. Orr Ditch is in foreground. Trailer park seen at left in 1967 view is hidden by trees thirty years later. In 1996, urban development in the form of a subdivision coexists with irrigated lands.

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ABSTRACT

Land-use changes and increased ground-water withdrawals are expected as a result of increased urban development in Spanish Springs Valley, about 5 miles northeast of Reno, Nevada. Currently (1994), imported Truckee River water used for irrigation makes up more than 50 percent of the total source of ground-water recharge to the basin-fill aquifer. The long-term estimate of ground-water recharge from precipitation is about 770 to 830 acre-feet per year. Ground-water withdrawals have increased from about 500 acre-feet in 1979 to nearly 2,600 acre-feet in 1994. An estimated 300,000 to 600,000 acre-feet of recoverable water is stored in the upper 330 feet of saturated basin fill. Augmented yield of the basin-fill aquifer in Spanish Springs Valley, determined for 1994 conditions, was estimated to be about 2,400 acre-feet, including about 1,400 acre-feet of secondary recharge from imported Truckee River water.

Estimates of ground-water recharge and discharge to the basin-fill aquifer were made for 1994 conditions on the basis of field and empirical techniques and evaluated using a mathematical flow model. The flow model constructed during this study was calibrated principally in accordance with the hydrologic data observed and collected during 1979-94 because few predevelopment data were available. An estimated difference between ground-water recharge and discharge of 1,700 to 2,200 acre-feet in 1994 suggest that an imbalance was created by ground-water withdrawals.

The probable response to land-use changes and increased ground-water withdrawals is evaluated by simulating three hypothetical development scenarios. Simulated responses to the scenarios suggest that, although recharge from imported surface water prevented water-level declines in the irrigated area, declines from 20 to 60 feet may be expected throughout much of the modeled area after 20 years of simulated pumping. In model simulations without recharge from imported surface water, 8 percent to nearly 20 percent of the basin-fill aquifer would be dewatered after 20 years of hypothetical ground-water withdrawal, and water levels would decline more than 60 feet in the southeastern part of the valley.

INTRODUCTION

Increasing population in the Reno-Sparks area of west-central Nevada has resulted in urban development in outlying areas. Spanish Springs Valley is undergoing rapid growth because of its proximity to the Reno-Sparks area. To accommodate this additional growth, land-use changes (from agricultural to suburban) and increased ground-water withdrawals are anticipated. For more than a century, flow from the Truckee River has been imported to Spanish Springs Valley by way of the Orr Ditch for agriculture. Transmission losses from the Orr Ditch and infiltration of applied irrigation water are the largest components of ground-water recharge to the basin-fill aquifer in the valley. As ground-water withdrawals increase to support urban development and are accompanied with decreases in agricultural land use, the potential for ground-water overdraft has become a concern. As a result, the U.S. Geological Survey (USGS), in cooperation with the Nevada Division of Water Resources, began a 5-year study in 1992 to improve the understanding of the water resources in Spanish Springs Valley.

Purpose and Scope

The purposes of this report are to describe and analyze the ground-water flow system in Spanish Springs Valley and to evaluate and refine estimates of the water budget and yield of the basin-fill aquifer. The ground-water budget and yield, estimated from field data and empirical techniques, were determined for 1994 hydrologic conditions. The report also discusses the results of a ground-water flow model used to simulate transient-flow conditions for a 16-year period (1979-94) and for several hypothetical development scenarios. The selected scenarios were designed to simulate the removal of imported surface water and projected increases in ground-water withdrawal. In scope, the study includes Spanish Springs Valley and parts of the surrounding mountainous area. Hydrologic data, including water levels, ground-water withdrawals, precipitation, surface-water discharge, and water-chemistry analyses, were considered in this study. Geochemical techniques were used to determine sources and relative ages of ground water. Geophysical methods were used to help define the geologic framework and describe the general character of the hydrogeologic units.

Work began in the spring of 1992. Principal work elements included (1) reviewing published information and compiling well-construction, water-level, and pumpage data; (2) installing and maintaining two surface-water gages; (3) establishing a well-monitoring network; (4) drilling several observation wells; (5) installing nine precipitation stations and constructing an isohyetal map for the study area; (6) collecting ground-water, precipitation, and surface-water samples for chemical analysis; and (7) constructing a ground-water flow model to test and refine the analysis of the ground-water system within the basin fill.

Location and General Features of Study Area

Spanish Springs Valley is a north-trending basin in west-central Nevada, about 5 mi northeast of Reno, and is tributary to the Truckee River (fig. 1). The study area covers 80 mi^2 including the Spanish Springs Valley Hydrographic Area[1] and a 7-mi^2 topographically closed subbasin of the Tracy Segment Hydrographic Area, hereafter called Dry Lakes. The valley floor is 3 to 4 mi wide, 11 mi long, and the altitude ranges from 4,400 ft above sea level in the south to 4,600 ft in the north. The drainage area of the valley floor is about 34 mi^2 including a small internally drained area in the north part of the valley.

Spanish Springs Valley is bounded on the east by the Pah Rah Range, whose highest summit, Spanish Springs Peak, is about 7,400 ft. Hungry Ridge and its unnamed southern extension make up the western boundary, with summits approaching 6,000 ft. The northern boundary separating Spanish Springs Valley from Warm Springs Valley is a narrow (less than 0.5 mi) topographic divide lying between bedrock outcrops of the Hungry Ridge and the Pah Rah Range. The southern boundary is bedrock and includes a low alluvial divide where an irrigation ditch and drain enter and exit the study area.

Agricultural land generally has been restricted to the southern part of the valley that is encompassed by the Orr Extension of the Spanish Springs Valley Ditch, hereafter referred to as the Orr Ditch (fig. 1). Water diverted from the Truckee River for irrigation has been delivered by way of the Orr Ditch since 1878 (Nevada State Journal, 1879). Irrigation return flow in Spanish Springs Valley is collected in the North Truckee Drain and returned to the Truckee River downstream from the City of Sparks. Within the area encompassed by the Orr Ditch are several storage ponds where water from the ditch is impounded. Excluding the North Truckee Drain, no streams within the study area are perennial.

Spanish Springs Valley and Spanish Springs Peak were named by Alces Blum after several springs on the valley floor; the springs were called Spanish Springs by early Mexican shepherds who wintered sheep there (Carlson, 1974, p. 221). A land survey made on June 24, 1872, noted the spring area as being 1 chain long (66 ft) and 50 links wide (33 ft), with numerous other small springs nearby (C.E. Hunter, written commun., 1980). Access to the study area from the Reno-Sparks metropolitan area, hereafter called the Truckee Meadows, is provided by State Route 445 (Pyramid Highway), which passes through the south and north boundaries and continues north to Pyramid Lake.

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[1]Formal hydrographic areas in Nevada were delineated systematically by the U.S. Geological Survey and Nevada Division of Water Resources in the late 1960's for scientific and administrative purposes (Rush, 1968; Cardinalli and others, 1968). The official hydrographic area names, numbers, and geographic boundaries continue to be used in Geological Survey scientific reports and Division of Water Resources administrative activities.

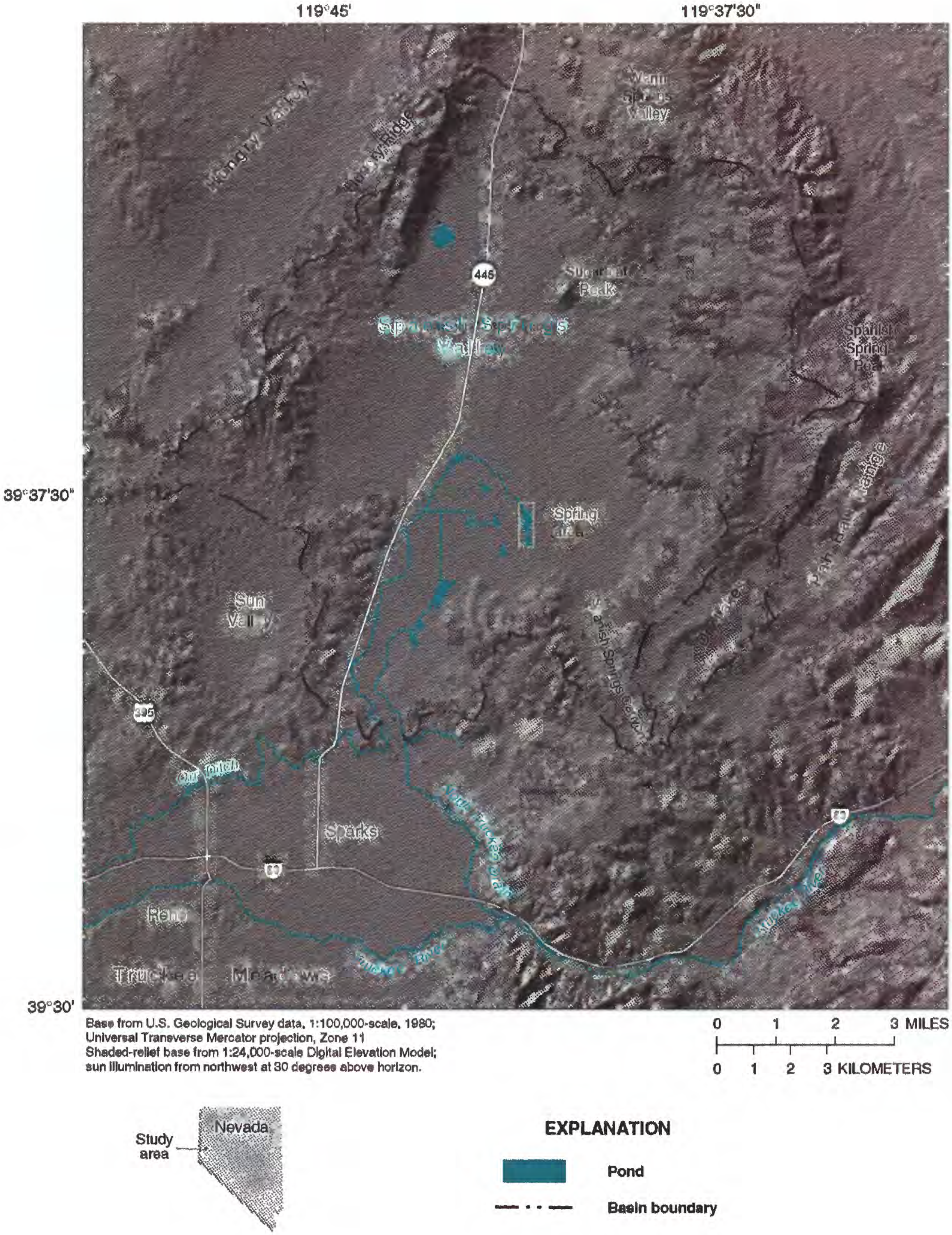


Figure 1. Location and general features of Spanish Springs Valley area, west-central Nevada. Dry Lakes, a subbasin of the Tracy Segment Hydrographic Area, is part of the study area.

Urban Development

Development in Spanish Springs Valley through about 1960 was virtually non-existent, except for homesteads within the southern part of the valley that were, and still are, associated with agriculture. Comparison among aerial photographs taken in 1956, 1977, and 1994, and parcel data, showed that general agricultural land use within the area serviced by the Orr Ditch for the most part has remained unchanged, although some additional acreage has been developed in the southwestern part. Growth and urban development proceeded at a fairly slow pace until the late 1970's when a second mobile home park was established and the first of five subdivisions was started. Population within Spanish Springs Valley has increased sharply from less than 800 in 1979 to more than 4,000 in 1990 (U.S. Bureau of the Census, written commun., 1995). Population in 1994 was projected to be about 9,300 (Washoe County Department of Comprehensive Planning, written commun., 1995). Most subdivisions have been constructed around the northern perimeter of the Orr Ditch, with smaller subdivisions in the southern part of the valley. In contrast, individual home sites are scattered generally in the northern part of the basin, in and adjacent to the surrounding mountains.

As of 1994, more than 3,000 houses associated with subdivisions had water supplied by a public utility; however, nearly 1,000 of these are permitted to receive water from outside the study area (Washoe County Assessors Office, written commun., 1995). Of the houses with public water supply, 1,600 had septic systems and about 1,400 were served by wastewater treatment facilities outside the basin. Nearly 200 houses had domestic wells with septic systems. Land-use summaries as of 1991 (Kennedy/Jenks/Chilton, 1991, table 4-1) indicate that 620 acres within the study area were designated rural, 810 acres were suburban, and more than 1,800 acres were agricultural. (Rural designations are defined as having 1 dwelling unit per 2.5 to 10 acres and suburban designations are defined as having 1 to 7 dwelling units per 1-acre parcel.) More than 46,700 acres were classified as non-designated areas. Comparison of land-use designations for 1979 and 1994 (fig. 2) shows an increase in parceled land with municipal water systems and domestic wells.

Previous Investigations

Many published and unpublished reports have been prepared on the hydrology and geology of the study area and vicinity. Descriptions of several reports pertaining to the hydrogeology of Spanish Springs Valley follow.

The first investigation, which described the general geology and hydrologic properties of the rocks and the occurrence and quality of ground water, was made by Robinson and Phoenix (1948). Wells within the valley were inventoried and chemical analyses of ground-water samples from selected wells were made. In 1964, W.F. Guyton and Associates prepared a report for Sierra Pacific Power Company to determine the feasibility of developing ground water to supply proposed urban development in the northern part of Spanish Springs Valley. This study increased the general knowledge of the distribution and properties of hydrogeologic units in the study area. Rush and Glancy (1967), in appraising water resources of the Warm Springs-Lemmon Valley area, included a reconnaissance of Spanish Springs Valley. They presented a ground-water budget for Spanish Springs Valley under natural conditions and conditions that incorporated the effects of imported surface water. Hadiaris (1988) describes the results of a two-dimensional mathematical model used to simulate steady-state conditions of ground-water flow in Spanish Springs Valley.

U.S. Geological Survey Site Designations

Each U.S. Geological Survey data-collection site is assigned a unique identification on the basis of geographic location. Wells and precipitation and surface-water sites are identified by a local (Nevada) system and a standard latitude-longitude system. For convenience, short site numbers (1 to 89) also are used for sites discussed in this report.

A local site designation is used in Nevada to identify a site by hydrographic area (Rush, 1968) and by the official rectangular subdivision of the public lands referenced to the Mount Diablo base line and meridian. Each site designation consists of four units. The first unit is the hydrographic area number. The second unit is the township, preceded by N to indicate location north of the base line. The third unit is the range, preceded by E to indicate location east of the meridian. The fourth unit consists of the section number and letters designating the quarter section, quarter-quarter section and so on (A, B, C, and D indicate the

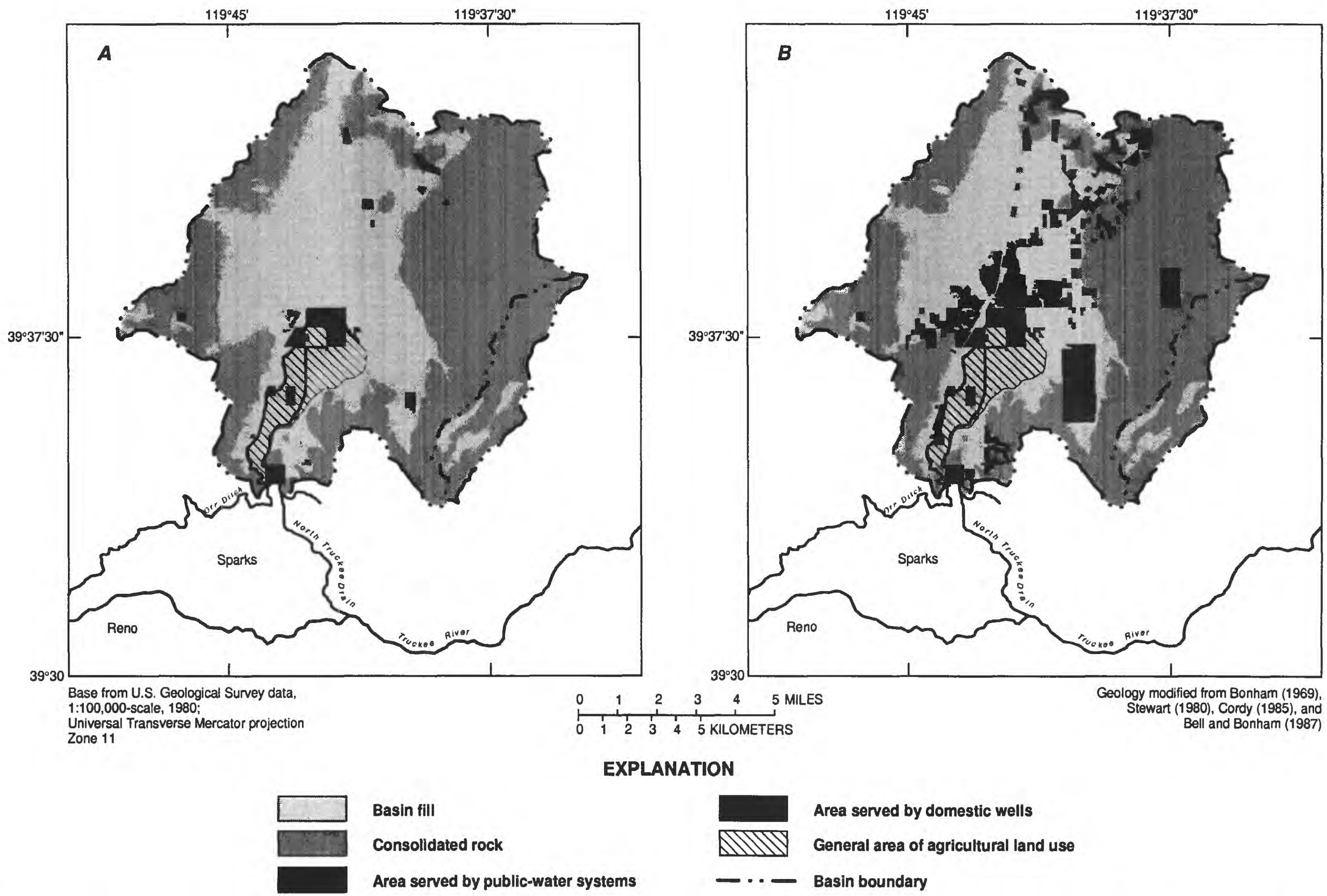


Figure 2. Parceled land with public-water systems and domestic wells and general area of agricultural land use in *(A)* 1979, and *(B)* 1994, Spanish Springs Valley, west-central Nevada. Data from Washoe County Department of Comprehensive Planning (written commun., 1995).

northeast, northwest, southwest, and southeast quarters, respectively), followed by a number indicating the sequence in which the site was recorded. For example, site 85 N21 E20 26CDBD1 is in Spanish Springs Valley (hydrographic area 85). It is the first site recorded in the southeast quarter (D) of the northwest quarter (B) of the southeast quarter (D) of the southwest quarter (C) of section 26, Township 21 North, Range 20 East, Mount Diablo base line and meridian.

The standard site identification is based on the grid system of latitude and longitude. The number consists of 15 digits. The first six digits denote the degrees, minutes, and seconds of latitude; the next seven digits denote the degrees, minutes, and seconds of longitude; and the last two digits (assigned sequentially) identify the sites within a 1-second grid. For example, site 393637119432901 is at 39°36'37" latitude and 119°43'29" longitude, and it is the first site recorded in that 1-second grid. The assigned number is retained as a permanent identifier even if a more precise latitude and longitude are later determined.

Acknowledgments

The authors express their appreciation to residents of Spanish Springs Valley for their cooperation in supplying data and permitting access to their wells. Further gratitude is expressed to the following individuals for allowing the installation of shallow observation wells and collection of geophysical and hydrologic data on their properties: Alan Oppio, David Kiley, Grecian Iratcabal, and the Capurro family. Information on the Orr Ditch was supplied by Matthew Allen of the Orr Ditch Company and by the office of the Federal Water Master. Municipal water-supply data were furnished by Sky Ranch Utilities and by the Washoe County Department of Public Works, Utility Division. The drilling of several observation wells and collection of borehole geophysical logs also were provided by the Washoe County Utility Division. Drillers' logs and water-rights information were obtained from the Nevada Division of Water Resources.

METHODS USED IN THIS STUDY

Several methods of investigation were used during the course of this study to provide information needed to analyze the ground-water flow system and to evaluate the water budget and yield of the basin-fill aquifer. These methods included the collection of hydrologic and geologic data and the application of several geochemical techniques and geophysical methods. Mathematical models that describe the relation between precipitation and altitude and that simulate ground-water flow in three dimensions also were used during this study. General descriptions of the types of data used, collection procedures, and data applications are presented in the following paragraphs.

Collection of Hydrogeologic Data

Basic data collected consist of depth-to-water and precipitation measurements; continuous measurements of surface-water discharge; and water-chemistry analyses of ground-water, precipitation, and surface-water samples. In addition, lithologic information was collected during the installation of observation wells and from geologic mapping in the field. The site number, location, and type of data collected from sites used during this study are listed in table 1. Site numbers and locations are shown in figure 3. Ground-water levels, precipitation, surface-water discharge, and general water-chemistry data collected as part of this study were published by the U.S. Geological Survey in annual water-data reports (Hess and others, 1993, p. 382-383, p. 444-447; Emett and others, 1994, p. 387-390, p. 552-567; Clary and others, 1995, p. 466-467, p. 726-747; Bauer and others, 1996, p. 704-711).

Depth-to-water measurements were made at 77 wells monthly from May 1992 through December 1994 and then quarterly through September 1995 (sites 1-77, table 1). These data were used to determine ground-water flow directions and to characterize the effects of seasonal flows of imported surface water on the shallow ground-water system. Water levels in several wells

EXPLANATION

Basin fill

Consolidated rock

Basin boundary

Sites used in this study—Solid symbol indicates water chemistry (except sites 52, 53, 75). Number corresponds to table 1

○76 Well (sites 1-77; site 77 is east of map area)

⊙75 Well (chemistry only; sites 52, 53, and 75)

◇83 Precipitation station (sites 78-87)

▲88 Surface-water gage site (sites 88 and 89)

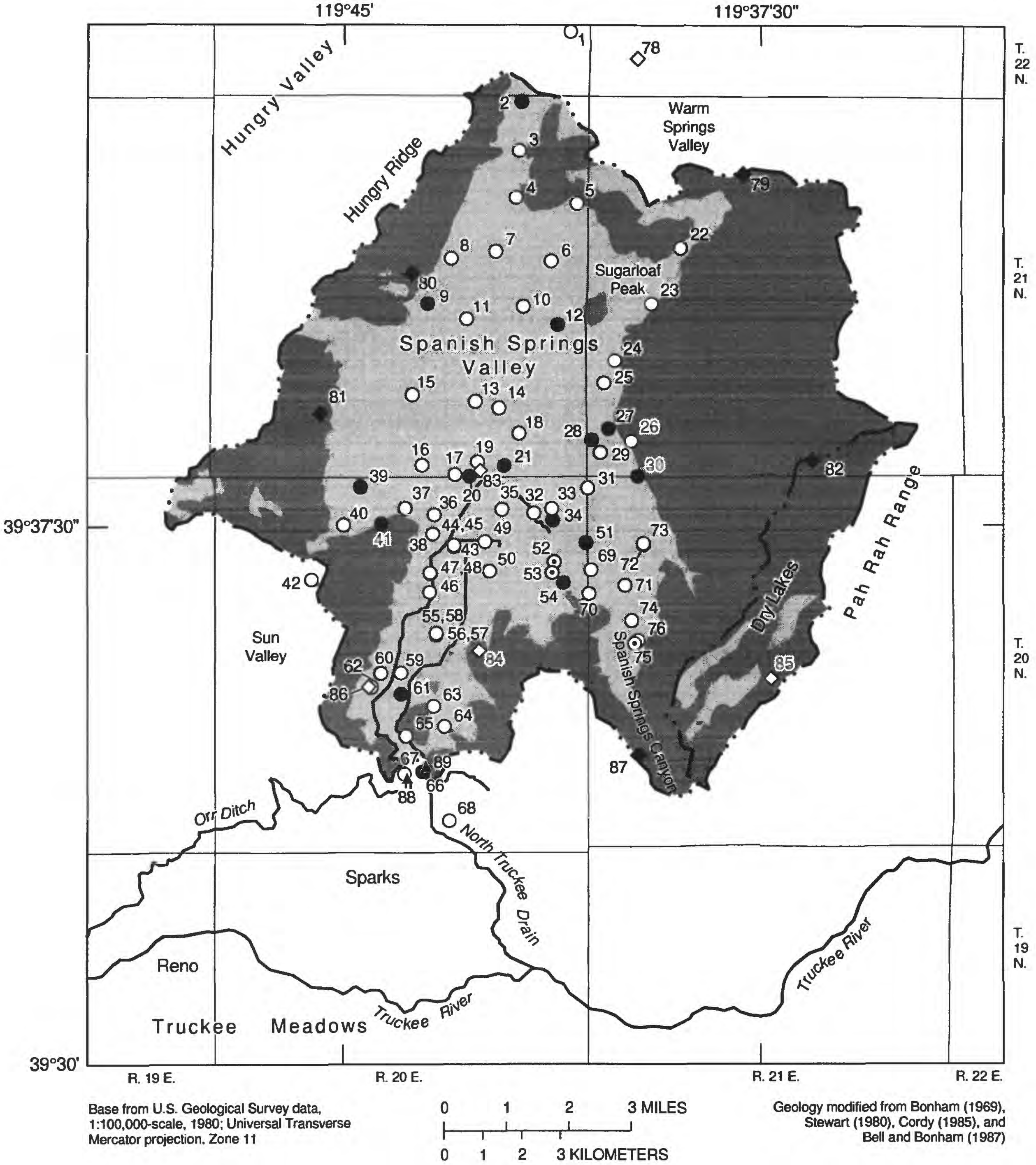


Figure 3. Wells, precipitation stations, surface-water gages, and water-chemistry sampling sites, Spanish Springs Valley, west-central Nevada. Site 77 is not shown because it is outside map area.

Table 1. Site number, location, and type of data available for well, precipitation, and surface-water sites, Spanish Springs Valley area, west-central Nevada

[Available data: GL, geophysical logs; P, precipitation; Q, discharge; QW, water chemistry; WL, ground-water levels. Data from Hess and others (1993), Washoe County (1993), Emett and others (1994), Clary and others (1995), and Bauer and others (1996)]

Site number (fig. 3)	U.S. Geological Survey site designations [1]		Site name	Available data
	Local identification	Standard identification		
		Well sites		
1	84 N22 E20 25DDCA1	394422119404901	Brown, D.	WL
2	85 N21 E20 02AAAC1	394321119415101	O'Hair	WL,QW
3	85 N21 E20 02DDAC1	394240119415001	SSP-9	WL,GL
4	85 N21 E20 11DABA1	394202119415301	SSP-10	WL
5	85 N21 E20 12DACD1	394154119405401	Wardrup	WL
6	85 N21 E20 13CAAC1	394109119411501	SSP-7	WL
7	85 N21 E20 14BDDA1	394117119421501	SSP-8	WL,GL
8	85 N21 E20 15DABB1	394111119430301	Sha-Neva gravel pit	WL
9	85 N21 E20 22BADD1	394035119432901	Airport	WL,QW
10	85 N21 E20 23ADAA1	394032119414601	Donovan No. 1	WL
11	85 N21 E20 23BCCD1	394021119424601	SSP-6	WL,GL
12	85 N21 E20 24BDDA1	394023119412001	Donovan No. 2	WL,QW
13	85 N21 E20 26CDBD1	393917119423601	Alyce Taylor School	WL
14	85 N21 E20 26DCCB2	393858119421301	SS-1a	WL
15	85 N21 E20 27CBDA1	393917119434401	SSP-5	WL,GL
16	85 N21 E20 34CDAD1	393813119425301	Hawco monitoring	WL
17	85 N21 E20 34DDCC1	393812119425701	Washoe Co. Utilities North	WL
18	85 N21 E20 35ADBD1	393847119415101	SS-3	WL
19	85 N21 E20 35CCAD1	393821119423601	Golden West North	WL
20	85 N21 E20 35CCCD1	393812119424401	USGS-Park Observation	WL,QW
21	85 N21 E20 35DCBA1	393819119420501	SS-6	WL,QW
22	85 N21 E21 17CDCC1	394120119385601	Cole	WL
23	85 N21 E21 20BBCB1	394040119392801	Cancilla	WL
24	85 N21 E21 30ABCC1	393944119400701	Armbruster	WL
25	85 N21 E21 30CAAA1	393927119401301	Mack	WL
26	85 N21 E21 31ADCC1	393839119394801	Sanders	WL
27	85 N21 E21 31BABC1	393903119402001	Casale	WL,QW
28	85 N21 E21 31BCBC1	393849119404001	Brown, W.	WL,QW
29	85 N21 E21 31CACA1	393828119401601	May	WL
30	85 N21 E21 31DDCC1	393812119394001	Colby	WL,QW
31	85 N20 E20 01AADD1	393800119403601	Washoe Co. Countryside North	WL
32	85 N20 E20 01CBAB1	393743119413601	Huers	WL
33	85 N20 E20 01DABA1	393743119411501	Hon	WL
34	85 N20 E20 01CACB1	393737119411501	Murray	WL,QW
35	85 N20 E20 02DBBA1	393743119420801	USGS-Oppio Observation	WL
36	85 N20 E20 03ACDC1	393738119432101	Washoe Co. Utilities South	WL
37	85 N20 E20 03BCCC1	393744119435101	Falk	WL
38	85 N20 E20 03CDDC1	393720119432701	Springwood Utilities monitoring	WL
39	85 N20 E20 04BBAD1	393804119443901	Sullivan	WL,QW
40	85 N20 E20 04CCBB1	393737119445201	Grube	WL
41	85 N20 E20 04DBDB1	393735119441701	Pace	WL,QW
42	86 N20 E20 08DBBC1	393643119453401	Kangas	WL
43	85 N20 E20 10AACB1	393713119430001	USGS-Lazy5a Observation	WL,QW
44	85 N20 E20 10AACB2	393713119430002	USGS-Lazy5b Observation	WL
45	85 N20 E20 10AACB3	393713119430003	USGS-Lazy5c Observation	WL
46	85 N20 E20 10CDAB1	393637119432901	Kiley No. 1	WL
47	85 N20 E20 10DBBC1	393649119432301	Kiley No. 2	WL
48	85 N20 E20 10DBBC2	393649119432302	Kiley No. 3	WL
49	85 N20 E20 11BAAA1	393715119422801	Gaspari No. 2	WL
50	85 N20 E20 11BDDA1	393655119421901	Gaspari No. 1	WL

Table 1. Site number, location, and type of data available for well, precipitation, and surface-water sites, Spanish Springs Valley area, west-central Nevada—Continued

Site number (fig. 3)	U.S. Geological Survey site designations [1]		Site name	Available data
	Local identification	Standard identification		
51	85 N20 E20 12AAAA1	393717119403701	SSP-4	WL,QW,GL
52	85 N20 E20 12BDDA1	393700119411201	Wingfield Ranch No. 1	QW
53	85 N20 E20 12CAAB1	393651119411401	Wingfield Ranch No. 2	QW
54	85 N20 E20 12DBCC1	393643119410401	D'Anna	WL,QW
55	85 N20 E20 15DBBB1	393559119430801	Kiley No. 4	WL
56	85 N20 E20 15DBBA2	393559119431902	USGS-Kiley4a Observation	WL,QW
57	85 N20 E20 15DBBA3	393559119431903	USGS-Kiley4b Observation	WL,QW
58	85 N20 E20 15DBBA4	393559119431904	USGS-Kiley4c Observation	WL
59	85 N20 E20 21AAAA1	393527119435701	Springcreek North	WL
60	85 N20 E20 21AABC1	393529119441601	Blue Gem	WL
61	85 N20 E20 21ADDA1	393515119435701	Springcreek Abandoned	WL,QW
62	85 N20 E20 21BDDA1	393513119443501	Bailey	WL
63	85 N20 E20 22DBCA1	393459119432201	USGS-Iratcabal2 Observation	WL
64	85 N20 E20 22DCDC1	393442119431001	Iratcabal No. 1	WL
65	85 N20 E20 27BBCA1	393434119435201	USGS-Capurro Observation	WL
66	85 N20 E20 27CACA1	393405119433401	Bria	WL,QW
67	85 N20 E20 27CCCB1	393400119435401	Brandsness	WL
68	87 N20 E20 34DABB1	393322119430801	Winners Corner Exxon	WL
69	85 N20 E21 07CBCB1	393648119403301	Sweger No. 2	WL
70	85 N20 E21 07CCCC1	393631119403401	Sweger No. 1	WL
71	85 N20 E21 07DCCA1	393642119395601	Tucker No. 2	WL
72	85 N20 E21 08BBCA1	393714119393501	SSP-2	WL,QW,GL
73	85 N20 E21 08BBCA2	393714119393502	SSP-2a	WL
74	85 N20 E21 18DABD1	393558119395001	Tucker No. 1	WL
75	85 N20 E21 18DAD 1	393552119394501	Berry	QW
76	85 N20 E21 18DADB1	393544119394701	Mills	WL
[2]77	83 N20 E22 21CDDD1	393446119311701	Tracy	WL
		Precipitation sites		
78	84 N22 E21 31ACAB1	394401119395401	Bacon Rind Flat	P
79	85 N21 E21 09BACC1	394221119374901	Curnow Canyon	P,QW
80	85 N21 E20 15CCAB1	394100119434801	Hungry Ridge North	P,QW
81	85 N21 E20 29DCDD1	393903119452501	Hungry Ridge South	P,QW
82	85 N21 E21 34DBCD1	393903119423101	Spanish Springs Peak	P,QW
83	85 N21 E20 35CCDA1	393824119363401	Fire Station	P
84	85 N20 E20 14CDBB1	393545119423301	Vista	P
85	85 N20 E21 22BCBA1	393522119371901	Dry Lakes	P
86	85 N20 E20 21ACBC1	393515119443201	Oasis Trailer Park	P
87	85 N20 E21 30DAAB1	393418119394101	Canoe Hill	P,QW
		Surface-water sites[3]		
88	85 N20 E20 27CACC1	393358119435101	Orr Ditch	Q,QW
89	85 N20 E20 27CCAD1	393408119433101	North Truckee Drain	Q,QW

[1] See report section titled "U.S. Geological Survey Site Designations."

[2] Not shown in figure 3; outside map area.

[3] USGS station numbers: 10348220, Orr Ditch at Spanish Springs Valley near Sparks, Nev.; 10348245, North Truckee Drain at Spanish Springs Road near Sparks, Nev.

in adjacent basins were measured to provide water-level information in areas of possible ground-water movement from or to Spanish Springs Valley (sites 1, 42, 68, and 77).

In cooperation with Washoe County Department of Public Works, Utility Division, nine observation wells were drilled in areas of the valley where geologic and hydrologic information was sparse. The drilled depths of the observation wells (sites 3, 4, 6, 7, 11, 15, 51, 72, and 73) ranged from 185 ft to 565 ft; differing lengths of 2-inch slotted-steel pipe were installed for sampling access. Lithologic and geophysical logs for these observation wells were described by Washoe County (1993). In addition, several shallow holes (sites 20, 35, 43, 44, 45, 56, 57, 58, 63, and 65) near the Orr Ditch and irrigated fields were augered and 2-inch diameter pipe with 2-ft stainless steel screens was installed by the USGS.

Precipitation was measured monthly or as necessary at seven can-type collectors and quarterly at three bulk-storage collectors (sites 78-87, table 1). Each collector contained a mixture of light oil and ethylene glycol to prevent freezing and evaporation. Most precipitation sites were either on low hills or at higher altitudes in mountains that border the study area. Site 83, however, is on the valley floor (fig. 3) and is maintained by personnel at the Spanish Springs Valley Fire Station. Precipitation data were used in developing a precipitation-altitude relation for the study area. The period of record for most precipitation data is July 1992 through September 1995. Bulk-precipitation (dry and wet fall) collectors similar in design to those described by Likens and others (1977, p. 16) were installed at the precipitation sites to collect samples for water-chemistry analyses. Results from the water-chemistry analysis were used in a chloride-balance technique for estimating ground-water recharge from precipitation.

Continuous stage-recording devices were used to compute discharge on the basis of stage and channel geometries where either instantaneous or mean daily discharges could be determined. Daily-mean discharge of the Orr Ditch (site 88) as it enters Spanish Springs Valley and of the North Truckee Drain (site 89) as it leaves the valley were computed from April 1992 to September 1995. In addition, miscellaneous discharge measurements using a standard USGS wading rod and flow meter were made along the Orr Ditch as it traverses the valley floor. These measurements were made to estimate ground-water recharge by transmission losses from the Orr Ditch.

Water-chemistry data were collected from 22 ground-water, 5 precipitation, and 2 surface-water sites. Ground-water and surface-water samples were analyzed for major ions, bromide, stable isotopes of hydrogen and oxygen, tritium, and selected species of nitrogen and phosphorus. Samples from 19 ground-water sites were analyzed for chlorofluorocarbons (CFC's). Precipitation samples were analyzed for selected species of phosphorus, bromide, and major anions. Results of the ground-water-chemistry analyses, including the results from environmental tracer samples (stable isotopes, tritium, and CFC's), were used to support the conceptualization of the ground-water flow system determined from ground-water-level data.

Field procedures for the collection of water samples were similar to those described by U.S. Geological Survey (1977, chapters 1, 2, and 5) and by Wood (1976). Water-quality variables measured onsite included (1) temperature, by using a hand-held thermometer, accurate to ±0.5°C; (2) pH, by using a meter with digital readout, accurate to ±0.1 unit; (3) alkalinity (reported as calcium carbonate, bicarbonate, and carbonate), by incremental-pH titration of 50-mL filtered sample water with a field instrument, accurate to ±1 mg/L as $CaCO_3$; (4) specific conductance, by using a meter with digital readout, accurate to ±1 μS/cm; and (5) dissolved oxygen, by digital field instrument, accurate to ±0.1 mg/L. Field instruments were calibrated immediately before each use according to methods described by Wood (1976). Except for alkalinity, which is titrated, field measurements of surface-water chemistry were made instream and measurements of ground-water chemistry were recorded using a flow-through cell. At each well, a minimum volume equivalent to three times the volume of water in the well casing was allowed to discharge prior to sample collection. Ground water was then pumped through the flow-through cell and field measurements of water temperature, electric conductivity, dissolved oxygen, and pH were recorded to verify that these properties had stabilized. Stable measurements were assumed to indicate that the discharging ground water was representative of water from the aquifer. Field-measurement techniques and instruments were quality-assured through annual participation in the U.S. Geological Survey National Field Quality Assurance program (Janzer, 1985).

