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GROUND-WATER RESOURCES AND SIMULATED EFFECTS OF WITHDRAWALS IN THE BOUNTIFUL AREA, UTAH

By

David W. Clark

Prepared by the
United States Geological Survey
in cooperation with the
Utah Department of Natural Resources
Division of Water Rights

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre	0.4047	hectare
acre	4,047	square meter
acre-foot	0.001233	cubic hectometer
cubic foot per second	0.02832	cubic meter per second
foot	0.3048	meter
foot per second	0.3048	meter per second
foot squared per day	0.0929	meter squared per day
foot squared per second	0.0929	meter squared per second
gallon per minute	0.06309	liter per second
inch	25.4	millimeter
inch	2.54	centimeter
mile	1.609	kilometer
square mile	2.590	square kilometer

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.

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By David W. Clark,

U.S. Geological Survey

ABSTRACT

Ground-water resources in the Bountiful area, Utah, were studied to document changes in ground-water conditions and to simulate the effects of increased ground-water withdrawals and changes in recharge. The aquifer system is in basin-fill deposits and is primarily a confined system with unconfined parts along the mountain front.

Recharge to the aquifer system was estimated to range from about 22,000 to 32,000 acre-feet per year during 1947-85. Discharge was estimated to range from 26,000 to 30,000 acre-feet per year during 1947-85.

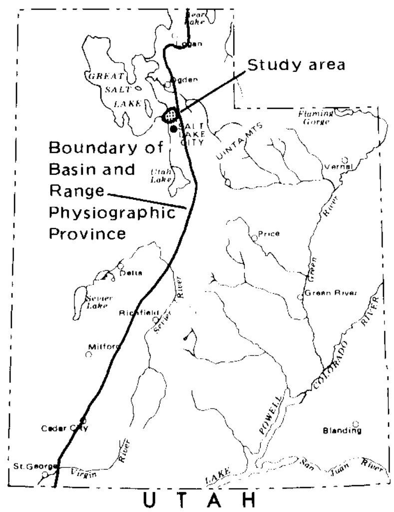
Long-term trends of ground-water levels indicate a steady decline at most observation wells from 1952 to 1962. Importation of surface water for irrigation in 1962 resulted in decreased ground-water withdrawals, causing water levels to rise. Water levels fluctuated from 1962 to 1985, depending on changes in withdrawals and precipitation.

A computer model of the aquifer system was constructed and calibrated using water-level data from 1946 and changes in ground-water withdrawals from 1947-86. Simulations of aquifer responses to projected withdrawals were based on a 50-percent increase in the 1981-85 rate of municipal and industrial withdrawals for 20 years using both average and less-than-average recharge rates. The simulations indicated water-level declines between 5 and 50 feet; a decrease in natural discharge to drains, by evapotranspiration, and to Great Salt Lake; and a decrease of ground water in storage after 20 years between 25,000 acre-feet using the average recharge rate, and 70,000 acre-feet using the less-than-average recharge rate.

INTRODUCTION

Increased ground-water withdrawal by municipal users in the Bountiful area, Utah (fig. 1), has caused water-level declines. State and local water managers and water users needed an updated evaluation of ground-water conditions and a tool with which to estimate the potential effects of future changes in recharge and discharge of ground water.

A study of the Bountiful area, Utah, was conducted by the U.S. Geological Survey from 1983-85, in cooperation with the Utah Department of Natural Resources, Division of Water Rights, to evaluate the ground-water resources. Objectives of the study were to improve understanding of the area's ground-water hydrology, to determine changes in the ground-water conditions since the 1946 study by Thomas and Nelson (1948) and the 1960-69 study by Bolke and



EXPLANATION FOR FIGURE 1

STUDY AREA

Bountiful area

Weber Delta area

4,200 — TOPOGRAPHIC CONTOUR--Shows altitude of land surface. Dashed contour represents historic high water elevation of Great Salt Lake. Contour interval, in feet, variable. National Geodetic Vertical Datum of 1929

