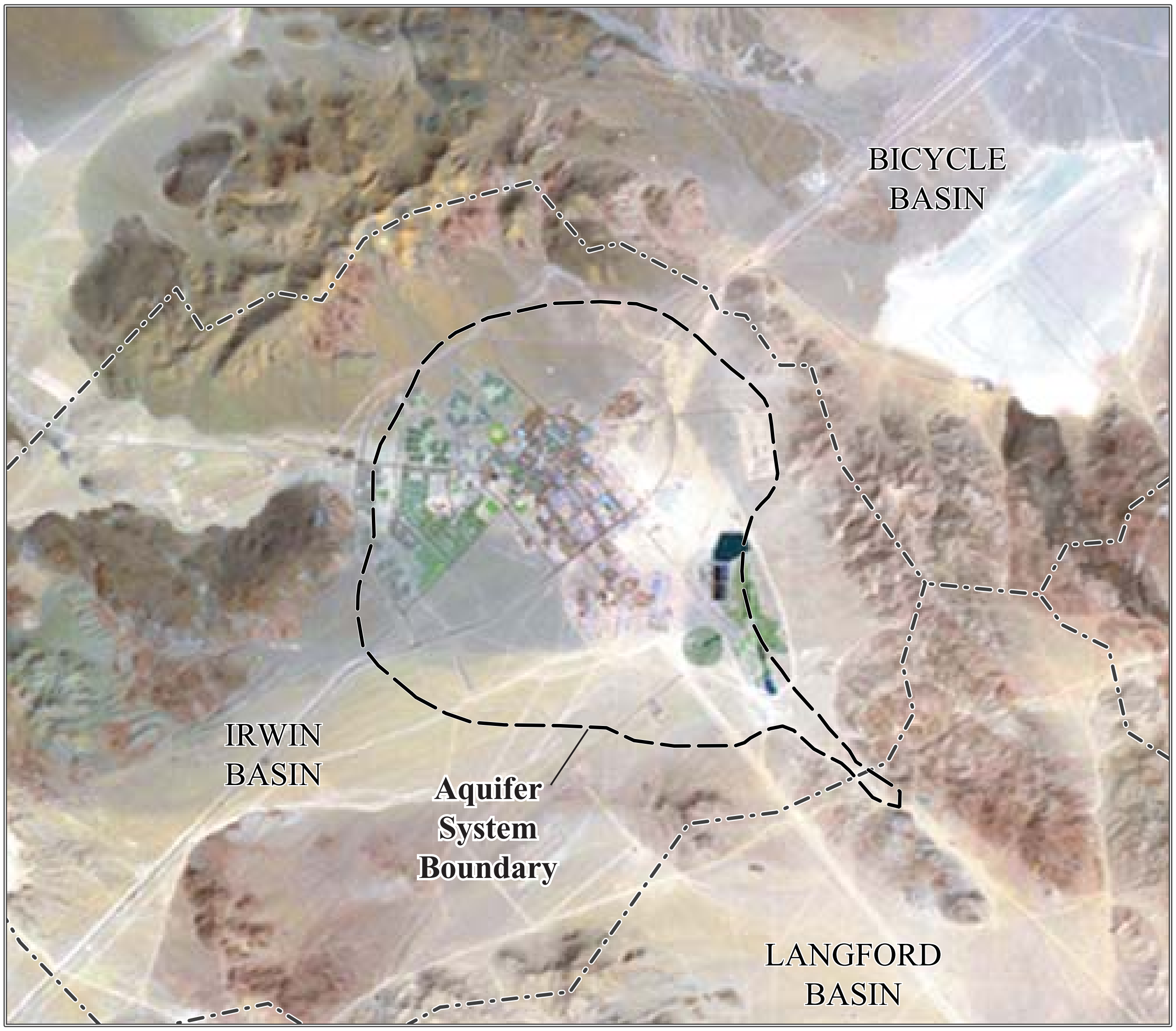
U.S. Department of the Interior
U.S. Geological Survey



SIMULATION OF GROUND-WATER FLOW IN THE IRWIN BASIN AQUIFER SYSTEM, FORT IRWIN NATIONAL TRAINING CENTER, CALIFORNIA

Prepared in cooperation with
FORT IRWIN NATIONAL TRAINING CENTER

Water-Resources Investigations Report 02-4264

science for a changing world

Simulation of Ground-Water Flow in the Irwin Basin Aquifer System, Fort Irwin National Training Center, California

By Jill N.Densmore

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 02-4264

Prepared in cooperation with the

FORT IRWIN NATIONAL TRAINING CENTER

5010-03

Sacramento, California
2003

U.S. DEPARTMENT OF THE INTERIOR

GALE A. NORTON, *Secretary*

U.S. GEOLOGICAL SURVEY

Charles G. Groat, *Director*

Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Government.

For additional information write to:

District Chief
U.S. Geological Survey
6000 J Street– Suite 2012
Sacramento, California 95819-6129
http://ca.water.usgs.gov

CONTENTS

FIGURES

TABLES

Table 3. Total annual pumpage from the Irwin, Bicycle, and Langford Basins, and range of estimated wastewater recharge calculated from wastewater inflow, potential evaporation and evapotranspiration in the Irwin Basin, Fort Irwin National Training Center, California, 1941–99 17

CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

CONVERSION FACTORS

Multiply	By	To obtain
acre-foot (acre-ft)	0.02832	cubic meter
acre-foot per day (acre-ft/d)	0.01427	cubic meter per day
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	2.54	centimeter
miles (mi)	1.609	kilometers
square mile (mi^2)	2.590	square kilometers

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=1.8\ °C+32.$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8.$$

VERTICAL DATUM

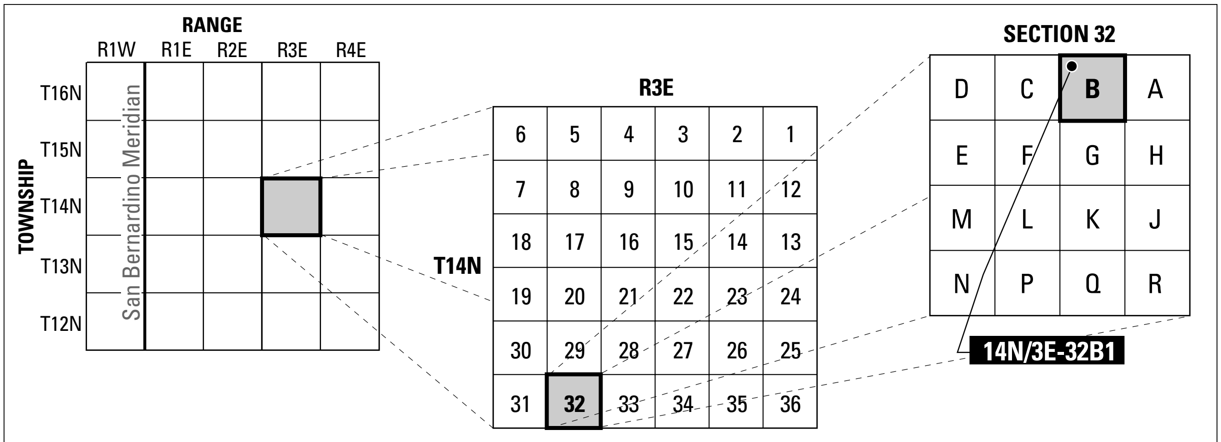
Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum *derived* from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

ABBREVIATIONS

BAS	basic
BCF	block-centered flow
GHB	general-head boundary
HFB	horizontal-flow boundary
MODFLOW	three-dimensional finite-difference modular ground-water flow model
MODPATH	particle tracking post-processing package
NTC	National Training Center
RECH	areal recharge package
SIP	strongly implicit procedure
USGS	U.S. Geological Survey

WELL-NUMBERING SYSTEM

Wells and springs are identified and numbered according to their location in the rectangular system for the subdivision of public lands. Identification consists of the township number, north or south; the range number, east or west; and the section number. Each section is divided into sixteen 40-acre tracts lettered consecutively (except I and O), beginning with "A" in the northeast corner of the section and progressing in a sinusoidal manner to "R" in the southeast corner. Within the 40-acre tract, wells are sequentially numbered in the order they are inventoried. The final letter refers to the base line and meridian. In California, there are three base lines and meridians: Humboldt (H), Mount Diablo (M), and San Bernardino (S). All wells in the study area are referenced to the San Bernardino base line and meridian (S). The letters (LYS) following the sequence number indicate a lysimeter. Well numbers consist of 15 characters and follow the format 014N003E032B001S. In this report, well numbers are abbreviated and written 13N/3E-5D1. Wells in the same township and range are referred to only by their section designation, 32B1. The following diagram shows how the number for well 14N/3E-32B1 is derived.



Well-numbering diagram (Note: maps in this report use abbreviated well numbers such as **"32B1"**)

Simulation of Ground-Water Flow in the Irwin Basin Aquifer System, Fort Irwin National Training Center, California

By Jill N. Densmore

ABSTRACT

Ground-water pumping in the Irwin Basin at Fort Irwin National Training Center, California resulted in water-level declines of about 30 feet from 1941 to 1996. Since 1992, artificial recharge from wastewater-effluent infiltration and irrigation-return flow has stabilized water levels, but there is concern that future water demands associated with expansion of the base may cause a resumption of water-level declines. To address these concerns, a ground-water flow model of the Irwin Basin was developed to help better understand the aquifer system, assess the long-term availability and quality of ground water, and evaluate ground-water conditions owing to current pumping and to plan for future water needs at the base.

Historical data show that ground-water-level declines in the Irwin Basin between 1941 and 1996, caused the formation of a pumping depression near the pumped wells, and that recharge from the wastewater-treatment facility and disposal area caused the formation of a recharge mound. There have been two periods of water-level recovery in the Irwin Basin since the development of ground water in this basin; these periods coincide with a period of decreased pumpage from the basin and a period of increased recharge of water imported from the Bicycle Basin beginning in 1967 and from the Langford Basin beginning in 1992. Since 1992, artificial recharge has exceeded pumpage in the Irwin Basin and has stabilized water-level declines.

A two-layer ground-water flow model was developed to help better understand the aquifer system, assess the long-term availability and quality of ground water, and evaluate ground-water conditions owing to current pumping and to plan for future water needs at the base. Boundary conditions, hydraulic conductivity, altitude of the bottom of the layers, vertical conductance, storage coefficient, recharge, and discharge were determined using existing geohydrologic data. Rates and distribution of recharge and discharge were determined from existing data and estimated when unavailable.

Results of predictive simulations indicate that in 50 years, if artificial recharge continues to exceed pumpage in Irwin Basin, water levels could rise as much as 65 feet beneath the pumping depression, and as much as 10 feet in the wastewater-treatment facility and disposal area.

Particle-tracking simulations were used to determine the pathlines and the traveltimes of water high in dissolved solids into the main pumping area. The pathlines of particles from two areas with high dissolved-solids concentrations show that in 50 years water from these areas almost reaches the nearest pumped well.

INTRODUCTION

This report describes one of a series of studies evaluating the geohydrologic conditions at the Fort Irwin National Training Center (NTC). In 1999, the Fort Irwin NTC obtained all of its potable water supply from ground water in the Irwin, Bicycle, and Langford Basins (fig. 1). Ground-water development began in the Irwin Basin in 1941. From 1941 to 1996, most of the ground-water pumpage was from the Irwin Basin which resulted in water-level declines of about 30 feet in the basin during this period. Pumping from the Bicycle and Langford Basins, began in 1967 and 1992, respectively; pumping from these basins has resulted in a decrease in the ground-water demand from the Irwin Basin. Since 1991, the combined pumping from the Bicycle and the Langford Basins has exceeded that of the Irwin Basin. Since the 1990's, reduced pumping and artificial recharge of wastewater from the Irwin, Bicycle, and the Langford Basins has caused water levels to stabilize or recover throughout much of the Irwin Basin. There is concern that future expansion of the base may cause additional water-level declines. Although water levels are currently recovering in the Irwin Basin, percolating treated wastewater through evaporite deposits underlying the wastewater-disposal areas has resulted in high concentrations of dissolved solids in ground water that is migrating toward the pumping depression near the center of the basin.

In 1992, the U.S. Geological Survey (USGS) entered into an agreement with the Fort Irwin NTC to evaluate the long-term availability and quality of ground water at the base using a phased approach. During the first phase, completed in 1997, the geohydrologic and geochemical framework of the Irwin Basin was determined (Densmore and Londquist, 1997). Potential problems identified were rising water levels and ground water containing high dissolved-solids concentrations. This current report presents the results of the second phase and documents the development and calibration of a numerical ground-water flow model of the Irwin Basin for which the geohydrologic information collected during phase 1 was used. The model will help to better understand the aquifer system, evaluate the long-term availability and quality of ground water, and ground-water conditions resulting from historical, current, and future pumping in the basin.

Location and Description of Study Area

The Fort Irwin NTC is about 130 mi northeast of Los Angeles and 35 mi northeast of Barstow in southern California (fig. 1). The base covers about 970 mi^2 of the northern part of the Mojave Desert and encompasses several ground-water basins. The Irwin, Bicycle, and Langford Basins currently supply water to the base (fig. 1).

The Irwin Basin has a fairly flat floor bordered to the east by Beacon Hill, to the north-northwest by Northwest Ridge, to the west by Southwest Ridge, and to the south by low-lying hills that separate the Irwin Basin from the Langford Basin (fig. 2). The surface-water drainage area of basin is about 30 mi^2 and the floor of the basin is about 7 mi^2. There are no perennial streams in the basin but there are several dry washes that convey surface flow during, or immediately after, large storms. Surface-water drainage out of the basin, when it occurs, is to the southeast through an unnamed ephemeral wash near Garlic Spring into the Langford Basin (fig. 2).

The basin climate is typical of the Mojave Desert having scant precipitation, hot summers, and cool winters. There are no official weather records for the basin, but records are available for nearby areas. At Goldstone, about 15 mi northwest of the basin (fig. 1), average annual precipitation is about 6.5 in., most of which occurs during the winter and the remainder occurs from a few isolated thunderstorms during the summer. At Barstow, 30 mi southwest of the basin, average annual precipitation is about 4.4 in. Between 1973 and 1999, the annual precipitation ranged from about 2 in. in 1975 to about 11.5 in. in 1983. Between 1940 and 1999, temperatures at Barstow ranged from 3° F to 116° F and averaged about 64° F. In Death Valley, about 80 mi north of the basin, the average annual potential evaporation is about 148 in., and at Newberry Springs, about 25 mi to the south, it is about 76 in. (National Oceanic and Atmospheric Administration, 1994; EarthInfo, Inc., 1995, 2000; David Inouye, California Department of Water Resources, written commun., 1996).

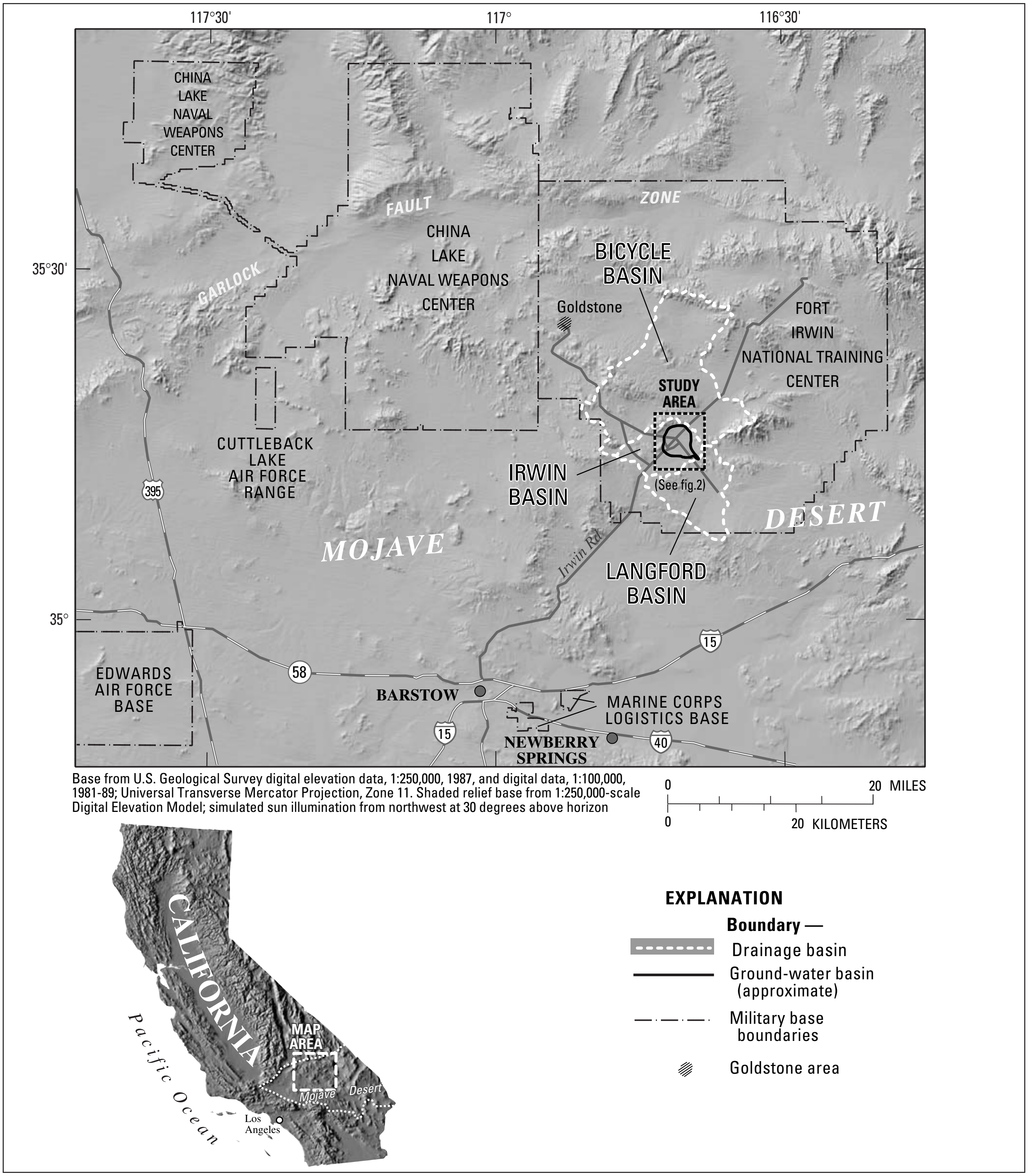


Figure 1. Mojave Desert region and location of study area at Fort Irwin National Training Center, California.

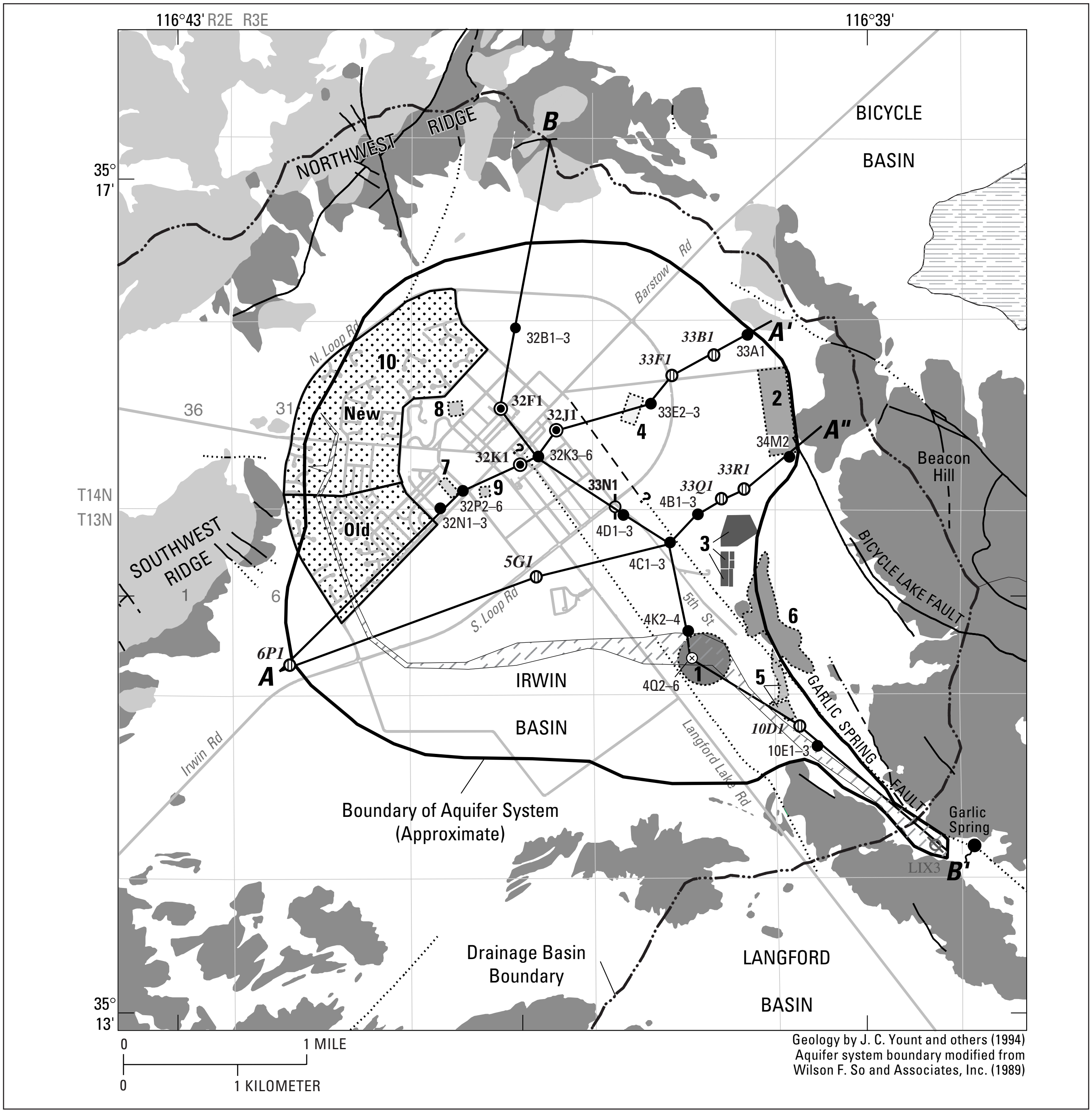


Figure 2. Generalized geologic map of the Irwin Basin, Fort Irwin National Training Center, California.

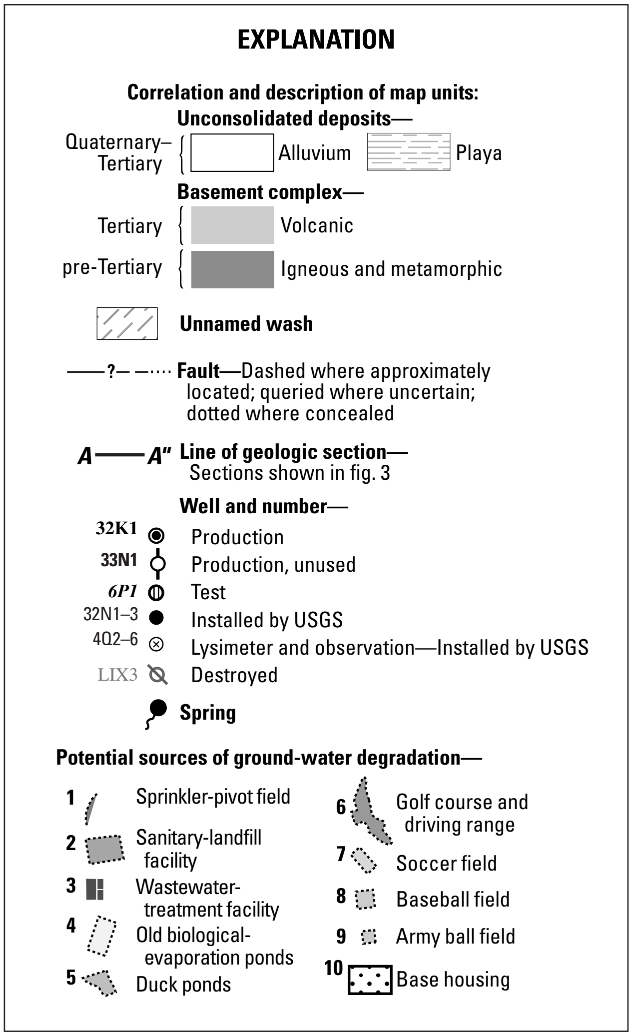


Figure 2.—Continued.

Acknowledgments

The author thanks the following personnel at Fort Irwin: Justine Dishart, Martha Shelby, and Muhammed Bari (Directorate of Public Works, Fort Irwin NTC) for providing funding to complete this model, and Walt Young (Directorate of Public Works, Fort Irwin NTC), John Sponsler, and the personnel at DynCorps for providing all available pumpage data. The author also thanks USGS co-workers Kathryn Koczot and Gregory Smith for entering 1990–96 pumpage data into a spreadsheet and Madeleine White for updating the pumpage data to 1999.

GEOHYDROLOGY

The geohydrology of the Irwin Basin is discussed in reports by C.F. Hostrup and Associates (1955), Kunkel and Riley (1959), James M. Montgomery and Associates, Inc. (1981), Wilson F. So and Associates, Inc. (1989), Yount and others (1994), and Densmore and Londquist (1997). The geohydrologic analysis presented by Densmore and Londquist (1997) is summarized here to provide the necessary background for understanding the construction of the numerical model discussed in the following sections.

Geologic Description of Aquifer System

The Irwin Basin is filled with as much as 950 ft of unconsolidated deposits that consist of younger alluvium of Quaternary age and older alluvium of late Tertiary to Quaternary age (fig. 3). The deposits are unconsolidated at land surface and become partly consolidated with depth. The unconsolidated deposits are the only water-bearing material in the basin from which appreciable amounts of ground water may be obtained. These deposits are underlain by a basement complex of volcanic rocks of late Tertiary to Quaternary age and igneous and metamorphic rocks of pre-Tertiary age, which convey insignificant amounts of ground water except in areas where they are jointed and fractured.

The older alluvium (fig. 3, QTa and Tl) consists of sand, gravel, and clay derived predominantly from granitic material—except in the northern part of the basin, where volcanic material dominates. Where the older alluvium consists predominantly of sand and gravel, it yields moderate amounts of water to wells. However, in the southeastern part of the basin, it consists almost entirely of low-permeability lacustrine deposits (fig. 3, B–B′, Tl) of silt and clay. These low-permeability deposits extend from well 14N/3E-33N1 near the center of the basin to well 13N/3E-10E1-3 in the unnamed wash that leads to Garlic Spring, and are bounded by the Garlic Spring Fault on the northeast and an unnamed fault on the southwest.

The younger alluvium (fig. 3, Qa) consists primarily of loose coarse sand and gravel with small amounts of clay. Some thin discontinuous clay lenses overlie the lacustrine deposits within the older alluvium in the area beneath the sprinkler-pivot field in the southeastern part of the basin (fig. 2) and may result in a perched water table in this area. Most of the younger alluvium lies above the water table; however, in areas where it is saturated, primarily in the center of the basin, it yields large quantities of water to wells (as much as to 1,000 gal/min). Wellbore-flow tests of selected base supply wells indicate that most of the water pumped comes from the younger alluvium (Densmore and Londquist, 1997).

The aquifer system in the Irwin Basin consists of an upper aquifer and a lower aquifer. The upper aquifer is unconfined and is contained within the saturated part of the younger alluvium. This aquifer reaches a maximum thickness of about 200 ft in the west-central part of the basin (fig. 3). The lower aquifer is confined throughout most of the basin and includes the older alluvium. This aquifer reaches a maximum thickness of more than 600 ft in the central part of the basin (fig. 3). Although some water is contained in the underlying basement complex, the effective base of the ground-water system is at the top of basement complex. The altitude of the surface of the basement complex in the Irwin Basin is shown in figure 4.

Faults and Ground-Water Boundaries

Numerous faults have been mapped in the bedrock hills surrounding the basin (Yount and others, 1994) (figs. 2 and 3); they include the Garlic Spring Fault, the Bicycle Lake Fault, and many unnamed faults. Most are buried beneath the unconsolidated deposits and thus, their presence within the basin is largely unknown. Yount and others (1994) mapped the Garlic Spring Fault into the unconsolidated deposits; they suggest that the fault may cut through both the younger and the older alluvium in the southeastern part of the basin. Water-quality and water-level data, presented by Densmore and Londquist (1997), indicate that the Garlic Spring Fault and a parallel unnamed fault may be acting, in part, as a partial barrier to horizontal ground-water flow, primarily in the lower aquifer. The water-quality data indicate that vertical flow is also being impeded on the west side of the Garlic Spring Fault, because of lithologic differences between the younger alluvium and the lacustrine deposits of the older alluvium. Minor compaction and deformation of the water-bearing deposits immediately adjacent to the faults, fault gouge along the fault zone, and cementation of the fault zone by the deposition of minerals from ground water are believed to cause the barrier effect of the faults.

The areal extent of the aquifer system is defined by the intersection of the water table and the surrounding rocks of the basement complex. During predevelopment conditions, the water table was about 2,300 feet above sea level. The boundary of the aquifer system coincides with the 2,300-foot altitude of the basement complex (fig. 4) (the approximate boundary of the basin is shown in figure 2). All the alluvial deposits above this altitude were unsaturated during predevelopment conditions.

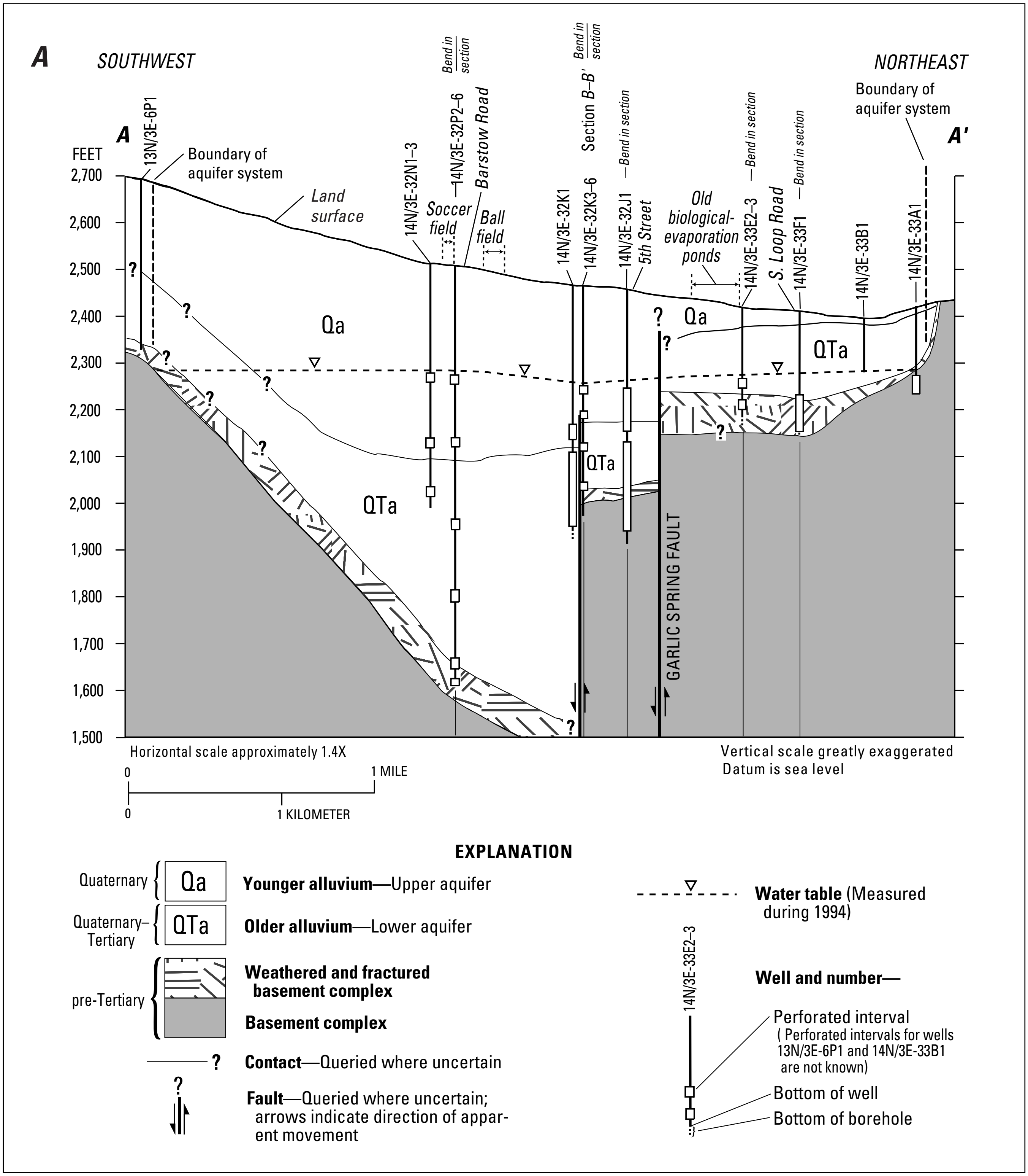


Figure 3. Generalized geology across the Irwin Basin, Fort Irwin National Training Center, California.

