GROUND-WATER FLOW AND SIMULATED EFFECTS OF DEVELOPMENT IN PARADISE VALLEY, A BASIN TRIBUTARY TO THE HUMBOLDT RIVER IN HUMBOLDT COUNTY, NEVADA

REGIONAL AQUIFER-SYSTEM ANALYSIS

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Ground-Water Flow and Simulated Effects of Development in Paradise Valley, A Basin Tributary to the Humboldt River in Humboldt County, Nevada

By DAVID E. PRUDIC *and* MARC E. HERMAN

REGIONAL AQUIFER-SYSTEM ANALYSIS—GREAT BASIN, NEVADA-UTAH

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Gordon P. Eaton
Director

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
acre	0.4047	square hectometer
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
foot (ft)	0.3048	meter
foot per foot (ft/ft)	1.000	meter per meter
foot per second (ft/s)	0.3048	meter per second
foot per day (ft/d)	0.3048	meter per day
foot per year (ft/yr)	0.3048	meter per year
cubic foot per second (ft3/s)	0.02832	cubic meter per second
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
pound per cubic foot (lb/ft3)	16.02	kilogram per cubic meter
square mile (mi2)	2.590	square kilometer

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

GROUND-WATER FLOW AND SIMULATED EFFECTS OF DEVELOPMENT IN PARADISE VALLEY, A BASIN TRIBUTARY TO THE HUMBOLDT RIVER IN HUMBOLDT COUNTY, NEVADA

By David E. Prudic and Marc E. Herman

ABSTRACT

Ground-water flow in Paradise Valley, a basin tributary to the Humboldt River in north-central Nevada, was studied as part of a regional aquifer-system analysis in the Great Basin region of Nevada, Utah, and adjacent States. The valley was chosen because it is typical of the many basins that drain into the river. The principal technique used to analyze ground-water flow in Paradise Valley was with a computer program that simulates ground-water flow in three dimensions. Results from computer simulations are used to illustrate the possible effects that increased pumpage could have on ground-water flow in Paradise Valley and, by analogy, in other similar basins tributary to the Humboldt River.

Basin fill, which consists mostly of discontinuous lenses of gravel, sand, silt, and clay, and lesser quantities of volcanic deposits, forms the primary aquifer in Paradise Valley. The deposits may exceed 8,000 feet in thickness near the center of the valley but pinch out around the valley edges where consolidated rocks are exposed. The elongate valley (at most 13 miles wide and about 40 miles long) trends northeasterly and is bounded by mountains on the north, west, and east sides; it merges with Humboldt River Valley to the south.

Recharge to the basin-fill aquifer is primarily from streams that enter the valley from the surrounding mountains and from two streams that enter the northeastern part of the valley from adjacent areas by way of narrow canyons. Estimated average annual streamflow into the valley is about 72,000 acre-feet. During periods of high streamflow, surface water flows to sand dunes that cross the southern end of the valley, forming a lake that remains until the water seeps into the ground, is evaporated, or is drained to the Humboldt River if a temporary channel is dredged through the dunes.

Discharge from the basin-fill aquifer is primarily from evapotranspiration in the valley lowlands adjacent to streams. Results of a simulation of conditions prior to ground-water pumpage indicates that southward ground-water flow from Paradise Valley into Humboldt River Valley was only 1,800 acre-feet per year, whereas as much as 1,300 acre-feet per year may have been flowing northwestward from Humboldt River Valley into Paradise Valley near Golconda Butte.

Ground-water pumpage in Paradise Valley increased slowly from about 200 acre-feet in 1948 to 6,800 acre-feet in 1970. Pumpage increased dramatically in the 1970's when the southern end of the valley was determined to be an ideal location for growing potatoes; in 1982 pumpage totaled about 44,000 acre-feet. The increase in pumpage altered the direction of ground-water flow, which prior to development was from the margins of the valley toward its axis and then southward toward the Humboldt River. As of 1982, ground-water flow in Paradise Valley was toward a water-table depression near the heavily pumped area in the southern end of the valley.

Five different development scenarios were simulated in which pumpage was concentrated in different areas of Paradise Valley. The purpose of these simulations was to illustrate the effects of different ground-water development patterns on ground-water flow in Paradise Valley. The first scenario assumed pumpage equal to net pumpage (total pumpage less what was estimated to return to the aquifer) of about 39,000 acre-feet per year estimated for 1982: 36,000 acre-feet per year in Paradise Valley and about 2,800 acre-feet per year in adjacent Humboldt River Valley. After 300 years of pumpage, results showed water-level declines in the southern part of Paradise Valley of more than 200 feet. These declines were near the area where pumpage was most concentrated in 1982. Ground-water flow from Paradise Valley to Humboldt River Valley had decreased 1,700 acre-feet per year, whereas ground-water flow from Humboldt River Valley into Paradise Valley increased 7,400 acre-feet per year. Net pumpage for the other four scenarios was set equal to 72,000 acre-feet per year, but the location of pumpage in Paradise Valley changed. The distribution of pumpage in the valley for each simulation included, respectively, wells concentrated at the southern end; wells concentrated at the northern end; wells concentrated along the central part; and wells distributed throughout the area of evapotranspiration prior to pumpage. Concentrating pumpage at either end of the valley resulted in simulated water-level declines that locally exceeded 400 feet after only 75 years of pumping in the northern end and after 100 years of pumping in the southern end. In addition, pumpage concentrated at the southern end of the valley produced a reversal of net flow between Paradise Valley and Humboldt River Valley. Prior to pumping, the estimated net flow was 500 acre-feet per year from Paradise Valley into Humboldt River Valley, whereas after a simulated period of 50 years, the net flow was 15,000 acre-feet per year from Humboldt River Valley into Paradise Valley. Simulations in which pumpage was concentrated in the central part of the valley and distributed throughout the area of evapotranspiration resulted in water-level declines of generally less than 200 feet after 300 years; both simulations nearly reached a new equilibrium and captured much of the predevelopment evapotranspiration.

In conclusion, concentrating pumpage in the northern and southern areas of Paradise Valley might produce large water-level declines without effectively reducing natural discharge in the central part of the valley. Concentrating pumpage in the southern end might also induce flow from Humboldt River Valley and, depending on the quantity of pumpage, might ultimately affect flow in the river.

INTRODUCTION

Paradise Valley, a basin tributary to the Humboldt River in north-central Nevada (fig. 1), was chosen as one of several areas to be studied in detail as part of the Great Basin Regional Aquifer-

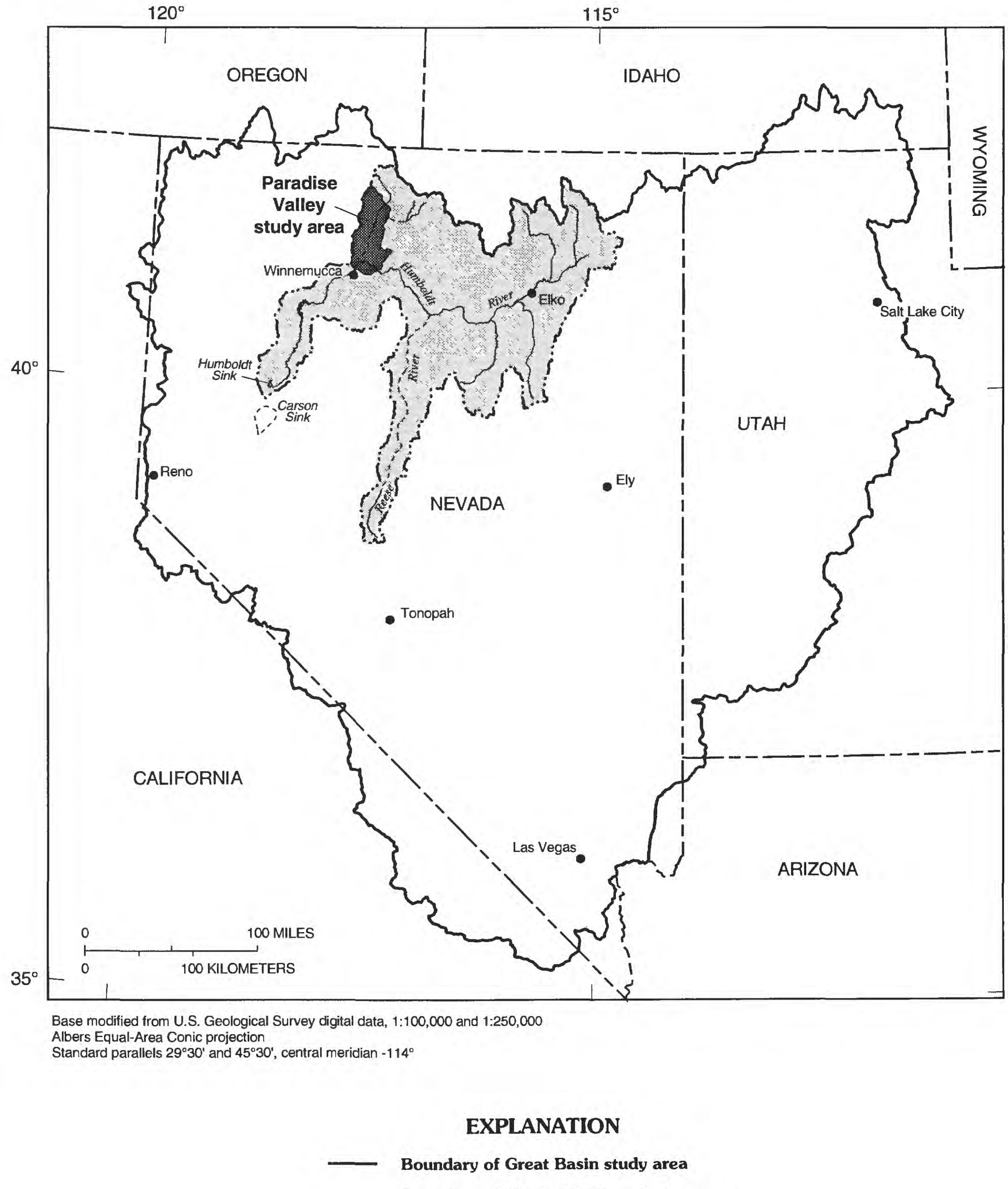


FIGURE 1.—Location of Paradise Valley study area relative to Humboldt River drainage area and Great Basin study area.

System Analysis (RASA) project. The Great Basin RASA project includes much of Nevada, the western half of Utah, and small parts of Arizona, California, Oregon, and Idaho. The purpose and objectives of the Great Basin RASA project are discussed by Harrill and others (1983). Paradise Valley was chosen because it has characteristics similar to those of many basins that drain to the Humboldt River, and because recent increases in ground-water pumping in Paradise Valley have produced a water-table decline of as much as 80 ft. The water-table decline allowed for an improved calibration of a computer model.

The Humboldt River begins in northeastern Nevada (fig. 1) and flows in a westerly to southwesterly direction across the north- to northeast-trending mountains and basins that characterize the Great Basin Region of Nevada and Utah. The river ends at the Humboldt Sink in western Nevada (fig. 1), but during years of exceptionally high runoff, some of the accumulated inflow to the Humboldt Sink may spill into the neighboring Carson Sink. The Humboldt River has a drainage area of 16,800 mi^2 and includes 33 basins (Scott and others, 1971, p. 31). Because the river and its alluvium connect many of the basins, its drainage area can be considered one large regional system. Instead of analyzing the entire system, one basin was selected to illustrate the possible effects of ground-water development in a tributary basin on the water resources of the Humboldt River.

PURPOSE AND SCOPE

The purposes of this report are to describe and analyze the ground-water flow system in Paradise Valley and to evaluate, by using a ground-water flow model, the response of the flow system to selected development scenarios. The selected scenarios are designed to be compared with results from similar investigations in other selected basins within the Great Basin RASA study area.

Field work began in March 1981 and continued through December 1982. The work consisted of (1) canvassing most of the wells in the valley, (2) making multiple measurements of water levels in wells to ascertain seasonal and long-term trends and gathering previously collected data, (3) obtaining estimates of pumpage, (4) mapping land use and types of crops, and estimating water use by crop type, (5) mapping geologic and hydrologic features, and (6) making detailed gravity and seismic measurements for the purpose of determining the thickness of basin fill. In addition, continuous streamflow data were collected at three sites in or near the study area during and before the study as part of the stream-gaging network in Nevada. The gravity data are presented by Schaefer and others (1986) and Schaefer (1988).

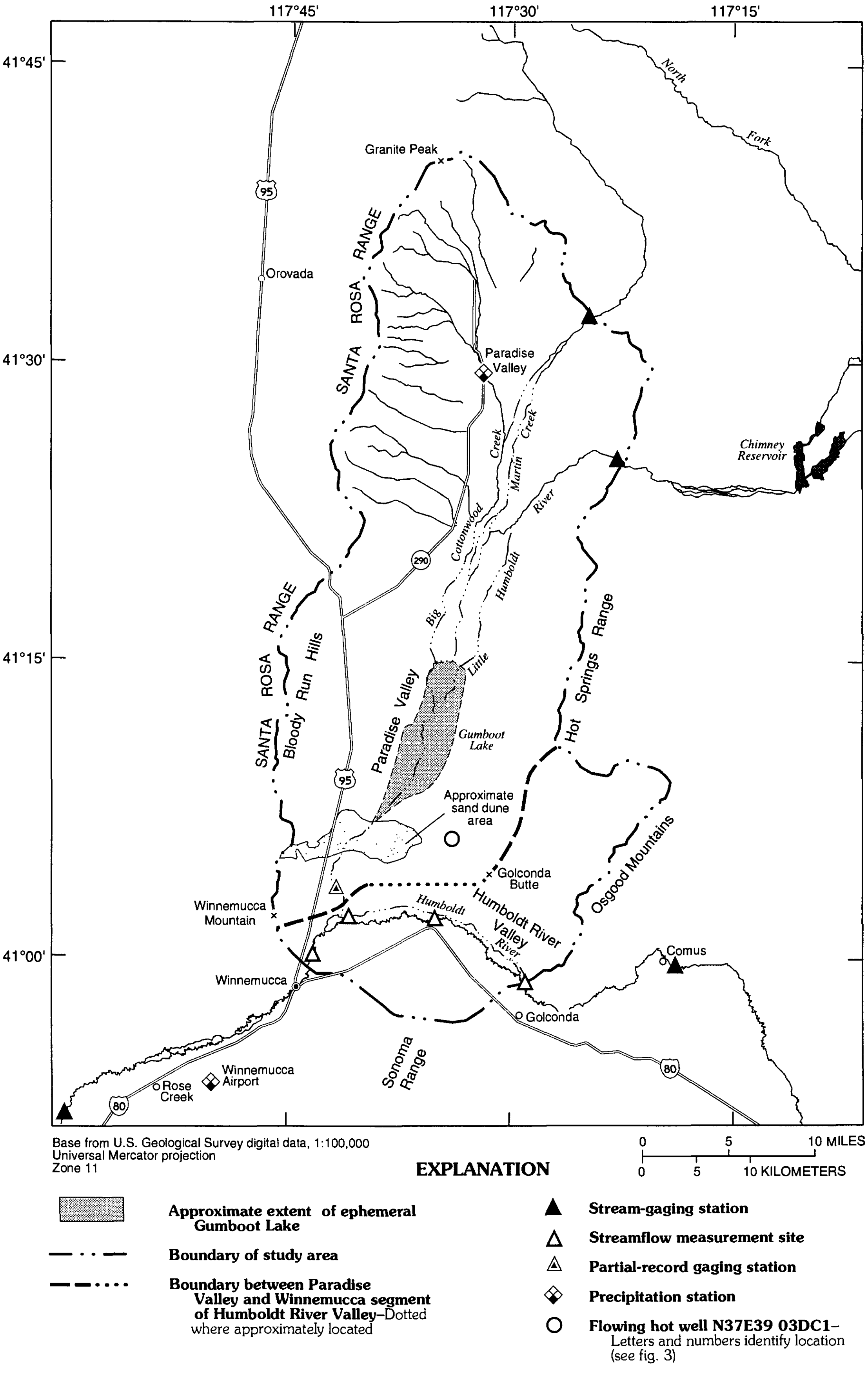
The principal technique used to analyze ground-water flow in Paradise Valley was a finite-difference model (McDonald and Harbaugh, 1988) that simulates flow in three dimensions. The model was used to evaluate the aquifer properties and to determine the response of the flow system to five different development scenarios, including the 1982 distribution of pumpage. Each scenario was simulated for a pumping period that ranged from 75 to 300 years in duration, and for a recovery period of 300 years. Similar scenarios were used for the other basins studied as part of the Great Basin RASA project. The long time periods were used to determine how long each basin took to reach a new state of equilibrium.

LOCATION AND GENERAL FEATURES OF STUDY AREA

The study area (fig. 2) includes all or part of two hydrographic areas as defined by Rush (1968): Paradise Valley (area number 69) and part of the Winnemucca segment of Humboldt River from Golconda to Winnemucca (area number 70); the latter is referred to as the Humboldt River Valley in this report. The boundary between the two areas is shown in figure 2.

Paradise Valley is long and narrow, extending about 40 mi northward from the Humboldt River near Winnemucca (fig. 2). The valley is bordered by the Santa Rosa Range and the Bloody Run Hills to the west, the Santa Rosa Range and low-lying volcanic hills to the north and northeast, the Hot Springs Range to the east, and Humboldt River Valley to the south. The valley has a maximum width of 13 mi and an area of about 330 mi^2. Humboldt River Valley is included in this study because ground-water flow is not impeded between the two areas. The Humboldt River generally flows from east to west through the study area and is bordered on the south by the Sonoma Range.

The mountain ranges in the study area trend generally northward. Altitudes of the crests range from about 6,500 ft above sea level in the Hot Springs Range to more than 9,000 ft in the Santa Rosa Range, where Granite Peak reaches an altitude of 9,779 ft. The altitude of the valley floor near the town of Paradise Valley is about 4,520 ft.


117°45'
117°30'
117°15'
41°45'
41°30'
41°15'
41°00'
North Fork
Granite Peak
95
Orovada
SANTA ROSA RANGE
Paradise Valley
Chimney Reservoir
Martin Creek
Creek
River
Cottonwood
Humboldt
290
Big
Little
SANTA ROSA RANGE
Bloody Run Hills
Paradise Valley
Hot Springs Range
Gumboot Lake
Approximate sand dune area
Golconda Butte
Osgood Mountains
Humboldt River Valley
Humboldt River
Winnemucca Mountain
Comus
Winnemucca
Golconda
Sonoma Range
Winnemucca Airport
Rose Creek
80
Base from U.S. Geological Survey digital data, 1:100,000
Universal Mercator projection
Zone 11
0 5 10 MILES
0 5 10 KILOMETERS
EXPLANATION
Approximate extent of ephemeral Gumboot Lake
Boundary of study area
Boundary between Paradise Valley and Winnemucca segment of Humboldt River Valley–Dotted where approximately located
Stream-gaging station
Streamflow measurement site
Partial-record gaging station
Precipitation station
Flowing hot well N37E39 03DC1–Letters and numbers identify location (see fig. 3)

The valley floor gently slopes southward to Humboldt River Valley. The altitude of the Humboldt River near Golconda is about 4,340 ft; near Winnemucca, it is about 4,260 ft.

PREVIOUS INVESTIGATIONS

The earliest comprehensive study of ground-water flow in Paradise Valley was by Loeltz and others (1949). Their study provided information during a period of little pumpage. The distribution of gravel deposits in the valley was described by Bredehoeft (1963). He also presented estimates of hydraulic conductivity for stream-associated gravel deposits in the lower Humboldt River drainage basin. Another comprehensive study of the valley was reported by Harrill and Moore (1970); it included a period when ground water was being developed as a supplemental source for the irrigation of meadows and alfalfa. They also reported estimates of streamflow losses in the valley. A Bouguer gravity map of the valley and water-chemistry data for selected wells were included in a geothermal-resource appraisal of the valley by Flynn (1981). Philip Cohen authored several reports pertaining to aquifer characteristics and water resources along the reach of the Humboldt River that forms the southern boundary of this study (Cohen, 1961, 1962, 1963a, b, 1964; Cohen and others, 1965).

Although no comprehensive study on the basin-fill aquifer in Paradise Valley has been published since 1970, data on ground-water levels, streamflows into the valley, and crop types and the number of active irrigation wells have been routinely collected by the Nevada Division of Water Resources and by the U.S. Geological Survey. These data were used in this study.

INVENTORY OF WELLS AND SPRINGS

Data on most wells, including location, altitude, water levels, depth, diameter, lithologic descriptions (when available), and construction, were entered into the U.S. Geological Survey data-base system known as WATSTORE (National Water Data Storage and Retrieval system). Data about springs and stream-measuring sites in or near Paradise Valley also are stored on the WATSTORE system.

FIGURE 2.—General features, stream-gaging stations, and precipitation stations in and adjacent to Paradise Valley, Humboldt County, Nevada.

The local site-identification system used in this report is based on an index of hydrographic areas in Nevada (Rush, 1968) and the 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 an N or S to indicate location north or south of the base line. The third unit is the range, preceded by an 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 northeastern, northwestern, southwestern, and southeastern quarters, respectively), followed by a number indicating the sequence in which the site was recorded (fig. 3). For example, well 69 N40E39 01AAA1 is in Paradise Valley and is the first well recorded in the northeast quarter of the northeast quarter of the northeast quarter of section 1 in Township 40 North and Range 39 East, Mount Diablo base line and meridian.

ACKNOWLEDGMENTS

The residents of Paradise Valley were very cooperative in allowing access to their wells. Winnemucca Farms also provided detailed information on well construction, well tests, and lithologic logs of their wells. Nevada First Corporation, Winnemucca Farms, and many other ranchers provided information about the acreage and types of crops irrigated, and the methods and approximate rates used to irrigate the crops. Roger Johnson (Nevada Division of Water Resources) provided water-level measurements of numerous wells in the valley and pumpage estimates determined from the number of irrigation wells and types of crops irrigated. Donald Schaefer (U.S. Geological Survey) did the seismic refraction profiles at five locations and interpreted the data. He also provided instruction and assistance in estimating the thickness of basin fill from the gravity data.

HYDROGEOLOGIC SETTING

GENERAL CHARACTER OF HYDROGEOLOGIC UNITS

Hydrogeologic units in the study area are divided into two groups on the basis of their ability to store and transmit water. The first group consists of basin fill that includes dune sand; older and younger alluvium of gravel, sand, silt, and clay; and lesser quantities of lacustrine and volcanic deposits. In places, the older alluvium is consolidated. The second group consists of rocks exposed in the surrounding mountains and includes indurated and metamorphosed sediments, igneous intrusives, and lava flows. In this report, rocks in the surrounding mountains are referred to collectively as consolidated rocks and are presumed to underlie the basin fill. The hydrogeologic units and their general hydrologic properties are described in table 1 and are based on work by

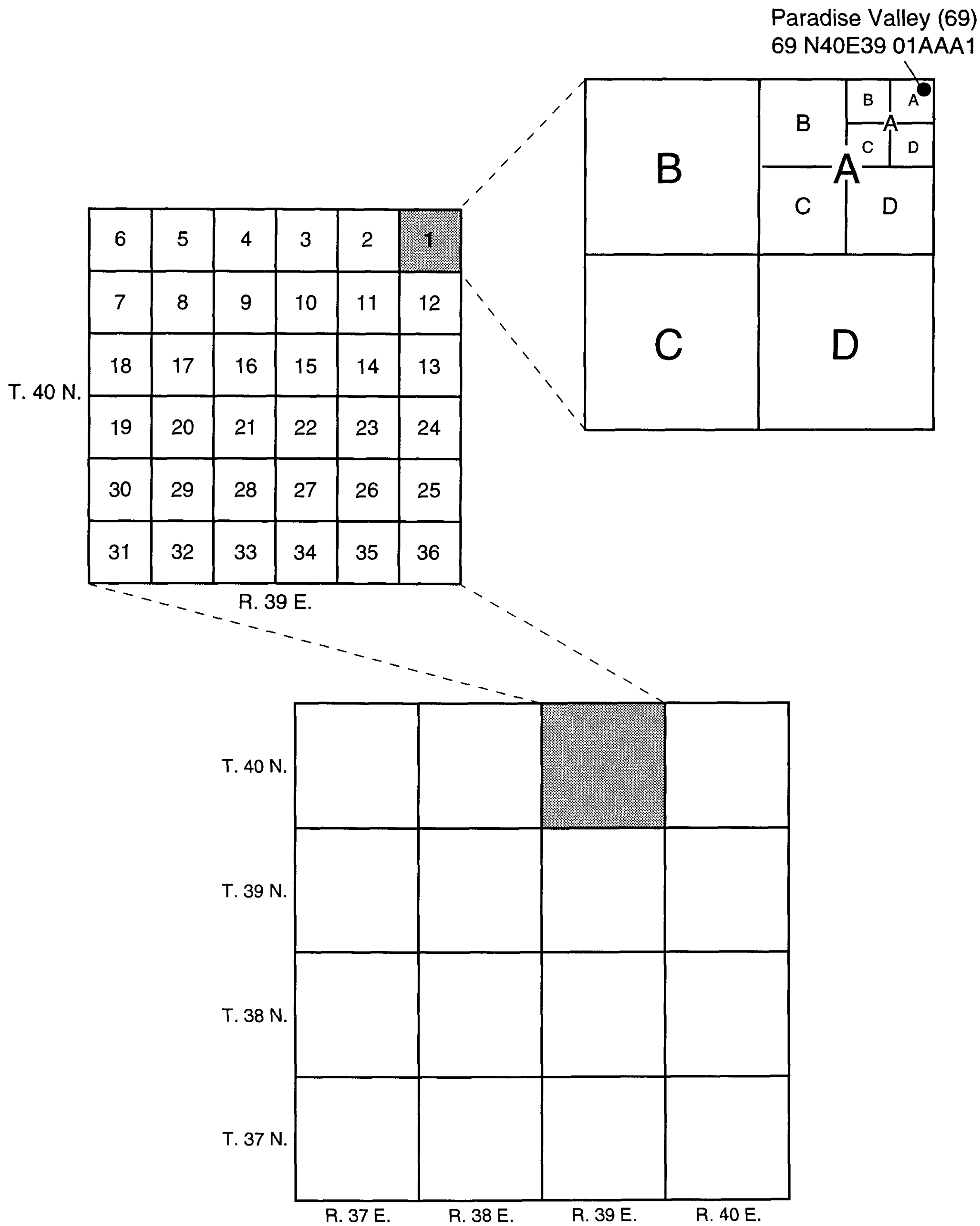


FIGURE 3.—Numbering system for wells and springs in Nevada.

Willden (1964) and Harrill and Moore (1970). Distribution of hydrogeologic units is shown in figure 4.

In general, the consolidated rocks have a low porosity and permeability that restricts their ability to store and transmit water. However, the Tertiary lava flows, along the northern edge of Paradise Valley (fig. 4) and in the highlands over which the tributaries to Martin Creek and the Little Humboldt River flow, can store and transmit water because they are commonly jointed and fractured. These rocks may underlie the basin fill at the northern end of the valley (Loeltz and others, 1949, p. 26). Drillers' logs for a few of the deeper wells (400 to 650 ft) reported lava rocks between unconsolidated deposits of gravel, sand, silt, and clay, but it is uncertain whether these lava flows are connected to those exposed in the mountains. The quantity of water available in lava flows beneath Paradise Valley is unknown. Reported yields of wells that encountered lava flows are less than 500 gal/min. Wells completed in the unconsolidated deposits in the basin fill generally yield less than 500 gal/min along the margins of the valley and more than 3,500 gal/min in the central part.

A basalt flow (or flows) extends eastward from Winnemucca Mountain in the extreme southwestern part of the valley (fig. 4). These basaltic rocks are Quaternary in age (Stewart, 1980, p. 108) and may overlie older alluvium, as indicated by basin-fill thicknesses estimated from gravity and seismic surveys (see section titled "Areal Extent and Thickness"). Even if the basalt extends into the basin fill at depth, the rocks are well jointed and fractured and may not restrict movement of ground water in the area.

The basin fill generally has a much higher porosity and permeability than the consolidated rocks, except perhaps some of the basalts, and thus stores and transmits much greater quantities of water. These deposits constitute the principal aquifers in the study area.

GEOLOGIC HISTORY DURING LATE TERTIARY AND QUATERNARY TIME

A major change in the tectonic activity of Nevada began about 17 million years ago when major structural forces changed from compressional to tensional (Stewart, 1980, p. 110). Block faulting caused by extension produced basins and ranges that are characteristic of the present-day topography throughout Nevada. The movement along the predominately northeast-trending normal faults resulted in relative uplift of linear segments to form mountains and a relative sinking of adjacent segments to form basins. Vertical displacement along the complex system of faults is generally 6,000 to 15,000 ft (Stewart, 1980, p. 110). In addition to the northeast-trending normal faults, six northwest-trending lineaments have been identified by Sales (1966) in the vicinity of Paradise Valley. He interpreted the lineaments to be shears caused by tensional strike-slip faulting. These shears have structurally altered the rocks in the mountain blocks and may extend beneath the basin fill.

At about the same time (17 million years ago), the volcanic rock composition changed from generally rhyolitic to generally basaltic (Stewart, 1980, p. 102). The basalt flows at the northern end of Paradise Valley preceded the basin and range faulting (Loeltz and others, 1949, p. 29). However, the basalt flow at the southwestern end of the valley (fig. 4) has been dated at less than 6 million years old (Stewart, 1980, p. 108) and, as previously noted, may overlie older alluvium.

Movement along the faults that formed the mountains and basins has probably continued intermittently throughout the past 17 million years, and with the formation of the mountains came the continuing accretion of basin fill in the valleys. These deposits consist of a variety of fluvial and lacustrine units and contain variable quantities of volcanic deposits.

The present Humboldt River drainage system developed prior to Lake Lahontan, a Pleistocene lake that formed over many basins in northwestern Nevada (Loeltz and others, 1949, p. 29). During the Pleistocene, Lake Lahontan extended into Paradise Valley at least twice, and each time it deposited a thin layer of lake sediments in the lower end of Paradise Valley (Loeltz and others, 1949, p. 30). Both the Little Humboldt and Humboldt Rivers deposited sediments in their channels upstream from the lake and formed deltas where they entered the lake. After the last retreat of Lake Lahontan in late Pleistocene time, both rivers began eroding sediments previously deposited and the Humboldt River developed meander scrolls and oxbow lakes in its flood plain (Loeltz and others, 1949, p. 30). Sand dunes drifted across the southern end of Paradise Valley and periodically blocked the flow of the Little Humboldt River. How often the cycle of deposition and erosion has occurred in the valley as a result of changes in stages of lakes in the area is uncertain. However, many cycles of wet and dry periods may have occurred over the past several million years.

TABLE 1.—*Description of hydrogeologic units and their general hydrologic properties in Paradise Valley, Humboldt County, Nevada*

[Modified from Harrill and Moore (1970, table 2)]

SYSTEM	SERIES	Hydrogeologic unit	Estimated thickness (feet)	Lithology	Occurrence	General hydrologic properties
QUATERNARY	HOLOCENE	Dune sand	0-75	Sand, medium-grained and well-sorted.	Eolian deposits at south end of Paradise Valley, where dunes obstruct channel of Little Humboldt River.	Porosity estimated at 20 to 30 percent; permeability moderate to high. Water readily infiltrates from surface to saturated zone; functions as recharge area when Gumboot Lake is formed.
		Humboldt River flood-plain deposits	0-20	Gravel, sand, silt, and clay, poorly sorted to well-sorted. Contains thin layers of volcanic ash and windblown material.	Along Humboldt River, includes coarse-grained channel deposits and fine-grained deposits in oxbow lakes, drainage channels, and other depressions.	Sand and gravel deposits are highly permeable and finer grained deposits are relatively impermeable. Recharge is largely by seepage from streams and by overbank flooding. Unit stores and transmits large amounts of water.
	PLEISTOCENE & HOLOCENE	Younger basin fill	0-150±	Interbedded sand, gravel, silt, and clay, poorly sorted to well-sorted. Deposits form lenticular bodies. Includes lacustrine deposits.	Primarily stream-channel deposits in center of Paradise Valley; includes some slope wash and ephemeral stream deposits around margin of Paradise Valley. Superficial amounts of lacustrine deposits associated with Gumboot Lake. Underlain by more extensive lacustrine deposits associated with Lake Lahontan in southern part of Paradise Valley and parts of Humboldt River Valley.	Sand and gravel deposits are highly permeable and can yield large quantities of water to wells. Stream-channel deposits form most productive units. Finer grained or poorly sorted deposits are less capable of yielding water to wells.
	PLEISTOCENE	Older basin fill	0-8,000±?	Gravel, sand, silt, and clay, poorly sorted to well-sorted. Partially consolidated (cemented) locally and at depth. Deposits at depth in center of valley generally moderately to well sorted. Some lacustrine deposits may be present.	Along margin of Paradise Valley, primarily as fan deposits; also slope wash, talus, and upland alluvial surfaces. Fan deposits have been dissected by younger stream channels. Occurs at depth in center of Paradise Valley primarily as stream-channel deposits. Deposits may overlie basin fill of older age not exposed in area.	Sand and gravel deposits associated with buried stream channels are highly permeable and readily yield water to wells. Finer grained deposits generally have low permeability and do not transmit large quantities of water. Porosity and permeability may decrease with depth due to compaction by overburden.

TABLE 1.—*Description of hydrogeologic units and their general hydrologic properties in Paradise Valley, Humboldt County, Nevada—Continued*

SYSTEM	Hydrogeologic unit	Estimated thickness (feet)	Lithology	Occurrence	General hydrologic properties
TERTIARY & QUATERNARY	Basalt flows	—	Vesicular olivine basalt, well-jointed.	Near confluence of Little Humboldt and Humboldt Rivers in extreme southwest corner of Paradise Valley. Possibly overlies older basin-fill deposits.	Basalt is well fractured and, where saturated, can allow water to transmit through it. However, basalt flows are generally above saturated zone.
	Volcanic rocks	—	Primarily rhyolite, dacite, andesite, and basalt. Includes some interbedded sedimentary rocks.	Primarily at north end of Paradise Valley. May extend beneath or into basin fill. Lesser amounts are exposed along margins of Santa Rosa and Hot Springs Ranges and Osgood Mountains.	Commonly have little or no interstitial porosity, except where highly vesicular. May transmit water through joints and zones between basalt flows.
CRETACEOUS & TERTIARY	Intrusive rocks	—	Mostly granodiorite.	Exposed primarily along core of Santa Rosa Range.	Virtually no interstitial porosity and permeability; may transmit small quantities of water where fractured and weathered.
TRIASSIC THROUGH CRETACEOUS	Metamorphic rocks	—	Primarily phyllite, slate, quartzite, and slightly metamorphosed mudstone; some calcareous shale, calcareous sandstone, and lenses of limestone and dolomite.	Mostly along flanks of Santa Rosa Range and Bloody Run Hills. Localized exposures in Hot Springs Range and northeastern end of Paradise Valley.	Very low porosity and permeability; some water may be transmitted along fractures.
CAMBRIAN THROUGH PERMIAN	Sedimentary rocks	—	Sequences of quartzite, chert, limestone, dolomite, sandstone, shale, and conglomerate. Interstratified volcanic deposits present in parts of section.	Predominant rock type in Hot Springs Range and Osgood Mountains.	Generally have low interstitial porosity and permeability. May transmit some water along fractures or where solution features have developed in carbonate rocks.

HYDROLOGIC SETTING

CLIMATE

The climate of Paradise Valley is arid to semi-arid, has large diurnal fluctuations in temperature, is strongly influenced by the prevailing westerly winds, and is largely controlled by the orographic effect of the Sierra Nevada, which are approximately 150 mi to the west. Warm moist air masses from the Pacific Ocean are forced aloft at the Sierra Nevada causing the air masses to cool and moisture to condense, resulting in heavy precipitation. Consequently, the air masses moving eastward across western Nevada and the study area

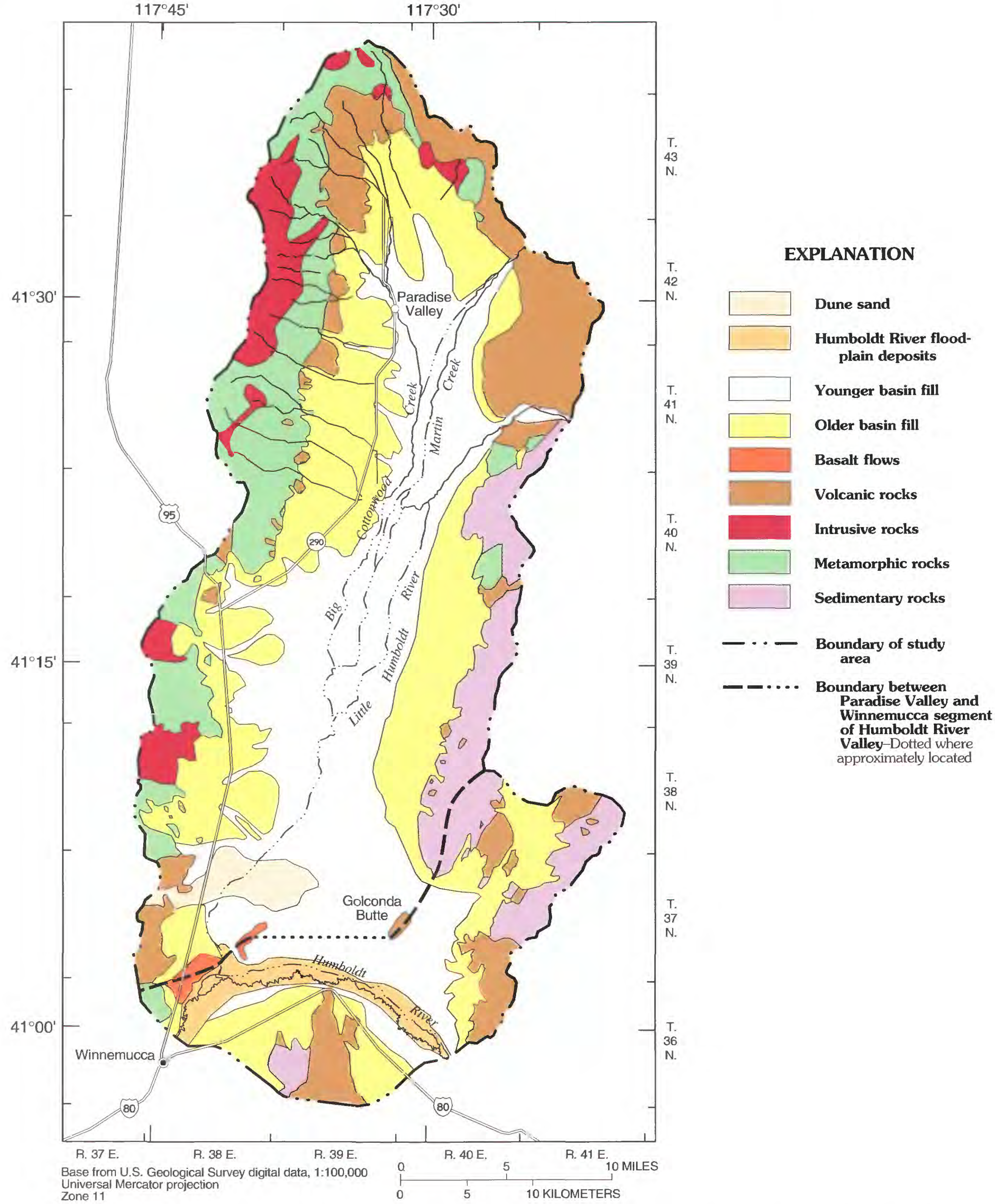


FIGURE 4.—Distribution of hydrogeologic units in Paradise Valley, Humboldt County, Nevada. Geology from Harrill and Moore (1970, pl. 1) and Willden (1964, pl. 1).

are usually moisture deficient. Local mountains surrounding Paradise Valley have a similar but somewhat lesser effect on the local climate. The valley floor commonly receives less moisture than do the mountains. Daily temperature fluctuations of as much as 40°F are not uncommon. The mean daily temperature is slightly below 50°F. The maximum summer temperature may exceed 100°F, and the winter minimum may drop below 0°F.

Annual precipitation at the town of Paradise Valley in the northern end of the valley averaged 9.43 in. for the period 1955–82. Annual precipitation at Winnemucca, which is at the southwestern corner of the study area, averaged 8.07 in. for the same period and 8.37 in. for the 112-year period 1871–1982. The difference in precipitation between the two stations is attributed to differences in altitude and variations in winter-storm tracks. Precipitation in the mountains usually exceeds 20 in. annually (Hardman, 1936; Harrill and Moore, 1970, p. 12).

Almost half of the average yearly precipitation falls from November through February (fig. 5) and is usually in the form of snow. The period of July through September usually has the least quantity of precipitation. Summer precipitation generally is the result of localized thunderstorms of short duration and high intensity.

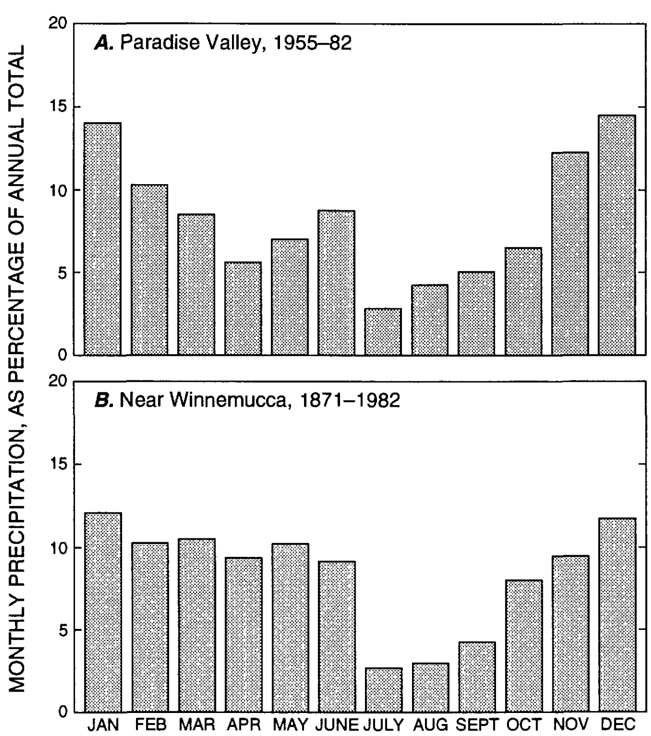


Figure 5.—Monthly distribution of average annual precipitation (*A*) at Paradise Valley (1955–82) and (*B*) near Winnemucca (1871–1982), Nevada.

SURFACE WATER

The two major streams in Paradise Valley are Martin Creek and the Little Humboldt River (fig. 2). Martin Creek enters the valley through a narrow canyon at the northeastern corner, about 6 mi northeast of the town of Paradise Valley. The Little Humboldt River enters the valley by way of a narrow passage cut through the northern end of the Hot Springs Range. The two streams join through a series of channels about halfway through the valley. The Little Humboldt River joins the Humboldt River at the southwest corner of Paradise Valley. During periods of high runoff, water flows as far as the sand dunes (fig. 2) that block the channel of the Little Humboldt River near the southern end of the valley. Water collects behind the sand dunes to form Gumboot Lake, which remains until the water seeps into the ground, is evaporated, or a channel is dredged through the dunes.

Numerous streams begin on the eastern and southern slopes of the Santa Rosa Range and flow generally eastward or southward to the valley floor. Many of these streams join Big Cottonwood Creek, which flows along the western side of the valley floor, parallel to Martin Creek and Little Humboldt River (fig. 2). Most streams are perennial in the mountains but become intermittent in the valley, particularly during the late summer and fall. Runoff usually reaches the valley floor from late winter to early summer, where it is diverted for irrigation. Streams that begin in the Bloody Run Hills along the southwestern margin of the valley seldom flow to the valley floor, but they do reach the bordering fans during the late winter and early spring. Streams that head in the lower and drier Hot Springs Range on the eastern side of the valley are intermittent, and runoff occurs only after major storms.

A gaging station that continuously records stream stage has been operated on Martin Creek where it enters Paradise Valley since October 1921, although records are incomplete until 1922. Gaging stations also have been operated on Little Humboldt River where it enters Paradise Valley from October 1921 to June 1928 and continuously since October 1943, and on Humboldt River near Comus (about 5 mi east of Golconda) intermittently from October 1894 to September 1926 and continuously since October 1945. Locations of these gaging stations are shown in figure 2. Streamflow data for these stations prior to water year 1961 (water years are from October 1 through September 30) are published in U.S. Geological Survey Water-

Supply Papers 1314 and 1734 (1960 and 1963, respectively); data for water years 1961–83 are published in annual volumes of Water Resources Data for Nevada (U.S. Geological Survey, 1962–84).