Samples for determination of calcium, magnesium, sodium, potassium, sulfate, chloride, fluoride, silica, boron, bromide, orthophosphate, and selected species of nitrogen (ammonia, nitrite, nitrate) were passed through 0.45-μm pore-size capsule filters and collected in clean polyethylene bottles after rinsing with filtered sample water. Samples for cation analysis were collected in acid-washed polyethylene bottles and acidified with nitric acid to pH of about 2. Samples for determination of nitrogen and phosphorus were collected in opaque polyethylene bottles (to which mercuric chloride was added as a biocide), immediately iced, and shipped to the laboratory within 5 days to minimize microbial degradation. Samples for determination of major ions, boron, bromide, silica, and species of nitrogen and phosphorus were shipped to the USGS National Water Quality Laboratory in Arvada, Colo., for analyses (Fishman and Friedman, 1989). Quality-control procedures used in the laboratory are described by Friedman and Erdmann (1982) and Jones (1987).

Unfiltered water was collected in 60-mL glass bottles for stable-isotope analysis (oxygen-18 relative to oxygen-16 and deuterium relative to hydrogen-1) and in 1-L high-density polyethylene bottles for tritium analysis. Polyseal caps were used on these bottles to prevent evaporation of the sample. Stable-isotope analyses were done by the USGS isotope fractionation project in Reston, Va. Hydrogen-isotope ratios were determined using a hydrogen equilibration technique described by Coplen and others (1991) and oxygen-isotope ratios were determined using the CO_2 equilibration technique described by Epstein and Mayeda (1953). Samples collected for determination of tritium (^3H), the radioactive isotope of hydrogen, were analyzed by the USGS Tritium Laboratory in Reston, Va. Electrolytically enriched samples were analyzed by the liquid scintillation counting method (Thatcher and others, 1977).

Samples for determination of chlorofluorocarbon concentrations were collected with an apparatus that excludes contact with air, and samples were flame-sealed into borosilicate-glass ampules for transport and storage prior to analysis (Busenberg and Plummer, 1992, p. 2257-2258). CFC analyses were done by the USGS Chlorofluorocarbon Laboratory in Reston, Va., using a purge-and-trap gas chromatography procedure with electron-capture detector (Busenberg and Plummer, 1992, p. 2259-2260). Precautions were taken regarding the type of pump used for ground-water sample acquisition and types of material the sample water might contact prior to its entry into the sampling apparatus. These precautions were necessary because the use of CFC's as an age-dating tool is dependent on atmospheric concentrations and the temperature of recharge water at the time when infiltrating water no longer is in contact with air. In general, pumps that might affect the pressure of sample water and contact with most plastics, rubbers, greases, and oils were avoided.

Geochemical Techniques

Water-chemistry characteristics, such as stable and radioactive isotopes, chloride ions, and CFC's, that were determined as part of this study were used to evaluate inferred recharge sources and volumes and ground-water ages using documented geochemical techniques described in this section. Appropriate data for application of these geochemical techniques were collected in Spanish Springs Valley during 1992-94.

The stable isotopes evaluated were oxygen-18 relative to oxygen-16 ($^{18}O/^{16}O$) and deuterium (hydrogen-2) relative to hydrogen-1 ($D/^1H$). Each ratio is determined for a sampled water and is then related mathematically to the comparable ratio for an international reference standard known as Vienna-Standard Mean Ocean Water (V-SMOW). By convention, the computed results are expressed as delta oxygen-18 ($\delta^{18}O$) and delta deuterium (δD); the units of measure are parts per thousand (abbreviated "permil" or $^0/_{00}$). The terms "isotopically heavier" and "isotopically lighter" are relative and are used for comparing the composition of water samples. A negative delta value indicates that the sample water is isotopically lighter than the standard (that is, the sample has a smaller proportion of oxygen-18 or deuterium relative to oxygen-16 or hydrogen-1 than the standard). Because $\delta^{18}O$ and δD measure relative isotopic compositions of the two elements that constitute the water molecule (hydrogen and oxygen), they are ideal tracers of water movement where the isotopic fractionation of both are usually covariant. Isotopic fractionation results from physical, chemical, or biological processes, which cause the delta value of the stable isotopes of water to change. For example, during the physical process of evaporation, $\delta^{18}O$ increases because ^{16}O is lighter and leaves water at a faster rate than the heavier ^{18}O. Given two inferred ground-water flowpaths composed of water with different isotope compositions, the proportion of flow that each flowpath may have contributed to a receiving flowpath can be evaluated on the basis of an isotopic mass balance. In addition, $\delta^{18}O$ and δD compositions are useful for indicating ground-water source areas.

Tritium is a radioactive isotope of hydrogen with an atomic mass of 3 and a half-life of 12.43 years (Plummer and others, 1993, p. 257). Tritium is produced naturally at low levels in the atmosphere by interaction of cosmic rays with nitrogen and oxygen (Drever, 1988, p. 379), but thermonuclear-weapons testing between 1952 and 1969 introduced amounts of tritium into the atmosphere that produced concentrations in precipitation as much as three orders of magnitude greater than natural levels. This increased tritium concentration serves as a marker of the timing of thermonuclear-weapons testing and thus provides a useful indicator of the age (the time since the water has been isolated from the atmosphere) of ground water.

In 1993, mean levels of tritium in precipitation were approaching the pretesting level of about 25 pCi/L (Portland, Oreg., 16 pCi/L; Albuquerque, N. Mex., 37 pCi/L; Robert L. Michel, U.S. Geological Survey, written commun., 1995). Tritium generated prior to thermonuclear-weapons testing would have decayed to levels of about 1 pCi/L in 57 years. Samples collected in 1993 from Spanish Springs Valley having tritium concentrations less than 1 pCi/L are older than 57 years; concentrations between 1 and 10 pCi/L represent ground water that is either a mixture of pre- and post-thermonuclear weapons testing water or water that is about 38 to 57 years old; concentrations between 10 and 100 pCi/L represent water that is either a mixture of pre- and post-thermonuclear weapons testing water or water that is younger than 38 years; and concentrations greater than 100 pCi/L represent water from 1958-59 or 1962-69 (Welch, 1994, p. 16).

The chloride-balance method was used in the present study as a reconnaissance effort to complement other techniques for estimating natural recharge. Because the concentration of chloride dissolved in ground water generally is not affected by sorption or ion-exchange processes, it has been used as a natural tracer for estimating ground-water recharge from precipitation, assuming that all sources of chloride are known (Dettinger, 1989; Claassen and others, 1989). This method is based on the balance between total chloride concentration in bulk precipitation (dry and wet fall) that falls in recharge-source areas and chloride concentration in ground water in and near recharge areas. Potential chloride sources to ground water include (1) dissolution of evaporite minerals, (2) weathering of nonevaporite minerals, (3) mixing with formation water, (4) anthropogenic sources (for example, road salt, wastewater leachate), and (5) atmospheric sources (both dry and wet fall; Dettinger, 1989, p. 57). In Spanish Springs Valley, atmospheric sources of chloride are dominant and runoff is negligible. Careful sample-site selection and sample handling were used to avoid interference from other sources. On the basis of the chloride-balance method, the volume of recharge can be approximated as follows:

$$R = P(Cl_p/Cl_r) \ , \quad (1)$$

where,

R is recharge, in acre-feet per year;
P is total precipitation that falls in recharge-source area, in acre-feet per year;
Cl_p is chloride concentration in bulk precipitation, in milligrams per liter; and
Cl_r is chloride concentration of recharge water, in milligrams per liter.

CFC's are relatively stable, volatile, organic compounds that are present worldwide as a result of continuous releases to the atmosphere since the 1930's. No natural sources of CFC's are known, which makes CFC's useful age-dating compounds for hydrologic investigations (Plummer and others, 1993, p. 268). Dichlorodifluoromethane (CCl_2F_2 or CFC-12) was the first CFC compound manufactured. Production of trichlorofluoromethane (CCl_3F or CFC-11) began in the 1940's. These two compounds account for about 77 percent of the total CFC production. A third CFC compound—trichlorotrifluoroethane ($C_2Cl_3F_3$, or CFC-113)—went into production in the 1960's and accounts for the remaining 23 percent of the global CFC market. All CFC's eventually are released to the atmosphere, where they become partitioned into the hydrosphere by gas-liquid exchange equilibria. In 1990, atmospheric volume fractions of CFC-12, CFC-11, and CFC-113 were about 480, 285, and 77 parts per trillion, respectively, and these levels have been increasing at an average rate of about 3.7 percent annually (Plummer and others, 1993, p. 268). Low analytical reporting levels (1 pg/L for CFC-12 and CFC-11), relatively smooth, monotonic increase in atmospheric releases, resistance to degradation and transport retardation, and relative ease of reconstructing atmospheric concentrations make CFC's useful as hydrologic tools for identifying ground water that has recently received recharge and estimating the timing of recent ground-water recharge. Detection of as little as 0.01 percent modern water in a mixture with pre-1940 ground water is possible because of the low analytical reporting level.

The presence of CFC-12 indicates that a portion of the sample water is composed of water that was recharged since 1940; CFC-11 indicates recharge since 1945; and CFC-113 indicates recharge as recent as 1966.

The age (time since infiltrating water recharged an aquifer) of ground water may be estimated with a precision of ±1-2 years because the relatively smooth, monotonic increase in atmospheric releases is known (reconstructed from production records from 1940 to 1975 and from atmospheric measurements since 1975; Busenberg and Plummer, 1992). This "CFC model" of recharge age assumes that infiltrating water maintains equilibrium with air in the unsaturated zone during recharge—an application of the process of gas solution, based on Henry's law solubilities of CFC in water. The temperature at the base of the unsaturated zone is required to define the Henry's law solubility constant for nonstandard conditions. A recharge temperature of 10°C was assumed for deeper wells sampled for the Spanish Springs Valley investigation on the basis of the long-term mean temperature for the weather station at the Reno-Tahoe International Airport (hereafter referred to as the Reno airport). Shallow wells (less than 45 ft below land surface) within irrigated areas were assigned a recharge temperature of 14°C to reflect the temperature of infiltrating irrigation water. The measured CFC concentration of a water sample can be converted to an equivalent air concentration at the appropriate recharge temperature by using the solubility of the compound. By comparing the equivalent air concentration to an atmospheric air-concentration curve, the air concentration can be equated to a recharge date or age (Cook and others, 1995, p. 432). Details of CFC-model age-dating are described by Busenberg and Plummer (1992).

Recent efforts to characterize transport properties of CFC's indicate that CFC-12 was the most conservative, CFC-11 shows degradation in an organic-rich unsaturated zone and in anaerobic ground water, and CFC-113 shows retardation due to sorption (Cook and others, 1995, p. 432-433). Soil and aquifer characteristics in Spanish Springs Valley suggest that organic content is relatively low, but some wells did have dissolved-oxygen concentrations of less than 1 mg/L. Relative agreement between CFC-model ages determined with CFC-12 and CFC-11 indicates that these compounds act conservatively.

Water recharged in urban areas may contain concentrations of CFC's in excess of expected concentrations due to equilibrium with tropospheric air because of local industrial releases. Likewise, sewage effluent and (presumably) septic-system leachate can contain CFC concentrations that are orders of magnitude greater than expected concentrations (Plummer and others, 1993, p. 272) due to domestic use of propellants in aerosol cans. These sources of CFC's can result in CFC-model ages that are younger than the actual age of ground water. Relatively few CFC-discharging industries are based in northern Nevada and those that are have a minimal effect on atmospheric levels. However, septic systems are relied on for disposal of domestic waste and wastewater in some parts of Spanish Springs Valley, representing a potential source of CFC introduction into ground water.

Geophysical Methods

In defining the ground-water flow regime of a basin-fill aquifer system, the hydrogeologic framework is described in terms of flow conditions at the boundaries of the system, together with the hydrologic properties of the basin fill. Lateral boundaries lie along the periphery of the valley floor and the bedrock boundary lies beneath the basin fill. Because most wells within the study area do not penetrate through the basin fill to bedrock, geophysical methods were used to determine thickness of the basin fill and to improve the knowledge of the bedrock geometry. Geophysical methods used for this study are gravity, magnetic, and seismic refraction. Intrinsic differences in density, magnetic susceptibility, and seismic velocity are used by these methods to define the contact between hydrogeologic units. Borehole-geophysical logs also were collected and used to characterize the hydrogeologic units found during drilling of observation wells.

Gravity and aeromagnetic data were evaluated by qualitatively inspecting anomaly maps of the gravity and magnetic fields within the study area and by geophysical profile modeling. The anomaly map of the gravity data are the complete Bouguer anomaly, which have been corrected for latitude, elevation, and terrain. The magnetic data are presented as total magnetic intensity or field strength. Anomalies within a gravity or magnetic field are perturbations represented by highs and lows in an otherwise uniform field. They provide information about the subsurface distribution and general geophysical character of hydrogeologic units. Gravity data obtained during this study and in earlier studies (Saltus, 1988) were used in combination with aeromagnetic data (Hildenbrand and Kucks, 1988) to create the anomaly maps.

The gravity and aeromagnetic data also were used in an interactive geophysical profile modeling program (Webring, 1985) that fits theoretical gravity and magnetic responses from a geologic model to measured gravity and magnetic data. A mathematical representation of the geologic model includes locations of several rock types as well as physical properties (bulk densities and magnetic susceptibilities) of the rock. The geophysical modeling during this study used three profiles, across the northern, central, and southern parts of Spanish Springs Valley. The profiles were selected so that at least one well penetrating bedrock was intersected along the profile and used as a control point. Surficial geology at and near land surface and drill-hole information were used to constrain the model in terms of basin-fill thickness. Although the model results are non-unique, additional constraints on the model were provided by simultaneously using two geophysical methods—gravity and magnetics—that measure and respond to different properties of the subsurface geology. Once the adjusted modeled profiles coincided with the conceptualization of the subsurface that was consistent with available data, the profiles were used to guide the development of a map showing basin-fill thickness. Additional description of this type of gravity- and magnetic-profile modeling is presented by Schaefer and Whitney (1992, p. 5).

Seismic refraction was used at two sites to provide detailed information about the condition of the flow boundaries beneath the low alluvial divides at the north and south ends of the valley. Determining the thickness of basin fill beneath these areas aided in estimating the possible movement of ground water leaving or entering the study area through basin fill. A third seismic refraction line was done to determine depth to bedrock prior to installation of two observation wells (sites 72 and 73). Additional information on the use of seismic refraction in water-resources investigations is presented by Haeni (1988).

Borehole-geophysical logs were collected in six observation wells drilled during this study (sites 3, 7, 11, 15, 51, and 72) and are presented in a report by Washoe County (1993). Borehole geophysics used in this study include caliper, natural-gamma, spontaneous-potential, acoustic, and resistivity logs. In general, responses on natural-gamma, spontaneous-potential, and resistivity logs can be used, in part, to determine changes in relative grain size. These changes in grain size may represent contacts between different hydrogeologic units. Units composed of mostly coarse-grained deposits have a different response on the logs than fine-grained deposits. This allows a qualitative estimate on the relative ability of different units to transmit water. Acoustic transit-time logs can be used to provide information about lithology and porosity under a wide range of conditions. Transit times measured by an acoustic log decrease with an increase in rock hardness and cementation. Caliper logs provide a continuous measurement of diameter of uncased drill holes. Additional information on the application of borehole geophysics to ground-water investigations is presented by Keys (1990).

Hydrologic Models

To determine the distribution of precipitation in Spanish Springs Valley, precipitation data for 34 stations, including 9 in the study area, were analyzed to develop a mathematical relation between precipitation and altitude. Stations range in altitude from 3,900 ft to 6,960 ft. Those stations outside the study area were selected because they lie in the rain shadow of the Sierra Nevada, as does Spanish Springs Valley. (Areas in a rain shadow lie on the lee side of a topographic obstacle where the rainfall is noticeably less than on the windward side.) The distribution of annual precipitation was used to estimate the potential for ground-water recharge from precipitation within the study area.

The U.S. Geological Survey modular finite-difference model commonly called MODFLOW (McDonald and Harbaugh, 1988) was used to simulate ground-water flow through the basin-fill aquifer in Spanish Springs Valley. The digital model can simulate flow in three dimensions and was used to test the conceptual model of ground-water flow developed during this study and to estimate effects of hypothetical changes in land-use patterns and ground-water withdrawal. General features of the ground-water flow model of the basin-fill aquifer in Spanish Springs Valley are explained in the section "Simulation of Ground-Water Flow."

HYDROGEOLOGIC FRAMEWORK

The geologic history of western Nevada and particularly the Spanish Springs Valley area is complex. The area is situated in a transitional zone between the

Basin and Range and Sierra Nevada physiographic provinces. Structural features associated with these provinces, in part, define the hydrogeologic framework of the study area. For purposes of this report, five major geologic units identified in Spanish Springs Valley were divided into two general groups on the basis of their hydrogeologic properties: (1) consolidated rock, which commonly have low porosity and permeability, except where fractured; and (2) basin fill, which generally has high porosity and transmits water readily. The areal distribution of the five geologic units is shown in figure 4 and general hydrologic properties are presented in table 2.

Geologic History and Structural Setting

Outcrops of rocks older than Mesozoic age are sparse in western Nevada and are not found within the study area. Consequently, geologic evidence from adjacent areas is used to describe the region during that time. Stewart (1980, p. 35-36) suggests that, during pre-Mesozoic time, western Nevada was the site of deep-water deposition with little tectonic activity. During most of the Mesozoic era, tectonic activity, which included compressional folding and thrusting, may have been continuous. The oldest rocks exposed within the study area are metavolcanic and metasedimentary rocks of late to middle Mesozoic age (Triassic and Jurassic periods) that were regionally metamorphosed prior to intrusion by granitic plutons during the late Mesozoic (Cretaceous period; Bonham, 1969, p. 42). A second period of deformation associated with extensional faulting formed the present-day topographic features of the study area, including the structural depressions underlying Spanish Springs Valley. This period of deformation began during the middle to late Tertiary period and has continued to the present (Bonham, 1969, p. 42). Tertiary volcanic rocks consisting of several types of flows and tuffs interbedded with clastic sediments were extruded and deposited unconformably on the Mesozoic granitic and metamorphic rocks within the structural depressions. Most of the basin fill accumulated as a result of ongoing deposition of detritus from surrounding mountains bordering Spanish Springs Valley.

The Spanish Springs Valley area lies between major tectonic structures of the Sierra Nevada Frontal Fault Zone and the Walker Lane (Bell, 1981, p. 35). Range-front faulting associated with the formation of the structural depression beneath Spanish Springs Valley is indicated by steep increases in basin-fill thickness near the contact between basin fill and consolidated rock along the west side of the study area. Although extensional faulting is thought to have developed present-day topographic features, fault systems associated with the Walker Lane also have created a high degree of structural deformation. Faults that border the Dry Lakes area and other faults in the southeastern part of the study area that generally trend northeast (fig. 4) may be related to the Olinghouse Fault Zone, a left-lateral conjugate shear zone of the Walker Lane (Bell, 1981, p. 38). As a result of this combined deformation, bedrock permeability has developed adjacent to and within highly fractured zones. In other places, faults may act as barriers to ground-water flow because of cementation along fault surfaces within basin fill and because of the offsetting of deposits with contrasting permeabilities.

General Character of Hydrogeologic Units

Fractured consolidated rock and the unconsolidated sediments that constitute the basin fill together make up the ground-water reservoirs recognized within the study area. However, basin fill currently forms the principal water-bearing hydrogeologic unit.

Consolidated Rock

Tertiary rocks make up most of the consolidated rock exposed in the study area (fig. 4); they are generally of volcanic origin and have intercalated lenses of sedimentary rocks. The Pah Rah Range consists almost entirely of Tertiary rocks, which can be characterized by high-amplitude magnetic anomalies (fig. 5). These rocks generally have little or no interstitial porosity, except where volcanic-flow units have abundant vesicles. Interbedded sedimentary rocks of the Tertiary unit consist mostly of fine-grained, partly consolidated lacustrine deposits with low permeability, but may store a moderate amount of water.

The complete Bouguer gravity field shown in figure 6 indicates that the volcanic rocks that compose most of the Pah Rah Range are relatively less dense (greater negative Bouguer values) than the intrusive rocks that make up the western boundary and volcanic rocks of the southern boundary (fig. 4). This finding suggests that the northern and central parts of the Pah Rah Range are composed of a substantial amount of low-density material. In addition, magnetic signatures

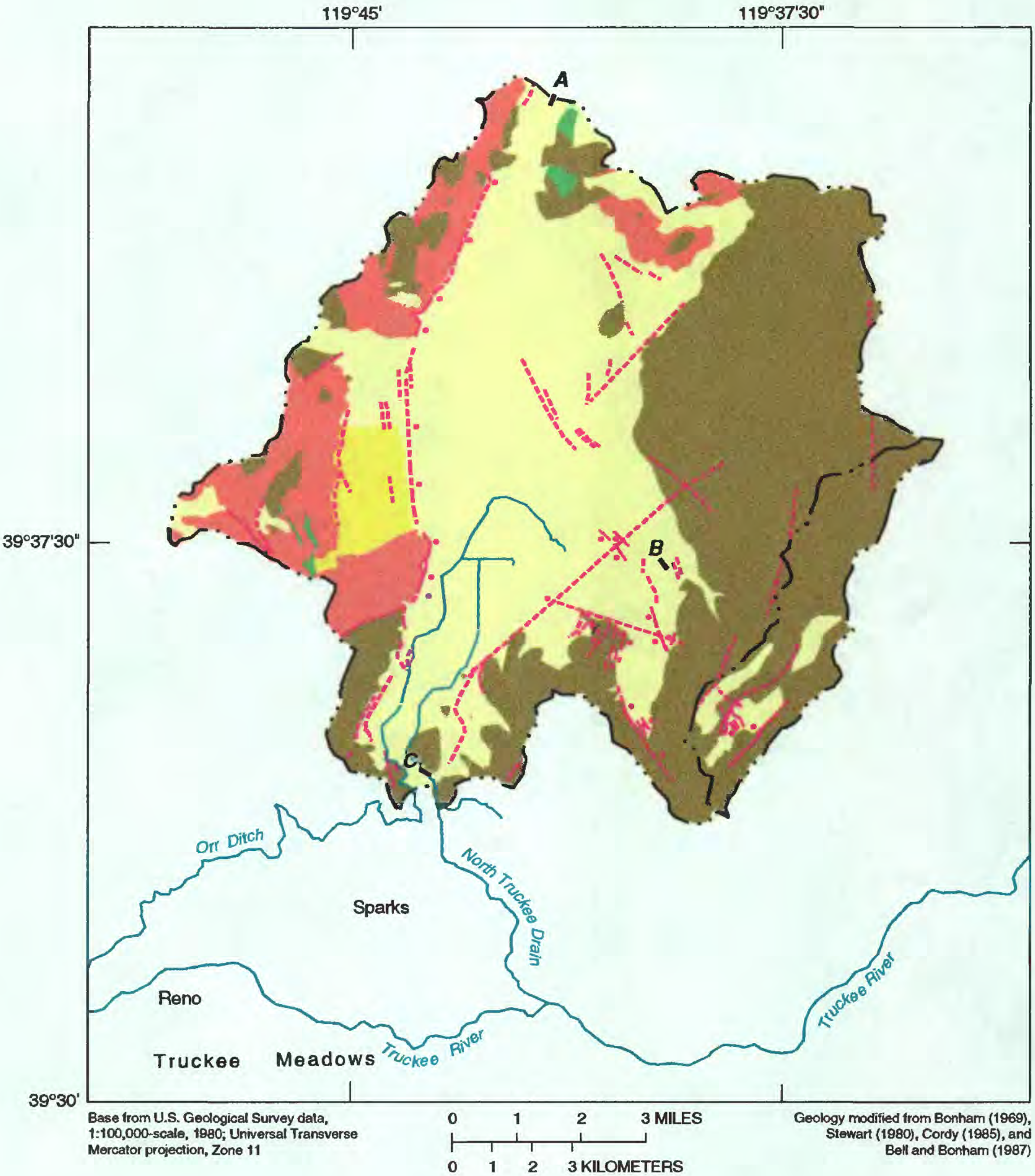


Figure 4. Generalized geologic units, structural features, and seismic-refraction lines, Spanish Springs Valley, west-central Nevada.

of the Pah Rah Range indicate that the volcanic rocks that compose the southern boundary may be a different lithologic unit than those that compose the central and northern parts.

The difference in geophysical responses of the volcanic rocks can be seen on profiles shown in figures 7-9. On the basis of geophysical interpretations and information from drillers' logs, Tertiary rocks that make up the Pah Rah Range were modeled as two separate lithologic units (units 3 and 4 in figs. 7-9 and table 3) that extend beneath the eastern and southern parts of the valley. Lithologic unit 4, which represents volcanic rock, was used to simulate measured magnetic and gravity highs on profiles *B-B′* and *C-C′* centered at about the 4-mi mark along the profiles (figs. 8 and 9). These measured highs are assumed to be caused by a buried northern extension of volcanic rocks of the southern boundary and, as a result, are assumed to have different geophysical properties than volcanic rocks represented by lithologic unit 3. The measured magnetic and gravity lows along profile *A-A′* were simulated by lithologic unit 3 (fig. 7). This interpretation of two volcanic units is in agreement with the geologic map of Bell and Bonham (1987), who differentiated the Lousetown Formation of the Pah Rah Range from the Alta Formation, which forms the southern boundary of the study area. Although detailed investigation of the hydrologic character of these Tertiary volcanic rocks is beyond the scope of this study, their hydrologic importance at a regional scale may be significant. Cretaceous intrusive rocks, which form the western and northern boundaries (fig. 4), and which were modeled to underlie much of the study area, have virtually no interstitial permeability. Thickness of the basin fill is presented in figure 10.

EXPLANATION

- Younger alluvium (Holocene and Pleistocene)
- Older alluvium (Pleistocene)
- Volcanic and sedimentary rocks (Tertiary)
- Intrusive igneous rocks (Cretaceous)
- Metavolcanic and metasedimentary rocks (Jurassic and Triassic)
- Basin boundary
- Fault lines—Ball on downthrown side. Dashed where approximately located
- *C* — Seismic-refraction line

As a result of structural deformation, secondary permeability in the form of fractures has developed within the consolidated rock. In localized areas, consolidated rock may be capable of storing and transmitting large quantities of water. For example, wells in fractured volcanic rocks beneath the southeastern part of the valley reportedly have produced an average 300 to 400 gal/min and as much as 1,500 gal/min during a 5-day aquifer test (W.E. Nork, Inc., 1988a; site 70, fig. 3 of this report). Anomalous spikes on the focused-resistivity and acoustic logs collected by Washoe County (1993, p. 5) at well 72 suggest that the volcanic rock is highly fractured and that it may yield water in the interval between 180 and 315 ft. Below this interval, the rock has considerably fewer fractures and presumably lower permeability. However, most consolidated rock in the study area produce about 10 to 40 gal/min and the probability of intercepting fractures within consolidated rock for developing high-yield wells is low.

A relatively transmissive hydraulic connection between basin fill and volcanic rocks in the southeastern part of the basin was suggested by pumping effects on vertical gradients measured in nearby observation wells. Hydrographs for November 1993 through September 1994 from site 72, which is a well screened in fractured volcanic bedrock, and site 73, which is a well screened within the overlying basin fill, are shown in figure 11. These wells are next to each other about 0.5 mi from the contact of the basin fill with rocks of the Pah Rah Range (fig. 3). The upward vertical gradient measured between the two wells is interpreted as ground-water recharge to the basin-fill aquifer generated within the Pah Rah Range to the east. The gradient, however, was reversed in response to ground-water pumping in the springs area during the 1994 irrigation season (April through September). During 1995, no additional ground water was withdrawn in the springs area; consequently, the vertical gradient between sites 72 and 73 returned upward.

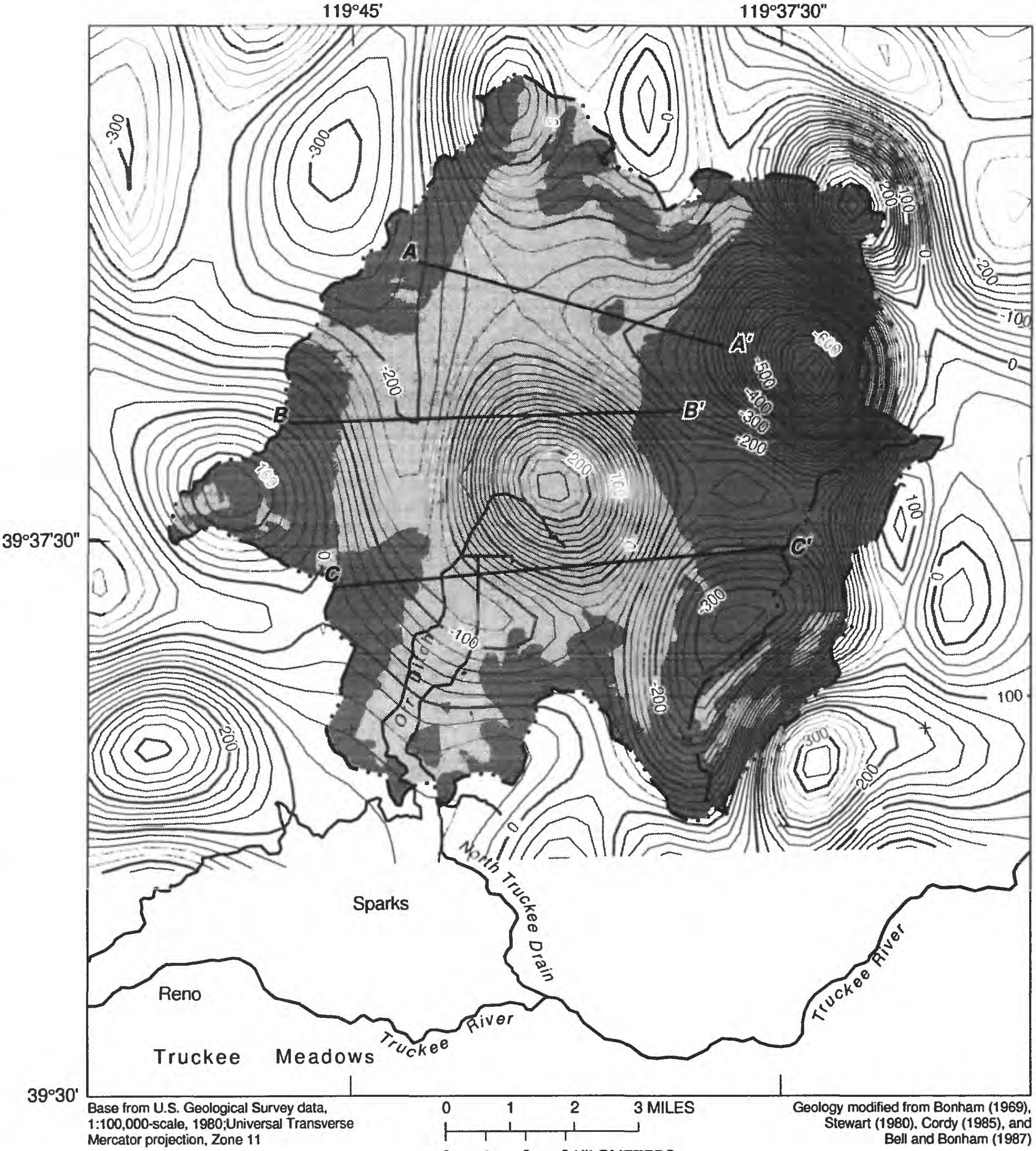
Basin Fill

The structural depression occupied by Spanish Springs Valley is partly filled by interbedded deposits of sand, gravel, clay, and silt derived primarily from adjacent mountains. These deposits form the basin-fill aquifer, which is bounded and underlain by consolidated rock.

Table 2. Age, lithology, and general hydrologic properties of principal hydrogeologic units in Spanish Springs Valley area, west-central Nevada

[Descriptions based on those of Bonham (1969), Harrill (1973), Stewart (1980), Cordy (1985), and Bell and Bonham (1987); geologic units shown in figure 4.]

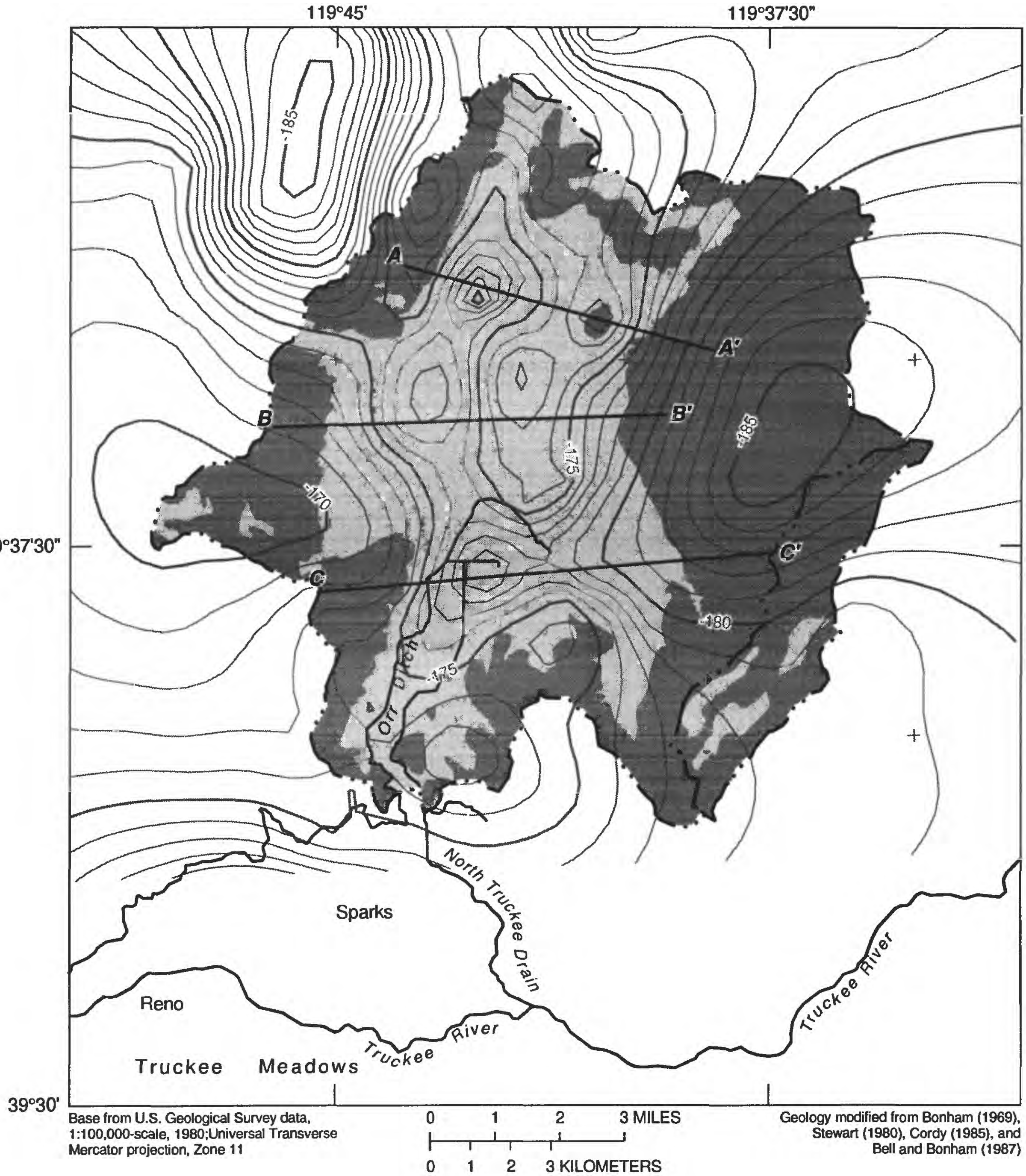
Age	Geologic unit	Lithology	Occurrence	General hydrologic properties
		Basin-Fill Sediments		
Holocene and Pleistocene	Younger alluvium	Unconsolidated alluvial and basin-fill deposits of interbedded sand, gravel, silt, and clay. Deposits generally form lenticular units and are moderately to poorly sorted.	Alluvial-fan deposits along margins of valley and fine-grained deposits on valley floor. Also occur as eolian sand deposits as dunes or sheets in Spanish Springs Canyon and Dry Lakes area.	Deposits have generally high porosity and permeability. Where saturated, are principal ground-water reservoir.
Pleistocene	Older alluvium	Unconsolidated to partly consolidated alluvial and basin-fill deposits of clay, sand, silt, and gravel.	Older alluvial fan along east margin of unnamed southern extension of Hungry Ridge. Deposits underlie younger alluvium and are structurally deformed.	Deposits may transmit moderate to large amounts of water; permeability decreases with depth. Upper saturated part makes up principal ground-water reservoir. Faults within deposits may form barriers to ground-water movement.
		Consolidated Rock		
Tertiary	Volcanic and sedimentary rocks	Volcanic rocks consist of flows of andesite, basalt, and rhyolite, flow breccia, flow tuffs, air-fall tuffs, and intercalated clastic rock. Includes Lousetown, Kate Peak, and Alta Formations and undifferentiated volcanics, formerly called Hartford Hill Rhyolite tuff. Sedimentary rocks are interbedded siltstone, shale, conglomerates, and stratified bouldery gravels. Deposits are moderately indurated. Includes Coal Valley Formation (correlative to Truckee Formation).	Small outcrops within Hungry Ridge and unnamed southern extension and along northern mountains. Forms Pah Rah Range (Lousetown Formation; greater than 12,000 ft thick) and low hills along southern boundary (Alta Formation) of study area. Underlies basin fill along eastern and southern part of valley.	Virtually no interstitial porosity except where vesicular. May transmit moderate quantities of water through fractures and joint sets. Sedimentary rocks may have high porosity due to generally fine-grained texture, but have low permeability.
Cretaceous	Intrusive igneous rock	Medium- to coarse-grained granodiorite.	Faulted blocks form western and northern boundaries of study area. Underlies basin fill and Tertiary rocks.	Virtually no interstitial porosity and permeability; locally may transmit moderate quantities of water if highly fractured or weathered.
Jurassic and Triassic	Metavolcanic and metasedimentary rocks	Regionally metamorphosed volcanic flows, tuffs, breccias, and associated sedimentary deposits. Includes the Peavine Sequence.	Small isolated roof pendants in unnamed southern extension of Hungry Ridge and small outcrop surrounded by Tertiary volcanic rock in mountains form northern boundary of study area.	Low interstitial porosity and permeability. May transmit water through fractures.