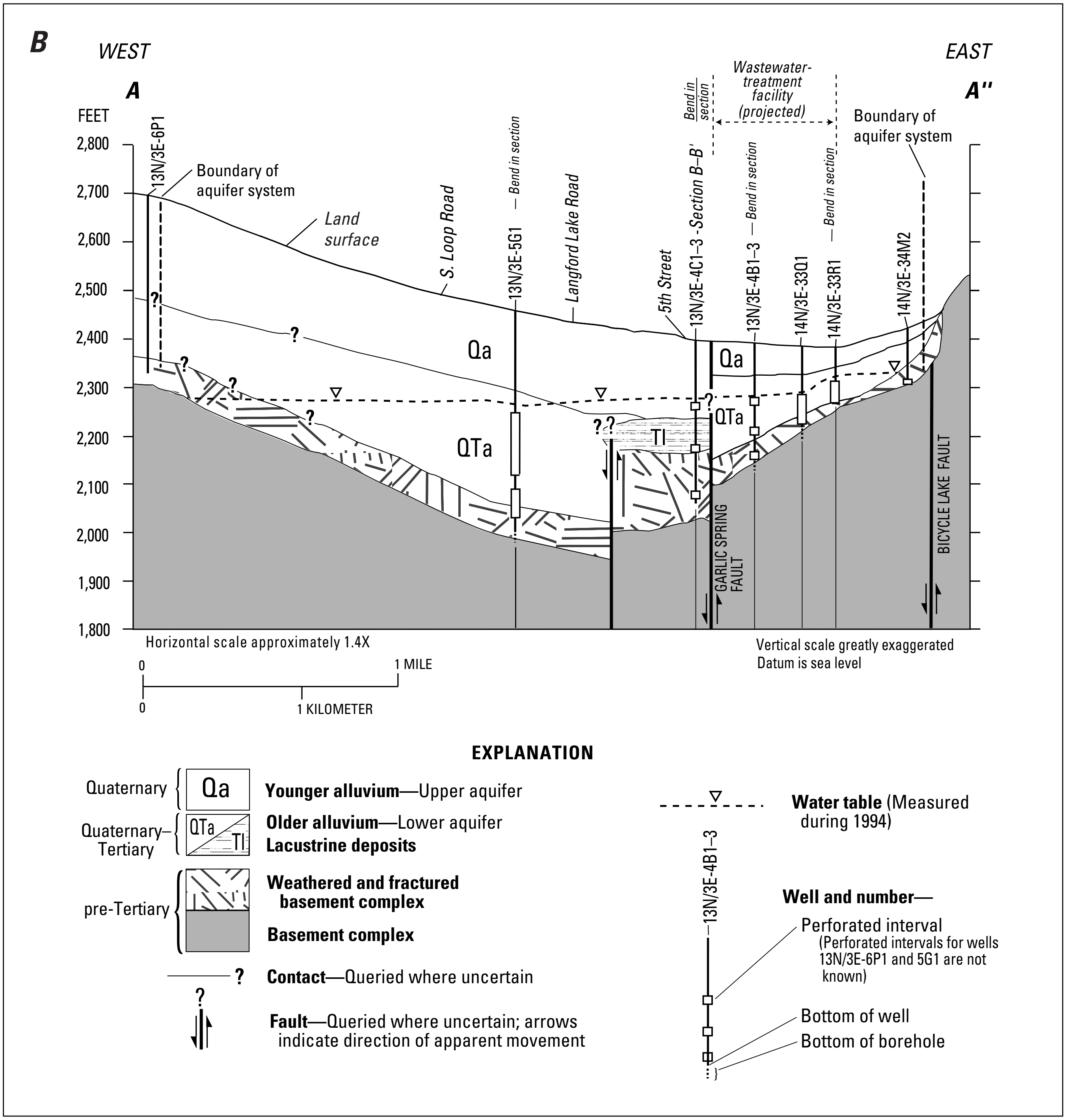


Figure 3.—Continued.

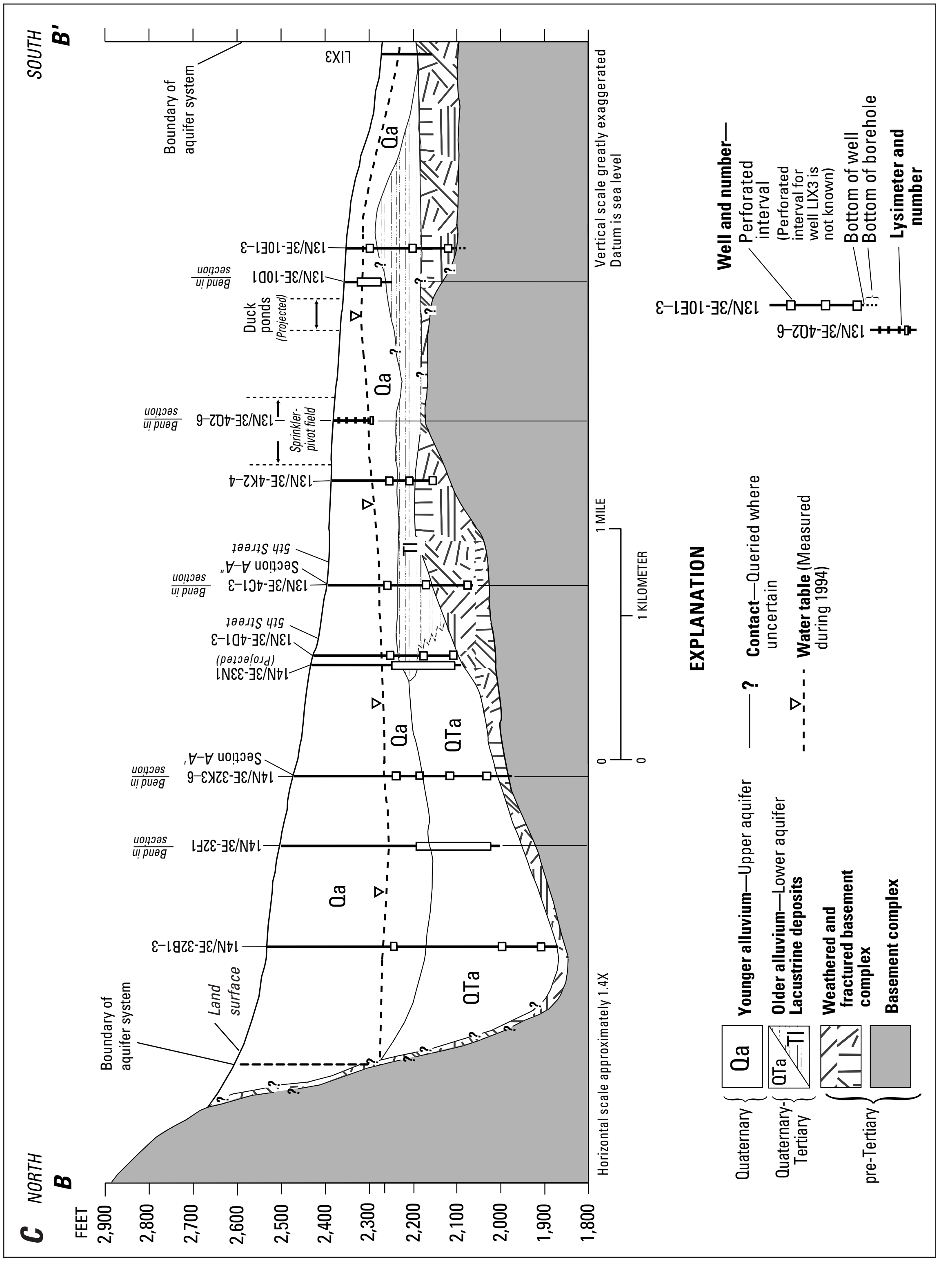


Figure 3.—Continued.

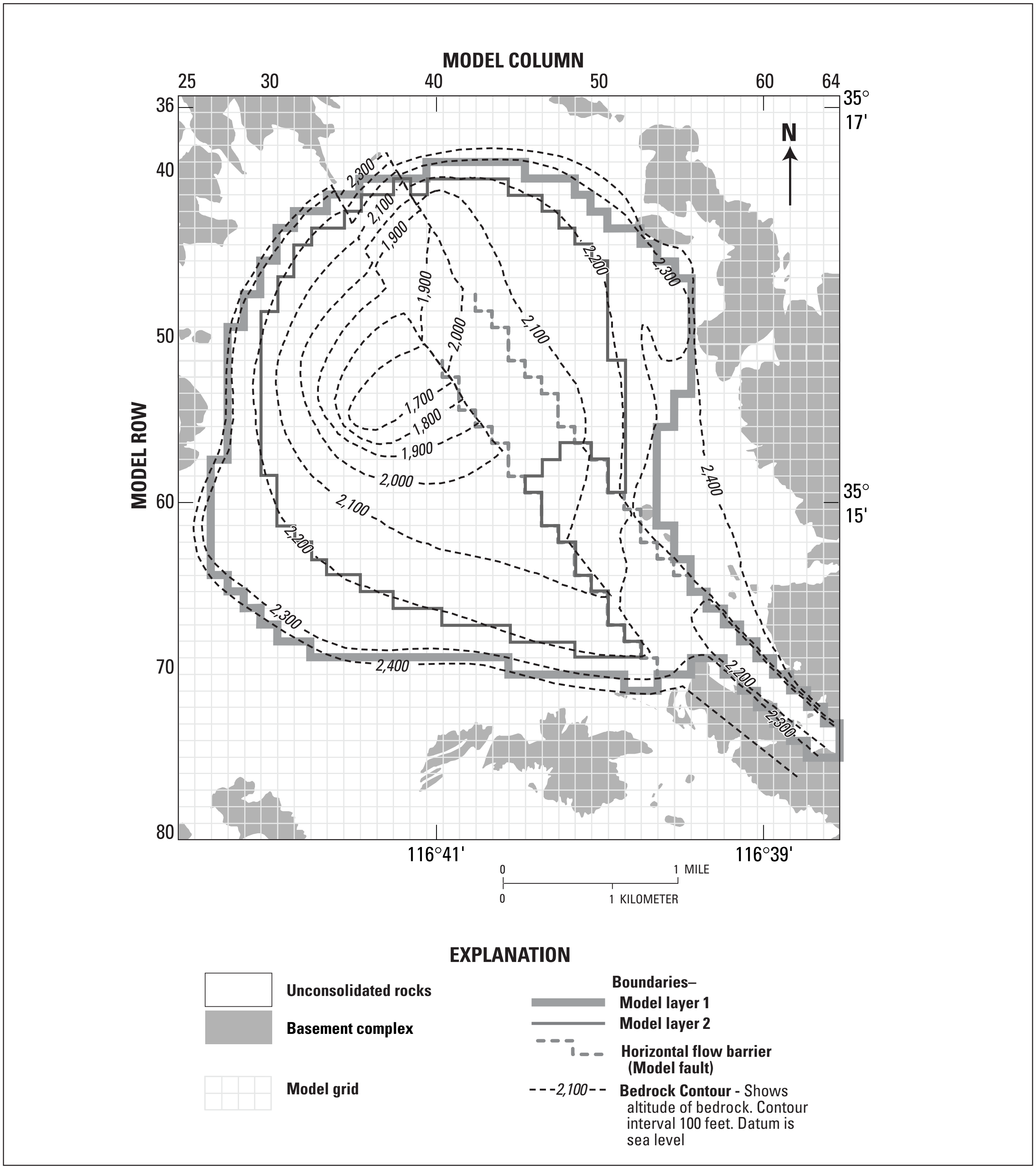


Figure 4. Altitude of the basement complex and boundaries of model layers for the Irwin Basin, Fort Irwin National Training Center, California.

Aquifer Properties

Hydraulic Conductivity and Transmissivity

Hydraulic conductivity is defined as the capacity of a rock or unconsolidated material to transmit water (Heath, 1983). Transmissivity is defined as the rate at which water is transmitted through an aquifer (Heath, 1983) and is equal to the hydraulic conductivity multiplied by the aquifer thickness.

The hydraulic conductivity and transmissivity of the unconsolidated deposits in Irwin Basin were initially estimated from specific-capacity data (table 1) compiled for this study. Specific capacity is the yield of a well per unit of drawdown (for example, gallon per minute per foot [(gal/min)/ft] of drawdown). Specific-capacity tests on production wells in the Irwin Basin have been done by Southern California Edison Co., James M. Montgomery and Associates, Inc. (1981), and Wilson F. So and Associates, Inc. (1989). The specific capacity of production wells in the basin ranges from about 2 to 31 (gal/min)/ft (table 1). Thomasson and others (1960, p. 222) reported that for valley-fill deposits in the Sacramento Valley, California, the specific capacity in gallons per minute per foot, multiplied by 230, approximates the transmissivity, in units of ft^2/d (foot squared per day) (table 1, column B). This relation between specific capacity and transmissivity was assumed to be representative of the unconsolidated deposits in the Irwin Basin. Hydraulic conductivity was estimated by dividing the transmissivity by the saturated thickness of the aquifer (table 1, column C). The hydraulic-conductivity values estimated by these calculations may be too low if water is not being supplied to the well by the entire thickness of the aquifer. The low estimates can be corrected by assuming that the values of transmissivity calculated from specific-capacity tests apply only to the perforated interval of the well (Heath, 1983, p. 61). To estimate transmissivity for the entire aquifer thickness, the calculated transmissivity is divided by the length of the perforated interval to determine the hydraulic conductivity (table 1, column F), and the result is then multiplied by the entire saturated thickness of the aquifer (table 1, column G). These hydraulic conductivity values may be too large if the thickness of the zone supplying water to the well is greater than the screen length. The estimated values determined from the calculations of transmissivity and hydraulic conductivity probably represent the low and high ranges of the actual hydraulic conductivity and transmissivity.

Table 1. Transmissivity and hydraulic conductivity estimated from specific-capacity data from wells in the Irwin Basin, Fort Irwin National Training Center, California

[Well locations shown on figure 5. col, column; (gal/min)/ft, gallon per minute per foot; ft^2/d, foot squared per day; ft, foot; ft/d, foot per day]

State well number	Average specific capacity (gal/min)/ft [col. A]	Trans-missivity (ft^2/d) [col. B= A x 230]	Saturated thickness of aquifer (1994) (ft) [col. C]	Hydraulic conductivity based on total saturated thickness (ft/d) [col. D=B/C]	Length of perforated interval (ft) [col. E]	Hydraulic conductivity based on length of perforated interval (ft/d) [col. F= B/E]	Trans-missivity (ft^2/d) [col. G= C x F]
13N/3E-4M1	14.14	3,252.20	325	10	200	16.3	5,298
13N/3E-5G2	11.1	2,553.00	300	9	230	11.1	3,330
13N/3E-5D1	8.75	2,012.50	620	3	265	7.6	4,712
14N/3E-32F1	31	7,130.00	330	22	194	36.8	12,144
14N/3E-32H1	29	6,670.00	320	21	255	26.2	8,384
14N/3E-32J1	9.6	2,208.00	250	9	304	7.3	1,825
14N/3E-32K1	18.3	4,209.00	800	5	180	23.4	18,720
14N/3E-32L1	2	460.00	292	2	226	2.0	584
14N/3E-32P1	8.13	1,869.90	311	6	198	9.4	2,923
14N/3E-32Q1	8.25	1,897.50	250	8	207	9.2	2,300
14N/3E-32Q2	1.75	402.50	343	1	279	1.4	480
14N/3E-32Q3	2.8	644.00	750	1	516	1.2	900

Storage Coefficient

The storage coefficient of an aquifer is the volume of water that is released from or taken into storage per unit surface area per unit change in head (Driscoll, 1986). For this ground-water flow model of Irwin Basin, layer 1 was simulated as an unconfined aquifer and layer 2 was simulated as a confined aquifer in all the modeled areas. For unconfined aquifers, the storage coefficient is virtually equal to the specific yield. Specific yield is the ratio of the volume of water that will drain by gravity per unit volume of the formation. The estimated average specific yield for the upper 150 ft of sediment in Irwin Basin is 0.19, or 19 percent (James M. Montgomery and Associates, Inc., 1981). In unconfined aquifers, water released from storage comes from an actual dewatering of the soil pores and results in lowering of the water table; however, in a confined aquifer, water released from storage comes from expansion of the water and from compression of the aquifer and results in lowering of the potentiometric surface (Heath, 1983, p. 28). Thus, the storage coefficient for a confined aquifer will be much lower than that for an unconfined aquifer.

Natural Recharge and Discharge

Natural recharge in the Irwin Basin is solely from precipitation runoff within the surface-water drainage basin (an area of about 30 mi^2) and probably occurs only during and shortly after high-intensity or long-duration storms. Although no precipitation records are available for the Irwin Basin, nearby Barstow and Goldstone areas receive on average only 4.4 and 6.5 in. of rain per year, respectively. Most of the natural recharge likely occurs in the coarse deposits along the normally dry washes, where precipitation runoff from the surrounding bedrock areas is diverted by dikes around the base housing (fig. 2) and temporary buildings that make up the cantonment area near the center of the basin. Recharge to the aquifer system from direct precipitation is considered minimal because precipitation or runoff do not adequately meet evapotranspiration and soil-moisture requirements. Recent work in the upper Mojave Basin by Izbicki and others (2000) suggests that infiltration does not occur at depths below the root zone except in areas of some intermittent washes.

C.F. Hostrup and Associates (1955) estimated that the average annual recharge from precipitation runoff in the Irwin drainage basin between 1941 and 1951 was about 150 acre-ft/yr. This estimate is based on ground-water pumpage and water-level changes during the 10-year period. Ground water from wells unaffected by artificial recharge in the Irwin Basin does not contain measurable concentrations of tritium (^3H) (Densmore and Londquist, 1997), indicating that natural recharge rates through the thick (as much as 270 ft in the northern part of the basin) unsaturated zone are fairly low.

Natural discharge occurs from the ground-water system in the Irwin Basin into the Langford Basin as subsurface underflow beneath the unnamed wash near Garlic Spring (fig. 2). Prior to ground-water development in 1941, ground-water discharge was the only discharge from the basin. Evaporation from the water table was negligible because depth to ground water was more than 10 ft below land surface throughout the basin. Therefore, prior to ground-water development (1941) the ground-water basin was likely in a steady-state condition with natural discharge by subsurface underflow equal to the natural recharge to the basin.

Discharge by subsurface underflow beneath the unnamed wash near Garlic Spring for predevelopment conditions is unknown. However, discharge for 1994, estimated by Densmore and Londquist (1997) using Darcy's law, was about 85 acre-ft/yr (10,000 ft^3/d). This estimate of natural discharge is lower than the natural recharge of 150 acre-ft/yr estimated by C.F. Hostrup and Associates (1955). For predevelopment (steady-state) conditions, recharge should equal discharge; therefore, either the natural recharge is overestimated or the natural discharge from the basin in 1994 underestimates the predevelopment natural discharge. In any case, these estimates indicate that the natural recharge and discharge are fairly low and of the same order of magnitude.

Ground-Water Pumpage, Water Use, and Artificial Recharge

Ground-water pumpage in the Irwin Basin began in 1941 with the drilling and installation of the first two wells for water supply at Camp Irwin. From 1941 to 1966, all the water used at the base was supplied from wells in the Irwin Basin. In 1967, the U.S. Army began pumping ground water from the Bicycle Basin to the north of the Irwin Basin, and in 1992, they began pumping ground water from the Langford Basin to the southeast of the Irwin Basin (fig. 1). Most of the water pumped from the Bicycle and the Langford Basins was piped to the Irwin Basin. Pumpage from 1941 to 1999 is summarized in table 2 for these three basins. The location of production and observation wells in the Irwin Basin is shown in figure 5. Total ground-water pumpage from the three basins ranged from about 30 acre-ft in 1941 to more than 3,000 acre-ft in 1999, with as much as 1,927 acre-ft (the largest volume) being pumped from the Irwin Basin in 1987 (table 2).

Most of the water that has not been consumed in the Irwin Basin has been discharged to the wastewater-collection system and treatment facility in the basin. From 1941 to 1955, wastewater was collected in biological-evaporation ponds in the northeastern part of the basin (shown as old biological-evaporation ponds in figure 5), and from 1955 until present (1999), it was collected and treated at the wastewater-treatment facility in the southeastern part of the basin. Densmore and Londquist (1997) estimated that a maximum of 70 percent of total pumpage and a minimum of 58 percent of total pumpage was collected at the biological-evaporation ponds during 1941-55 and then at the wastewater-treatment facility between 1955 and 1993 (table 3); these values also were assumed valid for the recent period 1994 through 1999 (table 3).

The percolation (infiltration) of wastewater to the water table is the largest source of ground-water recharge in the Irwin Basin (Densmore and Londquist, 1997). Between 1941 and 1955, untreated wastewater was disposed in the old biological-evaporation ponds, but since 1955 it has been treated and disposed in ponds at the wastewater-treatment facility in the southeastern part of the basin (fig. 5). Some of the treated wastewater is diverted from the wastewater-treatment facility ponds to irrigate the base golf course/driving range and sprinkler-pivot field, and to infiltrate the subsurface sediments beneath two overflow ponds, referred to as duck ponds (fig. 5). The golf course and driving range were irrigated from 1955 to 1971 and from 1981 to 1999. Although part of the golf course and driving range lies outside the basin boundary, the water used to irrigate these areas is assumed to recharge the ground-water system. In 1986, a sprinkler-pivot field was added in the southeastern part of the basin to provide additional disposal. Since 1996, when the first phase of this study showed that ground-water degradation occurred due to leaching evaporite deposits beneath the sprinkler-pivot field, all disposal of wastewater through the sprinkler-pivot field has ceased (Kevin Maggs, Fort Irwin National Training Center, oral commun., 2000). The duck ponds are filled intermittently, depending on demand for the treated wastewater.

Another source of recharge not present before development of the base is the infiltration of water used to irrigate lawns and playing fields that is not consumed by the plants. About 14 acres of lawn was watered during the mid-1960s to the early 1980s; this includes lawns at the base housing and at an Army ball field. In 1983, the housing area increased to about 25 acres. During 1984–85, an additional 8 acres of irrigated area (soccer field and a baseball field complex) was added adjacent to the base housing in the western part of the basin (fig. 2). By the mid-1980’s, the total irrigated area was 33 acres. The potential artificial recharge from irrigation-return water (applied irrigation water in excess of that used by the plants) for these 33 acres was about 90 acre-ft/yr before the early-1980s, and about 210 acre-ft/yr from the early 1980s to present (1999) (Densmore and Londquist, 1997).

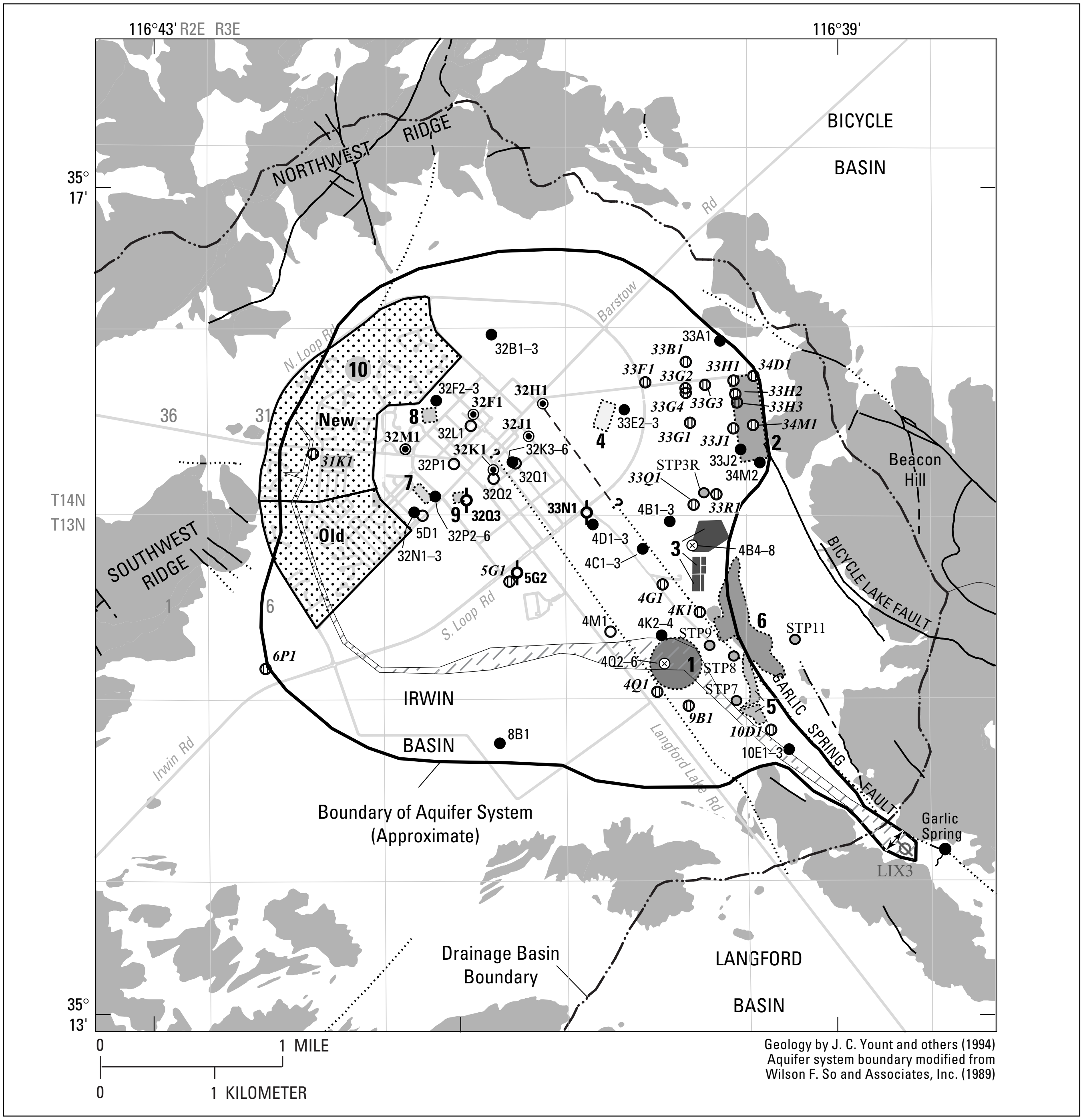


Figure 5. Location of production and other observation wells and sources of recharge in the Irwin Basin, Fort Irwin National Training Center, California.

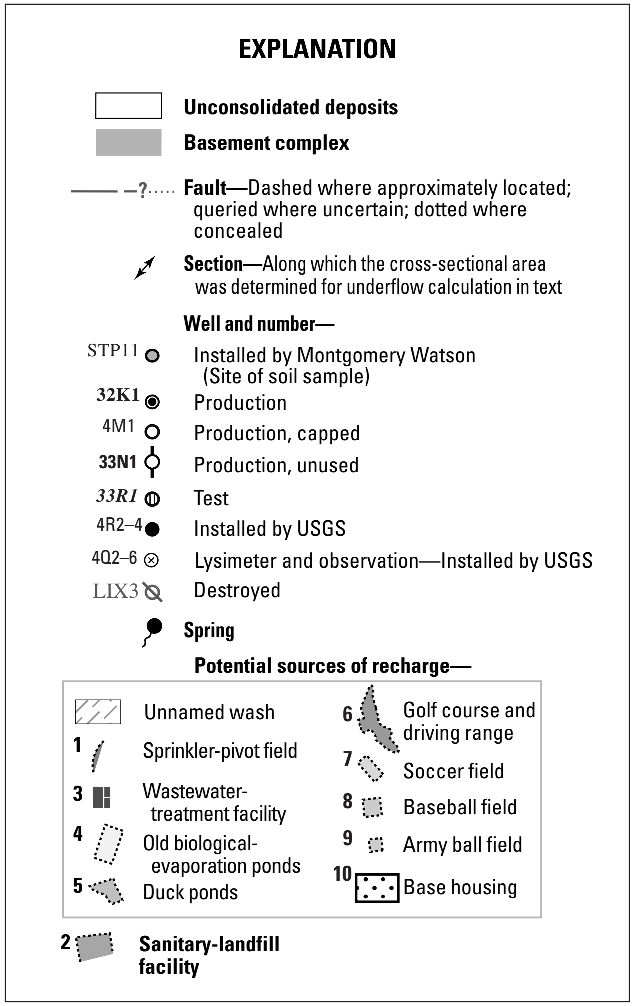


Figure 5.—Continued.

Ground-Water Levels and Movement

Prior to development of the Irwin Basin, the ground-water gradient was fairly flat, with a slight tilt toward the unnamed wash near Garlic Spring. The water-table altitude averaged about 2,305 ft above sea level during the early 1940s when the first six wells were drilled in the Irwin Basin (Kunkel and Riley, 1959). Ground water was discharged from the Irwin Basin to the Langford Basin as underflow beneath the unnamed wash near Garlic Spring (James M. Montgomery and Associates, Inc., 1981). Before ground-water development began in 1941, the direction of ground-water flow probably was from the margins of the alluvium near the mountain fronts toward the unnamed wash near Garlic Spring, through which ground water discharges to the Langford Basin.

Table 2. Annual ground-water pumpage for the Irwin, Bicycle, and Langford Basins, Fort Irwin National Training Center, California, 1941–99

[—, no pumping]

Year	Ground-water pumpage, in acre-feet				Year	Ground-water pumpage, in acre-feet			
	Irwin Basin[1]	Bicycle Basin[2]	Langford Basin[3]	Total[4]		Irwin Basin[1]	Bicycle Basin[2]	Langford Basin[3]	Total[4]
1941	33	—	—	33	1971	364	608	—	972
1942	130	—	—	130	1972	399	480	—	879
1943	350	—	—	350	1973	321	157	—	478
1944	480	—	—	480	1974	200	170	—	370
1945	182	—	—	182	1975	236	210	—	446
1946	57	—	—	57	1976	236	393	—	629
1947	55	—	—	55	1977	64	123	—	187
1948	55	—	—	55	1978	283	493	—	776
1949	55	—	—	55	1979	502	462	—	964
1950	55	—	—	55	1980	721	866	—	1,587
1951	293	—	—	293	1981	660	793	—	1,453
1952	336	—	—	336	1982	630	758	—	1,388
1953	671	—	—	671	1983	720	866	—	1,586
1954	668	—	—	668	1984	1,675	689	—	2,364
1955	598	—	—	598	1985	1,133	1,243	—	2,376
1956	602	—	—	602	1986	1,315	1,329	—	2,644
1957	704	—	—	704	1987	1,927	822	—	2,749
1958	686	—	—	686	1988	1,700	1,033	—	2,733
1959	655	—	—	655	1989	1,696	829	—	2,525
1960	746	—	—	746	1990	1,868	1,312	—	3,180
1961	881	—	—	881	1991	1,331	1,380	—	2,711
1962	1,119	—	—	1,119	1992	1,110	1,134	619	2,863
1963	1,147	—	—	1,147	1993	997	757	1,114	2,868
1964	1,202	—	—	1,202	1994	1,180	964	1,006	3,150
1965	1,305	—	—	1,305	1995	1,270	1,051	816	3,137
1966	1,509	—	—	1,509	1996	1,138	1,226	663	3,027
1967	827	822	—	1,649	1997	580	1,780	656	3,016
1968	764	820	—	1,584	1998	484	2,292	328	3,104
1969	727	954	—	1,681	1999	781	2,075	394	3,250
1970	549	896	—	1,445					

[1]Pumpage in Irwin Basin: for 1941–71, 1973–77, and 1980 from James M. Montgomery and Associates, Inc. (1981); for 1972, 1978–79, and 1981 estimated by the U.S. Geological Survey for this study; for 1982–83 from Wilson F. So and Associates, Inc. (1989); for 1984–99 from Rene Quinones, Walt Young, and Suzanne Beauchamp (U.S. Army, Fort Irwin Directorate of Public Works, written commun., 1996, 1998, and 2000, respectively).