Most of the streamflow that enters Paradise Valley is runoff from snowmelt (Harrill and Moore, 1970, p. 41). Greatest streamflows are generally from March through June (fig. 6), whereas the least quantities are during August through October.

Peak discharge for Humboldt River near Comus is generally later in the year than either Martin Creek or Little Humboldt River where they enter Paradise Valley (fig. 6). The delay in peak discharge of Humboldt River near Comus is caused by later snowmelt from high mountainous areas in the upper Humboldt basin near Elko (fig. 1). Similarly, the slight delay in peak discharge for Martin Creek compared with Little Humboldt River is caused by later snowmelt from high altitudes in the Martin Creek drainage area.

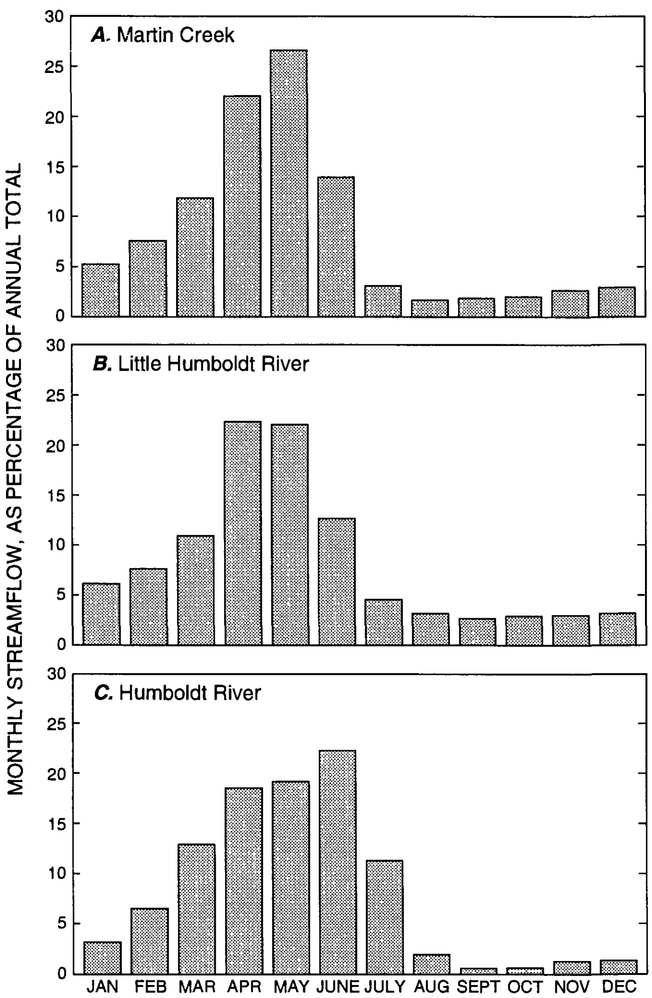


Figure 6.—Average monthly streamflows as percentage of average annual streamflow for (*A*) Martin Creek where it enters Paradise Valley, (*B*) Little Humboldt River where it enters Paradise Valley, and (*C*) Humboldt River at Comus, Nevada. Average monthly values are based on 60 years of record (1923–82) for Martin Creek, 28 years (1944–71) for Little Humboldt River, and 37 years (1946–82) for Humboldt River.

Average annual streamflow at the Martin Creek gage for water years 1923–82 (a 60-year period) was 23,000 acre-ft/yr. The largest annual streamflow was 64,000 acre-ft, in 1952 (fig. 7*A*). Streamflow was generally below average for water years 1923–42 as shown by the downward slope on the graph of cumulative departure from average (fig. 7*B*). Between water years 1969 and 1982, streamflow at the Martin Creek gage was generally above average.

Variations in annual discharge of Little Humboldt River for water years 1946–82 are similar to those for Martin Creek except after 1975, when Chimney Reservoir (location shown in fig. 2), 11 mi upstream from the gage on Little Humboldt River, began storing runoff. Average annual streamflow at the Little Humboldt River gage for a 45-year period of record spanning 1921–82 was 18,000 acre-ft/yr.

Streamflow usually reaches the southern end of Paradise Valley during spring snowmelt, but on the average Gumboot Lake contains appreciable water only about once in 5 years (Harrill and Moore, 1970, p. 81). Relatively large lakes formed three times between 1950 and 1982 (in 1952, 1958, and 1969) when the annual combined discharge for Martin Creek and Little Humboldt River exceeded 70,000 acre-ft/yr. Large lakes also formed in 1983 and again in 1984—both of which were years of abnormally high streamflow.

Prior to development, water flowed from Paradise Valley to the Humboldt River only when the sand dunes were breached. Such occurrences were recorded in 1890, 1907, 1910, and 1914 (Harrill and Moore, 1970, p. 69). Beginning in the early 1950's, the lake was drained by dredging a channel through the dunes so flooded lands could be used for agriculture. Flow in the channel of Little Humboldt River below the sand dunes was observed in 12 of the 30 years between 1953 and 1982 (table 2). Streamflow estimates ranged from no flow for several years to 33,000 acre-ft in 1958.

The Humboldt River is the largest stream in the study area. Average annual discharge at a gage near Comus (location shown in fig. 2) for a 68-year period of record spanning water years 1894–1982 is about 214,000 acre-ft/yr (U.S. Geological Survey, 1983, p. 170). Annual streamflow ranged from as little as 27,000 acre-ft during water year 1920 to 688,000 acre-ft during water year 1907. More than 1,000,000 acre-ft of streamflow was estimated during water year 1983 (U.S. Geological Survey, 1984, p. 148).

GROUND WATER

Ground water in Paradise Valley and the adjacent Humboldt River Valley originates as precipitation. Recharge to ground water is primarily by percolation of precipitation, infiltration of streamflow, and percolation of irrigation water.

Most of the readily available ground water in the study area occurs in unconsolidated deposits (basin fill) under both unconfined (water-table) and confined conditions. In general, water levels in the central and southern parts of Paradise Valley do not vary between adjacent wells of different depths, suggesting little vertical flow. In the northern end, however, water levels in shallow wells are higher than water levels in deeper wells, indicating a downward component of flow. Except for a flowing hot well in the southeastern part of the valley (see fig. 2), water levels in wells are at or below land surface. In a few localized areas, water levels in deeper wells are higher than shallow wells, indicating an upward flow component. These localized areas are usually near the contact between the older and younger alluvium (fig. 4), where lenses of silt and clay confine water in the underlying deposits.

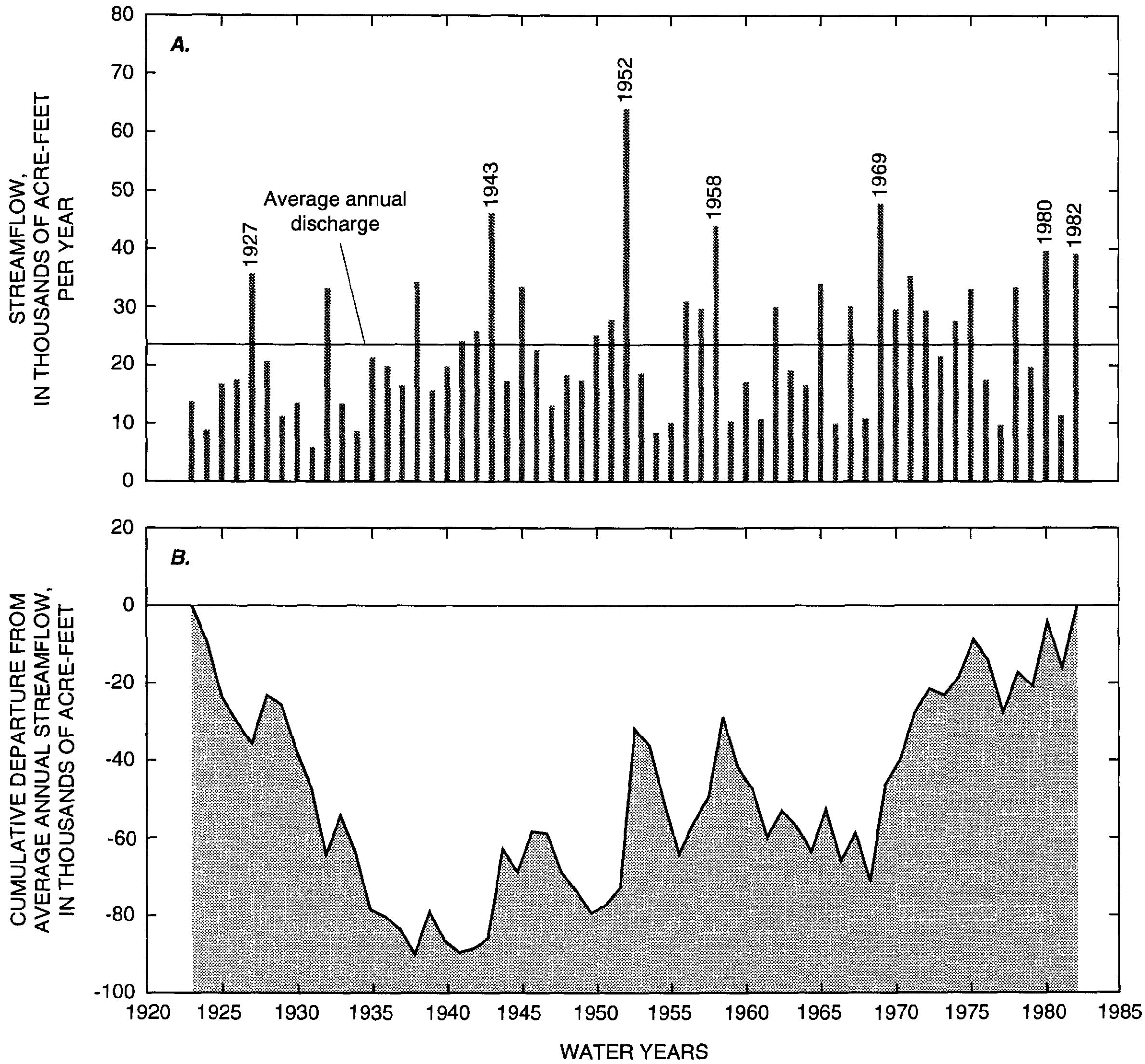


FIGURE 7.—Annual streamflow (*A*) and cumulative departure from average annual streamflow (*B*) for Martin Creek where it enters Paradise Valley, Humboldt County, Nevada, water years 1923–82.

TABLE 2.—*Estimated annual streamflow of Little Humboldt River near confluence with Humboldt River, Humboldt County, Nevada, 1948–82*

[--, no streamflow reported]

Years	Period of observed flow (month/day)[1]	Estimated streamflow (acre-feet per year)[1]
1948-52	—	0
1953	spring[2]	25,000
1954-57	—	0
1958	summer[3]	33,000
1959-68	—	0
1969	4/09-6/13	22,000
1970	5/25-6/26	3,000
1971	2/01-6/30	22,000
1972	3/11-5/05	17,000
1973	3/14-3/22	50
1974	4/08-5/05	2,000
1975	6/12-7/03	700
1976-77	—	0
1978	5/19-6/30	2,500
1979	—	0
1980	6/01-6/23	1,100
1981	—	0
1982	5/15-6/10	1,100

[1] Estimated volumes of streamflow and periods of observed flow are from Roger Johnson (Nevada Division of Water Resources, written commun., 1984)

[2] Channel excavated through sand dunes during spring 1953 (Harrill and Moore, 1970, p. 81)

[3] Channel excavated through sand dunes in June and July 1958 (Harrill and Moore, 1970, p. 81)

Depth to ground water in 1968, prior to large quantities of ground-water pumpage, was generally less than 10 ft along the valley bottom and Humboldt River (fig. 8). Depths, however, increased to more than 100 ft on the alluvial fans adjacent to the mountains. The configuration of the water table in 1968 is shown in figure 9.

The general direction of ground-water flow in Paradise Valley is from the adjacent mountains to the valley lowlands, then southward toward the Humboldt River Valley (based on the assumption that ground-water movement is generally perpendicular to the water-table contours). Much of the recharge to ground water in Paradise Valley is by infiltration from streams in the valley bottom; much of this ground water subsequently is discharged by evapotranspiration. Ground water not discharged by evapotranspiration flows into the Humboldt River Valley. Ground-water flow in the Humboldt River Valley is generally westward and parallel to the river.

BASIN-FILL AQUIFER

The basin fill generally functions as one hydraulic unit, even though it consists of a mixture of discontinuous lenses of gravel, sand, silt, and clay with minor quantities of volcanic rocks; near the margins, the system also consists of heterogeneous mixtures of gravel and sand in a silt and clay matrix. No extensive unit that can be classified as an aquifer has been identified from the drillers' logs. Cohen and others (1965) did map a predominantly sand and gravel unit along the Humboldt River at the southern boundary of the study area. This unit could perhaps be considered a single aquifer. Bredehoeft (1963, p. 32) mapped the percentage of gravels in the upper 100 ft of basin fill in Paradise Valley and concluded that the gravels were associated with major streams. Whether the gravels mapped by Bredehoeft constitute a single aquifer is uncertain. The entire basin fill in Paradise Valley and adjacent Humboldt River Valley, however, can be considered as one aquifer and will be referred to as the basin-fill aquifer.

AREAL EXTENT AND THICKNESS

The contact between consolidated rocks and basin fill marks the outer boundary of the basin-fill aquifer in Paradise Valley and adjacent Humboldt River Valley. Narrow bands of alluvial deposits associated with the Humboldt River extend upstream and downstream from the study area and provide a continuous link to the Humboldt River.

Gravity surveys were used to estimate the thickness of the basin fill because wells drilled in the study area, which range in depth from about 15 ft to about 800 ft, generally do not extend into the consolidated rocks. The magnitude of gravity at any location is dependent on latitude, altitude, tidal effects, topography of the surrounding terrain, and density distribution in the subsurface (Telford and others, 1976, p. 14). Typically, basin fill has much lower densities than the adjacent and underlying consolidated rocks. This difference is used to estimate thickness of basin fill after the gravity values have been corrected for the other factors.

About 400 gravity stations were used to construct a Bouguer anomaly map of Paradise Valley

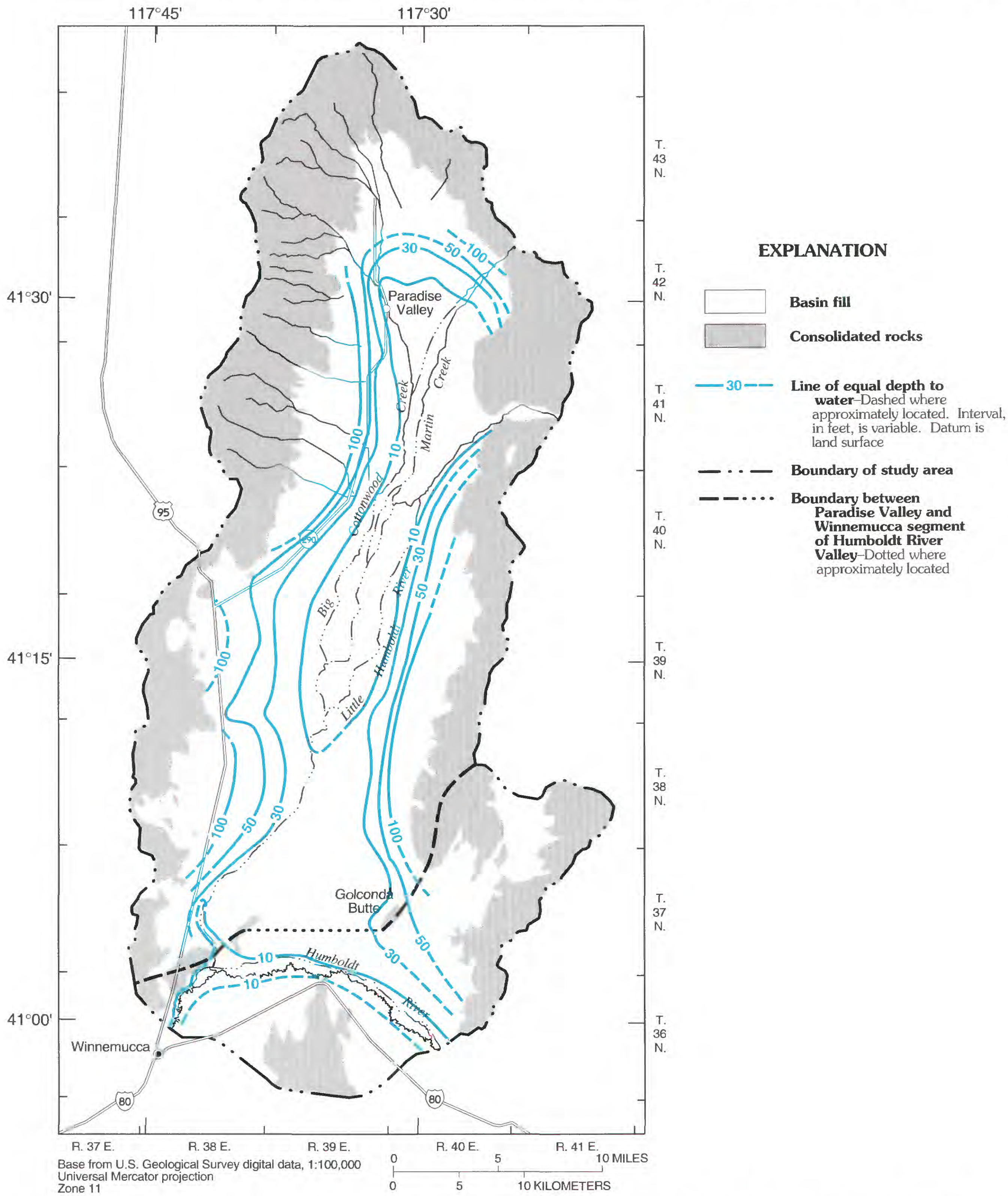


FIGURE 8.—Depth to ground water prior to large quantities of pumpage (pre-1969), Paradise Valley, Humboldt County, Nevada. Modified from Harrill and Moore (1970, fig. 5) and Loeltz and others (1949, pl. 1.). In recharge areas on the apron at north and northwest end of valley, depth to water varies with well depth. Depth to water shown on map in these areas is for wells deeper than 100 feet.

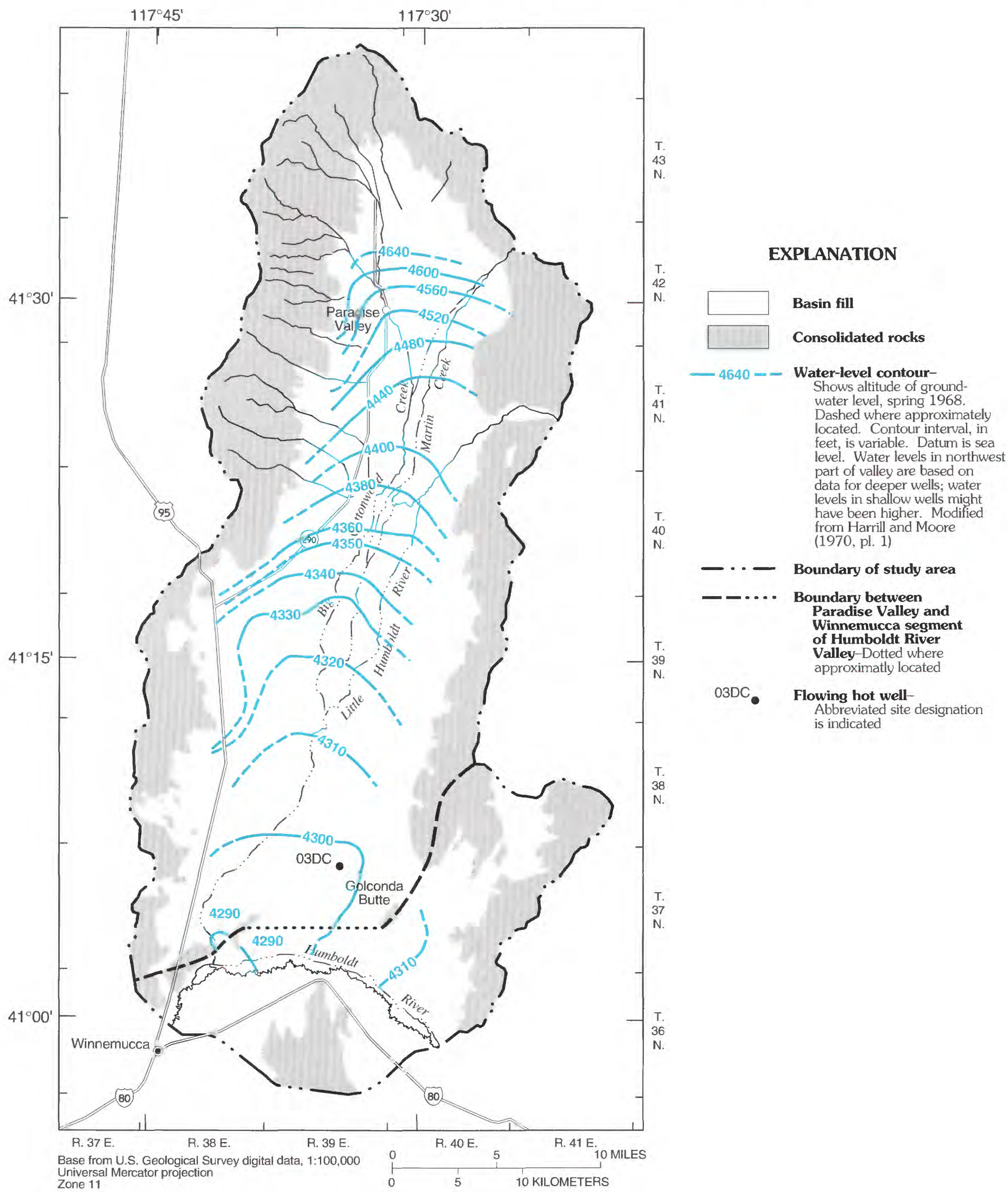


FIGURE 9.—Ground-water levels, Paradise Valley, Humboldt County, Nevada, spring 1968.

and the adjacent part of Humboldt River Valley (Flynn, 1981; Schaefer and others, 1986; Schaefer, 1988). The thickness of basin fill in the study area was determined from the Bouguer anomalies. Briefly, a regional surface was determined for all anomalies corresponding to outcrops of consolidated rocks, using a computer program that compares the observed surface with surfaces generated from mathematical formulas (Davis, 1973). The observed regional surface was reasonably approximated by a first-order (linear) trend surface. The computed regional surface was subtracted from the Bouguer anomalies, producing residual values that represent the gravity field of the lower-density basin fill.

Thickness of the basin fill was estimated from these residual values, using a three-dimensional gravity inversion model (Cordell, 1970), by specifying a density contrast between basin fill and consolidated rocks. A density contrast of 31.2 lb/ft^3 (0.5 g/cm^3) was used in estimating the thickness of basin fill; this value was based on an average density for saturated basin fill of 135.4 lb/ft^3 (2.17 g/cm^3) and an average density for consolidated rocks of 166.7 lb/ft^3 (2.67 g/cm^3). The density used for basin fill is within the range of densities determined from borehole gravity data for two wells in Paradise Valley (Robbins and others, 1985, p. 14–16).

The estimated thickness of basin fill is shown in figure 10. The valley is divided into at least four structural depressions, which suggest that complex structures are present beneath the valley. Maximum thickness of basin fill exceeds 8,000 ft in the center of the valley. On the basis of topography and geology in the mountains surrounding Paradise Valley, Sales (1966, pl. 11) drew northwest-trending shears that he interpreted as being caused by strike-slip faulting. These features generally coincide with the areas between structural depressions (fig. 10). On the basis of the basin-fill thickness, additional shears (not mapped by Sales) may trend in the same direction. Thus, in addition to the predominant northeast-trending normal faults that bound the valley on the eastern and western sides, several faults, which have both vertical and horizontal displacement, may structurally divide the valley into several smaller basins. Thermal springs in the area are located near the intersection of the northeast-trending normal faults and the northwest-trending shears (Flynn, 1981, p. 100), which suggests that small quantities of water might be moving along these features.

Reversed seismic-refraction profiles were taken at five locations in the valley to estimate the thickness of basin fill for comparison with estimates from gravity measurements (Donald H. Schaefer, U.S. Geological Survey, written commun., 1992). Locations of the seismic profiles are shown in figure 10. Measurements were taken using 12- and 24-channel seismographs. Explosives were used as the energy source for generating sound waves and were placed at progressively greater distances at the end of either side of the geophones along each profile. The geophones were spaced at intervals of 100 ft.

Thickness of the basin fill was estimated along each profile by determining a change in velocity on time-distance plots of the data, as explained by Haeni (1988, p. 3). Velocity of the basin fill is generally about 6,000 ft/s, whereas the velocity of the consolidated rocks is generally 10,000 ft/s or greater. Thickness of the basin fill was determined from the seismic profiles by Donald H. Schaefer (U.S. Geological Survey, written commun., 1992) and is summarized in table 3. Thicknesses estimated from gravity measurements also are listed for comparison. For the three profiles where the basin fill exceeds 2,000 ft (S1, S3, and S5), estimated thicknesses from seismic-refraction profiles are less than or equal to those from gravity data. For the other two profiles (S2 and S4), estimated thicknesses from the seismic-refraction profiles exceed those estimated from gravity data. The latter two profiles are along the southwestern side of the valley where the depth to ground water exceeds 100 ft (fig. 8).

Thickness of basin fill calculated from gravity measurements is underestimated near the margins of the valley. A large part of the basin fill is unsaturated near the valley margins, where depth to ground water can exceed 100 ft. Unsaturated basin fill has a lower density than saturated basin fill (Robbins and others, 1985). The computer program used to calculate thickness from gravity is based on one density contrast. The value chosen for this study is the density difference between saturated basin fill and consolidated rocks. The use of a density contrast greater than the one chosen, to account for the unsaturated sediments, is not warranted because unsaturated sediments are a fraction of the total basin-fill thickness except along the margins.

HYDRAULIC PROPERTIES

The water-transmitting properties of the basin fill are determined by estimating the aggregate

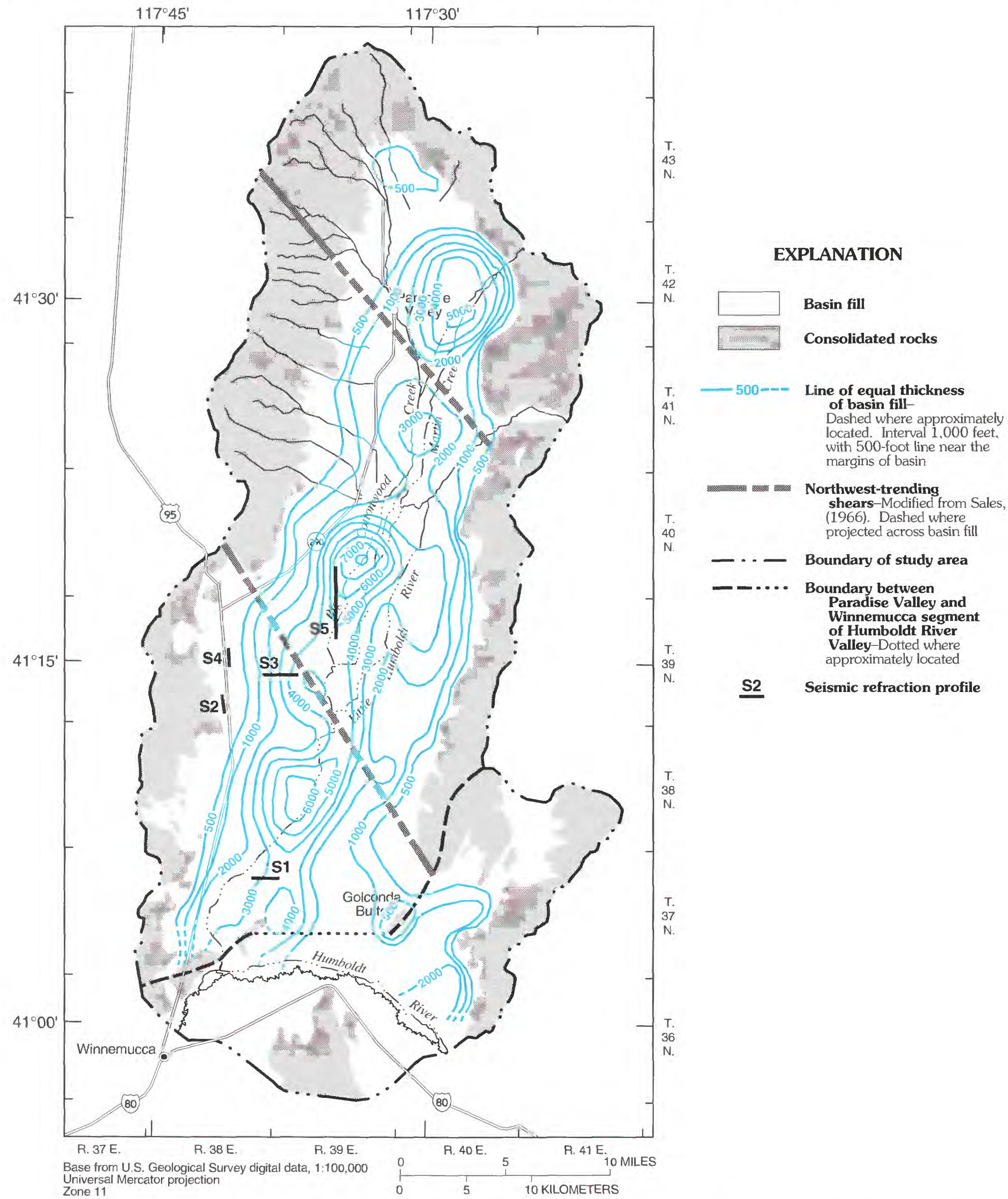


FIGURE 10.—Thickness of basin fill in Paradise Valley, Humboldt County, Nevada. Thickness estimated from gravity measurements by Schaefer and others (1986) and Flynn (1981).

Table 3.—*Comparison of basin-fill thickness at five sites in Paradise Valley, Humboldt County, Nevada, estimated using seismic-refraction and gravity methods*

Site of seismic-refraction profile (fig. 10)	Thickness of basin fill (feet)	
	Gravity	Seismic refraction[1]
S1	3,000–3,500	2,000
S2	<500	700
S3	2,000–4,000	3,000
S4	<500	1,300
S5	5,000–6,000	5,700

[1] Beneath seismic-refraction profiles, thicknesses determined by Donald H. Schaefer (U.S. Geological Survey). Thicknesses calculated from gravity measurements differ from place to place, as shown in figure 10.

hydraulic conductivity of the many discontinuous lenses of gravel, sand, silt, and clay, whereas the quantity of water that the deposits can store is determined by estimating the aggregate storage coefficient of the deposits. Both of these properties depend on the environment of deposition as well as the types of earth materials that compose the basin fill. Deposits derived from the Hot Springs Range, which consists mostly of older sedimentary rocks, are potentially more productive than deposits from the Santa Rosa Range, where the rocks are mostly granitic and fine-grained metamorphic rocks that tend to decompose more readily to clay (Harrill and Moore, 1970, p. 21). Clean sand and gravel deposits in the basin fill usually produce the greatest quantities of water; thus, identifying areas of sand and gravel deposits usually results in locating the most productive areas for development. The percent of gravel in the upper 100 ft of basin fill in Paradise Valley was mapped by Bredehoeft (1963, p. 32) using data from drillers' logs. The greatest accumulations of gravel are just below points where Martin Creek and the Little Humboldt River enter Paradise Valley. Additional information from drillers' logs of deeper wells supports this observation and indicates that the gravel deposits continue to depths of at least 400 ft.

HYDRAULIC CONDUCTIVITY

Estimates of hydraulic conductivity of the basin fill were obtained from specific-capacity data reported on drillers' logs, from values of transmissivity derived by Harrill and Moore (1970), and from aquifer tests of several wells drilled on the southwestern side of the valley. Theis (1963) presented an equation for estimating transmissivity (hydraulic conductivity multiplied by thickness of the aquifer) from specific-capacity data assuming no difference in water level between the well and aquifer material a short distance from the well. The equation can be written as:

$$T = 0.000177(Q/s)\left[-0.577 - \ln\left(\frac{r^2S}{4Tt}\right)\right] \quad (1)$$

where Q/s = specific capacity, in gallons per minute per foot of drawdown;
Q = pumping rate, in gallons per minute;
s = drawdown of the well, in feet;
T = transmissivity, in feet squared per second;
t = pumping period, in seconds;
r = effective well radius, in feet; and
S = storage coefficient (dimensionless).

Specific capacity of a well usually is less than an ideal well because well entrance losses produce lower water levels in the well than in the aquifer immediately adjacent to the well (Meyer, 1963, p. 339). Specific capacity of a well also is affected by pumping period and effective well radius (Walton, 1962, p. 12–13; Meyer, 1963, p. 339). However, specific capacity values do not change greatly for tests exceeding 8 hours (28,800 seconds), nor do the values change greatly for wells with a radius from 0.67 to 1.08 ft (Bredehoeft, 1963, p. 35), the normal radius of irrigation wells drilled in Paradise Valley.

Estimates of hydraulic conductivity were determined for 90 wells in Paradise Valley by dividing the estimated transmissivity determined from specific-capacity data by the length of the screened interval of the well. The average hydraulic conductivity of the upper 600 ft of basin fill (approximate interval of the wells), assuming a storage coefficient equal to a specific yield of 0.3, was 3.7×10^{-4} ft/s (32 ft/d) with a standard deviation of 8×10^{-4} ft/s (69 ft/d). The average hydraulic conductivity assuming a specific yield of 0.1 was 4.1×10^{-4} ft/s (35 ft/d) with a standard deviation of 9×10^{-4} ft/s (78 ft/d). The minimum estimate of hydraulic conductivity was 6×10^{-6} ft/s (0.5 ft/d), whereas the maximum was 2×10^{-3} ft/s (173 ft/d).

Distribution of hydraulic conductivity in the upper 600 ft of basin fill as determined from specific-capacity tests is shown in figure 11. In general, the

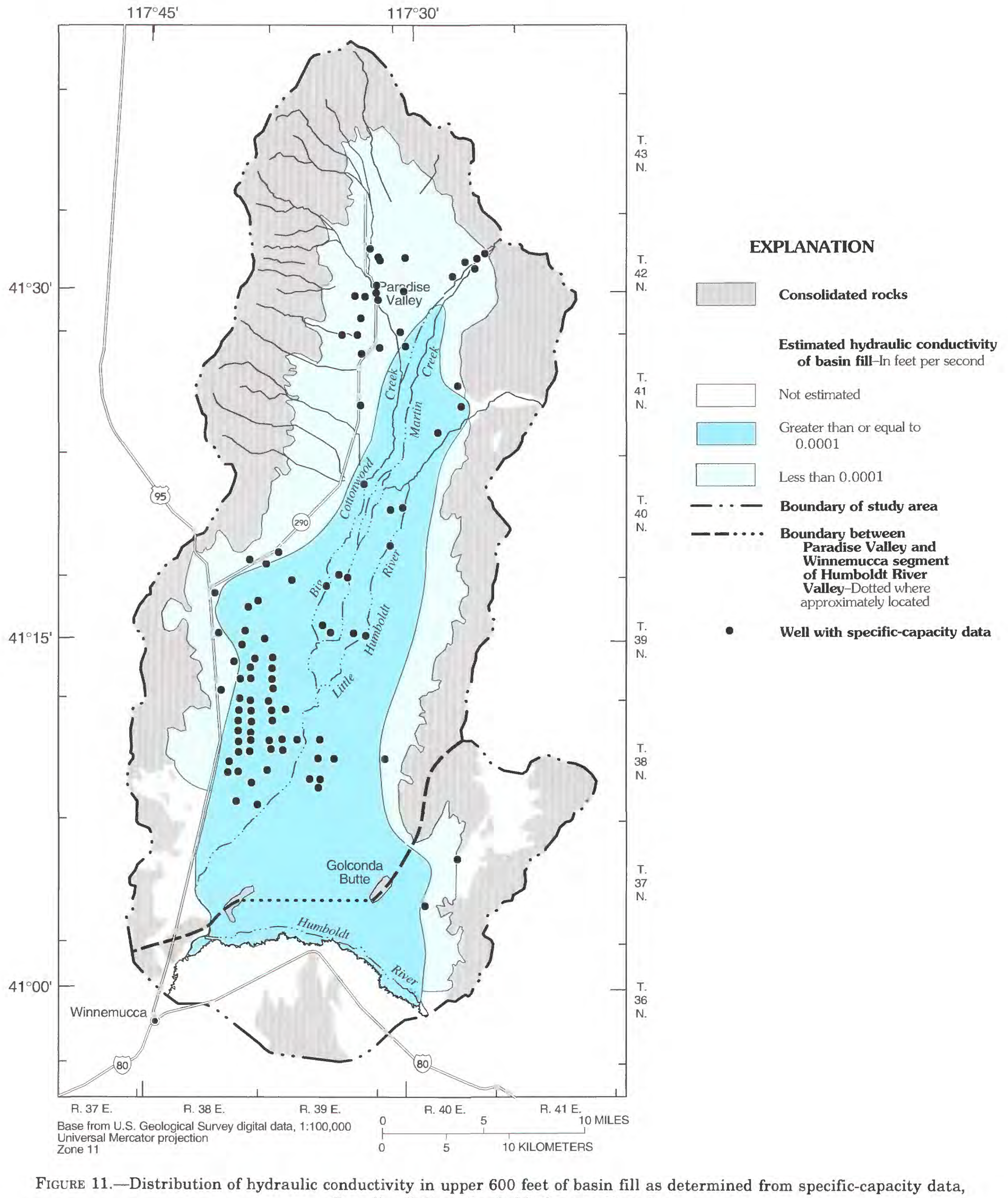


FIGURE 11.—Distribution of hydraulic conductivity in upper 600 feet of basin fill as determined from specific-capacity data, Paradise Valley, Humboldt County, Nevada.

higher values of hydraulic conductivity are in the center of the valley, with the area of higher values increasing in width from north to south. The approximate contact between basin fill with hydraulic conductivities less than 1×10^{-4} ft/s (9 ft/d) and basin fill with hydraulic conductivities greater than 1×10^{-4} ft/s is similar to the contact between older and younger alluvium (compare figs. 4 and 11). Although values of hydraulic conductivity as determined from specific-capacity data are only approximate, the values indicate that permeability of the basin fill, at least in the upper 600 ft, is less on the valley margins than in the center of the valley. The hydraulic conductivity of the basin fill below the deepest water wells is unknown, but for purposes of this study, it is assumed to be similar in distribution to the values determined for the upper 600 ft. The errors involved in calculating transmissivity, and therefore hydraulic conductivity, from specific-capacity data result in values that are probably low. Specific-capacity values of a well are generally lower than specific-capacity values of the aquifer because of well losses, which in turn lower the estimates of transmissivity and, therefore, hydraulic conductivity. The low values may be in part offset by having underestimated the effective well radius, which is probably greater than the radius of the well casing or the gravel pack (if any) used in the calculations. Well development most likely causes the effective well radius to extend beyond the casing or gravel pack (Bredehoeft, 1963, p. 36). Uncertainties in the actual storage coefficients also result in an uncertainty in the estimate of transmissivity, but large changes in storage coefficient only result in small changes in transmissivity.

The estimates of horizontal hydraulic conductivity from specific-capacity data from wells may be high when comparing the values with an average value that includes the finer grained deposits because most wells are screened only next to the more permeable (coarser) deposits.

STORAGE COEFFICIENT

The term storage coefficient is used to describe water released from or taken into storage in an aquifer. Water from storage is derived from (1) expansion of water, (2) compression of the aquifer, (3) compression of clay beds or lenses within the basin-fill aquifer, and (4) gravity drainage of the pore spaces in the unconfined zone. The volume of water released by gravity drainage of the pore spaces is referred to as specific yield and is expressed as a percentage of the volume of drained aquifer. The volume of water released per unit change in head is usually much greater than the volume released by the other three processes. Therefore, the storage coefficient in the unconfined part of the basin-fill aquifer is assumed equal to the specific yield.

Estimates of average specific yield in the upper 200 ft of saturated basin fill were made from lithologic descriptions from drillers' logs, laboratory analyses of samples collected along the Humboldt River and reported by Cohen (1963a), and results of borehole-gravity surveys of two wells in the valley.

The lithologic descriptions from drillers' logs were divided into six categories and were assigned specific-yield values (table 4) that were based on results by Cohen (1961, 1963a), Morris and Johnson (1966), and Harrill and Moore (1970). Silts normally have a specific yield of less than 10 percent; Cohen (1961, p. 44), however, reported an average specific yield for silts of 19 percent for samples along the Humboldt River near Winnemucca. This was the specific-yield value assigned to silts in Paradise Valley. Cohen (1963a, p. 23) noted that the higher-than-normal specific yield of the silts might be caused by their relatively high porosity, the compaction of the material during the laboratory tests, and the centrifuge-moisture equivalent tests used to compute specific yield. Because the centrifuge tends to expel more water than would otherwise drain by gravity, the specific yield reported by Cohen from the centrifuge test could be too high, particularly for fine-grained material (Smith, 1961, p. 11).

Distribution of the estimated specific yield for Paradise Valley is shown in figure 12, which is similar to the distribution estimated by Harrill and Moore (1970, p. 28). In general, the highest specific yields are in areas of major streams. The high specific yields at the southern end of the valley are the result of buried channel deposits from the Humboldt River, from the Little Humboldt River, or from both (Harrill and Moore, 1970, p. 26). Low specific-yield values generally are associated with fan deposits, particularly along the western side of the valley.

Specific yield was estimated at two wells in Paradise Valley from borehole gravity surveys (location of wells shown in fig. 12). Bulk densities of the deposits were determined from repeated gravity measurements at selected depth intervals in each well as described by Robbins and others (1985). The difference in bulk densities above and below the water table was assumed to be caused only by the difference in the quantity of water

Table 4.—*Estimated specific yield of lithologies described in drillers' logs, Paradise Valley, Humboldt County, Nevada*

Terms used by well drillers	Assigned specific yield[1] (percent)
Sand	30
Sand and gravel; sand and cobbles; sand and boulders; cobbles; gravel	25
Silt	19
Boulders, silt, and clay; cobbles, silt, and clay; gravel and clay; cemented gravel; gravel, sand, silt, and clay; sand and silt; sand, gravel, and clay	15
Clay and sand; sand and clay; sand, some clay; silt and clay	10
Clay	6

[1] Based on information from Cohen (1961, p. 44; 1963a, p. M19), Morris and Johnson (1966, p. 36), and Harrill and Moore (1970, p. 27)

within the pores; that is, grain density and porosity were assumed constant. The average bulk density for 20 ft above the water table in the northern well (well 02AA1 in fig. 12) was 119.2 lb/ft^3 (1.91 g/cm^3), whereas the average bulk density for 55 ft below the water table was 131.7 lb/ft^3 (2.11 g/cm^3), or a difference of 12.5 lb/ft^3 (0.2 g/cm^3). Assuming 1 lb of water is equal to 0.016 ft^3 of water, the volume of water drained per total volume was 0.2 ft^3/ft^3, resulting in an estimated specific yield of 20 percent. This compares to a specific-yield estimate of 14 percent from the lithologic description of materials found in the well. The difference in bulk density above and below the water table in the well at the southern end of the valley (well 23BDA1 in fig. 12) was 18.7 lb/ft^3 (0.3 g/cm^3), which results in a specific-yield estimate of 30 percent. The estimate of specific yield from the lithologic description was 20 percent. On the basis of results from these two wells, specific yield estimated from the borehole gravity data was higher than that estimated from lithologic logs.

The estimated specific yields from the borehole gravity data may be in error because both the grain density and the porosity can vary depending on the types of deposits found with depth in the wells. However, estimates of specific yield from lithologic descriptions also may be in error owing to inaccuracies in the description of the type of deposits reported in drillers' logs and to the actual specific yield of a particular type of deposit being different than the assigned value. Although the borehole gravity surveys give better estimates of specific yield, lithologic descriptions from drillers' logs are used to estimate specific yield throughout the valley because only two estimates of specific yield are available from borehole gravity data.