EXPLANATION

- Basin fill
- Consolidated rock
- Basin boundary
- A——A' **Location of geologic section**—See figures 7, 8, and 9
- —100— **Line of equal magnetic intensity**—Shows total-intensity magnetic field of Earth relative to arbitrary datum (1,000 feet above land surface). Interval, in nanoteslas, is variable. Magnetic contouring by D.L. Berger, 1994; based on data from Hildenbrand and Kucks (1988)

Figure 5. Total-intensity magnetic field, Spanish Springs Valley area, west-central Nevada.



EXPLANATION

- Basin fill
- Consolidated rock
- Basin boundary
- A——A' **Location of geologic section**—See figures 7, 8, and 9
- -175 **Lines of equal Bouguer gravity anomaly**—Interval 1 milliGal, at density of 2.67 grams per cubic centimeter. Gravity contouring by D.L. Berger, 1994; based in part on data from Saltus (1988)

Figure 6. Complete Bouguer gravity field, Spanish Springs Valley area, west-central Nevada.

Table 3. Physical properties for lithologic units in geologic section along geophysical profiles, Spanish Springs Valley area, west-central Nevada

Body No.	Modeled lithology	Density (grams per cubic centimeter)	Magnetic susceptibility (centimeter-gram-second units)
	Profile *A-A'* (figure 7)		
1	Granitic rocks	2.75	0.0009
2	Basin fill	1.91	.00001
3	Volcanic rocks	2.46	.0001
	Profile *B-B'* (figure 8)		
1	Granitic rocks	2.71	0.0006
2	Basin fill	1.97	.00001
3	Volcanic rocks	2.42	.0007
4	Volcanic rocks	2.75	.003
	Profile *C-C'* (figure 9)		
1	Granitic rocks	2.71	0.001
2	Basin fill	1.90	.00001
3	Volcanic rocks	2.47	.0001
4	Volcanic rocks	2.72	.003

Areal Extent and Thickness

The areal extent of the basin-fill aquifer is approximated by the contact between consolidated rock and basin fill along the periphery of the valley floor. Total surface area of basin fill is about 34 mi^2, almost 43 percent of the total drainage area of Spanish Springs Valley. The basin fill is bounded on the east by the Pah Rah Range and on the west by Hungry Ridge and its southern extension. On the north, an alluvial divide exists between Spanish Springs and Warm Springs Valleys. Results of a seismic refraction survey (line A, fig. 4) and drill-hole data indicate that this topographic divide is underlain by consolidated rock at shallow depths (less than 50 ft). At the southern boundary of the study area, the saturated basin fill in Spanish Springs Valley may be continuous with saturated basin fill of Truckee Meadows. This boundary, which is not a topographic divide, is underlain by consolidated rock at depths of less than 20 ft. Basin fill also occupies the structurally controlled basins of the Dry Lakes area in the southeastern part of the study area.

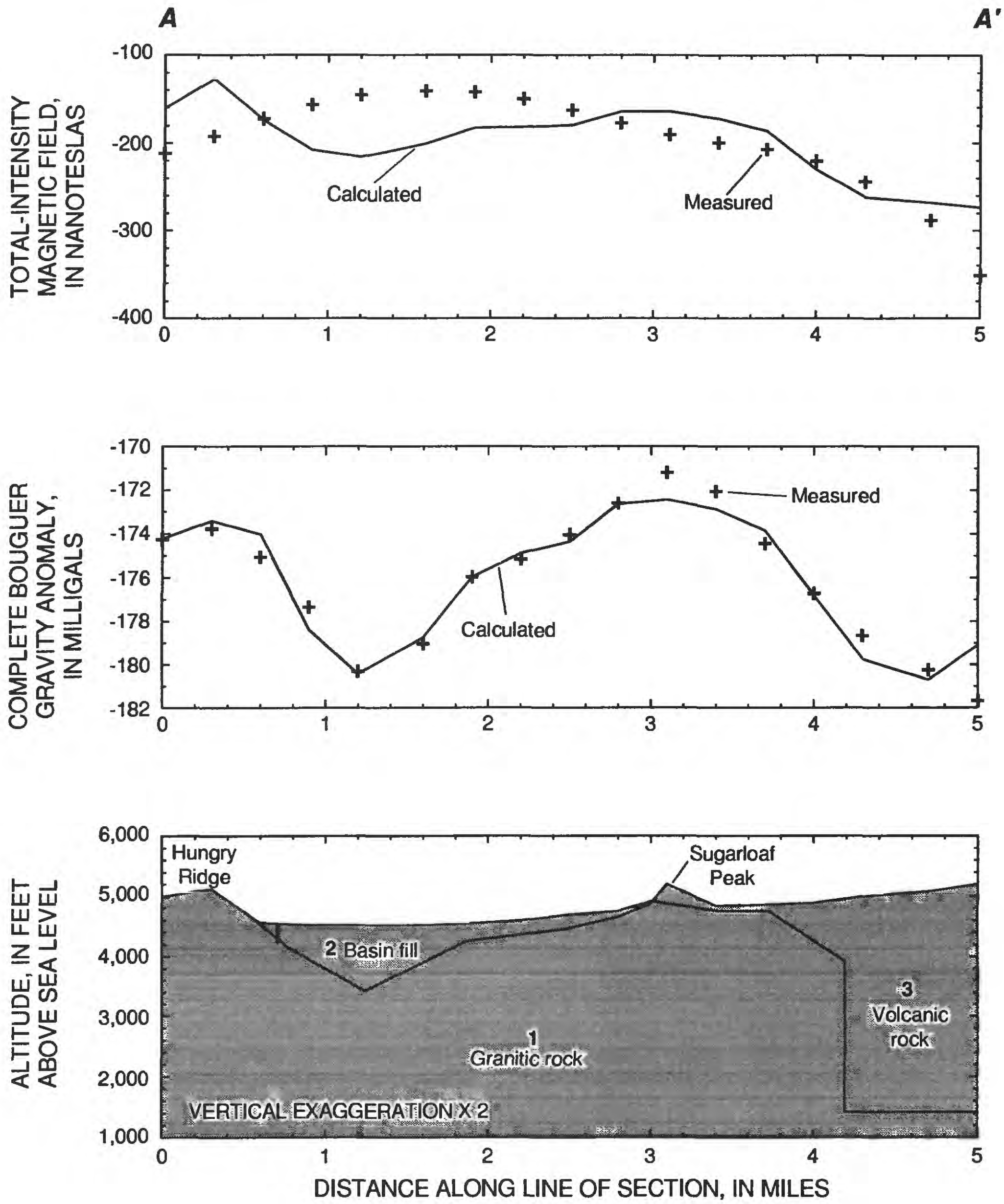
Wells drilled in Spanish Springs Valley range in depth from several tens of feet to more than 800 ft, with most completed in basin fill. Discrepancies in basin-fill thickness as reported on drillers' logs for several wells limited the areal use of these logs as a tool to estimate basin-fill thickness. The basin-fill-thickness map (fig. 10), which was developed partly by geophysical methods, indicates that basin fill is thickest along a northeast trending trough-like feature close to the mountain front of Hungry Ridge. Results from profile *A-A'* (fig. 7), which transverses the northern part of this feature, suggest that the maximum thickness is at least 1,000 ft. In general, the basin fill is thickest beneath the western part of Spanish Springs Valley and thins toward the east. Beneath the southern part of the valley, depth to bedrock is less than 100 ft and becomes shallower toward the southern boundary. On the basis of data from an abandoned well in the Dry Lakes area, unsaturated basin fill is at least 350 ft thick and reportedly consists almost entirely of clay.

Hydraulic Properties

Two hydraulic properties used to express water-bearing characteristics of aquifers are hydraulic conductivity and storage. Hydraulic conductivity is a measure of the ability of an aquifer to transmit water. The term "storage coefficient" is used to describe the water-storage capabilities of an aquifer.

Typical values of hydraulic conductivity for coarse-grained deposits (sand and gravel) in other basins of Nevada range from 5 to more than 150 ft/d (Harrill, 1973, table 5; Berger, 1995, p. 21). In fine-grained deposits (clay, silt, and fine sand), the range is generally from 0.1 to 4 ft/d (Harrill, 1986, p. 10). Hydraulic conductivity can be determined from estimates of transmissivity and aquifer thickness. Transmissivity values determined from results of several aquifer tests were used to calculate hydraulic conductivities, which ranged from 0.5 to about 12 ft/d (Shaw Engineering, 1984, appendix; Guyton and Associates, 1986, p. 61; W.E. Nork, Inc., 1987, 1988b, 1989; Washoe County, 1991). Data from these aquifer tests represent transmissivities of mixtures of coarse- and fine-grained deposits within the upper 330 ft of saturated basin fill.

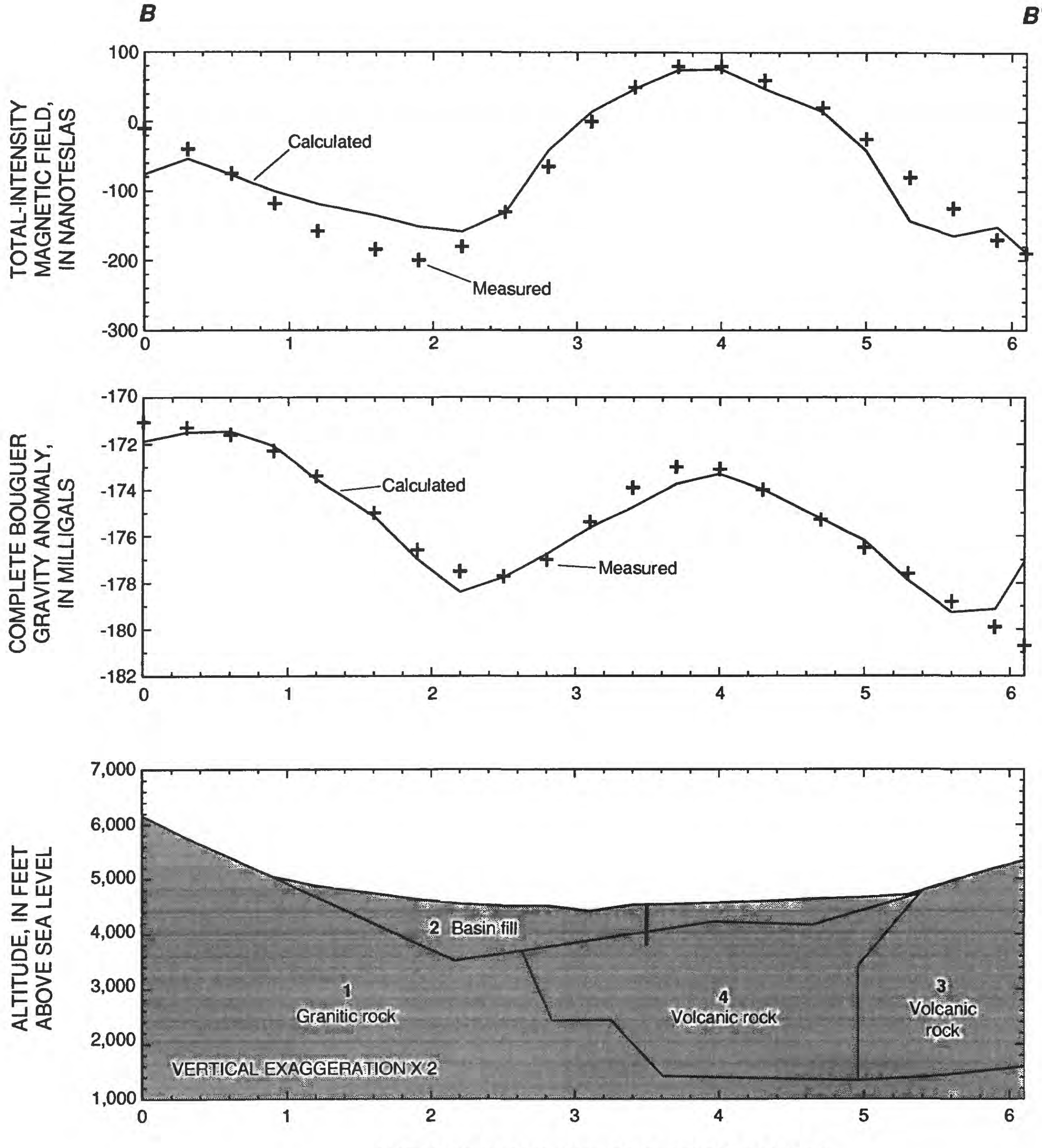
Analysis of geophysical and lithologic logs and grain-size distributions collected from some of the observation wells drilled as part of this study (wells 7, 11, 15, 51, and 72; Washoe County, 1993) provided qualitative estimates of the ability of the basin-fill aquifer to transmit water. In general, basin fill that originates in upland volcanic-rock terrains is predominantly composed of finer grained deposits, resulting in an overall lower hydraulic conductivity than basin fill derived from granitic rocks, which is predominantly sands and gravels. Hydraulic conductivity beneath the deepest wells is unknown, but probably is lower than that of the upper 330 ft due to additional compaction and induration. The distribution of hydraulic conductivity within the basin-fill aquifer was refined by using the ground-water flow model.



EXPLANATION

I	**Well**—Penetrates consolidated rock underlying basin fill 300 feet below land surface

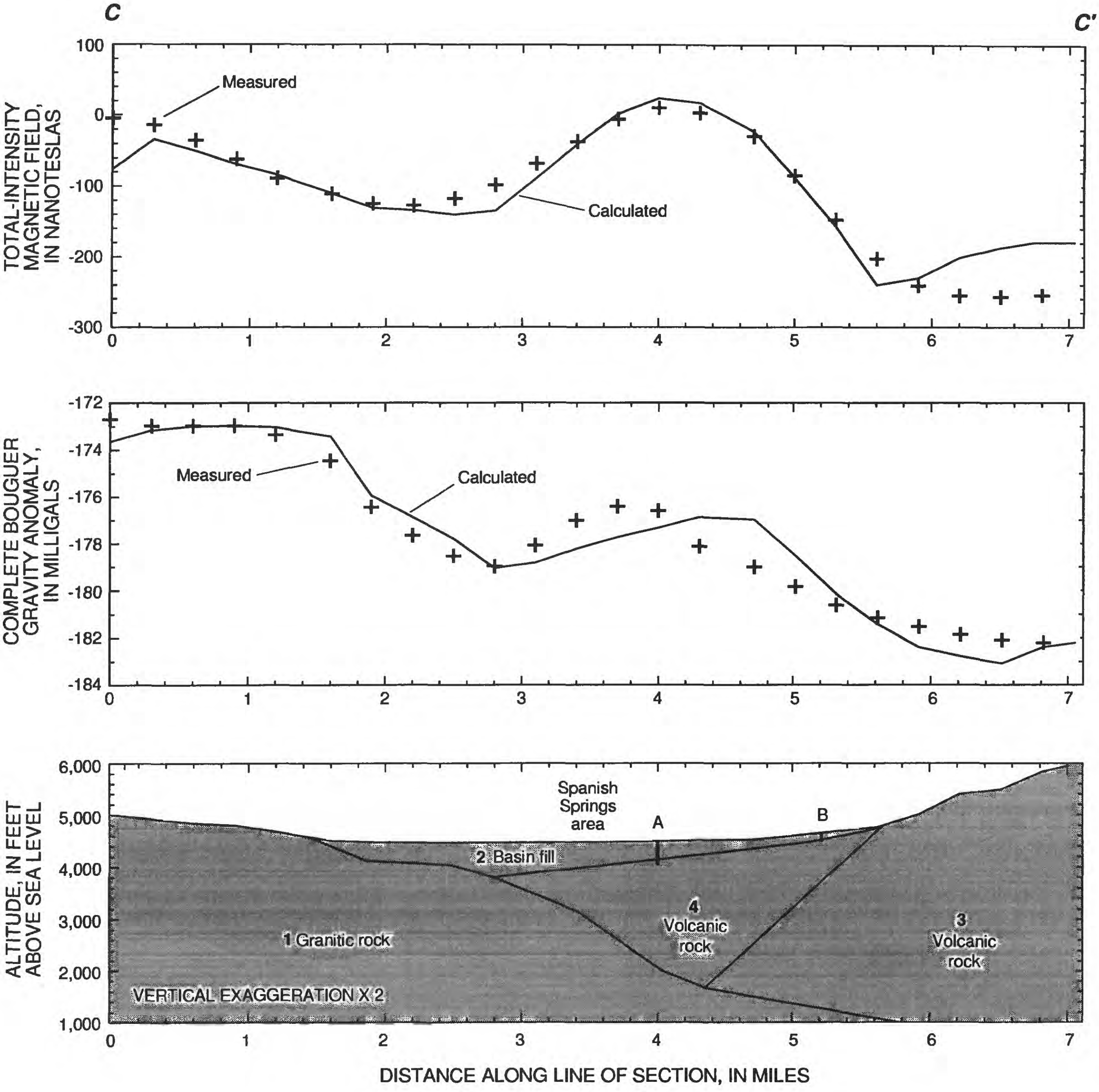
Figure 7. Measured and calculated total-intensity magnetic anomaly and complete Bouguer gravity anomaly, and generalized geologic section *A-A'* showing distribution of lithologic units determined from geophysical modeling, Spanish Springs Valley, west-central Nevada. See figures 5 and 6 for section location and table 3 for physical properties of lithologic units.



EXPLANATION

| **Well**—Penetrates consolidated rock underlying basin fill 600 feet below land surface

Figure 8. Measured and calculated total-intensity magnetic anomaly and complete Bouguer gravity anomaly, and generalized geologic section *B-B'* showing distribution of lithologic units determined from geophysical modeling, Spanish Springs Valley, west-central Nevada. See figures 5 and 6 for section location and table 3 for physical properties of lithologic units.



EXPLANATION

| **Well**—Penetrates consolidated rock underlying basin fill (A) 460 feet and (B) 180 feet below land surface

Figure 9. Measured and calculated total-intensity magnetic anomaly and complete Bouguer gravity anomaly, and generalized geologic section *C-C'* showing distribution of lithologic units determined from geophysical modeling, Spanish Springs Valley, west-central Nevada. See figures 5 and 6 for section location and table 3 for physical properties of lithologic units.

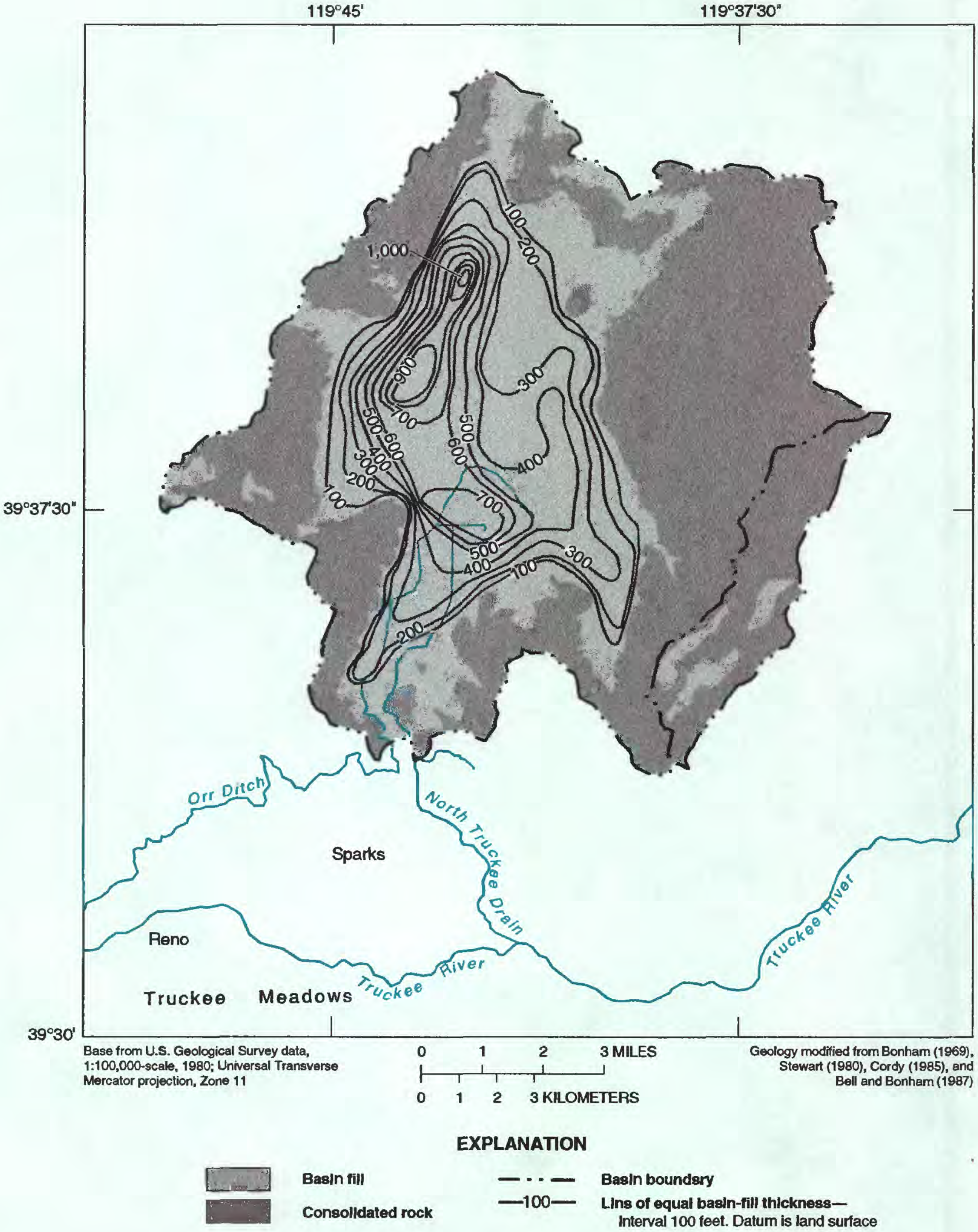


Figure 10. Thickness of basin fill, Spanish Springs Valley, west-central Nevada.

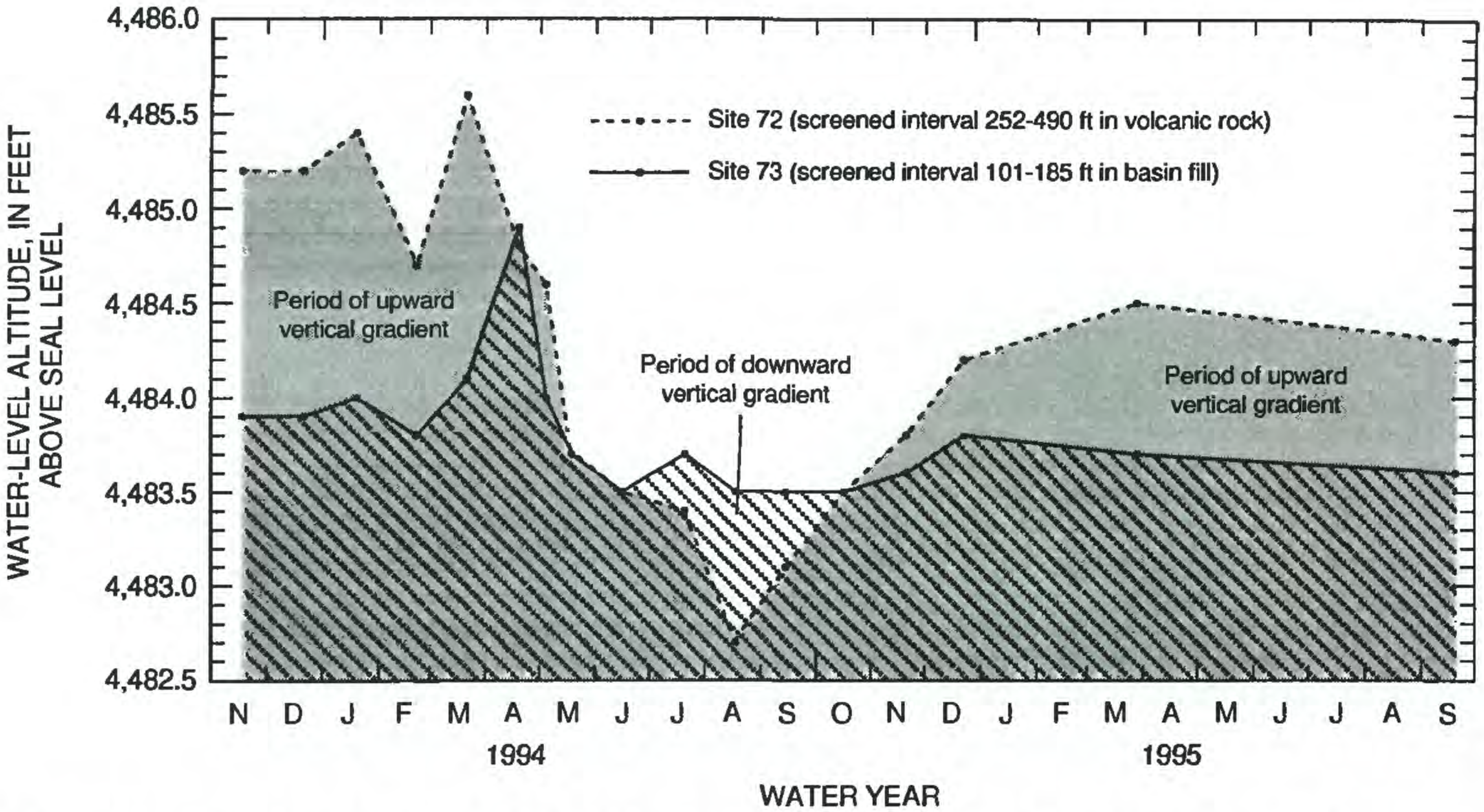


Figure 11. Water levels for sites 72 and 73, November 1993-September 1995, Spanish Springs Valley, west-central Nevada.

Storage coefficient is defined by Lohman (1972, p. 8) as the volume of water an aquifer releases or takes into storage per unit surface area of aquifer per unit change in head. The amount of ground water available from storage in basin-fill aquifers depends on whether the aquifer is under unconfined or confined conditions. Under unconfined conditions, the storage coefficient is virtually equal to specific yield, which is the amount of water released from storage by gravity drainage. Water released from storage under confined conditions depends on the elastic characteristics of the aquifer and the expansion of water. Storage coefficients for confined aquifers are three to five orders of magnitude smaller than the specific yield of unconfined aquifers.

Specific yield of basin fill ranges from about 30 percent in well-sorted sands or gravel to less than 5 percent in compacted clay (Johnson, 1967). Estimates of specific yield in the upper 330 ft of saturated basin fill (unconfined conditions) in Spanish Springs Valley average about 13 percent and range from 10 to about 20 percent on the basis of basin-fill textures reported from drillers' logs and aquifer tests (W.E. Nork, Inc., 1988a, 1988b). Values of storage coefficient for confined basin-fill aquifers are on the order of 0.005 or less (Fetter, 1994). Analysis of a short-term (980 minutes) aquifer test at a well near the center of the valley resulted in a storage coefficient of 0.0005 (D.A. Mahin, Washoe County, written commun., 1984). For deeper parts of the basin fill assumed to be confined, aquifer storage coefficients were estimated by multiplying the thickness of the deposits (in feet) by 1×10^{-6}, as suggested by Lohman (1972, p. 53). In the study area, thickness of saturated basin fill ranges from 0 to about 1,000 ft. If water yield is entirely from the expansion of stored water in the confined aquifer and none is from the compaction of fine-grained material, the storage coefficient for confined deposits that are 100 to 1,000 ft thick would range from 0.0001 to 0.001.

The potentially recoverable water stored in basin fill can be estimated as the product of an area, a thickness, and a specific yield. Thickness of saturated basin fill was determined from data shown in figure 10 and depths to water measured in December 1994. The total amount of recoverable water stored in the basin-fill aquifer in the upper 330 ft of saturated basin fill, assuming a range of specific yield of 10 to 20 percent, is estimated to be between 300,000 and 600,000 acre-ft.

HYDROLOGIC SETTING

Spanish Springs Valley lies at the extreme western margin of the Great Basin desert region and within the rain shadow of the Sierra Nevada. These physiographic features create an arid to semi-arid environment that dominates the hydrologic setting of the study area.

Climate and Vegetation

The principal sources of moisture to the region are the Pacific Ocean and the Gulf of California. The most important source is the Pacific Ocean, which provides moisture from October to June; the Gulf of California produces most of the moisture from July to mid-September (Houghton, 1969, p. 5; Brenner, 1974). Moisture-laden air moving eastward from the Pacific Ocean cools and condenses as it rises over the Sierra Nevada, resulting in as much as 70 in. of precipitation on the west slopes, with considerably less in valleys to the east (Klieforth and others, 1983, p. 4). During summer months, tropical air from the Gulf of California produces scattered but intense convective showers. The summers are hot and dry, with daytime temperatures occasionally exceeding 100°F, and winters are cool, with temperatures sometimes falling below 0°F.

No long-term precipitation stations operate within the study area; however, precipitation data are available for calendar years 1938-94 at the Reno airport about 5 mi south of the study area. The Reno airport is at about the same altitude as the south end of Spanish Springs Valley. During this period, average annual precipitation at the Reno airport was about 7.2 in. (fig. 12*A*), with a maximum of 13.2 in. (1983) and a minimum of 1.6 in. (1947). Precipitation in 1993 and 1994 was greater at the Reno airport than recorded at the station on the valley floor in Spanish Springs Valley (site 83, table 4). Weather data collected at the Reno airport, however, were assumed to be fairly typical of the study area.

Annual precipitation on the valley floor in Spanish Springs Valley is generally less than 8 in. and annual evaporation is probably greater than 40 in. (Van Denburgh and others, 1973, p. 53). The surrounding mountains receive 9 to 11 in. in an average year, and more than 13 in. may fall in the higher altitudes of the Pah Rah Range. The total precipitation estimated within the study area is about 36,000 acre-ft annually, of which nearly 3,500 acre-ft falls within the topographically closed Dry Lakes area in the southeast (table 5).

The greatest precipitation in the study area falls from December through February, mainly in the form of snow and freezing rain; minor amounts of precipitation accompany summer convective storms. Successive years with above- or below-average annual precipitation are shown by the cumulative departure from average in figure 12*B*. An upward slope to the right indicates above-average precipitation and downward slope indicates below-average precipitation. A trend of below-average precipitation is indicated beginning about 1984. Hydrologic data were collected as part of the current study during this trend of below-average precipitation, which may have some effect on water levels measured during this study. Precipitation at the Reno airport was 75 percent of the long-term average during 1992, 92 percent during 1993, and 72 percent during 1994.

The estimated distribution of precipitation in Spanish Springs Valley, shown in figure 13, was developed on the basis of a regression model between average annual precipitation and altitude for 34 stations (table 4). Data for complete full-year periods were used to determine the average annual precipitation representing that period of record for each station. A long-term average was then estimated for each station from the 57-year period of record (1938-94) at the Reno-airport station. The calculated linear regression equation, shown in figure 14*A*, was selected by evaluating graphs of residual values versus predicted precipitation generated from several forms of the regression equation. Using a linear relation, residual values, which are the difference between measured and predicted precipitation, are scattered an approximately equal distance above and below zero in figure 14*B*. The residual graph indicates that a linear model does not violate the assumptions of normal regression analysis and thus, a linear regression is a valid representation of the precipitation-altitude relation derived from the 34 sites. The coefficient of determination indicates that about 62 percent of the variance within the data can be explained by the linear regression model. A longer or shorter record may result in a slightly different regression equation. In addition, estimates of average annual precipitation above 7,000 ft are increasingly uncertain because this relation is not supported by high-altitude stations above 6,960 ft. Only about 11 acres near Spanish Springs Peak in the Pah Rah Range are above 7,000 ft.

The pattern of natural vegetation in Spanish Springs Valley reflects the general long-term distribution of precipitation and average depth to water. The principal vegetation is referred to as northern desert shrub (Lorain and Tueller, 1976, p. 22) and is dominated by sagebrush (*Artemisia tridentata*) with localized areas of rabbitbrush (*Chrysothamnus* sp.), greasewood (*Sarcobatus vermiculatus*), shadscale (*Atriplex confertifolia*), and several other shrubs and grasses. In areas having altitudes of 5,500 ft or higher, mixed woodlands of juniper (*Juniperus utahensis*) and

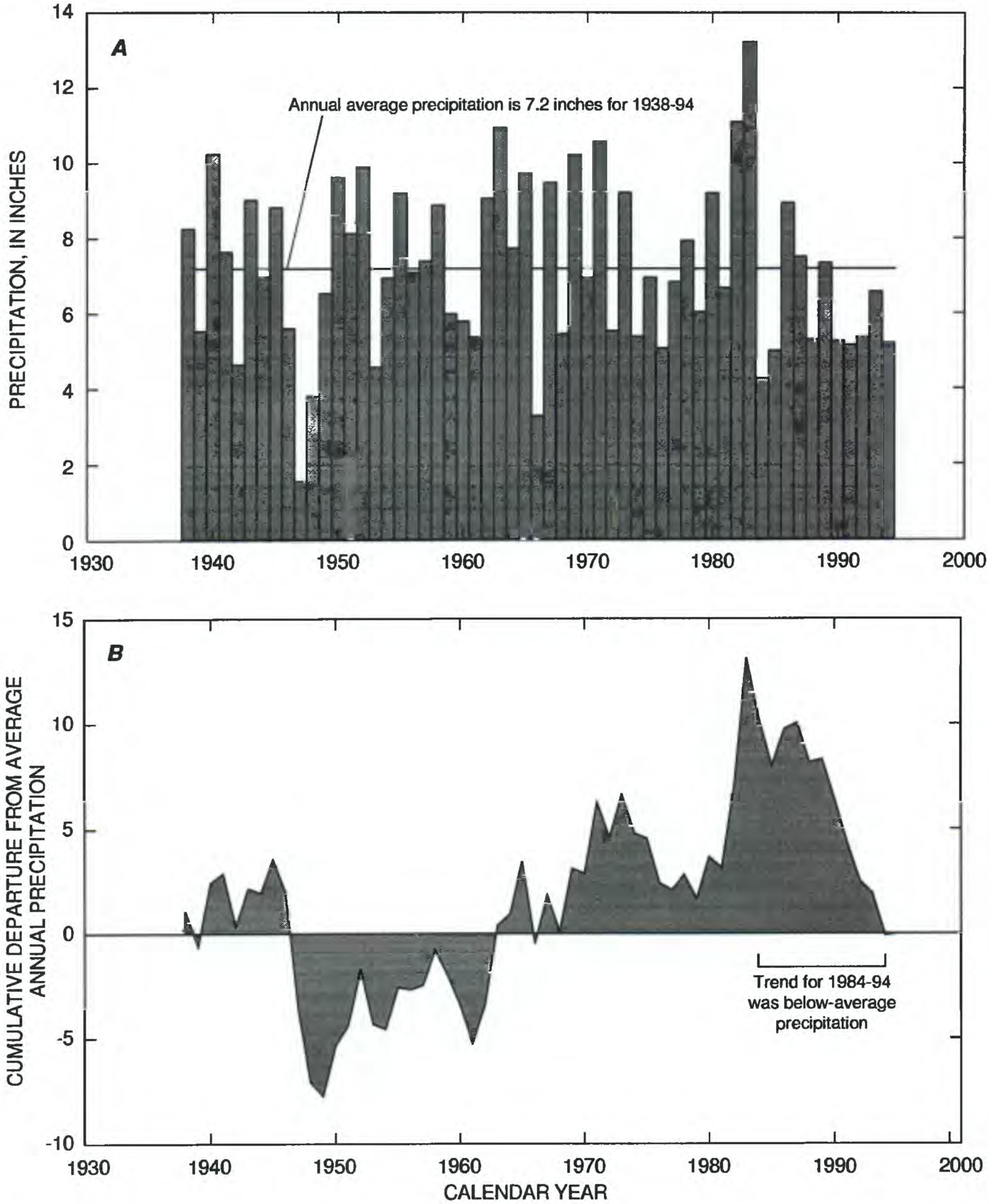


Figure 12. Annual precipitation (*A*) and cumulative departure from average precipitation (*B*) at Reno airport for 57-year period of record, 1938-94, west-central Nevada (data from National Climatic Center).

Table 4. Average annual precipitation at stations in and near Spanish Springs Valley, west-central Nevada

[Data from National Climatic Center, Harrill (1973), Joung and others (1983), Klieforth and others (1983), and H.E. Klieforth (Desert Research Institute, written commun., 1995).]