CLIMATOLOGIC STATIONS

1 Bear River Refuge

2 Ogden Sugar Factory

3 Ogden Pioneer Powerhouse

4 Pineview Dam

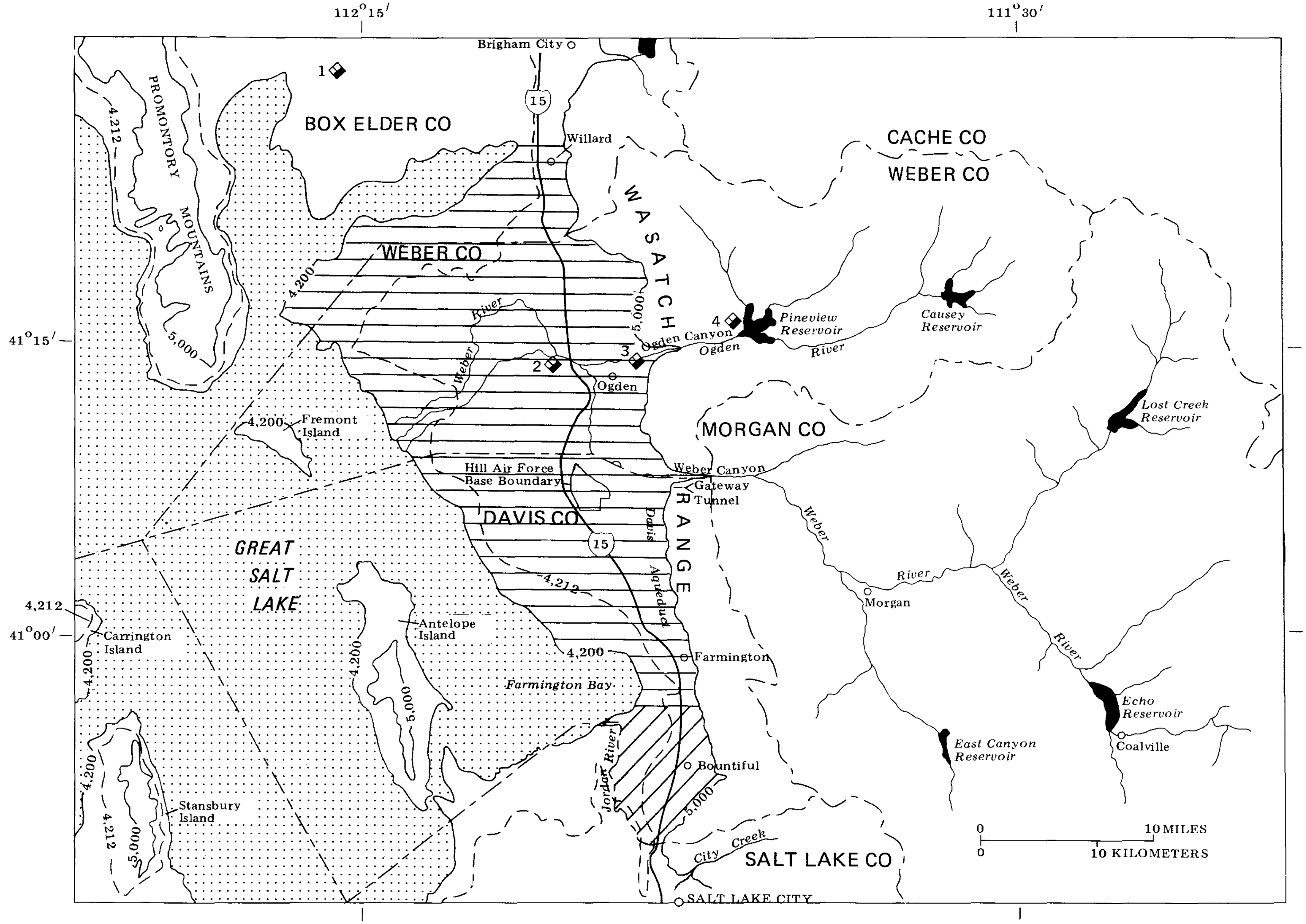


Figure 1.--Location of study area.

Waddell (1972), and to simulate the effects of increased ground-water withdrawals and changes in recharge on ground-water levels, discharge, and storage.

This study was part of a larger investigation of ground-water resources of the East Shore area of Great Salt Lake (Clark and others, 1990). Results and interpretations presented here are primarily based on data and analyses presented by Plantz and others (1986) and Clark and others (1990).

Information collected during this study included discharge from wells, water levels in wells, drillers' logs of wells, seepage losses from or gains to streams and drains, and hydraulic properties of aquifers. A digital-computer model of the ground-water system was constructed on the basis of this and other information.

Purpose and Scope

The purpose of this report is to describe the ground-water resources in the basin-fill deposits of the Bountiful area, referred to as a part of the East Shore aquifer system (Clark and others, 1990). This report describes ground-water conditions including recharge, movement, water-level changes, and discharge. In addition, this report describes a computer simulation of increased withdrawals on the aquifer system in the Bountiful area, including simulated effects of potential changes in ground-water recharge and discharge.

Location and Physiography

The study area is north of Salt Lake City between the western margin of the Wasatch Range and the eastern shore of Great Salt Lake (fig. 1) and is at the eastern edge of the Basin and Range physiographic province. The area is urban and industrial and, because of its proximity to downtown Salt Lake City, has a rapidly growing suburban population.

The project area is about 8 miles long and 2 to 8 miles wide. It includes the southern part of Davis County. The southern boundary is the Davis-Salt Lake County line, and the northern boundary is the line between T. 2 N. and T. 3 N. The eastern boundary is the Wasatch Range, the northwestern boundary is Farmington Bay of Great Salt Lake, and the western boundary is the Jordan River.

The extent of the project area fluctuates with the level of Great Salt Lake. During this study, the level of the lake rose at an unprecedented rate, inundating large tracts of low-lying land near the eastern shore. During 1969-82, the level of the lake was at an average altitude of 4,199 feet, whereas during 1983-84, the lake rose rapidly to an altitude of about 4,209 feet. The size of the project area at a lake level of 4,199 feet is about 45 square miles, whereas at an altitude of 4,209 feet, the total area is only about 30 square miles. Most of the land inundated by the lake was generally undeveloped and consisted of marshlands, pasture, mudflats, and waterfowl refuges.