GROUND WATER IN STORAGE

A large quantity of ground water is in storage in the basin-fill aquifer. Approximately 1.8 million acre-ft of water is estimated to be stored in the upper 50 ft of saturated basin fill in the entire study area, on the basis of the product of the area, thickness, and distribution of specific yield shown in figure 12. About 1.6 million acre-ft of water is stored in the upper 50 ft of saturated basin fill in Paradise Valley—slightly less than the estimate of 1.8 million acre-ft reported by Harrill and Moore (1970, p. 72). The lower estimate for this study is the result of slightly lower estimated specific yields along the northern and western sides of the valley. The quantity of water stored in the upper 200 ft of saturated basin fill is approximately 7 million acre-ft for the entire study area (includes Humboldt River Valley) and about 6.2 million acre-ft for Paradise Valley.

GROUND-WATER RECHARGE

Almost all the water that recharges the basin-fill aquifer in Paradise Valley is from precipitation in the drainage basin. Recharge to the basin-fill aquifer is from (1) infiltration of precipitation on the valley floor, (2) subsurface inflow from adjacent mountains, (3) infiltration of water from streams that cross the basin fill, and (4) infiltration of applied irrigation water. Infiltration of applied irrigation water is discussed in later sections titled "Infiltration of Water from Streams" and "Ground-Water Pumpage." A summary of recharge estimates prior to large quantities of pumpage is presented in table 5.

PRECIPITATION ON VALLEY FLOOR

An average of about 250,000 acre-ft/yr of precipitation falls on the drainage basin of Paradise Valley (Harrill and Moore, 1970, p. 39). Most of this precipitation is directly evaporated, but some of it runs off as surface flow, some replenishes soil

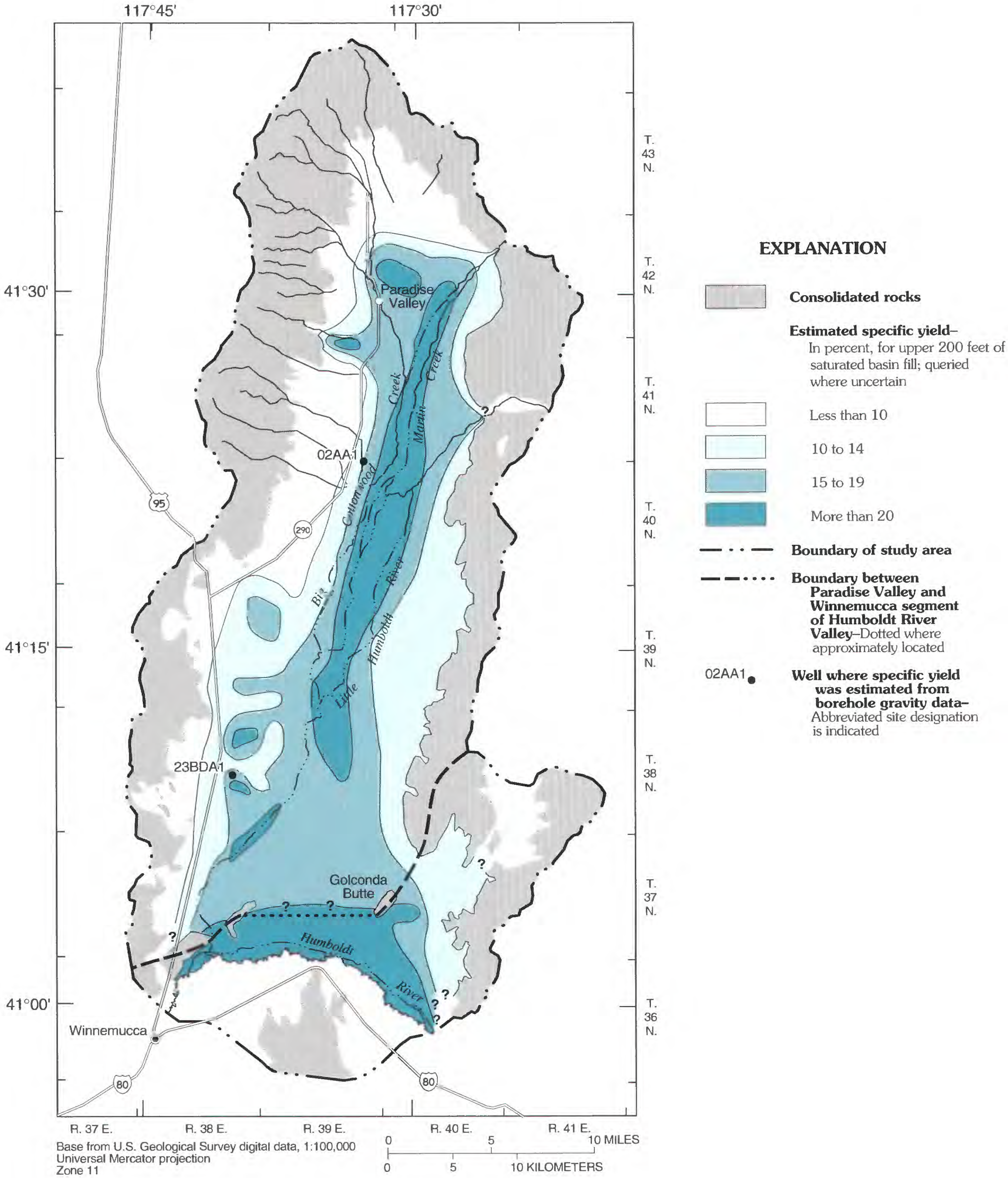


FIGURE 12.—Distribution of specific yield in upper 200 feet of saturated basin fill as determined from drillers' logs, Paradise Valley, Humboldt County, Nevada.

TABLE 5.—*Estimates of annual ground-water recharge and discharge for basin-fill aquifer in Paradise Valley, Humboldt County, Nevada, and adjacent segment of Humboldt River Valley prior to large quantities of pumpage*[1]

[Values in acre-feet per year and reported to two significant figures]

Water-budget component		Estimated quantity
RECHARGE		
	Paradise Valley	
Precipitation on valley floor		minor
Leakage from streams[2]		40,000
Recharge near contact between basin fill and consolidated rocks		1,000
	Total	41,000
	Humboldt River Valley	
Precipitation on valley floor		minor
Underflow upstream from study area		350–700
Recharge from Osgood Mountains		1,000
Recharge from Sonoma Range		3,000–4,000
Leakage from Humboldt River		11,000–18,000
Underflow from Paradise Valley		3,000–3,500
	Total	18,000–27,000
	Paradise and Humboldt River Valleys	
Combined total recharge		59,000–68,000
DISCHARGE		
	Paradise Valley	
Evapotranspiration		40,000
Underflow to Humboldt River Valley		3,000–3,500
	Total	43,000–44,000
	Humboldt River Valley	
Evapotranspiration		13,000–25,000
Underflow downstream from study area		2,000
	Total	15,000–27,000
	Paradise and Humboldt River Valleys	
Combined total discharge		58,000–71,000

[1] Values are based on estimates of Harrill and Moore (1970, table 14) for Paradise Valley and Cohen and others (1965, p. 47, 78, and 91) for Humboldt River Valley. See text for discussion of estimates.

[2] Harrill and Moore (1970, p. 65) estimate that, for average conditions, about half of streamflow entering Paradise Valley is lost to evapotranspiration prior to reaching aquifer. Much of this loss, however, is in area of evapotranspiration from ground water. Because amount of streamflow evapotranspiration was unknown for different periods of varying streamflow, results of model simulations assume that stream leakage into aquifer system was equal to inflow less outflow. Thus, estimates of evapotranspiration in model simulations include direct evapotranspiration of surface water.

moisture that is later transpired by plants, and some eventually infiltrates to the water table. However, precipitation on the valley floor averages about 9 in/yr, and most of this precipitation is evaporated directly or used to support plant growth. Loeltz and others (1949) estimated that, on average, 9 in/yr of precipitation is evapotranspired in the Martin Creek drainage above the stream gage. At least that much is probably lost in Paradise Valley.

About half of the precipitation in the study area falls during December through March, when potential evapotranspiration is small. The winter precipitation is usually as snow. A small part of this precipitation probably recharges the basin-fill aquifer, particularly in the valley lowlands where depth to water is less than 10 ft during the winter months. What does recharge the aquifer in the valley lowlands during the winter months is probably used by plants during the following summer. Thus, average annual recharge to the basin-fill aquifer from valley-floor precipitation is probably a small component of the total recharge to the basin, except perhaps during years of exceptionally high precipitation, such as 1983.

SUBSURFACE INFLOW FROM ADJACENT MOUNTAINS

The subsurface inflow from the adjacent mountains to the basin-fill aquifer is considered small because permeability of the consolidated rocks is generally low. Harrill and Moore (1970, p. 62) estimated subsurface inflow to be about 1,000 acre-ft/yr. Loeltz and others (1949, p. 33) reported that some water from consolidated rocks probably recharges the basin-fill aquifer because several thermal springs and one thermal well (well 03DC1 in fig. 2) are in or near Paradise Valley, but the quantity of inflow is probably small because the temperature of water in all other wells pumped in the valley was cool, below 70°F. Water in most wells drilled since 1950 also has a temperature below 70°F.

INFILTRATION OF WATER FROM STREAMS

Recharge to the basin-fill aquifer is primarily from infiltration of water through stream channels of intermittent and perennial streams that flow across the basin fill. Additional recharge occurs from the infiltration of surface water that has been diverted for irrigation.

Average annual runoff into Paradise Valley was estimated by Harrill and Moore (1970, p. 51–53) to be about 70,000 acre-ft/yr. The value was revised during this study to 72,000 acre-ft/yr on the basis of a greater average flow in Martin Creek for the period 1923–82. About 41,000 acre-ft/yr of this total runoff (57 percent) is from the combined annual flow of Martin Creek and Little Humboldt River. Of the remaining 31,000 acre-ft/yr, about 27,000 acre-ft/yr is runoff from the Santa Rosa Range and volcanic rocks that border the northwestern side and northern end of Paradise Valley (Harrill and Moore, 1970, p. 53).

Runoff into Paradise Valley is largely lost within the valley by infiltration to ground water, by evaporation and transpiration along the stream and irrigation channels, and by consumption from irrigated crops. Only a small percentage of the runoff reaches the Humboldt River and then only when the sand dunes that block the channel of the Little Humboldt River are breached or excavated to drain Gumboot Lake. The annual surface outflow to Humboldt River was estimated by Harrill and Moore (1970, p. 69) to be about 2,000 acre-ft. However, the estimated annual outflow for 1948 through 1982 (table 2) was about 3,700 acre-ft.

Only about one-third to one-half of the runoff into the valley recharged the basin-fill aquifer, according to Loeltz and others (1949, p. 39). The average annual recharge to the basin-fill aquifer in Paradise Valley was estimated by Harrill and Moore (1970, p. 65) at about 40,000 acre-ft; this included small quantities of water that entered the aquifer from consolidated rocks and as underflow beneath the channels of Martin Creek and Little Humboldt River.

Each time Gumboot Lake forms, some water recharges the ground water at the southern end of Paradise Valley, even though the surficial sediments in the area are generally fine grained. Because a lake of appropriate size forms, on average, only about once in 5 years, with large accumulations even less frequent, the annual recharge is estimated to be only 1,000 acre-ft (Harrill and Moore, 1970, p. 81). However, significant recharge does periodically occur from Gumboot Lake. For example, in 1952 and 1953, a large lake covered an area of about 10,000 acres and may have averaged 4 to 5 ft deep prior to it being drained. Water levels rose more than 10 ft in one nearby well. Recharge from the lake was estimated at 6,000 acre-ft during 1952–53 (Harrill and Moore, 1970, p. 81). In this report, recharge from Gumboot Lake is, for modeling purposes, included in the estimate of recharge from stream leakage.

Areas that are irrigated from diversions of streamflow account for most of the streamflow loss by evapotranspiration and are usually found where the water table is within a few feet of land surface; much of the water applied during the spring may actually reach the water table, from which it is consumed by the crops in the summer when streamflows are low. Although about half of the average annual streamflow entering Paradise Valley is lost to evapotranspiration prior to recharging the aquifer (Harrill and Moore, 1970, p. 65), estimates of direct evapotranspiration of surface water for selected time intervals with varying quantities of runoff are unknown. To simplify the model simulations in this report, none of the streamflow was lost directly to evapotranspiration in the model simulations prior to recharging the basin-fill aquifer, but rather surface water was allowed to recharge the aquifer where it was then discharged nearby as evapotranspiration. The final result is the same in that most of the water (precipitation, streamflow, and ground water) in Paradise Valley is discharged by evapotranspiration.

INFILTRATION OF WATER FROM HUMBOLDT RIVER

The deposits along the Humboldt River are generally in hydraulic continuity with the river. Seepage losses from the river to the basin-fill aquifer in Humboldt River Valley occur at a few localities throughout the year, but most of the infiltration of river water to the basin-fill aquifer occurs between April and July when the river's stage and flow are normally at their peaks (Cohen and others, 1965, p. 80). The average annual loss in streamflow measured between the Comus gage (about 21 mi east of Winnemucca, fig. 2) and the Rose Creek gage (about 15 mi southwest of Winnemucca, fig. 2) for the 14-year period 1949–62 is 17,000 acre-ft (Cohen, 1964, p. 41). The average loss between the months of February through June of each year from 1949 to 1962 is 28,000 acre-ft, whereas for the months of July through January of each year the river gains 11,000 acre-ft. This increase is due to ground water discharging into the river, mostly from bank storage of river water that had infiltrated into the flood-plain deposits during the previous spring when runoff was high (Cohen, 1964, p. 42).

Most of the measured loss in streamflow in the Humboldt River from February through June was along the reach between Comus and Winnemucca and is based on several measurements between the Comus and Rose Creek gaging stations taken during the months of April and June of years 1960–62 (Cohen and others, 1965, p. 49–56). Between 80 and 95 percent of the measured total loss in streamflow was between Comus and Winnemucca, and between 50 to 75 percent of the total loss was between Golconda and Winnemucca (fig. 2), the reach of the river that lies within the study area. Assuming that the measured losses along the Humboldt River on specific dates are typical of losses from February through June, between 14,000 and 21,000 acre-ft is lost along the reach between Golconda and Winnemucca during this 5-month period. In addition, about 30 percent of the total increase in streamflow was measured between Golconda and Winnemucca on the basis of several measurements of streamflow between the Comus and Rose Creek gages between August and December of years 1959–63. Assuming these measured gains are representative for the 7-month period from July through January, the increased flow for the period is about 3,300 acre-ft. Combining the two estimates results in an annual loss along the Humboldt River from Golconda to Winnemucca of 11,000 to 18,000 acre-ft.

Much of the streamflow lost between Golconda and Winnemucca temporarily recharges the basin-fill aquifer near the river, where it is later evapotranspired by both native vegetation and cropland. Some streamflow is trapped in shallow depressions and oxbow lakes in the flood plain, where it is evaporated, but the water table near the standing bodies of water is usually close to the water level in the lakes and ponds; thus, the standing bodies of water can be considered part of the basin-fill aquifer.

SUBSURFACE INFLOW ALONG HUMBOLDT RIVER

Some water flows beneath the Humboldt River where it enters the study area. Underflow near the Comus gage (see fig. 2 for location) is about 350 to 700 acre-ft/yr (Cohen and others, 1965, p. 78). Underflow along the Humboldt River increases near Golconda because of leakage from the Humboldt River, inflow to the valley from the Sonoma Range, and inflow to the valley from the hot springs at Golconda. About 3,000 to 4,000 acre-ft/yr is estimated as underflow from tributary areas in the Sonoma Range. This underflow enters the Humboldt River Valley near Golconda and, to a lesser extent, to the west (Cohen and others, 1965, p. 77).

GROUND-WATER DISCHARGE

Ground-water discharge from the basin-fill aquifer in Paradise Valley is by evapotranspiration from irrigated crops, native vegetation, and bare soils where the water table is shallow; by subsurface outflow to the adjacent Humboldt River Valley; and by pumping of ground water for irrigation, stock watering, and domestic use. A summary of discharge from the basin-fill aquifer is presented in table 5.

EVAPOTRANSPIRATION

Prior to the early 1970's, the principal form of ground-water discharge from the basin-fill aquifer was evapotranspiration from phreatophytes in areas where depth to ground water was generally less than 20 ft. Ground water also discharged directly from evaporation where the water table was close to land surface.

In Paradise Valley, about 100,000 acres of phreatophytes and crops annually consumed approximately 70,000 acre-ft through evapotranspiration from 1949 to 1968 (Harrill and Moore, 1970, p. 67), about 40,000 acre-ft of which was estimated from ground water. Rates of evapotranspiration ranged from 2.5 ft/yr for crops (primarily alfalfa and pasture) to 0.1 ft/yr for low-density stands of greasewood and rabbitbrush near the southern end of Paradise Valley.

Evapotranspiration from phreatophytes and crops is also the principal form of ground-water discharge from the basin-fill aquifer in Humboldt River Valley. Although evapotranspiration of ground water along the reach of the Humboldt River in the study area has not been estimated, about 25,000 to 50,000 acre-ft/yr was estimated as the quantity of evapotranspiration along Humboldt River Valley between Comus and Rose Creek (fig. 2) for water years 1949–62 (Cohen and others, 1965, p. 91). The area of evapotranspiration used in this estimate is about twice the area included in the present study. Thus, annual evapotranspiration along the segment of Humboldt River included in this study is assumed to be between about 13,000 and 25,000 acre-ft.

SUBSURFACE OUTFLOW TO HUMBOLDT RIVER VALLEY

Prior to the early 1970's, ground-water flow was generally southward in Paradise Valley to Humboldt River Valley, where the predominant flow direction was westward, parallel to the river (fig. 9). The quantity of ground-water flow leaving Paradise Valley was estimated by Loeltz and others (1949, p. 42) to be about 3,200 acre-ft/yr. Their estimate was based on a streamflow gain of 4.4 ft^3/s between Golconda and Winnemucca on the Humboldt River (fig. 2) measured in September and October 1947. A range between 3,000 and 3,500 acre-ft/yr was reported by Cohen (1963b, p. 65). His estimate was based on a streamflow gain of 2.7 ft^3/s measured in the falls of 1960 and 1961 and included an estimate in the gain in underflow that was moving parallel to the river.

Some of the gains in flow of the Humboldt River measured by Loeltz and others (1949) and Cohen (1963b) may be water that seeped into the flood-plain deposits during spring runoff of snowmelt only to discharge back to the river when the river stage declined (referred to as bank storage by Cohen and others, 1965, p. 83). Thus, the actual volume of ground water discharging from Paradise Valley into the Humboldt River Valley prior to large-scale pumping may be less than previously reported.

SUBSURFACE OUTFLOW ALONG HUMBOLDT RIVER

Some water leaves the study area as underflow beneath the channel of the Humboldt River Valley. The quantity of underflow is estimated to be about 2,000 acre-ft/yr (2.8 ft^3/s) near Winnemucca. This value is based on the reported extent of a gravel unit (Cohen and others, 1965, pl. 1), on a water-level gradient of 0.001 ft/ft (Cohen and others, 1965, pl. 3), and on a representative hydraulic conductivity of about 8×10^{-3} ft/s (650 ft/d; Cohen and others, 1965, p. 33).

GROUND-WATER PUMPAGE

Prior to 1948, water pumped from wells was used primarily for domestic purposes and for livestock. The total quantity of water pumped in 1947 was about 200 acre-ft from 100 wells equipped mostly with pumps that had a capacity of about 5 gal/min (Loeltz and others, 1949, p. 39). Estimates of water pumped from wells for domestic purposes and to supply water for the school and public buildings in the town of Paradise Valley increased from 30 acre-ft/yr in 1948 (Harrill and Moore, 1970, p. 71) to about 120 acre-ft/yr in 1982. These estimates are based on the number of people who were living in the valley and the number of wells that were used for domestic purposes. The quantity of water pumped from wells for stock watering remained at about 100 acre-ft/yr from 1948 to 1966

(Harrill and Moore, 1970, p. 71) and increased to about 120 acre-ft/yr between 1967 and 1982. These estimates are based on the number of wells used for stock watering and discussions with local ranchers.

Estimates of ground-water pumpage for irrigation from 1948 through 1968 were obtained from Harrill and Moore (1970, p. 71). Pumpage from 1969 through 1982 was estimated from the number of irrigation wells drilled in the valley, the types of crops irrigated, and the methods used to irrigate the crops. Power consumption records were not available between 1969 and 1980 because the power companies routinely disposed of the records after a few years. In addition, the greatest pumpage in Paradise Valley is at the southwestern part of the valley, where an integrated irrigation system with several booster pumps and interconnected distribution lines make estimates using power consumption tenuous.

Estimates of ground-water use per crop type and irrigation system are listed in table 6. These estimates are based on information furnished by local residents. In general, more water is used to flood irrigate a field than is used by sprinklers. Estimates of water use per acre of crop at Winnemucca Farms are based on values supplied by farm manager A.J. Evans (Winnemucca, Nev., oral commun., 1982) and are the lower value for sprinkler systems in table 6. Also, wells used for flood irrigation are generally used to supplement irrigation needs not met by streamflow and are normally used only during the late summer and early fall. During years of above-normal streamflows, such as 1980 and 1982, some irrigation wells were not used at all.

Only a small quantity of ground water was pumped for irrigation in 1947 (Loeltz and others, 1949, p. 51). Ground-water pumpage in Paradise Valley began to increase in the mid-1950's, when 11 wells were drilled to irrigate crops. Most of the wells were drilled along the flood plain of Little Humboldt River and were used primarily to supplement surface-water supplies during periods when streamflow was insufficient to irrigate crops. Pumpage increased slowly until 1966 (fig. 13*A*), when below-normal runoff in 1966 and 1968 (see fig. 7) resulted in a substantial increase. Pumpage decreased substantially in 1969 (fig. 13*A*) because runoff into Paradise Valley was 200 percent of normal and many supplemental wells were not used.

According to drillers' logs submitted to the Nevada State Engineer's office, only 36 irrigation wells were drilled in Paradise Valley prior to 1968. These wells and the distribution of irrigated lands for 1968 are shown in figure 14. Water from only two wells was pumped into sprinkler systems in 1968 (Harrill and Moore, 1970, pl. 1); the other irrigation wells were used to supplement surface water.

TABLE 6.—*Estimates of annual ground-water pumpage by crop type and irrigation system, Paradise Valley, Humboldt County, Nevada*

[Values in acre-feet per acre. Symbol: "--," irrigation type is not used for irrigated crop type.]

Crop type	Flood irrigation[1]	Sprinkler irrigation[2]
Alfalfa	0–3	2.5–2.8
Grain (wheat, barley)	0–1	0.8–1.0
Potatoes	--	2.5–2.8
Pasture and hay	0–3	--

[1] Range in values depends on whether well supplements surface-water supplies and on the amount of runoff available during the year.

[2] Lower values were used for Winnemucca Farms; slightly higher values were used for systems in remainder of study area. Lower use rate for grain is for special varieties of wheat; otherwise, 1.0 acre-foot per acre was used throughout the study area.

An additional 91 wells were drilled in the valley between 1972 and 1982, of which 19 were drilled to replace older wells. Thirty-one irrigation wells were drilled in 1973—the most drilled during a single year in Paradise Valley. In addition to the wells drilled in Paradise Valley, eight irrigation wells were drilled in 1972–73 just east of Golconda Butte in Humboldt River Valley. Pumping from these wells affects ground-water flow between Paradise Valley and Humboldt River Valley. The quantity of pumpage from wells in the adjacent segment of Humboldt River Valley ranged from an estimated 1,900 acre-ft/yr in 1973 to 5,300 acre-ft/yr in 1977 (fig. 13*B*).

Most of the new irrigation wells drilled between 1969 and 1982 are located in the southern part of Paradise Valley (fig. 15). This area uses ground water as the principal source for irrigation, and thus pumpage increased rapidly between 1969 and 1981. Pumpage increased from about 6,800 acre-ft in 1970 to about 47,000 acre-ft in 1981 (fig. 13*A*). An additional 3,700 acre-ft was pumped in 1981 from wells located in the adjacent segment of Humboldt River Valley (fig. 13*B*). Pumpage estimates in 1980 and 1982 were less than in 1981 because some wells that are used to supplement streamflows were not used owing to above-normal streamflows. Pumpage in Paradise Valley was estimated at 43,000 acre-ft in 1980 and 44,000 acre-ft in 1982; an additional 2,600 and 3,800 acre-ft was pumped in 1980 and 1982, respectively, in the Humboldt River Valley. Although not estimated, pumpage for 1983 and 1984 most likely was less than 1981 because of continued above-average streamflows.

Not all the ground water pumped from wells is consumed; some water returns to the basin-fill aquifer, particularly along the flood plains of Martin Creek and Little Humboldt River, where depths to water are only a few feet below land surface. Net pumpage shown in figure 13 is an estimate of the quantity of pumpage consumed by the plants or evaporated from the soils. The quantity of irrigation pumpage that returns to the basin-fill aquifer is dependent on the method of irrigation, the character of the soil, the slope of the field, and other factors (Harrill and Moore, 1970, p. 70). This quantity probably ranges from 10 percent of the total in fields where ground water is pumped through pressured sprinklers, to about 60 percent in some fields near streams where ground water is pumped to supplement surface-water irrigation. Prior to the 1970's, most of the ground water was pumped into unlined ditches in the valley bottom and the quantity of recirculated pumpage averaged about 40 percent (Harrill and Moore, 1970, p. 70). In the 1970's, much of the ground water pumped was applied using pressurized sprinkling systems, which reduced the quantity of water that returned to the basin-fill aquifer. Because of the pressurized sprinkling systems, only about 20 percent of the total pumpage was estimated to return to the basin-fill aquifer between 1972 and 1982. For example, total pumpage for Paradise Valley of 47,000 acre-ft in 1981 resulted in an estimated net pumpage of about 38,000 acre-ft.

SIMULATION OF GROUND-WATER FLOW

The principal technique used to analyze ground-water flow and yield of the basin-fill aquifer was with a digital computer model. The remainder of this report describes the type of model used, the general features of the model, and the model results. The model was first calibrated to a period

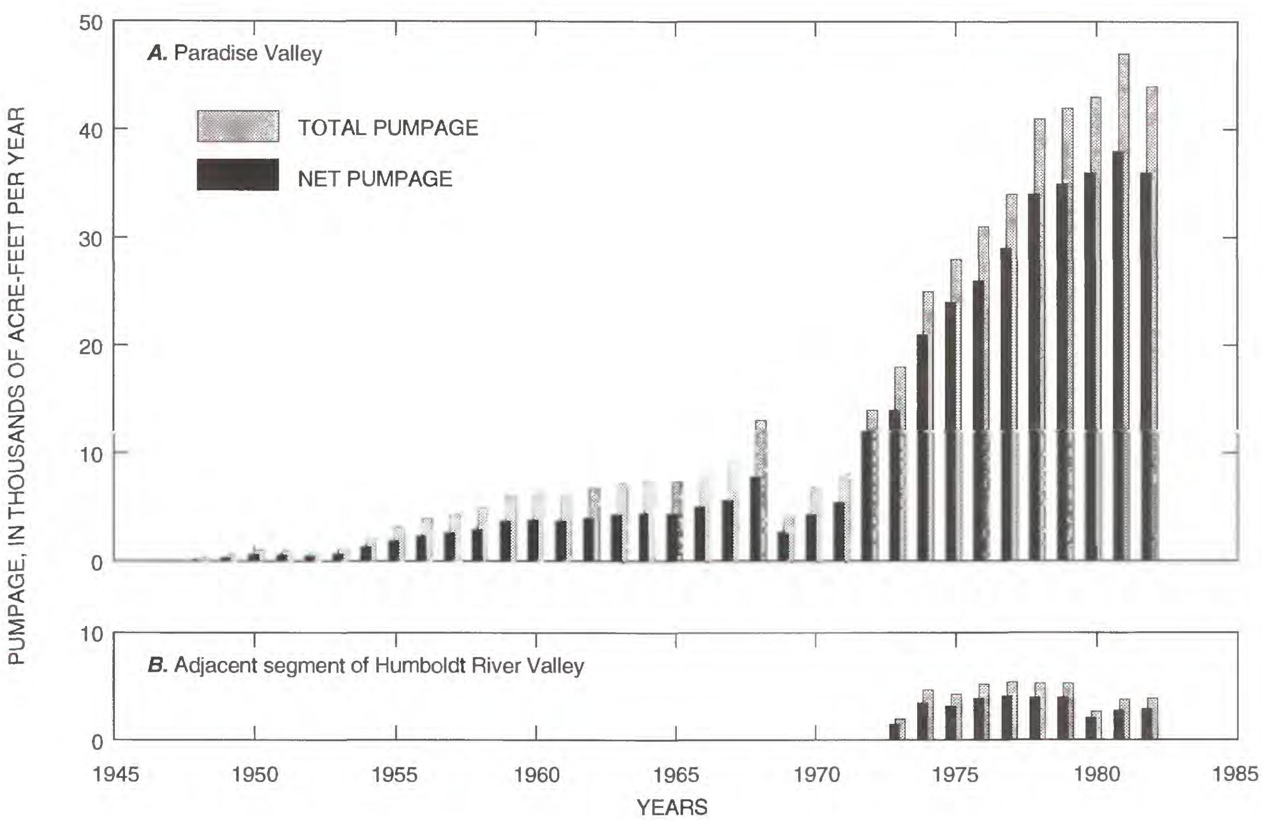


FIGURE 13.—Annual ground-water pumpage, 1948–82, for (*A*) Paradise Valley and (*B*) adjacent segment of Humboldt River Valley, Humboldt County, Nevada. Net pumpage equals total pumpage minus amount estimated to return to basin-fill aquifer.

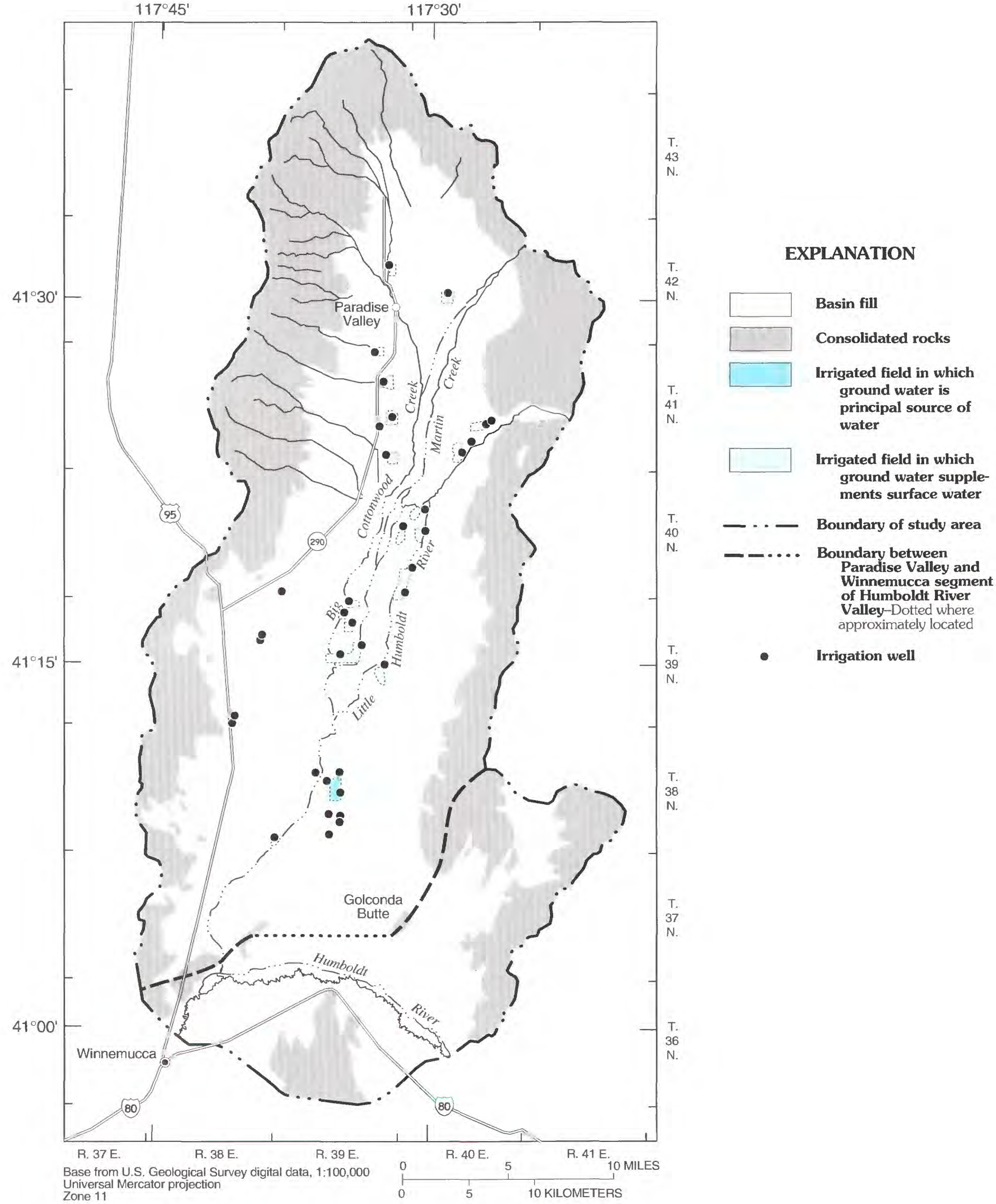


FIGURE 14.—Distribution of irrigated lands and irrigation wells as of 1968, Paradise Valley, Humboldt County, Nevada.

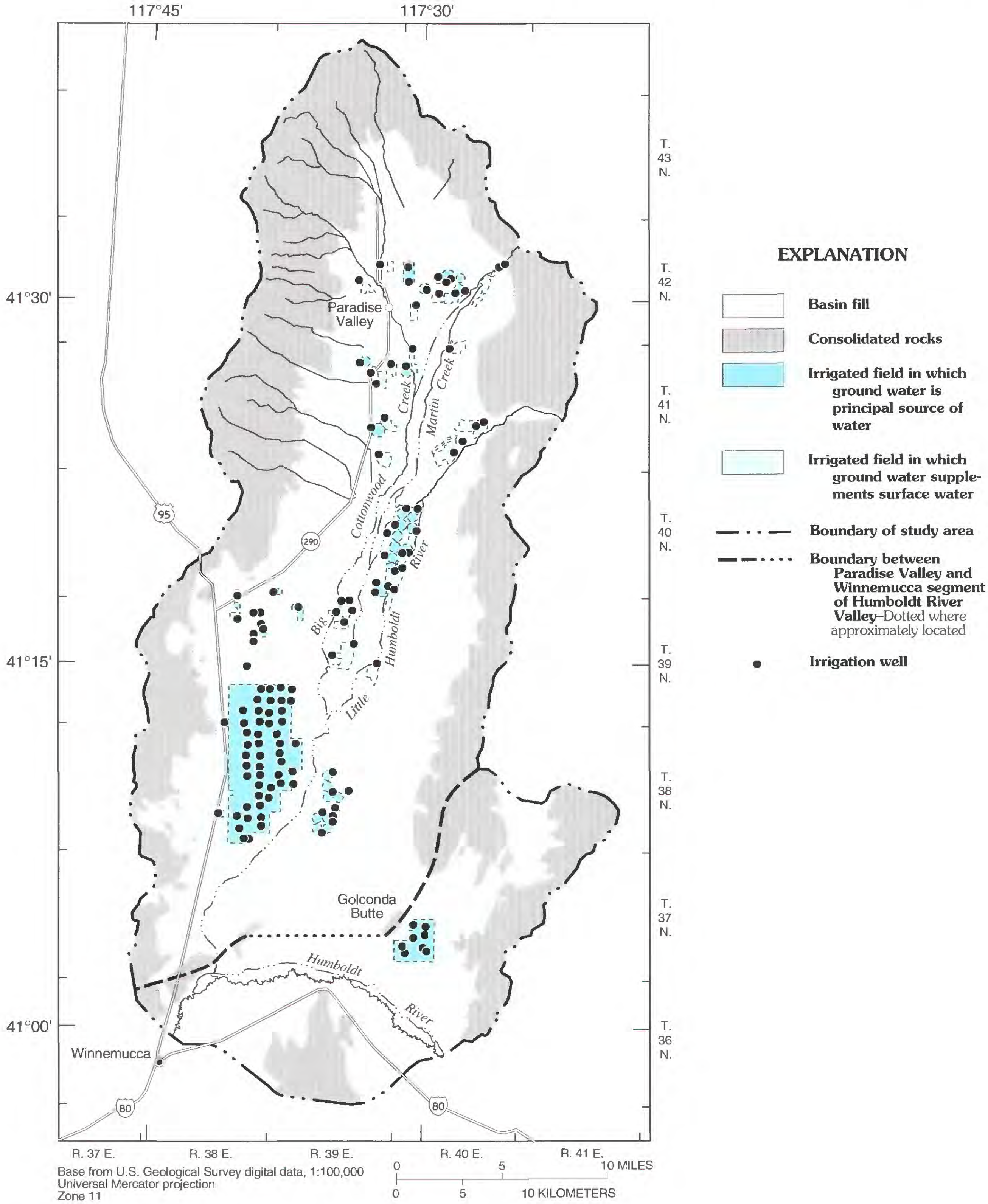


FIGURE 15.—Distribution of irrigated lands and irrigation wells as of 1981, Paradise Valley, Humboldt County, Nevada.

of average conditions with little ground-water pumpage (1948–68) and then recalibrated to selected periods of varying climatic conditions and changes in ground-water pumpage (1948–82). The calibrated model was used to simulate long-term trends that describe probable future response to selected ground-water development in the valley.

DIGITAL COMPUTER MODEL

A computer program written by McDonald and Harbaugh (1988) was used to simulate ground-water flow in Paradise Valley. The program solves the three-dimensional equation of ground-water flow using finite-difference approximations. The equation solved by the program can be written as follows:

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

where S_s = specific storage, in per foot;
h = hydraulic head, in feet;
t = time, in seconds;
K_{xx}, K_{yy} = hydraulic conductivity in the principal horizontal directions, in feet per second;
K_{zz} = hydraulic conductivity in the vertical direction, in feet per second;
w = volumetric flux of recharge or discharge per unit volume, in per foot; and
x, y, z = Cartesian coordinates, in feet, aligned along the major axes of hydraulic conductivity.

The continuous derivatives in equation 2 are replaced with finite-difference approximations at a point or node. Surrounding each node is a model block with dimensions x, y, and z, in which the hydraulic properties are assumed to be uniform. Thus, to simulate the field conditions using the computer program, the aquifer was divided into blocks, and values of aquifer properties were estimated for each block.

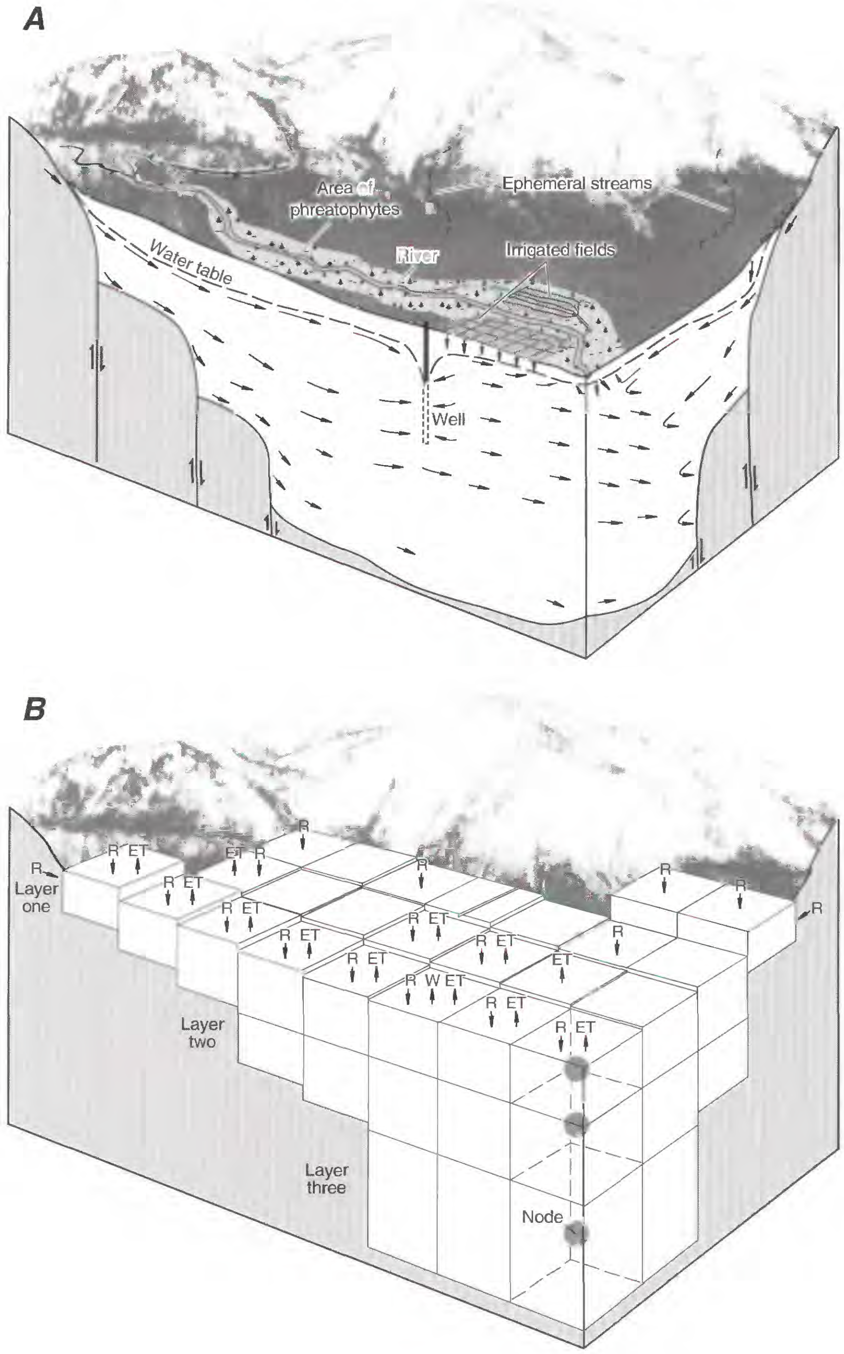
The strongly implicit procedure was used in the computer program to solve the unknown head for each time step in the model simulations (McDonald and Harbaugh, 1988, p. 12-1 through 12-65). The unknown head was solved by iterating through the finite-difference equations for each node until the head change between iterations was less than a specified value. The value specified for the model simulations of Paradise Valley was 0.1 ft. Once this criterion was met, the model advanced to a new time interval and the process of computing head values at each node was repeated. The numerical technique used to solve the ground-water flow equation is discussed in detail by McDonald and Harbaugh (1988).

GENERAL FEATURES OF MODEL

A simplified diagram (fig. 16*A*) shows the general pattern of recharge, discharge, and ground-water flow in Paradise Valley. The computer model can simulate many elements of the basin-fill aquifer (fig. 16*B*), including recharge from precipitation, stream leakage, and irrigated crops, and discharge by evapotranspiration, pumping, and stream leakage.

To simulate ground-water flow with the computer program, the basin-fill aquifer was divided into model blocks with horizontal dimensions of 2,500 ft on a side. A finite-difference grid of 33 columns and 89 rows was superimposed over a map of the study area and oriented so that a minimum number of blocks were outside the study area (fig. 17). At most, three layers of model blocks were used to represent the basin-fill aquifer vertically. The thickness of model blocks differed among layers and varied within a single layer. The uppermost layer (layer one in fig. 16*B*) corresponds to the interval incorporating at least parts of screened intervals for all wells. Layer one is present wherever the thickness of basin fill exceeds 250 ft, and it has a maximum thickness of 600 ft. Layer two is present wherever basin fill exceeds 600 ft, and it has a maximum thickness of 600 ft and, thus, a maximum depth of 1,200 ft. Layer two corresponds to an interval that is penetrated by only a few wells. Layer three, the bottom layer, represents basin fill below a depth of 1,200 ft. The thickness of model blocks in this layer may exceed 6,000 ft locally. Layer three corresponds to an interval in the basin fill for which no wells nor information on hydraulic properties exist. Layers two and three are included primarily to account for water stored in these intervals and for the small quantities of water that flow through them. Layer one is assumed to be unconfined, whereas layers two and three are considered to be confined. Numbers in the grid shown in figure 17 correspond to the number of layers used to simulate flow in the basin fill.