Station[1]	Altitude (feet above sea level)	Period of full-year record used (calendar years)	Average annual precipitation for period of record (inches)	Estimated long-term average annual precipitation[2] (inches)
Churchill Canyon can No. 11	6,960	1964-80	13.39	13.1
Churchill Canyon can No. 10	6,400	1964-80	13.31	13.0
Virginia City	6,340	1968-93	14.25	14.3
Churchill Canyon can No. 13	6,320	1964-77	11.03	10.9
Churchill Canyon can No. 12	6,020	1964-77	10.79	10.6
Churchill Canyon can No. 9	5,910	1964-80	12.60	12.3
Curnow Canyon, **site 79**	5,709	1993-94	[3]7.9	9.6
Churchill Canyon can No. 5	5,700	1964-80	7.76	7.6
Churchill Canyon can No. 7	5,680	1964-77	8.78	8.6
Churchill Canyon can No. 8	5,550	1964-80	10.68	10.4
Hungry Ridge South, **site 81**	5,358	1993-94	[3]7.8	9.5
Churchill Canyon can No. 6	5,330	1964-80	7.82	7.6
Churchill Canyon can No. 14	5,320	1964-77	8.82	8.7
Dry Lakes, **site 85**	5,282	1993-94	[3]6.8	8.3
Churchill Canyon can No. 16	5,220	1964-77	7.58	7.5
Churchill Canyon can No. 15	5,200	1964-77	7.10	7.0
Canoe Hill, **site 87**	5,200	1993-94	[3]6.3	7.7
Churchill Canyon can No. 4	5,070	1964-80	7.85	7.6
Bacon Rind Flat, **site 78**	5,052	1993-94	[3]7.4	9.0
Stead	5,046	1952-66	11.10	8.4
Hungry Ridge North, **site 80**	4,954	1993-94	[3]7.4	9.0
Churchill Canyon can No. 2	4,760	1964-80	6.35	6.2
Vista, **site 84**	4,710	1993-94	[3]6.4	7.8
Northwest Reno-HK	4,690	1973-94	9.17	9.5
Carson City	4,651	1949-93	10.58	10.3
Churchill Canyon can No. 1	4,620	1964-80	6.84	6.7
Junction 395/47-8	4,590	1969-94	10.62	10.7
Oasis Trailer Park, **site 86**	4,551	1993-94	[3]6.5	7.9
Fire station, **site 83**	4,496	1993-94	[3]4.1	5.0
Reno Airport	4,404	1938-94	7.19	7.2
Churchill Canyon can No. 3	4,390	1964-80	6.36	6.2
Fernley	4,160	1941-89	6.05	6.0
Sutcliff	3,980	1968-69, 1971, 1980-84, 1987-90	7.41	6.3
Nixon	3,900	1929-47, 1949 1952, 1963-69	6.99	6.1

[1] Stations are listed in order of descending altitude. Bold site numbers can be used to locate stations in figures 3 and 13.

[2] Adjusted to long-term averages on the basis of comparison with 57-year period of record, 1938-94, at the Reno airport.

[3] Partly estimated.

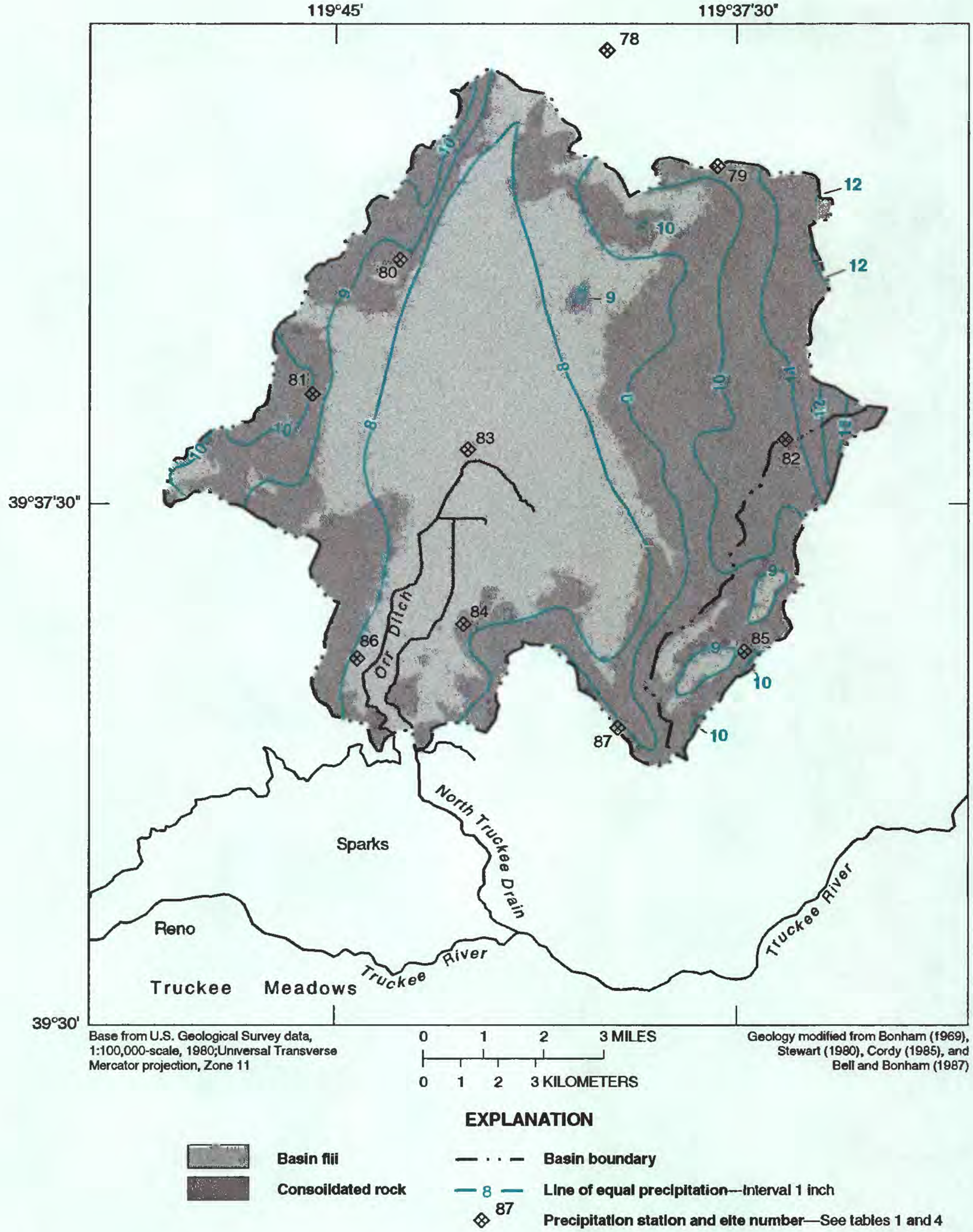


Figure 13. Precipitation stations and average annual precipitation, Spanish Springs Valley, west-central Nevada.

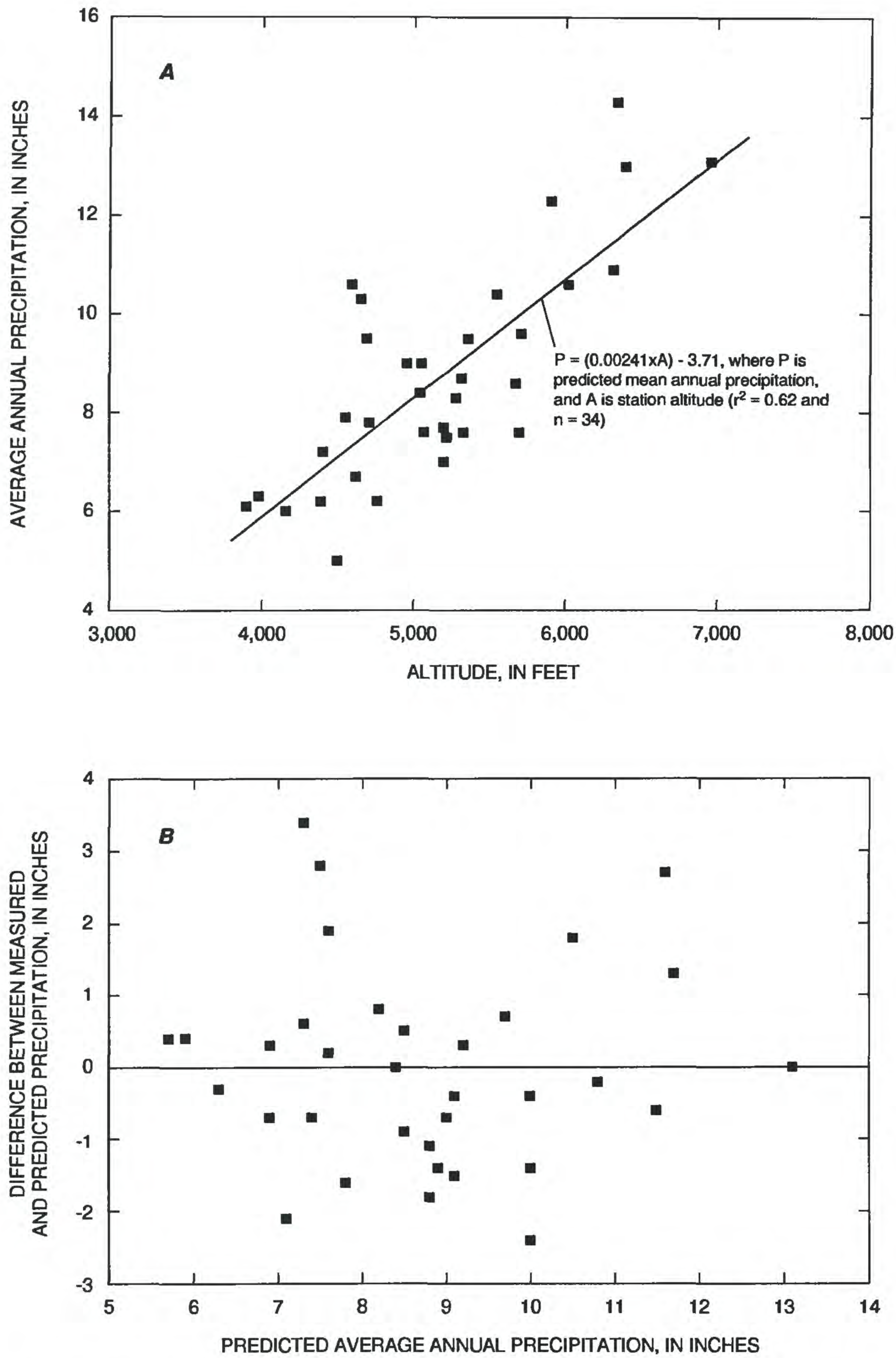


Figure 14. Relation of average annual precipitation to altitude for 34 precipitation stations used in determining distribution of precipitation *(A)* and relation of difference between predicted and measured precipitation (residual values) to predicted average precipitation *(B)*, Spanish Springs Valley, west-central Nevada.

Table 5. Estimated average annual precipitation and ground-water recharge in Spanish Springs Valley area, west-central Nevada

Precipitation zone [1] (inches)	Area (acres)	Average annual precipitation [2] Feet	Average annual precipitation [2] Acre-feet [3] (rounded)	Average annual recharge Assumed percent of precipitation	Average annual recharge Acre-feet per year [3] (rounded)
Spanish Springs Valley					
More than 12	240	1.10	260	7	18
8 to 12	29,130	.78	23,000	3	690
Less than 8	17,450	.58	10,000	minor	0
Subtotal	46,820		33,000		710
Dry Lakes area					
More than 12	330	1.08	360	7	25
8 to 12	3,780	.82	3,100	3	93
Subtotal	4,110		3,500		120
Total	50,930		36,000		830

[1] Developed from precipitation-altitude relation as part of this study.
[2] Area-weighted average precipitation within individual zones of more than 13 inches, 12 to 13 inches, 11 to 12 inches, 10 to 11 inches, 9 to 10 inches, 8 to 9 inches, and less than 8 inches.
[3] Rounded to two significant figures.

pinon pine (*Pinus monphylla*) are found in limited areas, mainly in the Pah Rah Range. With the onset of delivered imported water for irrigation in the southern part of the valley, riparian-type vegetation has developed along several irrigation ditches and numerous shallow ponds. Currently (1994), meadow grasses and crop land cover about 980 acres of the total ditch-irrigated area (about 3,800 acres), and several hundred head of cattle graze within the area encompassed by the Orr Ditch. Agricultural lands outside the influence of the Orr Ditch are irrigated solely with ground water. The growing season is about 120 to 160 days.

Surface-Water Flow System

Surface water in Spanish Springs Valley consists almost entirely of imported Truckee River water used to support agriculture in the southern part of the valley. However, several dry channels throughout the study area indicate that, occasionally, sufficient precipitation falls to produce some runoff from surrounding mountains. Annual potential runoff of 1,500 acre-ft was estimated by Rush and Glancy (1967, p. 18) on the basis of stream-channel geometries; however, no streamflow greater than about 5 gal/min (0.01 ft^3/s) was observed during their brief period of fieldwork. An internally drained area on the valley floor in the northern part of the study area supports a shallow ephemeral pond that probably has existed since long before settlement of the valley, based on archaeological evidence found near the pond. Currently, the pond is maintained by pumped ground water used in a nearby gravel-pit operation. The Orr Ditch has delivered water from the Truckee River through the southern boundary of the study area since 1878. The Ditch is unlined throughout its 7-mi length in Spanish Springs Valley and has numerous take-out gates to smaller ditches used for flood irrigation and stock watering. The Orr Ditch terminates in a shallow pond that also receives discharge water from the adjacent spring area. Several storage ponds, which cover about 140 acres, are within the area outlined by the Orr Ditch (fig. 1). The North Truckee Drain originates near the center of the irrigated lands within the area encompassed by the Orr Ditch. The drain conveys unused irrigation water and, to a lesser extent, ground-water discharge out of the study area to the Truckee River.

Flow volumes of the Orr Ditch as it enters the study area fluctuate annually depending on the availability of Truckee River water, which, in turn, depends on the amount of precipitation that falls in the Sierra Nevada. Daily mean discharge for the Orr Ditch (site 88) and the North Truckee Drain (site 89) for May 1992 through December 1994 is shown in figure 15. Generally, delivery of irrigation water begins in April and ends in late September for years with near-average conditions. Records kept by the Federal Water Master indicate that some flow is maintained from October to about February or March for stock watering. During the course of this study, the Orr Ditch was completely shut off by June for years 1992 and 1994 in response to below-average precipitation (fig. 15). During 1993, when conditions approached average (about 92 percent), flow remained at irrigation levels (about 30 ft^3/s and greater) until September, when it decreased to stock-watering levels (less than about 3 ft^3/s). The North Truckee Drain fluctuates in direct response to the availability of Orr Ditch water and the application of water for irrigation. During periods of no flow in the Orr Ditch, the base flow of the North Truckee Drain averages about 0.1 ft^3/s and represents part of the ground-water discharge leaving the valley.

For calendar years 1976 through 1984, average surface-water inflow to the study area from the Orr Ditch was about 16,600 acre-ft annually (Federal Water Master, written commun., 1994). In 1985, flow in the Orr Ditch was reduced to comply with the Final

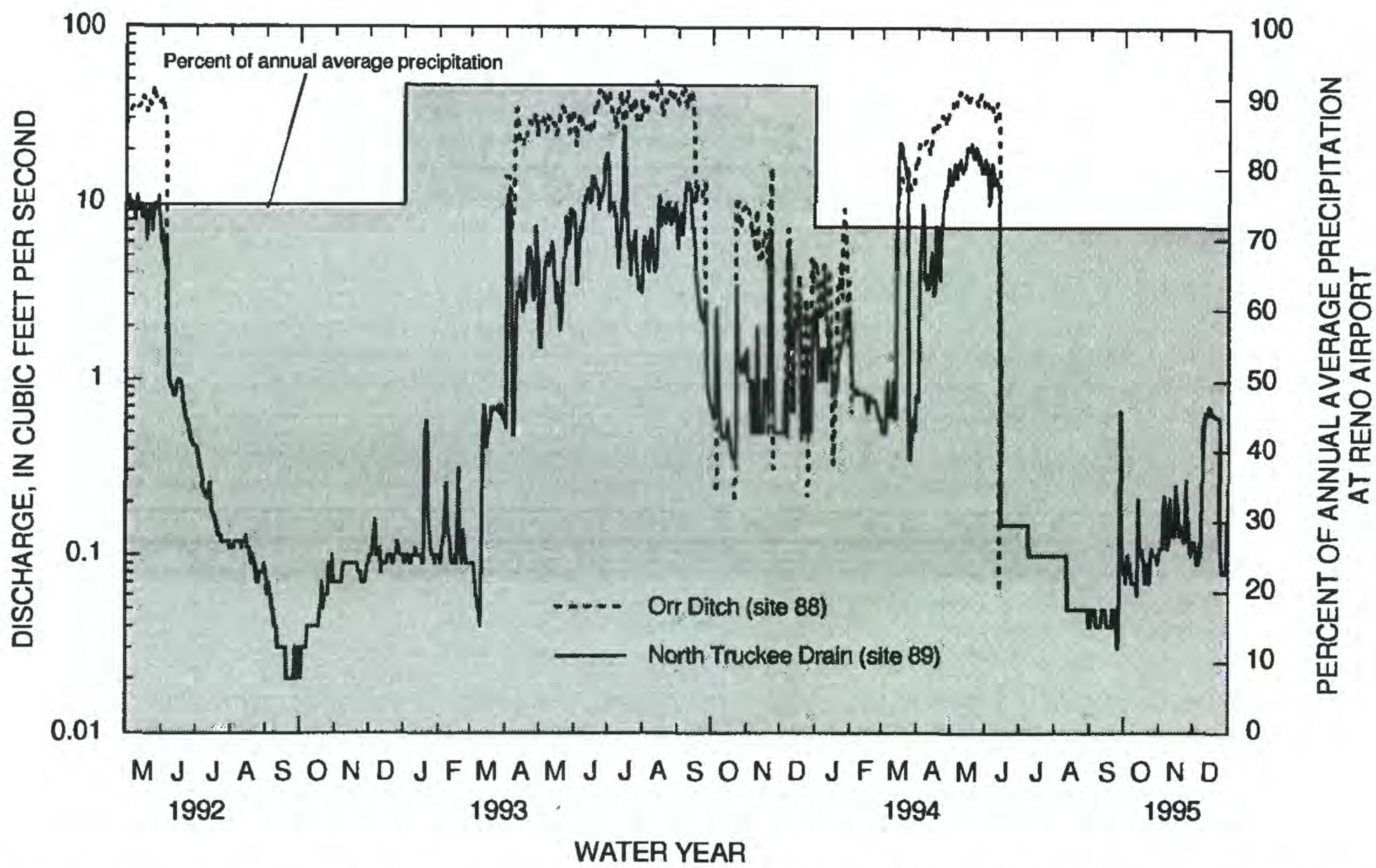


Figure 15. Daily mean discharge of Orr Ditch and North Truckee Drain, May 1992-December 1994, Spanish Springs Valley, and percent of average annual precipitation at Reno airport, 1992-94, west-central Nevada.

Federal Decree for the Orr Ditch Company (Hadiaris, 1988). Consequently, annual inflow to the study area for 1985 through 1994 averaged about 9,220 acre-ft. Surface outflow from the study area through the North Truckee Drain for 1977 through 1984 averaged about 9,430 acre-ft annually. No data are available for the North Truckee Drain for 1985 through April 1992. For calendar years 1993 and 1994, outflow of the North Truckee Drain was 2,710 and 2,370 acre-ft, respectively. On the basis of available data, the average difference between surface-water inflow and outflow for 1977 through 1984 was 7,930 acre-ft/yr. This difference represents water imported from the Truckee River that either was consumed in Spanish Springs Valley by evapotranspiration or was recharged to the shallow ground-water system. A summary of flow volumes for the Orr Ditch and North Truckee Drain is in table 6.

Stable-isotope ratios of oxygen ($\delta^{18}O$) and hydrogen (δD) and the activity of tritium were used to characterize imported surface water. The isotope composition of Truckee River water can be defined by an envelope (fig. 16) that encompasses data from 47 samples collected at Farad, Calif., along the Truckee River (Alan H. Welch, U.S. Geological Survey, written commun., 1994). The mean global meteoric-water line

Table 6. Summary of flow for Orr Ditch and North Truckee Drain, 1976-94, near Spanish Springs Valley, west-central Nevada

[Values are acre-feet (rounded); --, ungaged]

Year [1]	Orr Ditch (site 88)	North Truckee Drain (site 89)	Difference (inflow minus outflow)
1976	10,620	--	
1977	14,140	8,150	5,990
1978	19,980	10,730	9,250
1979	19,580	9,710	9,870
1980	17,690	9,650	8,040
1981	17,940	6,640	11,300
1982	16,440	8,350	8,090
1983	17,050	11,850	5,200
1984	16,030	10,330	5,700
1985	12,540	--	
1986	9,610	--	
1987	9,980	--	
1988	10,320	--	
1989	11,260	--	
1990	10,180	--	
1991	6,850	--	
1992	4,350	--	
[2]1993	11,640	2,710	8,930
[2]1994	5,510	2,370	3,140

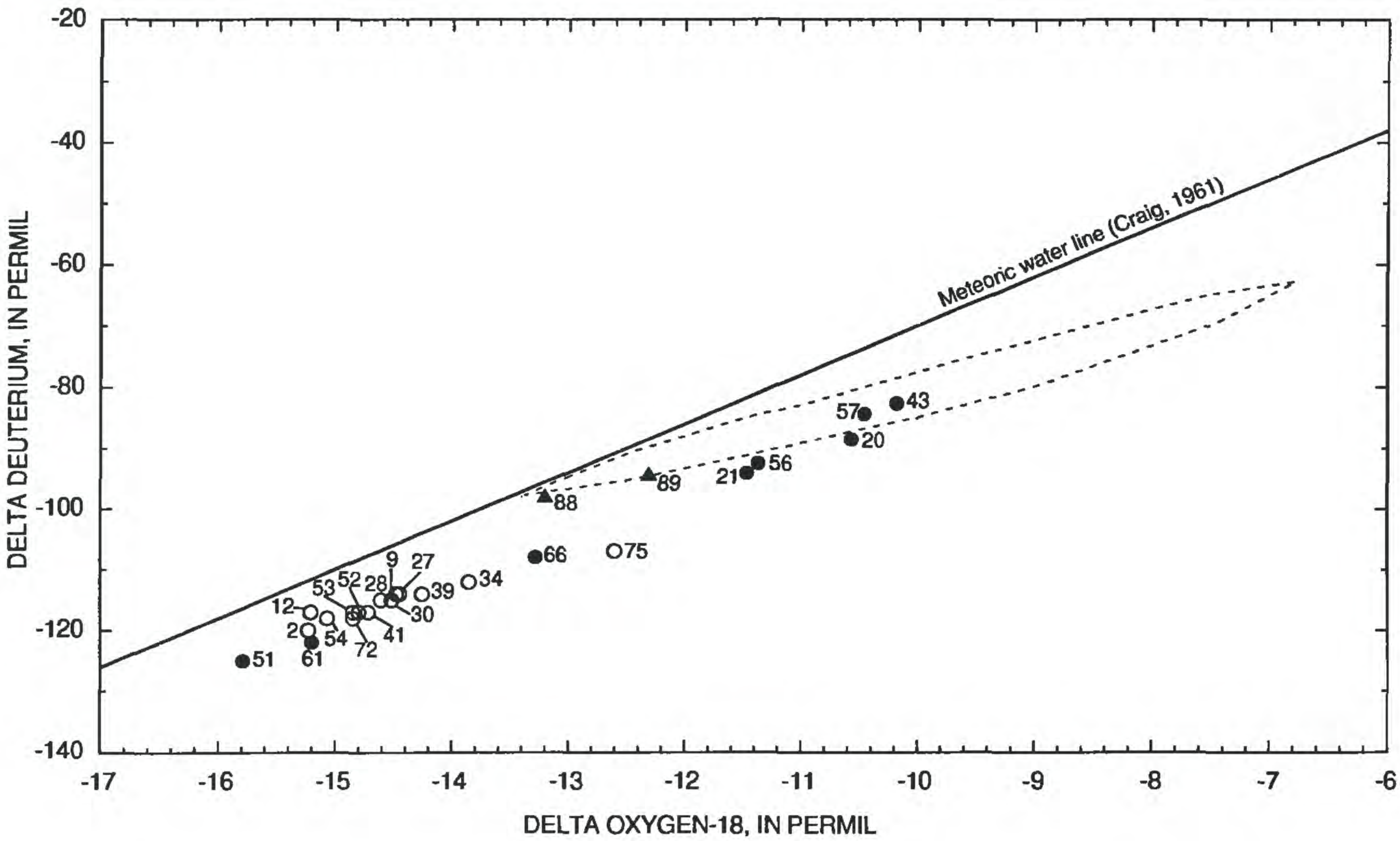
[1] Data from Federal Water Master, except as indicated; record for 1985-91 collected during irrigation season only.
[2] Data collected as part of this study.

[δD = 8(δ^{18}O) + 10; Craig, 1961] also is shown (fig. 16) and represents the isotope composition of precipitation. Average δ^{18}O and δD of Truckee River samples were -10.2 and -82 permil, respectively. Isotope ratio of the Truckee River samples showed some variability, partly due to seasonal evaporation and to temporal changes in upstream inflow. Samples from the Orr Ditch and North Truckee Drain collected at the gaging stations (sites 88 and 89) plot near the edge of the envelope. The tritium activities for the Orr Ditch and North Truckee Drain samples were 17 and 15 pCi/L, respectively. Stable isotope compositions for selected ground-water and surface-water sites in the study area are presented by Emett and others (1994, p. 557) and Clary and others (1995, p. 732).

Sources and Movement of Ground Water

Virtually all ground water in Spanish Springs Valley is derived from two sources: imported surface water and precipitation that falls within the drainage basin. Most ground water is found in saturated unconsolidated and partly consolidated alluvium of the basin fill under water-table and confined conditions. Ground water also is found in localized areas of highly fractured rock, generally under confined conditions.

Ground water moves along paths of least resistance, from areas of high hydraulic head to areas of low hydraulic head. Water-level contour maps, which show lines of equal hydraulic head, were constructed from water-level measurements collected in December 1992, May 1994, and December 1994 (figs. 17, 18, and



EXPLANATION

- - - - - - - **Boundary of envelope encompassing data from 47 Truckee River samples**—From Alan H. Welch (U.S. Geological Survey, written commun., 1994)

Site and number (table 1 and figure 3)—Solid symbol indicates tritium activity above 1 picocurie per liter

O 12 Ground-water sampling site

▲ 88 Imported surface-water sampling site

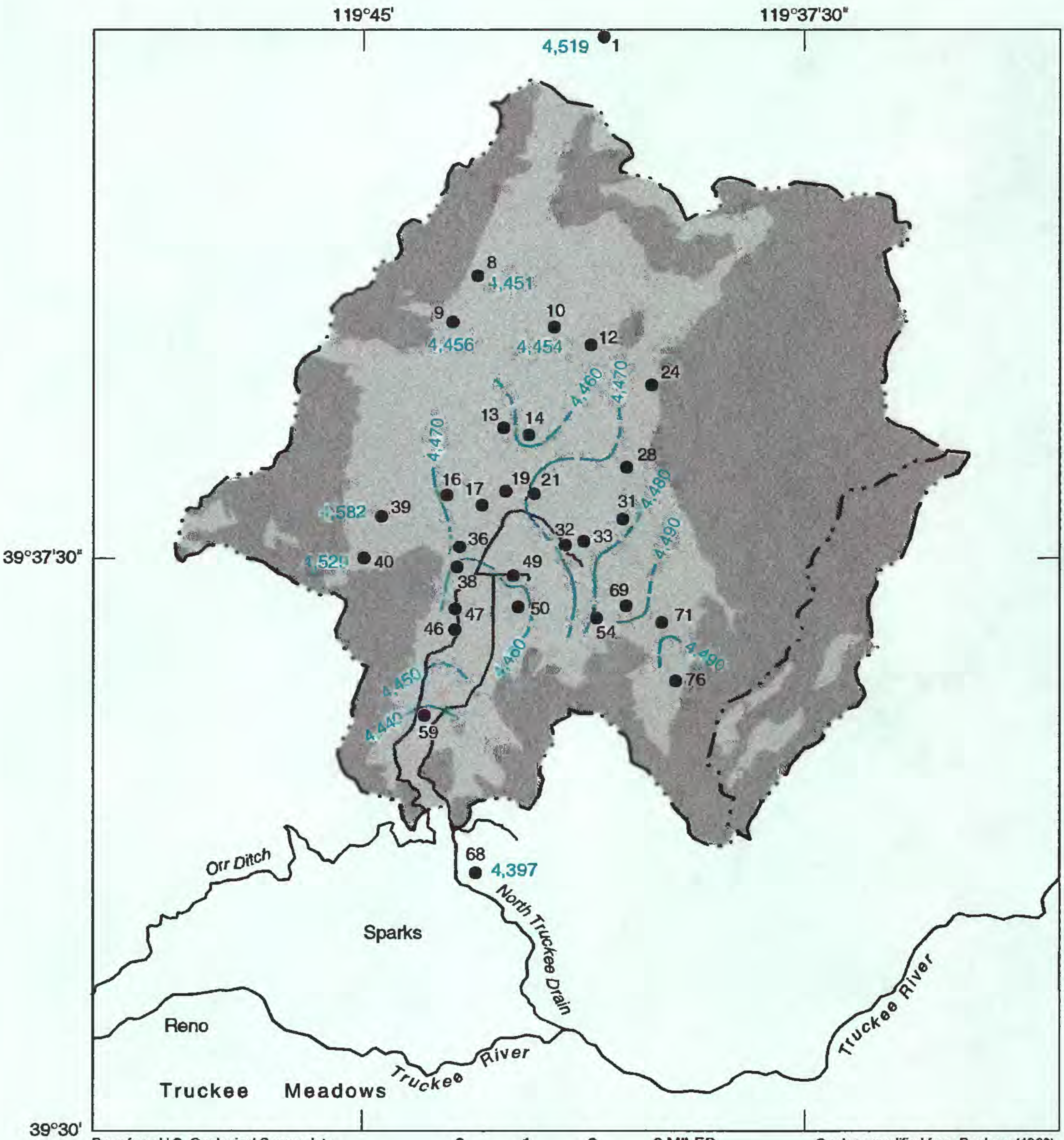
Figure 16. Relation of deuterium to oxygen-18 in sampled ground water and imported surface water, Spanish Springs Valley and Truckee River, west-central Nevada. Equation for meteoric water line, $\delta D = 8(\delta^{18}O) + 10$ (Craig, 1961). Number corresponds to sample site listed in table 1 and location shown on figure 3.

19, respectively). The water-level contours were constructed from measurements in wells reported to be screened within basin fill. For the most part, the screened interval or the gravel pack is through the entire saturated thickness penetrated by the well. This results in a hydraulic head that represents a composite water level not necessarily the same as the water table; however, owing to the discontinuous nature of the basin fill, the upper 200 to 300 ft probably acts as a single system. The December 1992 contour map (fig. 17) reflects ground-water conditions following several years of below average precipitation and no flow in the Orr Ditch since early June 1992. Water-level contours for May 1994 (fig. 18) show conditions following a year of near-average precipitation (1993) and a subsequent extended period of flow in the Orr Ditch. Water-level contours for December 1994 (fig. 19) show conditions following a season of below-average precipitation and no flow in the Orr Ditch since June 1994. Although the configuration of the shallow ground-water surface in Spanish Springs Valley changed seasonally, the direction of ground-water flow generally remained the same during these periods. In addition, a ground-water divide near the center of the valley is present during each time period.

During the irrigation season, transmission losses along the Orr Ditch and infiltration of water applied to fields result in the greatest source of recharge to the basin-fill aquifer system. Because of near-average precipitation in 1993 (about 92 percent of average, from data collected at the Reno airport, fig. 15), the Orr Ditch flowed almost continuously into Spanish Springs Valley from April 1993 through June 1994. Changes in ground-water levels shown in figures 20 and 21 illustrate the effects that near-average flow conditions have on the shallow ground-water system in the basin fill. Water levels beneath the irrigated area rose 5 ft or more from December 1992 through May 1994 in response to recharge from imported surface water (fig. 20). Water levels in wells adjacent to but outside the irrigated area also were affected by the Orr Ditch, with rises of 1 to 4 ft. The distribution of rises in water level defines the extent of a ground-water mound that develops beneath the southern part of the valley during periods of flow in the Orr Ditch and subsequent application of irrigation water. Declines in water levels for the same period were measured generally in the northern part of the valley in response to ground-water withdrawal with no substantial source of recharge. Between May and December 1994 (fig. 21), water-level declines were generally beneath the area of irrigation. These declines suggest that the ground-water mound that develops during the irrigation season dissipates with time.

Ground-water recharge from precipitation takes place in or adjacent to the mountains through weathered or fractured bedrock or when intermittent runoff infiltrates dry channel deposits. Precipitation that falls on the valley floor is considered to be a negligible source of recharge, although some recharge may be generated during extremely localized rain. In eastern and western parts of the valley, ground water in basin fill generally flows toward the center of the basin, away from recharge-source areas in the mountains. The stable-isotope composition of this water, sampled from several wells along edges of the basin and away from the effects of recharge from the Orr Ditch, is closely grouped when plotted on a graph of $\delta^{18}O$ versus δD in figure 16 (sites 2, 9, 12, 27, 28, 30, 39, 41, and 72). Samples from these sites are isotopically lighter than Truckee River water and are assumed to be indicative of locally derived recharge on the basis of comparison to the envelope defined by Truckee River water. Ages estimated from CFC data (table 7) collected at these sites (except site 72) indicate that the sampled ground water was more than 20 years old and probably more than 40 years old (Eurybiades Busenberg and L. Neil Plummer, U.S. Geological Survey, written communs., 1993, 1995). The tritium activities in these waters were below the analytical reporting limits (less than 1 pCi/L), indicating aquifers sampled by these wells have not yet received recharge from precipitation that fell prior to about 1952. Tritium levels of precipitation prior to above-ground nuclear testing (1952) are assumed to be similar to what present (1994) levels are approaching, about 25 pCi/L (Welch, 1994, p. 16). Radioactive decay of 25 pCi/L activity for about 60 years results in a tritium level less than 1 pCi/L. The absence of tritium activity in these waters and their relative positions on the $\delta^{18}O$ and δD plot in figure 16 support the conclusion that sampled ground water from these peripheral wells probably originated as precipitation within the study area.

Recharge generated from about 3,500 acre-ft of annual precipitation estimated to fall within the topographically closed Dry Lakes area (table 5) may enter the basin fill of Spanish Springs Valley at depth through fractures within the Pah Rah Range in the southeastern part of the study area. Stable-isotope composition ($\delta^{18}O$ and δD) of sampled water from two flowing wells (sites 52 and 53, fig. 3) near the spring area on the valley floor was isotopically lighter than Truckee River water.



Base from U.S. Geological Survey data, 1:100,000-scale, 1980; Universal Transverse Mercator projection, Zone 11

0 1 2 3 MILES

0 1 2 3 KILOMETERS

Geology modified from Bonham (1969), Stewart (1980), Cordy (1985), and Bell and Bonham (1987)

EXPLANATION

Basin fill

Consolidated rock

—4,490— — **Water-level contour, December 1992**—Shows altitude of water level in well screened in basin fill. Contour interval is 10 feet; dashed where approximately located. Datum is sea level

Basin boundary

● 68 4,397 **Well and sites number**—Location of well used as control point. For selected wells, water-level altitude is indicated

Figure 17. Ground-water levels in basin fill, December 1992, Spanish Springs Valley, west-central Nevada.

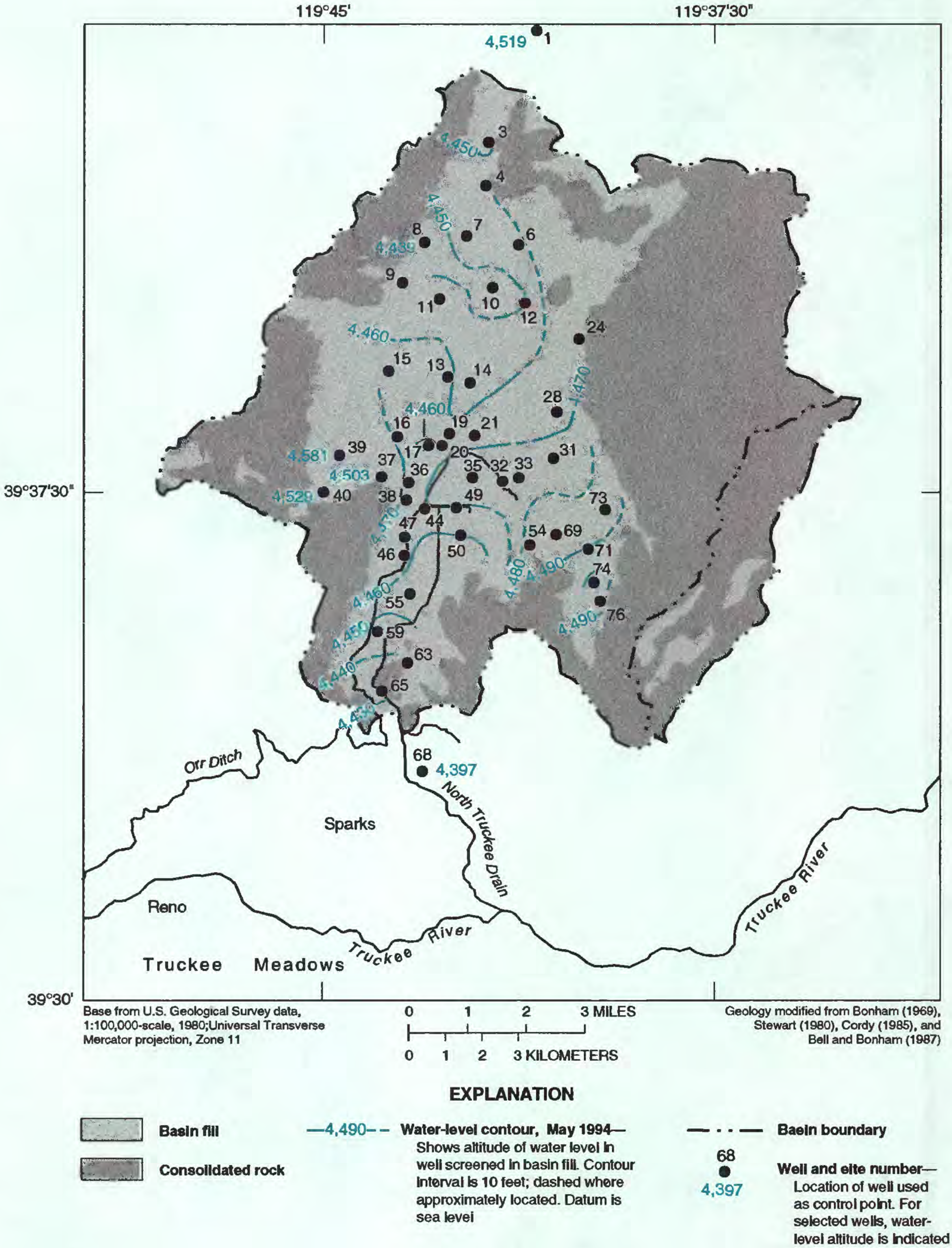


Figure 18. Ground-water levels in basin fill, May 1994, Spanish Springs Valley, west-central Nevada.