[2]Pumpage in Bicycle Basin: for 1967–71, 1973–79, 1980 from James M. Montgomery and Associates, Inc. (1981); for 1972 estimated by the U.S. Geological Survey for this study; for 1981–83 from Wilson F. So and Associates, Inc. (1989); for 1984–99 from Rene Quinones, Walt Young, and Suzanne Beauchamp (U.S. Army, Fort Irwin Directorate of Public Works, written commun., 1996, 1998, and 2000, respectively).

[3]Pumpage in Langford Basin: for 1992–99 from Rene Quinones, Walt Young, and Suzanne Beauchamp (U.S. Army, Fort Irwin Directorate of Public Works, written commun., 1996, 1998, and 2000, respectively).

[4]Total is the sum from all sources.

Table 3. Total annual pumpage from the Irwin, Bicycle, and Langford Basins, and range of estimated wastewater recharge calculated from wastewater inflow, potential evaporation and evapotranspiration in the Irwin Basin, Fort Irwin National Training Center, California, 1941–99

Year	Total pumpage from all basins[1]	Range of wastewater inflow[2,3]		Potential evaporation from ponds[4]	Potential evapotran-spiration from fields[5]	Range of estimated wastewater recharge[6,7]	
		Minimum (58 percent of total pumpage)	Maximum (70 percent of total pumpage)			Minimum	Maximum
1941	33	19	23	53	—	0	0
1942	130	75	91	53	—	22	38
1943	350	203	245	53	—	150	192
1944	480	278	336	53	—	225	283
1945	182	106	127	53	—	53	74
1946	57	33	40	53	—	0	0
1947	55	32	39	53	—	0	0
1948	55	32	39	53	—	0	0
1949	55	32	39	53	—	0	0
1950	55	32	39	53	—	0	0
1951	293	170	205	53	—	117	152
1952	336	195	235	53	—	142	182
1953	671	389	470	53	—	336	417
1954	668	387	468	53	—	334	415
1955	598	347	419	112	365	294	366
1956	602	349	421	112	365	0	0
1957	704	408	493	112	365	0	16
1958	686	398	480	112	365	0	3
1959	655	380	459	112	365	0	0
1960	746	433	522	112	365	0	45
1961	881	511	617	112	365	34	140
1962	1,119	649	783	112	365	172	306
1963	1,147	665	803	112	365	188	326
1964	1,202	697	841	112	365	220	364
1965	1,305	757	914	112	365	280	437
1966	1,509	875	1,056	112	365	398	579
1967	1,649	956	1,154	112	365	479	677
1968	1,584	919	1,109	112	365	442	632
1969	1,681	975	1,177	112	365	498	700
1970	1,445	838	1,012	112	365	361	535
1971	972	564	680	112	365	87	203
1972	879	510	615	112	—	398	503
1973	478	277	335	112	—	165	223
1974	370	215	259	112	—	103	147

See footnotes at end of table.

Table 3. Total annual pumpage from the Irwin, Bicycle, and Langford Basins, and range of estimated wastewater recharge calculated from wastewater inflow, potential evaporation and evapotranspiration in the Irwin Basin, Fort Irwin National Training Center, California, 1941–99

Year	Total pumpage from all basins[1]	Range of wastewater inflow[2,3]		Potential evaporation from ponds[4]	Potential evapotranspiration from fields[5]	Range of estimated wastewater recharge[6,7]	
		Minimum (58 percent of total pumpage)	Maximum (70 percent of total pumpage)			Minimum	Maximum
1975	446	259	312	112	—	147	200
1976	629	365	440	112	—	253	328
1977	187	108	131	112	—	0	19
1978	776	450	543	112	—	338	431
1979	964	559	675	112	—	447	563
1980	1,587	920	1,111	112	—	808	999
1981	1,453	843	1,017	112	365	366	540
1982	1,388	805	972	112	365	328	495
1983	1,586	920	1,110	112	365	443	633
1984	2,364	1,371	1,655	112	365	894	1,178
1985	2,376	1,378	1,663	112	365	901	1,186
1986	2,644	1,534	1,851	310	430	794	1,111
1987	2,749	1,594	1,924	310	430	854	1,184
1988	2,733	1,585	1,913	310	430	845	1,173
1989	2,525	1,465	1,768	310	430	725	1,028
1990	3,180	1,844	2,226	310	430	1,104	1,486
1991	2,711	1,572	1,898	310	430	832	1,158
1992	2,863	1,661	2,004	310	430	921	1,264
1993	2,868	1,663	2,008	310	430	923	1,268
1994	3,150	1,827	2,205	310	430	1,087	1,465
1995	3,137	1,819	2,196	310	430	1,079	1,456
1996	3,027	1,756	2,119	310	430	1,016	1,379
1997	3,016	1,749	2,111	310	365	1,074	1,436
1998	3,104	1,800	2,173	310	365	1,125	1,498
1999	3,250	1,885	2,275	310	365	1,210	1,600

[1]Total is sum of pumpage information from various sources.

[2]Minimum inflow estimated as 58 percent of total pumpage listed in table 2.

[3]Maximum inflow estimated as 70 percent of total pumpage listed in table 2.

[4]Potential evaporation is estimated by multiplying the area of the sewage ponds by the potential evaporation rate of 6.6 feet per year (David Inouye, California Department of Water Resources, written commun., 1996). The area of the ponds was 8 acres from 1941 to 1954, 17 acres from 1955 to 1985, and 47 acres from 1986 to 1999.

[5]Potential evapotranspiration is estimated by multiplying the areas of grass irrigated with wastewater (driving range, golf course, and sprinkler-system pivot) by the consumptive use of 6.3 feet per year (Sandra Owen-Joyce, U.S. Geological Survey, oral commun.,1996). The grass area included 0 acres from 1941 to 1954, 58 acres from 1955 to 1985, and 68 acres from 1986 to 1999.

[6] Minimum recharge was estimated by subtracting the sum of the estimated potential evaporation and evapotranspiration from the minimum estimated amount of wastewater inflow.

[7]Maximum recharge was estimated by subtracting the sum of the estimated potential evaporation and evapotranspiration from the maximum estimated amount of wastewater inflow.

Ground-water pumping and the recharge of wastewater have significantly modified predevelopment water levels in Irwin Basin. Since pumping began in 1941, water levels have fluctuated in response to ground-water withdrawals and wastewater disposal. Water levels from well 13N/3E-5D1, which was capped in the late 1990s, and wells 14N/3E-32N2 and -32N3, which are located nearby, were used to construct a long-term hydrograph for the period 1941–99 (fig. 6). Well 13N/3E-5D1 is perforated in the upper and lower aquifers, well 14N/3E-32N3 is perforated in the upper aquifer, and well 14N/3E-32N2 is perforated in the lower aquifer. As shown on the hydrograph, water levels declined about 30 ft between 1941 and 1967 with most of the decline occurring between 1953 and 1967. This decline corresponds with an increase in pumpage in the Irwin Basin (fig. 6). Water levels recovered about 16 ft between 1967 and 1982 as a result of the decrease in water pumped from the Irwin Basin and the increase in artificial recharge in the southeastern part of the basin owing to the importation, use, and disposal of water from the Bicycle Basin. From the early 1980s until the mid-1990s, increased pumpage from the Irwin Basin caused water levels to decline about 15 ft, slightly below the levels measured in the late 1960s. Although artificial recharge also increased during this time, it was insufficient to offset the increased pumpage. Since 1993, water levels have been recovering in the Irwin Basin in response to decreased pumpage from the basin and to continued artificial recharge of wastewater in the southeastern part of the basin.

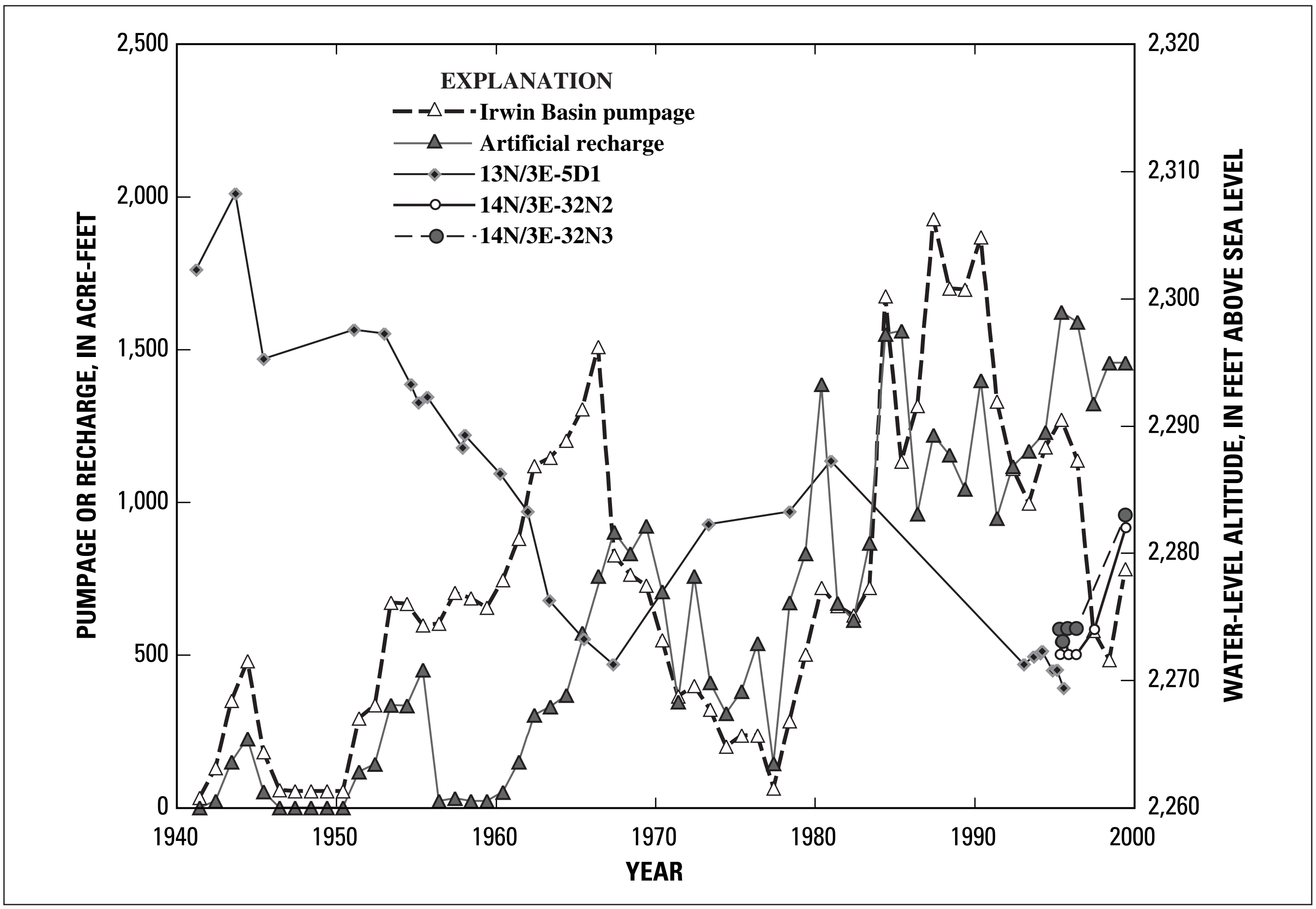


Figure 6. Pumpage and recharge, and water-level altitudes in selected wells in the Irwin Basin, Fort Irwin National Training Center, California, 1941–99.

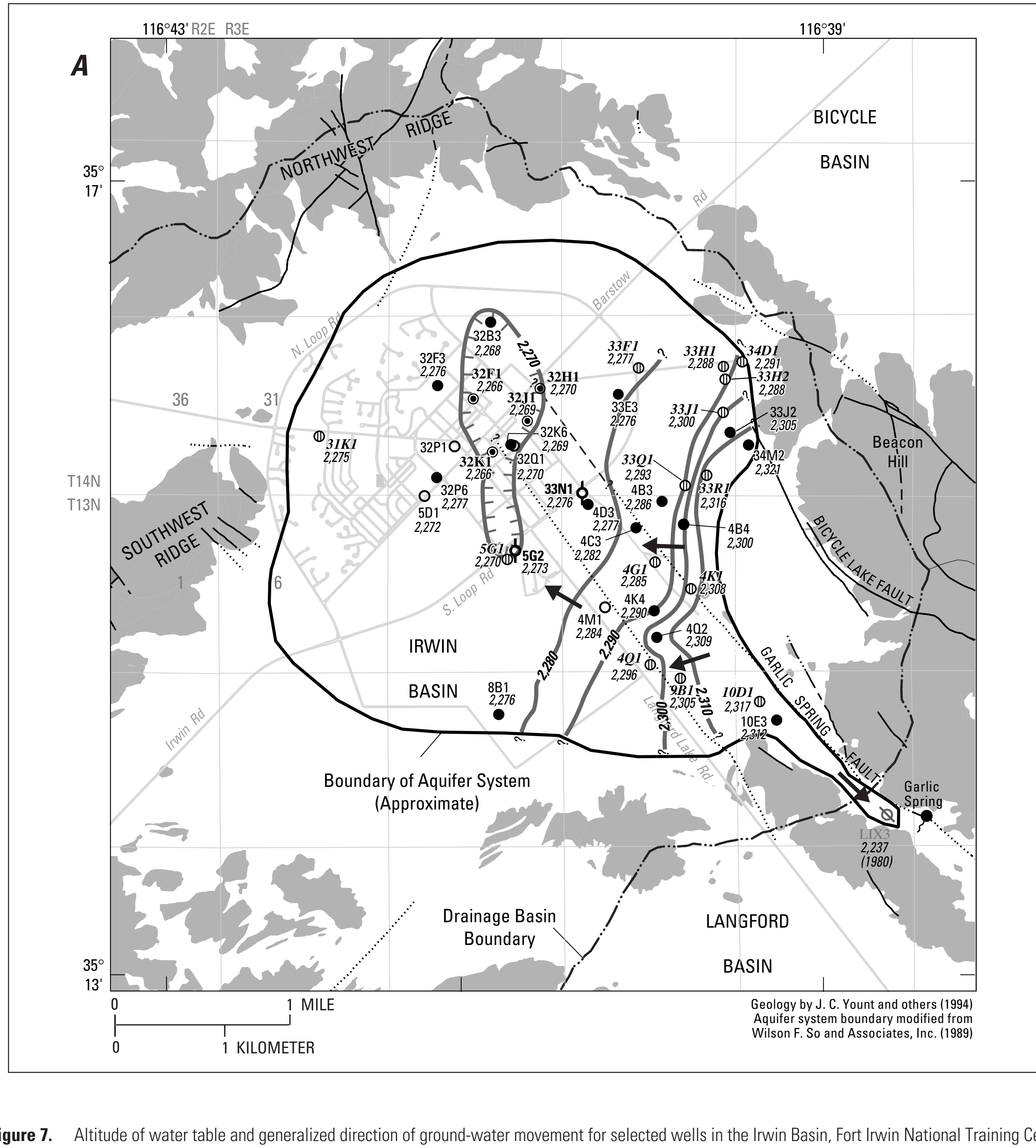


Figure 7. Altitude of water table and generalized direction of ground-water movement for selected wells in the Irwin Basin, Fort Irwin National Training Center, California. *A*, 1994, and *B*, 1999.

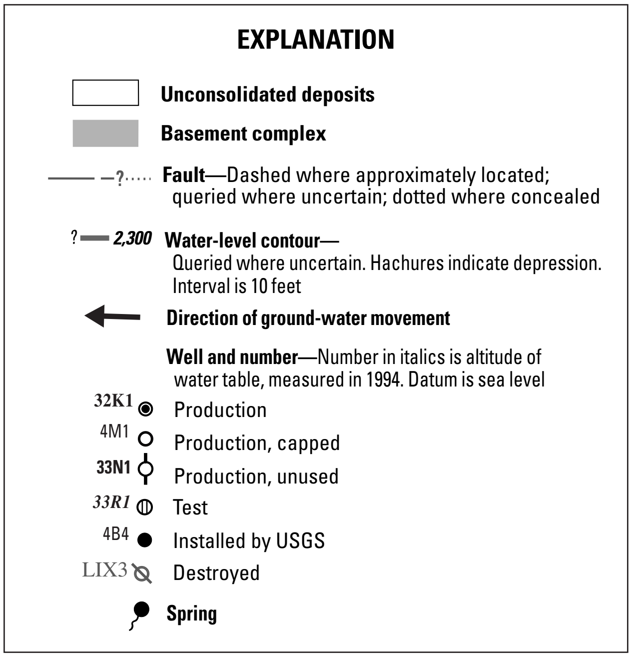


Figure 7,—Continued.

Water-level measurements from the shallowest well at multiple-well monitoring sites and from test wells, which generally are perforated near the water table, were used to develop 1994 and 1999 water-table maps shown in figure 7. The 1994 water-table map shows that pumpage has created a water-table depression (or pumping depression) in the central part of the basin (fig. 7A). The general direction of ground-water movement throughout most of the basin was from the margin of the basin toward the pumping depression. A ground-water mound and a ground-water divide have formed as a result of wastewater disposal in the southeastern part of the basin, where the water-table altitude was more than 2,310 ft above sea level (fig. 7A). The 1999 water-table map (fig. 7B) shows that the pumping depression remained in the central part of the basin beneath the well field; however, the altitude of the water table had risen about 8 ft from 2,269 ft above sea level in well 14N/3E-32K6 in 1994 to 2,277 ft in 1999. The direction of ground-water movement throughout most of the basin is still toward the pumping depression (fig. 7B). The ground-water mound and divide also are still present in the southeastern part of the basin (fig. 7B). The ground-water table has risen about 7 ft from 2,312 ft above sea level in well 13N/3E-10E3 in 1994 to 2,319 ft in 1999. Water from the mound continues to flow northwestward toward the ground-water depression in the central part of the basin and southeastward toward the unnamed wash near Garlic Spring.

Water-level data from multiple-well monitoring sites indicate that the hydraulic head (or water level) varies slightly with depth (Densmore and Londquist, 1997; Appendix B). Generally, the hydraulic head is higher in wells perforated in the upper aquifer than in wells perforated in the lower aquifer. This difference in hydraulic head indicates the potential for downward vertical flow. The largest differences in hydraulic head are about 3 ft at wells 13N/3E-10E1-3 in the southeastern part of the basin and about 8 ft at wells 14N/3E-32N1-3 and 32P2-6 in the west-central part of the basin (Densmore and Londquist, 1997). This difference in hydraulic head probably is due to wastewater disposal and irrigation return, respectively, near these sites (fig. 5).

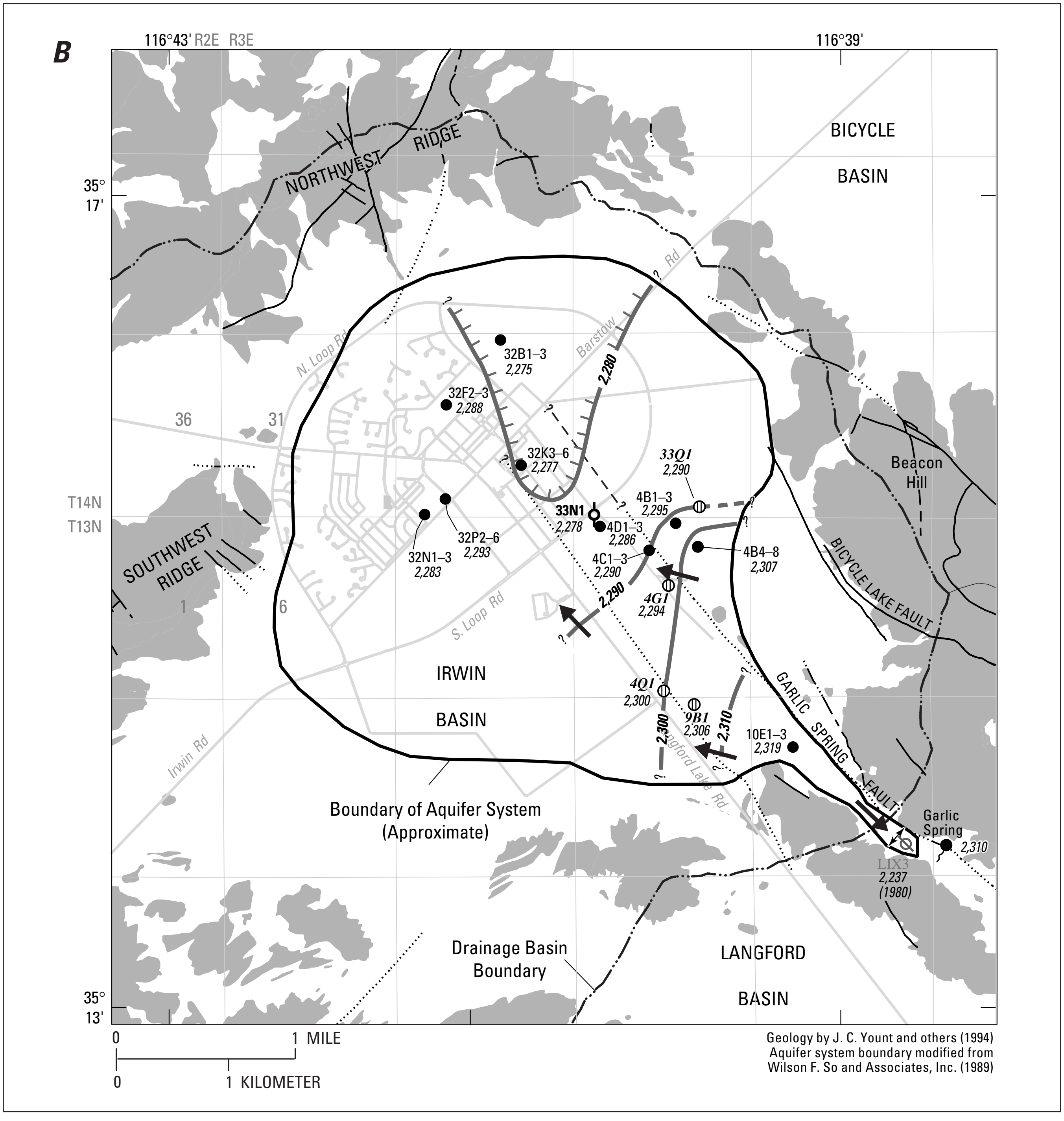


Figure 7.—Continued.

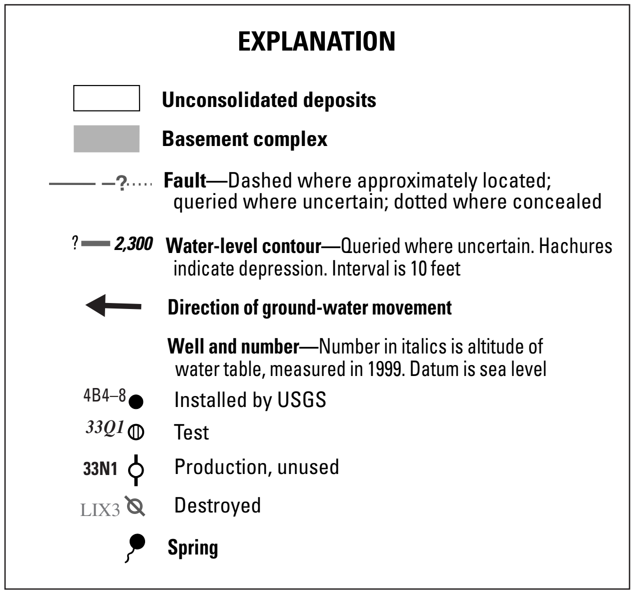


Figure 7.—Continued.

Ground-Water Quality

Water-quality samples collected between January 1992 and September 1996 indicate that the quality of ground water has degraded in three areas of the Irwin Basin owing to high dissolved-solids and nitrate concentrations (Densmore and Londquist, 1997). The three areas with high dissolved-solids concentrations are the entire wastewater-treatment facility and disposal area in the southeastern part of the basin, the soccer and Army ball fields, and an area near the pumping depression (figs. 7 and 8). Densmore and Londquist (1997) also identified high nitrate concentrations in the samples from the wastewater-treatment facility and disposal area, the soccer and Army ball fields, and north of the landfill in the eastern part of the basin. Although the following discussion focuses on the distribution of dissolved-solids concentrations, the findings are similar for the nitrate concentrations.

The dissolved-solids concentrations in ground water sampled during 1992–96 ranged from 433 to 6,380 mg/L (Densmore and Londquist, 1997). The concentrations generally were higher in the upper aquifer than in the lower aquifer. The highest dissolved-solids concentrations (greater than 2,000 mg/L) were in ground-water samples collected in the southeastern part of the basin near the wastewater-treatment facility, the golf course, and the sprinkler-pivot field. Dissolved-solids concentrations were much higher in the samples collected from the unsaturated zone beneath the sprinkler-pivot field than in the samples collected from the wastewater-treatment facility (Densmore and Londquist, 1997). Therefore, wastewater alone cannot be the source of the high dissolved-solids concentrations in the southeastern part of the basin; the dissolution of evaporite deposits into wastewater effluent as it infiltrates these deposits also is contributing to the high concentrations (Densmore and Londquist, 1997). This ground-water with high dissolved-solids concentrations is migrating from the southeastern part of the basin toward the pumping depression in the center of the basin. As previously stated, long-term pumping from production wells near the center of the basin has caused a decline in water levels in this area.

Another area of the basin that has fairly high dissolved-solids concentrations (in excess of 700 mg/L) is in the west-central part of the basin (the area of the ball fields) (fig. 8). Data from the wells 14N/3E-32N1-3, 32P2-6, and 32K3-6 indicate that the highest dissolved-solids concentrations are near the water table in the upper aquifer. Irrigation-return flow from the base-housing area and (or) leaking sewer pipes are probable sources of the high dissolved-solids concentrations in the ball field area (Densmore and Londquist, 1997).

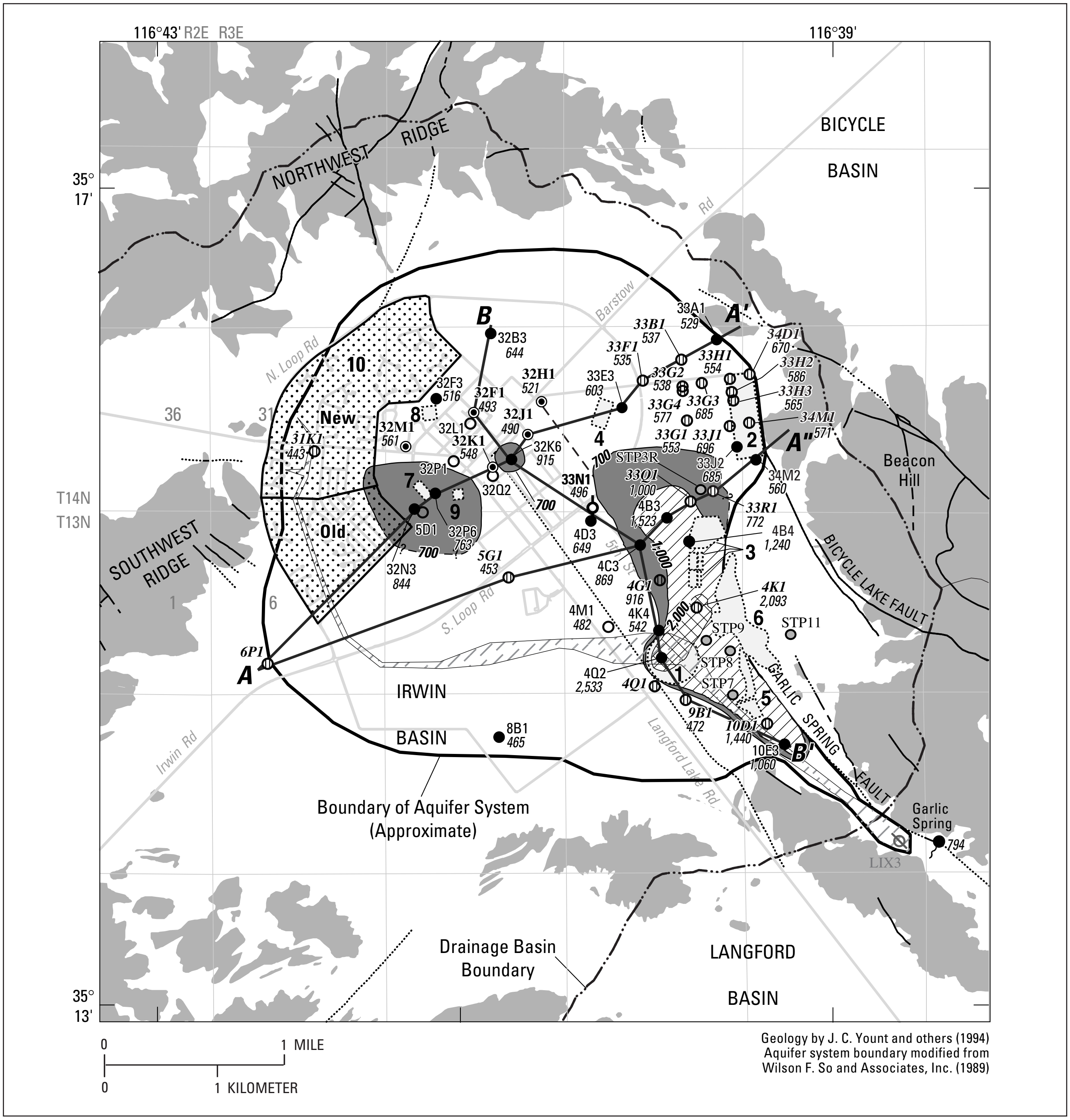


Figure 8. Areal distribution of the average dissolved-solids concentrations in ground water from shallow water-table wells and production wells in Irwin Basin, Fort Irwin National Training Center, California. Dissolved-solids concentrations from Densmore and Londquist (1997).

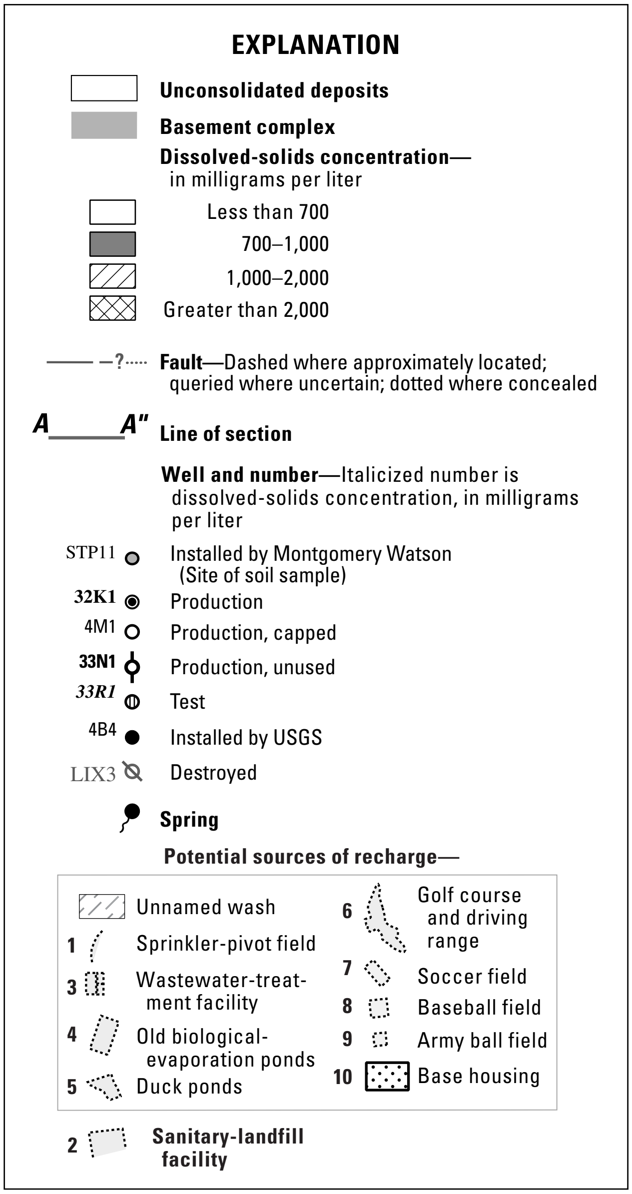


Figure 8.—Continued.