The study area contains two distinct physiographic units. The eastern unit is composed of benches (terraces) adjacent to the Wasatch Range that extend westward toward the study area in a series of step-like units (fig. 2). These terraces, formed by Pleistocene Lake Bonneville (Gilbert, 1890), have since been dissected by closely spaced, mountain-front streams. The second physiographic unit is a valley-lowland plain with little topographic relief that extends from the western edge of the terraces to the shores of Great Salt Lake. The plain ranges in width from about 1 mile near the north and south boundaries to about 5 miles in the center of the area, but this width varies with changing levels of Great Salt Lake.

The altitude of the study area ranges from about 5,000 feet near the Wasatch Range to, depending on the lake level, about 4,200 feet at the eastern margin of Great Salt Lake (fig. 1). The crest of the Wasatch Range rises 4,000 to 5,000 feet above the study area with the highest peaks being more than 9,400 feet (Clark and others, 1990, pl. 1).

Climate

The climate of the area is temperate and semiarid with a typical frost-free season from May to mid-October. Precipitation increases from west to east across the study area and in the adjoining mountains as elevation increases; whereas, there is little difference in the mean annual temperature across the study area. The normal annual precipitation ranges from about 15 inches near Great Salt Lake to about 20 inches near the mountain front, about 28 inches in the lower reaches of the Wasatch Range canyons, and more than 40 inches near the crest of the Wasatch Range. However, from 1981 through 1984, precipitation in the area was about 150 to 200 percent of normal (National Oceanic and Atmospheric Administration, 1982, 1983a, 1983b, 1984, 1985).

Population and Land Use

The Bountiful area is part of one of the fastest growing regions in the United States with the population increasing about 50 percent every 10 years. As of 1980, the population of the area was about 54,000 with nearly the entire population living within incorporated areas. The population has more than doubled since 1960, and in areas outside the city of Bountiful, the population has nearly tripled since 1960. The increase in population has occurred primarily in suburban areas, which have expanded onto former agricultural lands. Population statistics are presented in table 1.

From 1968-85, there was a shift in land use from irrigated cropland and natural vegetation to urban. There was an increase of about 2,000 acres of land classified as urban of which 60 percent was formerly classified as irrigated cropland. Total acres of irrigated cropland in the study area decreased by about 20 percent during 1968-85.

Geology

The Bountiful area is in an elongate graben bordered by the Wasatch fault zone on the east and an undefined fault zone to the west (fig. 2). Displacement along the Wasatch fault zone may be as much as 10,000 feet (Feth and others, 1966, p. 21).