The thickness of layer one is dependent on the depth of wells that have been drilled in the central



EXPLANATION

Basin-fill aquifer

Consolidated rocks

Direction of ground-water movement

Fault–Arrows indicate direction of movement

Abbreviations:

R	Recharge from stream leakage and as flow from bedrock
ET	Discharge from evapotranspiration
W	Discharge of pumped ground water

FIGURE 16.—Schematic three-dimensional diagram of basin-fill aquifer (*A*), and same diagram with basin fill represented by blocks for computer simulation (*B*), Paradise Valley, Humboldt County, Nevada.

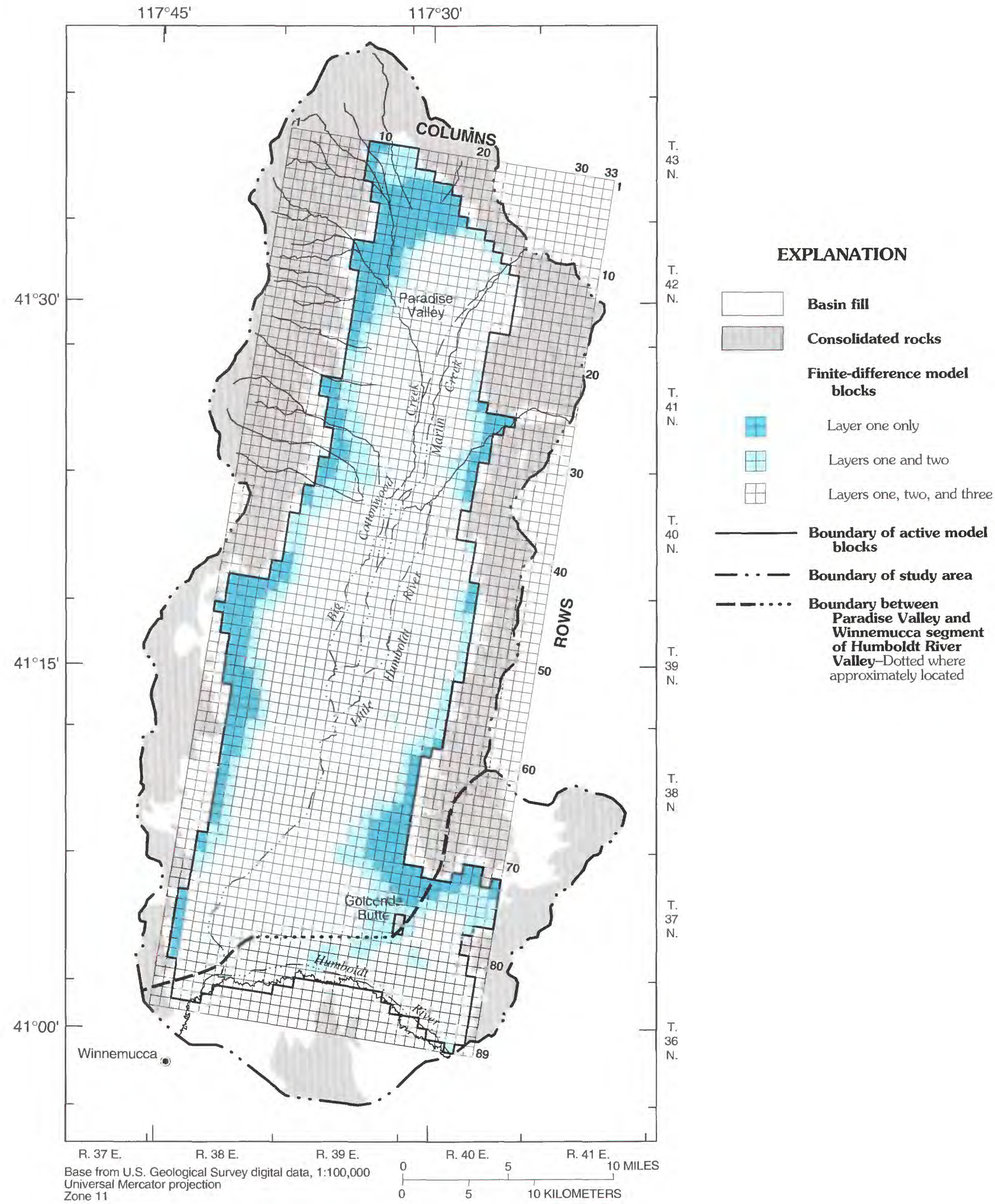


FIGURE 17.—Finite-difference grid used to simulate ground-water flow in the basin-fill aquifer, Paradise Valley, Humboldt County, Nevada.

and southern parts of Paradise Valley and water levels in wells. The response to pumping in this part of the valley suggests that the upper 600 ft of basin fill is essentially unconfined. Water levels vary little between wells of different depths (deepest wells are less than 800 ft below land surface) in most of the valley, and except for a flowing hot well (see fig. 2 for location) in the south-central part of Paradise Valley, water levels in wells are at or below land surface. The flowing hot well has a measured depth of 60 ft and is at a site of an old hot springs (Loeltz and others, 1949, p. 34). Wells drilled to depths of 500 ft within a few miles of the flowing well are neither hot nor flowing.

Downward hydraulic gradients, however, exist near the northwestern edge of the basin-fill aquifer and are caused by both lower permeabilities of the deposits and greater quantities of recharge than at other locations along the margins of the valley. The thickness of layer one was not decreased to simulate observed vertical gradients in this area because a greater thickness for layer one was needed to simulate large water-level declines for the hypothetical pumping patterns.

Model blocks in the finite-difference grid were designated either active or inactive. Model blocks corresponding to basin fill were generally designated as active except along the margins of the valley where the thickness of basin fill was less than 250 ft. Consolidated rocks were considered to have a much lower permeability than the basin fill, and for the purposes of the model, model blocks corresponding to consolidated rocks were designated inactive. Although Golconda Butte near the southeast corner of the study area (see fig. 17) also was assumed to be impermeable, the younger basalt flows near the southwest corner of the study area were assumed capable of storing and transmitting water, and the model blocks corresponding to these basalt flows were designated as active.

Model blocks south of the Humboldt River also were designated inactive because the Humboldt River was used to simulate the southern boundary of flow in Paradise Valley. Although some ground water enters Humboldt River Valley from the Sonoma Range to the south, much of this flow enters near Golconda. The general ground-water flow direction south of the river is parallel to the river with a small component to the river (Cohen, 1963b, p. 60). The small quantity of ground-water flow entering Humboldt River Valley from the south was incorporated into the estimated seepage from the Humboldt River. In addition, some ground water flows through alluvium where the Humboldt River exits the model area near Winnemucca; in the model, this flow was simulated as leakage to the Humboldt River.

STREAM LEAKAGE

Most of the recharge to the basin-fill aquifer is by seepage loss (leakage) from streams that cross the basin fill (Harrill and Moore, 1970, p. 62). Streamflows vary from year to year; consequently, recharge to the basin-fill aquifer is variable. To account for the variable recharge from streamflows, stream leakage was simulated in the model of Paradise Valley using a streamflow-routing program (Prudic, 1989) written specifically for the computer program of McDonald and Harbaugh (1988). In this program, the quantity of leakage to the aquifer is limited to the quantity of streamflow that enters the modeled area. To account for streamflows, streams are divided into two categories: reaches and segments. Each reach corresponds to individual model blocks in the finite-difference grid. Segments are groups of reaches connected in downstream order. Streamflows are specified for the first reach in each segment that enters the modeled area. The program then computes streamflow into adjacent downstream reaches in each stream segment as equal to streamflow in the upstream reach plus or minus leakage from or to the aquifer in the upstream reach. When streamflows of one or more segments are combined into one downstream segment, the inflow to the downstream segment is the sum of outflow from each tributary segment.

Leakage between a stream reach and model block is controlled by the head difference between the reach and model block and by a conductance term for the streambed (Prudic, 1989, p. 7). Leakage between a stream reach and model block is limited to the quantity of streamflow that enters the reach. If inflow to a reach is zero, then leakage from a reach to a corresponding model block is not allowed. However, if the head in a model block is greater than the altitude of the streambed in a corresponding stream reach, then leakage from the model block to the reach is simulated.

Actual altitudes of stream stage and channel are not known for every model block representing a stream reach. The average channel altitude for each reach was estimated from topographic maps. The error in these estimates is ±10 ft on the valley floor and ±20 ft on the adjacent alluvial fans. Stream stage typically is only 1 to 2 ft above the stream channel. Consequently, average stream-stage altitude for each reach was simply assigned the estimated channel altitude. The value of streambed conductance varied for each reach and was estimated from the length of the stream in a model block, the average stream width, the estimated hydraulic conductivity of the streambed that was the same as those estimated for the basin-fill aquifer ($1x10^{-5}$ ft/s along the alluvial fans to $1x10^{-4}$ ft/s in the valley bottoms), and a streambed thickness of 3 ft.

A total of 274 stream reaches and 27 segments was used to simulate stream leakage, including the section of the Humboldt River used as the southern boundary of the modeled area. The distribution of reaches used in the simulations are shown in figure 18. Average streamflow for each stream was specified where streams entered the modeled area. Streamflow entering the modeled area was averaged for each simulation period on the basis of streamflow gaging records for Martin Creek, Little Humboldt River, and the Humboldt River. For ungaged streams, streamflow was related to flow in Martin Creek on the basis of drainage area and altitude in a manner described by Moore (1968).

Constant recharge rates were assigned to model blocks along the margins of the valley to account for underflow from the adjacent mountains. In addition, streams for which average annual discharge did not exceed 1,200 acre-ft/yr (1.7 ft^3/s) are included in the constant recharge rates. The constant recharge rates are distributed over model blocks corresponding to areas of underflow and to the smaller streams. Values of recharge range from 0.001 to 0.8 ft^3/s. The distribution of blocks assigned a constant recharge rate is shown in figure 18. Several blocks, particularly along the east flank of the Santa Rosa Mountains (northwestern side of model grid), are assigned both a stream reach and a constant recharge rate.

The streamflow-routing program is a simplified technique that allows recharge to be simulated in the center of Paradise Valley from cyclic or periodic pulses of runoff. Assumptions used in the simulation of stream leakage that may affect results include the following: (1) streamflow entering the modeled area is instantaneously available to all downstream reaches; (2) leakage between streams and aquifer is instantaneous even if the stream and aquifer are separated by an unsaturated zone; and (3) none of the streamflow is lost directly to evapotranspiration prior to seeping into the ground. The first assumption probably does not affect the simulation results because streamflow entering the valley passes through it in a few days, whereas the changes in ground-water flow in the simulations were averaged over months and years. The second assumption may not be valid in areas where the unsaturated zone is many tens to hundreds of feet. Such conditions exist only near the margins of the valley where leakage from streamflow is generally constant with time. The third assumption was made to simplify transient simulations where rates of direct evapotranspiration of streamflow are unknown. Generally, however, direct evapotranspiration from streamflow is concentrated in the valley lowlands, where depth to ground water is only a few feet and where evapotranspiration from ground water is also concentrated. Thus, model results of evapotranspiration presented in this report include both evapotranspiration of ground water and surface water.

The version of the package used in this study does not include stream dynamics, in part because of the lack of information regarding the relations of stream width and stream stage to the discharge of the streams for each model reach. The package used to analyze ground-water flow and yield in Paradise Valley did, however, adequately simulate the effect of cyclic and periodic pulses of runoff in the valley.

EVAPOTRANSPIRATION

Most of the ground-water discharge in Paradise Valley prior to development was by evapotranspiration. Only a small part of the ground-water flow may have actually discharged to the Humboldt River. Discharge by evapotranspiration from the model was simulated with a head-dependent function that decreased linearly with depth (McDonald and Harbaugh, 1988, p. 316–320). A maximum evapotranspiration rate was simulated when the water table in layer one was at land surface. The maximum rate was assumed to be 3 ft/yr: this equals the rate of evaporation from open bodies of water (lakes and ponds) near Winnemucca, which is about 3.7 ft during the growing season (Robinson, 1965, p. 90), minus the average precipitation, which is about 0.7 ft/yr. The rate was decreased linearly to zero at a specified depth of 20 ft below land surface. To simulate discharge by evapotranspiration, values of land-surface altitude, of depth where evapotranspiration becomes zero, and of a maximum rate of evapotranspiration were specified for each active block in layer one.

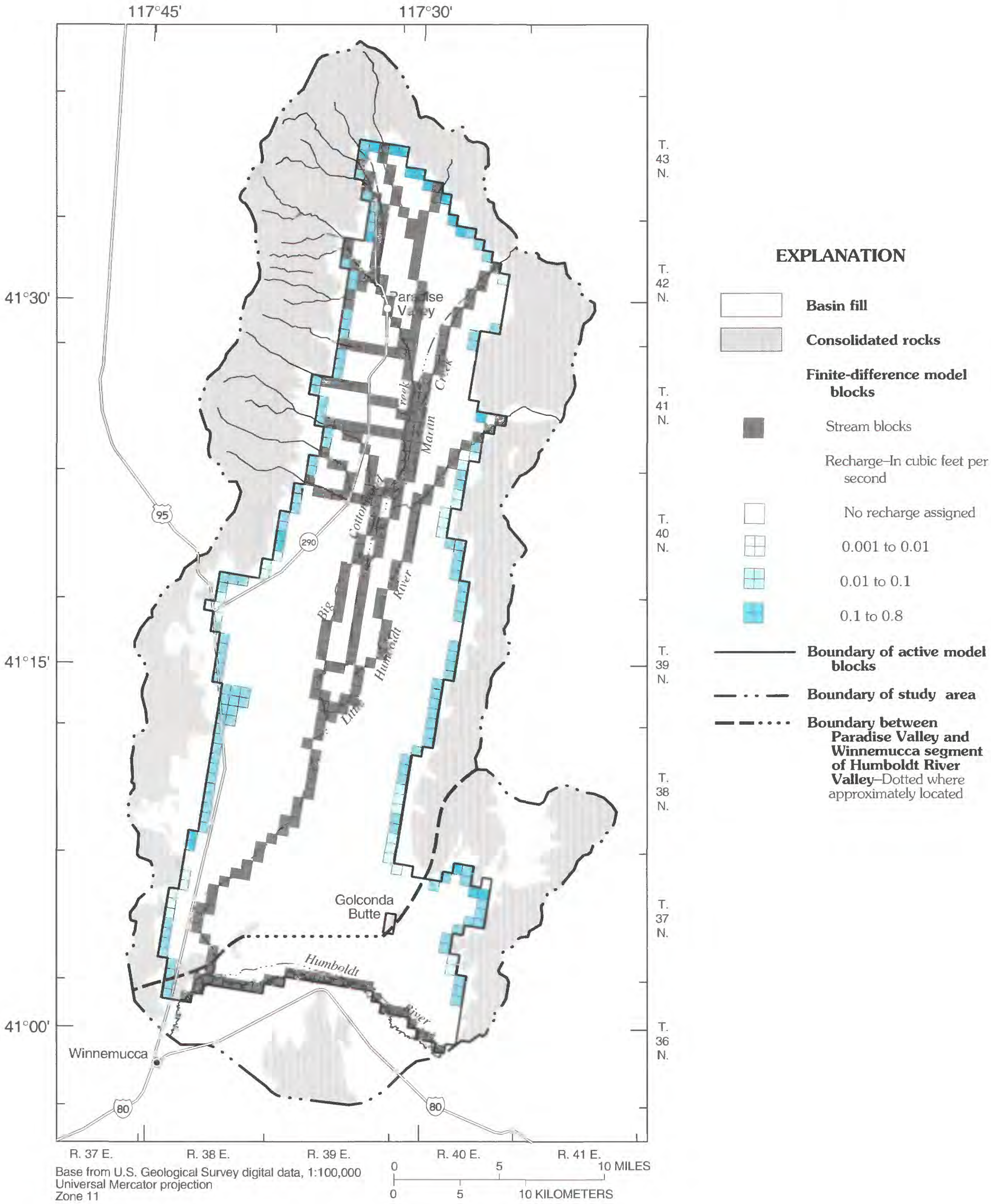


FIGURE 18.—Distribution of model blocks used to simulate recharge from or discharge to streams, and blocks assigned a constant recharge rate, Paradise Valley, Humboldt County, Nevada.

INITIAL CONDITIONS AND HYDRAULIC PROPERTIES

The initial water-level distribution for model layer one is based on spring 1968 water-level measurements (fig. 9). These water levels are assumed to represent equilibrium conditions that existed prior to the withdrawal of large quantities of ground water from the basin-fill aquifer beginning in the early 1970's. The same water levels were initially used for model layers two and three because no water-level data were available for these layers.

Transmissivities were assigned to the model blocks using two approaches. For model layer one, the transmissivity was calculated by the computer program. The saturated thickness was calculated during each model iteration by subtracting the bottom altitude of each block in layer one from the computed water level from the previous model iteration. This value was then multiplied by the assigned hydraulic conductivity to obtain the transmissivity. The value of hydraulic conductivity assigned to each model block is based on the distribution shown in figure 11. Transmissivities were assigned directly to model layers two and three and remained constant during a simulation. Transmissivities were initially determined as the product of the layer thickness and an assigned hydraulic conductivity. Hydraulic conductivity of the basin fill for model layers two and three are unknown, but initial estimates were determined assuming that hydraulic conductivity decreased with depth due to overburden pressures. Hydraulic conductivity used in model layer one was decreased 50 percent for every 1,200 ft of depth below layer one and is based on a relation reported by Durbin and others (1978, p. 76). Estimates of hydraulic conductivity were adjusted during model calibration, but the relation of decreased hydraulic conductivity with depth did not change. Thus, if values of hydraulic conductivity were decreased in model layer one, so were the values in model layers two and three.

Flow between model layers was simulated using a leakance term, which is expressed as the ratio of vertical hydraulic conductivity to the thickness of a confining unit (Lohman, 1979, p. 30). For purposes of the model simulations, the thickness used to determine leakance values was represented as the distance between the midpoints of two model blocks in adjacent layers. Because the basin fill is composed of numerous discontinuous lenses of coarse- and fine-grained deposits, an equivalent leakance value between model layers was used in the simulation. Initial estimates of vertical hydraulic conductivity were determined for the upper 600 ft of basin fill using the thicknesses of coarse- and fine-grained deposits reported in drillers' logs and the following equation:

$$K_v = \frac{b}{\frac{b_c}{K_{vc}} + \frac{b_f}{K_{vf}}} \tag{3}$$

where K_v = equivalent vertical hydraulic conductivity, in feet per second;
b = total thickness, in feet;
b_c, b_f = sum of the thicknesses of coarse- and fine-grained deposits, respectively, in feet; and
K_{vc}, K_{vf} = vertical hydraulic conductivities of coarse- and fine-grained deposits, respectively, in feet per second.

Vertical hydraulic conductivity of the fine-grained deposits was assumed to be 1×10^{-7} ft/s (0.003 ft/d) and is based on analyses of more than 200 core samples from fine-grained deposits in California (Johnson and others, 1968, table 5). Vertical hydraulic conductivity of the coarse-grained deposits was assumed equal to the hydraulic conductivity determined from specific-capacity data. The vertical hydraulic conductivity also was assumed to decrease with increasing depth in the same manner as the horizontal hydraulic conductivity. Vertical hydraulic-conductivity values were adjusted also during calibration of the model.

Specific-yield values were used as the storage coefficient in model layer one (an unconfined aquifer) for the transient simulations. The distribution of specific yield is shown in figure 12. The storage coefficients in model layers two and three varied according to the thickness assigned to each model block and were estimated by multiplying the thickness with a specific storage of 2×10^{-6} per ft. This value was used to represent the specific storage of basin fill that consists of a mixture of coarse- and fine-grained deposits. The value was obtained from studies in similar types of sediments (Nelson, 1982; Williamson and others, 1989).

RESULTS OF SIMULATION

PREDEVELOPMENT CONDITIONS

Prior to the withdrawal of water from wells, ground-water levels fluctuated only in response to variations in streamflow and to seasonal changes in the quantity of evapotranspiration. Water levels were generally highest in the spring and early summer, owing to infiltration of runoff from the surrounding mountains, and lowest in the fall and early winter, owing to discharge by evapotranspiration in the valley bottom during the previous summer. Yearly variations in ground-water levels were primarily caused by the abundance or lack of runoff. The first valley-wide measurement of water levels in wells was made in September 1947 (Loeltz and others, 1949), the next was in February 1968, and a third occurred in November 1968 (Harrill and Moore, 1970, p. 75). The difference in water levels in wells between the fall of 1947 and fall of 1968 was less than 5 ft. This difference is less than the seasonal fluctuations reported by Loeltz and others (1949, p. 75) from measurements in 10 wells during 1946 and 1947, and it is also less than fluctuations reported by Harrill and Moore (1970, p. 75) from measurements in many wells during 1968. Thus, the basin-fill aquifer in Paradise Valley was in a general state of equilibrium (referred to as steady state) between September 1947 and November 1968, as there was no long-term increase nor decrease in ground-water levels and, therefore, no net change in ground-water storage.

Water levels measured in the valley in September 1947 and November 1968 may not be the same as those when the valley was first settled in the 1800's. The practice of diverting streams for irrigation of crops in the late 1800's and early 1900's increased the quantity of recharge to the basin-fill aquifer (Loeltz and others, 1949, p. 33), particularly in that part of the valley north of T. 39 N. This increased recharge probably raised water levels over much of the valley. Thus, the steady-state simulations described in the following paragraphs are representative of water levels after the diversion of streams began in the late 1800's and early 1900's, and before the withdrawal of large quantities of water began in the early 1970's.

Calibration of Steady-State Simulations

Calibration of a ground-water flow model is usually achieved by changing the values of aquifer properties or the quantity and distribution of recharge and discharge, or both, until the model-calculated water levels match the measured water levels in the aquifer. The sequence of calibration used in the steady-state simulation was to adjust only the values of vertical and horizontal hydraulic conductivity and streambed conductance. The thickness of basin fill, streamflow entering the modeled area, recharge along the edges of the modeled area, maximum evapotranspiration rate, and depth where evapotranspiration ceases were assumed correct and not adjusted.

The model was considered calibrated on the basis of the following: (1) The mean departure of model-calculated water levels from measured water levels was near zero for the 169 model blocks corresponding to wells in layer one; (2) more than 95 percent of the model-calculated water levels were within 20 ft of measured water levels; (3) the simulated distribution of evapotranspiration approximated the estimated distribution; and (4) leakage from streams approximated streamflow losses.

Horizontal hydraulic conductivities were adjusted by uniformly changing the hydraulic conductivity throughout the modeled area, keeping the general pattern of hydraulic conductivity estimated from specific-capacity data. Next, model blocks associated with the major streams entering Paradise Valley and associated with the Humboldt River were adjusted to reflect suspected areas of higher conductivities. Vertical hydraulic conductivities were uniformly adjusted throughout the modeled area but were not adjusted between individual model blocks because no evidence existed to support such changes. Finally, streambed-conductance values were adjusted for model blocks that contained stream reaches until leakage per mile of stream channel approximated streamflow losses reported by Loeltz and others (1949) and all the average streamflow in Paradise Valley was simulated as leaking into the basin-fill aquifer. Even though some of the streamflow has discharged to the Humboldt River since 1953, most of this flow was the result of a channel being dredged through the sand dunes. The steady-state simulation presented in this report represents a time period when Gumboot Lake was not drained by dredging. The discharge of streamflow from Paradise Valley was simulated in the transient simulations presented in the section titled "Effects of Development, 1948 through 1982." Streambed-conductance values for model blocks that contain reaches of the Humboldt River were adjusted until leakage from the Humboldt River approximately equaled the estimated annual loss in streamflow between Golconda and Winnemucca of 11,000 to 18,000 acre-ft.

Usually, only one well corresponded to a model block (surface area of about 0.25 mi^2); in the few blocks having more than one well, the measured water levels from all wells within the model block were averaged. For the best-fit simulation, about

96 percent of the simulated water levels in layer one were within 20 ft of the measured water levels (fig. 19). In calibrating the model, differences of less than 20 ft were considered tolerable because altitudes of many wells in the valley were estimated from topographic maps that had a contour interval of 20 ft in the valley and 40 ft along the margins. Thus, errors in estimating the water-level altitudes measured from wells along the margins of the valley could be as much as half the contour interval or 20 ft. In addition, differences of more than 20 ft between the simulated and measured water levels in the northwestern part of the study area may be the result of downward gradients in the area. Simulated water levels are a composite over the thickness of the model block, whereas measured water levels either represent the measurement from one well or the average of a few wells.

The mean difference between simulated and measured water levels for the 169 model blocks was –0.77 ft with a standard deviation of 9.6 ft. On the average, the simulated water levels were slightly lower than the measured water levels. Overall, however, the simulated water levels matched measured water levels as shown by contours of both simulated and measured water levels (fig. 20). The contours of measured water levels are from figure 9.

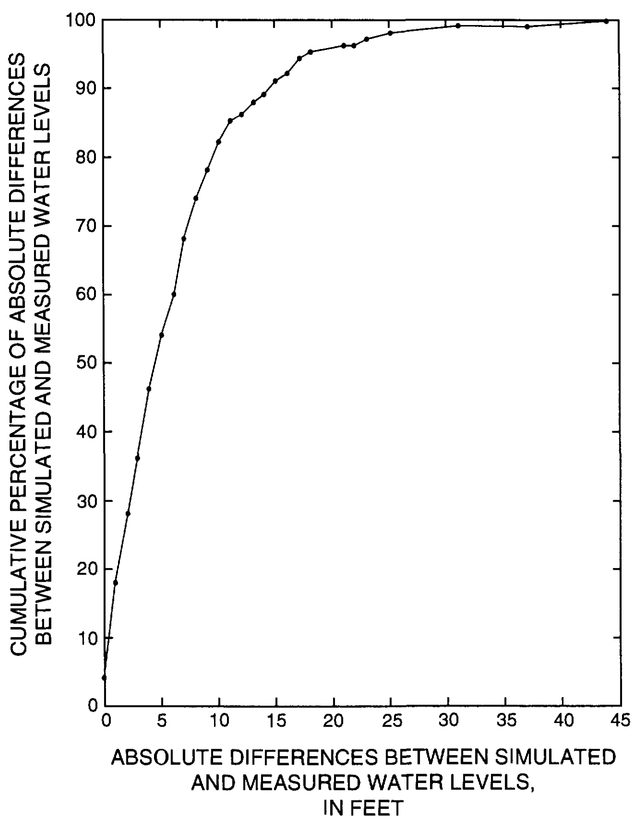


FIGURE 19.—Cumulative percentage of absolute differences between simulated and measured water levels for best-fit steady-state simulation, Paradise Valley, Humboldt County, Nevada.

The distribution of horizontal hydraulic conductivity from the best-fit steady-state simulation for model layer one is shown in figure 21. Where layers two and three are present, distribution of hydraulic conductivities were the same but the values of vertical and horizontal hydraulic conductivities were decreased to account for compaction by overburden, as discussed in the section "Initial Conditions and Hydraulic Properties." The average horizontal hydraulic conductivity for layer one was 2×10^{-4} ft/s (17 ft/d) and is about two times less than the average estimated from specific-capacity data. Most of the wells used to estimate hydraulic conductivity are perforated next to the coarser grained deposits. If only the thickness of the coarser grained deposits had been used in the model computations instead of the total thickness, the average model calibrated hydraulic conductivity would be about the same as the average estimated from specific-capacity and pumping-test data.

The general distribution of hydraulic conductivities for layer one is similar to that estimated from specific-capacity data (compare figs. 11 and 21). The highest computed hydraulic conductivities are along the Humboldt River and in the central part of Paradise Valley. These values are associated with well-sorted stream deposits. The lowest computed hydraulic conductivities are along the northern and western sides of Paradise Valley. The lower hydraulic conductivities along the western side of the valley are attributed to the weathering of granitic and metamorphic rocks eroded from the mountains to the west into silts and clays (Harrill and Moore, 1970, p. 24). Saturated thickness of layer one also is shown in figure 21; it is based on the difference between the simulated water level and the bottom altitude of layer one. The saturated thickness is greater than 500 ft throughout much of the valley. Only along the margins adjacent to the mountain ranges is the saturated thickness less than 250 ft.

Transmissivities in layer two, shown in figure 22*A*, generally reflect the distribution of hydraulic conductivity in layer one. Transmissivities in layer two range from 6×10^{-5} to 8.6×10^{-2} ft^2/s (5 to 7,500 ft^2/d). The lowest values are along the margins of

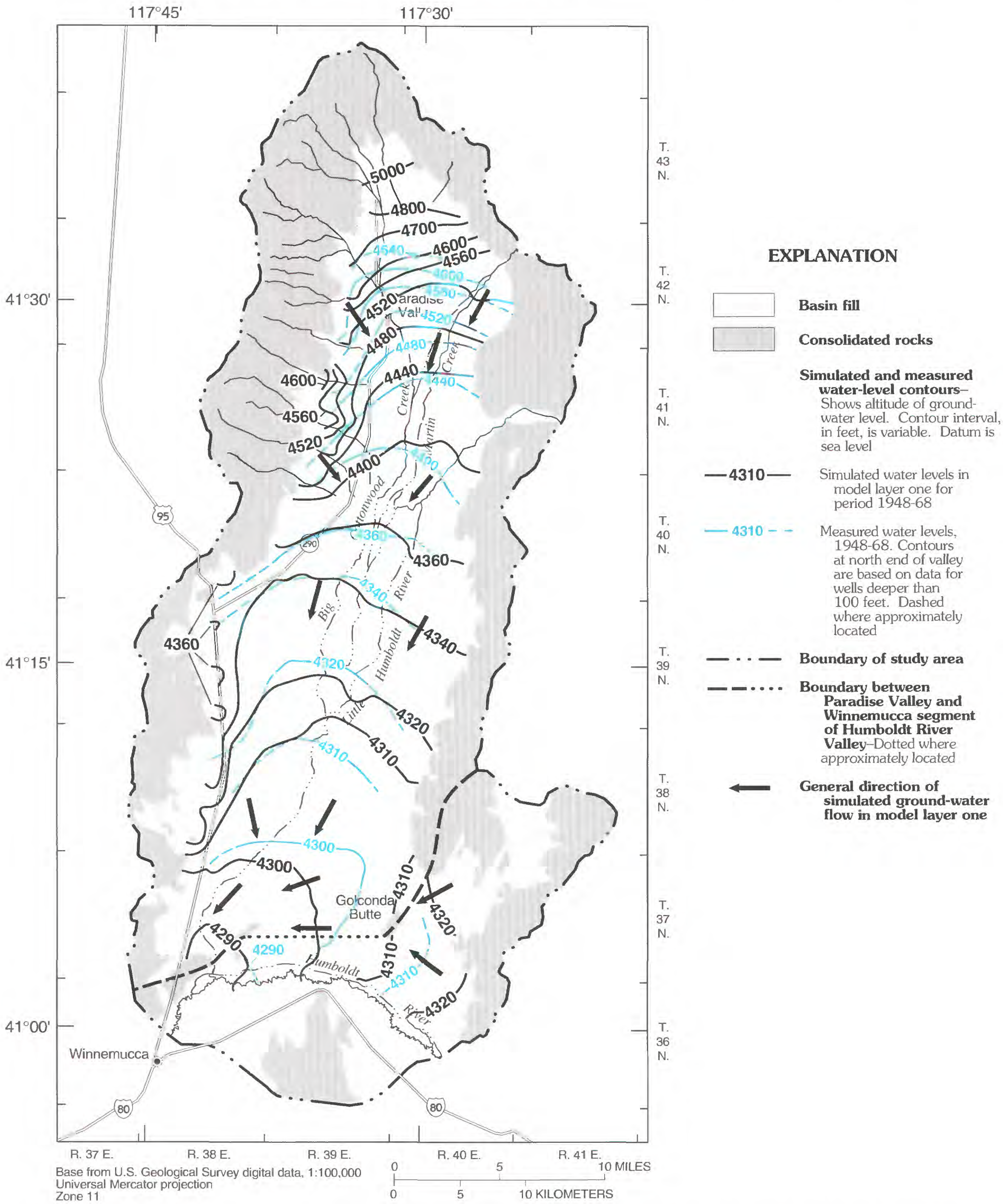


FIGURE 20.—Simulated and measured ground-water levels in upper 600 feet of basin fill for period 1948–68, Paradise Valley, Humboldt County, Nevada.

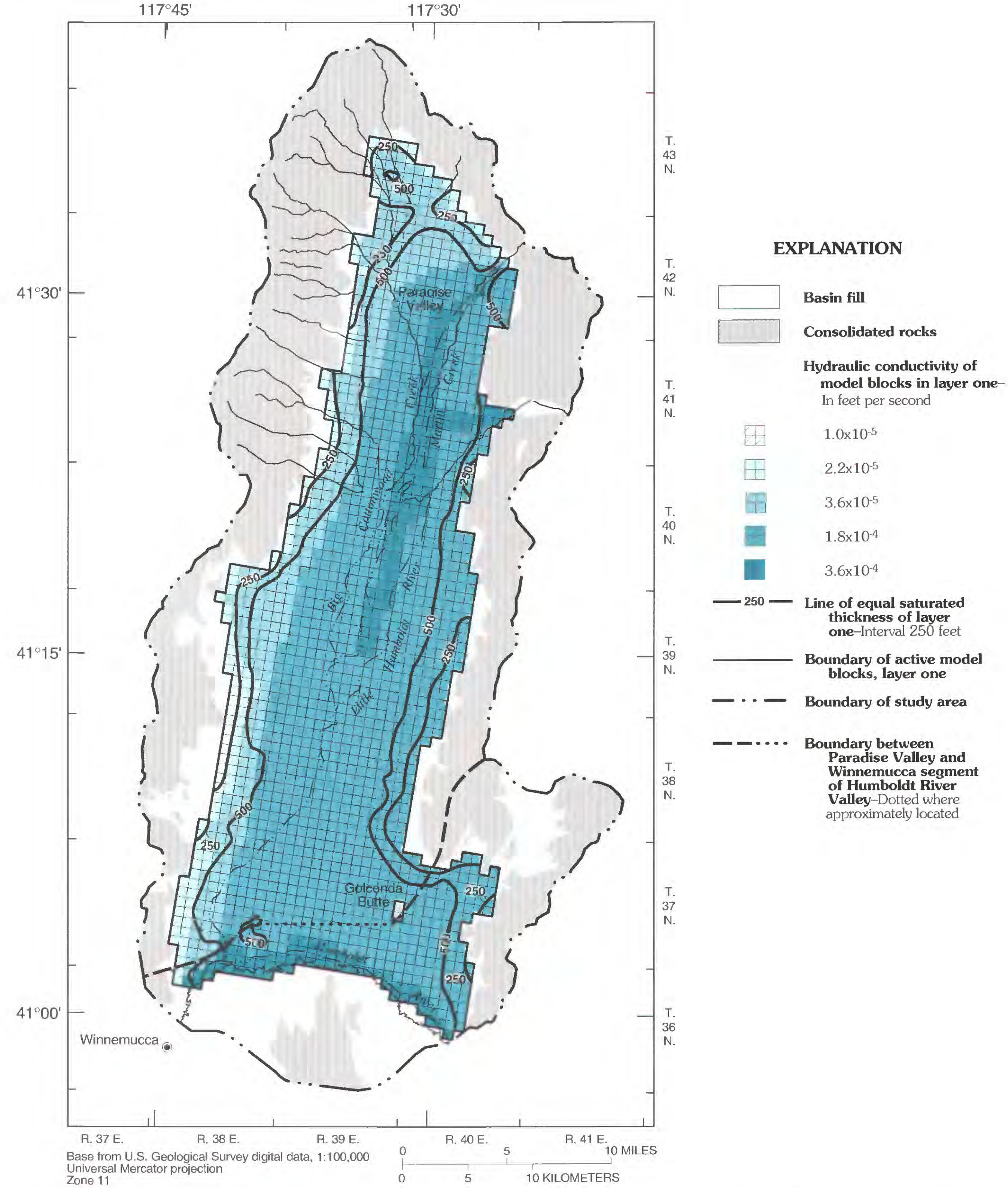


FIGURE 21.—Distribution of layer-one hydraulic conductivity and saturated thickness used in best-fit model simulations, Paradise Valley, Humboldt County, Nevada.

the valley and correspond to areas of lower hydraulic conductivity and areas where the thickness of layer two is less than 600 ft. Transmissivities in layer three, shown in figure 22*B*, are similar to those in layer two except in the center of the valley, where values range from 1×10^{-1} to 6×10^{-1} ft^2/s (8,640 to 50,000 ft^2/d). These high transmissivities are the result of including the entire thickness of basin fill below a depth of 1,200 ft in layer three and do not necessarily indicate a highly permeable zone.

The average vertical hydraulic conductivity is 3×10^{-6} ft/s (0.3 ft/d) between layers one and two and is 5×10^{-7} ft/s (0.04 ft/d) between layers two and three. Vertical hydraulic conductivity is incorporated in the model as a leakance term. Leakance is defined for the model of Paradise Valley as the vertical hydraulic conductivity divided by the distance between midpoints of blocks in adjacent layers. The distribution of leakance between layers one and two is shown in figure 23*A*. Values range from 9×10^{-10} to 3×10^{-8} per second. Highest leakances are simulated in the north-central part of Paradise Valley, along the southeastern margin of the valley (adjacent to the southwestern flank of the Hot Springs Range), and along the Humboldt River. The distribution of leakance between layers two and three is shown in figure 23*B*. Values range from 1×10^{-10} to 2×10^{-8} per second. Generally, leakance values are less between layers two and three than between layers one and two, for two reasons: a slightly lower vertical hydraulic conductivity, and a greater distance between the midpoints of blocks.

In the model simulations, the areal distribution of evapotranspiration was not specified as a boundary, except that discharge was simulated in areas where the calculated water level in layer one was less than 20 ft below land surface. The distribution of evapotranspiration from the best-fit steady-state simulation is shown in figure 24. The distribution approximates zones of phreatophytes mapped by Harrill and Moore (1970, pl. 1) in Paradise Valley and by Cohen (1964, fig. 6) in Humboldt River Valley. The distribution also corresponds to the more densely vegetated areas as determined from Landsat imagery in the early 1980's (J. LaRue Smith, U.S. Geological Survey, written commun., 1984).

Simulated Ground-Water Flow

Results of the best-fit simulation show that water-level altitudes in model layers two and three are generally lower than water levels in layer one in the northern end of Paradise Valley (fig. 25), where layer one receives much of its recharge. This trend indicates downward flow from layer one to layers two and three in an area where water-level differences between shallow and deeper wells also suggest downward flow. Water-level altitudes in layers two and three are generally higher than those in layer one near the southern end of the valley and along the western half of the Humboldt River, where any remaining flow in the model simulations must discharge. Water levels in layer two are lower than layer one where the Humboldt River enters the study area near Golconda, indicating downward leakage in this area.

Most of the ground-water flow in the best-fit steady-state simulation was in model layer one, which corresponds to the upper 600 ft of basin-fill deposits. Generally, recharge to this layer was from stream leakage in the valley lowlands, and discharge was by evapotranspiration near the streams. Only about 700 acre-ft/yr, or about 1 percent of the quantity recharged to the basin-fill aquifer, was simulated as flow in model layers two and three, which represents flow in deposits deeper than 600 ft.

A total of about 74,000 acre-ft/yr was simulated as recharge into the basin-fill aquifer in Paradise Valley, and another 20,000 acre-ft/yr was simulated in Humboldt River Valley north of the river (table 7). Of the recharge in Paradise Valley, about 72,000 acre-ft/yr was simulated as either streamflow entering the model area or as constant recharge along the edge of the model and is based on the long-term (1923–82) estimate of streamflows into the valley. About 800 acre-ft/yr of ground water was simulated as discharging into streams in the upper part of the valley, which was recharged back into the basin-fill aquifer farther down valley. In the steady-state simulations, all streamflow in Paradise Valley was assumed to recharge the basin-fill aquifer, even though some surface water has discharged to Humboldt River since 1953. Most of this flow was the result of a channel being dredged through the sand dunes to drain Gumboot Lake. Prior to 1953, the sand dunes were not dredged and rarely was streamflow from Paradise Valley discharged to Humboldt River. Thus, the steady-state simulation represents a time period when Gumboot Lake was not drained by dredging a channel. However, discharge of streamflows from Paradise Valley was simulated in the transient simulations, as discussed in the following section.

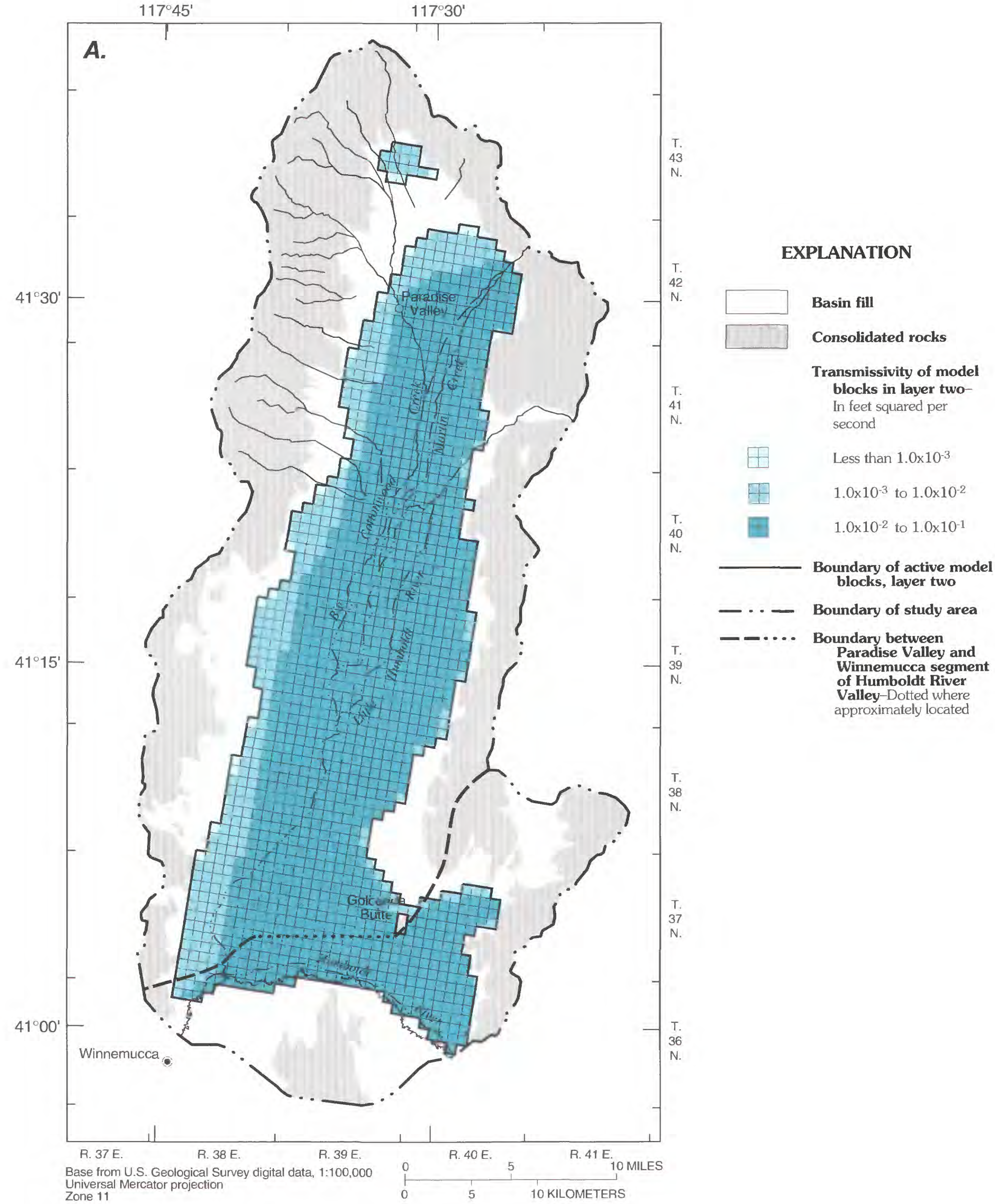


FIGURE 22.—Distribution of (*A*) layer two and (*B*) layer three transmissivities used in best-fit model simulations of Paradise Valley, Humboldt County, Nevada.