GROUND-WATER FLOW MODEL

A numerical ground-water flow model of the Irwin Basin was developed to better understand the aquifer system of the basin and to determine the long-term availability of ground water by simulating ground-water conditions resulting from historical pumpage for the period 1941–99 and simulating possible future conditions resulting from future ground-water pumpage for the period 2000–2050. The model was developed using assumptions and approximations to simplify the actual aquifer system. The model idealizes the complex geohydrologic relations of the actual system, thus, it is a simplification based upon the data and the assumptions used to develop it. Limitations of the model are discussed in a later section of this report.

The USGS Modular Three-Dimensional Finite-Difference Ground-Water Flow Model (MODFLOW) developed by McDonald and Harbaugh (1988) was used to simulate flow in the Irwin Basin. Although the model only is an approximation of the actual ground-water flow system, the model can be used to determine gaps and potential anomalies in data and in understanding the aquifer system. The ground-water flow system in the Irwin Basin was numerically defined by discretizing the aquifer system into a finite-difference grid, determining the boundary conditions for the aquifers, estimating the rates and distribution of recharge and discharge, and estimating the aquifer properties within the model. The accuracy of these input data, in part determines the accuracy of the model.

To simulate historical conditions, steady-state (predevelopment) and transient-state (postdevelopment) models were formulated and calibrated. Results of the steady-state simulation were used as initial conditions for the transient-state model.

Model Grid

The model is represented by a rectangular finite-difference grid discretized into rows and columns that form model cells where the ground-water flow equation is solved numerically at nodes at the center of each cell (McDonald and Harbaugh, 1988). Figure 9 shows the area of the local model grid for the Irwin Basin and the regional model grid for the Fort Irwin NTC. The regional grid consists of 152 rows and 125 columns. The origin of the regional grid (that is, the upper left corner of the grid; row 1, column 1) is at an easting of 2,373,237 ft and a northing of 669,380 ft in zone 5 of the California State plane coordinate system. The size of the regional grid is large enough to include the Irwin, Bicycle, and Langford Basins, all of which supply water to Fort Irwin. The regional grid was designed to include these three basins so that as future models of the Langford and Bicycle Basins are completed, they can be incorporated into one large model that can be used to help the Fort Irwin NTC manage water resources on a regional basis. The model cells are 500 ft by 500 ft along the x and y axis. The local grid for the Irwin Basin is within the regional grid. The same grid and cell sizes are used for the local model grid of the Irwin Basin, but only cells in rows 1 to 80 and columns 1 to 64 represent the local model grid for the Irwin Basin (fig. 9). For ease of viewing the figures showing model parameters, inactive cells in rows 1 to 35 and columns 1 to 24 are not shown: only cells in rows 36 to 80 and columns 25 to 64, which contain the Irwin Basin, are shown.

The aquifer system was vertically discretized into two horizontal layers of cells (figs. 10 and 11). Layer 1 represents the unconfined upper aquifer and has a variable thickness ranging from about 1 to 100 ft, depending on the saturated thickness of the aquifer materials (fig. 11). The top altitude of layer 1 represents the water table. The bottom altitude of layer 1 (the bottom of the upper aquifer) is 2,200 ft above sea level throughout most of the basin and consists of primarily younger alluvium. In the southeastern part of the basin, the bottom of layer 1 is defined as the top of the lacustrine deposits of the lower aquifer. Layer 2 represents the confined lower aquifer, underlies layer 1 throughout most of the model area, and has a variable thickness ranging from about 1 to 600 ft depending on the altitude of the underlying basement complex (fig. 11). The top of layer 2, which is the bottom of layer 1, is 2,200 ft above sea level where it underlies layer 1, and the bottom of layer 2 is the altitude of the underlying basement complex. Layer 1 and layer 2 contain 784 and 538 active cells, respectively. Layer 2 has fewer active cells than layer 1 because some of the cells, along the outer edge of the basin and in the mouth of the wash that passes Garlic Spring, bounded the Garlic Spring and unnamed faults, are in areas of the basement complex that are higher in elevation than that of the top of layer 2 (2,200 ft above sea level); thus, there is no layer 2 in these areas.

The MODFLOW packages used in this model include Basic (BAS), Block-Centered Flow (BCF), Well (WEL), General-Head Boundary (GHB), Horizontal-Flow-Barrier (HFB), and Strongly Implicit Procedure (SIP) [BAS, BCF, WEL, GHB, and SIP (McDonald and Harbaugh, 1988), and HFB (Hsieh and Freckleton, 1993)].

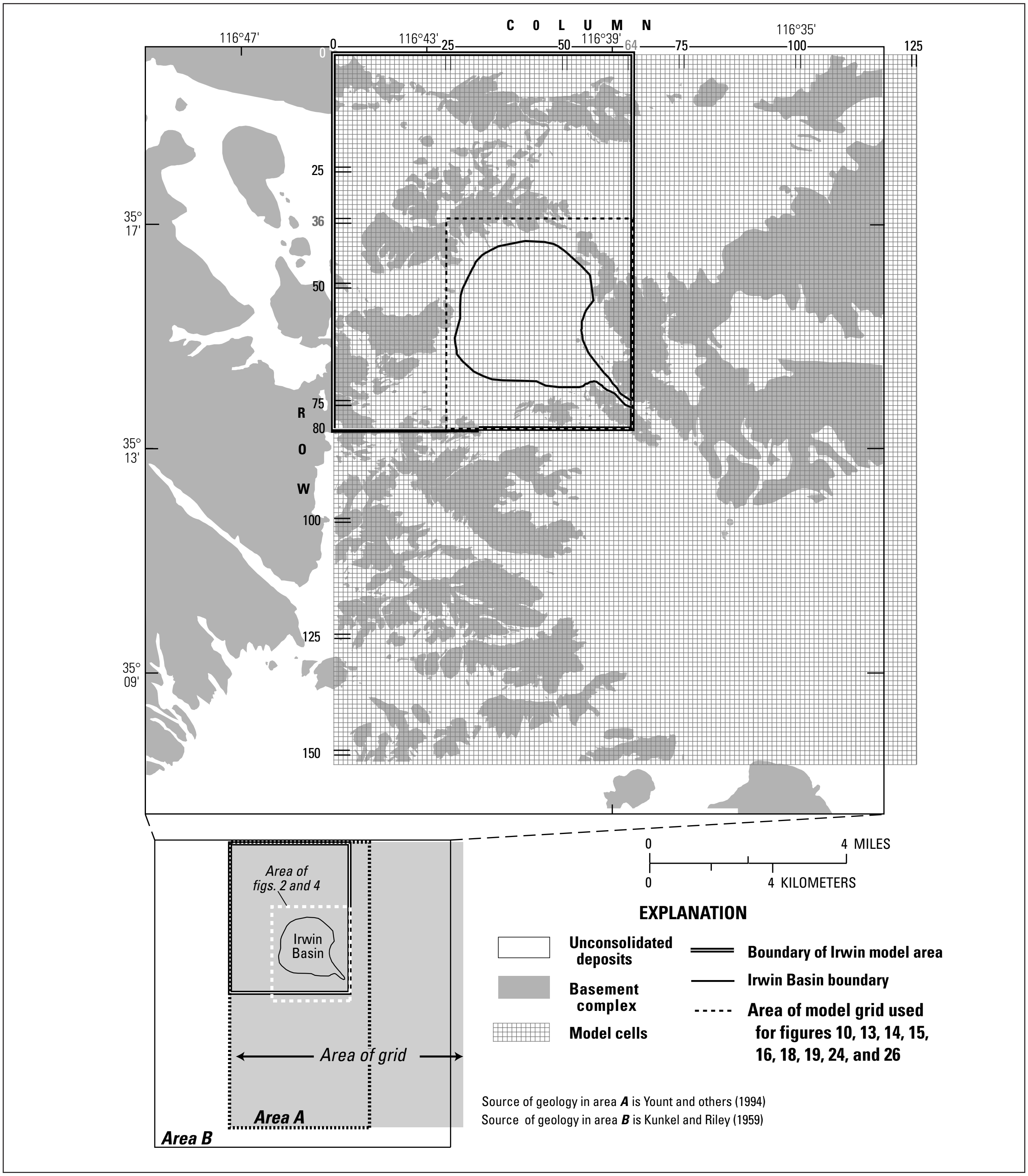


Figure 9. Local model grid of the Irwin Basin and the regional model grid of the Fort Irwin National Training Center, California.

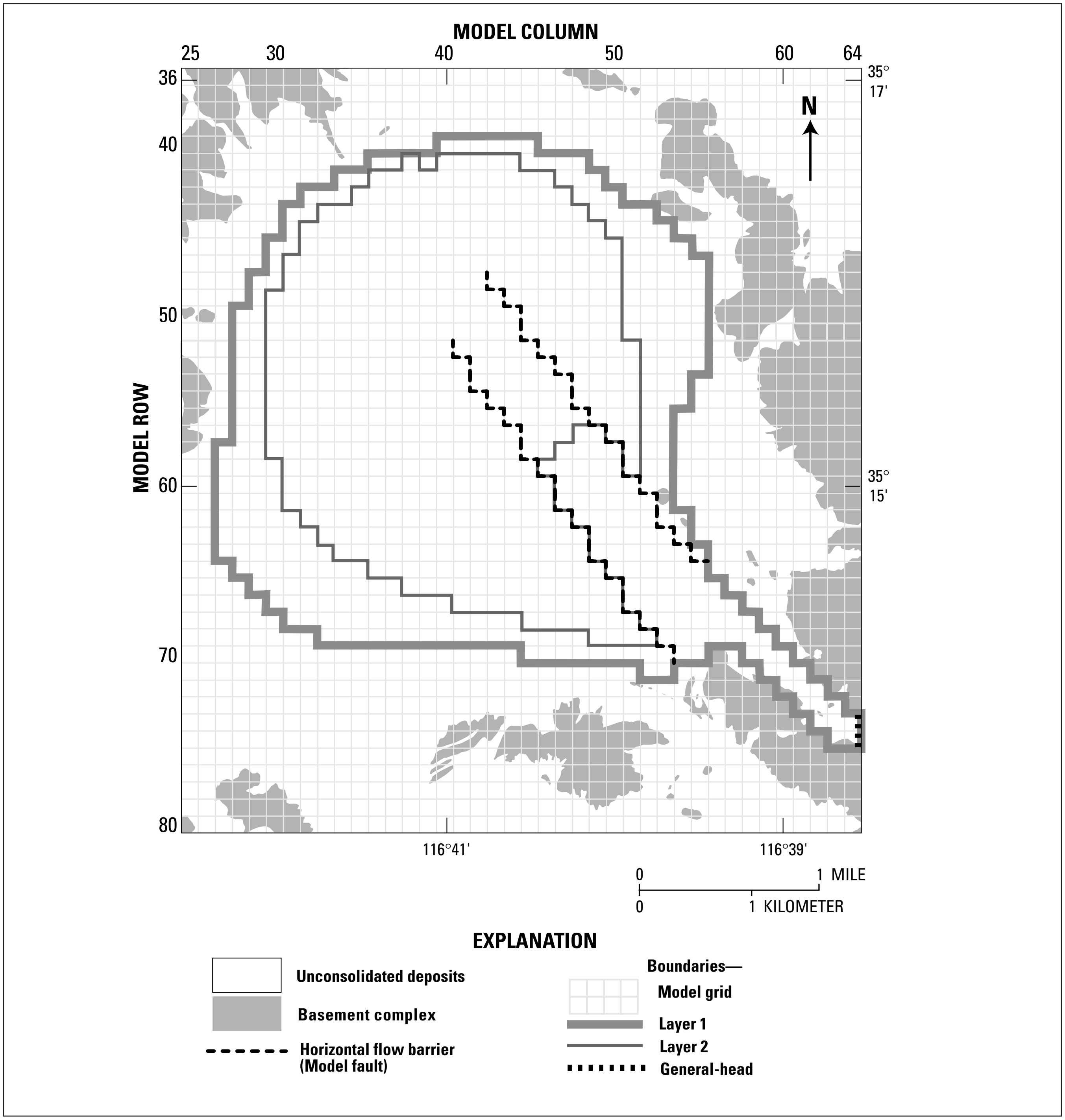


Figure 10. Model grid and location of the model boundaries of the Irwin Basin, Fort Irwin National Training Center, California.

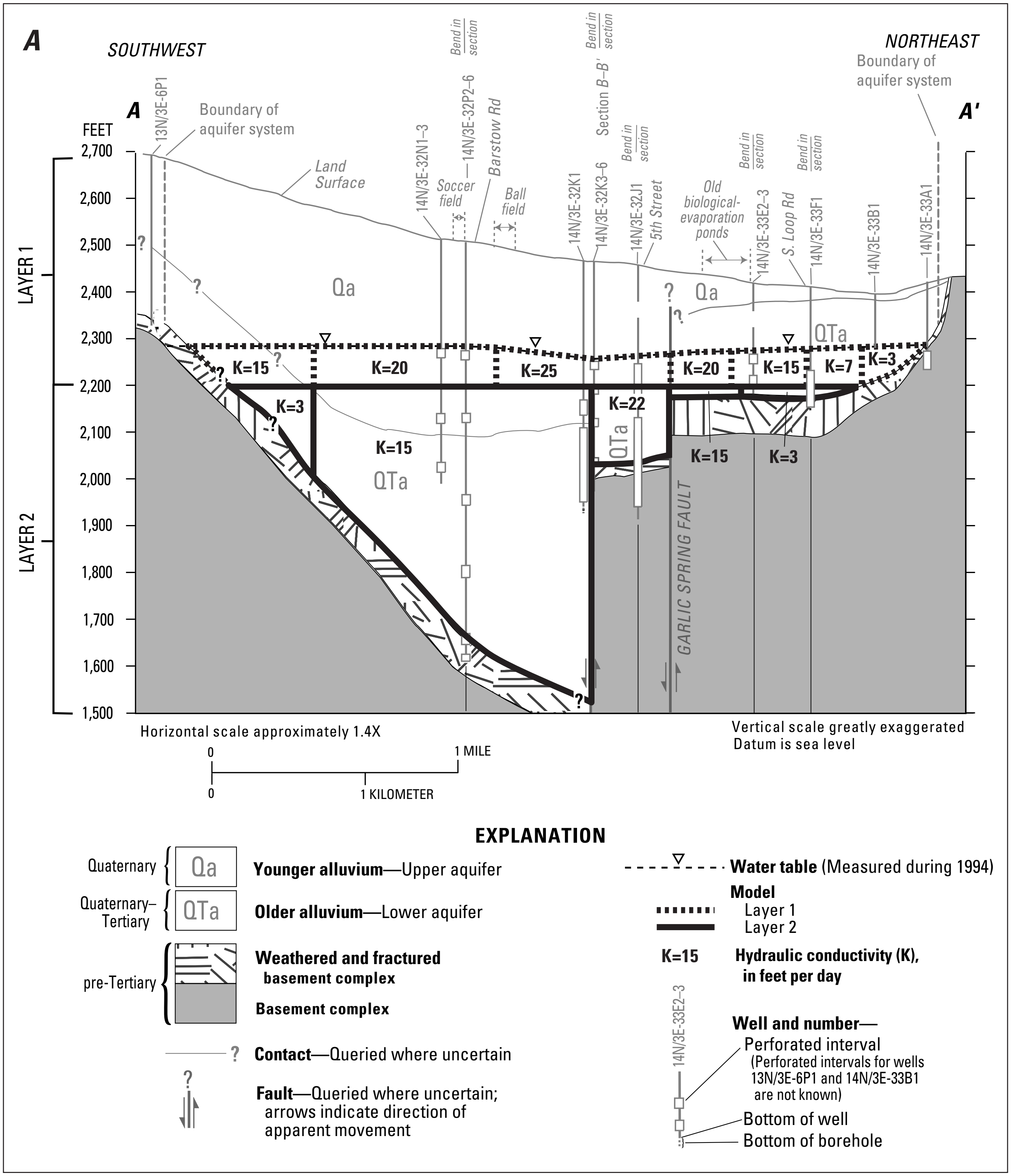


Figure 11. Cross-sectional view of model layers, hydraulic conductivities, and boundary conditions of the Irwin Basin, Fort Irwin National Training Center, California.

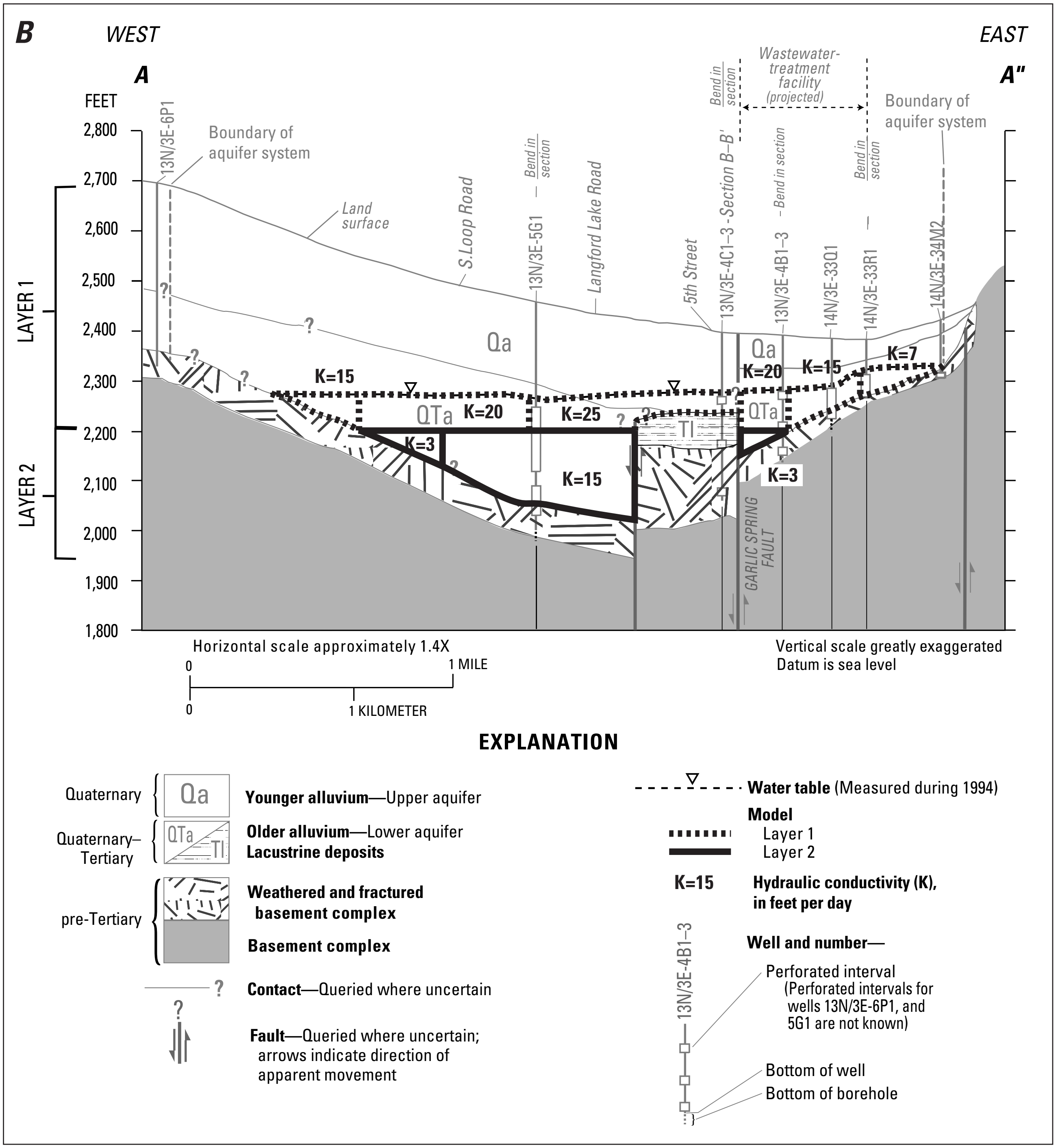


Figure 11.—Continued.

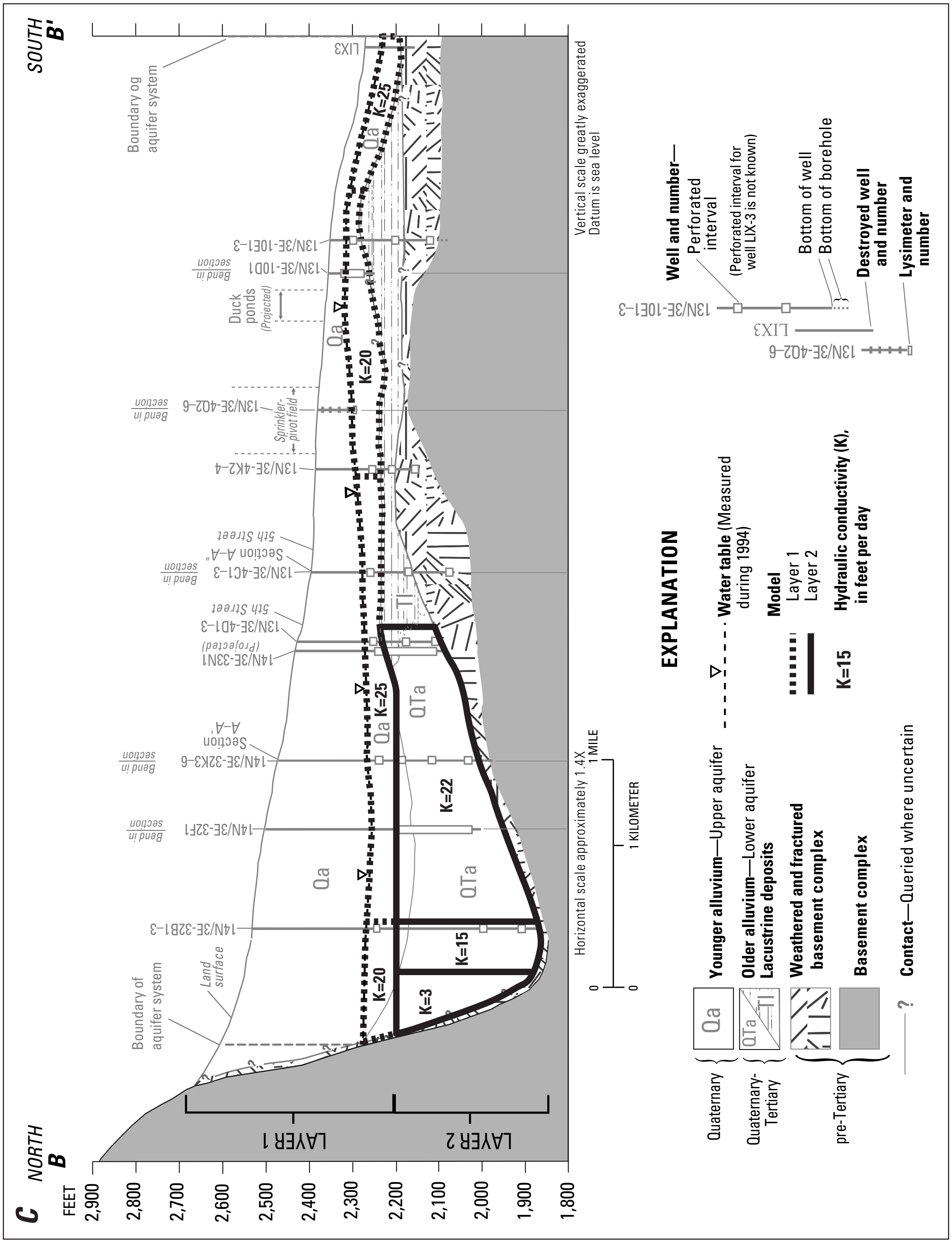


Figure 11.—Continued.

Model Boundaries

The model boundaries (figs. 10 and 11) were determined from the interpretations of the geology of the Irwin Basin. The lateral boundaries of the model coincide with the lateral boundaries of the aquifer system. The top boundary of the model, the water table, is simulated as a free-surface boundary (unconfined) to allow it to move vertically in response to changes between inflow and outflow. No-flow boundaries are used around and below the modeled area to represent contact with the basement complex and ground-water divides (figs. 10 and 11). The no-flow boundary indicates that there is no exchange of water between the model cell and the area outside the model.

The HFB package simulates faults that impede the horizontal flow of ground water; the boundary was simulated using the HFB package by Hsieh and Freckleton (1993). Flow across this boundary is proportional to the hydraulic-head difference between adjacent cells. The function of each barrier is to lower the horizontal conductances between the two adjacent model cells. In this model, the flow barrier is defined by a hydraulic characteristic. For confined aquifers, the hydraulic characteristic is the barrier transmissivity divided by the width of the barrier and has units of LT^{-1}. For unconfined aquifers, the hydraulic characteristic is the barrier hydraulic conductivity divided by the width of the barrier and has units of T^{-1}. This characteristic is determined during the calibration process.

The Garlic Spring Fault and a parallel unnamed fault were simulated using the horizontal-flow-barrier package (fig. 10). Water-quality data from Densmore and Londquist (1997) indicate that these faults act as a partial barrier to ground-water flow, suggesting that horizontal flow across the Garlic Spring Fault, primarily in the lower aquifer, is impeded. Based on model calibration, the hydraulic characteristics for the Garlic Spring Fault were assigned values of 0.002 ft/day and 0.002 ft/day for layer 1 and 2, respectively. The hydraulic characteristics for the parallel unnamed fault were assigned values of 0.01 ft/day and 0.01 ft/day for layer 1 and 2, respectively, thereby allowing slightly more horizontal flow across the unnamed fault than across the Garlic Spring Fault. Because it is not known if these faults cross the entire basin, the faults were modeled as only partly crossing the basin. Changes in the fault conductance made during calibration had minimal effect on the simulated water-level changes.

The GHB package (McDonald and Harbaugh, 1988, p. 11-1; table 3) was used to simulate underflow from layer 1 through the unnamed wash near Garlic Spring. A general-head boundary simulates a source of water outside the model area that either supplies water to, or receives water from, adjacent cells in proportion to the hydraulic-head differences between the source and model cell.

The exchange rate of water between the model cell and the outside source or sink is given by the equation

$$Q = C(HB - h)$$

where

Q	is the rate of flow into or out of the model cell [L^3/T],
C	is the conductance between the external source or sink and the model cell [L^2/T],
HB	is the head assigned to the external source or sink [L], and
h	is the hydraulic head within the model cell [L].

Values of C were initially calculated using the equation

$$C = KA/L,$$

where

K	is the hydraulic conductivity between the model cell and the boundary head [L/T],
A	is the cross-sectional area perpendicular to flow [L^2], and
L	is the flow distance [L].

Table 4. Final values for boundary head and hydraulic conductance used in the general-head boundary package of the model of Irwin Basin, Fort Irwin National Training Center, California.

[ft, foot; ft^2/d, foot squared per day]

Layer	Row	Column	Boundary head, HB (ft)	Conductance, C (ft^2/d)	Boundary
1	74	64	2,235	863.7	Southeastern boundary at the unnamed wash
1	75	64	2,235	630.8	Southeastern boundary at the unnamed wash

The initial values of *C*, ranging from 175–1,050 ft^2/d, were distributed across the model cells adjacent to the general-head boundary. The boundary head (*HB*) in the unnamed wash near Garlic Spring was assigned a head that was slightly less than that for the water-table altitude for well LIX3 (fig. 5). The head for well LIX3 was used, instead of the head for Garlic Spring, to approximate the water level in the wash because the well is located in the wash. Garlic Spring, on the other hand, is on the north side of Garlic Spring Fault. Because of the altitude of the spring (2,310 ft above sea level), it is believed that Garlic Spring does not drain the Irwin Basin aquifer system but may drain a local system northeast of the fault. The final values of *C*, determined during model calibration, are shown in table 4. The total conductance across the boundary is 1,494 ft^2/d, slightly higher than the initial estimate.

Aquifer Properties

Aquifer properties, such as hydraulic conductivity, transmissivity, vertical conductance, specific yield, and storage coefficient, control the rate at which water moves through the aquifer, the volume of water in storage, and the rate and areal extent of water-level declines caused by ground-water development. For this study, the aquifer-system properties were initially estimated from well logs, specific-capacity tests, and the published literature. Final estimates of these properties were made using a trial-and-error approach during steady-state and transient-state model simulations. These aquifer-property values can vary considerably spatially because of the heterogeneity of the aquifer-system material. To reduce the number of parameter values required in the model, the flow region of each model layer was divided into zones within the model domain and each zone was characterized by a uniform set of values. The definition of each zone was based on the analyses of available geologic and hydrologic data. The areal distribution of the aquifer properties used in the simulations is shown by zone in figure 12.

Hydraulic Conductivity and Transmissivity

Model layer 1 is divided into five hydraulic conductivity zones and model layer 2 is divided into three zones (fig. 12). The initial estimate of hydraulic conductivity determined from specific capacity data, range from 3 to 30 ft/d in layer 1 and 1 to 20 ft/d in layer 2 (table 5). The final estimates of hydraulic conductivity for layer 1 range from 3 to 25 ft/d (figs. 11 and 13; table 5). In general, the hydraulic-conductivity is highest (25 ft/d) near the center of the basin (fig. 13A), where younger alluvium (Qa) makes up a greater part of layer 1 (fig. 11). Hydraulic conductivity also is high (25 ft/d) in the wash near Garlic Spring (fig. 13A), where coarse-grained deposits are present. Hydraulic conductivity generally decreases (20 and 15 ft/d) away from the center of the basin (fig. 13A). Hydraulic conductivity is lower (3 to 7 ft/d) along the eastern edge of the basin (fig. 13A), where a thin layer of saturated younger and older alluvium (Qa and QTa, respectively) overlie the fractured basement complex (fig. 11).

The final estimate of hydraulic conductivity for layer 2 ranges from 3 to 22 ft/d (figs. 11 and 13B; table 5). Hydraulic conductivity is high (15–22 ft/d) near the center of layer 2 (fig. 13B), where about 50 to 100 ft of the younger alluvium (Qa) is included in layer 2. Hydraulic conductivity is low (3 ft/d) along the boundary of layer 2, where the entire thickness of layer 2 is older alluvium (QTa).