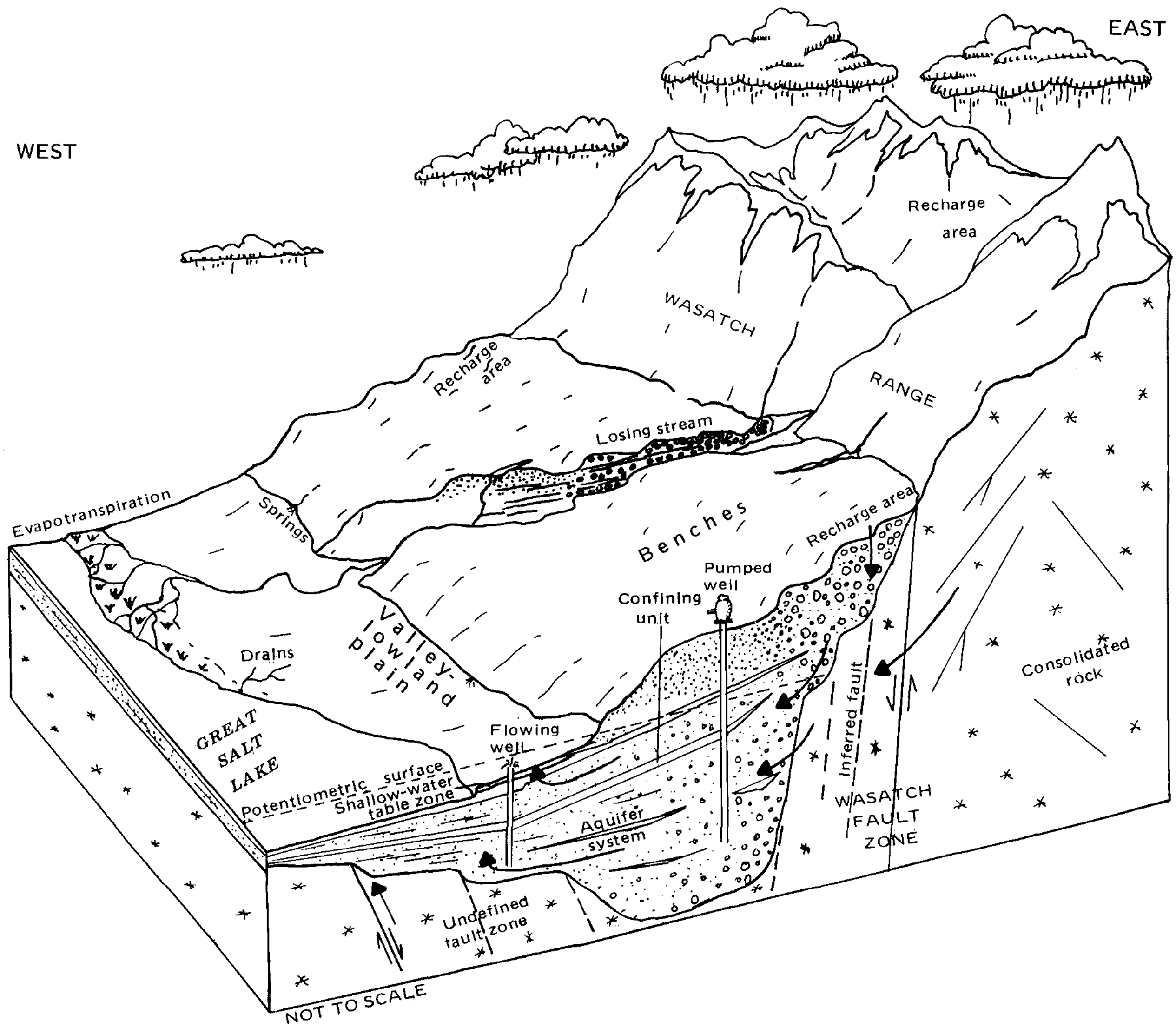


Figure 2.--Generalized block diagram showing aquifer system, probable directions of ground-water movement (arrows), and areas of recharge and discharge in the Bountiful area.

Table 1.—Population in the Bountiful area, 1960-80

(Data from U.S. Department of Commerce, Bureau of Census, 1971 and 1980.)

Location	1980 census	Percent change 1970-80	1970 census	Percent change 1960-70	1960 census	Percent change 1960-80
Bountiful	32,978	18.4	27,853	63.5	17,039	93.5
Centerville	8,041	146.1	3,268	38.4	2,361	240.6
North Salt Lake City	5,588	160.8	2,143	29.5	1,655	237.6
West Bountiful	3,559	185.6	1,246	31.9	945	276.6
Woods Cross	4,274	36.8	3,124	184.5	1,098	289.3
Total	54,440	44.6	37,634	62.9	23,098	135.7

On the western margin of the Bountiful area, the Wasatch Range is composed primarily of Precambrian metamorphic rocks and Tertiary sedimentary rocks. The Precambrian rocks extend north and east of Bountiful and consist of gneiss, schist, and some quartzite; the Tertiary rocks are south and east of Bountiful and consist of conglomerates with lenses of siltstone and sandstone (Davis, 1983).

Quaternary basin-fill deposits were eroded from the mountains during pre-Lake Bonneville and Lake Bonneville time. The basin fill is composed of unconsolidated and semi-consolidated sediments in a series of interbedded alluvial and lacustrine deposits. Most of the sediments are coarse grained near the mountains, particularly near the mouths of canyons where alluvial fan and mudflow sediments predominate. Farther from the mountains, the basin-fill deposits are alternating layers of gravel, sand, and clay. In the Bountiful area, Mill, Stone, and Barnard Creeks are downcutting or dissecting, whereas Centerville and Parrish Creeks have built alluvial fans (Davis, 1983). Fine-grained sediments predominate toward the west, where most of the deposits are lacustrine.

Basin-fill deposits have been estimated to be 6,000 to 9,000 feet thick north of the study area near Ogden (Feth and others, 1966, p. 22). The thickness of the basin fill in the study area generally is unknown; however, the deepest well in the area was completed in unconsolidated material at a depth of 1,985 feet (Thomas and Nelson, 1948, p. 86). Near the mountain front, the study area consists of mudflow deposits, which are poorly sorted and only slightly permeable, and sediments at the mouths of the major stream channels, which are coarse grained and more permeable. Farther from the mountains, the basin-fill deposits are alternating layers of gravel, sand, and clay, with variable permeability.

Surface Water

Surface water is used extensively for irrigation and by municipalities in the Bountiful area. Total annual surface-water inflow to the area from the adjoining mountains is estimated to average about 28,000 acre-feet for the water years[1] 1969-84. Also, about 20,000 acre-feet of surface water is imported annually to the Bountiful area from the Weber River, north of the study area, through the Gateway Tunnel and Davis Aqueduct (fig. 1). About 2,000 acre-feet of this imported water is for municipal use, and the remainder is for irrigation of suburban and agricultural areas.

Calculations of surface-water inflow from five major streams were based on partial records of water stage at stations correlated to long-term records from nearby streams. The flow for Ricks, Parrish, Stone, and Mill Creeks for 1969-84 is based on records of annual flow available from 1950-51 to 1966-68, which were correlated to long-term records of flow for City Creek, several miles south of the study area in northern Salt Lake County. The flow for 1981-84 for Centerville Creek is based on longer-term records of annual flow, which were correlated to discharge of City Creek. The estimated annual inflow for 1969-84 in the five major streams is shown in table 2.