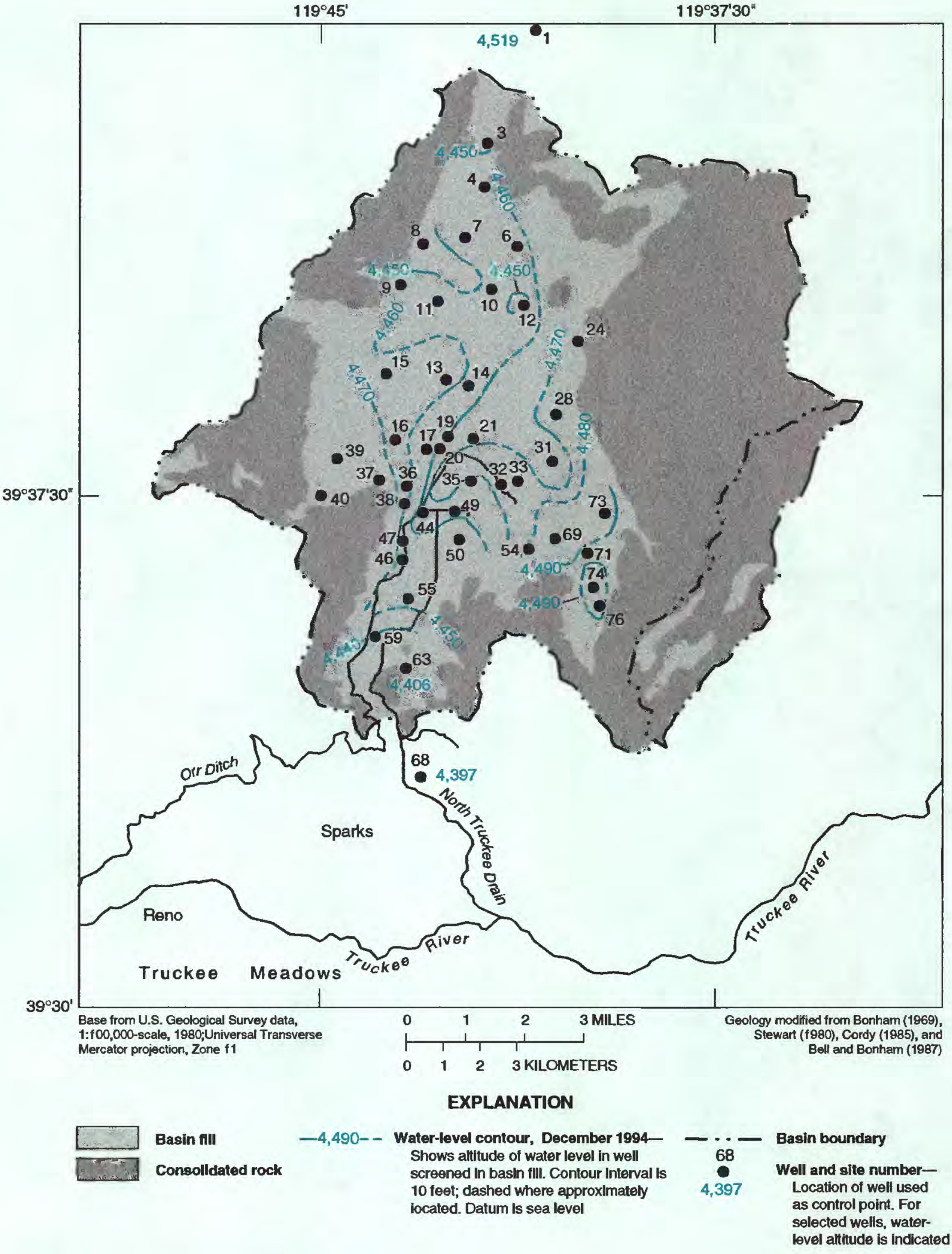


Figure 19. Ground-water levels in basin fill, December 1994, Spanish Springs Valley, west-central Nevada.

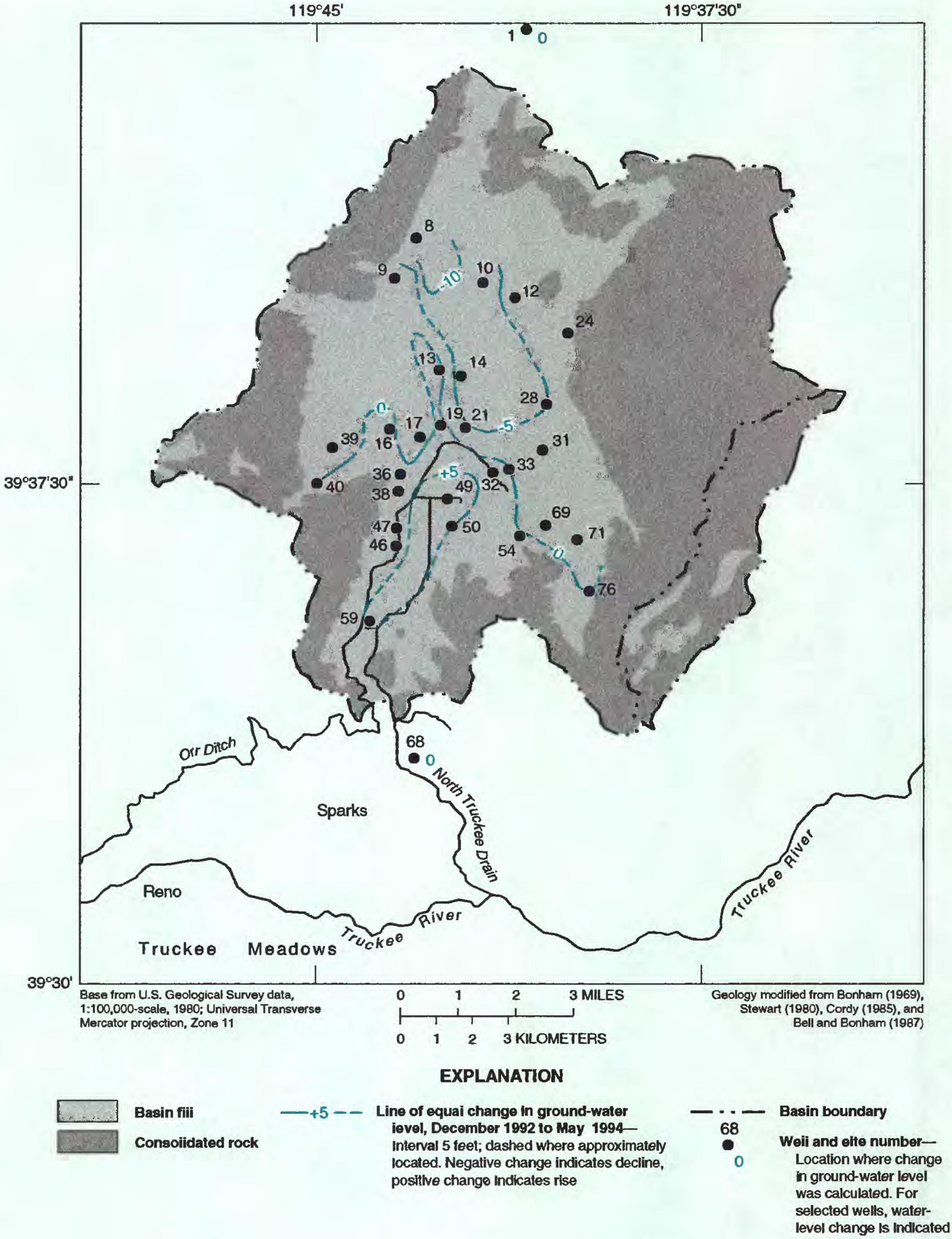


Figure 20. Change in ground-water level in basin fill from December 1992 to May 1994, Spanish Springs Valley, west-central Nevada.

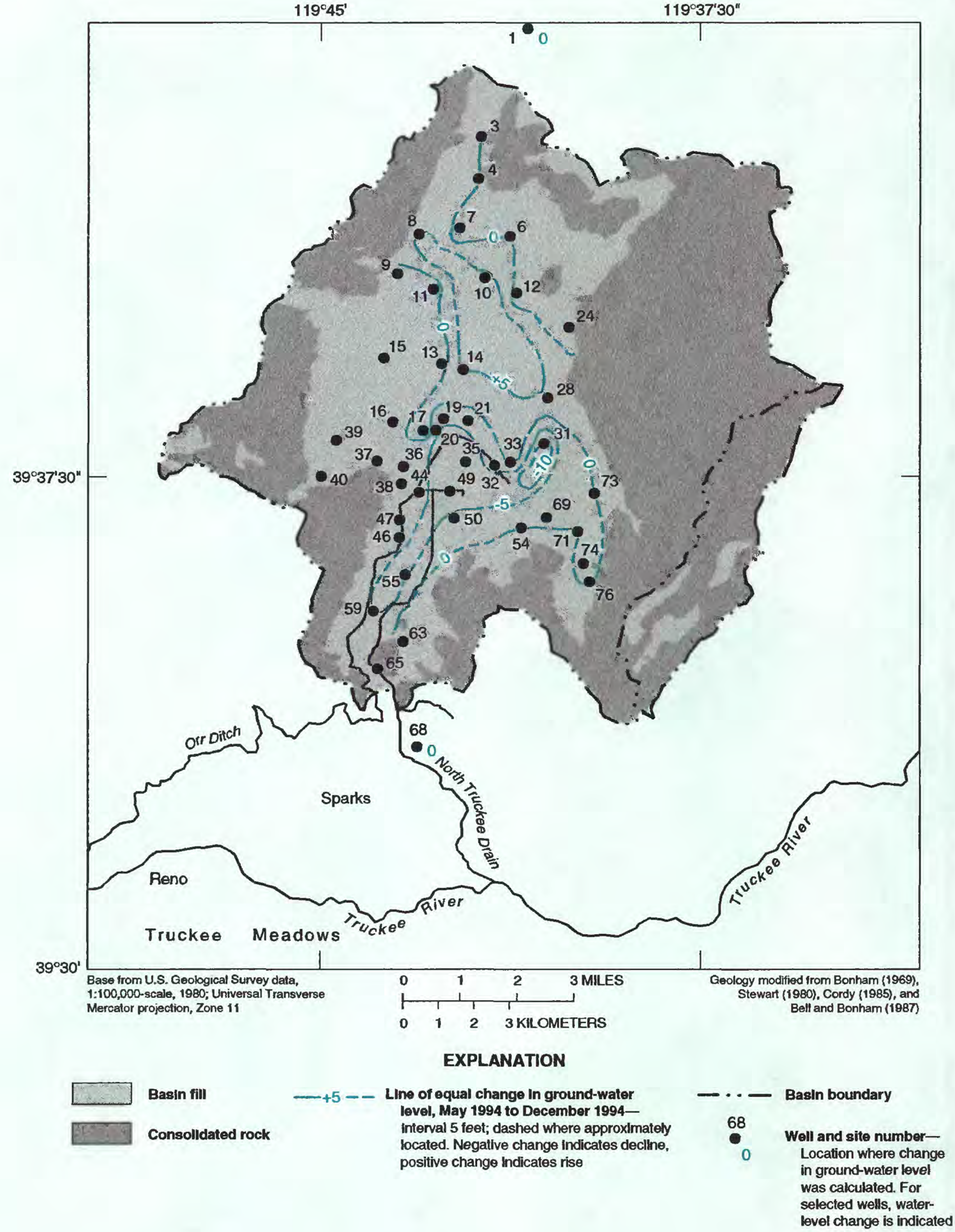


Figure 21. Change in ground-water level in basin fill from May 1994 to December 1994, Spanish Springs Valley, west-central Nevada.

Table 7. Concentrations of chlorofluorocarbons (CFC's) and tritium in ground water and corresponding CFC-model recharge ages in Spanish Springs Valley area, west-central Nevada

[Abbreviations and symbols: CFC-11, trichlorofluoromethane (CCl_3F); CFC-12, dichlorodifluoromethane (CCl_2F_2); CFC-113, trichlorotrifluoroethane ($C_2CL_2F_3$); pg/L, picogram per liter; pCi/L, picocurie per liter; --, not sampled or estimated; <, below analytical reporting limits. Data from USGS Chlorofluorocarbon Laboratory and USGS National Water Quality Laboratory]

Site number (fig. 3)	Sample date	CFC-11 (F-11, pg/L)	CFC-12 (F-12, pg/L)	CFC-113 (F-113, pg/L)	CFC-model recharge age [1]	Tritium (pCi/L)
2	8/19/93	6.6	11.4	<1	1954	<1
9	8/18/93	<1	1.0	<1	1945	<1
12	8/18/93	6.0	2,054	5.5	1954	<1
20	8/17/94	760	147	92	1980	13
21	8/18/93	2,012	128	281	1983	10
27	8/17/93	2.2	3.9	<1	1950	<1
28	8/17/93	3.3	3.6	<1	1950	<1
30	8/17/93	6.3	6.5	<1	1953	<1
34	8/17/93	1.2	1.3	<1	1946	<1
39	8/16/93	1.2	<1	<1	1940	<1
41	8/16/93	17	10.1	<1	1955	<1
43	8/15/94	66	120	34	1966	31
51	1/13/94	--	--	--	--	2
52	9/06/94	<1	<1	<1	1946	<1
53	9/06/94	1.0	1.5	<1	1947	<1
54	8/20/93	1.1	1.7	<1	1947	<1
56	8/11/94	138	81	12	1971	21
57	8/16/94	414	209	38	1984	29
61	8/19/93	47	79	6.7	1963	3
66	8/20/93	--	--	--	--	13
72	1/13/94	--	--	--	--	<1
75	8/19/93	21	414	<1	1959	<1

[1] Modeled age of ground water (time since infiltrating water recharged aquifer). Presence of CFC-12 indicates that part of sample water was recharged since 1940, CFC-11 indicates recharge since 1945, and CFC-113 indicates recharge as recent as 1966.

This suggests that deep ground water is moving upward into the basin fill aquifer beneath the southeastern part of the study area possibly from the Dry Lakes area. These data also indicate that infiltration of imported surface water appears to be mainly in the shallow basin fill.

Ground water flows southward out of Spanish Springs Valley through the basin fill and probably through fractured bedrock to Truckee Meadows. Water-level gradients to the south are about 16.5 ft/mi during the non-irrigation season (December) and about 19 ft/mi during the irrigation season (May). Stable-isotope data collected from a well screened in volcanic rock, located just south of the southern boundary (site 66, fig. 3), indicate that the water is a mixture of locally derived recharge and Truckee River water. Although pumping from this well may facilitate downward migration of near-surface ground water, analysis of the geochemical data suggests that ground water may leave the basin through fractured or weathered bedrock and through basin fill.

Ground water also flows from the ground-water divide toward the northern part of the study area. Geochemical data from a municipal well (site 21, fig. 3) screened in more than 120 ft of saturated basin fill suggest that the ground water is a mixture of local recharge and Truckee River water at least 2,000 ft north of the Orr Ditch. Using δD values of -116 permil for locally derived recharge and -82.1 permil for Truckee River water, ground water collected from the well is about 35 percent local recharge and 65 percent Truckee River water. A modeled CFC recharge date for this sample is 1983 (site 21, table 7), adjusted for the relative composition of Truckee River water. In addition, the sample contained a tritium activity of 10 pCi/L, implying that a component of the ground water was recharged since about 1958 (Welch, 1994, p. 16). These results all support the conclusion that imported Truckee River water moves northward from the Orr Ditch.

In the northern part of the valley unaffected by recharge from the Orr Ditch, stable-isotope analyses from ground water collected at sites 2, 9, and 12 (fig. 3) indicate that these samples have no component of Truckee River water. However, the 4,450-ft contour suggests that water generally moves northwestward (figs. 18 and 19), apparently in response to ground-water withdrawals from a gravel-pit operation. In addition, water-level measurements in two observation wells (sites 3 and 4) in the extreme northern part of the valley indicate a northern flow direction, more than 200 ft higher than recently measured water levels in adjacent Warm Springs Valley still farther to the north (Bauer and others, 1996, p. 554). These data suggest that a hydraulic gradient exists from Spanish Springs Valley to Warm Springs Valley. Seismic-refraction data indicate that basin fill is relatively thin and unsaturated beneath the northern topographic divide (line A, fig. 3). Consequently, for ground water to exit the study area to the north, it must flow through fractured bedrock. Lack of water-level data in the northern part of the valley prior to this study precludes the determination of flow conditions before large ground-water withdrawals began. However, results of a two-dimensional steady-state flow model of conditions representing 1980 water levels (assumed to represent pre-pumping conditions), suggest that ground water moved northward toward Warm Springs Valley (Hadiaris, 1988).

Chemical Composition of Ground Water

Ground-water samples from 22 wells within the study area (fig. 3) were analyzed for overall chemical composition and are summarized in the trilinear diagram in figure 22. Trilinear diagrams show the chemical character of water in terms of milliequivalent-per-liter percentages of major dissolved constituents (Hem, 1985). Results of the chemical analyses for samples collected as part of this study are presented by Emett and others (1994, p. 557) and Clary and others (1995, p. 732). Most ground water sampled in the study area is either a sodium bicarbonate (11 samples) or calcium bicarbonate (6 samples) type water. Samples assumed to represent locally derived recharge, based on stable-isotope composition (fig. 16), generally fall within these two water types. Ground-water samples from wells in the southern part of the study area (sites 61 and 66) are a sodium sulfate type water with dissolved-solids concentrations of 2,160 mg/L and 1,200 mg/L, respectively. Dissolved-solids concentrations for the remaining samples, except for those from site 20, range from 156 to 488 mg/L. Water from site 20, just north of the Orr Ditch near the center of the valley, is a calcium sulfate type with a dissolved-solids concentration of 2,680 mg/L.

Although water-quality determinations are not implicitly stated in the scope of work for the current study, a brief evaluation of the general ground-water quality as it relates to selected standards for beneficial use is warranted. Analyses of several constituents of concern (boron, chloride, dissolved solids, fluoride, nitrate as nitrogen, and sulfate) were obtained for use in geochemical techniques. Nevada water-quality standards for selected constituents were used as a basis for comparing reported concentrations with concerns for human consumption, aquatic life, irrigation, and watering livestock. Primary standards for public water systems were not exceeded for fluoride and nitrate (as nitrogen) in the sampled ground water. Secondary maximum standards for public water systems, which are based on esthetic qualities, were exceeded for chloride at site 20, for dissolved solids and sulfate at sites 20, 61, and 66, and for fluoride at site 22. Water-quality standards for support of aquatic life and for irrigation purposes were exceeded for boron at site 21. Standards for watering livestock were not exceeded in sampled ground water.

GROUND-WATER RECHARGE AND DISCHARGE

Components of ground-water recharge to and discharge from the basin-fill aquifer beneath Spanish Springs Valley under natural conditions include recharge from precipitation, discharge by evapotranspiration, and discharge by subsurface flow to adjacent basins. Under long-term natural conditions, the ground-water system is in a state of dynamic equilibrium, in which inflow equals outflow, with no appreciable net change in storage. Estimates of ground-water recharge and discharge under natural conditions were developed by Rush and Glancy (1967, table 20, p. 43). They suggested, on the basis of estimated total ground-water discharge, that about 1,000 acre-ft/yr represented the inflow to and outflow from the ground-water system in Spanish Springs Valley.

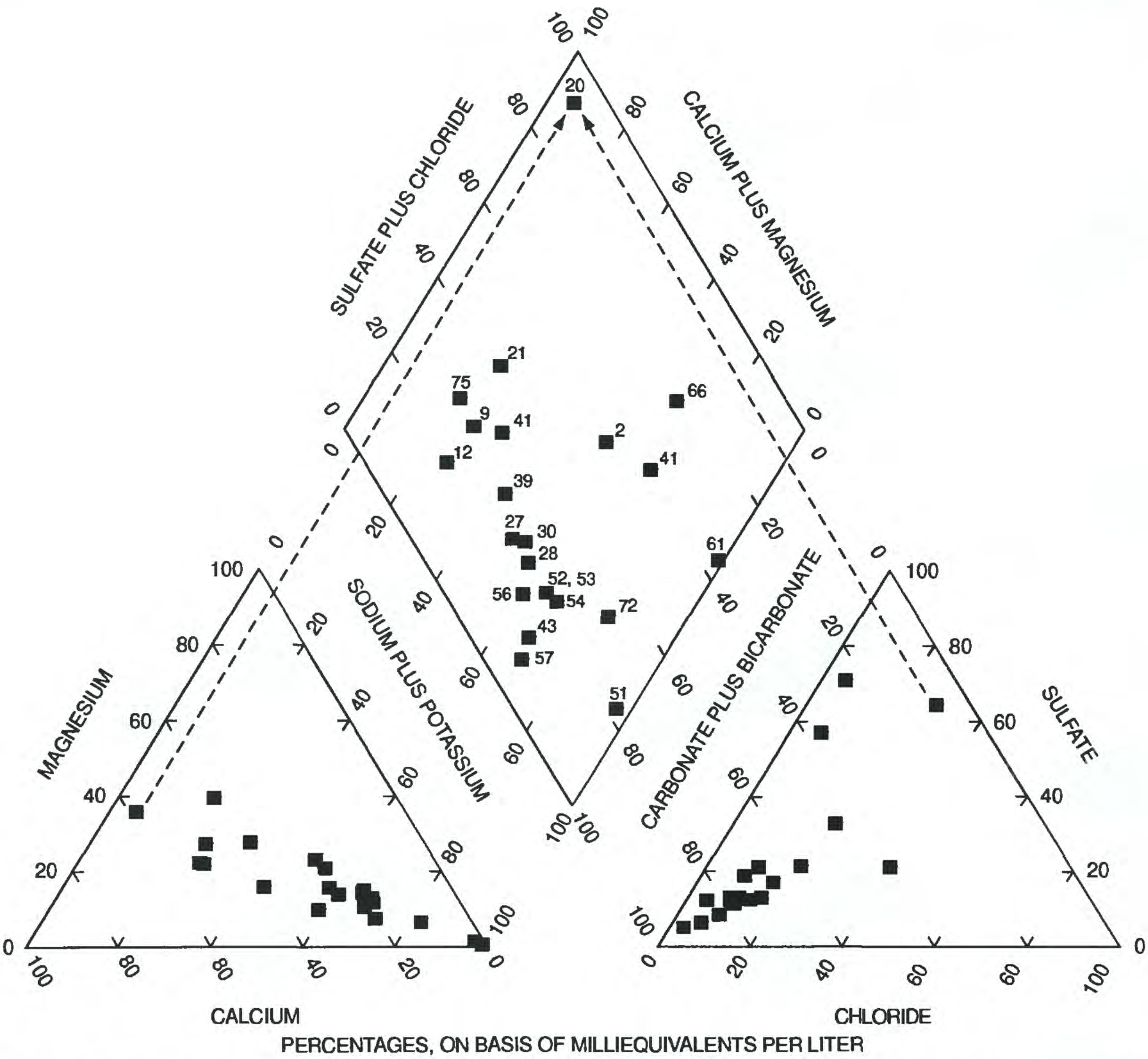


Figure 22. General chemical composition of sampled ground water, Spanish Springs Valley, west-central Nevada. Dashed lines and arrows show projection of values for a single sample (from site 20) from triangle to diamond that indicates water type.

In the current study, completely new estimates of recharge and discharge for natural conditions were not developed; instead, the existing ones were evaluated to see if any revisions were warranted on the basis of information gained since 1967. Because the Orr Ditch has delivered Truckee River water to Spanish Springs Valley for more than 110 years, the ground-water system was probably in dynamic equilibrium with recharge from the Orr Ditch and irrigated fields prior to 1979. With increased urban development (beginning about 1979), pumping for public water supply and secondary recharge from infiltration through septic systems again altered the conditions of equilibrium. A diagrammatic representation (fig. 23) illustrates the current conceptualization of several components of recharge and discharge to the basin-fill aquifer system. These components were estimated during this study from field and empirical techniques. The ground-water- flow model, discussed in later sections of this report, was used to help quantify those components that were either defined by a range of values or empirically estimated.

Figure 23. Three-dimensional, schematic conceptualization of ground-water recharge and discharge to basin-fill aquifer system, Spanish Springs Valley, west-central Nevada.

Recharge from Precipitation

Rush and Glancy (1967, table 8), using a method described by Maxey and Eakin (1949, p. 40-41) and Eakin and others (1951, p. 79-80), estimated ground-water recharge from precipitation in Spanish Springs Valley to be about 600 acre-ft/yr. This method, called the Maxey-Eakin method, estimates recharge as a percentage of average annual precipitation within specified altitude zones. The distribution of precipitation used by Rush and Glancy (1967) was developed by Hardman (1936) and resulted in an estimated total precipitation of 30,000 acre-ft/yr (Rush and Glancy, 1967, p. 23).

A revised precipitation map (fig. 13) was developed during this study on the basis of a precipitation-altitude relation constructed from selected stations that were assumed to represent conditions similar to those in Spanish Springs Valley. About 33,000 acre-ft/yr (table 5) of precipitation was estimated from the more recent map (fig. 13). Although, for this precipitation-altitude relation, precipitation was estimated to be somewhat greater at higher altitudes than those determined from the Hardman (1936) map, the general areal distribution of precipitation is similar. Areas within each 1-in. precipitation zone were determined by superimposing the precipitation data shown in figure 13 onto 7.5- and 15-minute topographic maps. The 1-inch precipitation zones were then combined into three zones (less than 8 in., 8 to 12 in., and greater than 12 in.) by using an area-weighted average. Areas within particular precipitation zones, which differ somewhat from those presented by Rush and Glancy (1967, table 8), reflect the revised precipitation map and the better topographic resolution of more recent maps. Applying the Maxey-Eakin percentages used by Rush and Glancy to the volume of precipitation in each precipitation zone (1967, table 8) results in an estimated average recharge of 710 acre-ft/yr in Spanish Springs Valley and 120 acre-ft/yr in the Dry Lakes area (table 5). Rush and Glancy (1967) did not include the Dry Lakes subarea in their investigation. However, results of the current study suggest that recharge within the Dry Lakes area may provide recharge to basin fill in Spanish Springs Valley through systems of fractures within the volcanic rocks of the Pah Rah Range. An estimated 830 acre-ft/yr was used to represent the total average annual recharge from precipitation to the basin-fill aquifer system in Spanish Springs Valley. Because about 72 percent of normal precipitation fell at the Reno airport in calendar year 1994, ground-water recharge from precipitation in the study area for the same period was assumed to be about 72 percent of the estimated average, or 600 acre-ft.

Although the Maxey-Eakin method was not initially developed to estimate annual recharge from precipitation, annual estimates were made for incorporation into the ground-water flow model. The results from model simulations using a constant annual recharge were compared to those using recharge estimates that vary annually, as discussed in following sections of this report.

Ground-water recharge also was estimated on the basis of chloride balance between precipitation and ground water for comparison to the Maxey-Eakin method. On the basis of distribution of precipitation determined during this study (fig. 13), about 23,000 acre-ft/yr is estimated to fall in recharge-source areas (areas with greater than 8 in. of annual precipitation; table 5). Rush and Glancy (1967, p. 23) estimated about 17,000 acre-ft of precipitation within recharge-source areas. Average chloride concentration in 24 samples of bulk precipitation collected from five stations (sites 79, 80, 81, 82, and 87; table 8) is 0.38 mg/L. Ground-water samples, collected from wells at the periphery of the basin (sites 2, 9, 12, 27, 28, 30, 39, 41, and 72; fig. 3, table 8) and assumed to represent locally derived recharge, had an average chloride concentration of about 13 mg/L. Estimated ground-water recharge determined from the chloride-balance method (eqn. 1) is about 670 acre-ft/yr. Applying the same criteria to 3,500 acre-ft of precipitation estimated to fall annually in the Dry Lakes area results in an additional 100 acre-ft/yr of recharge for a total of 770 acre-ft/yr. For 1994 conditions, assumed to be 72 percent of average, 550 acre-ft of recharge is estimated on the basis of the chloride-balance technique.

Although these estimates are slightly lower than those estimated using Maxey-Eakin percentages, they all indicate relatively low volumes of annual recharge and are considered to be reasonable. For purposes of estimating the ground-water budget, the ground-water recharge component based on the Maxey-Eakin method was used.

Infiltration of Imported Surface Water

The disposition of surface water delivered by the Orr Ditch to Spanish Springs Valley was simplified into four components: (1) transmission losses directly from

Table 8. Concentration of chloride in ground water and precipitation at selected sites in Spanish Springs Valley area, west central Nevada

Site number (fig. 3)	Date	Dissolved chloride (milligrams per liter)
Ground-Water Sites		
2	08-19-93	27
9	08-18-93	12
12	08-18-93	11
27	08-17-93	9.0
28	08-17-93	8.4
30	08-17-93	9.4
39	08-16-93	13
41	08-16-93	18
72	01-13-94	10
Precipitation Sites[1]		
79	12-11-92	0.28
	02-09-93	.08
	06-03-93	1.3
	09-03-93	.45
	10-18-93	.24
80	12-11-92	.17
	02-18-93	.36
	03-01-93	.17
	06-03-93	.23
	09-08-93	.44
	10-18-93	.30
81	02-09-93	.15
	09-08-93	.39
	10-18-93	.25
82	03-01-93	.24
	10-20-93	.57
	10-20-93	.49
87	12-07-92	.35
	12-11-92	.20
	02-09-93	.07
	06-02-93	.71
	09-03-93	.52
	09-03-93	.66
	10-19-93	.43

[1]Sample results with same date at same site indicate analyses were made from two bulk collectors at site.

the Orr Ditch, (2) deep percolation of water to applied fields as flood irrigation, (3) direct evaporation of ponded surface water, and (4) plant and soil-moisture evapotranspiration requirements of applied irrigation water prior to ground-water recharge. In 1994, an estimated 3,100 acre-ft of imported surface water was either recharged to the shallow ground-water system or consumed by evapotranspiration. The estimated disposition and budget of imported Truckee River water for 1994 conditions are presented in table 9.

Ground-water recharge from imported surface water takes place seasonally as transmission losses from the Orr Ditch and as infiltration of water applied to irrigated fields. To estimate transmission losses, a series of discharge measurements was made in April 1993 and May 1994 along the length of the Orr Ditch. Discharge through take-out gates used to provide water for flood irrigation was measured or estimated between each measurement of flow in the Orr Ditch. On the basis of these measurements, a maximum of 10 acre-ft per irrigation day was estimated to recharge the basin-fill aquifer as transmission losses directly from the Orr Ditch along its length. An irrigation day is herein defined as a day with an average daily discharge of about 30 ft^3/s or more as recorded at site 88 (fig. 3). From 1979 through 1984, the average number of irrigation days was 170 per year. Because flows in the Orr Ditch were decreased in 1985 and considering the effects of below average precipitation, the average number of irrigation days for 1985 through 1994 was decreased to about 124. During this study (1992-94), the number of irrigation days was 58, 158, and 59, respectively. On the basis of the number of irrigation days in 1994, an estimated 590 acre-ft of transmission loss recharged ground water (table 9).

The volume of ground-water recharge beneath irrigated fields is assumed to be a percentage of the amount of applied irrigation water. In basins with similar irrigation practices, about 40 percent of applied irrigation is assumed to infiltrate below the root zone and become ground water (Huxel and others, 1966, p. 41-42; Malmberg and Worts, 1966, p. 40; Nichols, 1979, p. 22). The remaining 60 percent is lost by evapotranspiration processes. The amount of applied irrigation water that potentially was available for ground-water recharge in Spanish Springs Valley was assumed to be the difference between the total volume of imported surface water (5,500 acre-ft), as measured at site 88, and the sum of transmission losses, evaporation from surface-water bodies, and the overland flow component entering the North Truckee Drain. The evaporation of about 460 acre-ft of ponded surface water was estimated by applying an evaporation rate of about 40 in/yr (Van Denburgh and others, 1973, p. 53) to 140 acres of surface-water bodies for 1994 (table 9).

Although flow in the North Truckee Drain responds nearly instantaneously to overland flow from flood irrigation (fig. 15), about 70 acre-ft in 1994 were estimated to be contributed from ground water as base flow. Thus, the overland flow component to the North Truckee Drain is estimated to be about 2,300 acre-ft in 1994. Using this simple water budget, approximately 2,200 acre-ft of imported Truckee River water was applied to the fields in the southern part of the study area in 1994. Assuming that about 40 percent infiltrated to the ground water, an estimated 860 acre-ft became ground-water recharge and nearly 1,300 acre-ft was lost to evapotranspiration (table 9). On the basis of these estimates, the total volume of imported surface water that was either recharged to the shallow ground-water system or consumed by evapotranspiration was 3,200 acre-ft in 1994; this agrees well with the measured difference between inflow and outflow at sites 88 and 89. The estimated total ground-water recharge from imported Truckee River water (transmission loss plus infiltration of applied ditch water) was about 1,400 acre-ft in 1994.

Discharge by Evapotranspiration

Prior to ground-water withdrawal for water supply, evapotranspiration was the principal mechanism of ground-water discharge from Spanish Springs Valley. Ground-water discharge by evapotranspiration includes direct losses from bare-soil evaporation and transpiration from vegetation. In areas where the water table is only a few feet below land surface, ground water can be discharged by evaporation. Under natural conditions, bare-soil evaporation in Spanish Springs Valley probably took place in the area surrounding the springs, where the water table is near land surface. Transpiration by phreatophytes has been documented in other arid basins in Nevada to consume relatively large quantities of ground water (Robinson, 1970; Harrill, 1973, table 9; Berger, 1995, p. 35). Vegetation that grows in areas where the water table or capillary fringe above the water table lies within reach of their roots are called phreatophytes (Meinzer, 1927, p. 1).

Estimates of ground-water discharge by evapotranspiration under natural conditions (conditions without the Orr Ditch) were made by Rush and Glancy (1967, table 14). They estimated that about 1,900 acres of phreatophytes discharged nearly 900 acre-ft of ground water annually. On the basis of recent field observations, about 1,000 acres of greasewood, sagebrush, and rabbitbrush lie along the outside of the Orr Ditch with a shrub density of about 20 percent, which suggests that a perennial source of water is available. Direct estimates of evapotranspiration using micrometeorological methods were beyond the scope of this study. Estimates of ground-water discharge as a function of shrub density, leaf-area index, and depth to water have been developed by Nichols (1993, 1994). Assuming the 1,000-acre area has a leaf-area index of about 2.5 (W.D. Nichols, U.S. Geological Survey, oral commun., 1995) and using 15 ft as an average depth to water, 360 acre-ft of ground water is estimated to discharge annually from areas just outside the Orr Ditch. Summing the previous estimate of 900 acre-ft (Rush and Glancy) with the additional 360 acre-ft results in a

Table 9. Estimated disposition and budget of imported Truckee River water for 1994, Spanish Springs Valley area, west-central Nevada

[Values in acre-feet per year, rounded to two significant figures]

Measured quantity		Estimated quantity	
Inflow in Orr Ditch	5,500		
		Surface-water losses and consumption	
		Transmission loss [1]	590
		Infiltration of applied water[1]	860
		Evaporation of ponded surface water	460
		Evapotranspiration of applied water	1,300
Outflow in North Truckee Drain	2,400		
Difference between measured inflow and outflow	3,100	**Total** estimated surface-water loss and consumption	3,200

[1] Transmission loss plus infiltration constitutes ground-water recharge from imported river water (1,400 acre-feet, rounded).

total estimate of ground-water discharge by evapotranspiration of about 1,300 acre-ft for 1994. The ground-water flow model was used to help quantify ground-water discharge by evapotranspiration within the irrigated land area and transpiration from areas of phreatophytes that lie outside the perimeter of the Orr Ditch.

Subsurface Flow to Adjacent Basins

Subsurface outflow from Spanish Springs Valley to the Truckee Meadows was estimated as 100-150 acre-ft/yr by Cohen and Loeltz (1964, p. 23) and Rush and Glancy (1967, table 16). These investigators evaluated subsurface outflow through the basin fill and did not attempt to estimate flow volumes through fractured bedrock. Although no attempt was made to directly estimate subsurface flow to the Truckee Meadows, flow probably moves through fractured or weathered bedrock, as indicated by stable-isotope data. The relative position of the sample from site 66 on the plot of $\delta^{18}O$ versus δD (fig. 16) suggests that the ground-water sample is a mixture of locally derived water and Truckee River water. A mass-balance calculation, using δD values of -116 permil for locally derived water and -82.1 permil for Truckee River water, indicates that the sample from site 66 is composed of about 24 percent Truckee River water and 76 percent local recharge. Site 66 is just south of the boundary between Truckee Meadows and the study area and the well penetrates more than 100 ft of bedrock (fig. 3). Consequently, subsurface outflow to Truckee Meadows may be greater than previously estimated if ground water flows through bedrock that underlies the boundary and through the saturated basin fill.

The potential for subsurface outflow to the north exists because water levels in Warm Springs Valley, north of the study area, are 200 ft lower than water levels in the northern part of Spanish Springs Valley. Subsurface flow may move northward through fractured bedrock at depth along the base of Hungry Ridge. No attempt was made to directly estimate ground-water flow northward from the study area because direct estimates of flow through fractured bedrock require specialized techniques and because it is likely to be a small percent of the total basin discharge. During the calibration of a steady-state flow model (Hadiaris, 1988), 280 acre-ft of subsurface outflow toward Warm Springs Valley was needed for a favorable statistical match between measured and simulated water levels. The steady-state model assumed no ground-water pumping. However, water levels used for calibration in the northern part of the basin were measured in the mid-1980's and may have been affected by ground-water withdrawals in the northern part of the study area. The potential for subsurface outflow toward Warm Springs Valley was evaluated using the ground-water flow model discussed later in this report.

Ground-Water Development

Spanish Springs Valley has been the site of agricultural activity for many decades. Ground-water discharge from springs and shallow flowing wells was used to irrigate small areas of mostly grass near the springs prior to construction of the Orr Ditch. With the importation of Truckee River water, the amount of developed and irrigated land increased. Currently (1994), about 980 acres in the southern part of the study area are serviced by the Orr Ditch irrigation system. In addition, about 60 acres in two areas outside of the area encompassed by the Orr Ditch are irrigated with ground water.