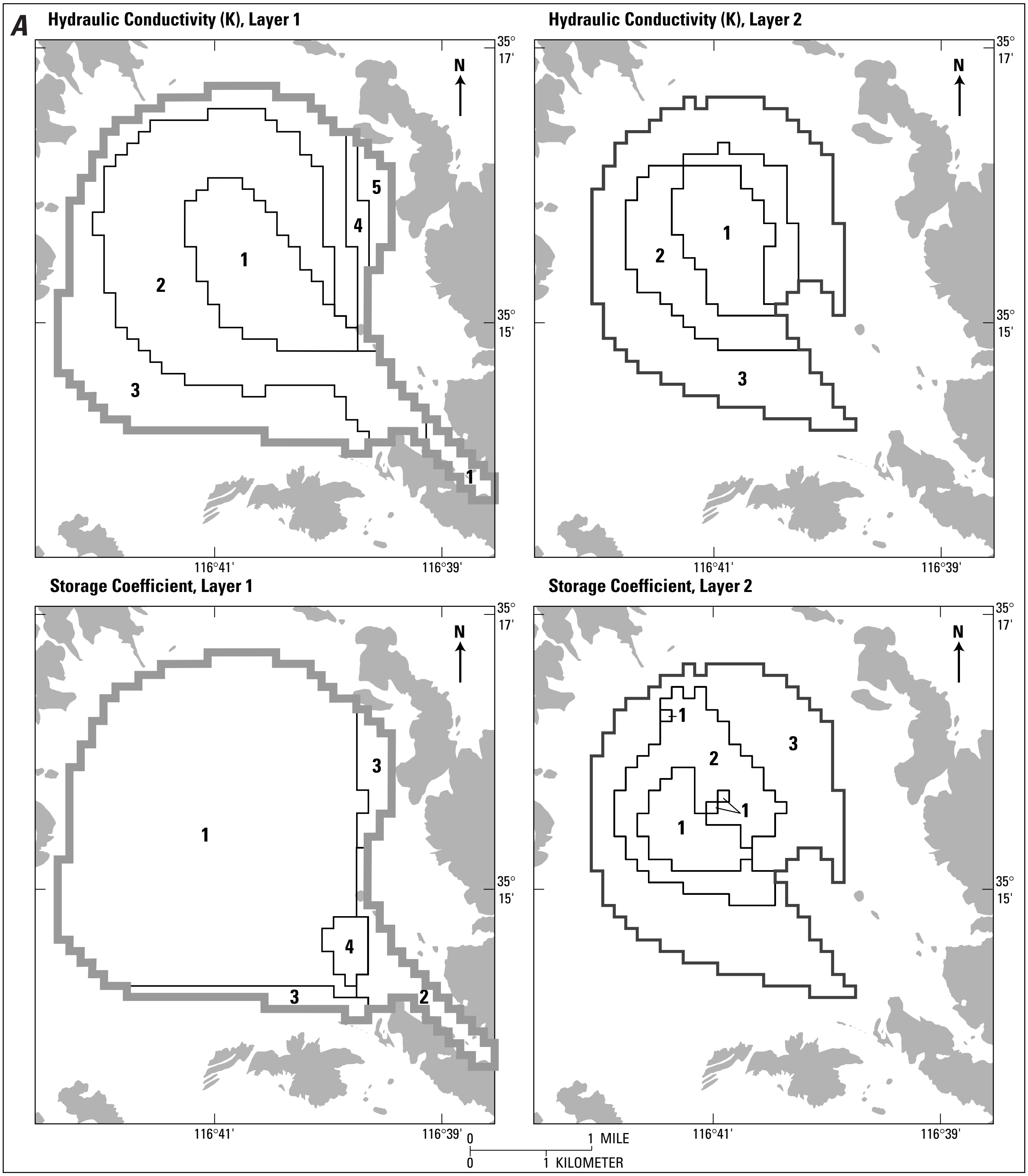


Figure 12. Areal distribution of zones of aquifer properties of the ground-water flow model of the Irwin Basin, Fort Irwin National Training Center, California.

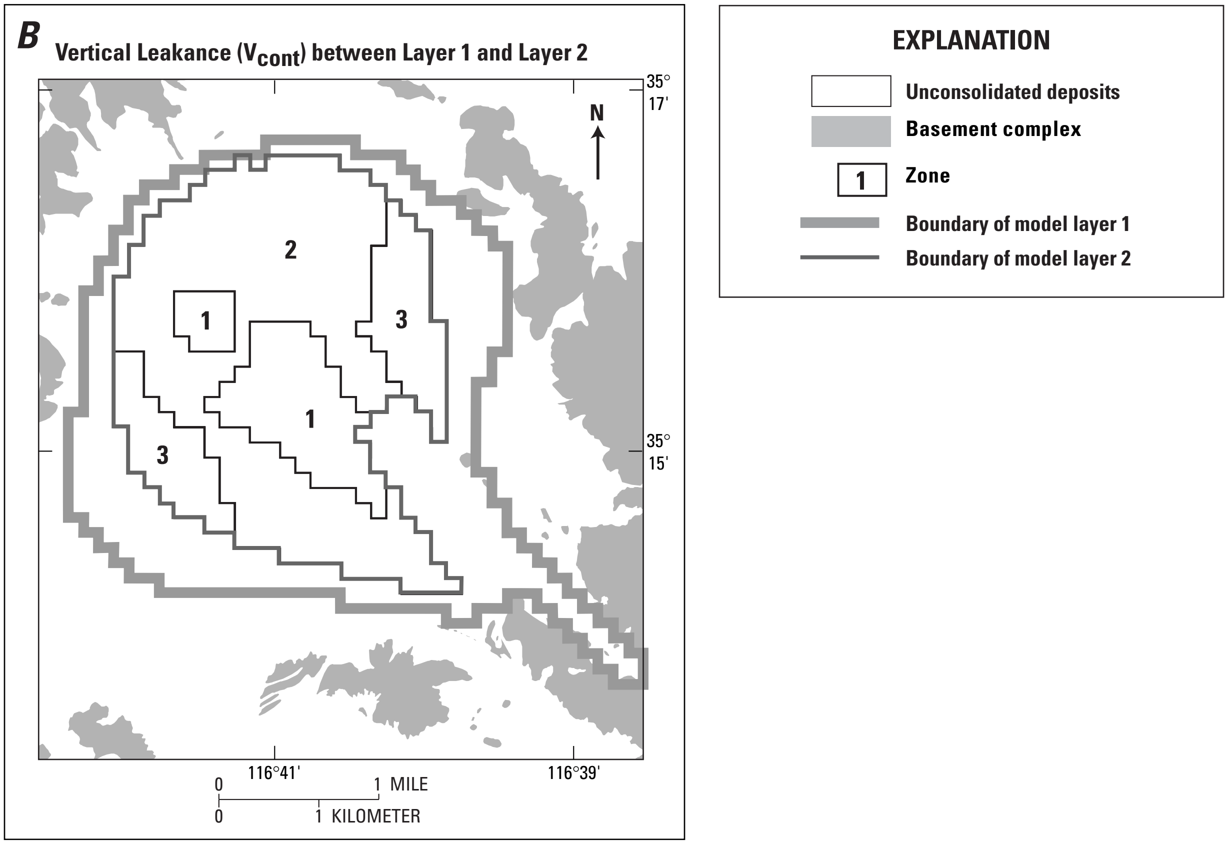


Figure 12.—Continued.

Vertical Leakance

Vertical leakage between layers 1 and 2 occurs only where layer 1 overlies layer 2 and where there is a hydraulic-head difference between the layers. The rate at which this leakage occurs is described by the equation

$$Q = C_V(H_2 - H_1)$$

where $C_V = V_{cont}(A)$

where $V_{cont} = \dfrac{1}{\dfrac{B_1/2}{K_{V1}} + \dfrac{B_2/2}{K_{V2}}}$

where

Q is the vertical leakage $[L^3/T]$,

C_V is the vertical conductance $[L^2/T]$,

H_1 is the hydraulic head in layer 1 [L],

H_2 is the hydraulic head in layer 2 [L],

V_{cont} is the vertical leakance, and the term used as input in the model [1/T],

A is the area of the cell $[L^2]$,

B_1 is the saturated thickness of model layer 1 [L],

B_2 is the saturated thickness of model layer 2 [L],

K_{V1} is the vertical hydraulic conductivity of material in layer 1 [L], and

K_{V2} is the vertical hydraulic conductivity of material in layer 2 [L].

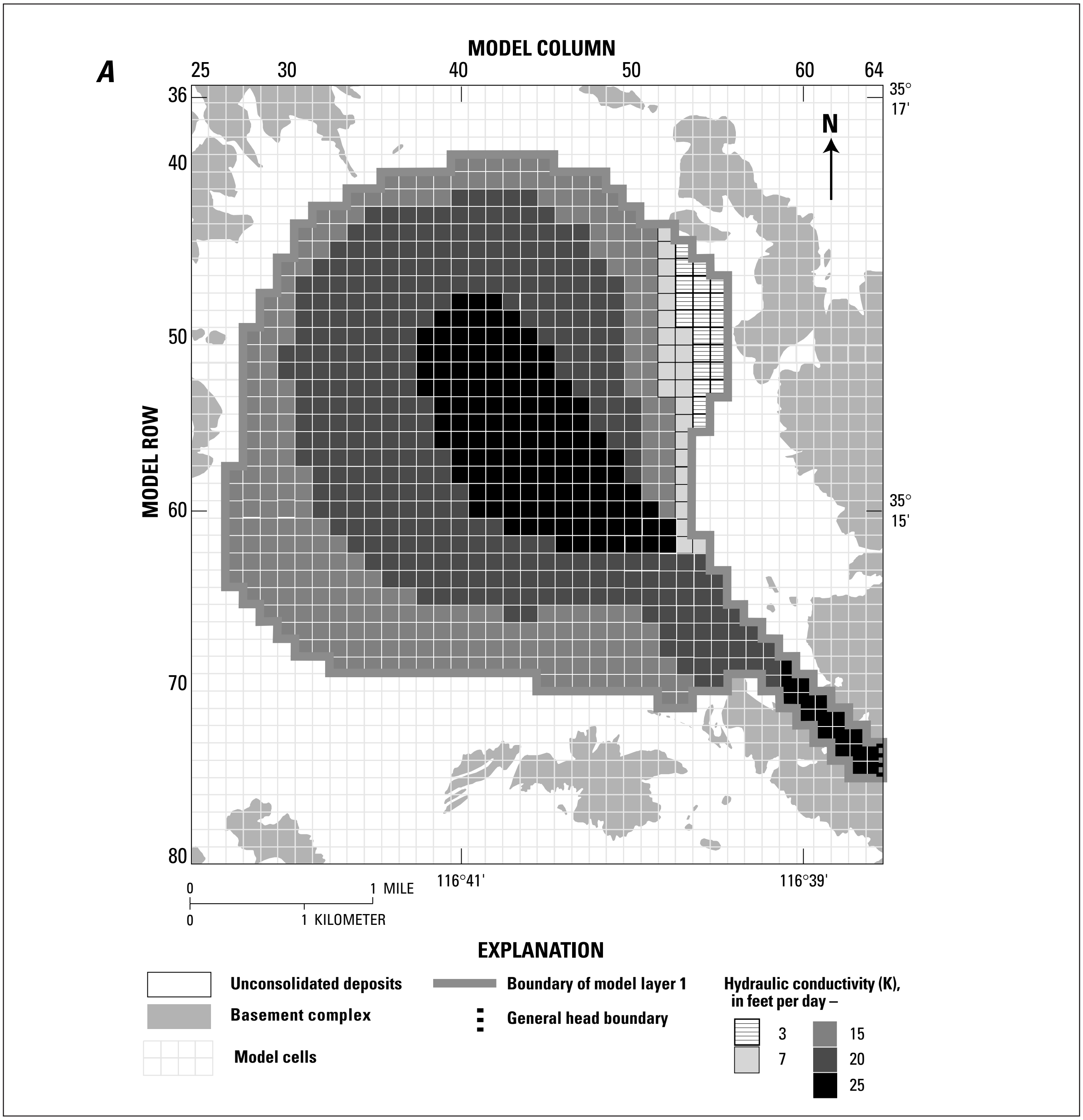


Figure 13. Areal distribution of hydraulic conductivity for layer 1 (*A*) and layer 2 (*B*) in the model of the Irwin Basin, Fort Irwin National Training Center, California.

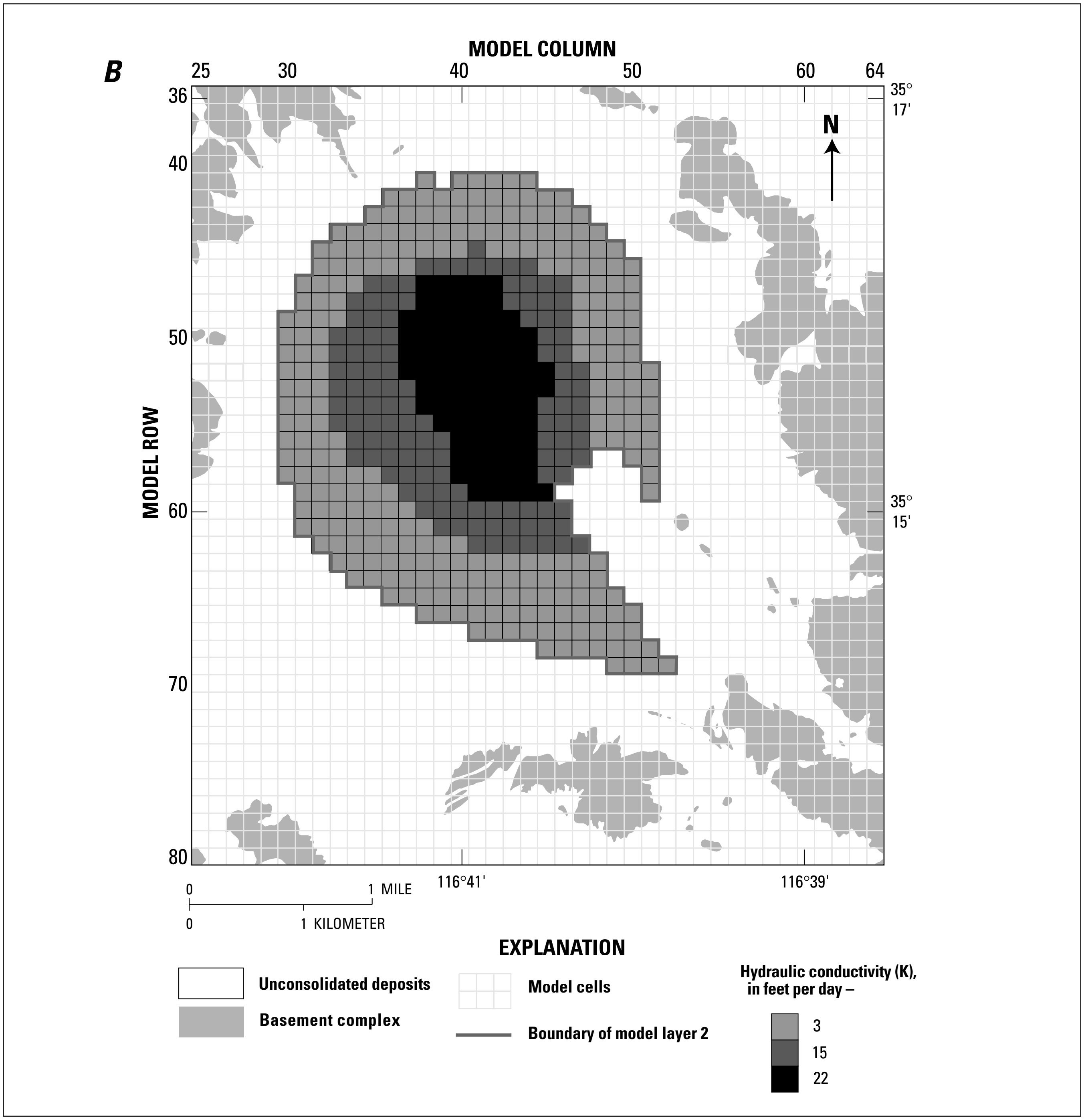


Figure 13.—Continued.

Table 5. Summary of initial and final parameter estimates used in the ground-water flow model of Irwin Basin, Fort Irwin National Training Center, California

[—, zone not present during initial run; na, not applicable]

Model layer	Zone 1 (Initial) Final	Zone 2 (Initial) Final	Zone 3 (Initial) Final	Zone 4 (Initial) Final	Zone 5 (Initial) Final
Hydraulic conductivity, in feet per day					
Layer 1	(25–30) **25**	(15) **20**	(3) **15**	(9) **7**	(—) **3**
Layer 2	(20) **22**	(15) **15**	(1) **3**	(—) **1**	(na) **na**
Vertical leakance, per day					
Between layer 1 and 2	(0.01) **0.01**	(0.005) **0.005**	(0.0005) **0.0005**	na **na**	(—) —
Primary storage coefficient					
Layer 1	(0.19) **0.12**	(0.19) **0.01**	(0.19) **0.05**	(0.19) **0.1**	(na) **na**
Layer 2	(0–00018) **0–.00018**	(.00018–.00036) **.00018-.00036**	(.00036p.0006) **.00036–.0006**	(na) **na**	(na) **na**

The vertical hydraulic conductivity of layers 1 and 2 was assumed to be one-tenth of the horizontal hydraulic conductivity of the layers. This assumption has been used in studies of other nearby desert basins (Londquist and Martin, 1991). The values of saturated thickness prior to ground-water development, when the water table was assumed to be about 2,300 ft above land surface, were used in the equation above; these values were not changed during steady-state or transient-state model calibration. The calculated areal distribution of vertical leakance between model layers 1 and 2 is presented in figure 14.

Storage Coefficient

Model layer 1 is divided into four storage-coefficient zones (fig. 12). Previous investigators (James M. Montgomery and Associates, Inc., 1981) estimated that the specific yield of the upper 150 ft of sediments is 0.19; this value was used as the initial estimate for each of the storage-coefficient zones. During the transient-state calibration of the model, specific yield was lowered to 0.12 throughout most of layer 1 where the aquifer consists primarily of younger and older alluvium (fig. 15).

The calibrated values were lowered to 0.1 for the part of the unnamed wash located in the southeastern end of the basin where coarser deposits are present. The calibrated values were the lowest in the southern and eastern edges of the basin (0.05) where the alluvium is finer grained and in the southeastern part of the basin (0.01) where evaporite deposits are present (fig. 15).

The storage coefficient for the confined lower aquifer, layer 2, was initially estimated by multiplying the layer thickness by a specific storage of $1x10^{-6}$ ft^{-1} (Lohman, 1972, p. 53). These values ranged from 0.00001 to 0.00058 (fig. 15B). Specific storage is the amount of water per unit volume of a saturated formation that is stored or expelled from storage owing to compressibility of the mineral skeleton and the porewater per unit change in head (Fetter, 1994). During the model calibration, the initial estimate was determined to best simulate conditions in layer 2.

Simulation of Recharge

Recharge to the Irwin Basin includes natural recharge by the infiltration of precipitation runoff along the normally dry wash that crosses the basin and by artificial recharge of irrigation-return flow and of infiltrated treated wastewater.

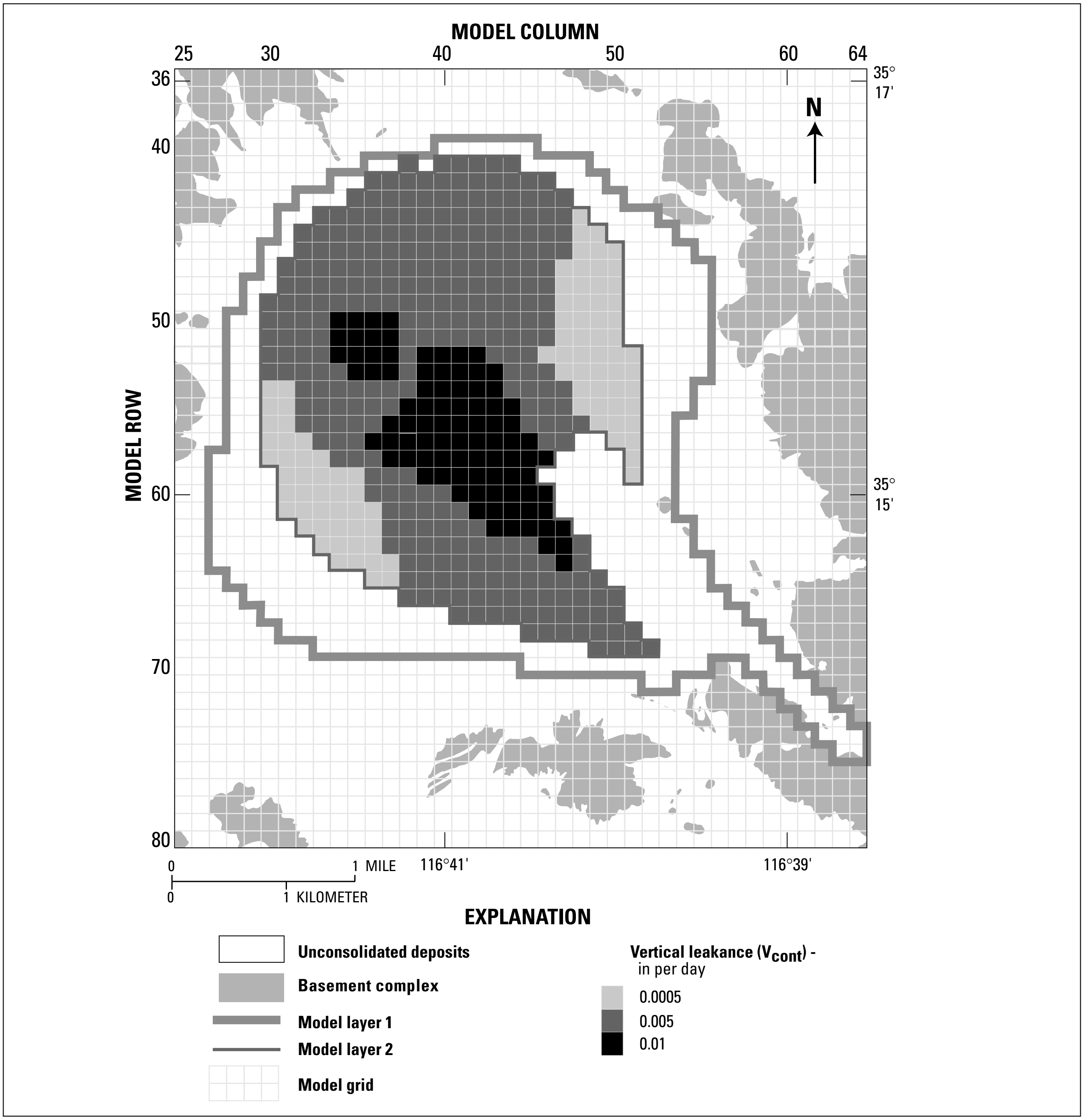


Figure 14. Areal distribution of vertical leakance (V_{cont}) in the Irwin Basin, Fort Irwin National Training Center, California.

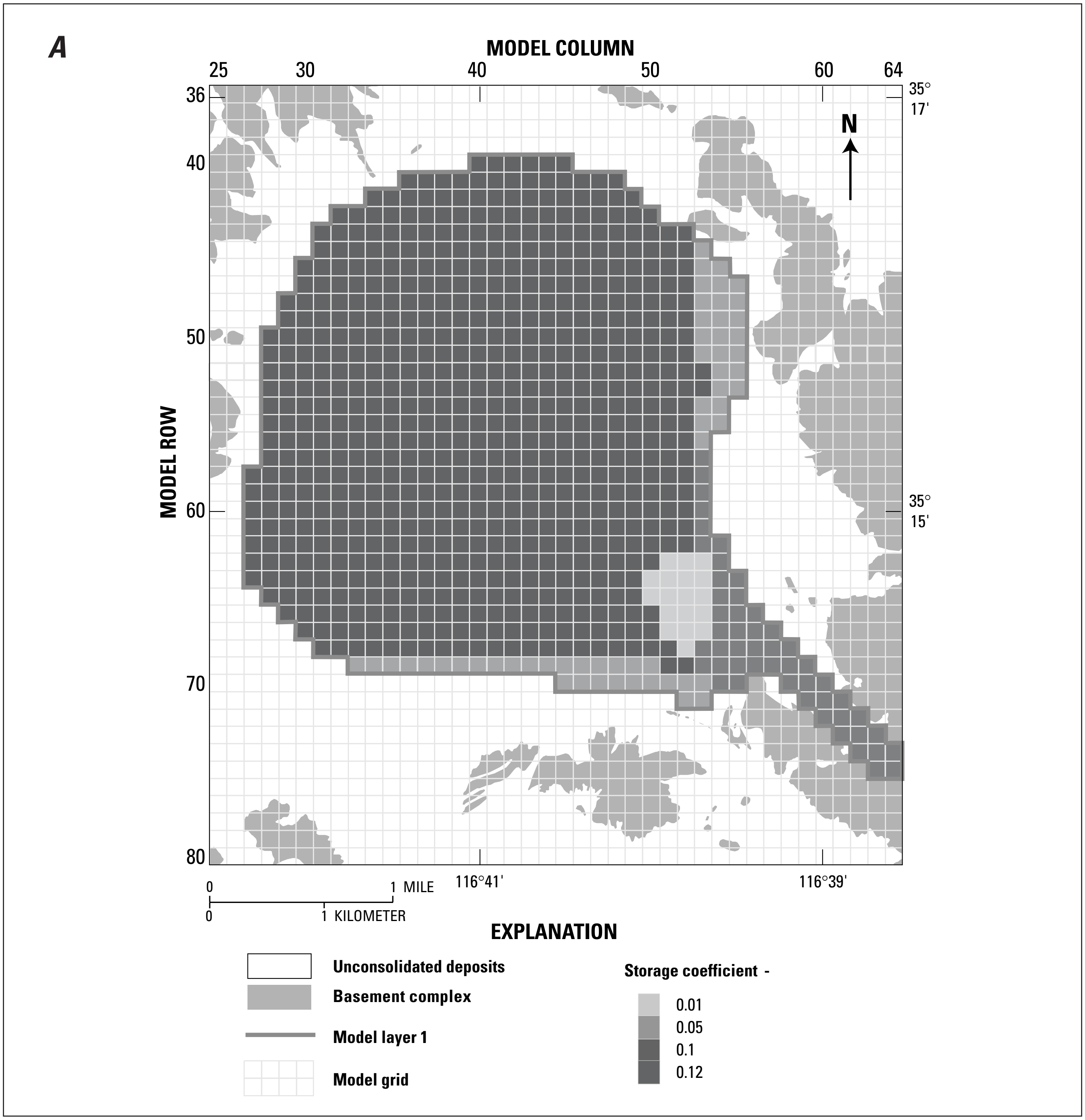


Figure 15. Areal distribution of storage coefficients for layer 1(*A*) and layer 2(*B*) in the model of Irwin Basin, Fort Irwin National Training Center, California.

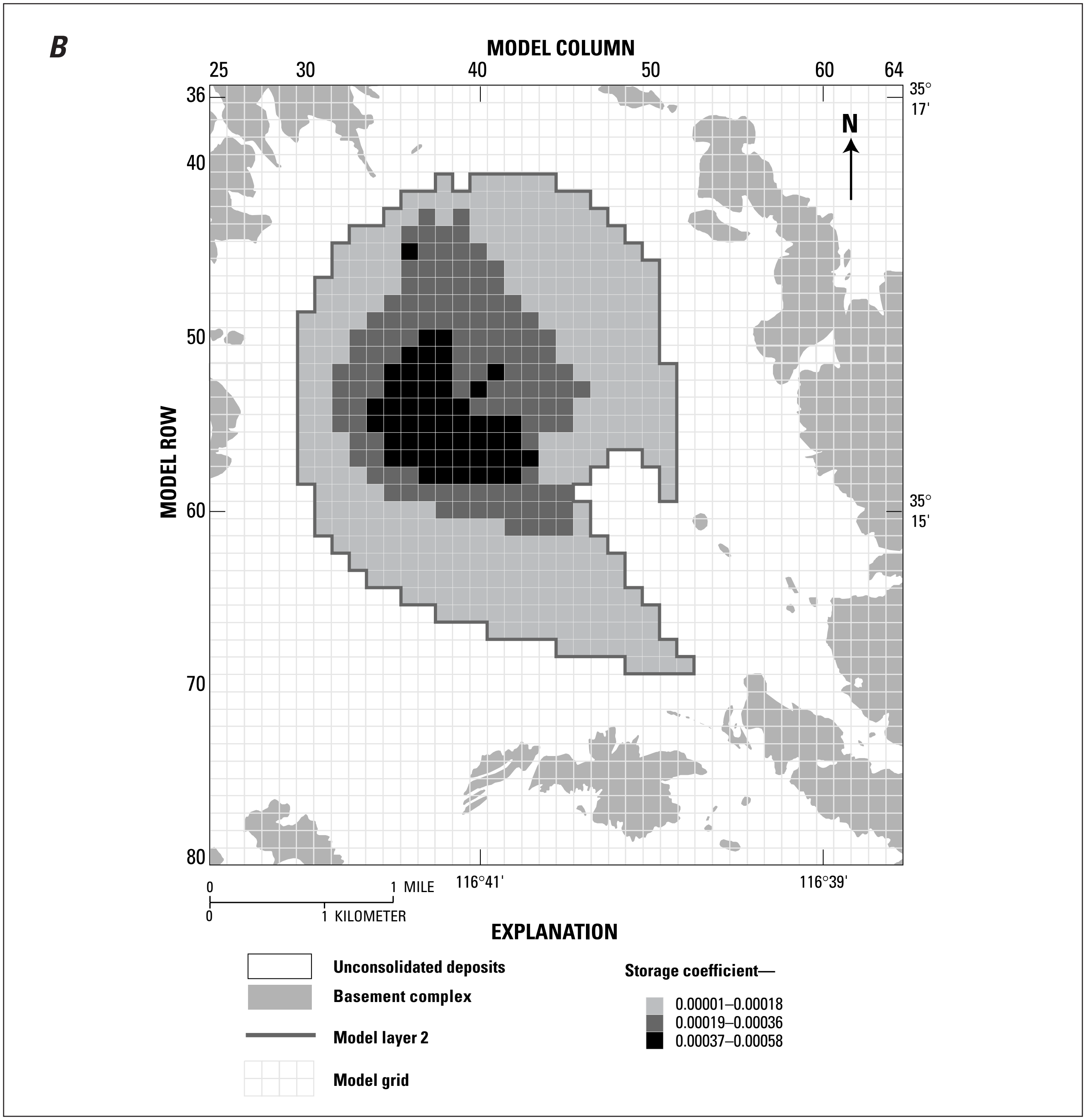


Figure 15.—Continued.

Natural Recharge

As previously stated, natural recharge in the Irwin Basin is solely by infiltration of precipitation runoff within the Irwin drainage basin (fig. 1). It was assumed that areal recharge from direct infiltration of precipitation was insignificant because of the infrequent occurrence of these events and because of the low precipitation and high evaporation rates in the study area. Recent work in the upper Mojave Basin by Izbicki and others (2000) shows that infiltration does not occur at depths below the root zone except in areas of some intermittent washes in arid desert environments. Thus, natural recharge was simulated only along the intermittent wash (fig. 16) that was formed by runoff from Northwest and Southwest Ridges (fig. 2) using the areal recharge package (RECH) developed by McDonald and Harbaugh (1988, p. 7–1).

The initial estimate of natural recharge from precipitation runoff used to calibrate the model was 150 acre-ft/yr (C.F. Hostrup and Associates, 1955). This estimate was lowered to about 50 acre-ft/yr during calibration of the steady-state and transient-state simulations. Two-thirds of the total recharge was simulated to infiltrate into the upper one-third of the wash; the remaining one-third of total recharge was simulated to infiltrate into the lower two-thirds of the wash (fig. 16).

Artificial Recharge

Artificial recharge to the basin was divided into two categories: infiltration of treated wastewater that was diverted to the base golf course, driving range, sprinkler-pivot field, and duck ponds; and irrigation-return flow from lawns and fields in the base housing areas that were irrigated using ground water. Artificial recharge was simulated using the areal recharge package (RECH) developed by McDonald and Harbaugh (1988) which distributed additional recharge to the cells underlying the wastewater disposal area and the irrigated areas. The areal distribution of artificial recharge is presented in figure 16.

Estimates of ground-water recharge from wastewater infiltration presented by Densmore and Londquist (1997) and updated for this study (table 3) were used as the initial estimates for the artificial recharge. These values were modified during calibration of the transient-state model (table 6). The final calibrated values of wastewater recharge generally were higher than the initial estimates for 1955–85 and lower than the initial estimates for 1991–94. The lower calibrated values of wastewater recharge for 1991–94 may reflect a decrease in water disposed at the wastewater-treatment facility owing to better conservation practices at base housing. The lower values also may reflect that more of the pumped water was being used outside of Irwin Basin. It is also possible that during this time, more of the wastewater was being distributed to the sprinkler-pivot field where more evaporation could occur which would result in less artificial recharge. The final estimates of irrigation-return flow generally were the same or lower than the initial estimates prior to 1964 and higher than the initial estimates for 1965–99.