The estimated average annual inflow to the Bountiful area from perennial, intermittent, and ephemeral streams for which there is no record of flow is about 7,000 acre-feet (table 3). The streams with mean annual flow of greater than 1,000 acre-feet generally are perennial upstream of the canyon mouths, and that water often reaches the study area during periods of high flow. Most of the flow from the other drainages infiltrates into alluvial fans or high benchlands, where the definable channels terminate.

The flow in streams listed in table 3 was computed by the equation:

$$Q = 7.69 \times 10^{-4} (A)^{0.883} (E)^{3.65} \quad (1)$$

where Q = mean annual flow, in cubic feet per second;
A = drainage area, in square miles; and
E = mean altitude of the drainage basin, in thousands of feet.

Equation 1 was derived from long-term flow records for 25 streams in the Wasatch Range with similar drainage-area size and mean altitude. The average standard error of estimate was 28 percent, and the correlation coefficient was 0.95.

The seasonal fluctuation of surface-water flow is large, with the largest flow resulting from spring snowmelt and runoff. The average monthly flow for 1968-80 in Centerville Creek, which is typical of the streams in the area, ranges from about 1.6 cubic feet per second during the low-flow months of September through February to about 13 cubic feet per second during May when snowmelt is at its peak.

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[1]All surface-water records in this report are given in water years. A water year is the 12 months ending September 30 and designated by the year in which it ends.

Table 2.--Estimated inflow in major streams, water years 1969-84, in thousands of acre-feet

Water year	Ricks Creek	Parrish Creek	Centerville Creek	Stone Creek	Mill Creek	Total
	Stream					
1969	2	2	2.4	4	8	18.4
1970	2	2	2.4	3	7	16.4
1971	3	2	3.4	4	9	21.4
1972	2	2	3.1	4	7	18.1
1973	2	2	2.8	3	7	16.8
1974	3	2	3.6	5	9	22.6
1975	3	2	3.5	5	11	24.5
1976	2	1	2.2	3	6	14.2
1977	1	1	1.3	1	2	6.3
1978	3	2	3.3	4	8	20.3
1979	2	1	1.8	2	4	10.8
1980	2	1	2.5	3	5	13.5
1981	2	1	2	2	4	11
1982	3	2	3	4	9	21
1983	3	2	3	5	10	23
1984	3	2	3	4	8	20
Annual Average	2.4	1.7	2.7	3.5	7.1	17.4

Previous Investigations

Thomas and Nelson (1948) conducted a comprehensive study during 1946-48 of the hydrology and geology of the Bountiful area. Encompassing about the same area as this study, their study included a detailed account of the Quaternary and Tertiary geology, surface-water inflow, geochemistry of surface and ground water, water-level and discharge measurements in more than 400 wells, and potentiometric surface maps. Bolke and Waddell (1972) included the Bountiful area in their study of the East Shore area, which reported ground-water levels and changes in ground-water quality during 1960-69.

Acknowledgments

Special acknowledgments are extended to the residents and officials of the various cities and towns, irrigation companies, conservancy districts, and industries in the Bountiful area, who gave permission for the use of their wells for water-level measurements and aquifer testing, and who provided other useful information for this study. The cooperation of the officials from the State of Utah and Davis County is appreciated.

Table 3.--Estimated inflow from ungaged perennial, intermittent, and ephemeral streams

Drainage name	Drainage area (A) (square miles)	Mean drainage altitude (E) (thousands of feet)	Mean annual inflow (Q) (cubic feet per second)	Mean annual inflow (Q) (acre-feet per year)
North of Ricks Creek	1.0	6.12	.6	430
Barnard Creek	1.7	6.73	1.3	940
South of Centerville Canyon	.5	5.75	.2	140
North of Stone Creek	1.0	6.19	.6	430
Holbrook Creek	4.9	7.16	4.1	3,000
North Canyon	2.4	6.26	1.3	940
Hooper Canyon	1.2	5.80	.6	430
Unnamed	3.6	5.01	.9	650
			Total (rounded)	7,000

Numbering System Used for Wells in Utah

The system of numbering wells in Utah is based on the cadastral land-survey system of the U.S. Government. The number, in addition to designating the well, describes its position in the land net. By the land-survey system, the State is divided into four quadrants by the Salt Lake Base Line and Meridian, and these quadrants are designated by the uppercase letters A, B, C, and D, indicating the northeast, northwest, southwest, and southeast quadrants, respectively. Numbers designating the township and range (in that order) follow the quadrant letter, and all three are enclosed in parentheses. The number after the parentheses indicates the section, and it is followed by three letters indicating the quarter section, the quarter-quarter section, and the quarter-quarter-quarter section--generally 10 acres[1]; the letters a, b, c, and d indicate, respectively, the northeast, northwest, southwest, and southeast quarters of each subdivision. The number after the letters is the serial number of the well within the 10-acre tract. If a well cannot be differentiated within a 10-acre tract, one or two location letters are used and the serial number is omitted. Thus, (A-2-1)18abd-12 designates the twelfth well constructed or visited in the SE$\frac{1}{4}$ NW$\frac{1}{4}$ NE$\frac{1}{4}$, sec. 18, T. 2 N., R. 1 E. The numbering system is illustrated in figure 3.