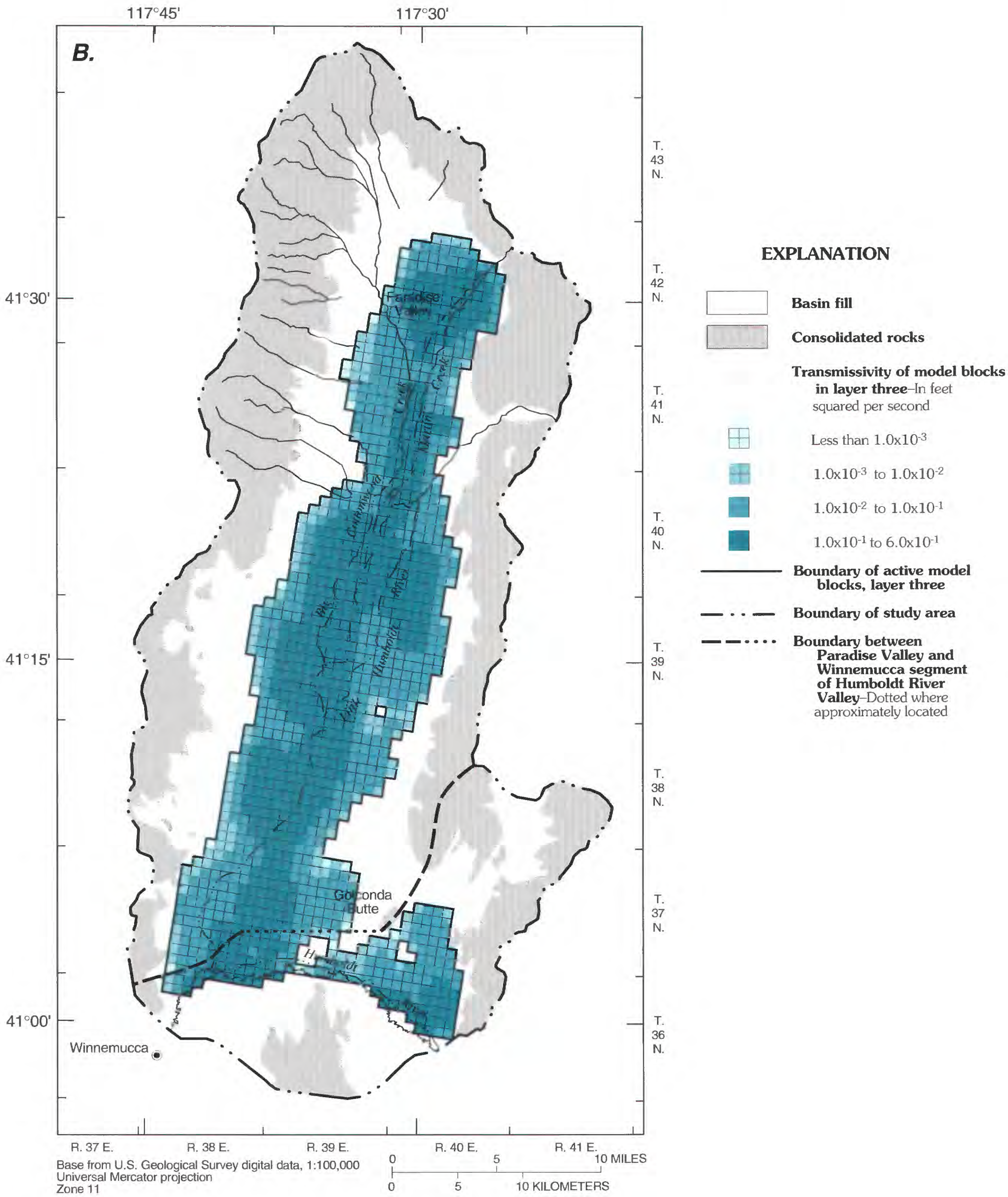


FIGURE 22.—Continued.

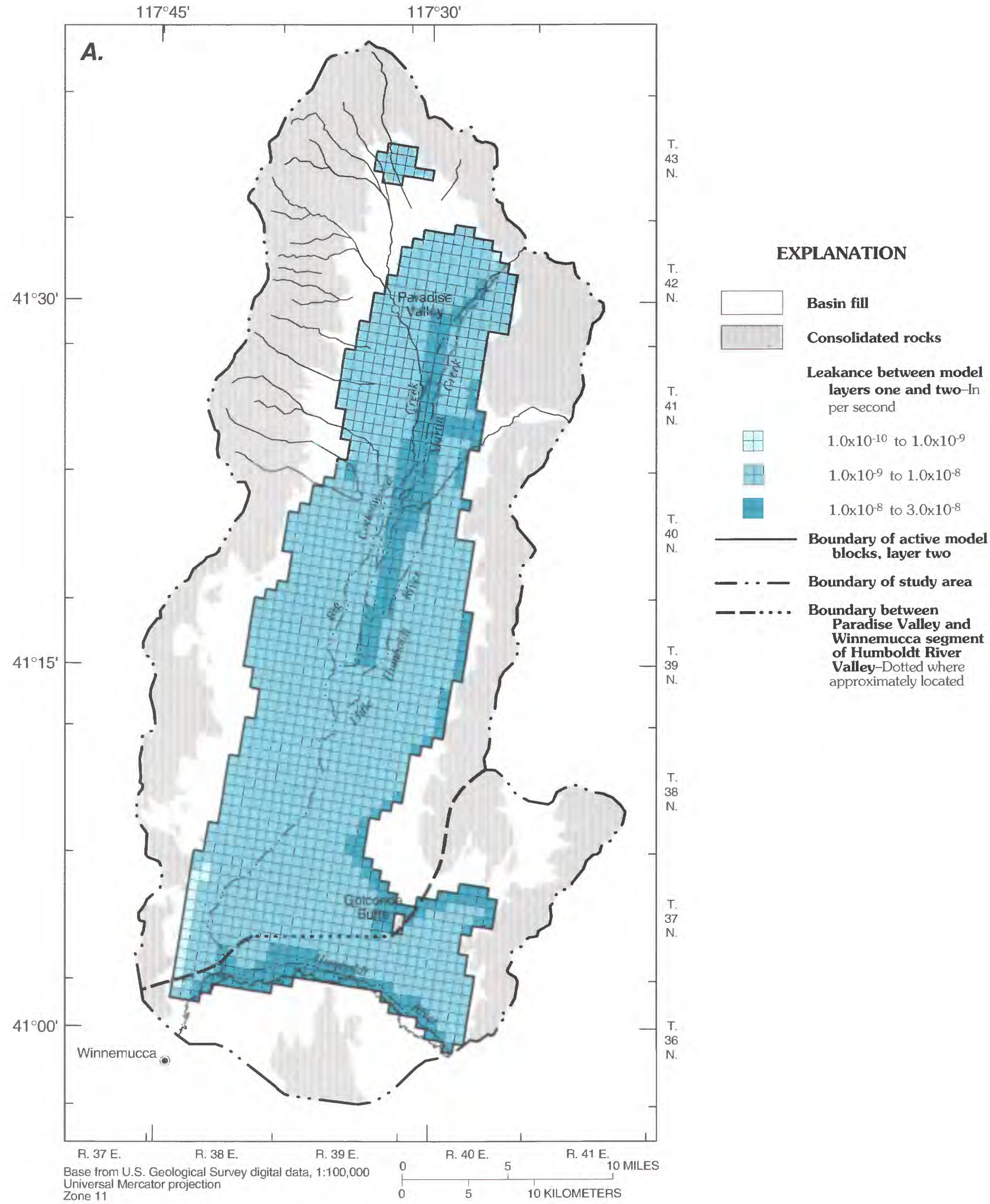


FIGURE 23.—Distribution of leakance between (*A*) layers one and two and (*B*) layers two and three used in best-fit model simulations, Paradise Valley, Humboldt County, Nevada.

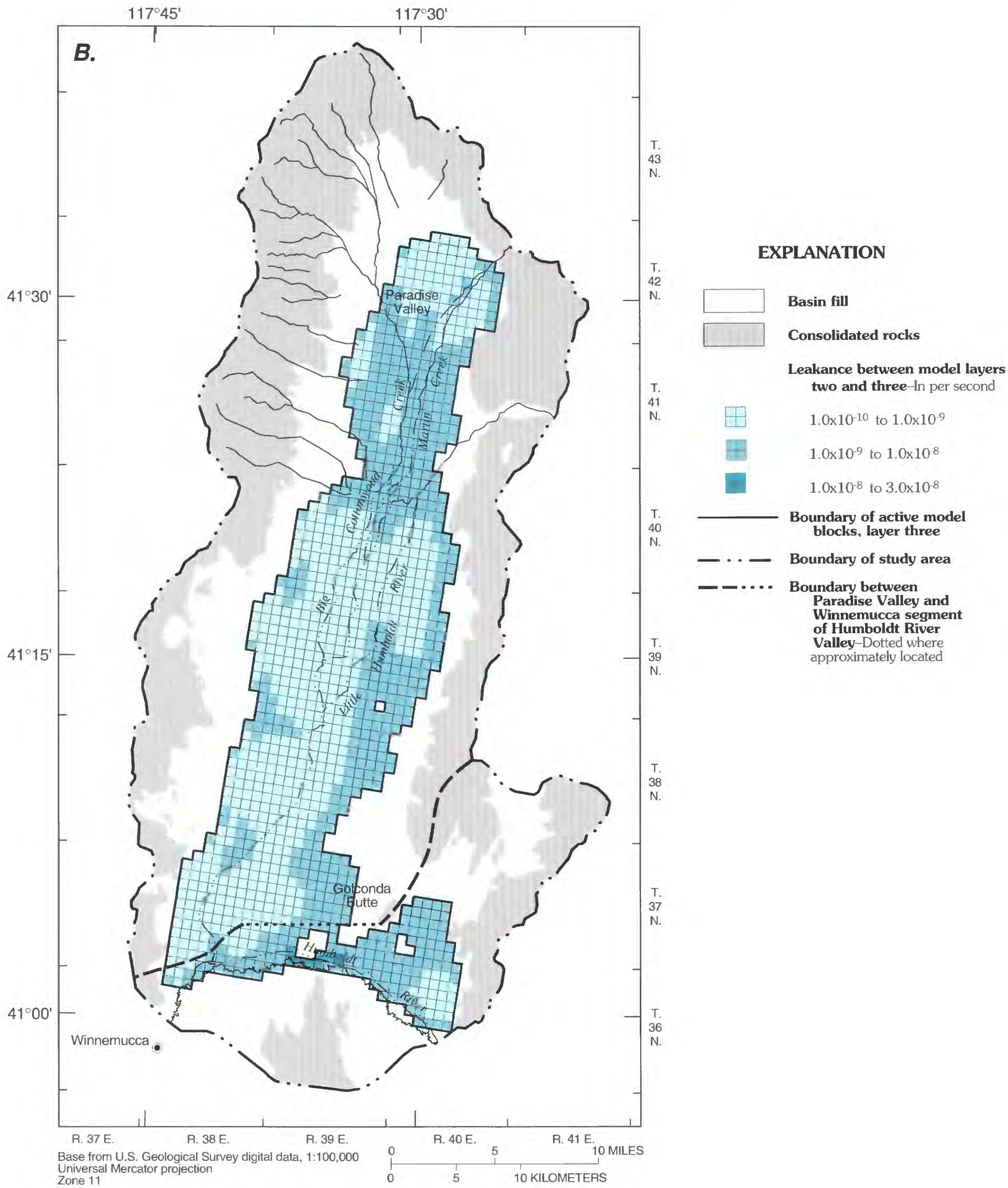


FIGURE 23.—Continued.

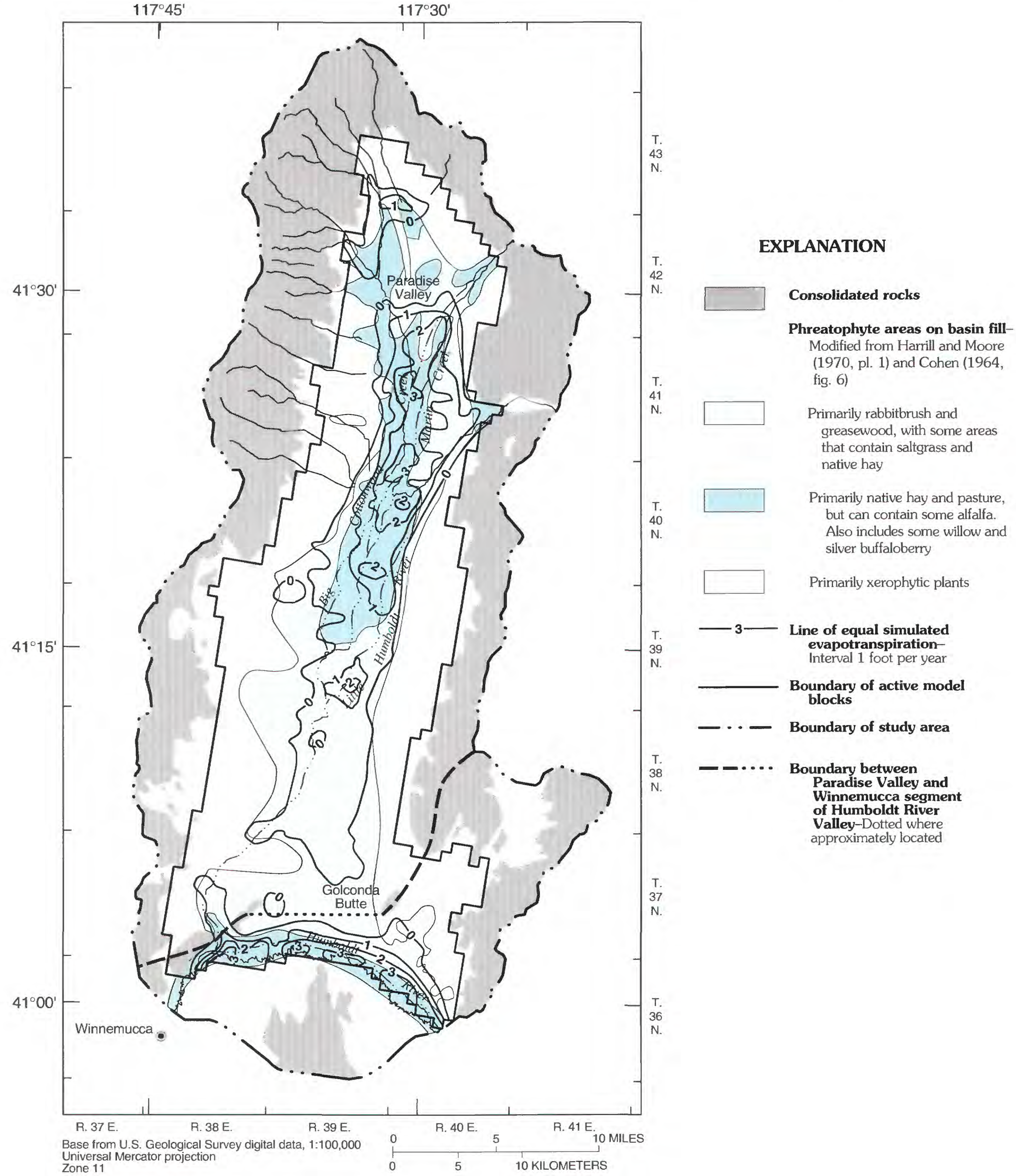


FIGURE 24.—Simulated evapotranspiration rates and mapped phreatophyte areas, Paradise Valley, Humboldt County, Nevada.

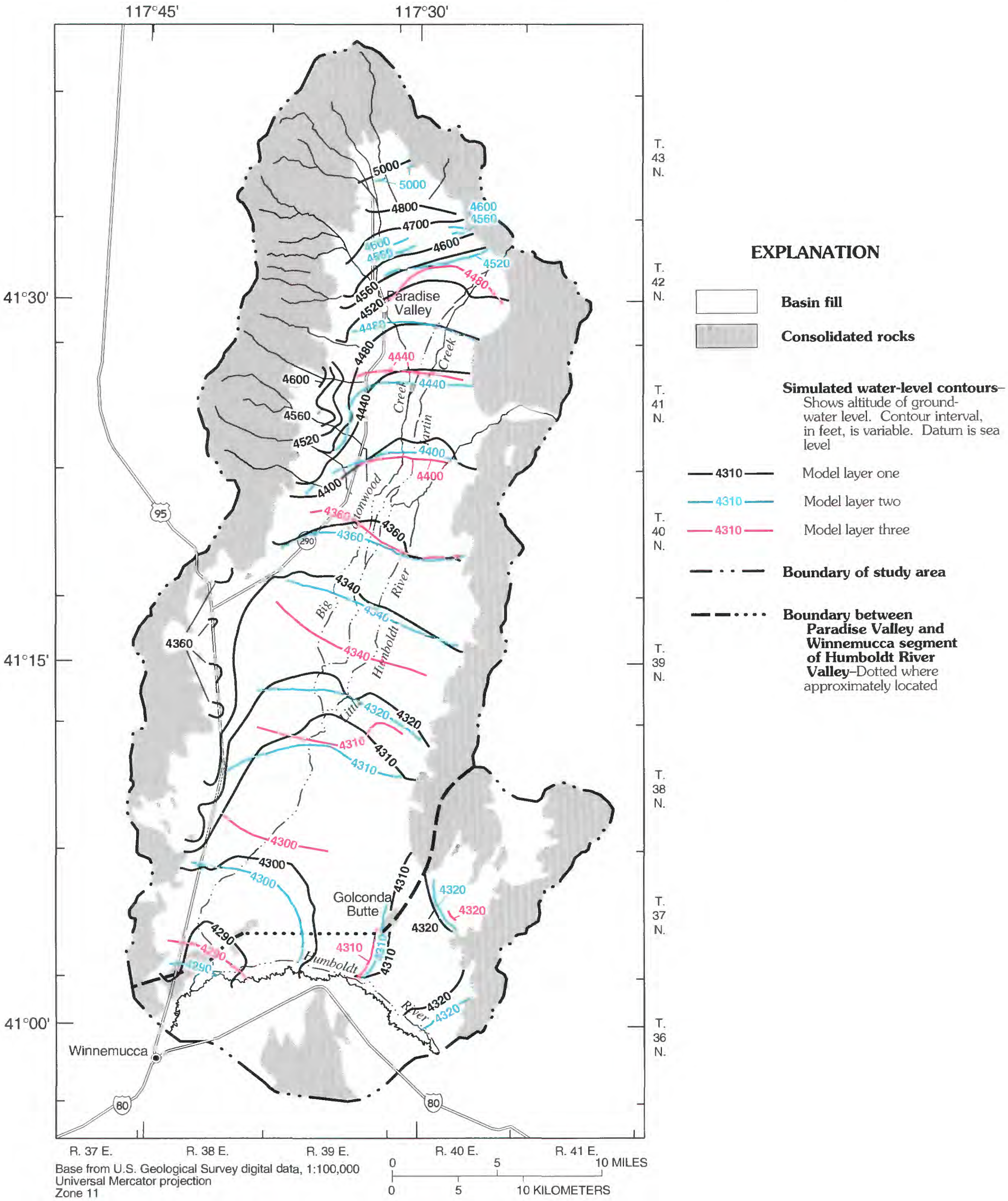


FIGURE 25.—Water levels in model layers one, two, and three for best-fit steady-state simulation, Paradise Valley, Humboldt County, Nevada.

TABLE 7.—*Average annual ground-water recharge and discharge for basin-fill aquifer in Paradise Valley, Humboldt County, Nevada, and adjacent segment of Humboldt River Valley prior to large quantities of pumpage for best-fit steady-state simulation*[1]

[Acre-feet per year reported to two significant figures]

Water-budget component		Estimated quantity
RECHARGE		
Paradise Valley		
Recharge near contact between basin fill and consolidated rocks[2]		7,200
Leakage from streams in Paradise Valley[3]		65,000
Underflow from Humboldt River Valley		1,300
	Total	74,000
Humboldt River Valley		
Recharge from Osgood Mountains near contact between basin fill and consolidated rocks[2]		1,000
Leakage from Humboldt River		17,000
Underflow from Paradise Valley		1,800
	Total	20,000
Paradise and Humboldt River Valleys		
Combined total recharge		94,000
DISCHARGE		
Paradise Valley		
Evapotranspiration[4]		71,000
Leakage to streams		800
Underflow to Humboldt River Valley		1,800
	Total	74,000
Humboldt River Valley		
Evapotranspiration		18,000
Underflow to Paradise Valley		1,300
	Total	19,000
Paradise and Humboldt River Valleys		
Combined total discharge		93,000

[1] Model-computed differences between combined total recharge and discharge was 600 acre-feet per year, or less than 1 percent.

[2] Includes leakage from streams where estimated annual flow is less than 1,200 acre-feet per year.

[3] Harrill and Moore (1970, p. 65) estimate that, for average conditions, about half of streamflow entering Paradise Valley is lost to evapotranspiration prior to reaching aquifer. Much of this loss, however, is in an area of evapotranspiration of ground water. Because amount of streamflow evapotranspiration was unknown for different periods of varying streamflows (but streamflows into and out of valley were known), stream leakage into basin-fill aquifer was assumed equal to inflow less outflow. Thus, evapotranspiration calculated in all model simulations includes evapotranspiration of both ground water and surface water.

[4] Includes evapotranspiration of streamflow, as explained in footnote 3.

The steady-state simulation also assumes that none of the streamflow entering the study area is lost directly to evapotranspiration. A previous study estimated that about half of the average annual streamflow entering Paradise Valley was lost to evapotranspiration prior to actually recharging the basin-fill aquifer (Harrill and Moore, 1970, p. 65), but that much of this evapotranspiration was in the same area as evapotranspiration of ground water. Because the quantity of evapotranspiration directly from streams is in the same general area as evapotranspiration from ground water and because the quantity of evapotranspiration directly from streams is unknown for different periods of time, stream leakage into the basin-fill aquifer included direct evapotranspiration of streamflow. Similarly, recharge from stream leakage along the Humboldt River in the steady-state simulation was calibrated to approximate the average river loss between Golconda and Winnemucca, Nev. (fig. 2), and includes direct evapotranspiration of streamflow.

Ground-water flow from Paradise Valley into Humboldt River Valley was simulated at 1,800 acre-ft/yr (table 7). This underflow was near the southwestern corner of the study area near where Little Humboldt River enters Humboldt River Valley (fig. 25). In addition, about 1,300 acre-ft/yr was simulated as underflow from Humboldt River Valley into Paradise Valley in the vicinity of Golconda Butte (fig. 25). This underflow continued in a northwesterly direction in the model simulations until reaching the center of Paradise Valley, where the predominant direction changed to the southwest. Thus, much of the water that was simulated as underflow from Paradise Valley into Humboldt River Valley may be ground water entering Paradise Valley as underflow from Humboldt River Valley.

Underflow from Paradise Valley to Humboldt River Valley computed in the steady-state simulation is about half that estimated by Loeltz and others (1949, p. 42) and Cohen and others (1965, p. 77). Their estimates are based on measured inflow along the Humboldt River between Golconda and Winnemucca during low-flow periods and might include ground-water flow moving parallel with the river or water from bank storage that entered the flood-plain deposits next to the river during periods of high streamflows.

EFFECTS OF DEVELOPMENT, 1948 THROUGH 1982

Flow in the basin-fill aquifer was simulated for the period 1948–82 to determine the effects of increased ground-water withdrawals and natural variations in streamflow; this period was simulated because pumpage increased from about 200 acre-ft/yr in 1948 to about 47,000 acre-ft/yr in 1981. (An additional 3,700 acre-ft was pumped in the adjacent segment of Humboldt River Valley during 1981.)

Since the early 1970's, the direction of ground-water flow has been altered because of increased pumpage in the southern end of Paradise Valley and the eastern part of Humboldt River Valley. As of 1982, this increased pumpage produced water-level declines of more than 80 ft (fig. 26), causing ground water to move toward the areas of greatest decline. The measured response to increased pumpage in the study area provided the basis for evaluation of yield in the basin-fill aquifer between 1948 and 1982 and for evaluation of results from the simulation of selected development scenarios. The interval 1948–82 was divided into three separate periods: 1948–68, 1969–78, and 1979–82.

Selection of Stress Periods for Simulation

Although changes in ground-water levels in Paradise Valley between 1948 and 1968 were less than 5 ft and the period was assumed steady state during the initial model simulations, transient simulations were made also for the period because pumpage increased from only 200 acre-ft/yr in 1948 to about 13,000 acre-ft/yr in 1968 (fig. 13). In addition, some years between 1948 and 1968 had distinctly more runoff and others considerably less (see fig. 7). Therefore, the purpose of the transient simulation from 1948 to 1968 was to determine if the basin-fill aquifer was in equilibrium (no net change in ground-water storage) and how the increased pumpage affected flow into and out of the basin-fill aquifer.

The 21-year period 1948–68 was divided into four stress periods, 1948–53, 1954–58, 1959–65, and 1966–68, to approximate variations in pumpage and streamflows (table 8). Each stress period was divided into equal time steps of 1-year duration. Thus, the first stress period (1948–53) has six time steps; the second (1954–58) has five; the third (1959–65) has seven; and the last (1966–68) has three. In another simulation, the number of time steps was increased to 10 for each of the first three stress periods and to 6 for the fourth period. Model results were the same for both simulations, indicating that the simulation with fewer time steps was adequate. Estimates of pumpage and streamflows were averaged over each stress period, as was recharge near the contact between basin fill and consolidated rocks. Streamflows from ungaged streams and recharge near the contact between basin fill and consolidated rocks were estimated by multiplying the values used in the steady-state simulations with the ratio of average streamflow of Martin Creek for the stress period to the average streamflow for the period 1923–82.

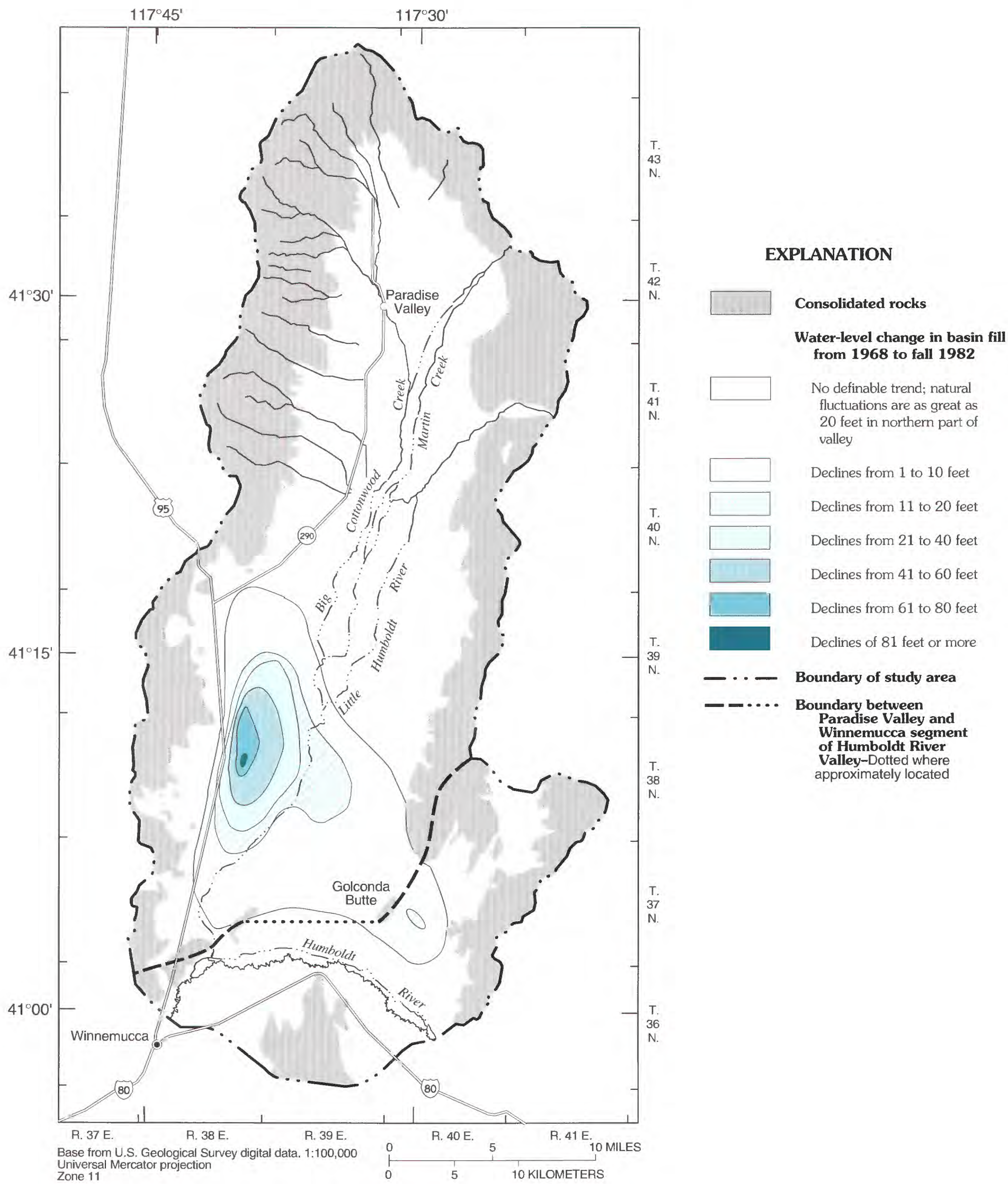


FIGURE 26.—Ground-water level declines between 1968 and fall 1982, Paradise Valley, Humboldt County, Nevada.

TABLE 8.—*Estimates of net ground-water pumpage in both Paradise Valley and adjacent segment of Humboldt River Valley, Humboldt County, Nevada, streamflow of gaged streams, and percentage of long-term mean flow at Martin Creek for selected model-stress periods, 1948–78*

[Abbreviation: ft^3/s, cubic feet per second]

Stress period (calendar year)	Net ground-water pumpage (ft^3/s)	Average streamflow of gaged streams: Humboldt River (ft^3/s)	Little Humboldt River (ft^3/s)	Martin Creek: Cubic feet per second	Martin Creek: Percentage of long-term average annual streamflow[1]
1948-53	0.7	307	30.9	39.2	122
1954-58	3.1	208	25.5	34.1	107
1959-65	5.6	229	18.3	27.2	85
1966-68	8.5	159	12.9	23.5	73
1969	3.7	549	71.3	65.6	205
1970	5.9	336	28.6	42.1	132
1971	7.5	701	37.8	48.8	153
1972	16.0	314	35.7	40.0	125
1973	21.9	440	27.2	30.0	94
1974	34.3	275	25.8	37.5	117
1975	37.0	737	24.3	46.9	147
1976	41.6	189	18.0	23.4	73
1977	45.6	73	8.8	13.7	43
1978	52.6	261	30.7	45.9	143

[1] Values used to estimate streamflow at ungaged streams and recharge near contact between basin fill and consolidated rocks. Average annual flow of Martin Creek for period 1923–82, 32 ft^3/s.

The purpose of the second transient simulation period, 1969–78, was to determine the effects of increased pumpage on ground-water flow in the valley. The 10-year period was divided into 10 stress periods of 1-year duration. Each stress period was divided into two time steps. The first time step for each period was 146 days and the second was 219 days. Doubling the number of time steps for each stress period did not change the model results. Pumpage and streamflows into the valley for gaged streams were averaged for each stress period (table 8). Streamflows of ungaged streams and recharge near the contact between basin fill and consolidated rocks were estimated in the same manner as in the first transient simulation.

The purpose of the third transient simulation period, 1979–82, was to determine the effects of cyclic runoff and pumpage on ground-water flow during each of 4 years. Most of the streamflow enters the valley from January through June (see fig. 6), whereas pumpage and evapotranspiration dominate from April through September. Thus, to simulate the cyclic changes in recharge and discharge in Paradise Valley, the 4-year simulation period was divided into 16 stress periods of 3-month duration: January–March, April–June, July–September, and October–December. Each 3-month stress period was divided into two time steps. The first was 36.5 days and the second was 54.8 days. Doubling the number of time steps for each stress period resulted in a slight increase or decrease in water levels at the end of the simulation (generally less than 0.2 ft) and a slight increase in the total volumes of water entering and leaving storage. (Volumes increased by about 3 percent.) This in turn resulted in an increase in total inflow and outflow of about 1 percent during the simulation, which is well within the uncertainties of the model results and estimated volumes.

Pumpage and evapotranspiration were simulated during only the two stress periods that included the period from April through September of each year. Streamflows into the modeled area for the Humboldt and Little Humboldt Rivers and Martin Creek were averaged over each 3-month period. Streamflows of ungaged streams, including streams that were simulated as constant recharge near the contact between basin fill and consolidated rocks were estimated by first multiplying the average annual streamflows and recharge values used in the steady-state model by the percent of average annual streamflow that occurred during each 3-month interval at Martin Creek for the period of record. These 3-month average values were then adjusted for each 3-month stress period from 1979 through 1982 by multiplying them by the ratio of the average streamflow at Martin Creek for each 3-month stress period to the long-term average streamflow for the corresponding 3-month period. Estimated net ground-water pumpage, average streamflows at Humboldt and Little Humboldt Rivers and Martin Creek, and percentage of long-term average streamflow at Martin Creek are shown in table 9.

Calibration of Transient Simulations

The same hydraulic properties of the basin-fill aquifer that were determined from the best-fit steady-state simulation were used in the transient simulations for 1948–82. Storage values for each model block were needed in the transient simulations because ground-water levels can change as a result of changing the quantity and distribution of recharge, discharge, or both. Estimates of specific yield were used in layer one and storage coefficients were used in layers two and three as explained in the section "Initial Conditions and Hydraulic Properties." Water-levels generated from the steady-state model were used as starting water levels in the first transient simulations from 1948 through 1968. Water levels generated at the end of the simulation from 1948 through 1968 were used as starting water levels in the transient simulation from 1969 through 1978, and water levels generated at the end of the simulation from 1969 through 1978 were used as starting water levels in the transient simulation from 1979 through 1982.

Calibration of the transient simulations was done primarily by adjusting specific yield of model layer one. Minor changes to the vertical and horizontal hydraulic conductivities also were made, in which case a steady-state simulation was repeated with the new values and the computed water levels were used as starting water levels in the transient simulations. The specific-yield estimates were reduced to 90 percent of the original estimates throughout the model in order to duplicate water-level fluctuations, particularly in the most heavily pumped areas. Perhaps the decrease in calibrated specific yield could be a slow drainage of the deposits; however, the 10-percent reduction is not unreasonable considering how specific-yield values were estimated. Alternatively, pumpage could have been increased by 10 percent and the results would have been similar. Either case is possible because the change is within the accuracy of both estimates of specific yield and pumpage.

Conductance values of streambed deposits also were adjusted in the transient simulations so as to approximate the discharge of Little Humboldt River just upstream from where it enters Humboldt River (fig. 2). In particular, conductance values of streambed deposits were increased 1.2 to 2 times for stress periods in which streamflows were well above normal. Increasing the conductance values for stress periods with above-normal streamflows is reasonable in that the width of the streambed increases during high flows, especially when ephemeral Gumboot Lake forms where the sand dunes block the channel of Little Humboldt River. In addition, the version of the computer program used to model streamflows in Paradise Valley did not account for changing head in the streams during a stress period. Although the variation in head is less important than stream width during high flows, a better technique, if data had been available, would have been to compute the head in the stream and allow the conductance value to change as a function of discharge.

Streambed-conductance values were not adjusted during low streamflow periods because the location where streams ceased flowing in the valley was not known precisely for each low-flow stress period and because most streams ceased flowing only a short distance into the valley. Also, streambed-conductance values were not adjusted in transient simulations for stress periods with slightly above normal to slightly below normal streamflow.

Adjusting the streambed conductance values during the transient simulations resulted in large changes in flow to layer one but only small changes in simulated water levels. For example, increasing streambed-conductance values by 2 for stress periods April–June 1980 and April–June 1982 resulted in an increase in stream leakage of 77 ft^3/s in Paradise Valley for the April–June 1980 stress period and an increase of 38 ft^3/s for the April–June stress period in 1982. Yet, the mean difference between simulated and observed water levels in 96 model blocks for the fall of 1982 changed from –0.52 ft to –0.88 ft and the standard deviation changed from 10.5 ft to 10.6 ft. Much of the additional recharge from stream leakage in the simulation was discharged as evapotranspiration.

Outflow of the Little Humboldt River in the transient simulations is similar to outflow estimated for the period 1948–82, as shown in table

TABLE 9.—*Estimates of net ground-water pumpage in both Paradise Valley and adjacent segment of Humboldt River Valley, Humboldt County, Nevada, streamflow of gaged streams, and percentage of long-term mean flow at Martin Creek for 3-month periods during 1979–82*

[Abbreviation: ft^3/s, cubic feet per second]

Stress period		Net ground-water pumpage[1] (ft^3/s)	Average streamflow of gaged streams		Martin Creek	
Year	Month/day		Humboldt River (ft^3/s)	Little Humboldt River (ft^3/s)	Cubic feet per second	Percentage of long-term average streamflow[2]
1979	1/1–3/31	0.1	540	8.5	28	86
	4/1–6/30	108	840	43	66	80
	7/1–9/30	108	87	19	7.0	89
	10/1–12/31	.1	40	7.4	8.4	89
1980	1/1–3/31	.1	510	11	68	209
	4/1–6/30	105	1,300	40	133	159
	7/1–9/30	105	360	12	10	122
	10/1–12/31	.1	86	7.6	11	115
1981	1/1–3/31	.1	160	7.6	14	44
	4/1–6/30	111	110	14	33	40
	7/1–9/30	111	6.4	6.8	4.5	57
	10/1–12/31	.1	.4	7.8	21	221
1982	1/1–3/31	.1	440	11	74	226
	4/1–6/30	107	1,200	37	111	133
	7/1–9/30	107	260	30	11	138
	10/1–12/30	.1	290	8.7	12	129

[1] Annual net pumpage equals sum of four 3-month averages, divided by four.

[2] Values used to estimate streamflow at ungaged streams and recharge near contact between basin fill and consolidated rocks. Average streamflows of Martin Creek for period 1923–82: January–March, 32.7 ft^3/s; April–June, 83.3 ft^3/s; July–September, 7.88 ft^3/s; and October–December, 9.40 ft^3/s.

10; however, considerable differences exist for individual years. Further adjustments of streambed-conductance values during each stress period may result in an even better match but are not justified because estimated outflows were determined from once-a-day readings of a staff gage on the Little Humboldt River and because stage-discharge relations were estimated from only a few streamflow measurements.

Water levels computed from the transient simulations were compared with measured water levels in wells at the end of selected time periods. Water levels at the end of the 1948–68 simulation period were compared with measured water levels for November 1968 (Harrill and Moore, 1970, table 22). A total of 101 model blocks in layer one correspond to wells in which water levels were measured. As in the steady-state simulation, 95 percent of the simulated water levels were within 20 ft of the measured water levels and more than 70 percent were within 10 ft (fig. 27). Also shown in figure 27 are the percentage of the absolute differences between simulated and measured water levels for stress periods ending in 1972, 1975, and 1978. Water levels were actually measured in November and December but were assumed the same as the end of the year. More than 95 percent of water levels computed from the simulations were within 20 ft of the measured water levels at the end of the selected years. The distribution of the absolute differences is slightly different for the end of 1972 when compared with the other distributions in figure 27. However, only 56 water-level measurements were made in wells near the end of 1972, and this small number of measurements may account for the variation. Similar distributions of the absolute differences between simulated and measured water levels are shown in figure 28 for the simulation period 1979–82, which included seasonal variations in streamflow, evapotranspiration, and pumpage.

TABLE 10.—*Estimated and simulated annual streamflow of Little Humboldt River near confluence with Humboldt River, Humboldt County, Nevada, 1948–82*

Simulation period (years)	Period of observed flow (month/day)[1]	Streamflow (acre-feet per year) Estimated	Simulated flow[2]
1948–53[3]	not recorded	25,000	35,000
1954–58[4]	not recorded	33,000	4,500
1959–68	no flow	0	0
1969	4/09–6/13	22,000	39,000
1970	5/25–6/26	3,000	2,000
1971	2/01–6/30	22,000	16,000
1972	3/11–5/05	17,000	7,000
1973	3/14–3/22	50	0
1974	4/08–5/13	2,000	0
1975	6/12–7/03	700	2,500
1976	no flow	0	0
1977	no flow	0	0
1978	5/19–6/30	2,500	0
1979	no flow	0	0
1980	6/01–6/23	1,100	10,000
1981	no flow	0	0
1982	5/15–6/10	1,300	5,700
Total, 1948–82, rounded		130,000	120,000

[1] Estimated volumes of streamflow and period of observed flow are from Roger Johnson (Nevada Division of Water Resources, written commun., 1984).

[2] Model results are sum for each simulation period.

[3] Channel excavated in sand dunes in spring 1953 (Harrill and Moore, 1970, p. 81).

[4] Channel excavated in sand dunes in June and July 1958 (Harrill and Moore, 1970, p. 81).

The absolute differences between simulated and measured water levels were determined for the spring and fall of each year.

AQUIFER RESPONSE

Water levels in most parts of Paradise Valley changed little in the transient simulation from 1948 through 1968. Generally, the changes were less than 5 ft in the central part of the valley, although water levels rose more than 10 ft at the extreme northern end of the valley. The cumulative quantity of water entering storage from 1948 to 1968 equaled the cumulative quantity leaving storage. Water entering storage averaged about 5,000 acre-ft/yr (table 11), which is less than 10 percent of the total simulated inflow. Thus, during the period 1948–68, the valley can be considered in a state of dynamic equilibrium because water levels changed little and because the quantity of water entering or leaving storage was a small component of the ground-water budget.

Total inflow into the basin-fill aquifer was nearly the same as in the steady-state simulation and averaged 74,000 acre-ft/yr (table 11) for Paradise Valley. However, discharge from the transient model included pumpage, which averaged 3,000 acre-ft/yr over the simulation period. This reduced the quantity of evapotranspiration computed by the steady-state simulation, which did not include pumpage, from 71,000 to 68,000 acre-ft/yr (compare tables 7 and 11).

The transient simulation for 1969–82 was during a period when streamflows were generally above normal (fig. 7) and pumpage for irrigation increased dramatically. Simulated water levels generally replicated measured water levels for the spring of 1982 after a total transient simulation period of 35 years, as shown by water-level contours of simulated and measured water levels in figure 29. Hydrographs of 16 selected wells, which were distributed throughout the valley, are shown in figure 30. Locations of the selected wells are shown in figure 29. Water levels simulated for the spring of 1982 closely matched measured water levels in the central part of the valley (fig. 29), including seasonal fluctuations in the areas of major pumpage (fig. 30; major pumping areas are shown in fig. 15). However, simulated water levels near the northern end of the valley did not match the measured water levels as closely. Some of the difference between simulated and measured water levels in the northern end of Paradise Valley may be caused by uncertainty in the altitudes of wells in that part of the valley. Land-surface altitudes of many wells in the northern part of the valley are not known within 20 ft, and because altitudes of water levels are obtained by subtracting depth to water from land-surface altitudes, the uncertainty in measured water levels is also 20 ft.

The difference also could be caused by differences in location of the screened interval of a well with respect to the model node, which is located at the center of a model block. Because the model simulates an average water level for a block at the node, any difference between location of the node and the screened interval of a well could result in differences between simulated and measured water levels, particularly where large vertical and horizontal gradients exist. Both horizontal and vertical gradients are larger in the northern end of Paradise Valley than elsewhere in the modeled area.