Simulation of Discharge

Ground-water pumpage is the main discharge from the basin. Ground-water pumpage in the Irwin Basin began in 1941 when the first two wells were drilled to supply water at Camp Irwin. All the water used at the base during 1941–66 was supplied from wells in the Irwin Basin (fig. 17). Pumping from the Bicycle Basin in 1967 and the Langford Basin in 1992 allowed for a reduction in pumping from the Irwin Basin. Although annual pumpage (fig. 17) was estimated during previous studies, the distribution of pumpage among the individual wells for 1941–89 was not reported for the Irwin Basin. Therefore, the distribution of pumpage for this period was estimated as a percentage of water based on well-capacity data from pump tests. For this study, annual pumpage for 1990–99 was obtained from records provided by Fort Irwin personnel (Rene Quinones, Walt Young, and Suzanne Beauchamp, Fort Irwin National Training Center, written commun., 1996, 1998, 2000). The pumpage from each model layer was distributed such that about two-thirds of the total pumpage per well comes from layer 1 and about one-third comes from layer 2. This estimated distribution was based on results of wellbore-flow tests described by Densmore and Londquist (1997).

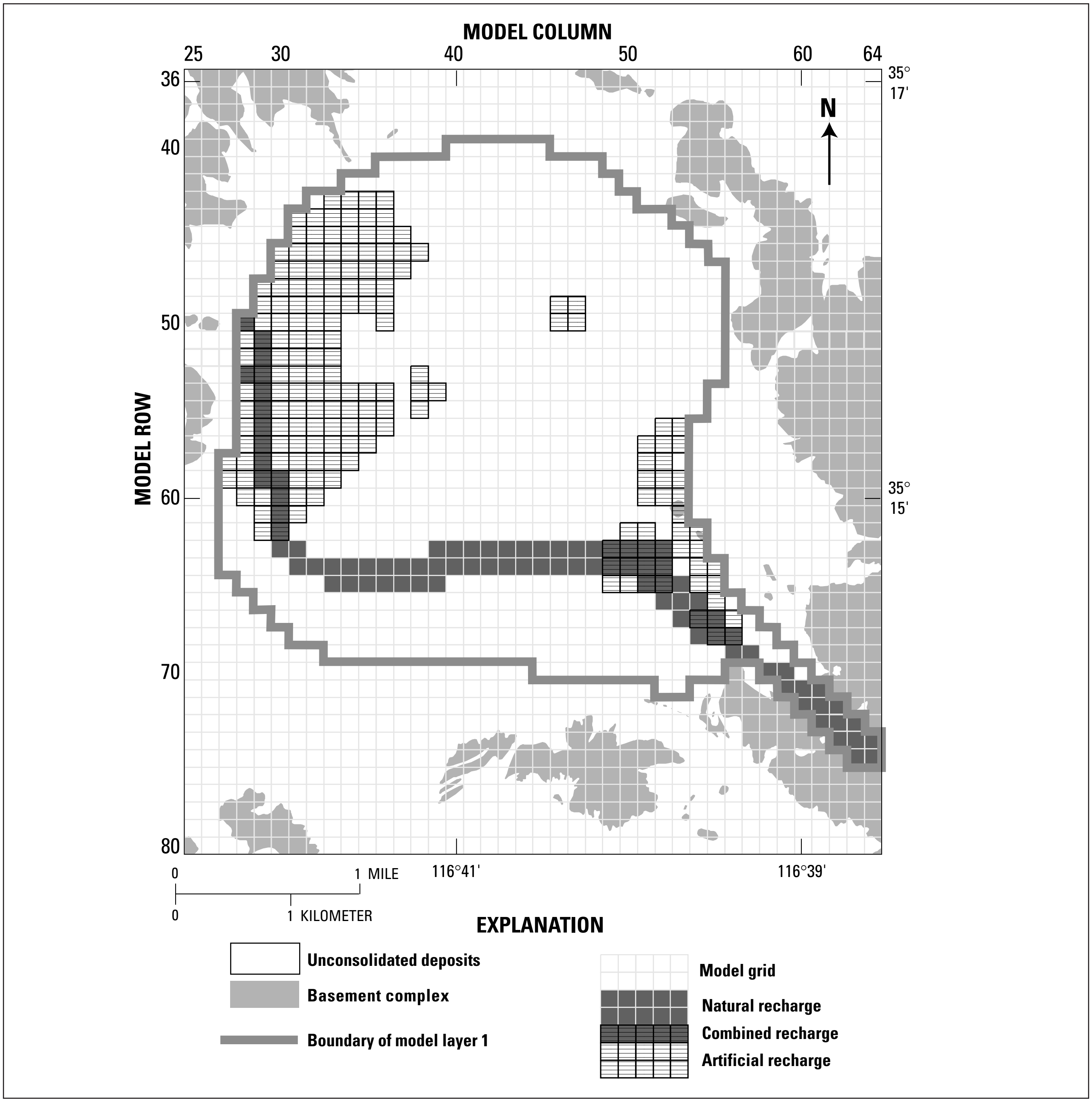


Figure 16. Areal distribution of natural and artificial recharge for model layer 1 in the model of the Irwin Basin, Fort Irwin National Training Center, California.

Table 6. Summary of artificial recharge and total artificial recharge from wastewater and irrigation-return flow by sources and range of initial and final

[See figure 5 for location of sources of artificial recharge. Numbers in parentheses are model cell numbers (row;column). —> indicates range of cells in

Year	Wastewater recharge					
	Old biological evaporation pond (49,46; 49,47; 50,46; 50;47)	Duck ponds (64,55; 65,55; 66,55; 67,55; 68,55)	Golf course and driving range (59,53; 60,53; 61,53; 62,53; 62,54; 63,53; 63,54)	Sprinkler-pivot field (63,49; 63,50; 63,51; 64,49; 64,50; 64,51; 64,52)	Wastewater-treatment facility (56,52—>53; 57,52—>53; 58,52; 59,52; 56,52)	Total recharge by infiltration of wastewater
1941	0	0	0	0	0	0
1942	21	0	0	0	0	21
1943	150	0	0	0	0	150
1944	225	0	0	0	0	225
1945	53	0	0	0	0	53
1946	0	0	0	0	0	0
1947	0	0	0	0	0	0
1948	0	0	0	0	0	0
1949	0	0	0	0	0	0
1950	0	0	0	0	0	0
1951	117	0	0	0	0	117
1952	142	0	0	0	0	142
1953	336	0	0	0	0	336
1954	334	0	0	0	0	334
1955	0	108	128	0	194	430
1956	0	0	0	0	0	0
1957	0	3	3	0	4	9
1958	0	0	0	0	0	0
1959	0	0	0	0	0	0
1960	0	8	8	0	13	29
1961	0	35	37	0	56	128
1962	0	68	85	0	129	282
1963	0	74	93	0	142	309
1964	0	87	104	0	157	347
1965	0	111	132	0	200	443
1966	0	158	188	0	283	629
1967	0	190	231	0	351	772
1968	0	175	209	0	317	702
1969	0	198	236	0	358	792

estimates of recharge in the Irwin Basin, Fort Irwin National Training Center, California, 1941–99.

column indicated. Values in acre-feet]

Irrigation-return flow						Range of initial estimated artificial recharge [1]		
Army ball field (54,38)	Baseball field (49,36; 50,36)	Soccer field (54,35; 54,36; 55,36)	Old base housing (54,32—>35; 55,28—>35; 56,28—>35; 57,28—>34; 58,27-->33; 59,28—>33; 60,28—>32; 61,29—>31) 61,29—>31)	New base housing (43,34—>36; 44,32—>36; 45,31—>37; 46,30—>37; 47,30—>37; 48,29—>36; 49,29—>35; 50,28—>33; 51,28—>33; 52,28—>33; 53,28—>33; 54,28—>33)	Total recharge by infiltration of irrigation-return flow	Low	High	Final artificial recharge
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	22	38	21
0	0	0	0	0	0	150	192	150
0	0	0	0	0	0	225	283	225
0	0	0	0	0	0	53	74	53
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	117	152	117
0	0	0	0	0	0	142	182	142
0	0	0	0	0	0	336	417	336
0	0	0	0	0	0	334	415	334
21	0	0	0	0	21	294	336	451
21	0	0	0	0	21	0	0	21
21	0	0	0	0	21	0	13	30
21	0	0	0	0	21	0	0	21
21	0	0	0	0	21	0	0	21
21	0	0	0	0	21	0	42	50
21	0	0	0	0	21	31	137	149
21	0	0	0	0	21	169	303	303
21	0	0	0	0	21	185	323	330
21	0	0	0	0	21	307	451	368
21	0	0	109	0	130	367	324	573
21	0	0	109	0	130	485	666	759
21	0	0	109	0	130	566	764	902
21	0	0	109	0	130	529	719	832
21	0	0	109	0	130	585	787	922

Table 6. Summary of artificial recharge and total artificial recharge from wastewater and irrigation-return flow by sources and range of initial and final

Year	Wastewater recharge					
	Old biological evaporation pond (49,46; 49,47; 50,46; 50;47)	Duck ponds (64,55; 65,55; 66,55; 67,55; 68,55)	Golf course and driving range (59,53; 60,53; 61,53; 62,53; 62,54; 63,53; 63,54)	Sprinkler-pivot field (63,49; 63,50; 63,51; 64,49; 64,50; 64,51; 64,52)	Wastewater-treatment facility (56,52—>53; 57,52—>53; 58,52; 59,52; 56,52)	Total recharge by infiltration of wastewater
1970	0	143	173	0	262	578
1971	0	59	63	0	96	217
1972	0	0	250	0	378	628
1973	0	0	111	0	168	279
1974	0	0	71	0	108	179
1975	0	0	100	0	151	251
1976	0	0	162	0	246	408
1977	0	4	5	0	7	15
1978	0	0	216	0	327	542
1979	0	0	280	0	424	703
1980	0	0	500	0	757	1,257
1981	0	145	157	0	238	540
1982	0	130	140	0	213	483
1983	0	210	208	0	315	733
1984	0	356	401	0	607	1,365
1985	0	359	404	0	612	1,375
1986	0	167	178	161	270	776
1987	0	197	192	174	291	855
1988	0	225	190	189	184	789
1989	0	193	163	162	158	677
1990	0	308	224	247	254	1,033
1991	0	170	136	166	111	582
1992	0	219	175	214	143	751
1993	0	233	187	229	153	802
1994	0	273	145	243	190	851
1995	0	370	218	371	285	1,244
1996	0	372	266	334	238	1,211
1997	0	356	346	0	238	940
1998	0	356	479	0	238	1,073
1999	0	356	479	0	238	1,073

[1]Densmore and Londquist (1997)

Irrigation-return flow						Range of initial estimated artificial recharge [1]		
Army ball field (54,38)	Baseball field (49,36; 50,36)	Soccer field (54,35; 54,36; 55,36)	Old base housing (54,32—>35; 55,28—>35; 56,28—>35; 57,28—>34; 58,27-->33; 59,28—>33; 60,28—>32; 61,29—>31) 61,29—>31)	New base housing (43,34—>36; 44,32—>36; 45,31—>37; 46,30—>37; 47,30—>37; 48,29—>36; 49,29—>35; 50,28—>33; 51,28—>33; 52,28—>33; 53,28—>33; 54,28—>33)	Total quantity of recharge by infiltration of irrigation-return flow	Low	High	Final artificial recharge
21	0	0	109	0	130	448	622	708
21	0	0	109	0	130	174	290	347
21	0	0	109	0	130	488	593	758
21	0	0	109	0	130	255	313	409
21	0	0	109	0	130	193	237	309
21	0	0	109	0	130	237	290	381
21	0	0	109	0	130	343	418	538
21	0	0	109	0	130	90	109	145
21	0	0	109	0	130	428	521	672
21	0	0	109	0	130	537	653	833
21	0	0	109	0	130	808	999	1,387
21	0	0	109	0	130	363	537	669
21	0	0	109	0	130	325	492	613
24	0	0	109	0	133	440	630	866
24	23	29	109	0	185	1,101	1,385	1,550
24	23	29	109	0	185	1,108	1,393	1,561
24	23	29	109	0	185	1,104	1,321	962
24	23	29	109	181	366	1,064	1,394	1,221
24	23	29	109	181	366	1,055	1,383	1,155
24	23	29	109	181	366	935	1,238	1,043
24	23	29	109	181	366	1,314	1,696	1,399
24	23	29	109	181	366	1,042	1,368	948
24	23	29	109	181	366	1,130	1,564	1,117
24	23	29	109	181	366	1,133	1,478	1,168
24	23	29	109	193	379	1,297	1,673	1,230
24	23	29	109	193	379	1,289	1,666	1,622
24	23	29	109	193	379	1,226	1,589	1,590
29	23	29	109	193	384	1,284	1,646	1,324
29	23	29	109	193	384	1,335	1,708	1,457
29	23	29	109	193	384	1,420	1,810	1,457

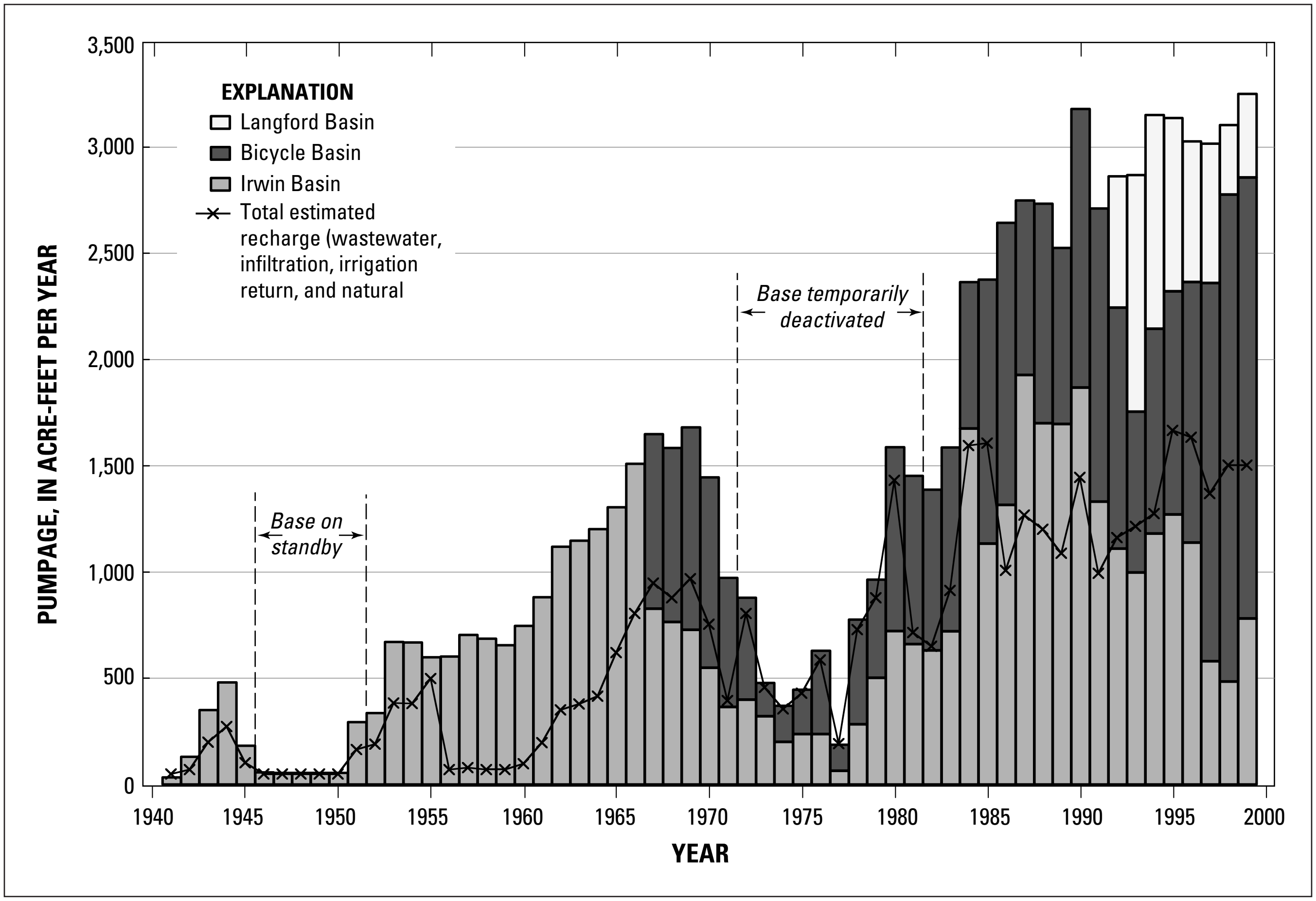


Figure 17. Annual pumpage from the Irwin, Bicycle, and Langford Basins, Fort Irwin National Training Center, California, 1941–1999.

Model Calibration

The Irwin Basin ground-water flow model was calibrated using a trial-and-error method in adjusting initial estimates of aquifer properties, recharge, and discharge to get a best match between simulated hydraulic heads and measured water levels, and selected water-budget items. The initial estimates for the aquifer properties were based on the geologic and hydrologic properties of the basin. These estimates were used in a steady-state simulation to provide initial conditions for the subsequent transient-state simulation. Steady-state flow conditions exist when inflow is equal to outflow, and aquifer storage does not change with time. Ground-water conditions prior to 1941 (representing predevelopment conditions) were used to calibrate the steady-state model and ground-water conditions for the period 1941–99 were used to calibrate the transient-state model. Transient conditions exist when inflow does not equal outflow, and hydraulic heads and volumes of water in storage change. The calibration process involved iterative simulations. The steady-state model was calibrated by trial-and-error adjustments of key parameters until simulated heads matched measured heads in six wells measured during 1941–43, and until simulated water-budget components matched published estimates. The steady-state heads were used as initial heads in the transient-state simulation. The transient model was calibrated by trial-and-error adjustments of only the key parameters specific to the transient model until simulated heads matched measured heads during the period 1941–99. The simulated boundary fluxes were checked for reasonableness.

Steady-State Model

The steady-state calibration involved matching the simulated hydraulic heads to measured water levels from wells in the Irwin Basin for 1941–43. Because pumpage was minimal during the initial years of development at Camp Irwin (33 acre-ft in 1941 and 130 acre-ft in 1942, table 2), it is reasonable to assume that the measured water levels for 1941–43 represent steady-state conditions.

Hydraulic heads for steady-state conditions are sensitive to the amount of water that recharges to, and discharges from, the ground-water system; the transmissivity of the aquifer system; the conductance across the faults that partially cross the basin; and the leakance between layers. Therefore, the steady-state simulation consisted of modifying the (1) initial estimates of transmissivity, (2) the quantity and distribution of recharge, (3) fault parameters (hydraulic characteristics), and (4) boundary conditions.

The measured water levels for six wells near the middle of the basin for 1941–43 (ranging from 2,299 to 2,306 ft), were assumed representative of the hydraulic heads of the basin prior to ground-water development. The average water level for these wells was assumed to represent steady-state conditions. The accuracy of the individual water-level measurements, however, is questionable because the water levels were measured from unspecified reference points and may have been made shortly after local pumping ceased. Because the 1941–43 water-level measurements are from wells perforated in both model layers 1 and 2 and because there is little difference between the present-day water-level measurements from wells perforated solely in layer 1 or in layer 2, it was assumed that layer 2 had the same initial hydraulic-head distribution as layer 1 in the area of these six wells.

The steady-state simulation of recharge resulted in a total simulated recharge of about 50 acre-ft/yr; the simulation of discharge at the general head boundary in the wash near Garlic Spring was equal to this amount. The ground-water gradient was fairly flat, with a slight incline of 0.0007 ft/ft toward the southeast (fig. 18). The simulated hydraulic heads for steady-state conditions generally were within 5 ft of the measured water levels for 1941–43 of these six wells (fig. 18).

Transient-State Model

Upon achieving a satisfactory steady-state calibration, transient ground-water conditions were modeled for the 59-year period between 1941 and 1999. The transient-state model consists of 59 annual stress periods. Each stress period has 5 time steps. The time units were days. Transient conditions are the result of stresses applied to the basin, such as pumpage from production wells and artificial recharge from sewage effluent and irrigation-return flow.

Changes in hydraulic head during the transient-state simulation are sensitive to natural recharge and discharge, artificial recharge, ground-water pumpage, the storage coefficient of the two model layers, the hydraulic conductivity of both model layers, the leakance between the layers, the fault hydraulic characteristics, and the boundary conditions. For the transient-state calibration, the quantity and distribution of natural recharge, the fault hydraulic characteristics, and the boundary conditions were assumed to be the same as those calibrated for the steady-state simulation. Estimates of total reported ground-water pumpage from the Irwin Basin were not modified for the model simulations because it was assumed that the estimates are fairly accurate. Because pumpage from individual wells generally was not available prior to 1990, the distribution of total pumpage from wells was based on well-capacity data. Since 1990, records of pumpage have been available for individual wells. Initially, the pumpage from an individual well was distributed such that about two-thirds of the total pumpage from a well was from layer 1 and about one-third was from layer 2. The distribution of pumpage was varied areally and vertically during calibration if the simulated heads resulting from the original estimated pumpage distribution did not to match the measured water levels.

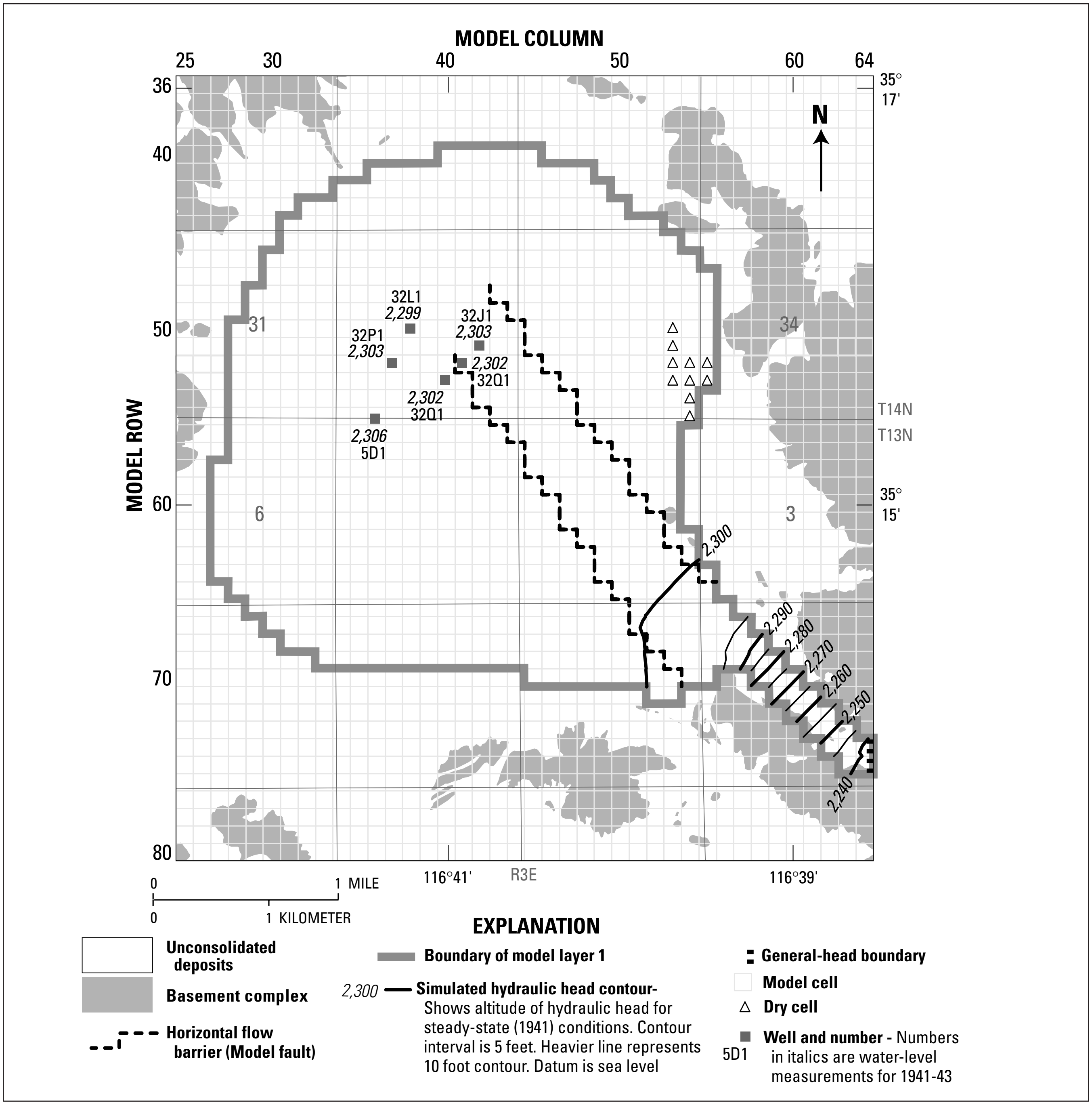


Figure 18. Measured water levels for 1941–43 and simulated hydraulic heads for steady-state conditions for model layer 1 of the Irwin Basin, Fort Irwin National Training Center, California.

The calibration procedure for transient conditions consisted of adjusting the storage coefficient (previously described) and the artificial recharge (described below) during 1941–99. Because the quantity and distribution of artificial recharge in the basin are not well documented, artificial recharge estimates were refined by making small adjustments in the quantity and distribution of this recharge during the calibration procedure. Final estimates of artificial recharge and the distribution of artificial recharge by source are shown on table 6. Calibration was achieved when the adjustments resulted in simulated hydraulic heads that approximated measured water levels. The measured water levels and the simulated hydraulic heads for 1994 are shown in figure 19. The simulated hydraulic heads matched the cone of depression that had formed by 1994 owing to extensive pumping in this area (figs. 7A and 19); the greatest water-level decline was at well 14N/3E-32K1. By 1999 (fig. 7*B*), the pumping depression was centered at well 14N/3E-32H1(fig. 5), which has become more heavily used since other wells in the basin have been decommissioned owing to ground-water-quality degradation. In addition to matching the measured water levels in the pumping depression, the simulated hydraulic heads also matched the mound of water that had formed by 1994; the mound formed in the area of the golf course, the duck ponds, and the sprinkler-pivot field as a result of infiltration of treated wastewater.

Measured water levels and simulated hydraulic heads for 1994 are plotted along the 1:1 correlation line in figure 20. After calibration, the simulated heads were within about 1 to 11 ft of measured water levels for the entire basin with root-mean-square error of about 4.6 ft and a mean error of about –1.7 ft. Simulated heads for wells near the center of the basin and near the duck ponds and sprinkler-pivot field were within 5 ft of measured water levels, and the simulated heads for wells near the wastewater-treatment facility were within 10 ft of the measured water levels. In general, the larger differences between simulated and measured values may be due, in part, to (1) an inaccurate distribution of pumpage to the individual wells, (2) an inaccurate estimation of the quantity and distribution of artificial recharge, and (3) inaccuracies in the reported water-level measurements.

Simulated hydraulic heads were compared with the measured water levels of 27 wells (fig. 21). The hydrographs show that the transient-state model reasonably simulates the timing and magnitude of long-term water-level changes in the Irwin Basin that have resulted from pumping and artificial recharge since 1941.

Model Results

For this study, the simulated water budgets at the end of the calibrated steady-state and the transient-state (1999) simulations were used to describe the flow characteristics in the basin; the water budgets of inflow (recharge) to) and outflow (discharge from) in the Irwin Basin are presented in table 7 and figure 22. The steady-state (pre-1941) water budget represents the state of the ground-water system prior to ground-water development; the transient (1999) budget represents the state of the ground-water system after 59 years of water-resources development in the basin. A simulation of future ground-water-flow conditions for the period 1999–2050 was made using the calibrated transient-state model and projected pumping estimates. The predicted (2050) water budget represents the state of the ground-water system after 110 years of water-resources development in the basin, which is based on the assumptions stated later in this report.

Results of the model simulations show that in the steady-state simulation, the total inflow, or recharge, was about 50 acre-ft/yr. All the recharge during steady-state conditions resulted from infiltration of precipitation runoff. The total outflow by underflow discharging the basin was equal to the total inflow (table 7; fig. 22).

The simulated water budget for the end of the transient-state simulation (1999) shows that, for 1999, about 1,460 acre-ft of water recharged the aquifer system and about 885 acre-ft discharged from the system (table 7; fig. 22). Most of the recharge was artificial recharge (about 1,410 acre-ft, or 97 percent) and only a small amount was from natural recharge (about 50 acre-ft, or 3 percent). Total discharge from the system was about 885 acre-ft, with about 780 acre-ft (88 percent) attributed to pumpage and about 105 acre-ft (12 percent) attributed to ground-water underflow out of the basin through the unnamed wash near Garlic Springs. The 575 acre-ft of inflow in excess of outflow in 1999 resulted in an increase in storage to the system. The rising water levels in the basin are indicative of this positive change in storage.

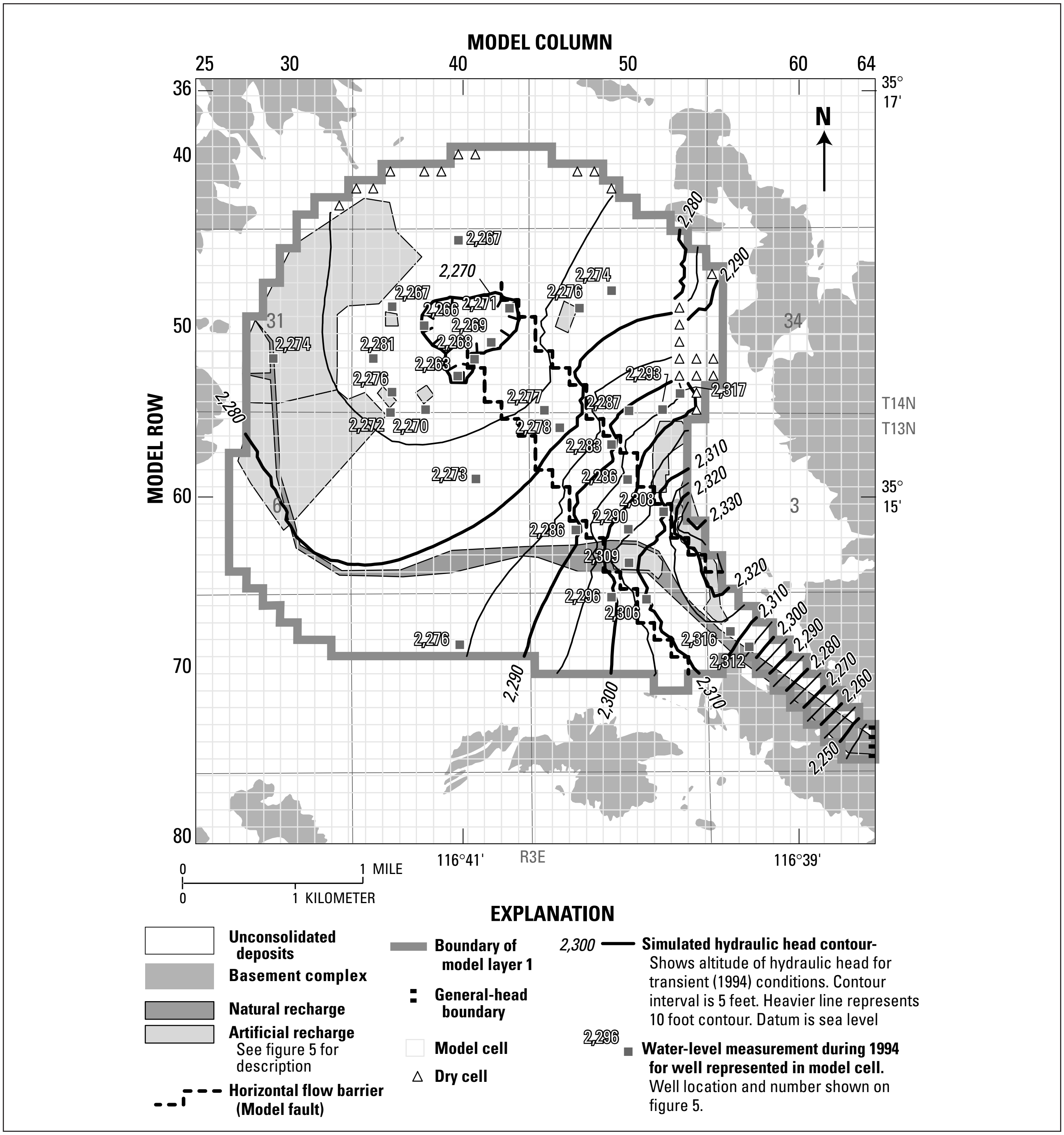


Figure 19. Measured water levels in 1994 and simulated hydraulic heads for transient conditions, layer 1 in the model of the Irwin Basin, Fort Irwin National Training Center, California.