Ground-water pumping is seldom used to augment irrigation during periods when flow in the Orr Ditch does not provide sufficient water for irrigation and stock-watering needs (Matthew Allen, Orr Ditch Company, oral commun., 1996). During periods of insufficient flow, minimal ground-water withdrawals are sometimes used for livestock watering; however, stock generally are moved to another valley and irrigation is continued from ponded water supplies. During this study, no ground-water pumping to supplement flow in the Orr Ditch was observed. As a result, the following estimates of ground-water withdrawals for irrigation were determined only for active agricultural lands outside the area serviced by the Orr Ditch. These areas include about 20 acres in the Spanish Springs Canyon area and about 35 acres in the northern part of the valley, west of Sugarloaf Peak (fig. 1). During 1994, several acres just east of the springs area, not previously farmed, were irrigated as a result of exercising a water right. Currently, no records of irrigation pumping are maintained. Consequently, ground-water withdrawals for irrigated areas not associated with the Orr Ditch system were determined on the basis of water-rights data, field observations, and discussions with land owners. Summaries of active ground-water rights were obtained from the Nevada Division of Water Resources (Kim Groenewold, written commun., 1995). Although the active ground-water rights within the basin for irrigation purposes, as of 1994, were about 2,300 acre-ft, only 720 acre-ft were estimated as pumped for irrigation and applied on lands outside the service area of the Orr Ditch. Estimates of ground-water withdrawals for 1979 through 1994 are presented in table 10.

Until 1983, agriculture was the principal user of ground water, accounting for more than half of the total withdrawn in the study area (table 10). As population grew, withdrawals for public supply became the dominant use of ground water. Meter records of ground-water discharge collected from several municipal water suppliers, including the Washoe County Utility Division, were used in conjunction with water-rights data to estimate that about 1,400 acre-ft of ground water was withdrawn for municipal use in 1994. Annual ground-water withdrawals for non-municipal domestic purposes were determined from residential water-use data and number of parcels with domestic wells. Estimates of residential water use range from 0.6 to about 0.8 acre-ft/yr per parcel (Kennedy/Jenks/Chilton, 1991, p. 4.2; Nevada Division of Water Planning, 1992, p. 36; Washoe County Department of Comprehensive Planning, written commun., 1995). Estimated ground-water withdrawals for domestic use increased from 20-30 acre-ft in 1979 to more than 110 acre-ft in 1994. A gravel-pit operation in the northern part of the study area was the principal industrial user of ground water in the study area, having an estimated withdrawal of about 300 acre-ft in 1994. An estimated additional 20 acre-ft of ground water was pumped for other industrial uses. Total ground-water withdrawals for all uses were estimated to be 2,600 acre-ft in 1994 (table 10).

Part of the ground water withdrawn to irrigate fields and to support urban development is recycled as secondary recharge. The amount of applied irrigation water that infiltrates beyond the root zone and recharges ground water, in part, depends on the application method of irrigation and depth to the water table. For application methods of either sprinkler or drip systems, the assumed percentage of pumped water consumed by crops is 65 percent and that lost by spray and surface evaporation is 10 percent (Harrill, 1968, p. 47).

Table 10. Summary of population and estimated ground-water withdrawals, 1979-94, Spanish Springs Valley area, west-central Nevada

[Population and withdrawal values rounded]

Year	Population[1]	Ground-water withdrawals (acre-feet per year)				
		Irrigation[2]	Municipal[3]	Domestic[4]	Industrial[5]	Total
1979	790	350	120	20-30	20	500
1980	1,080	350	180	20-30	20	600
1981	1,380	350	230	30-40	20	600
1982	1,510	350	260	30-40	20	700
1983	1,750	350	320	40-50	20	700
1984	2,080	350	430	40-60	20	800
1985	2,570	350	550	50-60	20	1,000
1986	2,780	350	610	50-70	20	1,000
1987	2,930	350	640	60-80	120	1,200
1988	3,240	350	640	70-90	610	1,700
1989	3,580	350	680	70-100	610	1,700
1990	4,060	350	820	80-100	610	1,900
1991	4,760	350	960	80-110	610	2,000
1992	6,040	350	930	90-110	610	2,000
1993	7,800	350	1,080	100-130	330	1,900
1994	9,320	720	1,400	110-150	320	2,600

[1] Estimates of population for 1979-90 from U.S. Bureau of the Census (written commun., 1995) and for 1991-94 from Washoe County Department of Comprehensive Planning (written commun., 1995).

[2] Ground-water withdrawals estimated from field observations and State water-rights data.

[3] Data from Washoe County Utility Department (written commun., 1995) and metered pumping records.

[4] Based on 0.6 and 0.8 acre-foot per parcel.

[5] Estimated from State water-rights data; includes estimates of commercial and construction water use.

The remaining 25 percent is assumed to be recycled back to the ground-water system. The percentage of applied irrigation by flooding that recharges ground water is 40 percent, similar to that assumed earlier for areas that are flood irrigated with water from the Orr Ditch. For this study, however, ground-water recharge from applied irrigation was considered not to be significant in areas not served by the Orr Ditch and where depth to water was 100 ft or greater. On the basis of these considerations, recharge from applied irrigation of ground water was estimated to be about 170 acre-ft in 1994 for irrigated lands outside the area encompassed by the Orr Ditch.

The amount of ground water recycled from municipal and domestic uses is assumed to be a percentage of the total withdrawals and differs with type of use and with individual systems, including those systems that remove wastewater to treatment facilities outside the study area. Water applied for outdoor uses (lawn and shrub watering) is mostly consumed by evapotranspiration and for this study was considered not to be a significant contributor to ground water. Secondary recharge from septic systems (indoor uses) is assumed to be 75 percent of the total amount of water delivered during winter months, when outdoor watering is at a minimum. This monthly volume of water, which is assumed to be constant, was then prorated for an entire year to arrive at an annual estimate of secondary recharge. For 1994, secondary recharge from septic systems was estimated at 450 acre-ft. This estimate of secondary recharge reflects only that percentage of delivered water remaining within the basin.

Evaluation of the Ground-Water Budget and Yield, 1994

This section describes the ground-water budget and augmented yield under 1994 conditions in Spanish Springs Valley. The augmented yield represents the natural yield of the basin fill plus the additional recharge from imported surface water.

A summary of estimated ground-water recharge and discharge components to and from the basin-fill aquifer system in Spanish Springs Valley for conditions representing 1994 is presented in table 11. On the basis of field and empirical techniques, total recharge from all sources was estimated at 2,600 acre-ft, nearly 54 percent of which was estimated to be derived from imported Truckee River water during 1994. Total discharge was estimated at 4,300 acre-ft. The imbalance between estimated recharge and discharge was 1,700 acre-ft for 1994 conditions.

The average water-level decline calculated from December 1993 to December 1994 is about 2 ft. The volume of water represented by this decline can be approximated by the product of the area of decline, the average water-level decline within this area, and an estimated specific yield of the basin-fill aquifer where the decline occurred. The area of water-level declines is about 8,500 acres. Applying specific yields of 10 and 20 percent, the estimated quantity of ground water removed from storage during 1994 was 1,700 to 3,400 acre-ft. The water-level declines and associated change in storage support the empirically estimated imbalance for 1994 conditions.

The perennial yield of a ground-water reservoir can be defined as the natural maximum amount of ground water that can be withdrawn and consumed economically each year for an indefinite period of time (Harrill, 1968, p. 56). The term commonly is called safe yield (Bear, 1979, p. 13; Fetter, 1994, p. 518). Fetter further defines safe yield as "the amount of naturally

Table 11. Estimated and simulated components of ground-water recharge and discharge, 1994 conditions, Spanish Springs Valley area, west-central Nevada

[Values in acre-feet per year, rounded to two significant figures]

Component	Based on field and empirical estimates	Based on transient simulation
Recharge		
Precipitation	[1]600	580
Infiltration of imported surface water	1,400	1,300
Recycled irrigation water	170	170
Secondary recharge from septic systems	450	400
Total recharge	2,600	2,400
Discharge		
Evapotranspiration	1,300	1,800
Subsurface outflow		
To south	[2]100-150	190
To north	[3]280	170
Ground-water withdrawal	2,600	2,400
Total discharge	4,300	4,600
Imbalance (discharge minus recharge)	1,700	2,200

[1] Estimated from Maxey-Eakin; represents 72 percent of average annual recharge.

[2] From Cohen and Loeltz (1964, p. 23) and Rush and Glancy (1967, p. 37). Estimate may be greater if ground water flows through fractured bedrock and through saturated basin fill.

[3] From Hardiaris (1988).

occurring ground water that can be withdrawn from an aquifer on a sustained basis, economically and legally, without impairing the native ground-water quality or creating an undesirable effect such as environmental damage."

Whenever water is initially withdrawn from a well, the withdrawal creates an imbalance between ground-water recharge and discharge, and water is removed from storage in the aquifer. The imbalance continues and ground-water levels decline in the aquifer until the withdrawals are balanced by a decrease in pre-pumping discharge or by an increase in recharge, or by a combination of the two. Ground-water recharge can increase only where surface water (a stream or lake) is directly connected to the aquifer (no intervening unsaturated interval) or where subsurface flow enters the aquifer from adjacent aquifers. The magnitude of sustained ground-water withdrawals, therefore, depends on the maximum quantity of pre-pumping discharge that can be captured for beneficial use (Bredehoeft and others, 1982) and on the maximum quantity of increased recharge. This maximum quantity is dependent partly on the placement of wells with respect to areas of pre-pumping discharge and to areas where recharge can be increased, as considerable time may be required to capture the pre-pumping discharge or to increase recharge.

The estimated perennial yield for Spanish Springs Valley for natural conditions, assuming that all the natural discharge can be captured, is about 1,000 acre-ft/yr (Rush and Glancy, 1967, table 12).

Because surface water, some of which has been imported into Spanish Springs Valley since the late 1800's, recharges the basin-fill aquifer, the term augmented yield is used herein to describe the total quantity of potentially available ground water, assuming that all the pre-pumping discharge can be captured. Augmented yield is defined as the perennial yield plus salvable secondary recharge resulting from the use of imported surface water (Harrill, 1973, p. 77-78). Thus, augmented yield of the basin-fill aquifer in Spanish Springs Valley is estimated to be about 2,400 acre-ft, assuming that 1,400 acre-ft of ground-water recharge was salvaged from infiltration of imported Truckee River water in 1994. The estimated augmented yield of 2,400 acre-ft is about the same volume as the total ground-water pumping estimate. However, if the quantity of imported surface water or its management changes, the augmented yield for the basin-fill aquifer must be revised to account for changes in ground-water recharge.

SIMULATION OF GROUND-WATER FLOW

A mathematical flow model was developed to simulate the effects of ground-water withdrawals on the ground-water flow system in the basin-fill aquifer beneath Spanish Springs Valley. The model simulation starts in 1979 when large increases in population and water demand began and ends in 1994 with the then-current state of urban development. The model was calibrated using estimated ground-water withdrawals from 1979 to 1994 and the resultant water-level declines. The calibrated model was then used to simulate changes in water levels that reflect the probable future response to selected ground-water development scenarios.

The accuracy with which the flow model simulates an actual ground-water flow system depends on how well the hydrologic processes of the system are understood and simulated. The accuracy and distribution of input data used to describe these processes are the determining factors that limit the model in simulating the actual system. A ground-water flow model is not necessarily a unique representation of a flow system; however, by using reasonable hydraulic properties and boundary conditions, the flow model can closely simulate the natural flow system of the study area.

Mathematical Basis

The numerical technique used in this study to analyze ground-water flow and yield of the basin-fill aquifer is a finite-difference ground-water flow model written by McDonald and Harbaugh (1988). The model solves the three-dimensional equation of ground-water flow by using finite-difference approximations; the equation can be written as follows:

$$\partial/x\,(K_{xx}\partial h/\partial x) + \partial/\partial y\,(K_{yy}\partial h/\partial y) + \partial/\partial z\,(K_{zz}\partial h/\partial z) - W = S_s\partial h/\partial t, \qquad (2)$$

where,

K_{xx}, K_{yy} are hydraulic conductivities in the principal horizontal directions, in length per unit time;

K_{zz} is hydraulic conductivity in the vertical direction, in length per unit time;

h is hydraulic head, in length;

W is volumetric flux of recharge or discharge per unit volume, in 1/time;

S_s is specific storage, in 1/length;

t is time; and

x, y, z are Cartesian coordinates aligned along the major axes of hydraulic conductivity.

The finite-difference method is used to obtain approximate solutions to the three-dimensional flow equation by replacing the continuous partial derivatives with systems of simultaneous algebraic difference equations. The difference equations are then solved in terms of the unknown hydraulic head at discrete points, or nodes, and time. The time derivative of head, *dh/dt*, is approximated by the backward difference procedure (Remson and others, 1971, p. 78). The approximation of the time derivative for each node is as follows:

$$(h_1 - h_0) / \Delta t \qquad (3)$$

where,

h_0 is hydraulic head at the beginning of a time step, in length;

h_1 is hydraulic head at the end of a time step, in length, which is unknown; and

$\Delta\tau$ is the time-step interval.

The strongly implicit procedure (McDonald and Harbaugh, 1988, p. 12-1) is used to solve the system of difference equations for each time step by iteration. Solution for each node is achieved when the head change between each iteration is less than a specified value. The value specified for the model simulations for Spanish Springs Valley was 0.03 ft. Each node is centered in a model-grid cell that has dimensions of x, y, and z. Hydraulic properties within each cell were assumed to be homogeneous, so that the model-derived hydraulic head represents the average head over the entire cell.

General Features of Flow Model

To translate the conceptual model of the hydrologic system into a mathematical flow model and solve the ground-water flow equation by finite differences, a block-centered grid was superimposed over a map view of the study area (fig. 24). The grid for the Spanish Springs Valley model contained 37 rows, 28 columns, and 2 layers that divided the saturated basin fill into discrete three-dimensional model cells. Variable node spacing was used to provide higher resolution in areas of ground-water recharge and discharge related to the importation of Truckee River water. Model-cell size ranged from a minimum of 0.02 mi^2 (820 ft by 820 ft) to a maximum of 0.10 mi^2 (1,640 ft by 1,640 ft). Of the 1,036 cells in each model layer, 625 were active in layer 1 and 282 were active in layer 2. The top 330 ft[1] of saturated basin fill was generally unconfined and was represented by layer 1. Processes of ground-water recharge and discharge were simulated in layer 1. Layer 2, which functioned as a conduit for deep flow and as a reservoir of stored water, extends from the bottom of layer 1 to the top of consolidated rock. Layer 2 was simulated by the model as a confined aquifer, but was allowed to convert to unconfined conditions if water levels dropped below the bottom of layer 1 due to simulated ground-water withdrawal. Although consolidated rock underlying and adjacent to the basin-fill aquifer may store and transmit moderate to large amounts of water, the hydraulic properties of that system are unknown. Inclusion of the consolidated-rock system into the ground-water flow model would add another level of complexity and uncertainty to the simulation. Consequently, only model cells representing saturated basin fill were used in this study.

Selection of Time Periods and Assigned Recharge and Discharge

The simulation of steady-state conditions in Spanish Springs Valley was not attempted due to the lack of predevelopment water-level data needed for steady-state calibration and the transient nature of ground-water recharge from imported surface water. Consequently, the flow model that numerically represents the basin-fill aquifer system was calibrated under transient conditions for a 16-year period (1979-94). Sixteen yearly stress periods were used to represent each calendar year beginning January 1979 and ending December 1994. Final heads from the previous annual stress period were used as initial heads for the following annual stress period. Each simulated calendar year was divided into 12 equal monthly stress periods to better represent the effect of seasonal conditions. During each monthly stress period, all assigned stresses to the system were held constant. Monthly stress periods were further subdivided into five time steps with each step increasing geometrically according to a specified multiplier. The initial time step was 3.71 days and each subsequent step was increased by 1.25 times the duration of the preceding time step. Because the initial conditions were not derived from a steady-state simulation, model responses in early stress periods of the transient simulation reflect not only specified

[1]The model was developed using metric units. Thus, 330 ft used in this study approximates 100 meters as used in the original model.

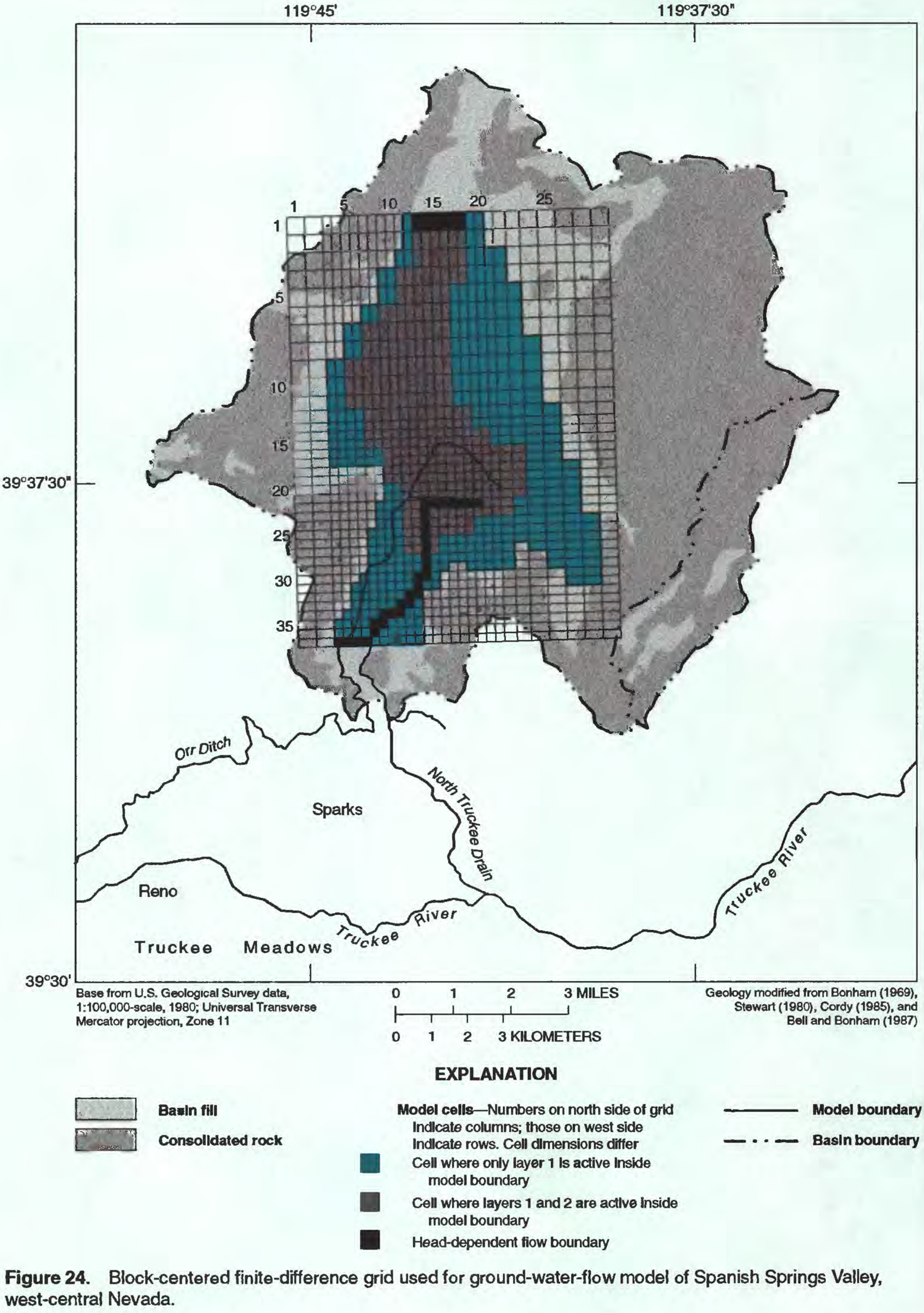


Figure 24. Block-centered finite-difference grid used for ground-water-flow model of Spanish Springs Valley, west-central Nevada.

stresses on the system, but also an adjustment of starting heads to boundary conditions and hydraulic properties.

Ground-water recharge from septic systems associated with municipal water supply, precipitation, and imported surface water were simulated in the model as assigned rates on the basis of either empirical estimates or measured quantities. The transient nature of the assigned values of recharge and discharge used in the model simulation is shown in figures 25 and 26. Recharge rates from precipitation and septic systems were assumed constant over a given annual stress period, but varied between annual stress periods depending on estimates for that particular year. Because recharge from imported surface water is seasonal as a function of flow in the Orr Ditch, recharge rates vary between monthly stress periods. Ground-water discharge for domestic and municipal pumping was simulated by assigning variable discharge rates for each monthly stress period on the basis of monthly meter records and estimates of water use. The extraction point of a domestic well was assumed to be in the same area (cell) as recharge from the associated septic system; as a result, model values of domestic pumping input to the model were the net difference between discharge and recharge. Model input of recharge from septic systems shown in figure 25 reflects only those homes that were served by municipal water systems, where the point of extraction was different from the point of use. Irrigation withdrawals were simulated as net pumping for lands outside the Orr Ditch irrigation system. Model cells with assigned pumpage for municipal, irrigation, and industrial discharge greater than 10 acre-ft for 1979 and 1994 are shown in figure 27.

Boundary Conditions

The ground-water-flow equation applied in the model has an infinite number of solutions. To develop a basin-specific model, information about conditions at the boundaries of the flow system and ground-water withdrawals within the flow system are required. Flow-boundary conditions are specified in the model on the basis of ground-water-flow concepts developed during this study. Active model cells represent saturated basin fill; inactive cells represent less-permeable consolidated rock and saturated basin fill less than about 30 ft thick. The boundary between active and inactive cells represents the model boundary (fig. 24). The model boundary was moved inward, toward the center of the valley (fig. 24), particularly in the northern and southeastern parts of the model, because of numerical instability along the boundary during initial simulations (fig. 24). The modeled area was consequently decreased in proportion to the reduced perimeter of the model grid.

Flow conditions along the model boundary were simulated by no-flow and head-dependent flow boundaries. Lateral and vertical boundaries between basin fill and consolidated rock were specified as no-flow boundaries. Head-dependent flow boundaries were used at the southern and northern part of the model to simulate subsurface flow between Truckee Meadows and Warm Springs Valley (fig. 24). Ground-water inflow and outflow conditions were simulated in layers 1 and 2 at head-dependent flow boundaries by extending external cells beyond the modeled region and specifying head values to those cells. A conductance term provides the link between the model and the external cell and is a function of the cross-sectional area of the cell perpendicular to the ground-water flow and horizontal hydraulic conductivity of the basin fill at the boundary. The specified head does not change in response to flows across the boundary calculated by the model. The specified external head used at the southern boundary was 4,397 ft above sea level, determined from water-level measurements in the Truckee Meadows. Saturated basin fill beneath the northern boundary of the model is believed to be several hundred feet thick because the northern boundary of the model is somewhat south of the actual basin boundary. Although continuity between saturated basin fill in Spanish Springs Valley and saturated basin fill in Warm Springs Valley is unlikely, a deeper hydraulic connection, perhaps along fractures within consolidated bedrock, is possible. To simulate this possible subsurface outflow condition, specified external heads used at the northern boundary range from 4,475 ft (cell: row 24, column 22) to 4,436 ft above sea level (cell: row 1, column 18). Conductances used for the head-dependent flow boundaries range from 180 ft^2/d to 650 ft^2/d.

Mountain front recharge from precipitation was simulated in model layer 1 as constant flow in active cells along the east and west sides of the model grid (fig. 28). The amount of recharge introduced to each cell depends on its position relative to a particular recharge-source area. The distribution of recharge was determined for each recharge-source area on the basis of the Maxey-Eakin method, as previously discussed.

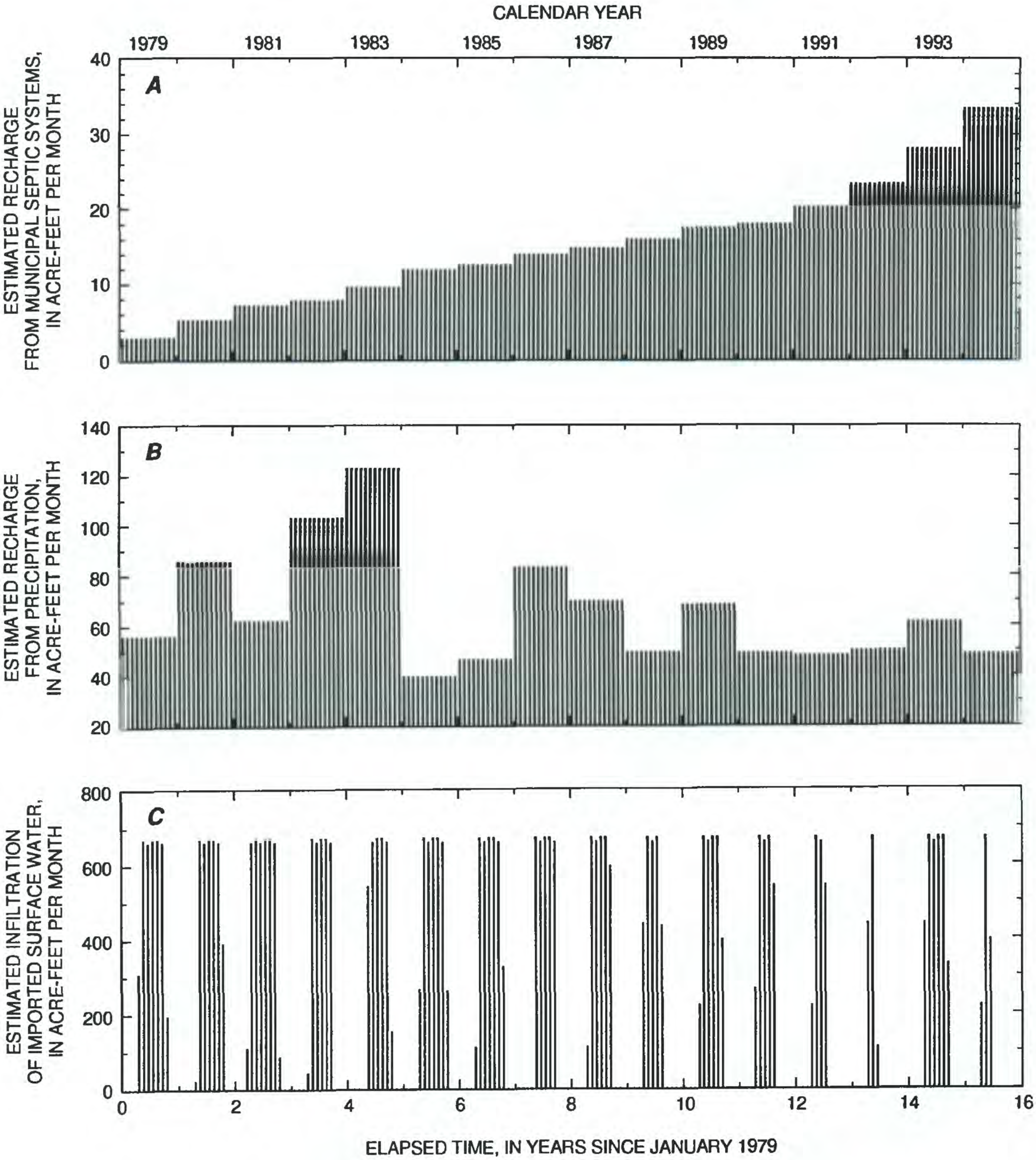


Figure 25. Assigned monthly recharge rates (monthly stress period) used as model input for transient simulations (1979-94), Spanish Springs Valley, west-central Nevada. Ground-water recharge estimated for *(A)* municipal septic systems, *(B)* precipitation, and *(C)* infiltration of imported surface water.

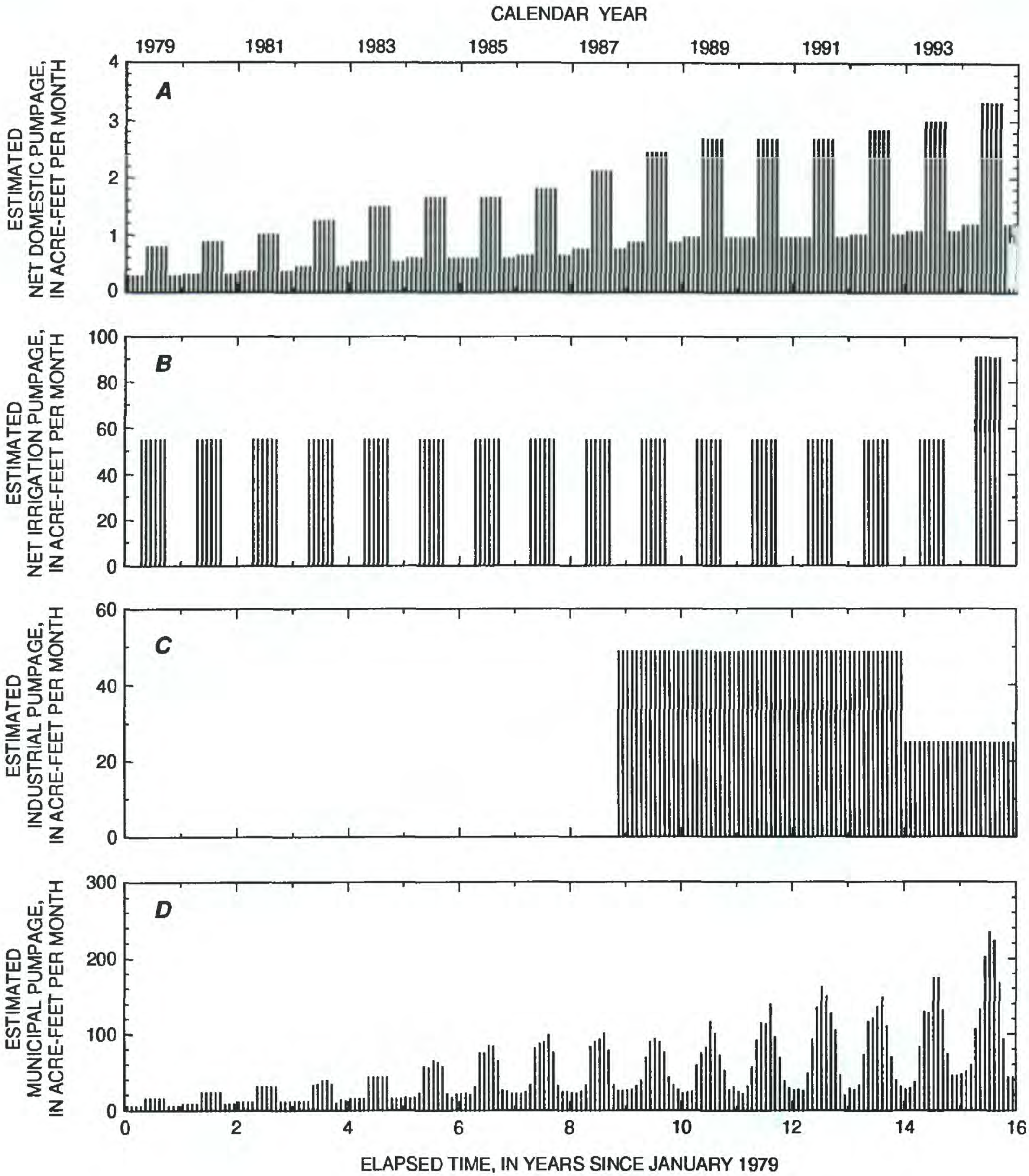


Figure 26. Assigned monthly discharge rates (monthly stress period) used as model input for transient simulations (1979-94), Spanish Springs Valley, west-central Nevada. Ground-water discharge estimated for (*A*) domestic pumpage, (*B*) irrigation pumpage, (*C*) industrial pumpage, and (*D*) municipal pumpage.

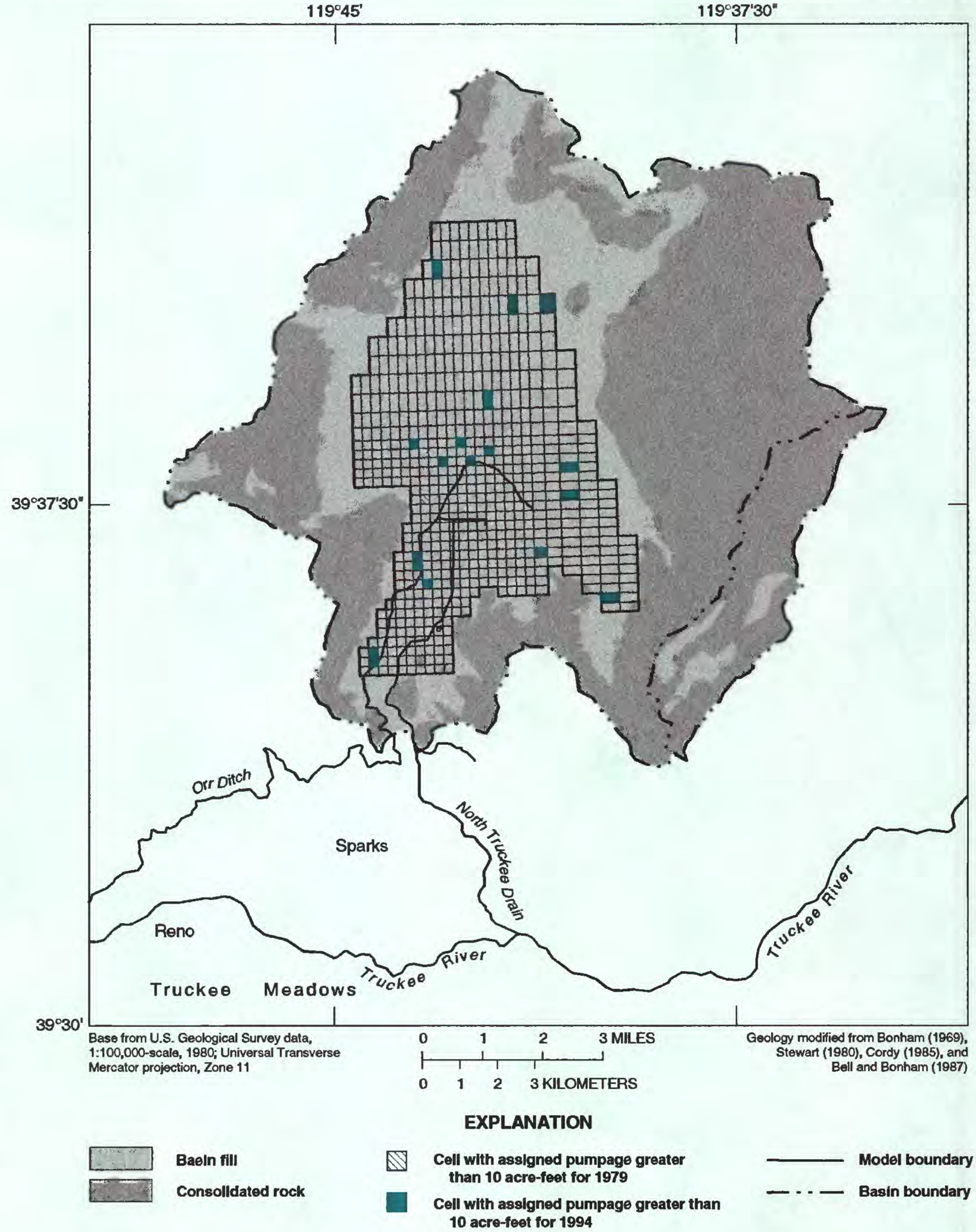


Figure 27. Cells with assigned ground-water pumpage for municipal, irrigation, and industrial use in annual stress periods respresenting 1979 and 1994 in model simulations, Spanish Springs Valley, west-central Nevada.

The Maxey-Eakin method uses long-term average precipitation to estimate long-term ground-water recharge.

In this study, recharge from precipitation was simulated in two ways. In the first approach, the recharge derived by using the Maxey-Eakin method was assumed constant throughout the 16-year transient simulation. In the second approach, an attempt was made to represent the annual variation in recharge that may result from changing annual precipitation rates. To approximate the recharge rate for a specific year, the Maxey-Eakin recharge rates were multiplied by the ratio of the precipitation for that year (measured at the Reno airport) to the long-term average precipitation. Although no data are available for Spanish Springs Valley to support this linear relation between annual precipitation and annual ground-water recharge, modeled hydraulic heads resulting from use of the second approach were slightly closer to observed heads than were those of the first approach.

Ground-water recharge from imported Truckee River water was simulated using flow records of the Orr Ditch. Transmission losses from the Orr Ditch were entered as a constant recharge at a rate proportional to the number of irrigation days during each monthly stress period. Recharge rates were distributed along the Orr Ditch from discharge measurements collected during this study. Simulation of recharge from infiltration of applied irrigation water using constant-flow cells also was proportional to the number of irrigation days during each monthly stress period. The spatial distribution of recharge from irrigation depended on each irrigator's allocation of Orr Ditch water and the area to which that allocation was to be applied (fig. 28).

Ground-water discharge by evapotranspiration was specified in model layer 1 as head-dependent flow boundaries and was assigned to selected active cells corresponding to plant distribution based on field observations. Evapotranspiration is simulated as a linear function with depth, and is computed from a maximum rate that is decreased linearly until the water level reaches the depth at which evapotranspiration is assumed to cease. This depth is called the extinction depth. Ground-water recharge from imported surface water is seasonal, which causes ground-water levels beneath irrigated lands and near the Orr Ditch to fluctuate. Because of these fluctuations, annual ground-water discharge from evapotranspiration simulated in the transient model is not constant in time or space.