[1]Although the basic land unit, the section, is theoretically 1 square mile, many sections are irregular. Such sections are subdivided into 10-acre tracts, generally beginning at the southeast corner, and the surplus or shortage is taken up in the tracts along the north and west sides of the section.

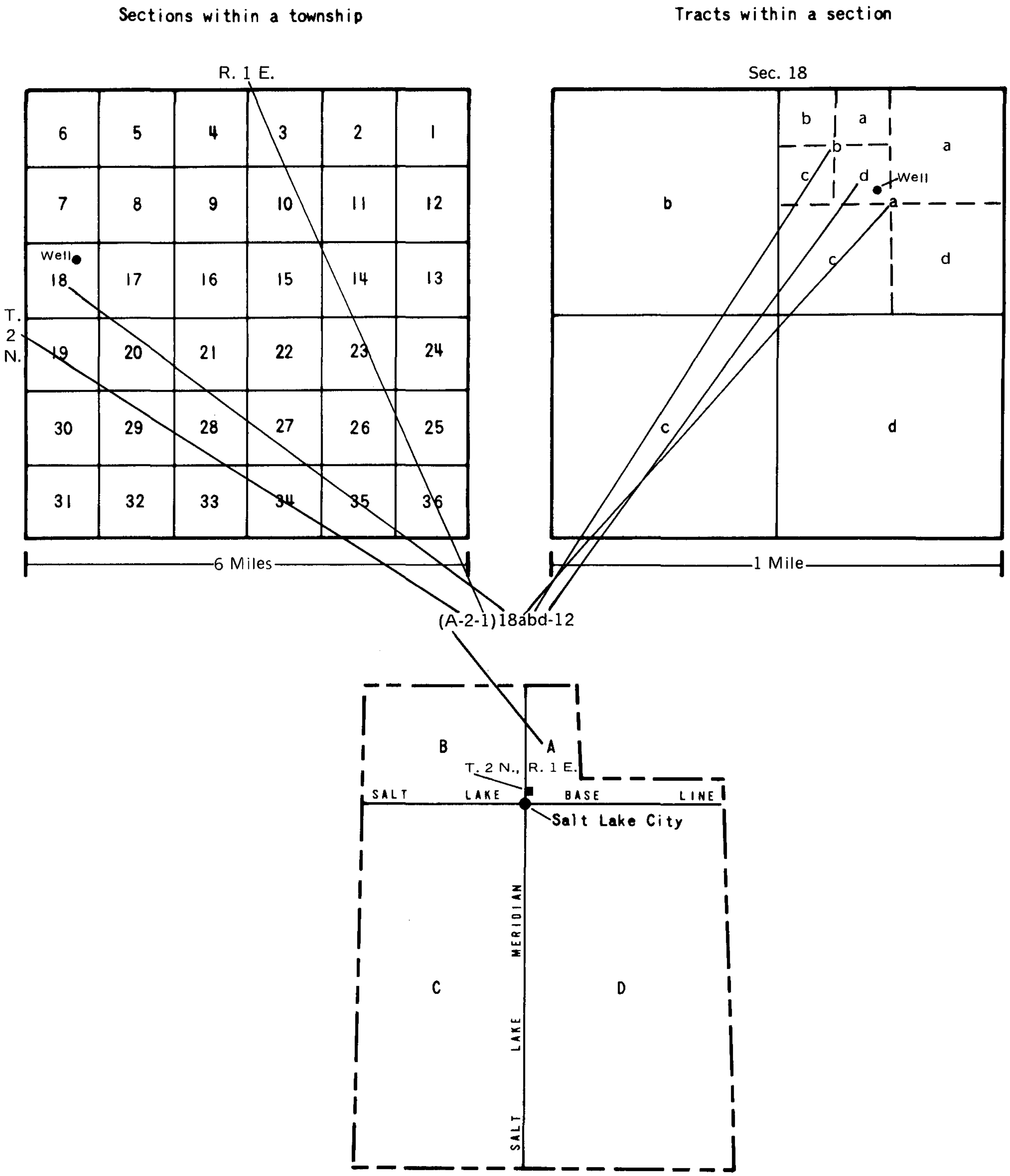


Figure 3.--Well-numbering system used in Utah.

GROUND-WATER RESOURCES

The ground-water resources in the Bountiful area described in this report are part of the East Shore aquifer system (Clark and others, 1990, p. 20). This aquifer system in the Bountiful area consists of saturated basin-fill deposits and includes artesian zones in the basin and a deep unconfined zone along the mountain front. A shallow water-table zone in the topographically low parts near the western boundary of the area is part of the overall ground-water system in the Bountiful area but is not considered part of the aquifer system as defined in this report. The shallow water-table zone was not included because of the lack of data on recharge to the zone by infiltration of precipitation, urban runoff, and irrigation, and a similar lack of data on discharge to waterways and by evapotranspiration.