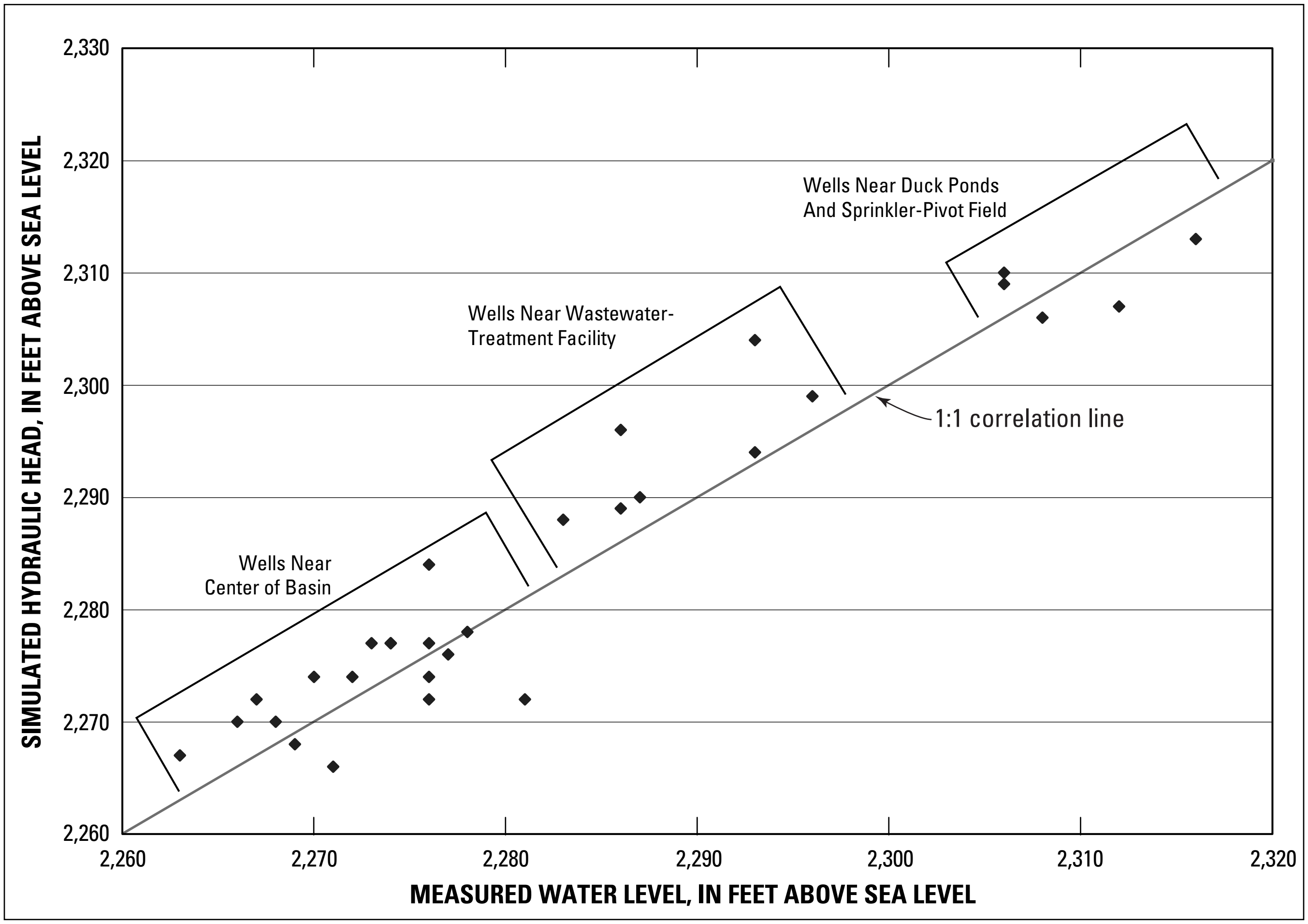


Figure 20. Simulated hydraulic head and measured water levels (1994) in selected wells in the Irwin Basin, Fort Irwin National Training Center, California.

Results of the simulations are shown in figure 22. As shown by the transient-state simulation results (1999), importation of water to the Irwin Basin has resulted in artificial recharge to the basin from infiltration of treated wastewater and irrigation-return flows. During 1999, artificial recharge exceeded pumpage from the Irwin Basin because additional wastewater resulted from imported water supplied by pumpage from the Bicycle and the Langford Basins. The increase in recharge combined with reduced pumping in the Irwin Basin has resulted in a rise in water levels in the Irwin Basin since the early 1990s, which in turn has resulted in an increase in ground-water storage in the basin.

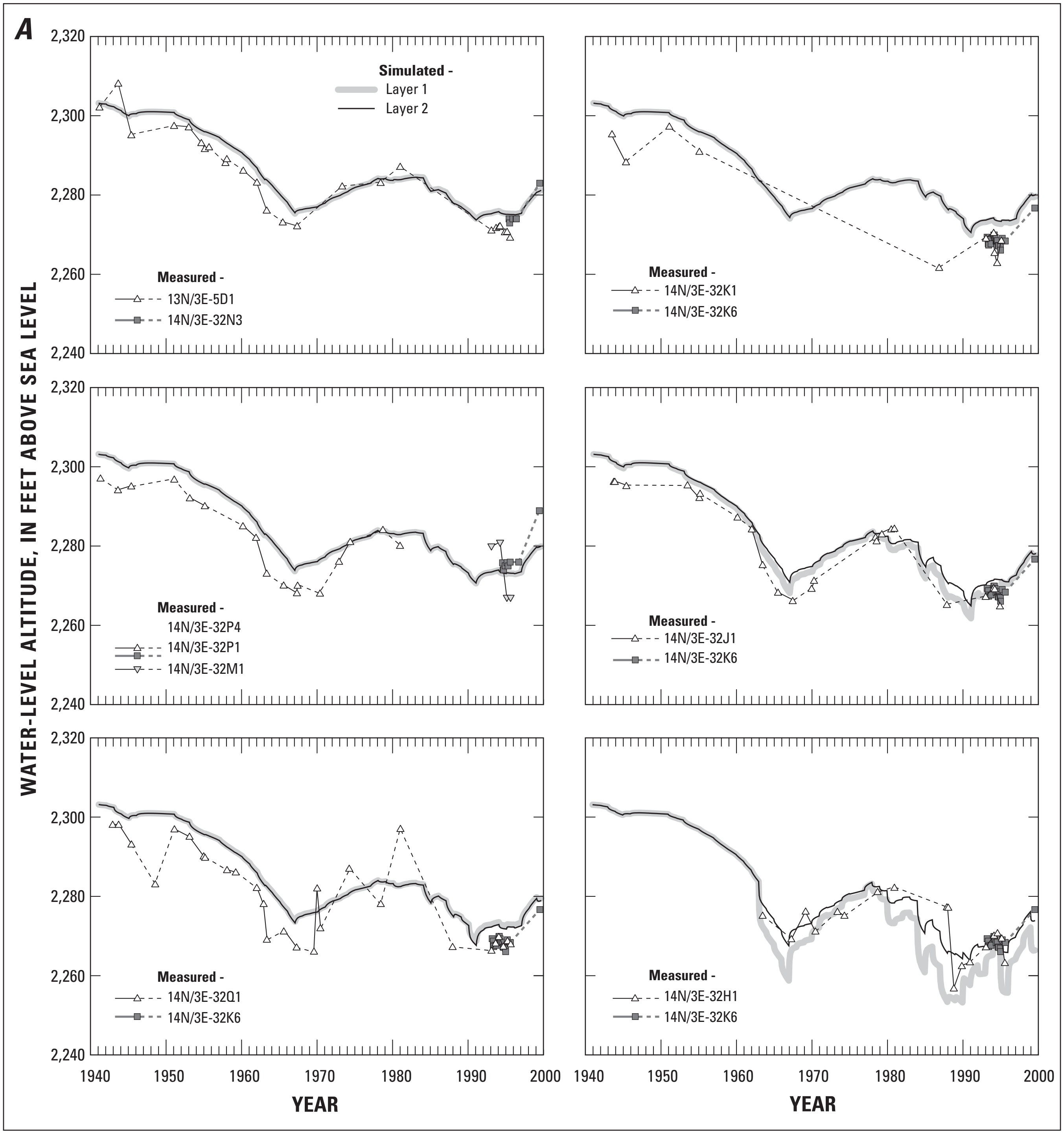


Figure 21. Measured water levels and simulated hydraulic heads for selected wells in the Irwin Basin, Fort Irwin National Training Center, California. *A*, 1941–99. *B*, 1980–99. and *C*, 1990–99.

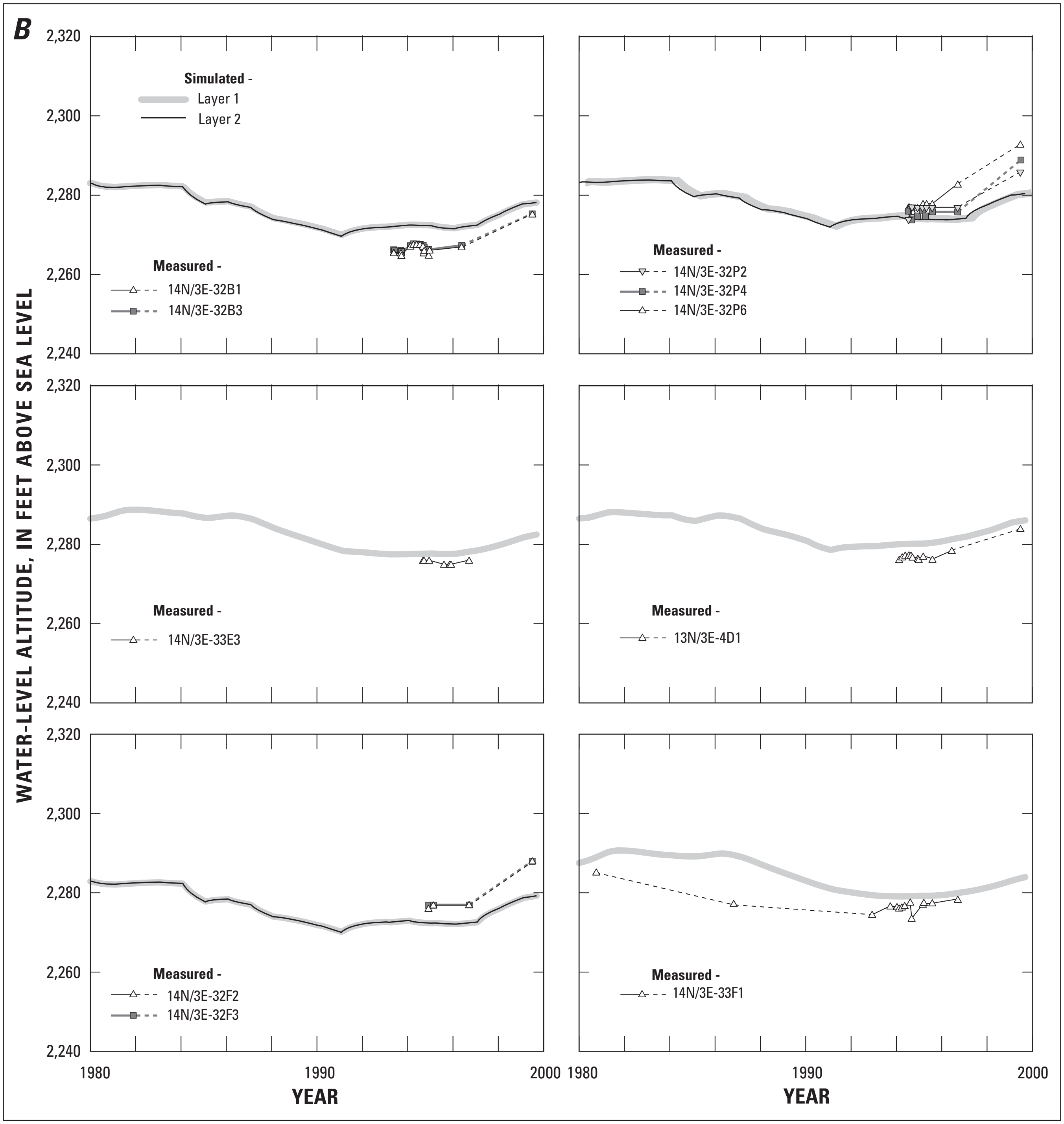


Figure 21.—Continued.

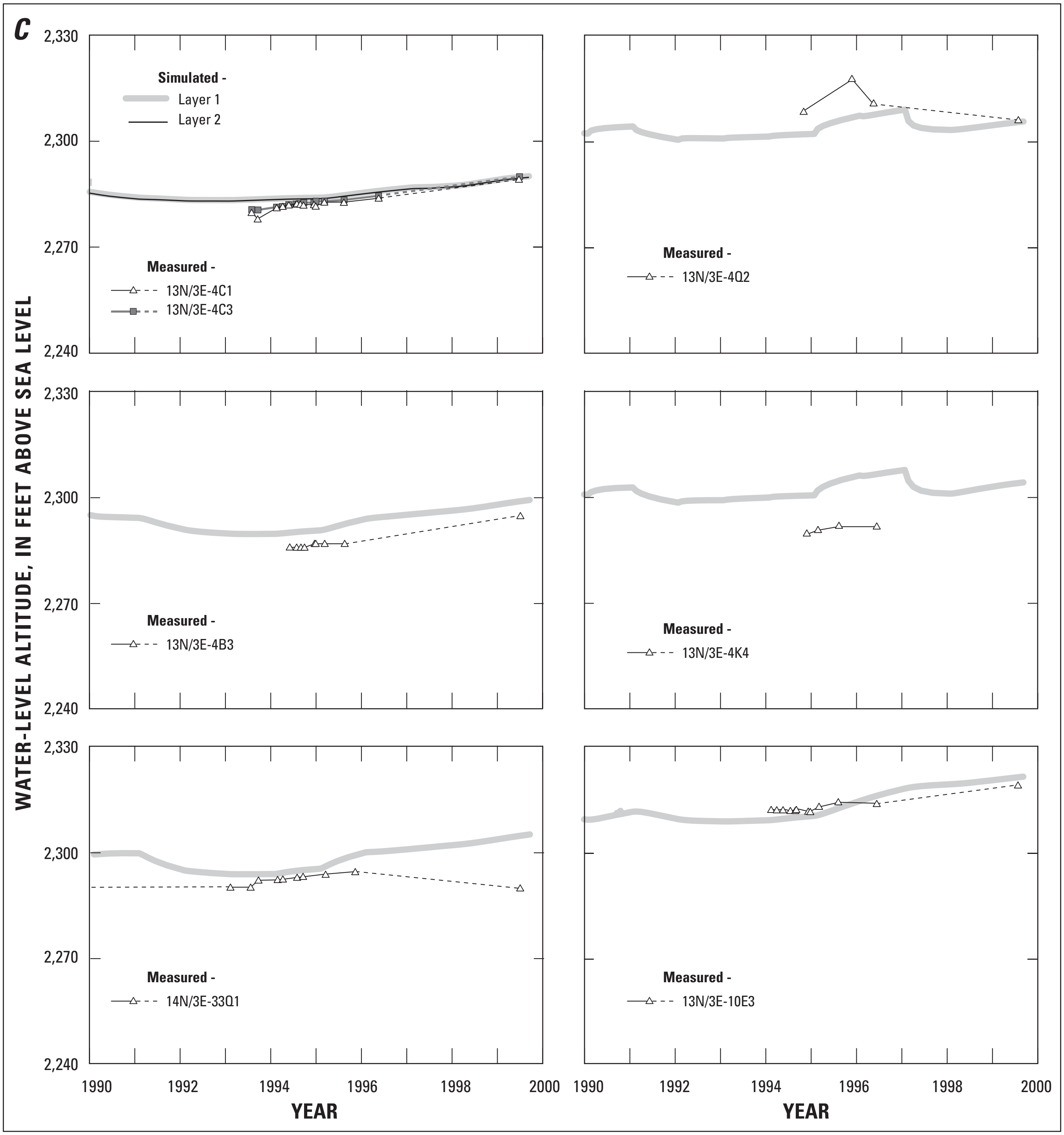


Figure 21.—Continued.

Table 7. Simulated water budgets for steady-state (pre-1941), transient (1999), and predictive (2050) conditions in the Irwin Basin, Fort Irwin National Training Center, California

	Steady-state (pre-1941) conditions (acre-feet)	Transient (1999) conditions		Predictive (2050) conditions (acre-feet)
		(acre-feet)	(in percent)	
Inflow:				
Natural recharge	49.6	49.6	3.4	49.6
Artificial recharge	0	1,411.1	96.6	1,411.1
Total in	49.6	1,460.7		1,460.7
Outflow:				
Pumpage	0	–781	88.2	–781
Underflow	–49.6	–104.7	11.5	–213.1
Total out	–49.6	–885.7		–994.1
Inflow-outflow	0	575		466.6

Model Sensitivity

Many assumptions and estimates are used in the design and construction of a ground-water flow model. To test the response of the calibrated model to a range of values for the initial hydraulic properties, a sensitivity analysis is done. This is done by varying the values of one input parameter while keeping all others constant. From this analysis, it is possible to observe the relative sensitivity of the model to various input properties. Thus, separate model simulations are made with varied input properties, and the changes in simulated hydraulic head and in components of the water budget are recorded. The results of the sensitivity analysis for this study were evaluated by calculating the root-mean-square deviation (error) between measured and simulated heads in the modeled area for 1994 conditions. The parameters and range of values used in the sensitivity analysis are shown in table 8.

The root-mean-square difference (errors) in water levels were plotted with the change factor for specific yield, storage coefficient, vertical leakance, fault hydraulic characteristics, and hydraulic conductivity (fig. 23*A–C*). A change factor of 1, indicated by a vertical line at the center of each plot, represents the value of the aquifer property used in the calibrated model and the corresponding root-mean-square difference. The greater the deviation of the water level from its original value at a change factor of 1, the greater the sensitivity of the model to an increase (change factor greater than 1) or decrease (change factor less than 1) for that aquifer property. To test the sensitivity of specific yield and hydraulic conductivity, the calibrated values were multiplied or divided by 2. The calibrated values of storage coefficient were tested by increasing and decreasing by one order of magnitude. The calibrated values of vertical leakance and fault hydraulic characteristics were tested by increasing and decreasing the values by three orders of magnitude.

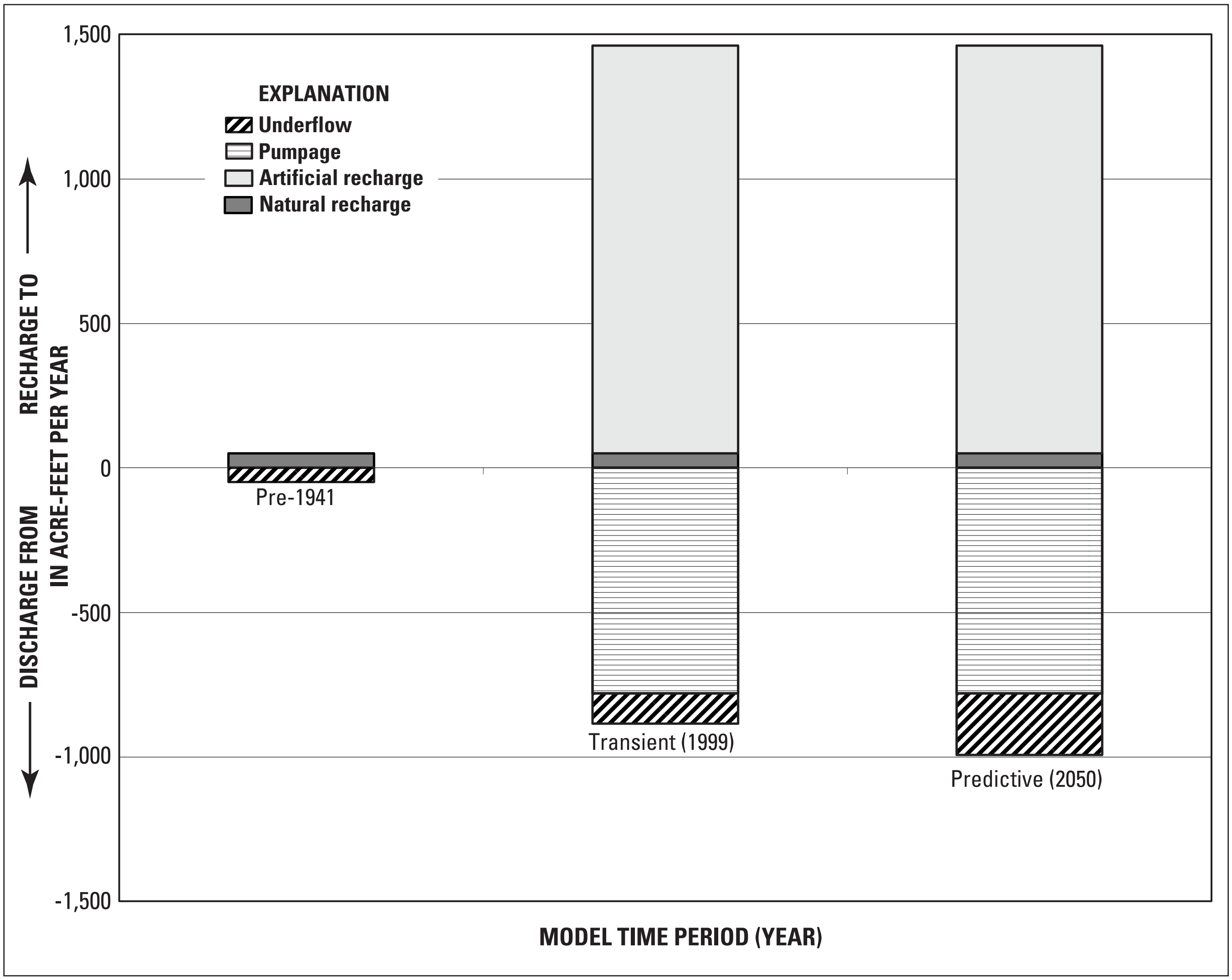


Figure 22. Ground-water recharge to, and discharge from, the Irwin Basin, Fort Irwin National Training Center, California.

As indicated in figure 23, simulated hydraulic heads are sensitive to changes in specific yield in layer 1 and hydraulic conductivity in layers 1 and 2. With respect to variations in hydraulic conductivity, simulated hydraulic heads are most sensitive to increases in the hydraulic conductivity of layer 1 and decreases in the hydraulic conductivity of layer 2 (fig. 23*C*). Simulated hydraulic heads also are very sensitive to a decrease in vertical leakance of more than one order of magnitude, but are only sensitive to an increase in vertical leakance of more than three orders of magnitude (fig. 23*B*). This indicates that the values of vertical leakance are not in the sensitive range. Simulated hydraulic heads are fairly sensitive to changes in the fault hydraulic characteristics (fig. 23*B*). This level of sensitivity reflects the nature of the faults as they have been modeled. As previously mentioned, because it is not known whether the faults extend across the entire basin, they were modeled as only partly crossing the basin. Because the simulated faults do not extend all the way across the basin, a change in fault hydraulic characteristics does not have the same effect as it would on a fault that crosses the entire basin.

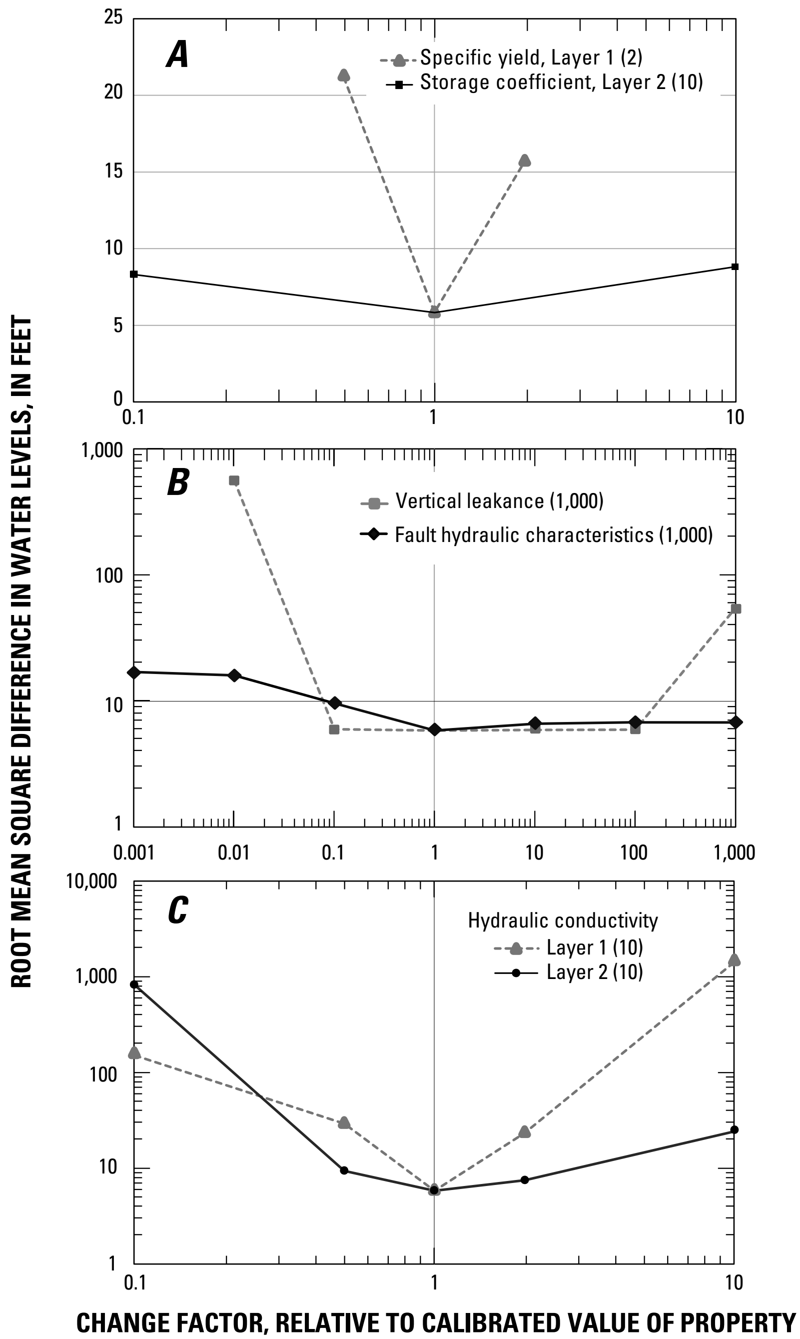


Figure 23. Results of sensitivity analysis of (*A*) specific yield and storage coefficient, (*B*) vertical leakance and fault hydraulic characteristics, and (*C*) hydraulic conductivity for 1994 conditions in the model of the Irwin Basin, Fort Irwin National Training Center, California.

Table 8. Aquifer parameter, model-calibrated value, and range of parameter values used in sensitivity analysis of the ground-water flow model of the Irwin Basin, Fort Irwin National Training Center, California

[/d, per day; ft/d, foot per day; ft^2/d, square foot per day]

Parameter	Model-calibrated value	Range of parameter values used in sensitivity analysis	
		Low	High
Specific yield	0.01– 0.12	0.0005– 0.06	0.02– 0.24
Storage coefficient	.001	.0001	.01
Fault hydraulic characteristic			
Layer 1	.001 ft/d	.001 ft/d	.01 ft/d
Layer 2	.0002–.0023 ft^2/d	.0002 ft^2/d	.0023 ft^2/d
Vertical leakance	.00009–.01 /d	.0000009–.0001 /d	.092–10 /d
Hydraulic conductivity:			
Layer 1	3–25 ft/d	1.5–12.5 ft/d	6–50 ft/d
Layer 2	1–22 ft/d	.5–11 ft/d	2–44 ft/d

It was also noted that simulated hydraulic heads were sensitive to small changes in the quantity and distribution of artificial recharge from wastewater disposal and irrigation-return flow. Because the quantity and distribution of artificial recharge in the basin are not well documented, artificial-recharge estimates were refined by making small adjustments in the quantity and distribution of this recharge. Better documentation of the quantity and distribution of both wastewater disposal and irrigation return flow will improve future model revisions.

Results of the sensitivity analysis show that small errors in estimating the aquifer properties values to which the model is most sensitive (specific yield) can have a significant effect on the model simulation results. Other properties, however, such as vertical leakance and hydraulic conductance, can be varied more than two orders of magnitude with little effect on the results.

Simulated Effects of Future Pumpage

The calibrated ground-water flow model can be used to simulate the potential effect of alternative water-management plans on hydraulic head and ground-water movement in the basin. As an example of the model's predictive capabilities, the model was used to simulate the effect of continuing the current rates and distribution of pumpage and artificial recharge for 50 years (2000–2050). For this scenario, the amounts of recharge and discharge for 1999 were held constant from 1999 through 2050. Recall that artificial recharge exceeded pumpage from the Irwin Basin during 1999 (table 7; fig. 22).

Results of the predictive simulation, during which artificial recharge exceeds pumpage, show that by 2050 water levels rise about 60 ft in the area of the 1999 pumping depression (figs. 24 and 25) and about 10–40 ft in the area of the mound of water beneath the golf course area and the duck ponds. Although the water level in the mound area would rise only about 10 ft based on this scenario, the water table would be within 20 ft of land surface. The simulated water budget for the end of the predictive simulation (table 7) shows that simulated total recharge in 2050 would be the same as that for 1999 (about 1,460 acre-ft); however, discharge from the system would increase to about 990 acre-ft (table 7; fig. 22) because of an increase in underflow. Simulated ground-water underflow increased from about 100 acre-ft in 1999 to about 210 acre-ft in 2050 (table 7; fig. 22).