The general direction of ground-water flow in Paradise Valley prior to development was southward toward the Humboldt River. Ground-water flow in the adjacent segment of Humboldt River Valley was generally parallel to the river and moving westward. Most of the ground-water recharge in Paradise Valley was discharged by evapotranspiration along the center of the valley, and little ground water from Paradise Valley actually flowed into Humboldt River Valley. Since 1968, the result of increased pumpage in Paradise Valley and in the adjacent segment of Humboldt River Valley, particularly near the southern end of the study area, has been to alter the direction of ground-water flow. As of 1982, pumpage has produced a water-table depression near the southwestern part of Paradise Valley and a smaller depression east of Golconda Butte (located in Humboldt River Valley), causing water to move toward the depressions. Results of model simulations indicate pumpage in Paradise Valley reduced evapotranspiration (table 11). In addition, pumpage near Golconda Butte resulted in a decrease in the quantity of ground-water flow entering Paradise Valley from Humboldt

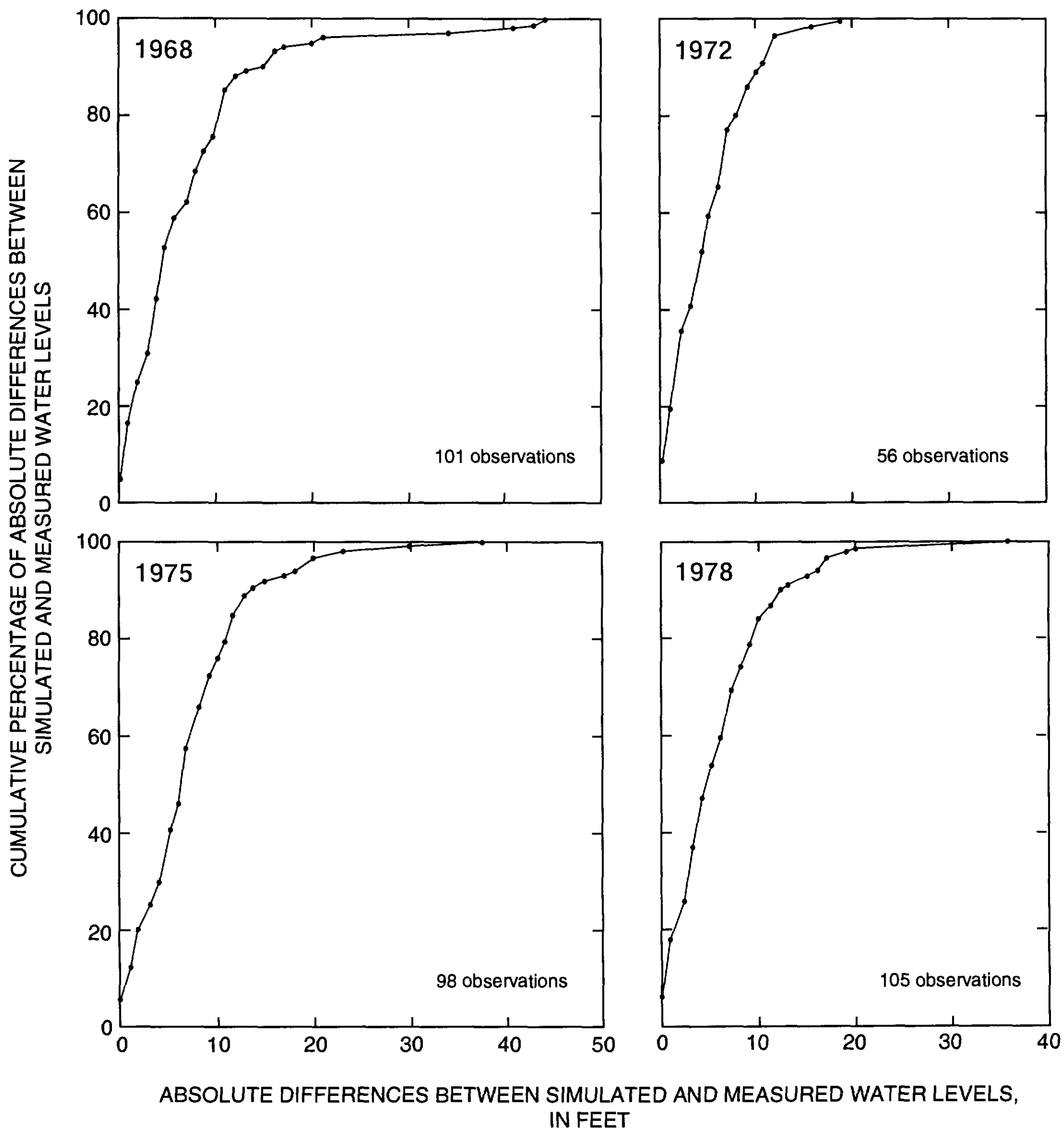


FIGURE 27.—Cumulative percentage of absolute differences between simulated and measured water levels for fall seasons of 1968, 1972, 1975, and 1978, Paradise Valley, Humboldt County, Nevada.

River Valley. Prior to pumpage in the southern end of the study area, about 1,300 acre-ft/yr was simulated as moving from Humboldt River Valley into Paradise Valley near Golconda Butte, whereas in 1982, flow had decreased to 700 acre-ft/yr. In addition, about 120 acre-ft/yr was simulated as moving from Paradise Valley near Golconda Butte southward into Humboldt River Valley as result of pumping east of Golconda Butte.

Discharge from the basin-fill aquifer in Paradise Valley increased dramatically between 1968 and 1982. The discharge increased from an average of 74,000 acre-ft/yr between 1948 and 1968 to 91,000 acre-ft/yr in 1982. Most of this increase was from pumpage (table 11). The cumulative changes in total discharge, net pumpage, and evapotranspiration from 1969 to 1982 are shown in figure 31A. The quantity of evapotranspiration that was simulated for each year decreased from a high of 79,000 acre-ft/yr in 1971 to a low of 43,000 acre-ft/yr in 1981 (table 11).

Recharge varied considerably during the period 1968–82 and in general was above average for the period, as shown in figure 31*B*. During this period, an additional 120,000 acre-ft of water was added to the basin-fill aquifer in Paradise Valley. The increased recharge during this period was caused by above-average streamflow entering Paradise Valley, as shown by flow at Martin Creek (fig. 7). Annual recharge ranged from 134,000 acre-ft in 1969 (table 11) to only 31,000 acre-ft in 1977 (not listed).

The quantity of ground water in storage increased about 75,000 acre-ft from 1969 through 1972 as a result of above-average recharge to the

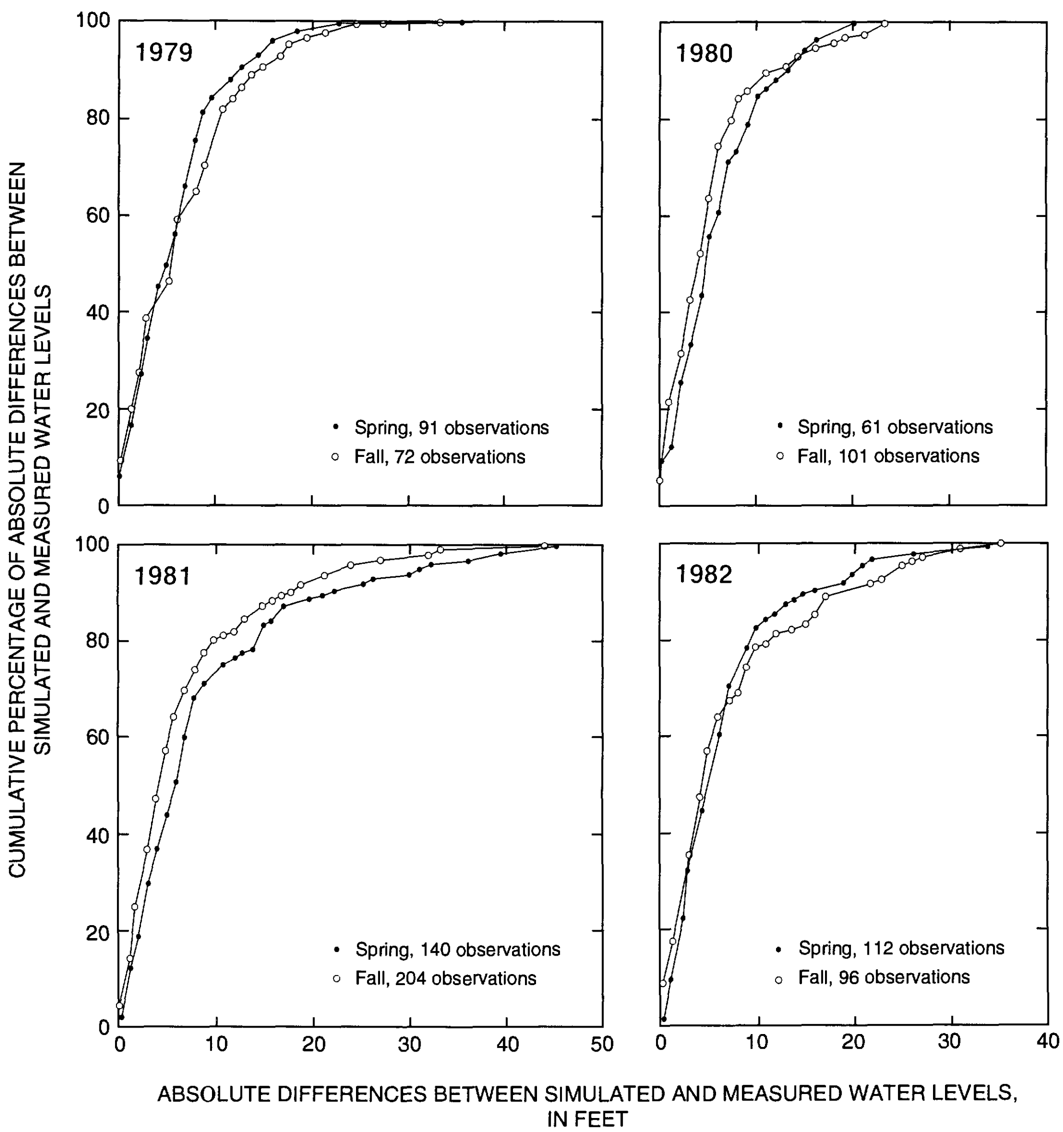


FIGURE 28.—Cumulative percentage of absolute differences between simulated and measured water levels for fall and spring seasons, 1979–82, Paradise Valley, Humboldt County, Nevada.

TABLE 11.—*Simulated ground-water budgets for basin-fill aquifer in Paradise Valley, Humboldt County, Nevada, for selected years during 1948–82*

[Values in acre-feet per year]

	1948–68	1969	1973	1981	1982
RECHARGE					
Recharge near contact between basin fill and consolidated rocks[1]	7,600	15,000	6,800	4,300	11,000
Leakage from streams	65,000	118,000	64,000	34,000	86,000
Underflow from Humboldt River Valley	1,300	1,100	1,100	800	700
Total recharge (rounded)	74,000	134,000	72,000	39,000	98,000
DISCHARGE					
Net pumpage[2]	3,000	2,700	14,000	38,000	36,000
Evapotranspiration	68,000	73,000	72,000	43,000	52,000
Leakage to streams	900	700	700	800	900
Underflow to Himboldt River Valley	1,800	2,400	1,400	1,700	1,700
Total discharge (rounded)	74,000	79,000	88,000	84,000	91,000
CHANGE IN STORAGE					
Net change in storage[3]	0	55,000	-16,000	-45,000	7,000
Water into storage	5,100	55,000	2,600	29,000	62,000
Water out of storage	5,100	100	19,000	74,000	55,000
Model computation error, in percent[4]	0.1	0.1	0.1	0.3	0.2

[1] Includes leakage from streams where estimated annual flow is less than 1,200 acre-feet per year.

[2] Total amount pumped, less that which is estimated to return to basin-fill aquifer.

[3] Net change in storage is difference between water added to storage and water removed from storage. Negative value means more water is removed from storage than added to storage.

[4] Error is due primarily to truncation and rounding during model computations. Percentage error is calculated from difference between all recharge (including water removed from storage) and all discharge (including water added to storage), divided by average of all recharge and discharge, and multiplied by 100. Because values for each component in this table are rounded, errors of recharge and discharge do not exactly match model computation error.

basin-fill aquifer (fig. 31*C*). However, the quantity of water in storage decreased dramatically after 1972 because of increased pumpage. Between 1972 and 1982, a total of 185,000 acre-ft was taken from storage. A total net depletion of 110,000 acre-ft was computed for the period 1968 through 1982. Thus, about 60 percent of the nearly 300,000 acre-ft of net pumpage (fig. 31*A*) was removed from storage, or about 50 percent of the 370,000 acre-ft of total pumpage. Although most, if not all, pumped ground water is removed from storage, the water removed is partly replaced by an increase in recharge and a decrease in natural discharge (fig. 31).

Assessing the quantity of water available in the future for pumpage in Paradise Valley is difficult, mainly because of the variability of streamflow and the location of irrigation wells. The basin seems suitable for conjunctive use of surface and ground water, where ground water is pumped during periods of low streamflow and replenished during periods of high streamflow. For example, model results indicate that storage decreased 45,000 acre-ft during the dry year of 1981, whereas during the wet year of 1982 storage increased 7,000 acre-ft (table 11). Replenishment of the basin-fill aquifer occurs even during dry years such as 1981. Water is added to storage by stream leakage during the January–March and October–December periods of each year, when pumpage and evapotranspiration are minor (table 12). Water is taken from storage by pumpage and evapotranspiration during April–September, when streamflow into the valley is receding. From 1982 through 1984, streamflows were consistently above normal. The 1984 water year had the greatest streamflows of record for the

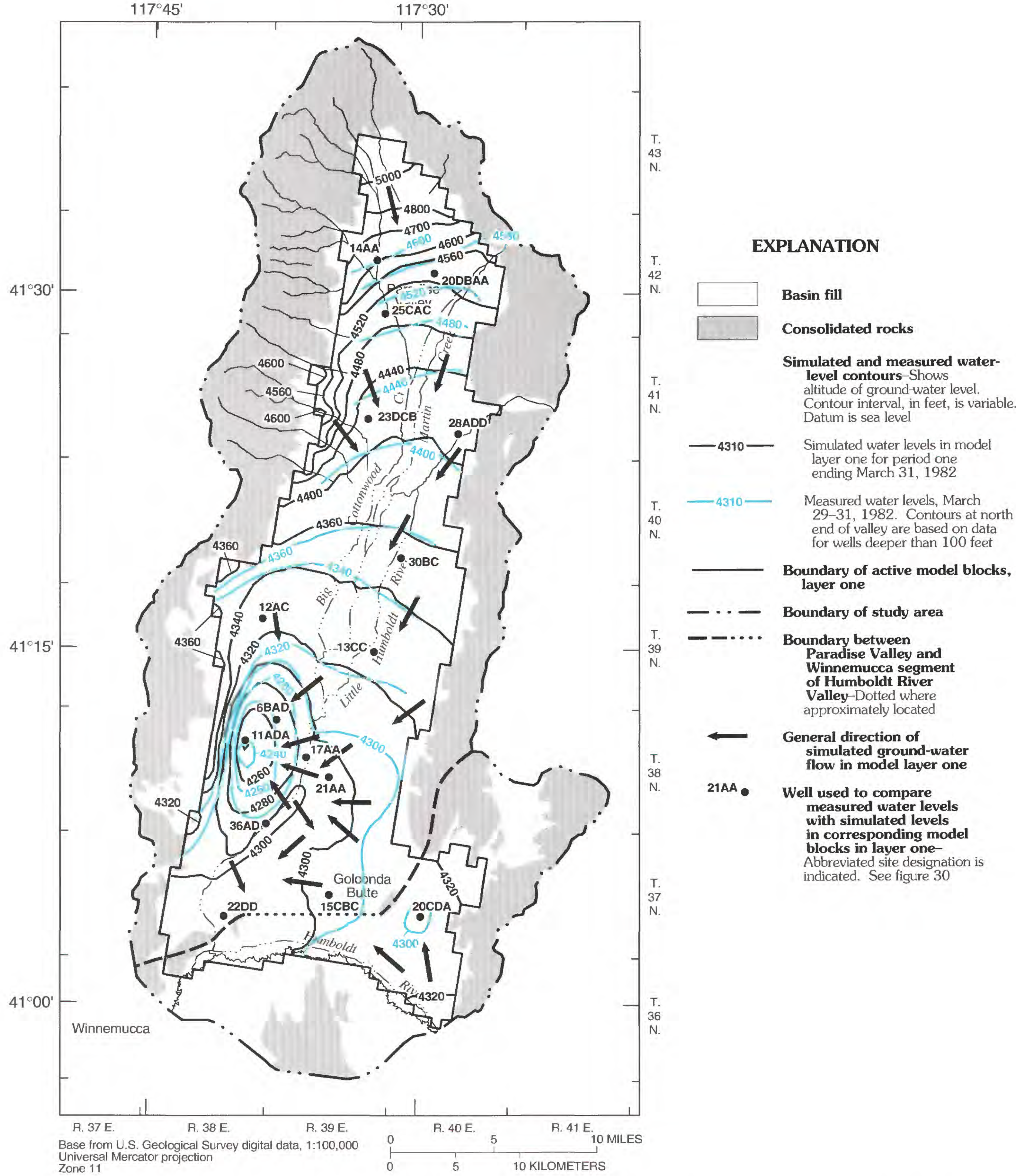


FIGURE 29.—Simulated and measured ground-water levels in upper 600 feet of basin fill for spring 1982, Paradise Valley, Humboldt County, Nevada.

Humboldt River basin. As a result, water levels rose several feet throughout much of Paradise Valley, and thus the quantity of water in storage increased.

EFFECTS OF REDUCED RECHARGE

The withdrawal of large quantities of ground water from the basin-fill aquifer from 1972 through 1982 coincided with a period of generally above-average streamflow and, hence, recharge in Paradise Valley. Results of detailed model simulations indicate that most of the recharge to the southern part of Paradise Valley occurred during periods when streamflow was sufficient to reach that part of the valley. Because pumpage of large quantities of water from the basin-fill aquifer coincided with a period of above-average streamflow, three additional simulations were made to determine the effects that pumpage may have on the aquifer during periods of less streamflow. Pumpage was divided into 14 periods of 1-year duration, with the average annual net pumpage for the period 1969–82 used in each simulation. Initial water levels for each simulation were the computed water levels at the end of the 1948–68 transient simulation. The first simulation assumed that streamflow into the modeled area was equal to the long-term average rate (1923–82); the second assumed that streamflow was equal to a 14-year period of lowest streamflows observed at the Martin Creek gage (1923–36; fig. 7), which averaged 74 percent of the long-term average; the third assumed average annual streamflow for the 14-year period 1969–82, which averaged 120 percent of long-term average. The first simulation is referred to as average streamflows, the second as lowest streamflow, and the third as actual streamflows. Simulations of long-term average and lowest streamflows were compared with the results of actual streamflows for the period 1969–82.

Differences in the water-levels at the end of two 14-year simulations of average and lowest streamflow conditions with respect to the simulation of actual streamflows are shown in figure 32*A* and *B*. Differences in water-levels between the first simulation assuming long-term average streamflows and the simulation of actual streamflows for 1969–82 were less than 5 ft except at the extreme northern end of the valley, the northwestern side of the valley, and the south-central part of the valley where water levels were as much as 20 ft lower (fig. 32*A*). The large declines in the northern part of the valley are the result of lower recharge rates assigned to model blocks at the edge of the modeled area. Much of this recharge is from small streams, that were not simulated as streams, but rather a constant rate was assigned to the first model block. The large declines in the south-central part of the valley result from streamflows not being sufficient to reach that part of the valley. Thus, in the simulation assuming average streamflows, more water was removed from storage in the vicinity of the heavily pumped area. When the 14-year period of lowest streamflows was simulated, the differences in water levels compared with the simulation of actual streamflows for the period 1969–82 were considerably more (fig. 32*B*). A much larger area of the valley had additional declines greater than 5 ft. Differences of 20 ft or more were simulated at several locations in the valley and result from reduced recharge to the basin-fill aquifer.

Hydrographs of water-level changes at six selected model blocks for all transient simulations of the 14-year period 1969–82 are shown in figure 33. Location of the six blocks is shown in figures 32*A* and 32*B*. Water levels in model blocks near where major streams enter Paradise Valley and along the Humboldt River did not vary between simulations (for example, see fig. 33*B*). The seasonal change of water levels measured in wells near where streams are perennial is usually less than 10 ft. Differences in water levels between the model simulations increase downstream toward the southern end of the valley, as shown in figures 33*B*–*F*. These differences are the result of changes in the quantity of leakage from streams. The greatest difference in water levels among the simulations is along Little Humboldt River just east of the most heavily pumped area (fig. 33*F*) and is caused by the presence or lack of streamflow near the model block. Results of the simulation suggest that if the climate from 1969 through 1982 had been similar to that from 1923 through 1936, the water level in well 17AA (location shown in fig. 29 and corresponding to model block 64, 13 in fig. 32) would have been about 15 ft lower than that actually observed. However, water levels within the most heavily pumped area declined more than 80 ft in all simulations (fig. 33*E*) and varied less than 7 ft between simulations. Water-level declines in this area (particularly on the western side) do not seem to be as sensitive to changes in streamflows along the Little Humboldt River, at least for the 14-year period of simulation. This suggests that most of the water pumped from the southern end of Paradise Valley is from storage.

Results of these model simulations suggest that if pumpage from 1969 through 1982 had occurred during a period of average streamflows, the net depletion of ground-water in storage would have been 175,000 acre-ft, or about 65,000 acre-ft more than was simulated assuming actual streamflows. In this simulation, recharge decreased by about 500 acre-ft/yr at the end of the 14-year period from that simulated for 1948–68 and is primarily the result of decreased underflow from Humboldt River Valley caused by ground-water pumpage east of Golconda Butte. Underflow from Paradise Valley to Humboldt River Valley decreased by 700 acre-ft/yr after 14 years in the simulation assuming average streamflows and was about the same as in the simulation using actual streamflows.

If pumpage from 1969 through 1982 had occurred during a period corresponding to lowest streamflows from 1923 through 1936, the net depletion of ground-water in storage in Paradise Valley would have been 240,000 acre-ft, or 130,000 acre-ft more than was simulated assuming actual streamflows. Recharge decreased by 18,000 acre-ft/yr and evapotranspiration decreased by 25,000 acre-ft/yr at the end of the 14-year simulation from that simulated for the period 1948–68. Underflow from Humboldt River Valley into Paradise Valley decreased by about 400 acre-ft/yr at the end of the 14-year simulation. Underflow from Paradise Valley to Humboldt River Valley decreased by 700 acre-ft/yr, the same as in the other simulations. Thus, even simulating lowest average streamflows,

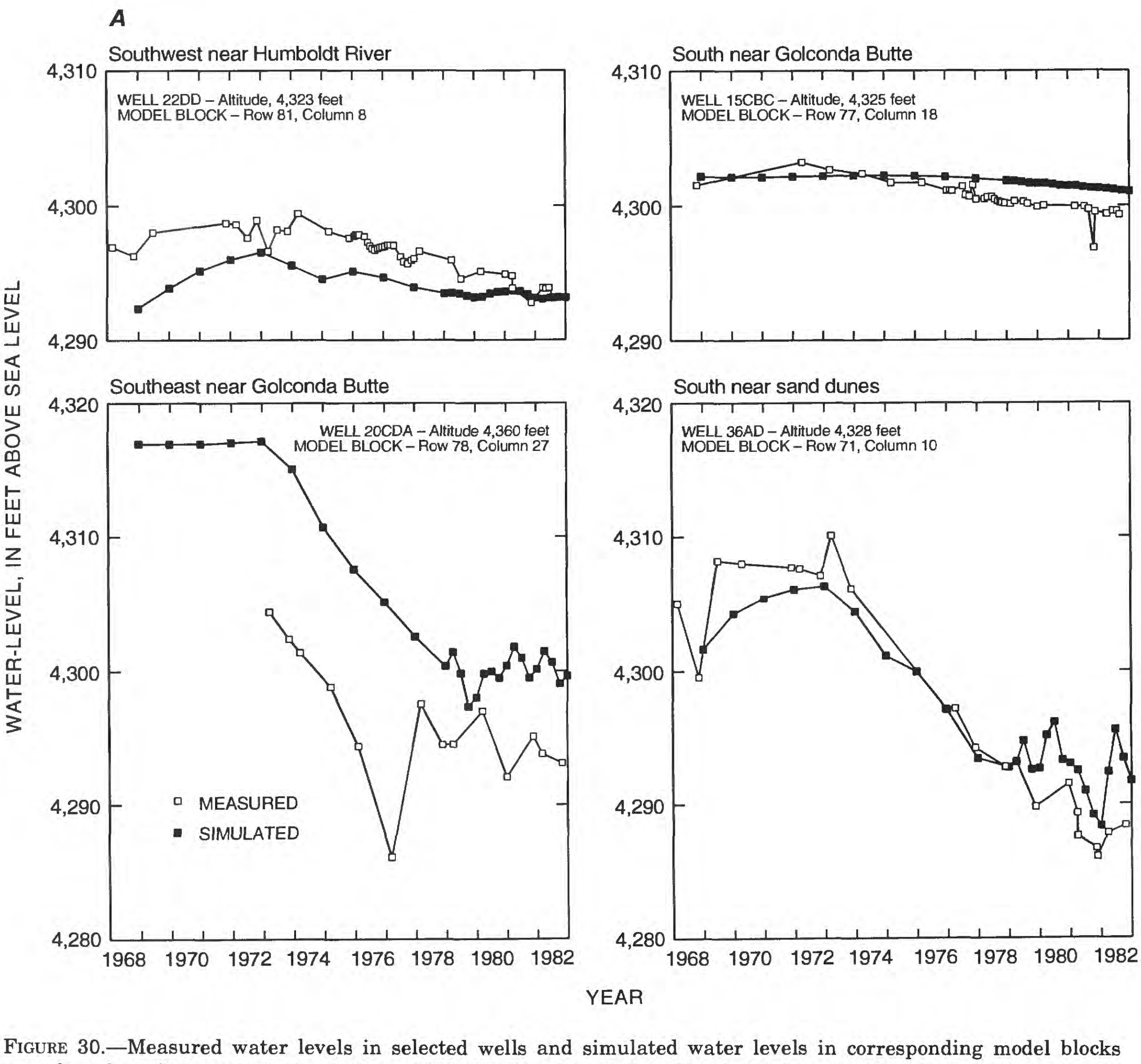


FIGURE 30.—Measured water levels in selected wells and simulated water levels in corresponding model blocks from best-fit transient simulations, 1968–82, Paradise Valley, Humboldt County, Nevada. Location of wells is shown in figure 29; model grid blocks are shown in figure 17. Land-surface altitude at well is given.

no additional water was induced from Humboldt River Valley to Paradise Valley by pumpage at the southern end of Paradise Valley during the 14-year period of simulation. This result again illustrates the large storage capacity of the basin-fill aquifer in Paradise Valley, which acts to buffer short-term changes in recharge and discharge.

In summary, reducing recharge over a 14-year period to simulate drier conditions resulted in a moderate lowering of the water table throughout much of the valley, which reduced the quantity of water discharged by evapotranspiration. However, the simulations did not greatly change the effects of ground-water pumping near the southern end of

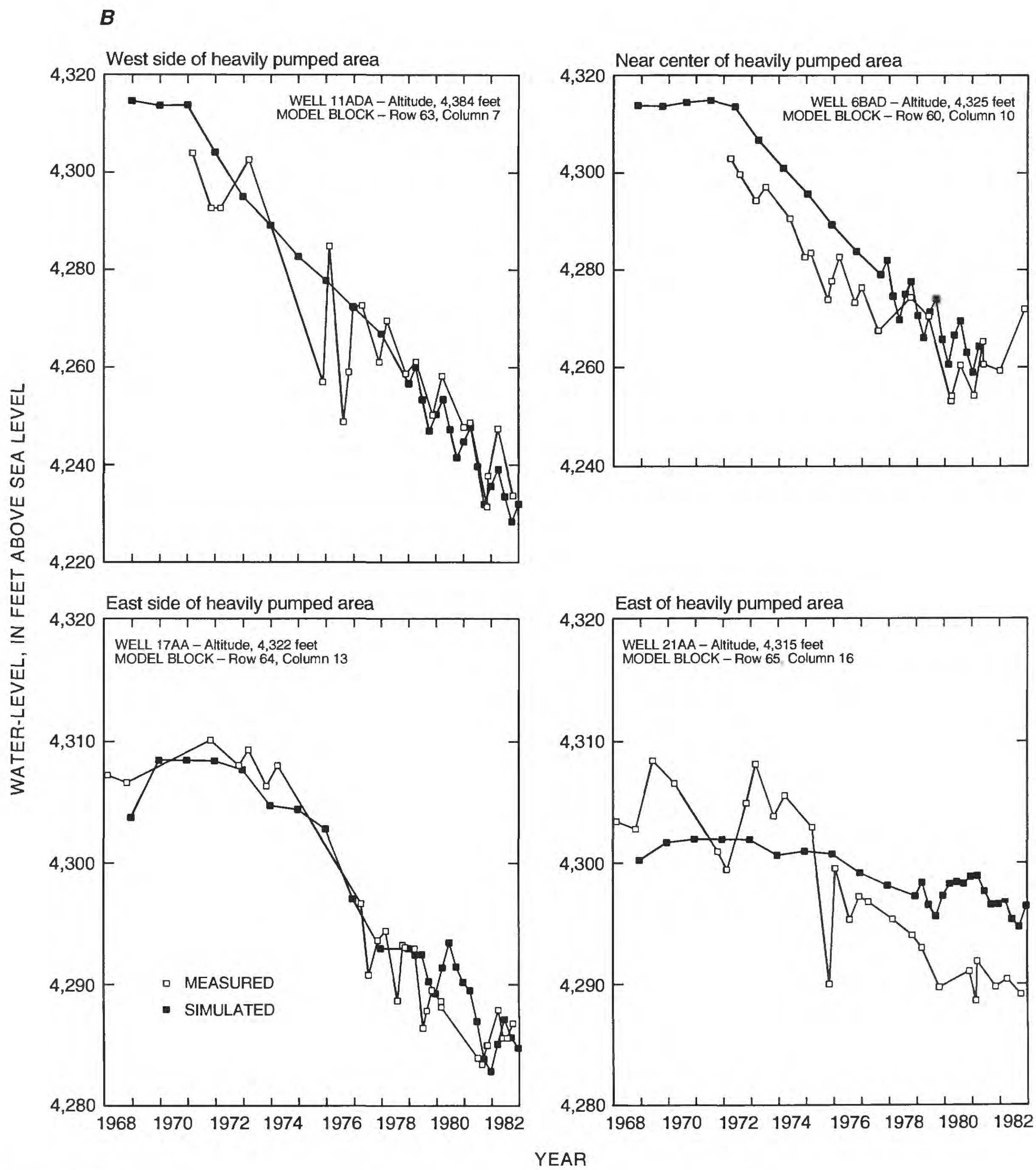


FIGURE 30.—Continued.

the valley, nor did the drier conditions greatly increase the underflow from Humboldt River Valley during the 14-year period.

SIMULATED RESPONSE TO SELECTED DEVELOPMENT SCENARIOS

The general response of the basin-fill aquifer in Paradise Valley to five selected development scenarios was evaluated using the calibrated ground-water flow model. Model simulations were initially made for an arbitrary period of 600 years: 300 years of pumping and 300 years of recovery. The length of the period was designed to allow the basin-fill aquifer to approach a new equilibrium, and then allow it to recover toward original conditions. For comparison purposes, the length of the pumping and recovery periods was the same for all basins studied as part of the Great Basin RASA project. In two of the scenarios (scenarios two and three), the length of the pumping period was reduced because water levels in several model blocks declined below the bottom altitude of the block, causing the block to be removed from further model computations. The model blocks could not resaturate during the recovery period, and recharge assigned to model blocks that went inactive was excluded from further computations, thus making the simulations unrealistic.

Hydraulic properties of the basin-fill aquifer were the same as those used in the best-fit model simulations. Streamflows and recharge values assigned to model blocks near the contact between the basin fill and consolidated rocks were set equal to the long-term average (1923–82). The number and locations of wells within the selected pumping areas were constrained by the following limitations: (1) only one well was permitted in each 2,500 by 2,500 ft model block; (2) maximum pumping rate was 720 acre-ft/yr (1 ft^3/s); (3) no wells were located where the initial depth to water exceeded 200 ft; (4) no wells were located where sand dunes

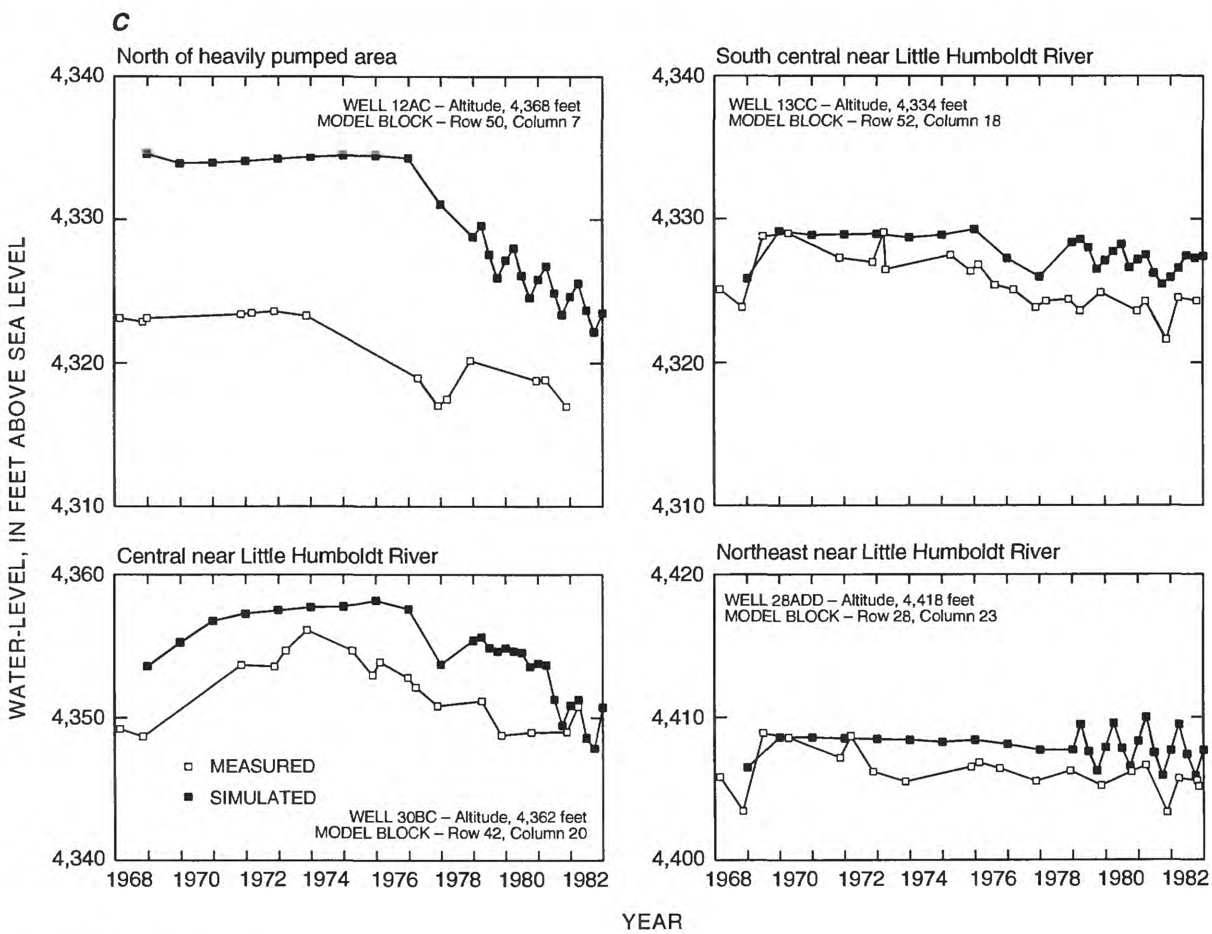


FIGURE 30.—Continued.

crossed the southern end of the valley; and (5) no wells were located in model blocks within layer one bounded on two or more sides by inactive blocks.

Ground-water pumpage was assumed equal to net pumpage during the hypothetical simulations to avoid the necessity of estimating and simulating recirculation of some of the pumped water back into the aquifer. Ground-water pumpage for the first scenario was set equal to net pumpage estimated for 1982. For the last four scenarios, ground-water pumpage was set equal to about 72,000 acre-ft, or the long-term average annual streamflow into Paradise Valley used in the steady-state simulations. The five selected scenarios include the following:

1. Wells distributed as of 1982, a distribution that includes some wells in the adjacent Humboldt River Valley;
2. Wells concentrated at the southern end of Paradise Valley;
3. Wells concentrated at the northern end of Paradise Valley;
4. Wells concentrated along the central part of Paradise Valley; and
5. Wells generally distributed throughout the area of simulated evapotranspiration in Paradise

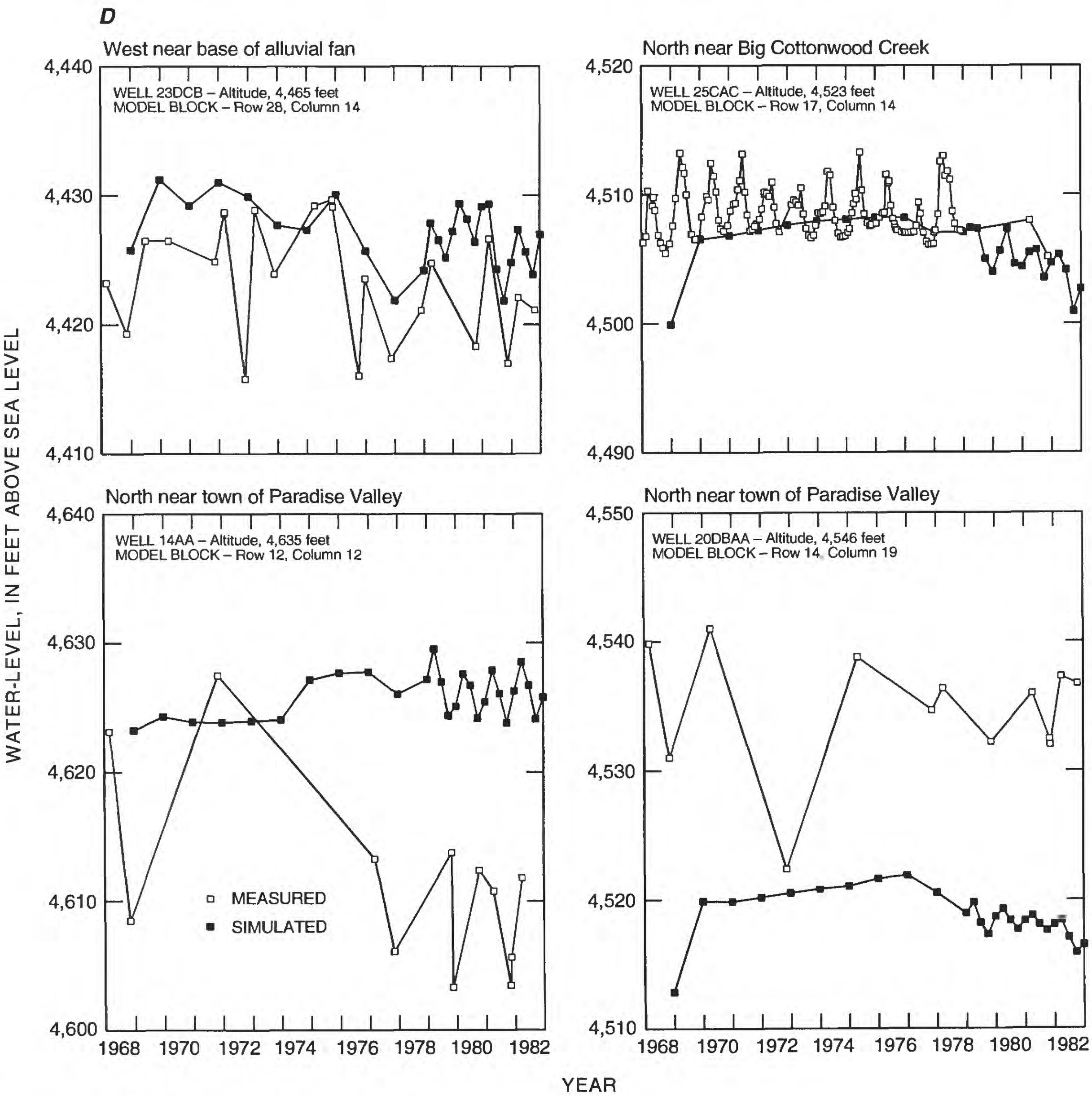


FIGURE 30.—Continued.

Valley prior to ground-water pumpage (fig. 24). Characteristics of the five patterns are summarized in table 13. Details of the simulations are presented in tables 14–18 and figures 34–38.

SELECTION OF SCENARIOS

The first scenario was evaluated to estimate the long-term effects of recent withdrawals, assuming climatic conditions equal to average conditions for 1923–82. Net pumpage for 1982 was used because it represents pumpage in a relatively stable agricultural community that developed rapidly in the 1970's. Scenarios two through five were simulated to test the concept of sustained yield in basins tributary to the Humboldt River where streams flow across, and supply water to, the basin-fill aquifer. To prevent long-term water-level declines, the States of Nevada and Utah, which contain most of the Great Basin, allocate water rights for each basin on the basis of the estimated average annual recharge. However, in long narrow basins like Paradise Valley and several others, the concentration of pumping in a particular area may produce excessive

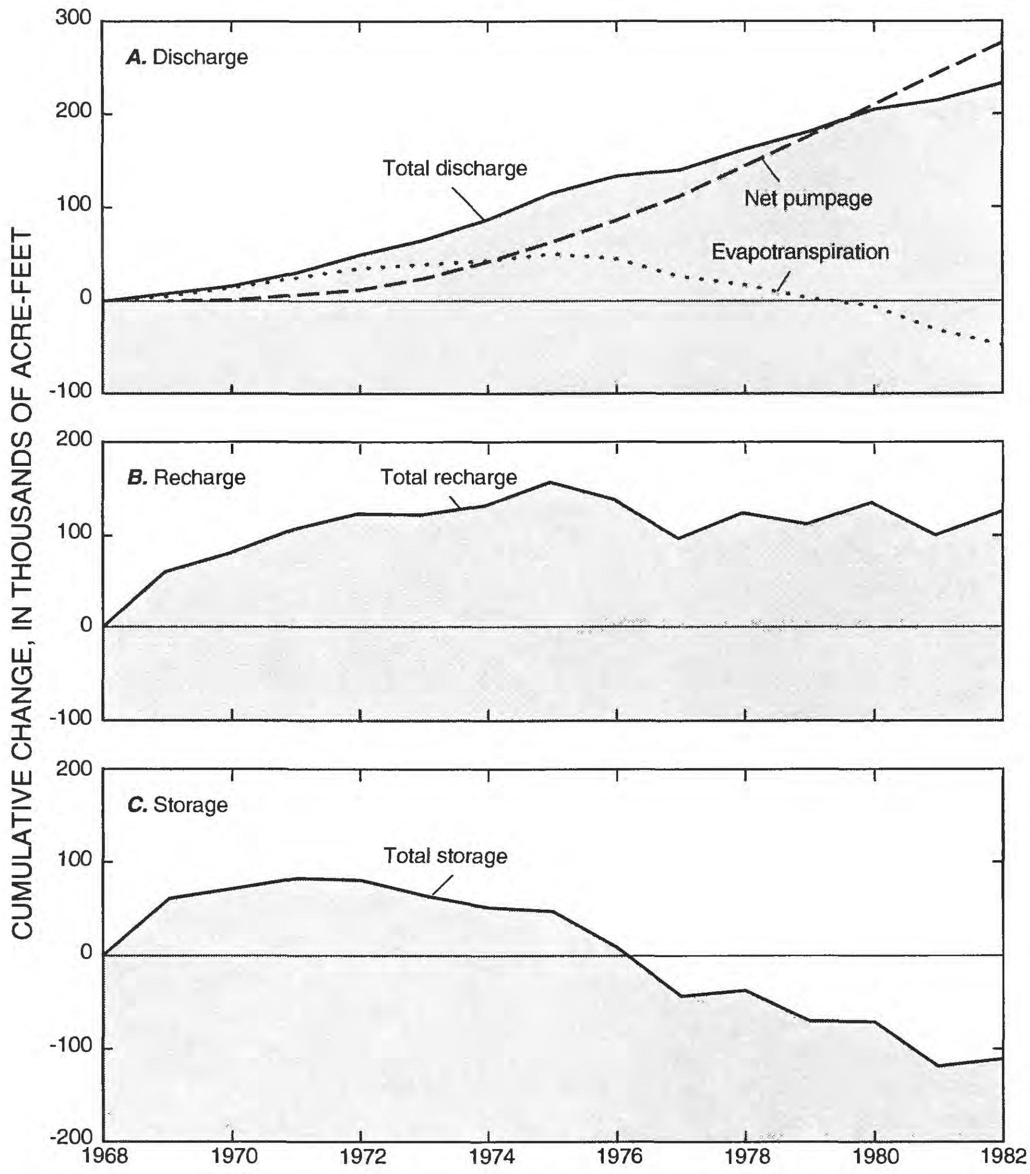


FIGURE 31.—Cumulative change in (*A*) annual ground-water discharge, (*B*) recharge, and (*C*) storage from results of best-fit transient simulations, 1968–82, Paradise Valley, Humboldt County, Nevada.