Thomas and Nelson (1948, p. 167-172) described the aquifer system in the Bountiful area as containing shallow, intermediate, and deep artesian aquifers. The shallow artesian aquifer was defined as being from 60 to 250 feet below land surface, the intermediate artesian aquifer from 250 to 500 feet below land surface, and the deep artesian aquifer as greater than 500 feet below land surface.

Thomas and Nelson (1948, p. 171) described slight head differences among the artesian aquifers in the eastern part of the study area; however, they also described a convergence of the potentiometric surfaces toward the central and western parts of the area. Therefore, in this report, the aquifers were not differentiated because of the lack of substantial lithologic differences and because no large vertical head differences were measured during this study among the previously defined aquifers.

For the purposes of this study, all wells greater than 100 feet deep were considered to be completed in the aquifer system in the Bountiful area. Wells less than 100 feet deep were considered to be in the shallow confining unit or the shallow water-table zone and are not considered part of the aquifer system as defined in this report. In the valley lowland plains, confined conditions exist at shallow depths, and unconfined conditions exist only within a few feet of land surface. The 100-foot designation is based on a general thickness of the Lake Bonneville beds as described by Thomas and Nelson (1948, p. 97-109), and because few wells presently used are less than 100 feet deep (only 3 of the 134 wells inventoried during the study)(Plantz and others, 1986, p. 4-10).

Unconfined conditions in the aquifer system in the Bountiful area generally occur only in a narrow deep area along the mountain front within the recharge area. The deposits in the unconfined parts of the aquifer system typically are coarse grained; finer grained confining layers are thin and discontinuous or absent. The coarse-grained deposits allow the infiltration of precipitation, streamflow, and irrigation water to reach the ground-water system. As water moves westward through the basin-fill deposits toward Great Salt Lake, it becomes confined by lacustrine beds of silt and clay. Unconfined ground water that is not part of the aquifer system in the Bountiful area as defined in this report is present in flood-plain deposits along stream channels, in isolated perched aquifers in the bench areas, and throughout the valley lowlands in the shallow water-table zone within a few feet of land surface.

Transmissivity values for the aquifer system in the Bountiful area were estimated in part from data derived from aquifer tests (table 4) and range from about 200 feet squared per day where the sediments are predominately fine-grained to 30,000 feet squared per day in thick, coarse-grained deposits. All tests were analyzed using the straight-line solution (Jacob and Lohman, 1952).

Table 4.--Results of aquifer tests

Location: P, pumped well; F, flowing well

Well location		Date	Discharge (gallons per minute)	Transmissivity (T) (feet squared per day)
(A-2-1)7dca-1	P	10-47	400	1,800
20cdd-1	P	10-47	26	6,700
28bca-1	P	4-76	1,500	5,000
32ccb-2	P	2-58	1,000	30,000
34cdb-1	P	7-81	240	600
34dcc-1	P	7-76	1,250	1,000
(B-2-1)13acd-1	F	3-47	38	200
13cdd-2	F	4-47	105	1,700
26bdd-2	F	3-47	250	2,000
26cdd-1	F	5-36	53	1,000
26dca-3	F	3-47	275	7,100

Values for storage coefficient and specific yield were not available for the aquifer system in the Bountiful area. Values for storage coefficient were determined for the confined aquifers of the entire East Shore area from aquifer test results (Clark and others, 1990); however, none of the results were from the aquifer system in the Bountiful area. Storage coefficients for the East Shore aquifer system were fairly consistent throughout the study area and ranged from about 3×10^{-6} to 1×10^{-4} and averaged about 9×10^{-5}. Specific yield values for the unconfined parts of the shallow water-table zone in the East Shore aquifer system were estimated to be 1×10^{-1}. Values for storage coefficient and specific yield in the aquifer system in the Bountiful area are probably similar.

Recharge

Annual recharge to the aquifer system in the Bountiful area is estimated to have averaged about 26,000 acre-feet during 1947-85, and ranged from about 22,000 to 32,000 acre-feet. The ultimate source of recharge is precipitation that falls in the mountains that are adjacent to the Bountiful area. Recharge to the aquifer system occurs by seepage losses from streams, irrigated fields, and lawns and gardens; by infiltration of precipitation; and by subsurface inflow from consolidated rock of the Wasatch Range to basin-fill deposits.

Recharge to the aquifer system in the Bountiful area was calculated only in an area near the mountain front, where the surficial and underlying sediments are permeable enough to transmit water downward to the aquifers. The zone of permeable sediments extends about 1.5 miles west from the mountain front, south of Bountiful, to less than 0.25 mile west of the mountain front north of Centerville (fig. 4).