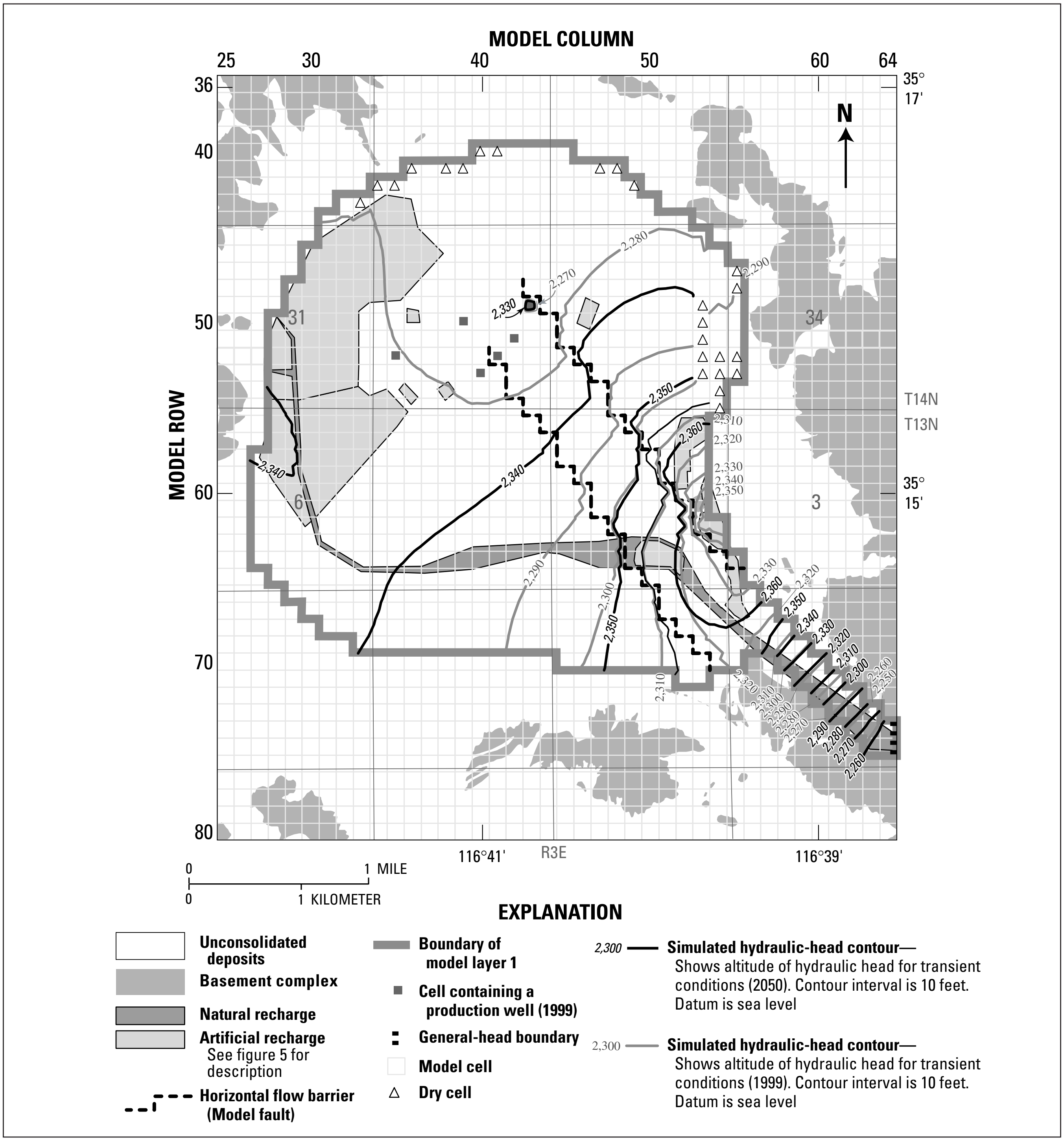


Figure 24. Simulated hydraulic heads for 2050 and 1999 in the Irwin Basin, Fort Irwin National Training Center, California.

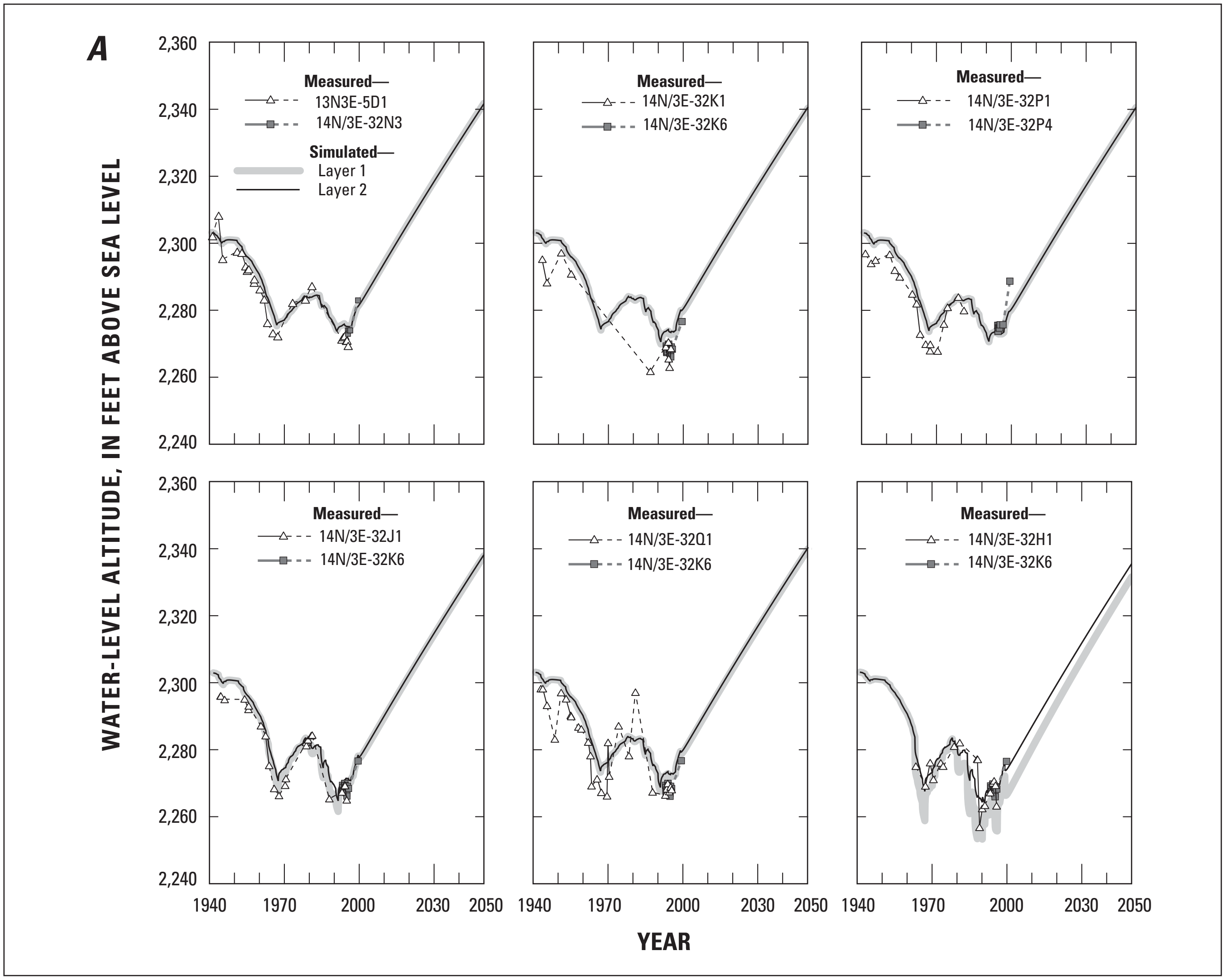


Figure 25. Simulated hydraulic heads and measured water levels for selected wells in the Irwin Basin, Fort Irwin National Training Center, California. *A*, 1941–2050. *B*, 1990–2050.

Ground-Water Flow Directions and Traveltimes

Poor quality ground water, caused by the percolation of treated wastewater and lawn watering, is migrating toward the pumping depression in the center of the basin. The area of poor quality water in 1996 was delineated by Densmore and Londquist (1997) and is presented in figure 8. As previously stated, long-term pumping from production wells near the center of the basin has caused a decline in water levels in this area. The problem posed by migrating water high in dissolved solids may intensify with continued pumpage from the Irwin Basin.

The calibrated ground-water flow model was used to simulate ground-water flow direction and traveltime. Advection by the ground-water flow system is one of the main processes controlling the fate and transport of solutes in ground water. The computer model MODPATH, developed by Pollock (1994), was used to simulate advective transport for this study. MODPATH uses particle-tracking techniques to compute pathlines and traveltimes based on the results of MODFLOW simulations (McDonald and Harbaugh, 1988). Results of the simulations of the ground-water flow model developed for the Irwin Basin were used in this application of MODPATH. Other processes controlling the fate and transport of solutes in ground water, for example dispersion, diffusion, adsorption, and chemical reactions, are not simulated using MODPATH. A complete description of the theoretical development of MODPATH, and of solution techniques and limitations are given by Pollock (1994).

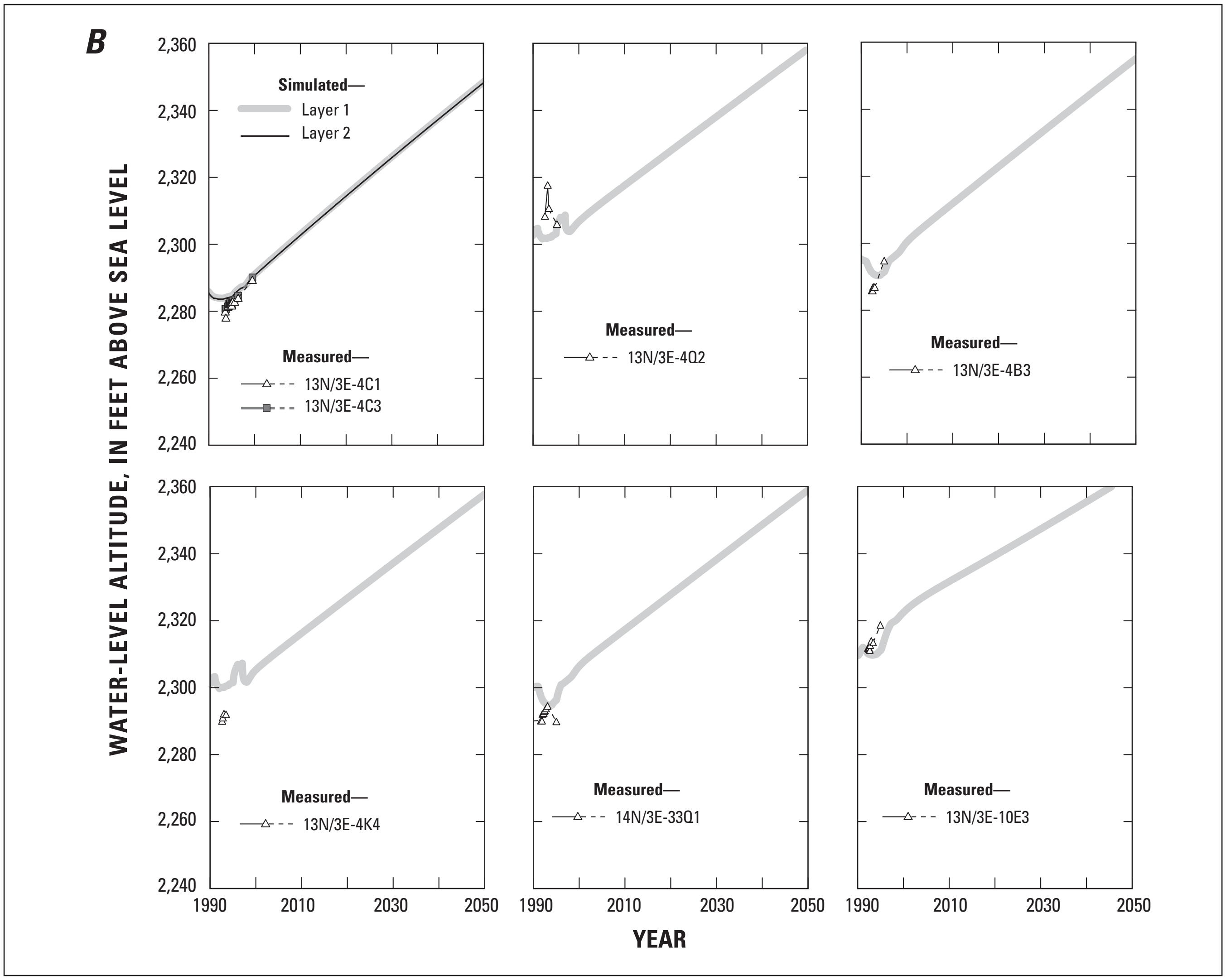


Figure 25.—Continued.

The effect of pumping on ground-water flow and traveltimes was demonstrated by introducing particles into model cells under transient (1941–99) ground-water conditions. The particle-tracking simulations were used to assess the potential for poor quality water to migrate into the main pumping area. Ground-water flow direction and distances traveled were shown by tracking particles through time.

For this study, particles were introduced in two areas; the old base housing area, which has moderate dissolved-solids concentrations in ground water, and the golf course and duck pond area, which has ground water high in dissolved-solids concentrations (fig. 8). Particles were released to the top face of the top cell in layer 1 for a single time period, 1955 (the year in which wastewater was first disposed of at the wastewater-treatment plant in the southeastern part of the basin). MODPATH simulated the path, along which the particles were advected under the transient conditions (1941–99), and the predictive conditions (1941–2050).

Results of the simulation for the 1941–99 period show that water primarily moves from the artificial recharge sources toward the pumped wells (fig. 26*A*). Particles introduced in the old base housing area moved about 500 ft (0.1 mi) between 1955–99, whereas particles introduced to the golf course and duck pond area moved about 4,000 ft (0.75 mi). By the end of the simulation (1999), the particles introduced to the golf course and duck ponds area were within 4,000 ft of the nearest active production well.

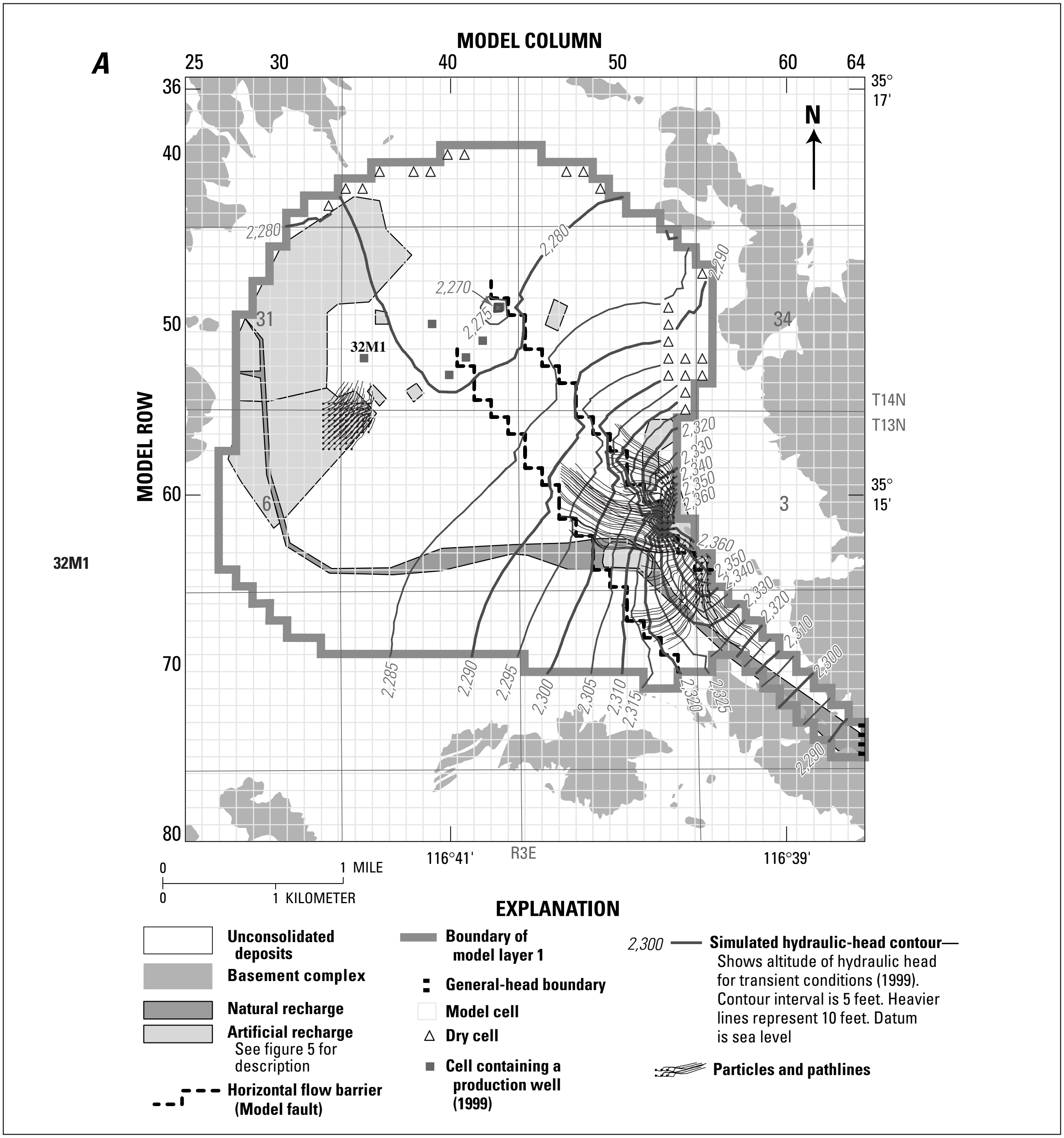


Figure 26. Simulated pathlines using particle tracking to determine ground-water movement in the Irwin Basin, Fort Irwin National Training Center, California. *A*, 1941–99. *B*, 1941–2050.

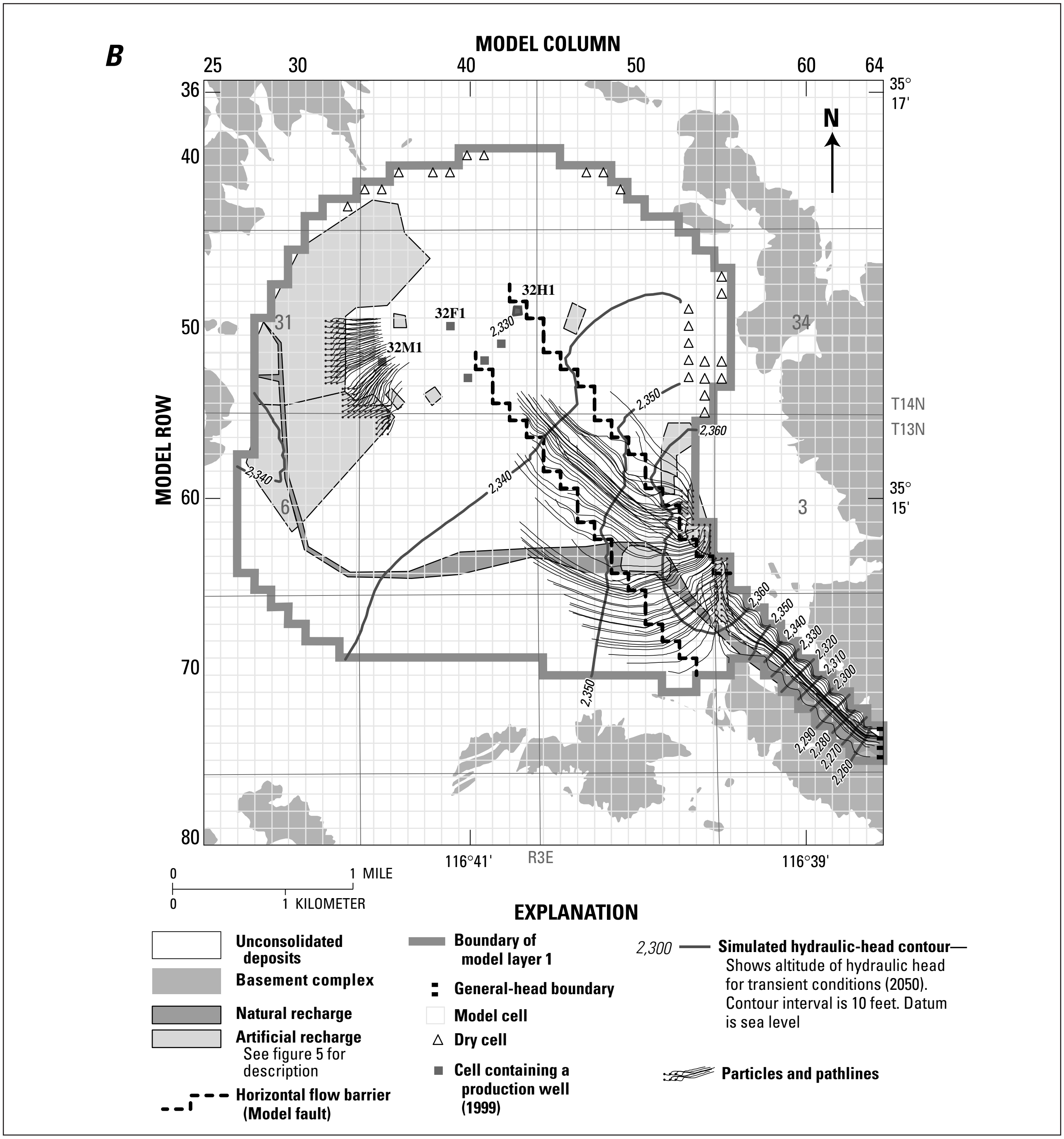


Figure 26.—Continued.

Results of the simulation for the 1941–2050 period show that by 2050 most of the particles introduced in the old base housing area in 1955 will have moved about 1,200 ft (0.25 mi), reaching the nearest well (14N/3E-32M1, believed to have last been pumped in 1996) (fig. 26*B*). Particles from the area of the golf course and duck ponds will have moved more than 5,500 ft (1 mi) toward pumped wells 14N/3E-32H1 and -32J1 in the northcentral part of the basin. These results indicate that with continued pumping the high dissolved-solids and nitrate water will eventually reach the production wells.

One significant limitation to using the particle-tracking results to determine ground-water pathlines and traveltimes is that the pathlines for instantaneous releases were calculated using the assumption that the particles were introduced into the system in 1955 when the first wastewater-treatment facility was built. Therefore, the pathlines generated by MODPATH for the base housing area, which was not built until the early 1960s, indicate that the particles have traveled farther than they actually would have.

Limitations of the Model

A numerical model is useful for testing and refining a conceptual model of a ground-water flow system, developing an understanding of the system, guiding data collection, and projecting aquifer responses to changes in aquifer stresses within specified limits. However, a model can only approximate the actual system and is based on simplified assumptions and on average and estimated conditions. Thus, the results of model simulations are only as accurate as the measured or estimated data used to constrain the simulations.

One limitation of this model for predicting aquifer responses to changes in aquifer stresses is due to early pumpage distribution among the wells, which may be inaccurate because distribution records prior to 1990 are not available. Another limitation of the model is that the artificial recharge estimates may be inaccurate because historical records on the quantities of water used for irrigation and discharged from the wastewater-treatment facility were not available. The data for these two sources, therefore, were estimated from pumpage data. Because the model was used to test different quantities and distributions of artificial recharge, the artificial recharge estimates were as representative as possible considering the data limitations. However, more accurate estimates of artificial recharge quantities and distribution could be used to update and verify the model as they become available.

This model is an approximation of the alluvial aquifer system of the Irwin Basin and, thus, it simulates responses of the ground-water flow system to recharge to and discharge from the alluvial aquifer system. Although the landfill area is included in the modeled area, the landfill area was modeled as a thin alluvial aquifer in this part of the basin and does not include the underlying fractured aquifer system which most likely occurs in the landfill area.

SUMMARY AND CONCLUSIONS

Ground-water pumping in the Irwin Basin underlying the Fort Irwin National Training Center (NTC), California resulted in water-level declines of about 30 ft in the central part of the basin between 1941 and 1996. Since 1996, pumpage from the Irwin Basin has decreased, but the decrease has been offset by an increase in pumpage in the Bicycle and the Langford Basins that is imported to the Irwin Basin. Artificial recharge from wastewater-effluent infiltration and irrigation-return flow stabilized water levels in the early 1990's; but there is concern that future water demands associated with expansion of the base may cause water-level declines in the more heavily pumped basins. To address these concerns, a ground-water flow model of the Irwin Basin was developed to better understand the aquifer system, assess the long-term availability and quality of ground water, evaluate ground-water conditions owing to current pumping, and to plan for future water needs at the base.

The Fort Irwin NTC, located about 130 mi northeast of Los Angeles in the northern part of the Mojave Desert, encompasses several ground-water basins. The Irwin Basin is one of three basins currently supplying ground water to the base. The Irwin Basin has a fairly flat floor and is bounded, for the most part, by rugged mountainous terrain. There are no perennial streams in the basin, but several dry washes indicate that there is some surface flow during, or immediately after, large storms. The climate of the Irwin Basin consists of scant precipitation, hot summers, and cool winters.

The Irwin Basin is filled with as much as 950 ft of unconsolidated deposits that consist of younger alluvium of Quaternary age and older alluvium of late Tertiary to Quaternary age. These deposits are underlain by volcanic rocks of late Tertiary to Quaternary age and igneous and metamorphic rocks of pre-Tertiary age, which do not contain significant water-bearing units except in areas where they are jointed and fractured.

The aquifer system in the Irwin Basin consists of an upper aquifer and a lower aquifer. The upper aquifer is unconfined and is contained within the saturated part of the younger alluvium. The lower aquifer is confined throughout most of the basin and includes the older alluvium. The effective base of the ground-water system is the top of the unweathered basement complex. Several faults cross the Irwin Basin and act as partial barriers to ground-water flow. Under predevelopment conditions, ground water discharged from the basin as underflow beneath the unnamed wash near Garlic Spring to the Langford Basin.

Natural recharge occurs only by infiltration of precipitation runoff during and shortly after high-intensity or long-duration storms, and most of the recharge probably occurs along the normally dry washes. During a previous study, average annual recharge to the Irwin Basin was estimated at about 150 acre-ft/yr for 1941–51. However, recent data indicate that little present-day precipitation reaches the water table. Thus, recharge from precipitation runoff is estimated to be less than 150 acre-ft/yr. Natural discharge is by subsurface underflow beneath the wash near Garlic Spring.

Ground-water pumping in the Irwin Basin began in 1941; pumpage from the basin has ranged from 30 to 1,927 acre-ft/yr. Fort Irwin began receiving additional ground water pumped from the Bicycle Basin in 1967 and from the Langford Basin in 1992. Most of the water that is not consumed in the Irwin Basin is discharged to a wastewater-collection system and treatment facility. Percolation of wastewater is the largest source of ground-water recharge to the basin. Between 58 and 70 percent of the total pumpage from the three basins delivered to the wastewater-treatment facility between 1941 and 1999 was estimated to recharge the ground-water system. This recharge is distributed over the base golf course, driving range, and sprinkler-pivot field in the southeastern part of the basin. Since 1996, wastewater disposal in the sprinkler-pivot field has ceased.

A ground-water flow model was developed to better understand the aquifer system and to assess the long-term availability and quality of ground water in the basin. The aquifer system was vertically discretized into two layers representing the upper and lower aquifers, and boundary conditions were determined for the aquifer system. Hydraulic conductivities, altitudes of the layer bottoms, vertical leakance, specific yields, storage coefficients, recharge, and discharge were determined using existing and newly collected geohydrologic data. Rates and distribution of recharge and discharge and aquifer properties were determined from existing data or estimated when and where data were unavailable, and assigned to the model grid.

The model was calibrated using a trial-and-error method in adjusting initial estimates of aquifer properties, recharge, and discharge to get a best match between simulated hydraulic heads and measured water levels, and selected water-budget items. Conditions simulated by the calibrated model of the Irwin Basin reflect measured water levels and show that ground-water levels in the Irwin Basin began to decline in 1941 and stabilized in the early 1990s. There is a pumping depression near the pumped wells and a mound of recharge in the wastewater-treatment facility and disposal area. There have been two periods of recovery in water level since the development of ground water the in Irwin Basin; these periods coincide with a period of decreased pumpage from the Irwin Basin and a period of increased recharge to the Irwin Basin as a result of the importation of ground water from the Bicycle Basin beginning in 1967 and from the Langford Basin beginning in 1992.

Since 1992, however, recharge has exceeded pumpage in the Irwin Basin. Assuming that this trend continues, predictive simulations show that water levels may rise as much as 60 ft by 2050 in the area of the pumping depression, and about 10–40 ft in the wastewater-treatment facility and disposal area. A water-level rise of 10–40 ft in the wastewater-treatment facility area will bring the water table to about 20 ft below land surface by 2050.

In addition to potential problems associated with rising water levels, there is a problem posed by the migration of ground water containing high dissolved-solids concentrations. The high concentrations are caused by the percolation of treated wastewater through evaporite deposits underlying the wastewater-treatment facility and disposal area. The poor quality ground water is migrating from this area toward the pumping depression beneath the main base. This problem was documented during the first phase of this study; the high concentrations can be expected to intensify with continued pumping from the Irwin Basin.

Particle-tracking simulations were used to determine the pathlines and traveltimes of ground water high in dissolved-solids concentrations and to assess its potential migration into the main pumping area. Particles, introduced in two areas where ground water has high-dissolved-solids—the old base housing area and the golf course and duck pond area—were tracked from 1955 to 1999 and 1955 to 2050. Results of the simulations show that water moves from these source areas toward the pumped wells. Particles introduced in the old base housing area in 1955 moved about 500 ft (0.1 mi) by 1999, whereas particles introduced to the golf course and duck pond area in 1955 moved about 4,000 ft (0.75 mi). Particle-tracking to 2050 show that most of the particles in the old base housing area will reach the nearest well, about 1,200 ft (0.25 mi) away, and particles in the area of the golf course and duck pond area will move about 5,500 ft (1 mi), toward pumped wells in the northcentral part of the basin.

SELECTED REFERENCES

C.F. Hostrup and Associates, 1955, Water Resources Survey Camp Irwin, California; 109 p.

Densmore, J.N., and Londquist, C.J., 1997, Ground-water hydrology and water quality of the Irwin Basin at Fort Irwin National Training Center, California: U.S. Geological Survey Water-Resources Investigations Report 97-4092, 159 p.

Driscoll, F.G., 1986, Groundwater and wells: St. Paul, Minnesota, Johnson Division, p. 75.

EarthInfo, Inc., 1995, National Climatic Data Center summary of the day—West 1994: Boulder, Colorado, EarthInfo, Inc. One CD-ROM.

———2000, EarthInfo CD2 reference manual—for all EarthInfo CD-ROM databases: Boulder, Colorado, EarthInfo, Inc.

Fetter, C.W., 1994, Applied Hydrogeology: Englewood Cliffs, New Jersey, Prentice-Hall, p. 116.

Heath, R.C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Hsieh, P.A., and Freckleton, J.R., 1993, Documentation of a computer program to simulate horizontal-flow barriers using the U.S. Geological Survey's Modular Three-Dimensional Finite-Difference Ground-Water Flow Model: U.S. Geological Survey Open-File Report 92-477, 32 p.

Izbicki, J.A., Radyk, J., and Michel, R.L., 2000, Water movement through a thick unsaturated zone underlying an intermittent stream in the Mojave Desert, southern California, USA: Journal of Hydrology, v. 238, p. 194–217.

James M. Montgomery and Associates, Inc., 1981, Water supply investigation, Fort Irwin, San Bernardino County, California: Phase II Final Report on Ground Water Basin Development and Management.

Kunkel, F., and Riley, F.S., 1959, Geologic reconnaissance and test-well drilling, Camp Irwin, California: U.S. Geological Survey Water-Supply Paper 1460-F, 271 p.

Lohman, S.W., 1972, Ground-water hydraulics: U.S. Geological Survey Professional Paper 708, 70 p.

Londquist, C.J., and Martin, Peter, 1991, Geohydrology and ground-water-flow simulation of the Surprise Spring Basin aquifer system, San Bernardino County, California: U.S. Geological Survey Water-Resources Investigations Report 89-4099, 41 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: Techniques of Water-Resources Investigations of the U.S. Geological Survey, book 6, chap. A1, 576 p.

National Oceanic and Atmospheric Administration, 1994, Climatological data, annual summary, California, 1994: Asheville, North Carolina, National Oceanic and Atmospheric Administration, v. 98, no. 13.

Pollock, D.W., 1994, User's guide for MODPATH/MODPATH-PLOT, Version 3: A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94-464, 245 p.

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

Wilson F. So and Associates, Inc., 1989, U.S. Army National Training Center at Fort Irwin, California, Water Basin Development Plan, Final Report, June 1989: 85 p.
Yount, J.C., Scherner, E.R., Felger, T.J., Miller, D.M., and Stephens, K.A., 1994, Preliminary geologic map of Fort Irwin Basin, north-central Mojave Desert, California: U.S. Geological Survey Open-File Report 94-173, 25 p.

DENSMORE — SIMULATION OF GROUND-WATER FLOW IN THE IRWIN BASIN AQUIFER SYSTEM, FORT IRWIN NATIONAL TRAINING CENTER, CALIFORNIA

WRIR 02-4264

USGS