TABLE 12.—*Simulated ground-water budgets for basin-fill aquifer in Paradise Valley, Humboldt County, Nevada, for 3-month periods in 1981*

[Values in acre-feet per year]

	January–March	April–June	July–September	October–December	Total for 1981
RECHARGE					
Recharge near contact between basin fill and consolidated rocks[1]	800	1,800	200	1,500	4,300
Leakage from streams	7,000	15,000	2,900	9,100	34,000
Underflow from Humboldt River Valley	200	200	200	200	800
Total recharge (rounded)	8,000	17,000	3,300	11,000	39,000
DISCHARGE					
Net pumpage[2]	24	19,000	19,000	24	38,000
Evapotranspiration	0	25,000	18,000	0	43,000
Leakage to streams	400	100	100	200	800
Underflow to Humboldt River Valley	200	400	700	400	1,700
Total discharge (rounded)	600	44,000	38,000	600	84,000
CHANGE IN STORAGE					
Net change in storage[3]	7,500	-27,000	-34,000	10,000	-45,000
Water into storage	13,000	720	14	16,000	29,000
Water out of storage	5,500	28,000	34,000	5,700	74,000
Model computation error, in percent[4]	0.5	0.1	0.1	0.4	0.3

[1] Includes leakage from streams where estimated annual flow is less than 1,200 acre-feet per year.

[2] Total amount pumped, less that which is estimated to return to basin-fill aquifer.

[3] Net change in storage is difference between water added to storage and water removed from storage. Negative value means more water is removed from storage than added to storage.

[4] Error is due primarily to truncation and rounding during model computations. Percentage error is calculated from difference between all recharge (including water removed from storage) and all discharge (including water added to storage), divided by average of all recharge and discharge, and multiplied by 100. Because values for each budget component in this table are rounded, errors of recharge and discharge do not exactly match model computation error.

water-level declines without reducing the natural evapotranspiration in other parts of the basin.

The scenarios were chosen as examples of possible alternatives of future development in basins tributary to the Humboldt River. The scenarios did not consider the economics of pumping ground water nor, did they include the effects of compacting fine-grained sediments that may result from substantial water-level declines in an aquifer. This process, which results in subsidence of the land surface, has been documented in several areas of the western United States (Poland and Davis, 1969; Chi and Reilinger, 1984) including Las Vegas Valley (Bell, 1981). Initially, compaction of the fine-grained sediments increases the quantity of water released from storage, but as compaction continues, the quantity of water decreases with time. More importantly, much of the water released from compaction of the fine-grained sediments is a one-time occurrence, which can never be replaced once pumping ceases and water levels recover. Whether or not pumpage from the basin-fill aquifer in Paradise Valley will result in substantial compaction of fine-grained sediments is unknown.

DISCUSSION OF RESULTS

Results for each scenario are summarized in tables 14 through 18 and figures 34 through 38. The results include illustrations depicting water-level declines in model layers one and two; changes in the average water-level declines within the

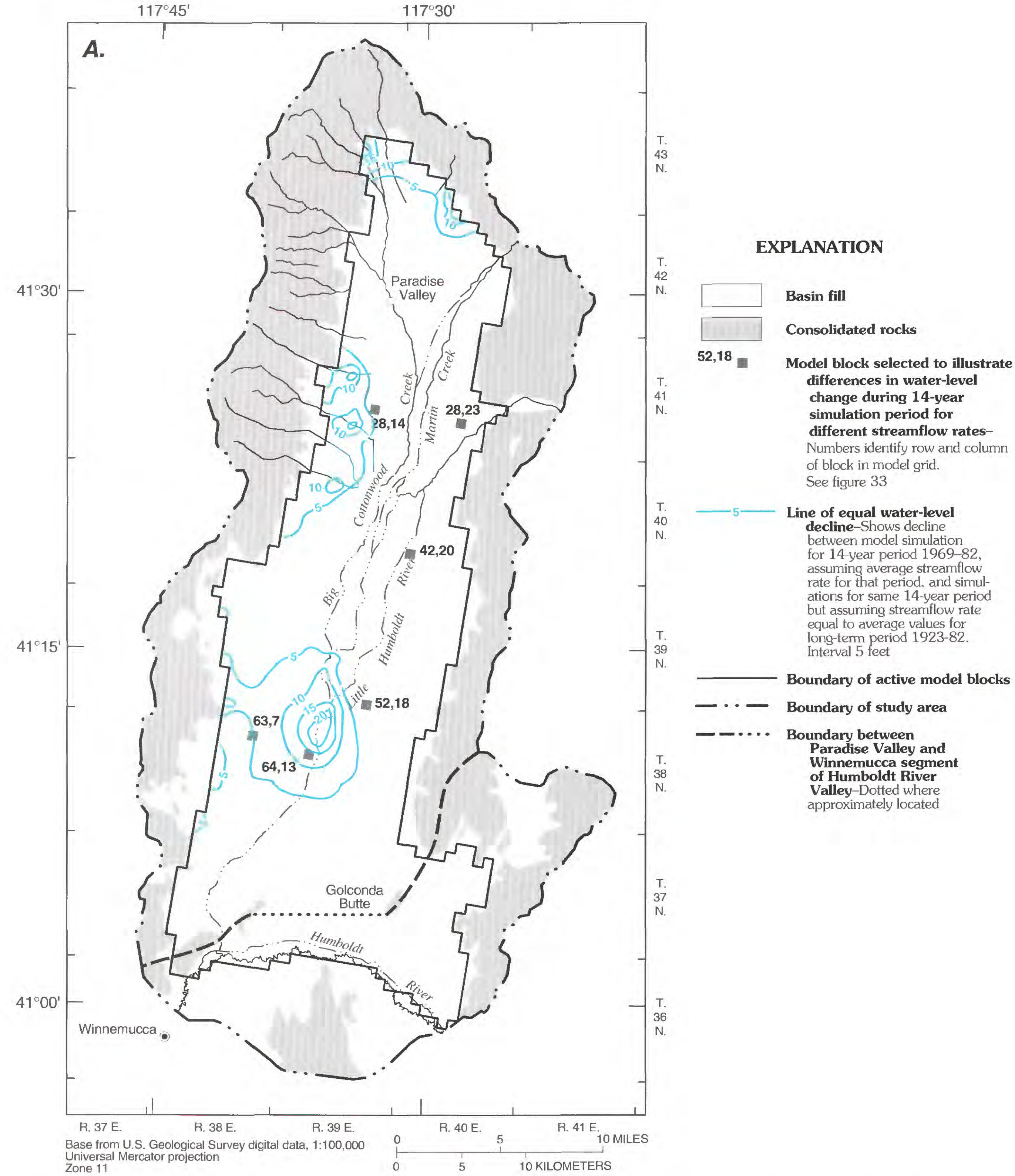


FIGURE 32.—Water-level decline between model simulation for 14-year period 1969–82, assuming average streamflow rate for that period, and simulations for same 14-year period but assuming streamflow rate equal to average values for (*A*) long-term period 1923–82 and (*B*) 14-year period of lowest flow (1923–36), Paradise Valley, Humboldt County, Nevada.

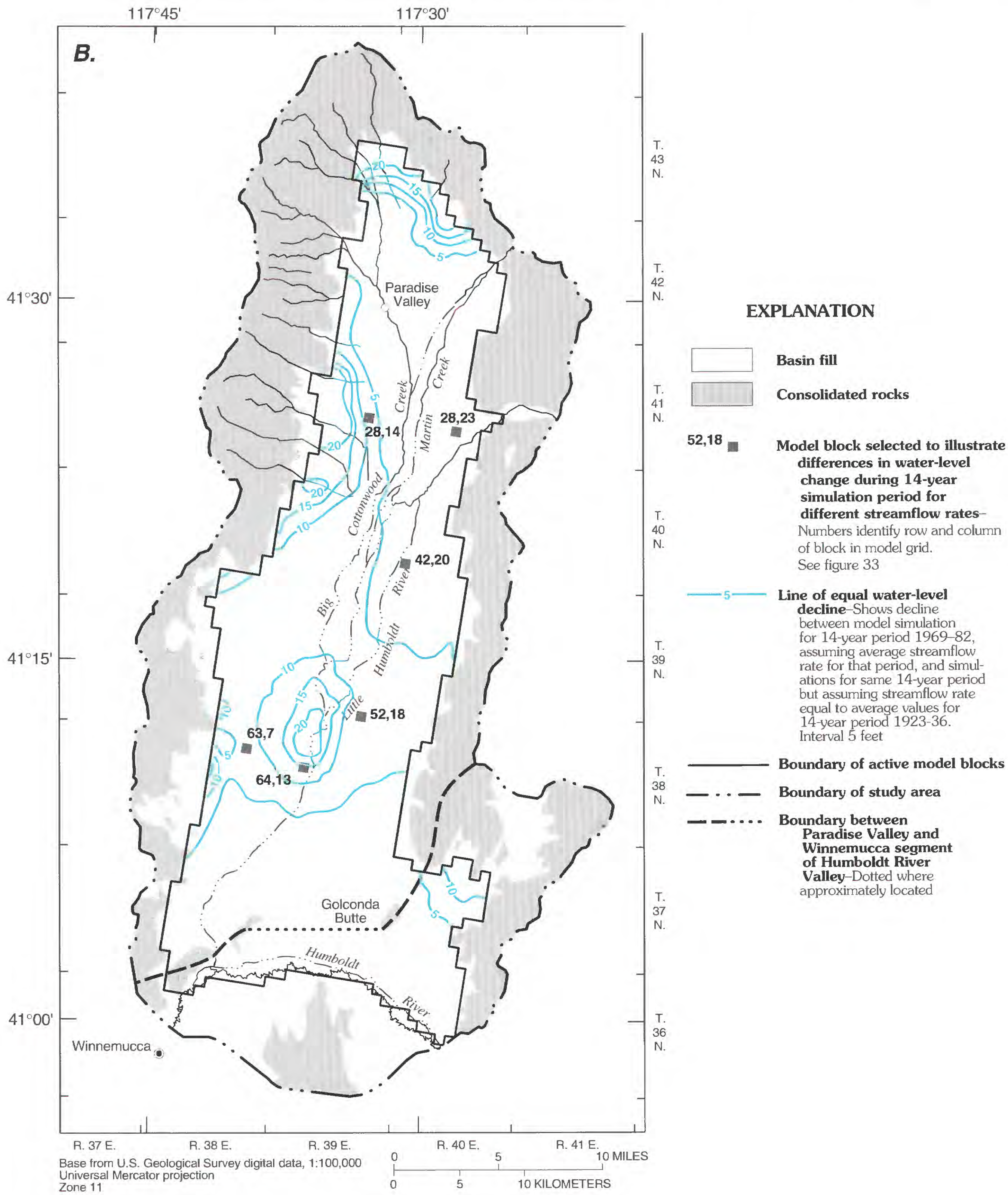


FIGURE 32.—Continued

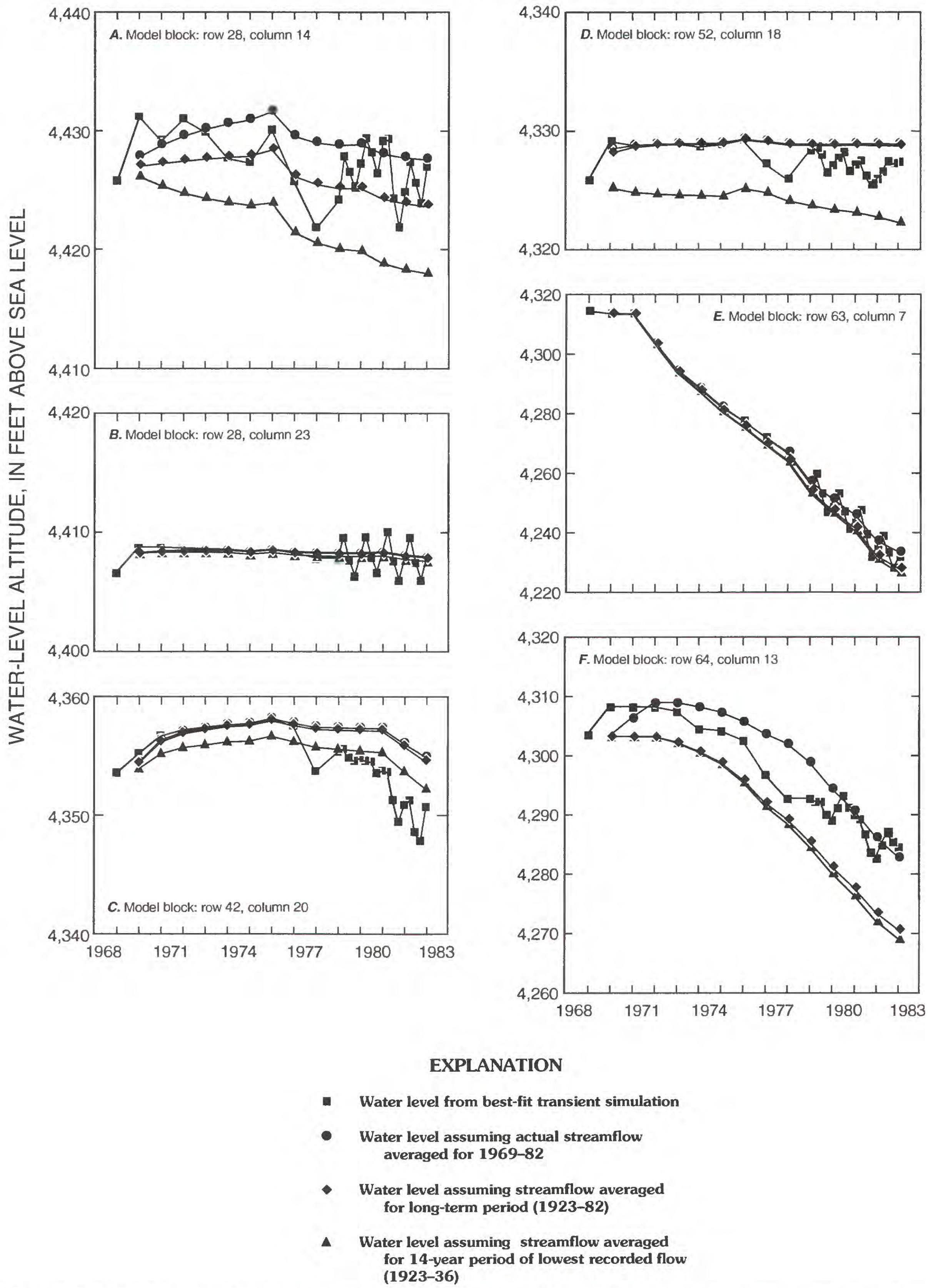


FIGURE 33.—Water levels at six selected model blocks in layer one showing differences in simulations caused by varying streamflow rate, Paradise Valley, Humboldt County, Nevada. Location of model blocks is shown in figure 32.

TABLE 13.—*Description of simulations for selected development scenarios, Paradise Valley, Humboldt County, Nevada*

Scenario	Pumpage[1] (acre-feet per year)	Distribution of pumpage[2]	Layers and number of model blocks with pumpage		Length of pumping and recovery periods (years)		Tables and figures that summarize simulation results	
			Layers	Blocks	Pumping[3]	Recovery	Table	Figure
1	36,000	As of 1982	1	184	300	300	14	34
2	72,000	South	1 and 2	400	100	300	15	35
3	72,000	North	1 and 2	340	75	300	16	36
4	72,000	Central	1	200	300	300	17	37
5	72,000	Area of evapotranspiration	1	200	300	300	18	38

[1] All pumpage is assumed to be consumed.

[2] Geographical designations refer to location of simulated pumping on valley floor. In scenario one, areas of pumping coincide with those of 1982, and therefore 2,800 acre-ft/yr of pumpage also was simulated in adjacent Humboldt River Valley. In scenario five, area of pumping coincides with area of phreatophytes as of 1982.

[3] Pumping periods in scenarios two and three were shortened because water levels in several model blocks declined below bottom of block during simulation, and thus specified recharge and discharge were eliminated for remainder of simulation.

pumped areas over the simulation period; changes in the rate of evapotranspiration and underflow to and from Humboldt River Valley, and cumulative change in storage during each scenario; and pie diagrams showing percentage changes in the quantity of water removed from storage, the quantity of decreased evapotranspiration, and the quantity of underflow between Paradise Valley and adjacent Humboldt River Valley in relation to pumpage. A table summarizes changes in the water budget and water-level declines at the end of selected time periods for each scenario. The table and figures associated with each scenario are listed in table 13.

The results of the five selected scenarios are consistent with the following statement by Theis (1940, p. 277):

> Under natural conditions, therefore, previous to development of wells, aquifers are in a state of approximate dynamic equilibrium. Discharge by wells is thus a new discharge superimposed upon a previously stable system, and it must be balanced by an increase in the recharge to the aquifer, or by a decrease in the old natural discharge, or by a loss of storage in the aquifer, or by a combination of these.

Each scenario includes the processes described by Theis in that water is removed from storage, natural discharge is decreased, and recharge is increased during the pumping periods.

The water-level declines computed for each scenario are not designed for predicting future water levels in Paradise Valley but instead are used to describe the effects of different development scenarios on ground-water flow in Paradise Valley and, hopefully, for similar tributary basins to the Humboldt River. Actual future declines in Paradise Valley may be different from those simulated because the actual distribution and quantity of pumpage may be different from those in the simulations. In addition, the scenarios assume that (1) average climatic conditions from 1923 through 1982 will exist for hundreds of years, (2) all pumped water is consumed or the quantity of pumpage is a net value (total pumpage less that recirculated), (3) all streamflow recharges the basin-fill aquifer as leakage (that is, none is lost directly to evapotranspiration, nor is any leakage stored in the unsaturated zone), and (4) no water is released by permanent compaction of fine-grained deposits as water levels decline.

Although net pumpage was set equal to the long-term average annual streamflow into Paradise Valley for scenarios two through five, in reality not all streamflow will be available for capture from pumped wells. In the model simulations that describe ground-water flow during the period 1948–82, the assumption is that no streamflow is lost to evapotranspiration prior to recharging the basin-fill aquifer; thus, all streamflow becomes available for pumpage. This assumption is reasonable for the simulation period 1948–82 because net pumpage was considerably less than available streamflow. The assumption simplified the model simulations for that period. However, the assumption may not be reasonable for the selected scenarios, as some streamflow will continue to be lost to evapotranspiration. Even though the scenarios may produce depths to water exceeding 20 ft below land surface throughout much of the valley and evapotranspiration will cease in the model simulations, plants will continue to extract moisture from the unsaturated zone near streams or some streamflow will continued to be used for flood irrigation. Thus, the scenarios are limited in their response as to what may actually result from the assumed pumpage.

For the first scenario, pumpage was assumed equal to the net pumpage for 1982. The estimated net pumpage for 1982 was 36,000 acre-ft/yr for Paradise Valley and 2,800 acre-ft/yr in Humboldt River Valley east of Golconda Butte (fig. 34*A*). The distribution of model blocks that coincide with the location of wells that pumped more than 7 acre-ft/yr in 1982 is shown in figure 34*A*. Model blocks with pumpage less than 7 acre-ft/yr are not shown. Pumpage was in model layer one, as none of the wells pumped in 1982 extended beyond a depth of 600 ft.

The decline in water levels simulated after 12.5 years (closest time step in the simulation to actual period of drawdown; fig. 34*A*) is similar to the measured decline between the fall of 1968 and fall of 1982 (see fig. 26). The slightly greater water-level declines in this simulation are the result of at least two factors. First, the measured water-level declines are actually for an 11-year period, as pumpage in the valley was minimal until 1972. Second, the estimated rate of net pumpage in the study area (including adjacent Humboldt River Valley) between 1972 and 1982 was not constant at the 1982 rate but increased from about 12,000 acre-ft/yr in 1972 to about 41,000 acre-ft/yr in 1981 and averaged only 78 percent of the quantity simulated.

Maximum water-level decline simulated after 12.5 years was 89 ft. Water-level declines were more than 10 ft in three areas (fig. 34*A*): (1) at the northern end of the valley where Martin Creek enters; (2) in Humboldt River Valley east of Golconda Butte; and (3) a large area in T. 38 and 39 N. where almost three quarters of the pumpage is located. Elsewhere, water levels were not affected by pumping. Underflow from Paradise Valley to Humboldt River Valley decreased 600 acre-ft/yr, and underflow from Humboldt River Valley into Paradise Valley also decreased by 160 acre-ft/yr because of pumping east of Golconda Butte.

Water-level declines after a simulation period of 300 years were more than 10 ft throughout the southern half of the valley and a small area near where Martin Creek enters the valley (fig. 34*A*). The maximum water-level decline was 273 ft along the western edge of the most heavily pumped area in the southwest part of the valley. The large declines are a result of concentrated pumpage near where the basin fill thins rapidly and are less permeable and where little water recharges from nearby mountains.

Less than 2 percent of the water pumped after 300 years was from storage depletion (table 14, fig. 34*E*); thus, the simulation was approaching a new equilibrium. In this scenario, a total of 1.5 million acre-ft of water was depleted from storage in Paradise Valley after 300 years (fig. 34*D*). This accounted for only 14 percent of the total net pumpage. The increase in discharge due to pumping of ground water resulted in a decrease of natural discharge by evapotranspiration of 25,000 acre-ft/yr (table 14, fig. 34*C*). It also resulted in an increase in underflow from Humboldt River Valley of 7,400 acre-ft/yr and a decrease in outflow to Humboldt River Valley of 1,700 acre-ft/yr (table 14, fig. 34*C*).

Pumping of ground water at the 1982 rate could, in the future, cause water from Humboldt River Valley to move northward into Paradise Valley. On the basis of the model simulations, if the 1982 pumping rate continues for 300 years and long-term average streamflows into Paradise Valley remain the same as those estimated for 1923–82, the change in ground-water flow between Paradise Valley and Humboldt River Valley would be approximately 9,100 acre-ft/yr, or about 5 percent of the average annual streamflow of the Humboldt River near Comus.

The scenarios where pumping was concentrated either at the southern end (scenario two) or the northern end (scenario three) resulted in localized water-level declines exceeding 400 ft (figs. 35 and 36). In the scenario with pumping concentrated at the southern end, pumping had little effect on the water resources of the northern end of Paradise Valley after 100 years. Similarly, concentrating pumping at the northern end had little effect on the water resources at the southern end of the valley. Concentrating pumping at the southern end of the valley produced a reversal in the net flow between Paradise Valley and Humboldt River Valley. Prior to development, the estimated net flow of ground water was about 500 acre-ft/yr from Paradise Valley into Humboldt River Valley (1,800 acre-ft of flow out of Paradise Valley less 1,300 acre-ft of flow into Paradise Valley; table 15). After 50 years the net flow was about 15,000 acre-ft/yr into Paradise Valley, and after 100 years it was about 21,000 acre-ft/yr (table 15). Concentrating pumping in the northern end of Paradise Valley did not affect underflow from Humboldt River Valley (table 16).

Scenarios where pumping was concentrated in the central part of Paradise Valley (scenario four) and where pumping was distributed throughout the area of evapotranspiration (scenario five) extended to 300 years as water-level declines never exceeded

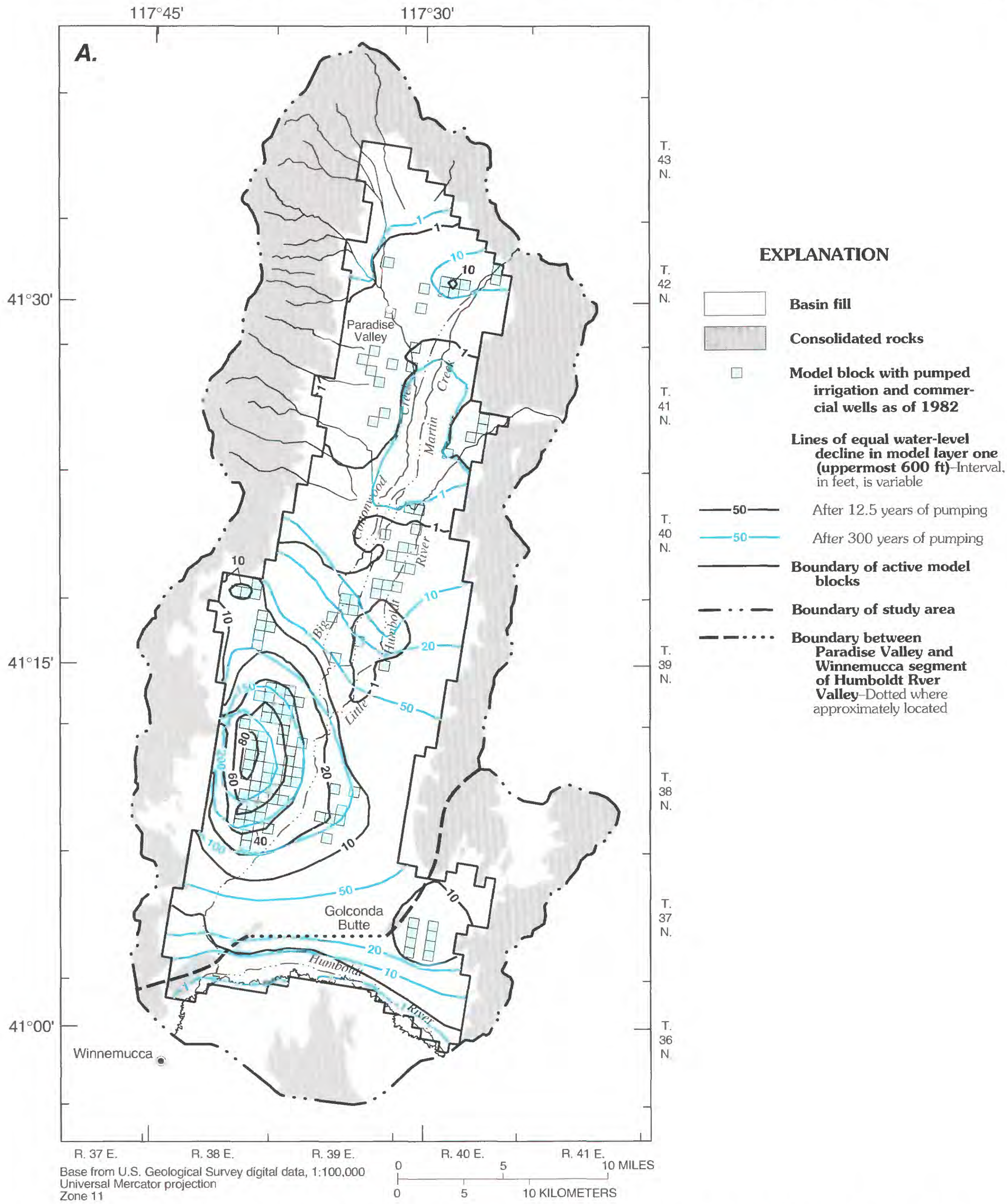


FIGURE 34.—Response of basin-fill aquifer to development scenario one, Paradise Valley, Humboldt County, Nevada. Net pumpage equal to estimated rate of 36,000 acre-feet per year for 1982 and distributed to match location of that pumpage; an additional 2,800 acre-feet per year of pumpage simulated in Humboldt River Valley. (*A*) Water-level declines in model layer one after 12.5 and 300 years; (*B*) average water-level declines in model blocks with pumpage during pumping and recovery periods; (*C*) changes in rate of evapotranspiration and underflow to and from Humboldt River Valley during pumping and recovery periods; (*D*) cumulative change in storage during pumping and recovery periods; and (*E*) sources of pumped water at end of selected time periods.

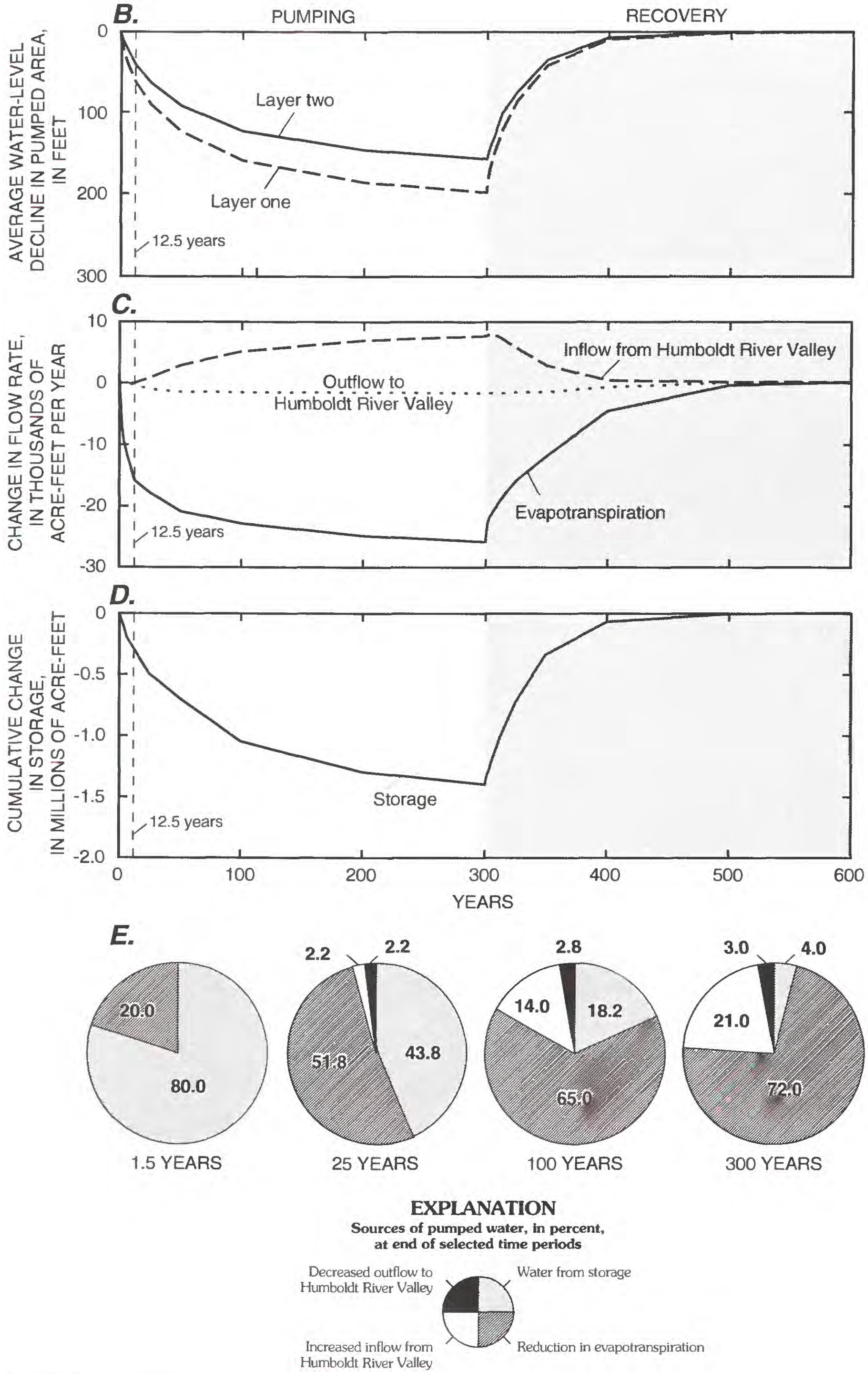


FIGURE 34.—Continued

TABLE 14.—*Simulated ground-water budgets after selected periods of pumping, Paradise Valley, Humboldt County, Nevada, development scenario one*

[Values in acre-feet per year]

	Predevel-opment conditions	Conditions after indicated period of pumping				
		1.5 years	12.5 years	25 years	50 years	300 years
RECHARGE						
Recharge near contact between basin fill and consolidated rocks[1]	7,200	7,200	7,200	7,200	7,200	7,200
Leakage from streams	65,000	65,000	65,000	65,000	65,000	65,000
Underflow from Humboldt River Valley	1,300	1,000	1,100	2,000	4,000	8,700
Total recharge (rounded)	74,000	73,000	73,000	74,000	76,000	81,000
DISCHARGE						
Pumpage[2]	minor	36,000	36,000	36,000	36,000	36,000
Evapotranspiration	71,000	64,000	55,000	53,000	50,000	46,000
Leakage to streams	800	800	800	700	700	700
Underflow to Humboldt River Valley	1,800	1,800	1,400	600	300	100
Total discharge (rounded)	74,000	103,000	93,000	90,000	87,000	83,000
DIFFERENCE (discharge minus recharge)	0	30,000	20,000	16,000	11,000	2,000
COMPUTED STORAGE DEPLETION[3]	0	28,000	19,000	15,000	10,000	1,000

[1] Includes leakage from streams where estimated annual flow is less than 1,200 acre-feet per year.

[2] An additional pumpage of 2,800 acre-feet per year in Humboldt River Valley is included in simulation but not in budget for Paradise Valley.

[3] Difference between estimates of recharge and discharge and storage depletion represents computational errors due primarily to truncation and rounding.

the thickness of layer one. Water-level declines in these scenarios were much less than when pumping was concentrated in the southern or northern ends (compare figs. 37 and 38 to 35 and 36). These lesser water-level declines resulted in a lesser quantity of water removed from storage (compare figs. 37*D* and 38*D* to 35*D* and 36*D*). At the end of the 300-year pumping period, both scenarios had nearly reached a new equilibrium, as less than 5 percent of the pumped water was from storage depletion (tables 17 and 18; figs. 37*E* and 38*E*). Concentrating pumpage in the central part resulted in water-level declines of more than 200 ft after 300 years (fig. 37*A*); however, average water-level declines in the pumped area were less than 200 ft (fig. 37*B*). This scenario captured the greatest quantity of evapotranspiration (compare figs. 34*C*–38*C*), as after 300 years only 8,100 acre-ft/yr was still being discharged as evapotranspiration (table 17). This is even less than in scenario five, where pumping was distributed throughout the area of evapotranspiration (table 18). Even so, scenario four caused ground water to flow from Humboldt River into Paradise Valley. The net flow, after 300 years, was simulated at 4,300 acre-ft/yr (table 17).

Water-level declines in scenario five were even less than in scenario four, although shifted to the south (compare figs. 37*A* and 38*A*). Scenario five resulted in the least quantity of water removed from storage when compared to the volume of water pumped. However, water-level declines could have been further reduced if about 15,000 of the 20,000 acre-ft/yr of pumpage in T. 37 and 38 N. had been moved north of T. 41 N. (see fig. 38*A*). This would have increased declines at the northern end of the valley, where about 14,000 acre-ft/yr of evapotranspiration was still simulated after 300 years (table 18) and decreased the quantity of underflow induced from Humboldt River Valley.

Concentrating the pumping in the southern and northern ends of the valley resulted in substantial water-level declines in model layer two (figs. 35*B* and 36*B*) compared with scenarios where pumping

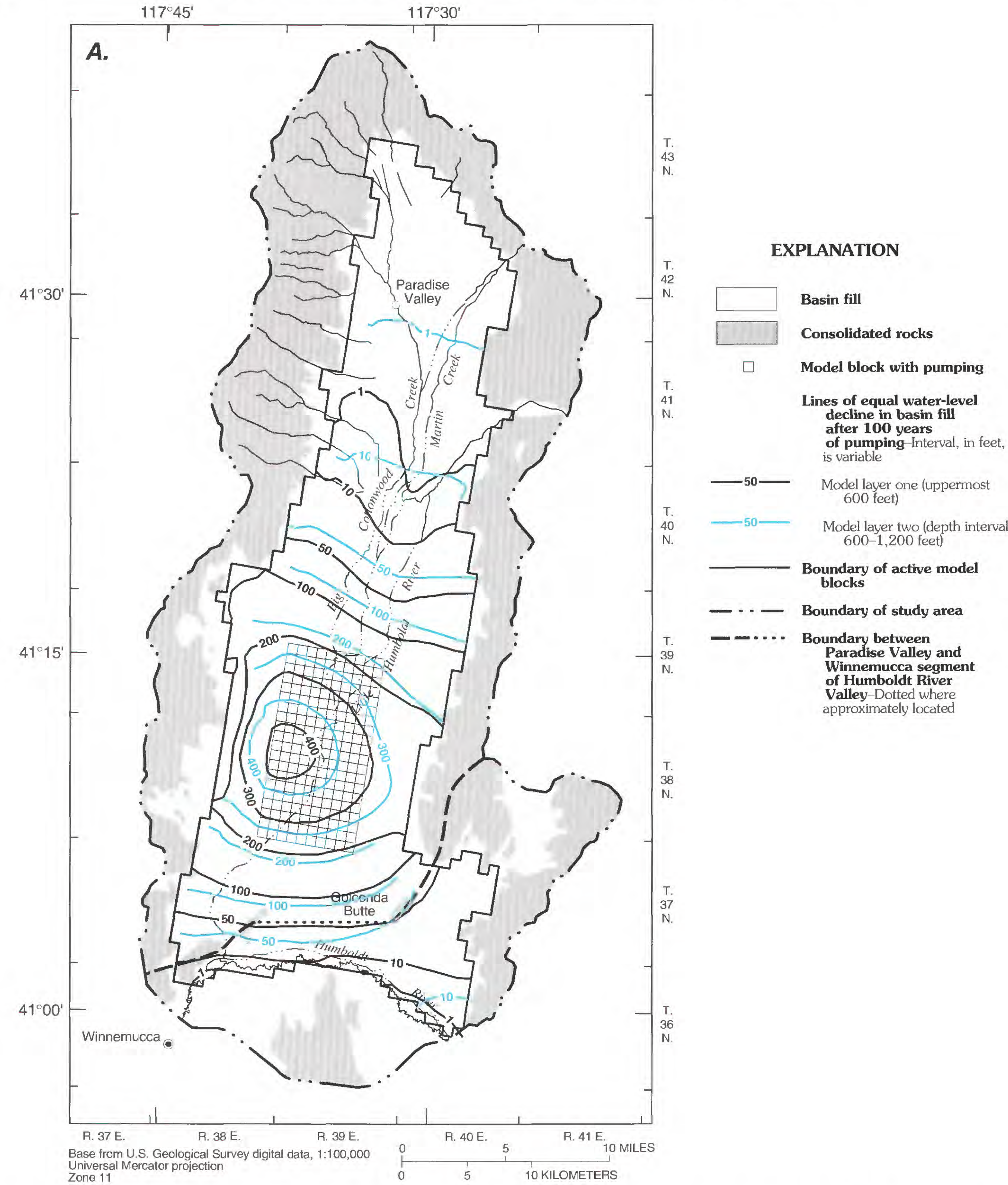
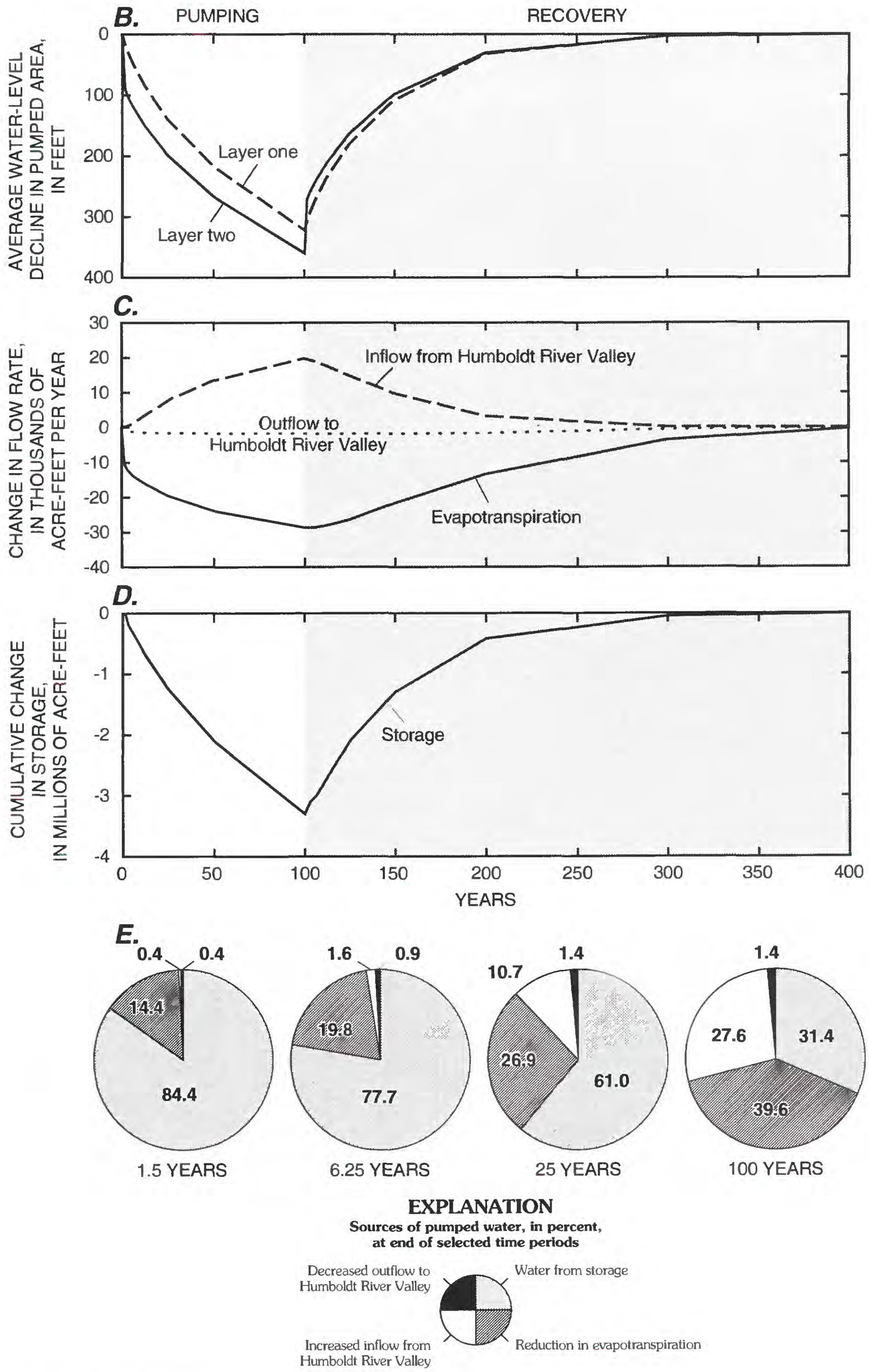


FIGURE 35.—Response of basin-fill aquifer to development scenario two, Paradise Valley, Humboldt County, Nevada. Net pumpage, 72,000 acre-feet per year, concentrated in southern end of Paradise Valley. (*A*) Water-level declines in model layers one and two after 100 years; (*B*) average water-level declines in pumped area during pumping and recovery periods; (*C*) changes in rate of evapotranspiration and underflow to and from Humboldt River Valley during pumping and recovery periods; (*D*) cumulative change in storage during pumping and recovery periods; and (*E*) sources of pumped water at end of selected time periods.