Recent work by W.D. Nichols (U.S. Geological Survey, written commun., 1995) suggests that evapotranspiration in areas where depth to water is less than about 8 ft may begin as early as mid-May and continue as late as early October. Evapotranspiration in the current study was simulated from June through September (about 120 days) during which time more than 60 percent of the annual evapotranspiration may occur. In Spanish Springs Valley, evapotranspiration of ground water is limited to the area encompassed by the Orr Ditch and along the outside of the Orr Ditch near the central and southeast parts of the valley. Inside the Orr Ditch where the depth to water is shallow, vegetation is predominantly meadow grasses and alfalfa separated by large areas of bare soil. A maximum evapotranspiration rate of 0.018 ft/d at land surface and an extinction depth of 9.8 ft were used to simulate evapotranspiration inside the area of the Orr Ditch (W.D. Nichols, U.S. Geological Survey, written commun., 1995). Outside the Orr Ditch, where natural shrubs dominate the vegetation, the maximum evapotranspiration rate was determined with an equation that uses plant density, leaf area index, and depth to water (Nichols, 1994). Assuming that evapotranspiration is at a maximum when depth to ground water is 3.3 ft, the maximum evapotranspiration rate used in the model for the area outside the Orr Ditch was 1.64×10^{-3} ft/d and the extinction depth was 32.8 ft (W.D. Nichols, U.S. Geological Survey, written commun., 1995).

Initial Conditions and Aquifer Properties

Before substantial urban development and accompanying ground-water withdrawals (prior to about 1979), the hydrologic system in Spanish Springs Valley may have been in a state of dynamic equilibrium, fluctuating in response to the quantity of surface water imported yearly into the valley. Long-term temporal water-level data needed to describe the response of the basin-fill aquifer to seasonal changes in recharge are not available. Because of the uncertainty in equilibrium conditions, steady-state conditions were not simulated. The distribution of ground-water levels shown in figure 29 was determined from sparse historical data (Robinson and Phoenix, 1948; Rush and Glancy, 1967) and from a preliminary conceptualization of the flow system in the basin fill. This distribution was assumed to represent water-level conditions prior to large pumping stresses and was the basis for assignment of initial

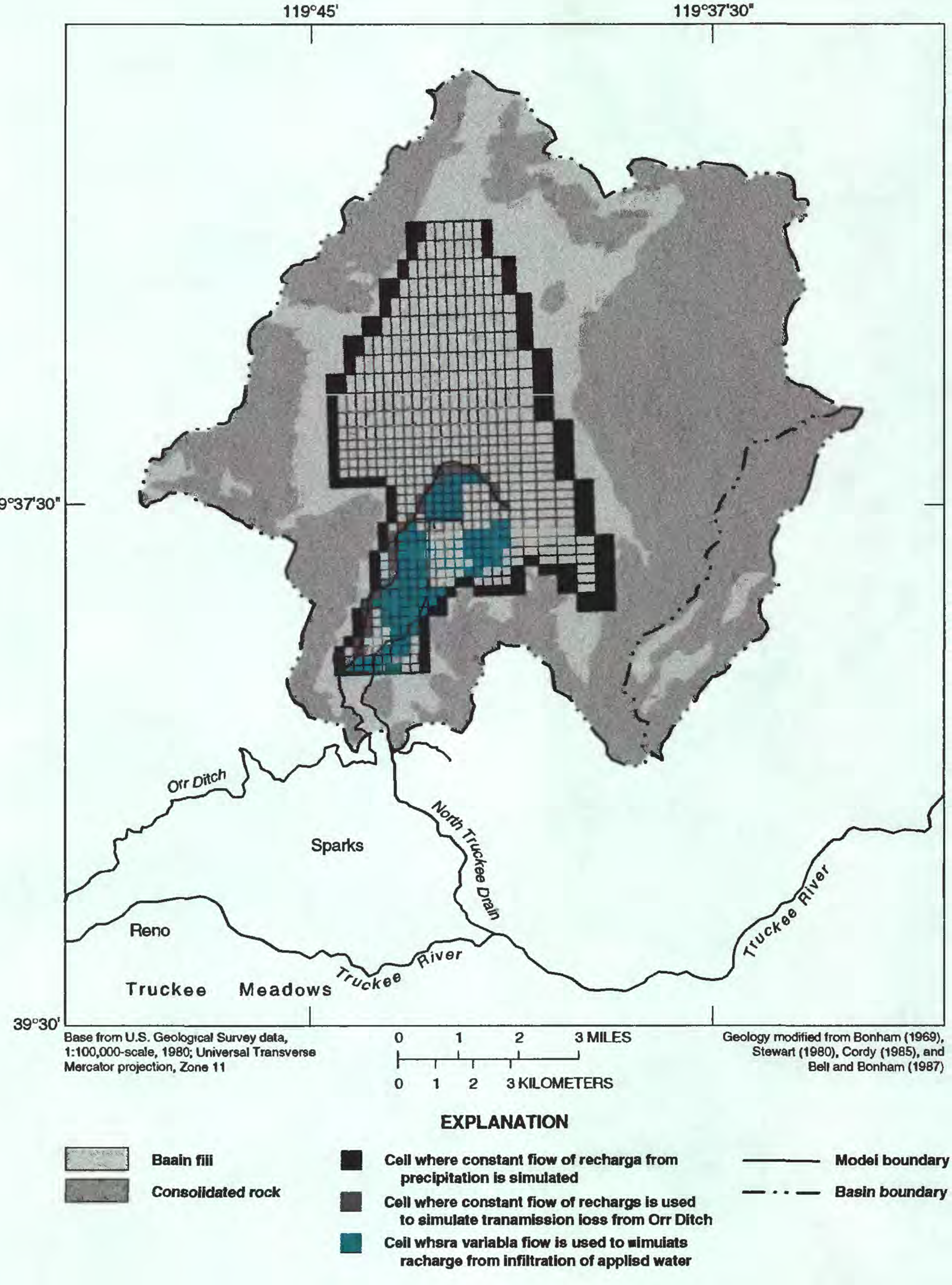


Figure 28. Model cells in layer 1 used to simulate ground-water recharge in transient model, Spanish Springs Valley, west-central Nevada.

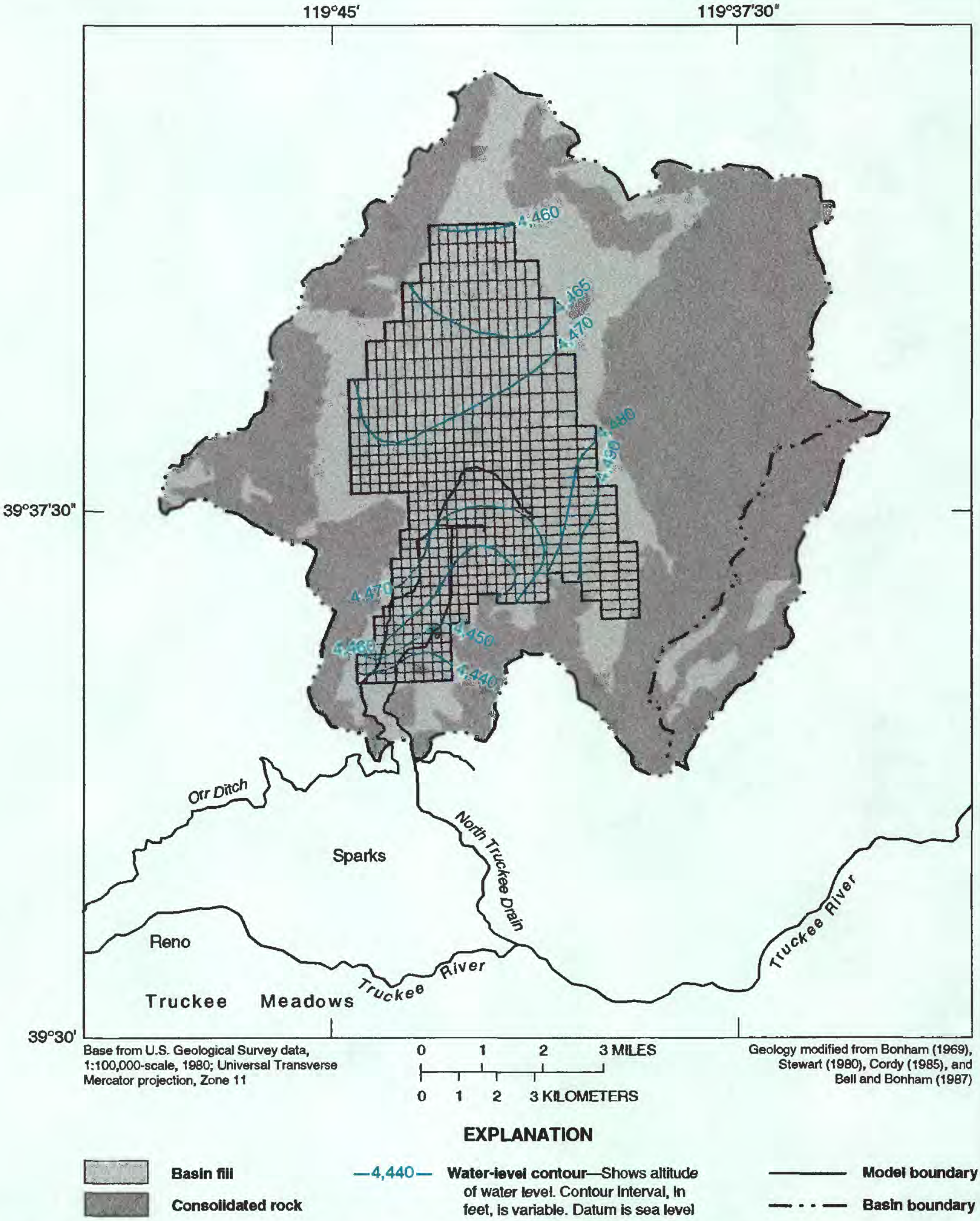


Figure 29. Ground-water levels assumed to represent water-level conditions prior to large pumping stresses (before 1979) and used as initial heads in model simulations, Spanish Springs Valley, west-central Nevada.

heads in the transient simulations. Initial heads for model layer 2 were assumed to be the same as heads for model layer 1.

The horizontal hydraulic conductivity of layer 1 (fig. 30) was estimated from lithologic and geophysical logs, distribution of hydraulic heads, and limited aquifer-test results. No laterally continuous deposits were identified from lithologic logs and no trend in bulk character of basin fill was apparent from available data. However, in the northern and southeastern parts of the study area, relatively flat hydraulic gradients suggest that hydraulic conductivity may be somewhat greater than elsewhere in the study area. In addition, hydraulic heads in the Spanish Springs Canyon area (fig. 1) were higher relative to the heads several miles north, suggesting that a barrier of low permeability may inhibit ground-water flow. The barrier may be caused by a fault within the basin fill that trends northeastward (fig. 4). During model calibration, cells at the approximate location of the fault were assigned a lower hydraulic conductivity than surrounding basin fill to simulate the observed water levels on either side of the presumed fault. Vertical hydraulic conductivities in the model were assumed to be 1 percent of horizontal conductivities (Freeze and Cherry, 1979). Owing to the vertical discretization used in the model, simulated heads were fairly insensitive to changes in vertical hydraulic conductivity. The transmissivity of layer 2 in the model was estimated as the product of the thickness and hydraulic conductivity (fig. 31). The values used for thickness of layer 2 were the total thickness of saturated basin fill between the bottom of model layer 1 and the top of the consolidated rock (fig. 10). The hydraulic conductivity of layer 2 was assumed to be about 60 percent of the assigned hydraulic conductivity of layer 1 on the basis of an increase of fine-grained deposits reported from wells that penetrated layer 2.

Although parts of the basin-fill aquifer simulated in layer 1 are locally confined or semi-confined, model layer 1 was assumed to be unconfined. Layer 1 was assigned a uniform specific yield of 0.13. Layer 2 is considered confined and each cell was assigned a storage coefficient by multiplying the thickness of the cell (in feet) by 1×10^{-6}, as suggested by Lohman (1972, p. 53). A secondary storage coefficient of 0.1 was specified for layer 2 if overlying cells were dewatered causing layer 2 to become unconfined. Hydraulic conductivity and storage coefficient distributions in the model are areally generalized. No attempt was made during the calibration process to locally adjust hydraulic properties of cells to achieve a better head match.

Simulation of Transient Conditions, 1979-94

A transient simulation was done for 1979 through 1994, a period of variations in natural recharge and discharge, changes in the quantity of imported surface water, and increases in ground-water withdrawals. An estimated 21,000 acre-ft of water was withdrawn from the basin-fill aquifer of Spanish Springs Valley from 1979 through 1994.

Calibration and Results

The flow model was calibrated under transient conditions because no data are available for the period before agricultural development began and few data are available prior to substantial ground-water withdrawals. Model calibration consisted of uniformly adjusting hydraulic properties for large groups of cells within layer 1 and rates of recharge from applied irrigation water until simulated water-level trends matched observed trends during the 16-year simulation. Hydrographs of measured water levels for five wells (sites 12, 19, 46, 50, and 69) screened within the part of the aquifer simulated by layer 1, and simulated water levels for the corresponding model cells, are shown in figure 32. These wells were selected because of their spatial distribution within the modeled area and their long period of record. The simulated water-level trends are in general agreement with measured trends. In particular, the amplitudes of seasonal change and general trends of water-level decline were reproduced fairly well by the model.

Water-level measurements collected in December 1994 from 27 wells were compared to model-derived heads calculated from the last monthly stress period of the simulation for cells corresponding to well locations. Calibration was discontinued when the sums of the difference between simulated and measured heads (bias) were near zero, and the root mean squared error between simulated and measured heads was less than 3.3 ft. The absolute maximum difference between simulated and measured heads for the 27 wells was about 10 ft. About 80 percent of these model-computed heads were within 5 ft or less of the measured value (fig. 33). The 5-ft difference between measured and computed heads is only 10 percent of the total difference in water

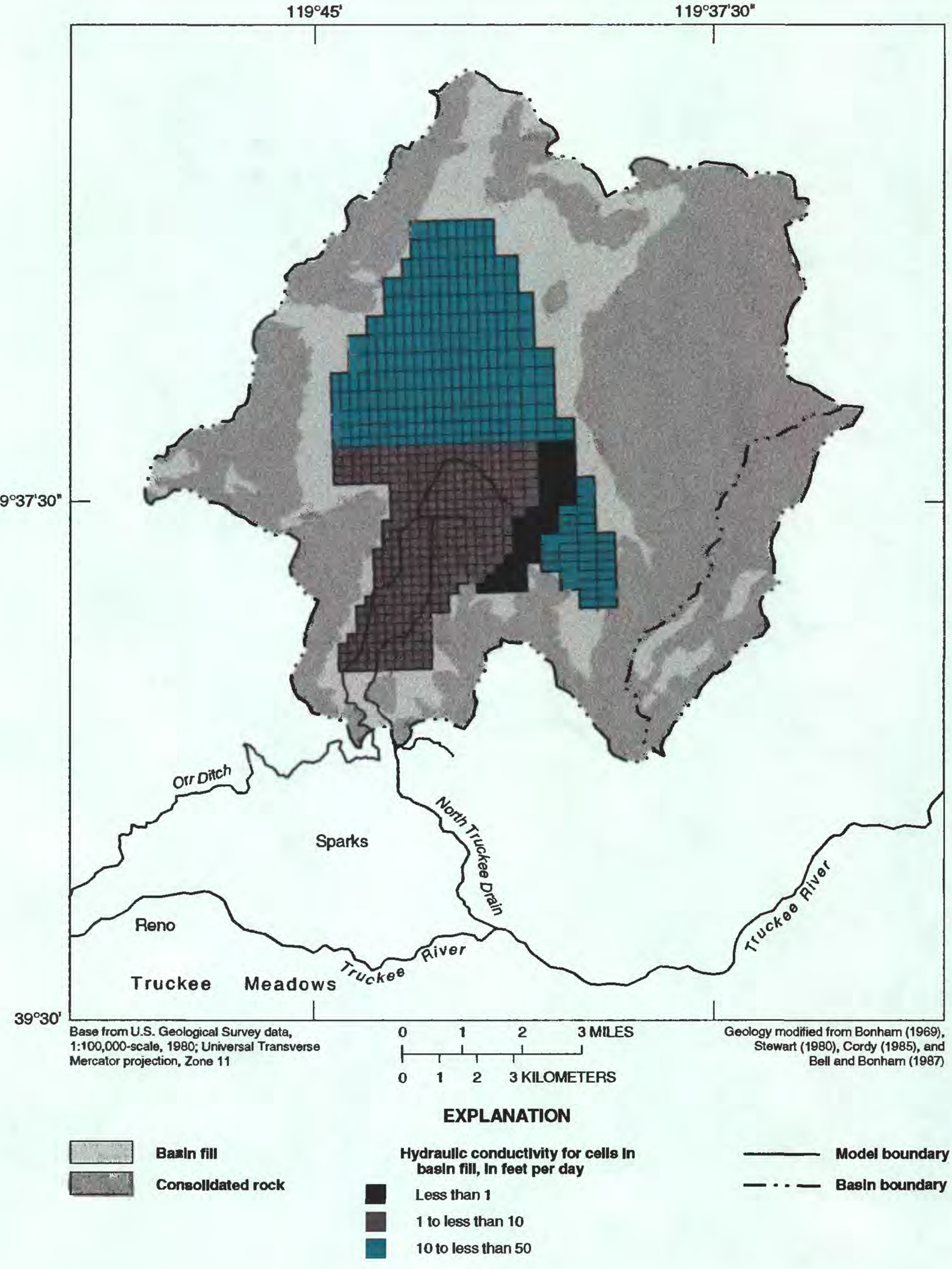


Figure 30. Horizontal hydraulic conductivity in layer 1 used in calibrated transient simulations, Spanish Springs Valley, west-central Nevada.

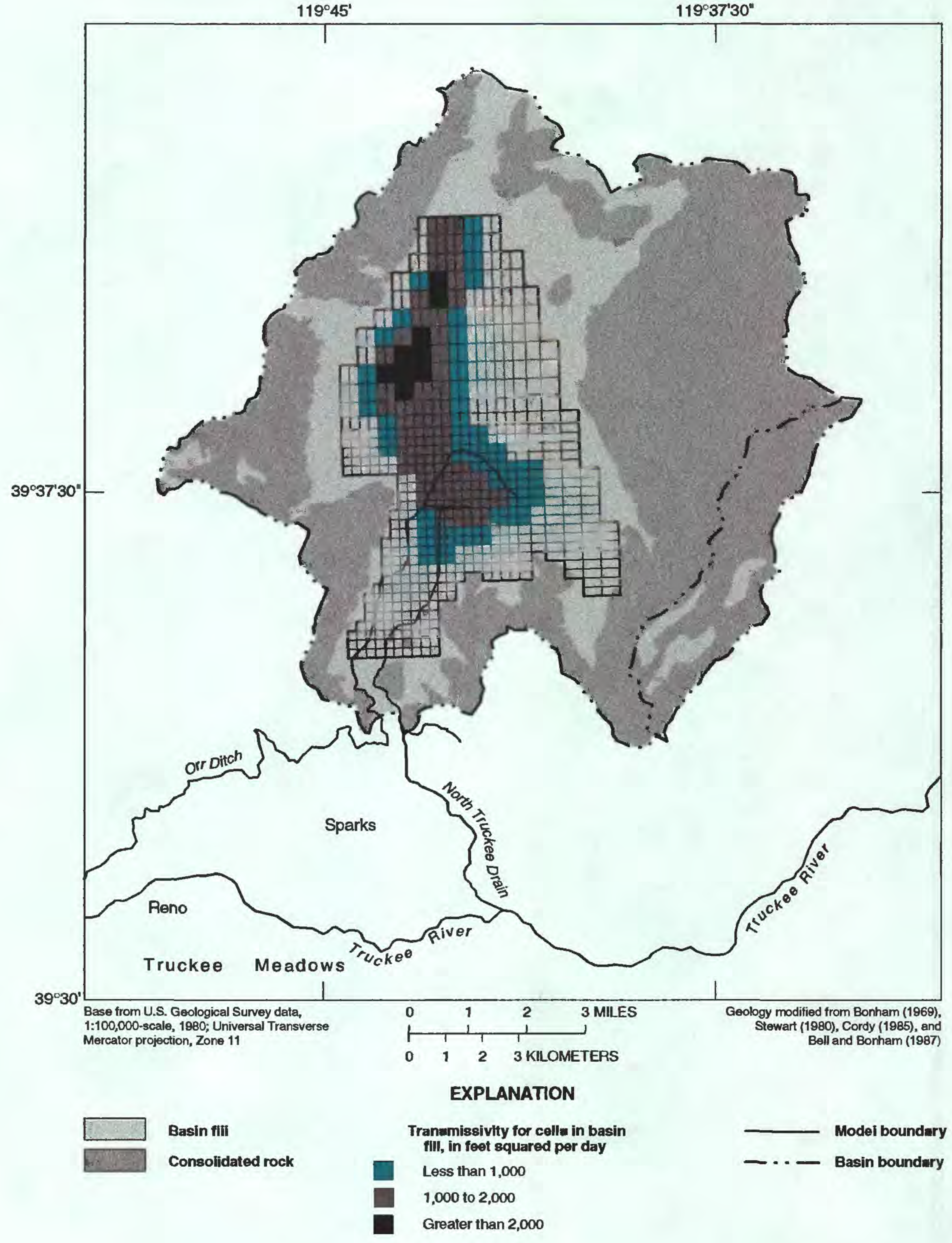


Figure 31. Transmissivity in layer 2 used in calibrated transient simulations, Spanish Springs Valley, west-central Nevada.

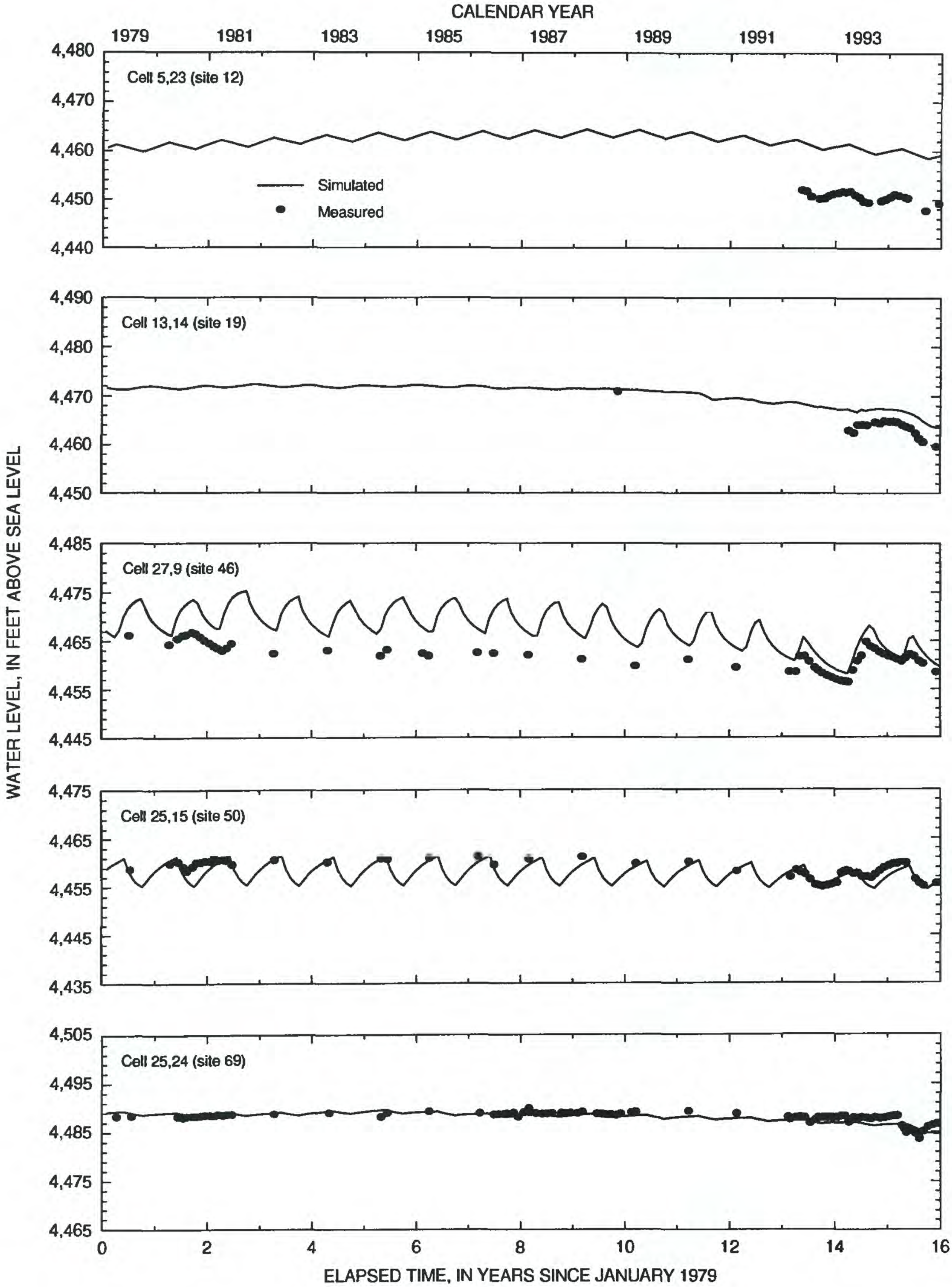


Figure 32. Measured and simulated ground-water levels for selected cells, layer 1, during transient simulations, Spanish Springs Valley, west-central Nevada.

levels in the model. The maximum altitude of the simulated water level was about 4,490 ft in the southeastern part of the model; in contrast, the minimum simulated altitude was less than 4,440 ft in the southern part (fig. 34).

The distribution of simulated heads for the monthly stress period representing December 1994 and the location of 27 cells used for comparison are shown in figure 34. The configuration of the model-derived heads in general agrees with the distribution of measured heads for December 1994 shown in figure 19. The general direction of ground-water flow simulated in the model agrees with the conceptualization of the flow system developed from data collected during this study. Ground water was simulated as flowing from the recharge-source areas in the surrounding mountains toward the valley and a broad ground-water divide beneath the central part of the valley. From the divide, ground water was simulated as flowing north and south under gradients similar to those measured in December 1994.

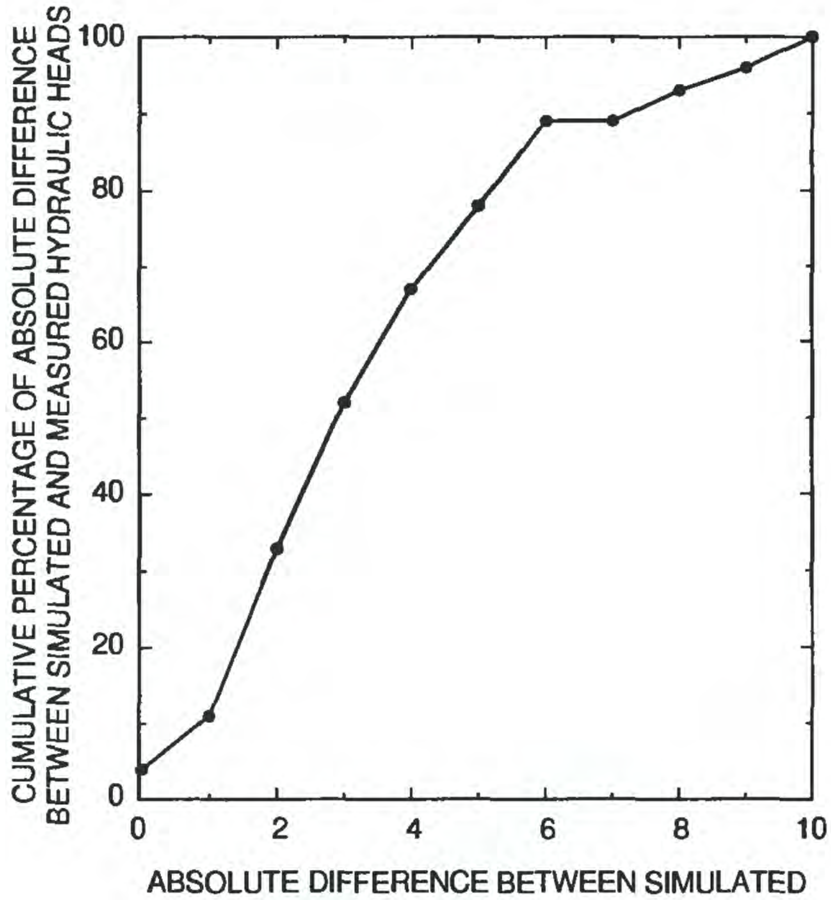
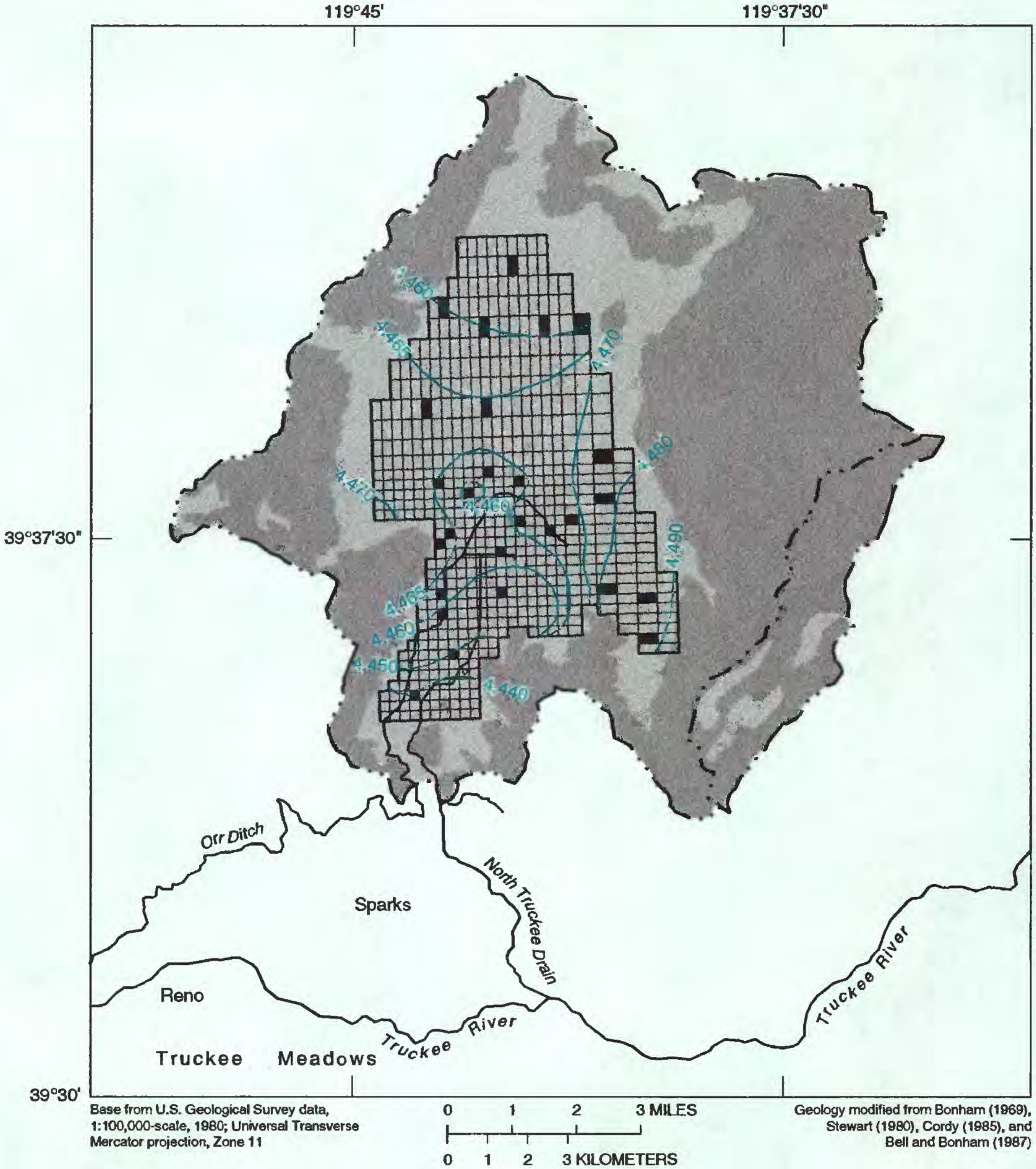


Figure 33. Cumulative percentage of absolute difference between 27 measured and simulated hydraulic heads for monthly stress period representing December 1994 of model simulation, Spanish Springs Valley, west-central Nevada.

Simulated Ground-Water Budget

The calculated water budget for the final monthly stress period of the transient simulation was used to represent 1994 conditions. Ground-water budgets listed in table 11 summarize the recharge to and discharge from the basin-fill aquifer system of Spanish Springs Valley for 1994. Figures based on field and empirical estimates are presented for comparison with the budget calculated by the model simulation. Most of the model results are in fairly good agreement with estimates based on field and empirical techniques (table 11). In particular, simulated total recharge and discharge are within 10 percent of the estimated values. However, discharge of ground water by evapotranspiration, as estimated by field methods, is 500 acre-ft less than that calculated by the transient model. Uncertainties in land-surface altitudes used in the model for computing evapotranspiration may account for the difference. Subsurface flows simulated by the model are slightly greater to the south and more than 50 percent less to the north than flows estimated by other investigators (Cohen and Loeltz, 1964, p. 23; Rush and Glancy, 1967, table 16; Hadiaris, 1988, p. 85). The imbalance between recharge and discharge simulated by the transient model for 1994 is about 2,200 acre-ft and is within the change in ground-water storage of 1,700 to 3,400 acre-ft estimated from water-level declines measured between December 1993 and December 1994.

Discharge from the basin-fill aquifer in Spanish Springs Valley increased between 1979 and 1994, mostly due to ground-water pumping. The simulated cumulative changes from 1979 to 1994 in total discharge, subsurface outflow, evapotranspiration, and ground-water pumpage are shown in figure 35*A*. The quantity of simulated evapotranspiration decreased below 1979 levels in response to increases in ground-water pumping. Recharge varied considerably during 1979-94 and was above 1979 levels until about 1988, when it began decreasing in response to decreases in recharge from imported surface water (fig. 35*B*). The quantity of ground water in storage increased slightly above 1979 estimates as a result of recharge to the basin-fill aquifer; however, the quantity of water in storage decreased after 1984 because of increased pumping (fig. 35*C*). Although most, if not all, pumped ground water was removed from storage, the water removed was partly replaced by an increase in recharge and a decrease in natural discharge.



EXPLANATION

- Basin fill
- Consolidated rock
- Model cell in basin fill containing well
- —4,440— Simulated water-level contour, December 1994—Shows altitude of water level. Contour interval, in feet, is variable. Datum is sea level
- Model boundary
- Basin boundary

Figure 34. Simulated heads in layer 1 calculated from monthly stress period representing December 1994 of model simulation, Spanish Springs Valley, west-central Nevada.

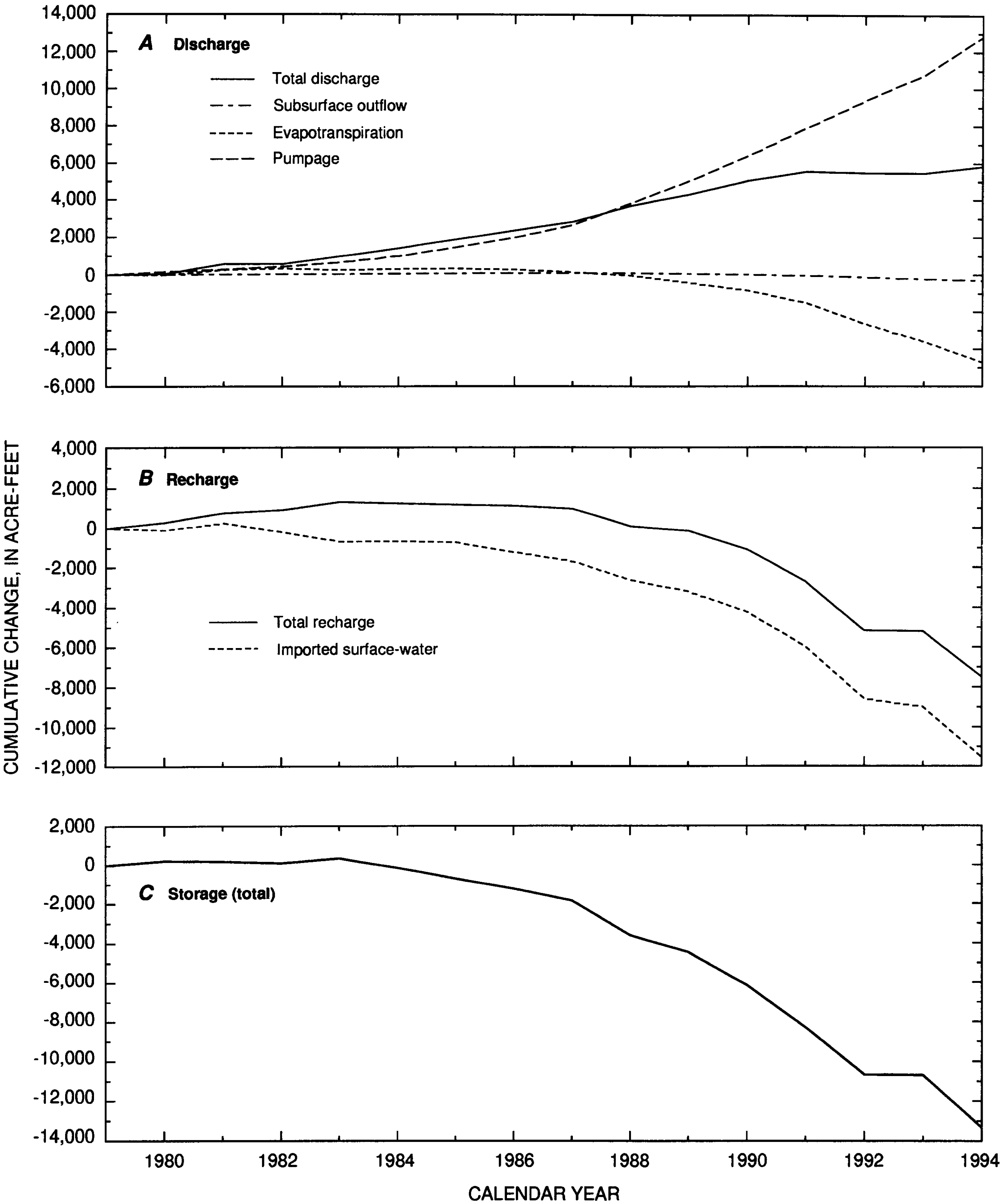


Figure 35. Cumulative change since 1979 in annual ground-water (*A*) discharge, (*B*) recharge, and (*C*) storage from results of transient simulations, 1979-94, Spanish Springs Valley, west-central Nevada.

Sensitivity Analysis

Model sensitivity to the uncertainty in estimates of hydraulic conductivity, specific yield, and the maximum rate of evapotranspiration was evaluated by six simulations using the calibrated transient model (table 12). Each model property was changed from its calibrated value to determine the effects on the differences between measured and simulated heads for 27 model cells (fig. 34) and flux rates for 1994 conditions at head-dependent boundaries. Only one modeled property was uniformly changed for a given simulation; the other properties remained constant. The modeled properties were doubled or reduced by one-half in all the simulations. Changes in hydraulic conductivity were made only to the horizontal hydraulic conductivity. Because solution to the flow model is not unique, the sensitivity analysis cannot be used to verify the accuracy of the model. However, the analysis can be used to test the response of the model to a range of hydrologic properties or conditions.

As presented in table 12, changes in evapotranspiration had the greatest effect on the final head distribution. The largest absolute difference between simulated and measured heads was 93.7 ft when the maximum evapotranspiration rate was decreased by one-half. These changes in evapotranspiration had a predictable effect on the distribution of hydraulic head. Increasing maximum evapotranspiration rate resulted in lowering the average head (negative bias) and decreasing the maximum rate raised the average head (positive bias). Changes in primary storage produced a change similar in magnitude to the change produced by variations in evapotranspiration. In addition, the rate of ground-water discharge to the North Truckee Drain was affected most when the maximum rate was decreased by one-half.

Limitations of Flow Model

A numerical ground-water model is a simplification of a complex physical system. The model is based on data that, to varying degrees, are uncertain. Errors in the conceptual model of the system, hydraulic properties, boundary conditions, initial conditions, and system stresses are reflected in the model results. Some data used in the model are estimated through the process of inverse modeling, whereby values of dependent variables (such as hydraulic head) are known and independent variables are manipulated until agreement is reached between simulated and measured values of the dependent variables. However, errors in model data

Table 12. Summary of model-sensitivity simulations at end of 1994 for Spanish Springs Valley area, west-central Nevada

Property varied	Part of model affected	Multiplication factor applied to property	Statistical difference between measured and simulated head for 27 model cells (feet)			Percentage of calibrated volume at head-dependent boundaries (calibrated volume, in acre-feet per year, in parentheses)			
			Absolute maximum difference	Root-mean squared error [1]	Bias [2]	Subsurface outflow: To south	Subsurface outflow: To north	Evapotranspiration	Ground-water discharge to North Truckee Drain
Calibrated transient simulation results at end of 1994									
None	All layers	1	10.0	4.1	+40.4	100 (190)	100 (170)	100 (1,800)	100 (170)
Sensitivity analysis									
Hydraulic conductivity	All layers	0.5	9.5	4.8	+63.0	87	68	101	65
		2	11.9	5.5	-4.2	119	115	99	142
Primary storage coefficient [3]	All layers	0.5	11.1	4.1	-45.4	98	86	85	111
		2	12.1	5.1	+90.6	105	108	113	102
Maximum ET rate	Layer 1	0.5	11.0	5.0	+93.7	107	104	84	282
		2	9.3	4.2	-1.4	96	97	106	29

[1] Average of squared differences between measured and simulated heads (standard deviation).

[2] Measurement of feet to which simulated heads are above (positive) or below (negative) measured heads.

[3] Primary storage in layer 1 is specific yield and in layer 2 is confined storage coefficient.

can cancel each other, producing non-unique solutions to the inverse problem. If a ground-water model contains these compensating errors, the model may successfully reproduce measured heads but fail to predict future aquifer response when system stresses have significantly changed (Konikow and Bredehoeft, 1992, p. 77). Further, Oreskes and others (1994, p. 643) argue that numerical models of natural systems can be neither verified nor validated, but only partly confirmed by agreement with observational data.

The flow model in this report is an approximation of ground-water movement in the basin-fill aquifer in Spanish Springs Valley. Some model data were derived from sparse records, from data of uncertain quality, or from empirical methods that are inherently uncertain (such as estimating recharge as a percentage of precipitation). Other properties of the system were estimated without observation or measurement (for example hydraulic properties of deep basin fill). Ground-water flow in consolidated rock underlying and adjacent to basin fill is unqualified and may have significant effects on hydraulic characteristics of the modeled aquifer. The nature of the hydraulic connections at the northern and southern boundaries of the study area are poorly understood, and hence the boundary conditions employed in the model are uncertain. Land-surface altitudes also have an associated uncertainty of about 10 ft.

Although substantial information exists on some system stresses (for example, municipal pumping), others, such as evapotranspiration rates and septic-system recharge, were estimated from values in the literature. Agricultural pumpage was based on quantities allocated to each user. Irrigation return flows and final hydraulic conductivities were derived through inverse modeling, a process that can produce non-unique solutions.

Identifying the uncertainties, or the magnitude of the uncertainties, in the above model data sets was not possible and that contributed to the lack of complete agreement between simulated and measured hydraulic heads. For this reason, no attempt was made to improve the head match by locally adjusting hydraulic properties in the model. Instead, hydraulic properties were kept general and were assumed to approximate the bulk character of the basin fill. Similarly, no adjustments were made to pumping rates or rates of recharge from precipitation to improve head match.

Simulation of Responses to Hypothetical Ground-Water Development Scenarios

The hydrologic response of the basin-fill aquifer system to three hypothetical ground-water development scenarios was evaluated using the 16-year transient model. The hypothetical scenarios were developed from projected water use within Spanish Springs Valley and discussions with representatives from the Nevada Division of Water Resources and Washoe County.

For each hypothetical scenario, the distribution and quantity of ground-water withdrawal was specified. To evaluate effects of changes in Truckee River importation and related recharge, each scenario was simulated with and without flow in the Orr Ditch. Model-computed water-level changes referenced to December 1994 levels were determined at the end of 5-, 10-, and 20-year periods to illustrate probable effects of ground-water withdrawal from results of the simulations. The final hydraulic head distribution shown in figure 34, which represents December 1994 conditions calculated from the 16-year transient model, was used as the initial head for each scenario. In all simulations, every residence was assumed to be connected to a sewer system (no recharge from septic systems), and the annual precipitation rate was assumed to be constant and equal to the long-term average estimated by use of the Maxey-Eakin method. The hydraulic properties of the basin fill, boundary conditions, location and amount of domestic-well pumpage, and distribution of evapotranspiration remained the same as in the transient model. Daily flow records of the Orr Ditch representing near-average conditions also were used in the simulations. Ground-water pumpage was specified in layer 1 (but not in layer 2) for each of the simulations. Stress periods, time-step methodology, and the transient character of assigned recharge and discharge used in the 16-year transient model also were applied in the development simulations.

Selection of Scenarios

Hypothetical development scenario 1 was used to represent continued ground-water pumping at 1994 rates (2,400 acre-ft/yr) and areal distribution. The location of model cells assigned pumpage greater than 10 acre-ft/yr in scenario 1 are shown in figure 27. Hypothetical development scenario 2 represents conditions resulting from projected maximum municipal pumping, as determined from water-rights data, while all other ground-water withdrawals remain at 1994 rates. Municipal pumpage for scenario 2 is specified to be 3,000 acre-ft/yr (out of about 4,000 acre-ft/yr of total basin withdrawal). Hypothetical development scenario 3 was used to represent conditions if all available water rights were used within Spanish Springs Valley to simulate the effects of maximum total-basin pumping by all users. The assigned total-basin pumpage was 6,000 acre-ft/yr. The distribution of cells assigned pumpage greater than 10 acre-ft/yr in scenarios 2 and 3 is shown in figure 36.

Discussion of Results

Simulation results of the three hypothetical development scenarios are presented in figures 37, 38, and 39. Figure 40 shows the cumulative depletion in ground-water storage within model layer 1 since December 1994, assuming a total storage of about 450,000 acre-ft. To meet part of the objectives of this study, the hypothetical scenarios were simulated with flow in the Orr Ditch (scenarios 1a, 2a, and 3a) and without flow in the Orr Ditch (scenarios 1b, 2b, and 3b) to evaluate the effects of completely removing imported water. Results of the hypothetical scenarios demonstrate general basinwide trends and illustrate the general responses. In several simulations, some model cells were completely dewatered. When a cell is dewatered, all recharge and discharge simulated in that cell cease for that annual stress period. For the cell in the northeast (cell 5,23) and one along the west boundary (cell 16,4), the initial saturated thickness was less than the simulated drawdown, causing these cells to go dry. The recharge and discharge assigned to these cells totaled about 6 acre-ft/yr and were insignificant. However, a cell in the southeast (cell 5,23) was dewatered after 20 years of simulated pumping because of the large pumping stress assigned to that cell (about 360 acre-ft/yr) and because the cell is within the area of low hydraulic conductivity used to simulate a possible fault zone.

Model-computed water levels in figures 37*A*, 38*A*, and 39*A*, which show simulated effects of continual seasonal flow in the Orr Ditch under the different pumping scenarios, rose as expected in the south end of the valley in response to recharge from imported water. Much of this rise can be attributed to the trend of below-average conditions simulated in the last several years of the transient model, as compared with average conditions used in the hypothetical development scenarios.

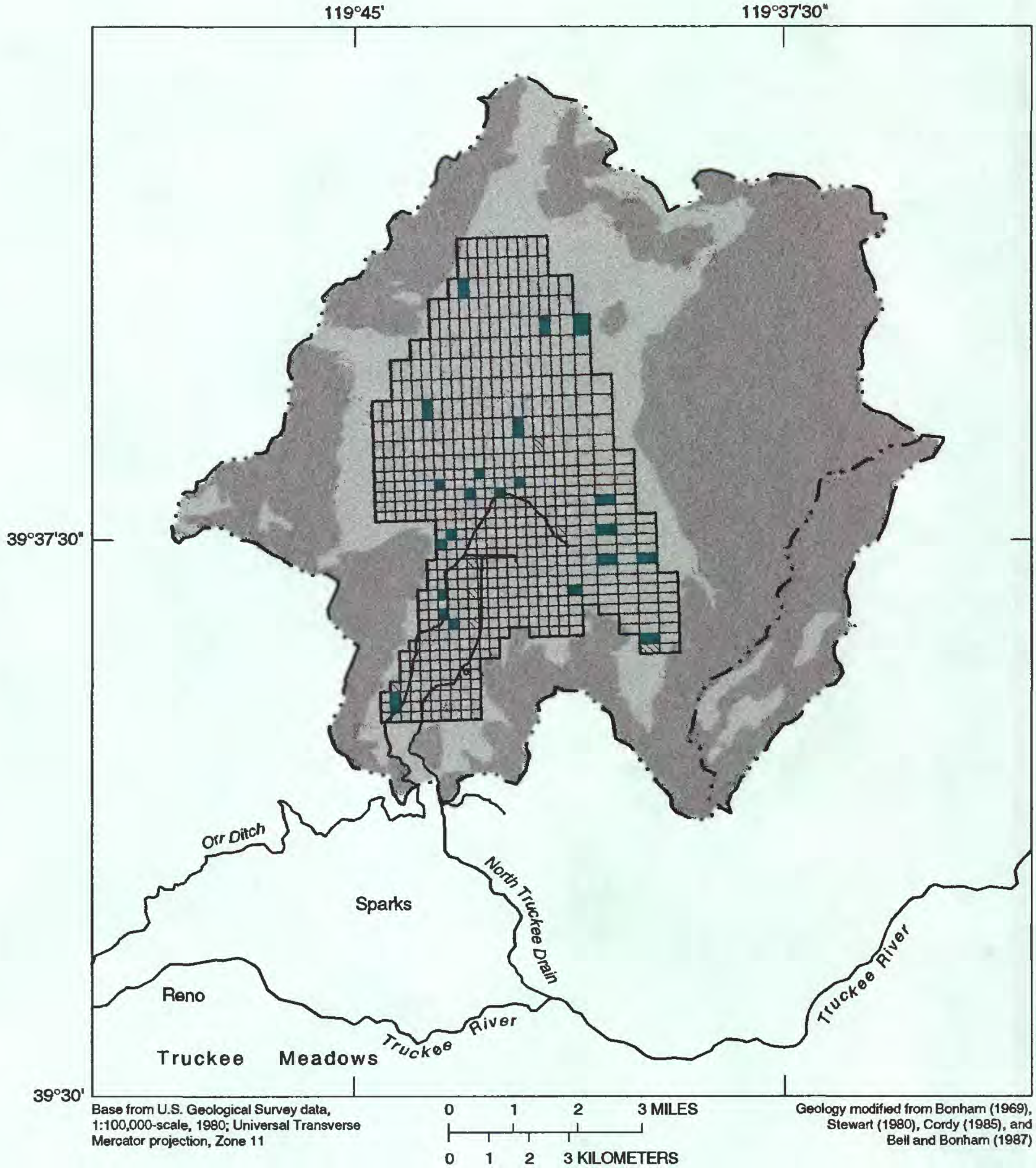
After 20 years of simulated ground-water withdrawal under 1994 pumping conditions (scenario 1), water-levels declined 10 to 20 ft in the entire northern half of the modeled area (fig. 37*A*). For the same scenario, but without simulated flow in the Orr Ditch (fig. 37*B*), water-level declines of 10 to 20 ft were indicated after only 5 years, and after 20 years, simulated water-levels had declined between 20 and 60 ft in a large area in the north-central part of the modeled area. For conditions represented by scenario 1, cumulative storage depletion increased about 5 percent (fig. 40) in the absence of recharge from imported surface water.

For model simulations that represent maximum municipal pumpage (hypothetical development scenario 2), much of the modeled area has simulated water-level declines of 20 to 60 ft after 20 years of pumping and simulated flow in the Orr Ditch (fig. 38*A*). The greatest decline (60 ft and greater) was in the southeastern part of the model area and was due to the location of simulated municipal wells. Without simulated flow in the Orr Ditch, results of scenario 2 (fig. 38*B*) indicate that nearly the entire modeled area would have water-level declines of 20 to 60 ft and more than 16 percent of the basin fill would be dewatered (fig. 40*A*).

Results of scenario 3 (ground-water withdrawals for all available water rights) indicate that nearly the entire modeled area would have water-level declines of 20 to 60 ft after 20 years. As in scenario 2, water-level declines of 60 ft and greater were simulated within the southeastern part of the area after 20 years of pumping (fig. 39) and nearly 20 percent of the area of the modeled aquifers were dewatered (fig. 40).

SUMMARY AND CONCLUSIONS

Infiltration of imported surface water for irrigation is the source of most ground-water recharge to the basin-fill aquifer in Spanish Springs Valley. As urban development increases, changes in land use from agricultural to suburban and resultant increases in ground-water withdrawal are anticipated. These changes may include reduction or complete elimination of surface-water importation to the valley. Because of potential ground-water overdraft associated with urban development, the U.S. Geological Survey, in cooperation with the Nevada Division of Water Resources, made a 5-year study to evaluate and refine estimates of the water budget and yield of the basin-fill aquifer in Spanish Springs Valley.



EXPLANATION

Basin fill

Consolidated rock

Cell with assigned pumpage greater than 10 acre-feet per year in scenario 2

Cell with assigned pumpage greater than 10 acre-feet per year in scenario 3

Model boundary

Basin boundary

Figure 36. Cells with assigned ground-water pumpage for municipal, irrigation, and industrial use in hypothetical development scenarios 2 and 3 used in model simulations, Spanish Springs Valley, west-central Nevada.

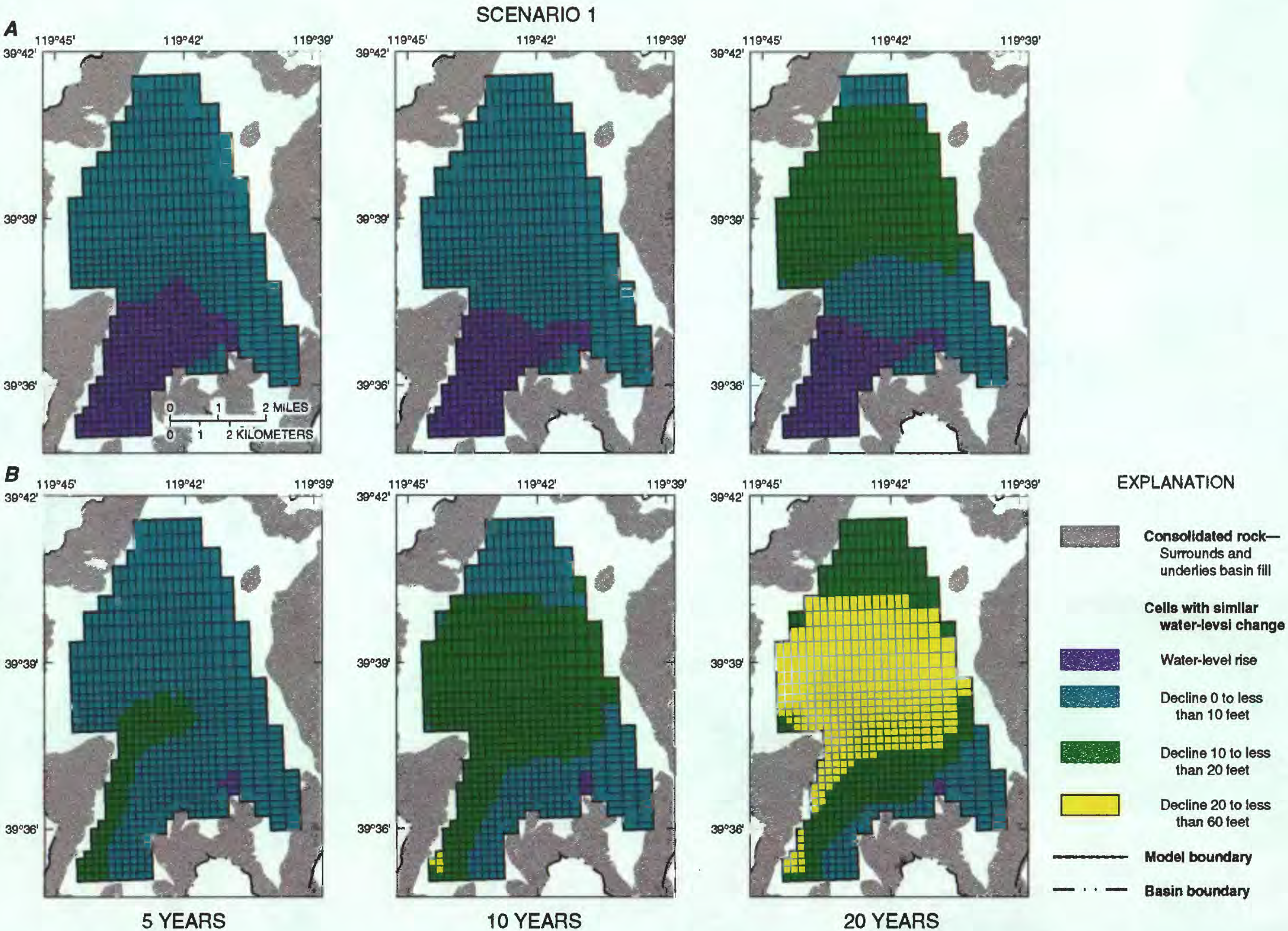


Figure 37. Model-computed water-level change at the end of 5, 10, 20 years since December 1994 for hypothetical development scenario 1 (continued pumping at 1994 rates) for simulation *(A)* with flow and *(B)* without flow in the Orr Ditch, Spanish Springs Valley, west-central Nevada.

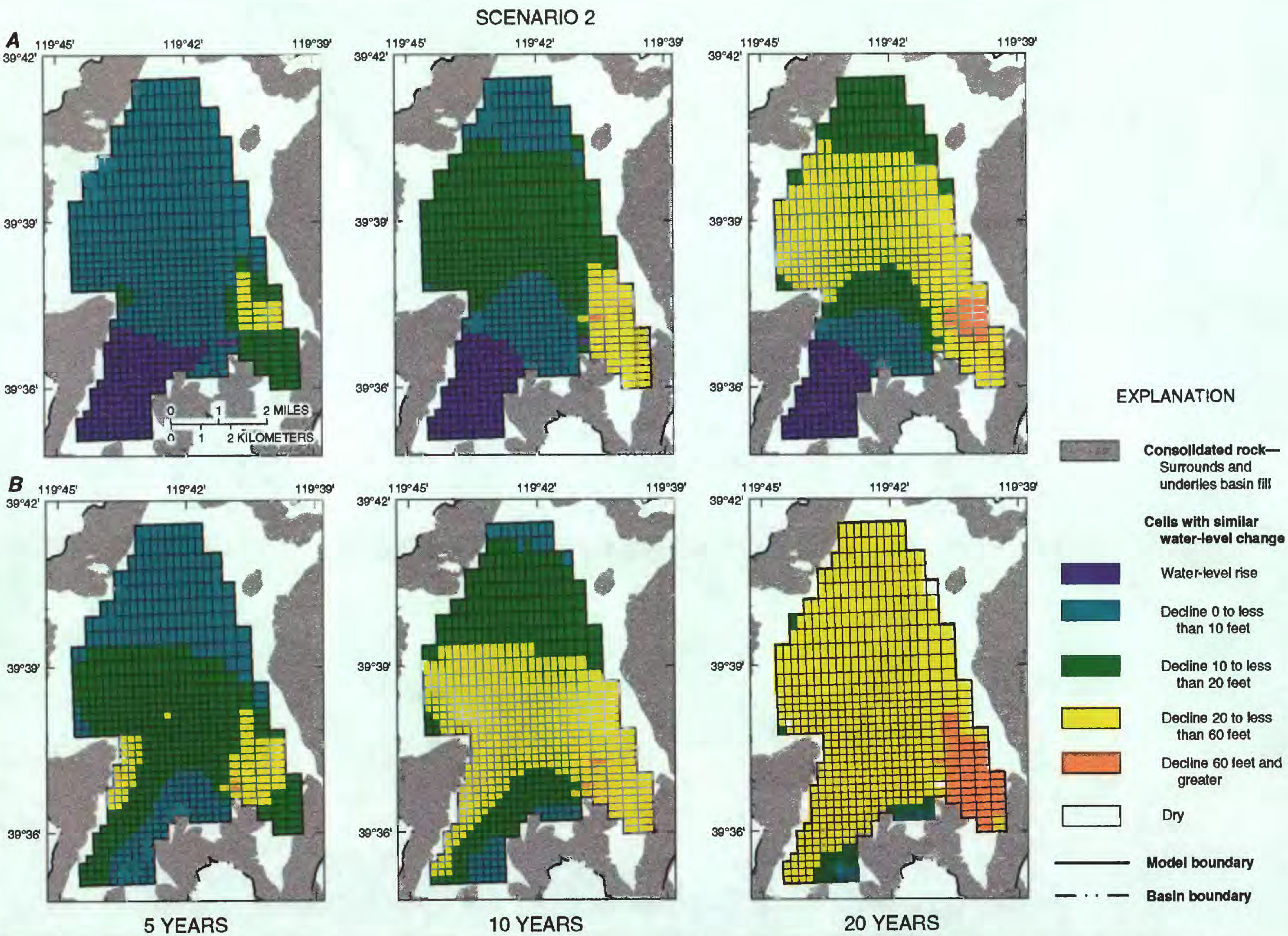


Figure 38. Model-computed water-level change at the end of 5, 10, and 20 years since December 1994 for hypothetical development scenario 2 (projected maximum municipal pumping rates) for simulation (*A*) with flow and (*B*) without flow in the Orr Ditch, Spanish Springs Valley, west-central Nevada.

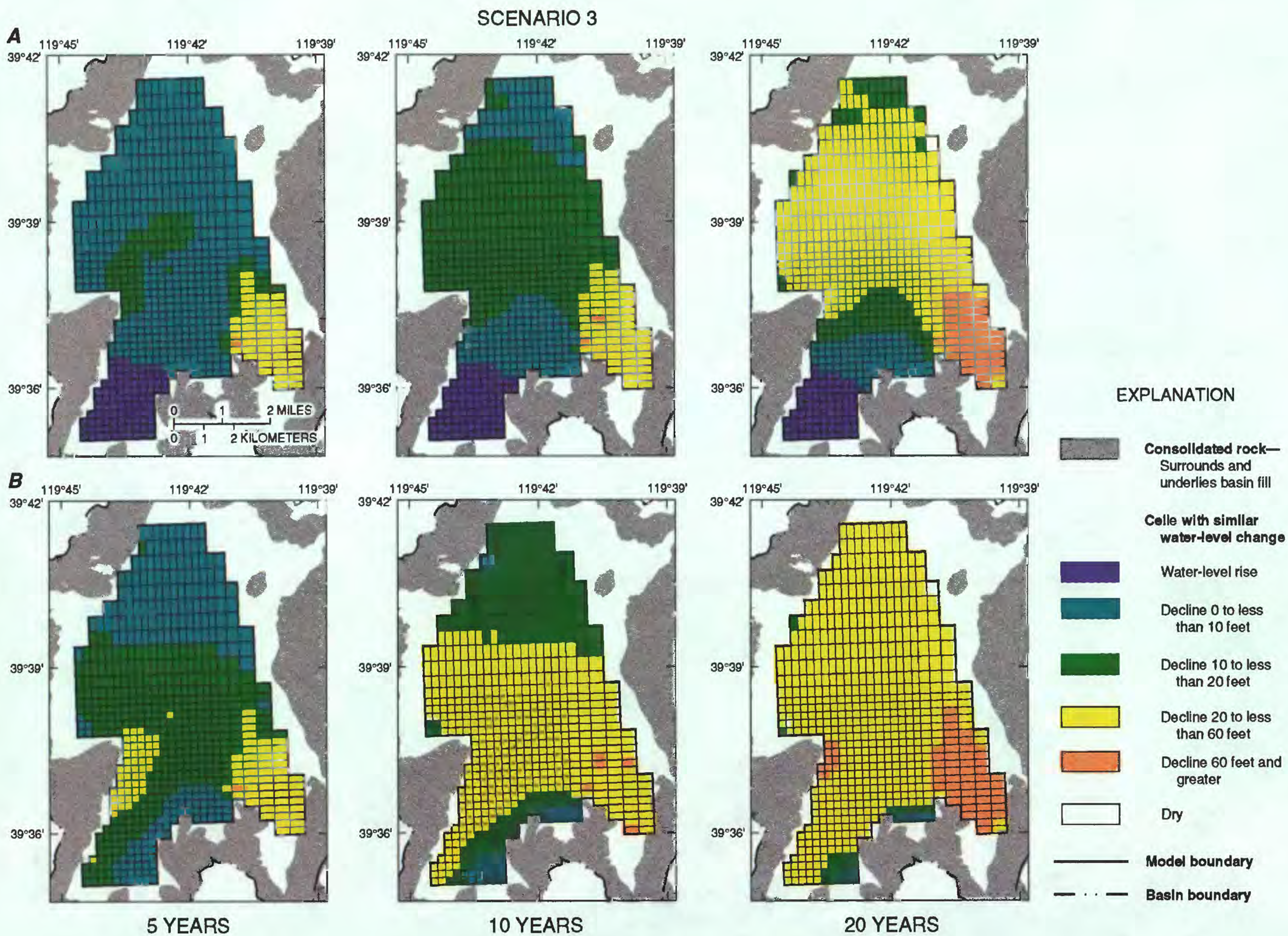


Figure 39. Model-computed water-level change at the end of 5, 10, and 20 years since December 1994 for hypothetical development scenario 3 (projected total-basin pumping rates of all available water rights) for simulation (*A*) with flow and (*B*) without flow in the Orr Ditch, Spanish Springs Valley, west-central Nevada.

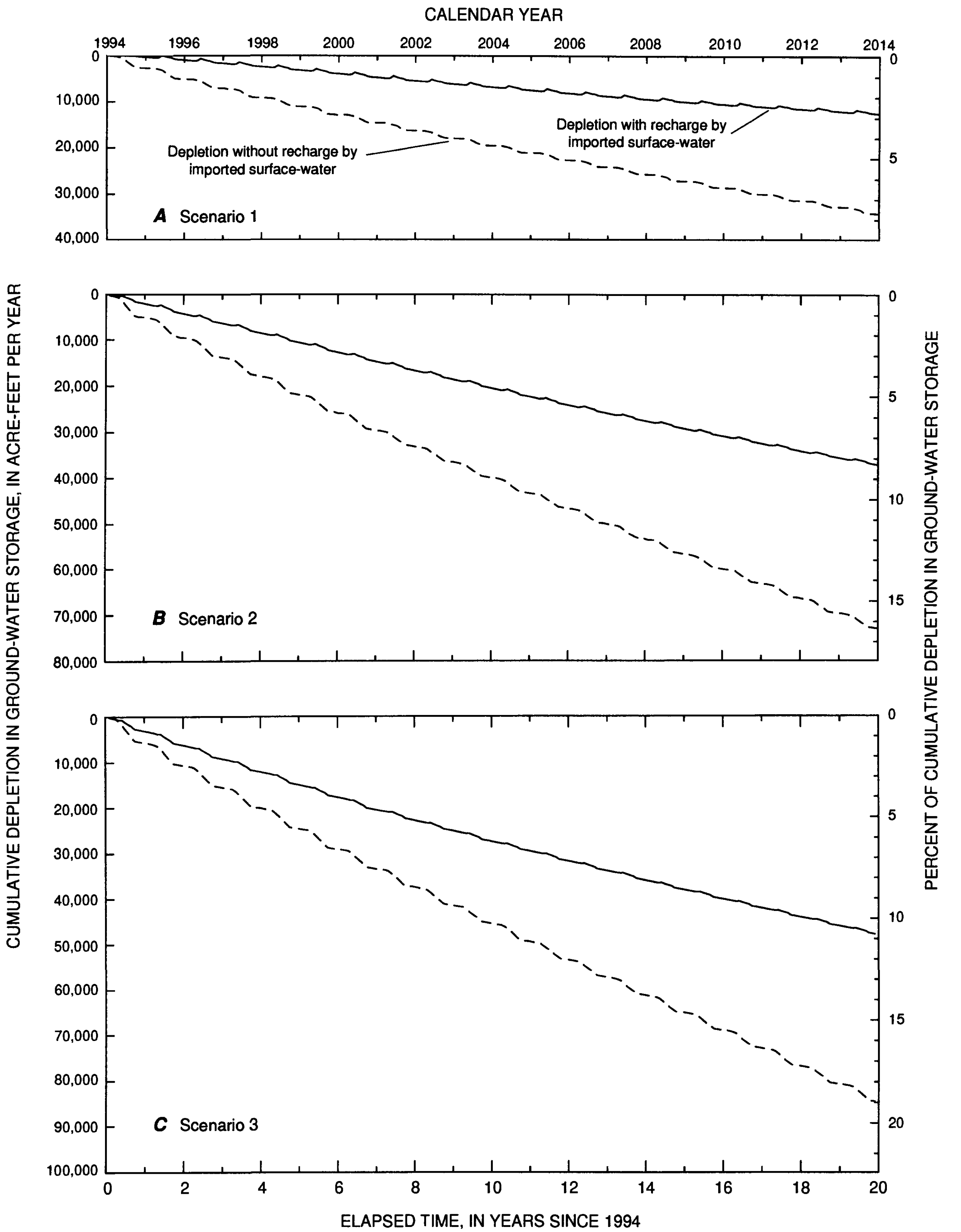


Figure 40. Simulated cumulative depletion in ground-water storage since December 1994 for hypothetical development: (*A*) scenario 1, continued pumping at 1994 rates, (*B*) scenario 2, projected maximum municipal pumping rate, and (*C*) scenario 3, projected total-basin pumping rates of all available water rights, Spanish Springs Valley, west-central Nevada.

Spanish Springs Valley is a north-trending structural basin in west-central Nevada, about 5 mi northeast of Reno, with a total area of about 80 mi^2. Substantial urban development of this valley began in the late 1970's. Population of less than 800 in 1979 increased to more than 4,000 in 1990 and was projected to be about 9,300 in 1994. More than 2,000 homes receive water from municipal suppliers within Spanish Springs Valley. An additional 200 homes derive water from domestic wells. Total ground-water withdrawal from the basin in 1994 was an estimated 2,600 acre-ft—about 2,000 acre-ft more than in 1979. Secondary recharge from septic systems, estimated from water-use records for 1994, may be as much as 450 acre-ft.

Several methods of investigation were used during this study, including the collection of basic hydrologic and geologic data and the application of several geochemical techniques and geophysical methods. The distribution of precipitation within the study area was estimated from a relation between precipitation and altitude. Estimates of ground-water recharge from precipitation were based on the distribution of precipitation. A flow model was developed to simulate the movement of ground water and to evaluate the empirical estimates of recharge and discharge. The calibrated flow model was then used to estimate effects of hypothetical changes in land use and ground-water development.

The study area lies between major tectonic structures of the Sierra Nevada Frontal Fault Zone and the shear zone of the Walker Lane. Extensional faulting is thought to have formed the present-day topographic features, including the structural depression underlying Spanish Springs Valley. Tertiary volcanic rocks, which make up most of the consolidated rock exposed in the area, underlie much of the eastern part of the valley. In the southeastern part, a relatively transmissive connection between basin fill and volcanic rocks is suggested by water-level responses to ground-water pumping. Although detailed investigation of the hydrologic characteristics of these Tertiary volcanic rocks was beyond the scope of this study, the volcanic rocks may be hydrologically significant at a regional scale. The structural depression underlying Spanish Springs Valley is filled in part by interbedded deposits of sand, gravel, silt, and clay with a maximum thickness of about 1,000 ft as determined by geophysical methods. Hydraulic conductivity of the basin fill in the upper 330 ft ranges from 0.5 ft/d to about 12 ft/d. Total amount of recoverable water stored in the basin-fill aquifer in the upper 330 ft is estimated to be between 300,000 and 600,000 acre-ft.

Annual precipitation on the valley floor is generally less than 8 in. The surrounding mountains receive about 9 to 11 in. annually and more than 13 in. may fall in the higher altitudes of the Pah Rah Range. The total precipitation estimated within the study area is about 36,000 acre-ft/yr, of which nearly 3,500 acre-ft/yr falls within the topographically closed Dry Lakes area in the southern part of the Pah Rah Range. Estimated ground-water recharge from precipitation ranges from 770 acre-ft/yr using a chloride-balance method to 830 acre-ft/yr using the Maxey-Eakin method. In 1994, recharge from precipitation was estimated at about 600 acre-ft, or 72 percent of the long-term average estimated using the Maxey-Eakin method.

Surface-water resources in the basin consist almost entirely of imported Truckee River water conveyed by the Orr Ditch to support agriculture in the southern part of the valley. During this study, the Orr Ditch was completely shut off by June in 1992 and 1994 in response to below-average precipitation. Flow in the North Truckee Drain, which removes irrigation return flow from Spanish Springs Valley to the Truckee River, fluctuates in direct response to the availability of Orr Ditch water and the application of water for irrigation. In 1994, the difference between Orr Ditch inflow and North Truckee Drain outflow was about 3,100 acre-ft, which represents the amount of imported surface water consumed in Spanish Springs Valley. Of the 3,100 acre-ft of imported surface water consumed in 1994, about 1,400 acre-ft is estimated to have recharged the shallow basin fill as transmission loss from the Orr Ditch and infiltration of applied irrigation water. Direct evaporation from ponded water and evapotranspiration prior to deep percolation make up the remaining consumed imported water.

Virtually all ground water in Spanish Springs Valley is derived from imported surface water and precipitation that falls within the drainage basin. During the irrigation season, Orr Ditch transmission losses and infiltration of water applied to fields raise shallow ground-water levels more than 5 ft, creating a ground-water mound that dissipates with time after irrigation ceases. The movement of ground water is generally from the recharge-source areas in the mountains toward the valley and a ground-water divide that has developed beneath the central part of the valley. From the divide, ground water flows northward toward Warm Springs Valley and southward to the Truckee Meadows. Locally derived ground water is distinguished from imported Truckee River water on the basis of stable-isotope compositions and environmental age-dating techniques. Mass-balance calculations suggest that imported Truckee River water makes up 65 percent of the discharge from a well 2,000 ft north of the Orr Ditch.

Estimates of ground-water recharge and discharge to the basin-fill aquifer for 1994 conditions were made using field and empirical techniques, and were evaluated using a two-layer mathematical flow model. The flow model was calibrated under transient conditions using estimated ground-water withdrawals from 1979 through 1994 and the resultant water-level changes. Model-computed ground-water recharge from imported surface water agreed well with the empirical estimate of 1,400 acre-ft for 1994. Field-derived estimates of evapotranspiration, however, are 500 acre-ft less than evapotranspiration simulated by the flow model for 1994. Lack of water-level data in the northern part of the valley precluded empirical estimates of subsurface flow to Warm Springs Valley. On the basis of the current conceptualization of the flow system, the calibrated flow model indicates that about 170 acre-ft of water may move northward toward Warm Springs Valley. In addition, model results indicate that 190 acre-ft of subsurface flow may be entering the Truckee Meadows to the south. An imbalance between ground-water recharge and discharge ranging from 1,700 acre-ft to 2,200 acre-ft was estimated for 1994 conditions.

The augmented-yield concept in this study is defined as the perennial yield plus salvable secondary recharge resulting from use of imported surface water. Augmented yield of the basin-fill aquifer in Spanish Springs Valley, determined for 1994 conditions, was estimated to be about 2,400 acre-ft, assuming that 1,400 acre-ft of ground-water recharge was salvaged from infiltration of imported Truckee River water. However, if the quantity of imported surface water or its management changes, the augmented yield for the basin-fill aquifer must be revised to account for changes in ground-water recharge.

The hydrologic response of the basin-fill aquifer system to three hypothetical ground-water development scenarios was evaluated using the 16-year transient model. For each scenario, the distribution and quantity of ground-water withdrawal was changed and each scenario was simulated with and without flow in the Orr Ditch. Simulated responses to the hypothetical development scenarios suggest that, although recharge from imported surface water prevents water-level declines in the southern part of the study area, after 20 years of pumping, water levels may decline between 20 and 60 ft throughout much of the area. For model simulations without recharge from imported water, 8 percent to nearly 20 percent of the basin-fill aquifer was dewatered and water-level declines were more than 60 ft in the southeastern part of the valley.

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