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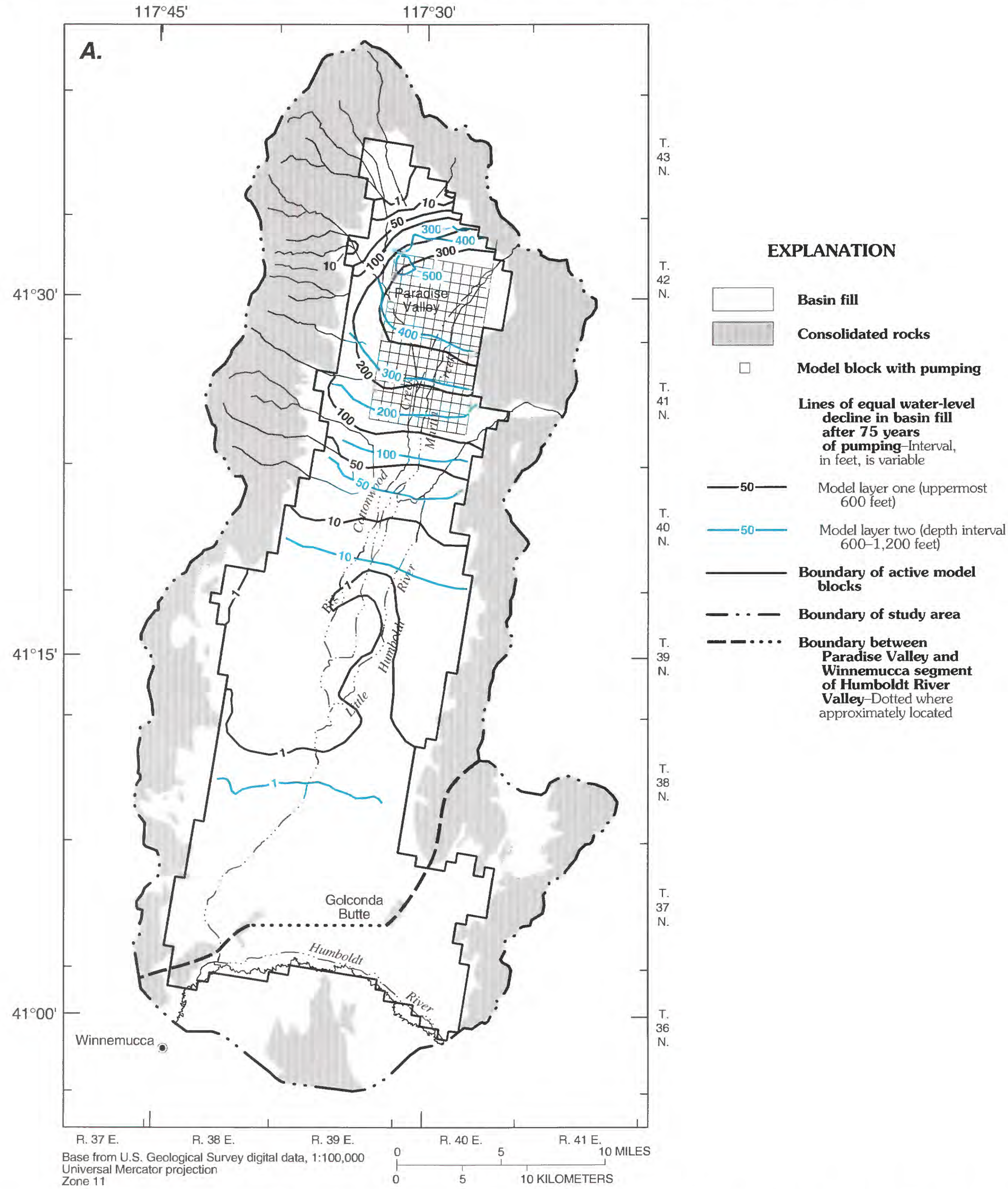


FIGURE 36.—Response of basin-fill aquifer to development scenario three, Paradise Valley, Humboldt County, Nevada. Net pumpage, 72,000 acre-feet per year, concentrated in northern end of Paradise Valley. (*A*) Water-level declines in model layers one and two after 75 years; (*B*) average water-level declines in pumped area during pumping and recovery periods; (*C*) changes in rate of evapotranspiration and underflow to and from Humboldt River Valley during pumping and recovery periods; (*D*) cumulative change in storage during pumping and recovery periods; and (*E*) sources of pumped water at the end of selected time periods.

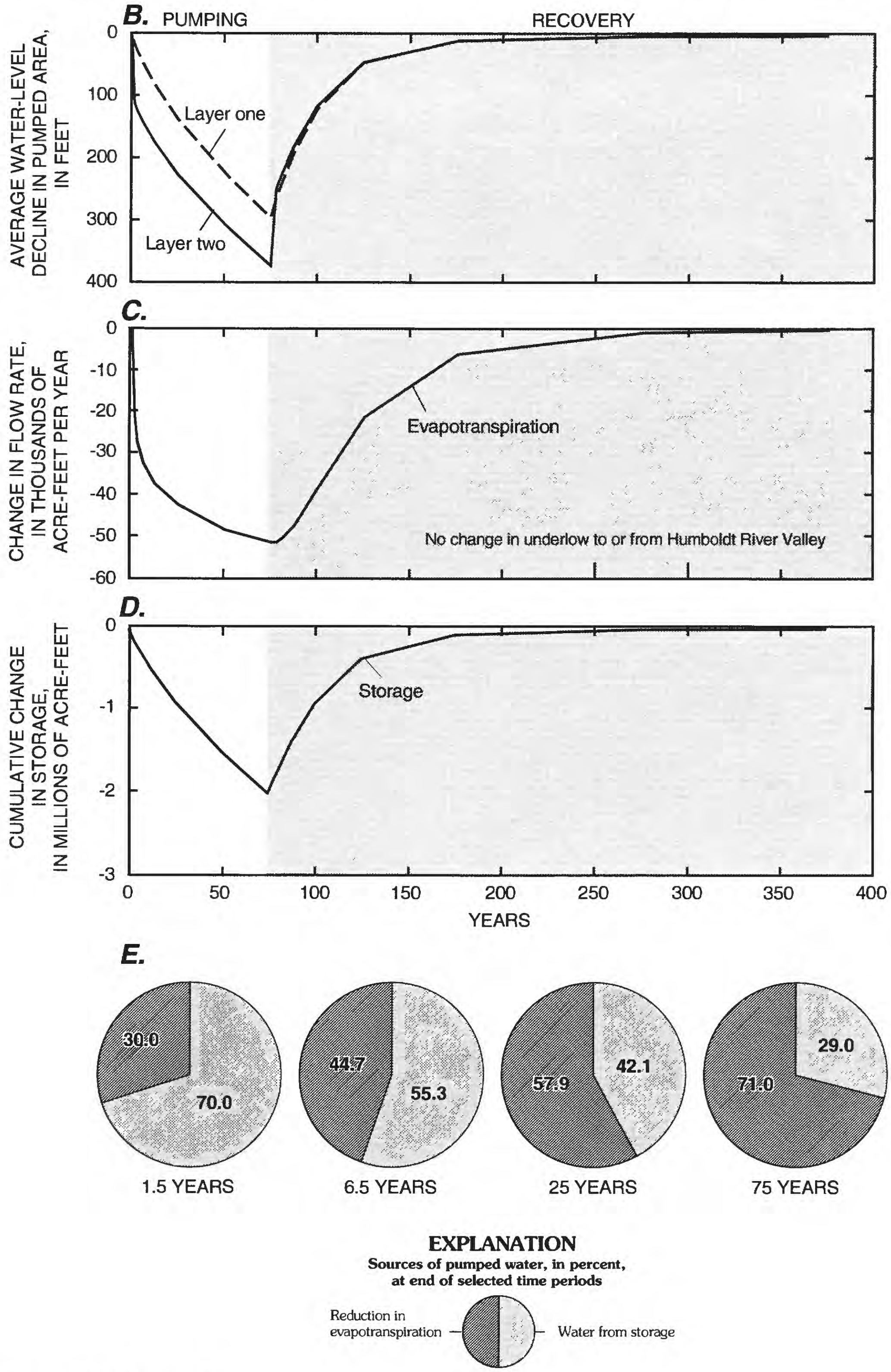


FIGURE 36.—Continued

TABLE 15. —*Simulated ground-water budgets after selected periods of pumping, Paradise Valley, Humboldt County, Nevada, development scenario two*

[Values in acre-feet per year]

	Predevelopment conditions	Conditions after indicated period of pumping				
		1.5 years	12.5 years	25 years	50 years	100 years
RECHARGE						
Recharge near contact between basin fill and consolidated rocks[1]	7,200	7,200	7,200	7,200	7,200	7,200
Leakage from streams	65,000	65,000	65,000	65,000	65,000	65,000
Underflow from Humboldt River Valley	1,300	1,500	4,700	8,900	15,000	21,000
Total recharge (rounded)	74,000	74,000	77,000	81,000	87,000	93,000
DISCHARGE						
Pumpage	minor	72,000	72,000	72,000	72,000	72,000
Evapotranspiration	71,000	61,000	55,000	52,000	48,000	43,000
Leakage to streams	800	800	800	800	800	800
Underflow to Humboldt River Valley	1,800	1,300	300	200	100	50
Total discharge (rounded)	74,000	135,000	128,000	125,000	121,000	116,000
DIFFERENCE (discharge minus recharge)	0	61,000	51,000	44,000	34,000	23,000
COMPUTED STORAGE DEPLETION[2]	0	59,000	51,000	44,000	33,000	23,000

[1] Includes leakage from streams where estimated annual flow is less than 1,200 acre-feet per year.

[2] Difference between estimates of recharge and discharge and storage depletion represents computational errors due primarily to truncation and rounding.

was concentrated in the central part and distributed throughout the area of evapotranspiration (figs. 37*B* and 38*B*). The greater declines in layer two are the result of simulating pumpage in that layer in an attempt to reduce declines in layer one. Reducing water-level declines in layer one restricted pumping periods to less than 100 years because water-level declines exceeded the thickness of model layer one in several model blocks. The greater declines in layer two when pumping at the northern end as compared with pumping at the southern end is the result of blocks with assigned pumping being closer to inactive blocks (no-flow boundaries) than at the southern end, and because the basin fill thins rapidly near the pumped area, resulting in lower transmissivities and storage coefficients in layer two. In addition, pumping at the southern end induced additional flow from the Humboldt River, thus reducing water-level declines in the area.

Leakage from streams in Paradise Valley did not increase in the scenarios (tables 14–18) when computed for the entire valley because all streamflow in these simulations recharged the basin-fill aquifer in Paradise Valley. The only difference between the scenarios was where streams stopped flowing in the valley. In the steady-state simulations, streamflow nearly reached the Humboldt River, whereas streamflow ceased several miles farther upstream in the selected development scenarios.

A slight reduction (less than 1,000 acre-ft/yr) in stream leakage into the basin-fill aquifer was simulated when pumping was concentrated at the northern end (scenario three). In the steady-state simulation, some ground water discharged to a few stream reaches near the town of Paradise Valley and was simulated as leakage back into the aquifer farther downstream. However, in the scenario where pumping was concentrated in the northern end of the valley, no ground water discharged to streams near the town, and therefore the total quantity of stream leakage decreased.

Most of the storage in the valley is replaced within the first 100 years after termination of pumping, and water levels eventually recover to within a few feet of their initial levels. The water

TABLE 16. —*Simulated ground-water budgets after selected periods of pumping, Paradise Valley, Humboldt County, Nevada, development scenario three*

[Values in acre-feet per year]

	Predevel-opment conditions	Conditions after indicated period of pumping				
		1.5 years	12.5 years	25 years	50 years	75 years
RECHARGE						
Recharge near contact between basin fill and consolidated rocks[1]	7,200	7,200	7,200	7,200	7,200	7,200
Leakage from streams	65,000	65,000	65,000	65,000	65,000	65,000
Underflow from Humboldt River Valley	1,300	1,300	1,300	1,300	1,300	1,300
Total recharge (rounded)	74,000	74,000	74,000	74,000	74,000	74,000
DISCHARGE						
Pumpage	minor	72,000	72,000	72,000	72,000	72,000
Evapotranspiration	71,000	50,000	34,000	30,000	24,000	20,000
Leakage to streams	800	300	200	200	100	60
Underflow to Humboldt River Valley	1,800	1,800	1,800	1,800	1,800	1,800
Total discharge (rounded)	74,000	124,000	108,000	104,000	98,000	94,000
DIFFERENCE (discharge minus recharge)	0	50,000	34,000	30,000	24,000	20,000
COMPUTED STORAGE DEPLETION[2]	0	50,000	35,000	30,000	24,000	20,000

[1] Includes leakage from streams where estimated annual flow is less than 1,200 acre-feet per year.

[2] Difference between estimates of recharge and discharge and storage depletion represents computational errors due primarily to truncation and rounding.

removed from storage during pumping is not mined because once pumping ceases, storage in the basin-fill aquifer is replenished much as it is on a yearly basis when the aquifer is replenished in the winter and spring and depleted during the summer and fall. If pumping should result in the irreversible compaction of the fine-grained deposits, then water released for the compaction is a one-time source that cannot be replenished once pumping stops and can be considered as mined. However, this process was not analyzed in any of the development scenarios. The effects of irreversible compaction on the basin-fill aquifer in Paradise Valley would have been to reduce water-level declines in the aquifer and to increase the quantity of water removed from storage.

In summary, maximum water-level declines and consequently the quantity of water removed from storage were more in the scenarios where pumping was concentrated away from the central part of the valley—the principal area of stream leakage and natural evapotranspiration. Because two scenarios could not be simulated for the entire 300-year period, comparison of the scenarios is summarized after 50 years in table 19. In general, concentrating pumping in the northern and central parts of the valley and in the area of evapotranspiration resulted in the greatest reduction in evapotranspiration, whereas concentrating pumping in the southern end of the valley caused the greatest increase in underflow from the adjacent Humboldt River Valley and also produced the most water removal from storage, mostly because of higher specific yields in the southern part of the valley. Even pumping ground water at the rate and distribution estimated for 1982 (where actual pumpage is concentrated at the southern end) also resulted in an increase in underflow from Humboldt River Valley after 50 years (table 19). Concentrating pumping in the northern end of the valley did not affect ground-water flow in the southern end of the valley, but water levels in the pumped area could be

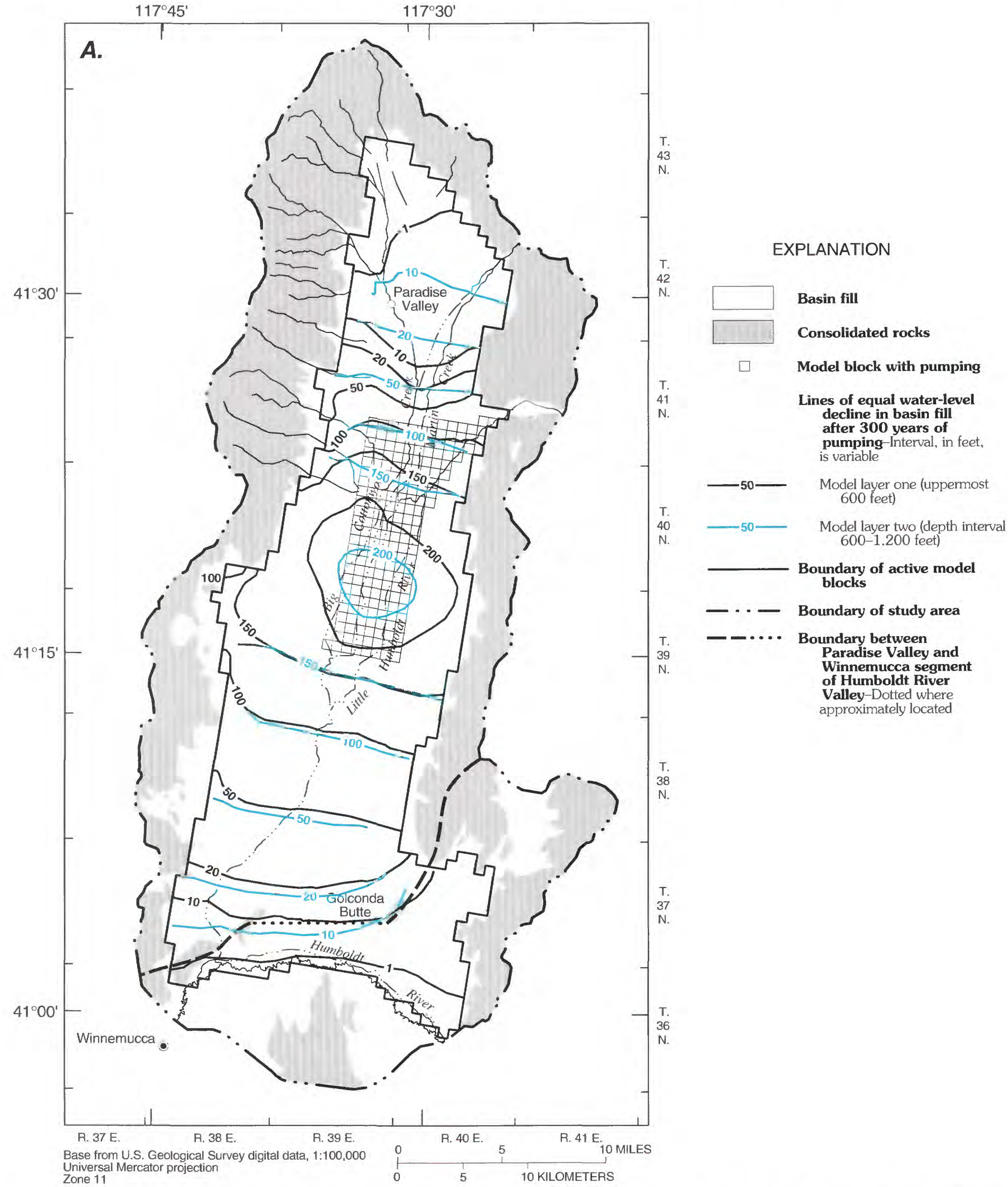
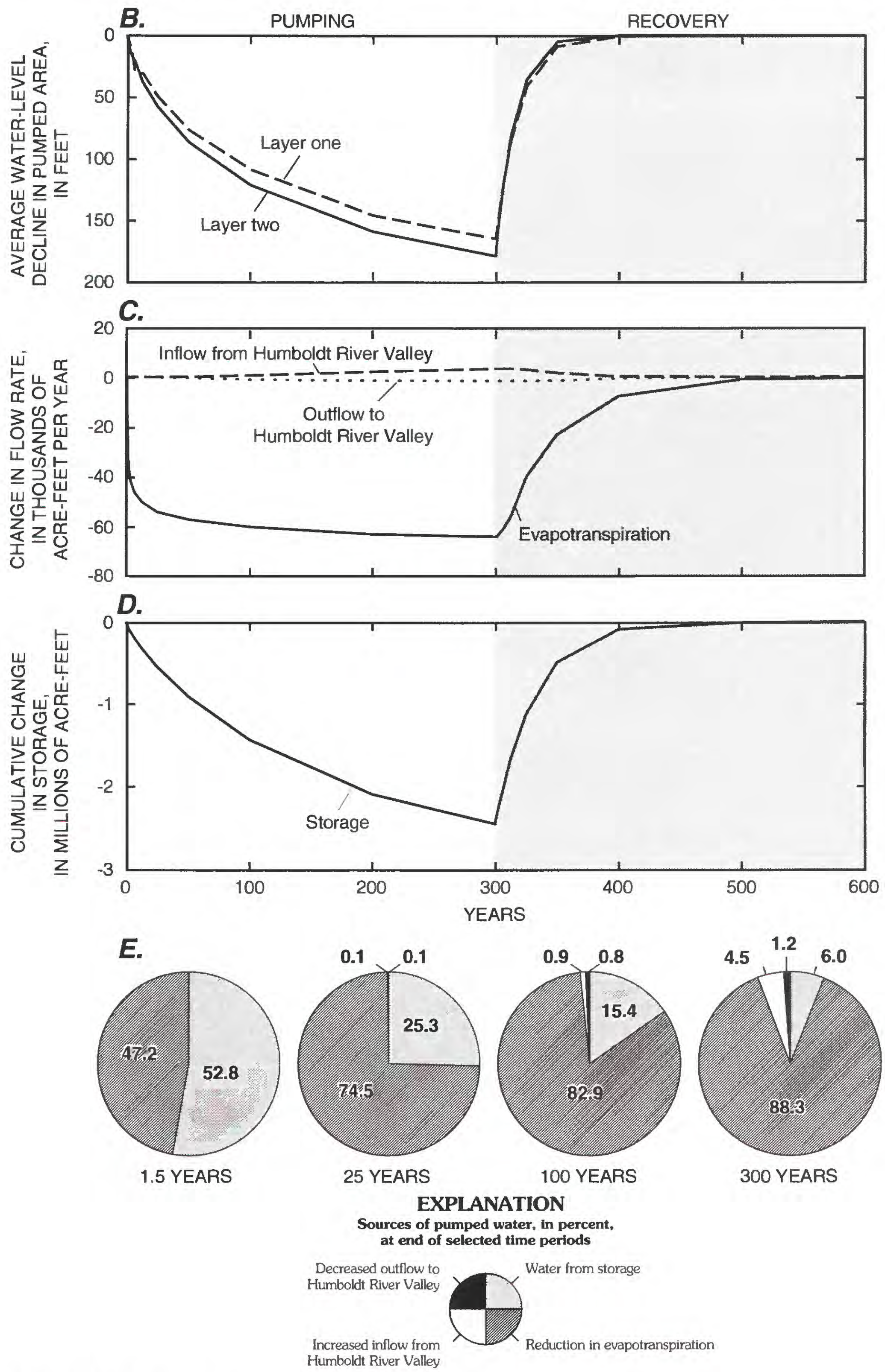


FIGURE 37.—Response of basin-fill aquifer to development scenario four, Paradise Valley, Humboldt County, Nevada. Net pumpage, 72,000 acre-feet per year, concentrated in central part of Paradise Valley. (*A*) Water-level declines in model layers one and two after 300 years; (*B*) average water-level declines in pumped area during pumping and recovery periods; (*C*) changes in rate of evapotranspiration and underflow to and from Humboldt River Valley during pumping and recovery periods; (*D*) cumulative change in storage during pumping and recovery periods; and (*E*) sources of pumped water at end of selected time periods.



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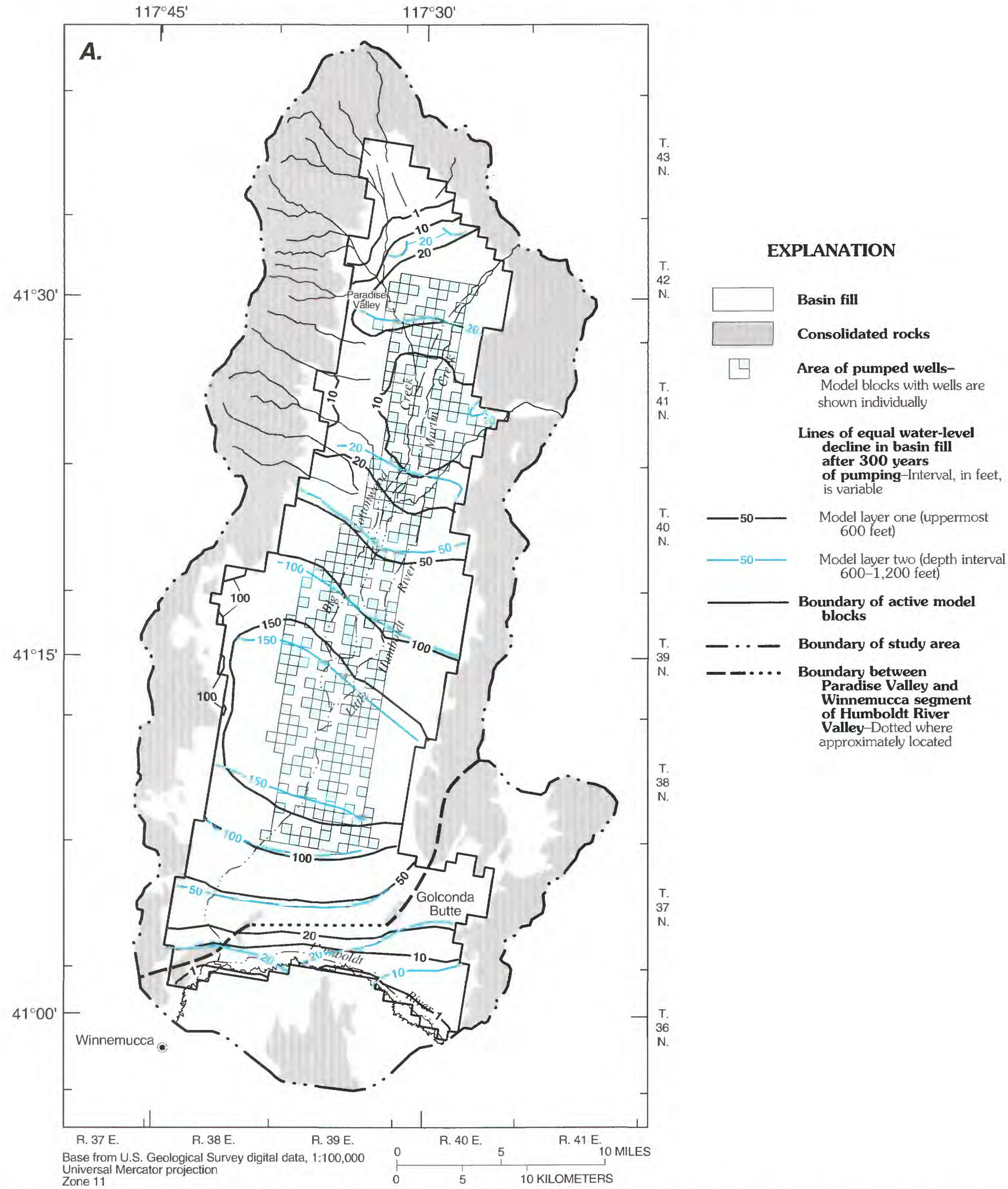

FIGURE 38.—Response of basin-fill aquifer to development scenario five, Paradise Valley, Humboldt County, Nevada. Net pumpage, 72,000 acre-feet per year, concentrated in area of evapotranspiration. (*A*) Water-level declines in model layers one and two after 300 years; (*B*) average water-level declines in pumped area during pumping and recovery periods; (*C*) changes in rate of evapotranspiration and underflow to and from Humboldt River Valley during pumping and recovery periods; (*D*) cumulative change in storage during pumping and recovery periods; and (*E*) sources of pumped water at the end of selected time periods.

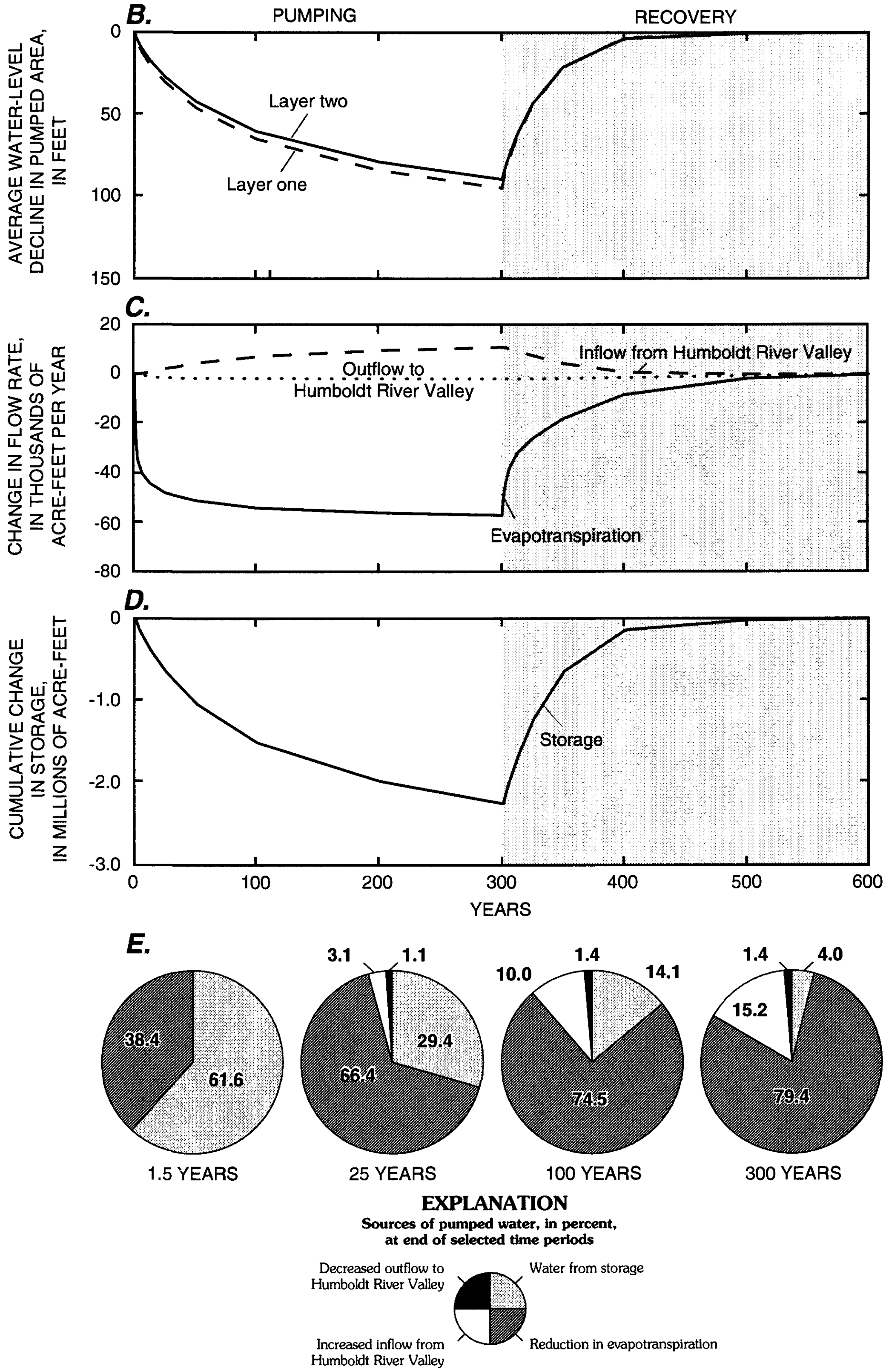

FIGURE 38.—Continued.

TABLE 17. —*Simulated ground-water budgets after selected periods of pumping, Paradise Valley, Humboldt County, Nevada, development scenario four*

[Values in acre-feet per year]

	Predevel-opment conditions	Conditions after indicated period of pumping				
		1.5 years	12.5 years	25 years	50 years	300 years
RECHARGE						
Recharge near contact between basin fill and consolidated rocks[1]	7,200	7,200	7,200	7,200	7,200	7,200
Leakage from streams	65,000	65,000	65,000	65,000	65,000	65,000
Underflow from Humboldt River Valley	1,300	1,300	1,300	1,300	1,400	4,500
Total recharge (rounded)	74,000	74,000	74,000	74,000	74,000	77,000
DISCHARGE						
Pumpage	minor	72,000	72,000	72,000	72,000	72,000
Evapotranspiration	71,000	37,000	21,000	17,000	14,000	8,100
Leakage to streams	800	700	400	300	300	300
Underflow to Humboldt River Valley	1,800	1,800	1,800	1,700	1,500	200
Total discharge (rounded)	74,000	112,000	95,000	91,000	88,000	81,000
DIFFERENCE (discharge minus recharge)	0	38,000	21,000	17,000	14,000	4,000
COMPUTED STORAGE DEPLETION[2]	0	36,000	21,000	18,000	14,000	3,600

[1] Includes leakage from streams where estimated annual flow is less than 1,200 acre-feet per year.

[2] Difference between estimates of recharge and discharge and storage depletion represents computational errors due primarily to truncation and rounding.

lowered below levels that are economical. Thus, concentrating pumping in certain areas of the valley could, with time, produce large water-level declines and induce flow from Humboldt River Valley, a process that could, in turn, induce flow from the Humboldt River.

SUMMARY AND CONCLUSIONS

Paradise Valley, in north-central Nevada near Winnemucca, was chosen as one of several basins to be studied as part of the Great Basin Regional Aquifer-System Analysis (RASA) project. The overall Great Basin RASA project includes much of Nevada, the western half of Utah, and small parts of Arizona, California, Oregon, and Idaho. Paradise Valley was chosen to represent the many basins that drain to the Humboldt River because recent large increases in ground-water pumping in this valley produced water-level declines of more than 80 ft; the increased pumpage and resulting water-level declines helped the analysis of ground-water flow by providing an observed stress and response that was used to calibrate a model of the basin-fill aquifer. The principal technique used to analyze flow in the basin-fill aquifer of Paradise Valley and to determine the effects of selected ground-water development scenarios was a computer program that simulates ground-water flow in three dimensions. The valley is an elongate basin that trends northeasterly. It is at most 13 mi wide and about 40 mi long and is bounded by mountains on the northern, western, and eastern sides. To the south, it merges with Humboldt River Valley.

The major hydrogeologic units in the study area were divided into two groups: basin fill that includes dune sands, younger and older alluvial

TABLE 18. —*Simulated ground-water budgets after selected periods of pumping, Paradise Valley, Humboldt County, Nevada, development scenario five*

[Values in acre-feet per year]

	Predevel-opment conditions	Conditions after indicated period of pumping				
		1.5 years	12.5 years	25 years	50 years	300 years
RECHARGE						
Recharge near contact between basin fill and consolidated rocks[1]	7,200	7,200	7,200	7,200	7,200	7,200
Leakage from streams	65,000	65,000	65,000	65,000	65,000	65,000
Underflow from Humboldt River Valley	1,300	1,300	2,100	3,400	5,700	12,000
Total recharge (rounded)	74,000	74,000	74,000	76,000	78,000	84,000
DISCHARGE						
Pumpage	minor	72,000	72,000	72,000	72,000	72,000
Evapotranspiration	71,000	43,000	27,000	23,000	20,000	14,000
Leakage to streams	800	400	300	200	200	200
Underflow to Humboldt River Valley	1,800	1,800	1,200	1,000	600	100
Total discharge (rounded)	74,000	117,000	100,000	96,000	93,000	86,000
DIFFERENCE (discharge minus recharge)	0	43,000	26,000	20,000	15,000	2,000
COMPUTED STORAGE DEPLETION[2]	0	42,000	26,000	20,000	15,000	2,600

[1] Includes leakage from streams where estimated annual flow is less than 1,200 acre-feet per year.

[2] Difference between estimates of recharge and discharge and storage depletion represents computational errors due primarily to truncation and rounding.

gravel, sand, silt, and clay, and lesser quantities of lacustrine and volcanic deposits; and consolidated rocks, which are exposed in the surrounding mountains and presumably underlie the basin fill. The basin fill forms the principal aquifer in Paradise Valley. These deposits may exceed 8,000 ft in thickness near the middle of the valley.

Both steady-state and transient models were used in the analyses of the basin-fill aquifer. The steady-state model was calibrated primarily by adjusting the vertical and horizontal hydraulic conductivities until simulated water levels matched measured water levels between 1948 and 1968. The conductance values of streambed deposits also were adjusted until simulated stream losses approximated the estimated losses. Three transient models were used to simulate ground-water flow from 1948 through 1982. The first transient model simulated the period 1948–68, in which streamflows and pumpage were averaged for 3- to 6-year periods. The second transient model simulated the period 1969–78, in which streamflows and pumpage were averaged for each year. The third model simulated the period 1979–82, in which streamflows and pumpage were averaged for 16 three-month periods. These transient models were calibrated primarily by adjusting the specific yield of the basin-fill aquifer and the conductance values of streambed deposits until simulated water levels matched measured water levels at the end of 12 selected time periods between 1948 and 1982. During the transient simulations, streambed-conductance values were increased for time periods of above-normal streamflow because stream widths and depths generally increased, resulting in greater infiltration.

Estimates of hydraulic conductivity in the upper 600 ft of basin fill were determined mainly from

TABLE 19.—*Summary of hydrologic effects on basin-fill aquifer in Paradise Valley, Humboldt County, Nevada after 50 years of pumping, using five selected development scenarios*

	Pumpage at net rate estimated for 1992; wells distributed as in 1982	Pumpage at estimated rate of recharge; wells concentrated in:			
		Southern end of valley	Northern end of valley	Central part of valley	Area of evapotranspiration
Development scenario	1	2	3	4	5
Pumpage (acre-feet per year)	[a]36,000	72,000	72,000	72,000	72,000
Increased underflow from Humboldt River Valley (acre-feet per year)[b]	2,700	13,000	0	120	4,500
Decreased underflow to Humboldt River Valley (acre-feet per year)[b]	1,500	1,700	0	300	1,600
Decreased evapotranspiration (acre-feet per year)[b]	21,000	24,000	48,000	57,000	51,000
Storage depletion (millions of acre-feet)	0.7	2.1	1.5	0.9	1.0
Maximum water-level decline (feet)[c]					
Layer 1	170	280	310	110	99
Layer 2	130	330	440	96	82

[a] Does not include net pumpage of 2,800 acre-feet per year in adjacent Humboldt River Valley, which was included in model simulation.

[b] Changes are relative to results from model simulations of predevelopment conditions (1948–68).

[c] Model layer one corresponds to uppermost 600 feet of basin fill. Model layer two corresponds to basin fill between depths of 600 and 1,200 feet.

specific-capacity data. The average hydraulic conductivity for 90 wells is 3.7×10^{-4} ft/s (32 ft/d), assuming a specific yield of 0.3, and 4.1×10^{-4} ft/s (35 ft/d), assuming a specific yield of 0.1. Higher hydraulic conductivities are generally in the center of the valley, where well-sorted stream deposits are common, and less along the margins, where poorly sorted fan deposits are dominant. The average hydraulic conductivity in model layer one is 2×10^{-4} ft/s (17 ft/d) for the calibrated model, or a factor of two less than that estimated from specific-capacity data, but the general distribution is the same. The reason for a decrease in the model-calculated hydraulic conductivities is that the values represent an average of both coarse- and fine-grained deposits, whereas hydraulic conductivities estimated from specific-capacity data generally represent the coarser deposits.

The same distribution of horizontal hydraulic conductivity is used in model layers two and three, except that the values are reduced 50 percent for every 1,200 ft of additional depth. Vertical hydraulic conductivities used to simulate flow between model layers averaged 3×10^{-6} ft/s (0.3 ft/d) between model layers one and two and 5×10^{-7} ft/s (0.04 ft/d) between model layers two and three.

Specific yield for the upper 200 ft of saturated basin fill was estimated by dividing the terms (generally lithologic descriptions) described in drillers' logs into six categories, each of which was assigned a specific-yield value. The highest specific yield is more than 20 percent, whereas the lowest value is less than 10 percent. The distribution of specific yield is similar to the distribution of hydraulic conductivity, whereby higher values are generally in the center of the valley and lower values along the margins. Specific yield was reduced by 10 percent during calibration of the model to duplicate the water-table depression near the southern end of the valley and seasonal water-level fluctuations throughout the study area. A specific-storage value of 2×10^{-6} per foot was used for the deeper deposits, on the basis of information obtained in similar basins that contain a mixture of coarse- and fine-grained deposits.

Recharge to the basin-fill aquifer is primarily from streams. Numerous small streams begin in the surrounding mountains, mostly at the northern end of the valley. The streams may be perennial in the mountains but usually lose their flow as they cross the fans into the valley. Streamflow onto the valley floor occurs normally during spring snowmelt. Two major streams (Martin Creek and Little Humboldt River) enter the valley through narrow canyons along the northeastern side. These streams join about halfway down the center of the valley and account for more than half of the estimated average annual recharge. During periods of high runoff, water flows to sand dunes that cross the southern end of the valley, where it forms a lake that remains until the water seeps into the ground, is evaporated, or is drained when a channel is dredged through the dunes. Prior to the early 1970's, discharge from the basin-fill aquifer in Paradise Valley was mainly by evapotranspiration, primarily along the valley floor where the depth to ground water was less than 25 ft. Evapotranspiration was highest in areas where the water table was near land surface and decreased as the depth to water increased. Much of the evapotranspiration was in the areas where streams were the source of ground water; thus, most of the water that recharged the basin-fill aquifer was discharged nearby. In the model simulations, no evapotranspiration was assumed when the depth to water below land surface exceeded 25 ft.

Prior to large quantities of pumpage in Paradise Valley, ground water flowed toward the Humboldt River; however, only a small part of the total recharge to the valley may have actually reached the river. Results from the best-fit steady-state simulation indicate that only about 1,800 acre-ft/yr of ground water left Paradise Valley near the channel of the Little Humboldt River as underflow to the adjoining Humboldt River Valley, and that perhaps as much as 1,300 acre-ft/yr entered Paradise Valley as underflow from Humboldt River Valley near Golconda Butte.

The quantity of water pumped from wells prior to 1948 was estimated to be less than 200 acre-ft/yr and was used for domestic purposes and livestock. Pumping of ground water began to increase in the mid 1950's, when several wells were drilled to supplement surface-water supplies used mostly to irrigate alfalfa and hay. Pumpage increased slowly to about 6,800 acre-ft/yr in 1970. It increased dramatically in the 1970's, when the southern end of the valley was determined to be ideal for growing potatoes. The estimated quantity of ground water pumped in 1982 was about 44,000 acre-ft, concentrated in the southern end of the valley. An additional 3,800 acre-ft was pumped from the basin fill in the adjacent Humboldt River Valley.

The increased pumpage has altered the direction of ground-water flow. The general direction of flow prior to development was from the margins of the valley to the center and then southward toward the Humboldt River, even though most of the water was discharged by evapotranspiration in the valley. By 1982, ground-water flow had shifted generally toward the water-table depression caused by pumping near the southern end of the valley.

The increase in pumpage occurred during a 14-year period of generally above-normal streamflows into the valley (120 percent of the long-term average for 1923–82). An extra 120,000 acre-ft of water was simulated as recharge to the basin-fill aquifer from 1969 through 1982. The quantity of water removed from storage between 1969 and 1982 was 110,000 acre-ft. Water in storage increased 75,000 acre-ft from 1969 through 1972, then decreased 185,000 acre-ft from 1973 through 1982. The quantity of water removed from storage from 1972 through 1982 accounted for about 50 percent of the total pumpage and 60 percent of the net pumpage.

Simulations assuming different quantities of streamflow indicate that if development had occurred during a period when flow equaled the long-term average for 1923-82, water-level declines near the southern end of the valley might have been as much as 20 ft more and an additional 65,000 acre-ft might have been removed from storage due to a reduction in recharge near the southern end of the valley. If, instead, development had occurred during a period when flow equaled the lowest recorded 14-year period from 1923 through 1936 (74 percent of the long-term average for 1923–82), water-level declines in the southern end would be similar to those of average conditions, but because of reduced recharge farther up valley, water levels might have declined 5 ft throughout much of the valley and an additional 130,000 acre-ft of water might have been removed from storage.

Five different development scenarios were simulated to determine what effects different pumping patterns might have on the basin-fill aquifer in Paradise Valley and, by analogy, in other tributary basins to the Humboldt River. Net pumpage for the first scenario was set equal to that estimated for 1982, and was about 36,000 acre-ft/yr in Paradise Valley and 2,800 acre-ft/yr in adjacent Humboldt River Valley. This scenario was designed to test the long-term effects of the recent pumpage on the basin-fill aquifer. Net pumpage in the last four scenarios was set equal to 72,000 acre-ft/yr, but the location of pumpage in Paradise Valley changed. The distribution of pumpage in the valley for each simulation included, respectively, wells concentrated at the southern end; wells concentrated at the northern end; wells concentrated along the central part; and wells distributed throughout the area of evapotranspiration prior to pumpage. All five scenarios are based on the assumptions that average climatic conditions for 1923–82 would continue for hundreds of years, that all streamflow recharges the basin-fill aquifer as leakage, and that no water is released from permanent compaction of fine-grained deposits. Although these assumptions limit the results of the hypothetical simulations, the general conclusions regarding the model simulations are nonetheless valid.

Results from the first scenario, which is based on an assumed net pumpage equal to that of 1982, produced water-level declines in the southern part of the valley of more than 200 ft after 300 years. These declines were near the area where pumpage was most concentrated in 1982. The simulation also indicated ground-water flow from Humboldt River Valley into Paradise Valley. After 50 years, ground-water inflow to Paradise Valley from Humboldt River Valley increased about 2,700 acre-ft/yr; after 300 years, the flow increased about 7,400 acre-ft/yr. Similarly, ground-water outflow from Paradise Valley to Humboldt River Valley decreased 1,500 acre-ft/yr after 50 years, and 1,700 acre-ft/yr after 300 years.

Concentrating pumpage at the northern and southern ends of Paradise Valley and away from the major area of stream leakage and natural evapotranspiration resulted in the greatest water-level declines, which exceeded 400 ft after 75 years of pumping in the northern end and 100 years of pumping in the southern end. Both scenarios resulted in greater quantities of water being removed from storage. In addition, concentrating pumpage at the southern end of the valley produced a reversal in the net flow between Paradise Valley and Humboldt River Valley. Prior to development, the estimated net flow of ground water was about 500 acre-ft/yr from Paradise Valley into Humboldt River Valley. After 50 years with pumping concentrated at the southern end of the valley, the net flow was from Humboldt River Valley into Paradise Valley at a rate of about 15,000 acre-ft/yr and increased to about 21,000 acre-ft/yr after 100 years.

Concentrating pumpage in the central part of the valley near the area where major streams recharge the basin-fill aquifer and where natural evapotranspiration occurs resulted in water-level declines generally less than 200 ft after 300 years. Water-level declines were slightly less when wells were distributed throughout the area of evapotranspiration. This simulation also had the least quantity of water removed from storage compared with the volume of water pumped. However, the simulation where pumpage was distributed throughout the area of evapotranspiration resulted in less capture of evapotranspiration and more underflow from Humboldt River Valley than the simulation where pumpage was concentrated in the central part. These differences were caused by pumpage in the area of evapotranspiration extending farther south, closer to the boundary between the two valleys.

In conclusion, concentrating pumpage in the northern and southern ends of Paradise Valley might produce large water-level declines without effectively reducing the natural discharge of ground water in the central part of the valley. In addition, concentrating pumpage in the southern end of the valley (the present-day pattern) might induce flow from Humboldt River Valley; depending on the quantity of pumpage, this in turn could affect the flow in the Humboldt River.

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