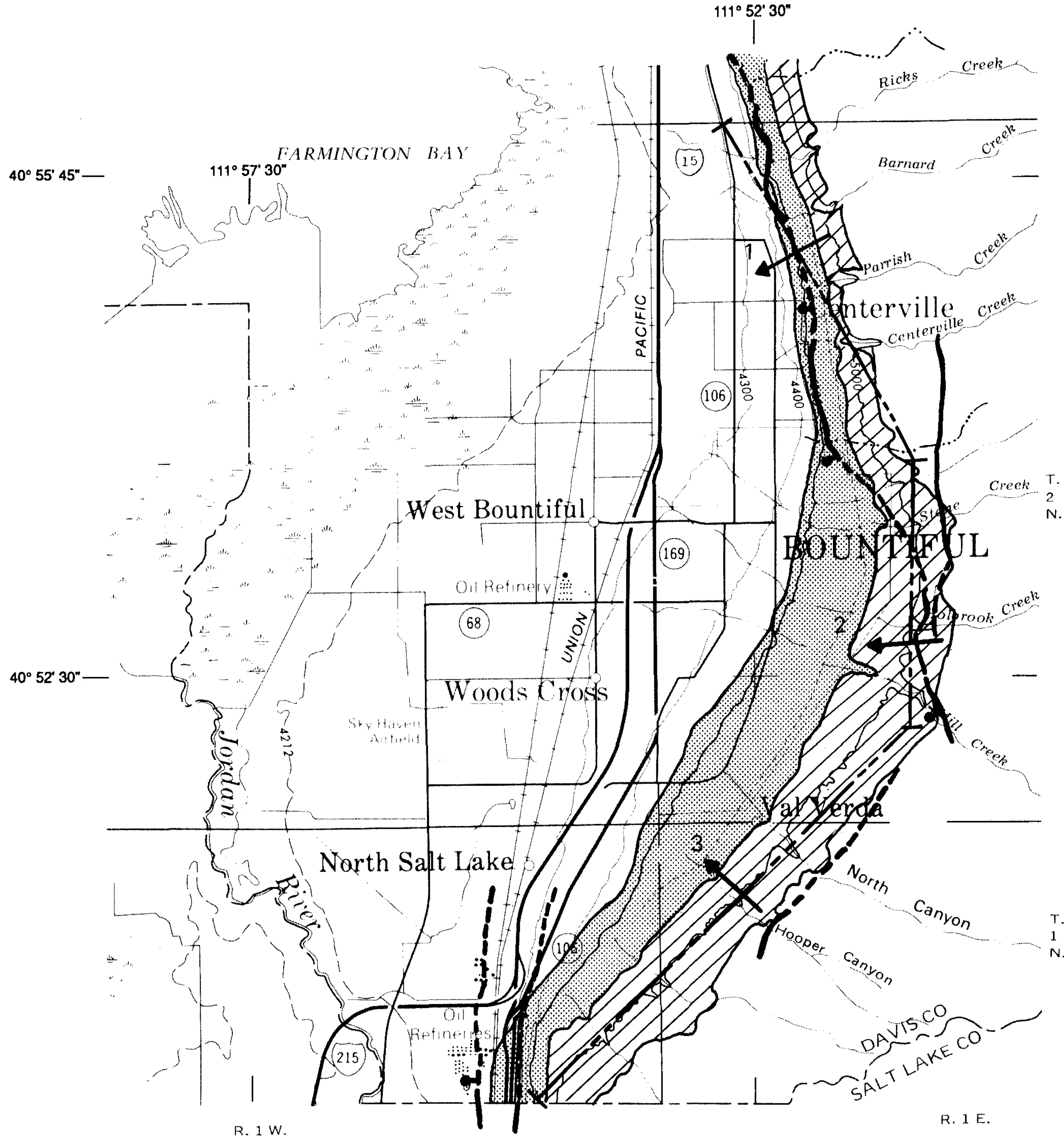
The recharge area consists of two subareas, totaling about 5,500 acres with different potentials for recharge by downward movement. The subareas were differentiated based on surficial grain-size information (Feth and others, fig. 10, p. 40) and surficial geology (Davis, 1983). The primary recharge area, 2,900 acres, is nearest the mountain front; it predominantly is underlain by permeable sand and gravel that enhance infiltration of recharge water. The secondary recharge area, 2,600 acres, is farther from the mountains; it is underlain by finer grained sediments that partially impede downward movement and, therefore, probably accept direct infiltration less readily than areas closer to the mountain front (Feth and others, 1966, p. 39). Although no direct relation was known for infiltration rates between the recharge areas, for the purpose of calculating recharge, it was assumed that the rate of infiltration in the secondary recharge area was one-half the rate for the primary recharge area.

More than 70 percent of the total recharge area (about 4,000 acres) is predominately urban with some suburban land use, including streets and buildings. This total includes about 2,300 acres in the secondary recharge area and 1,700 acres in the primary recharge area. The remaining 1,500 acres in the recharge area primarily are undisturbed and unirrigated benchlands with native vegetation and a few irrigated orchards.

Seepage from Stream Channels

The average annual recharge during 1969-84 by seepage from natural channels that cross the primary and secondary recharge areas was estimated to be about 7,100 acre-feet. In areas where streams enter the study area, the natural channels generally are in gravel and boulders, which are permeable and favorable for seepage. Fluctuations of water levels in some wells near stream channels show a relation to fluctuations in annual streamflow. The relation between the highest water levels in a well and the annual flow in Centerville Creek for the water years 1950-84 is shown in figure 5 and indicates possible recharge from the stream upgradient from the well.

Measurements to detect seepage losses were made on Mill, Parrish, and Holbrook Creeks during high flows in June 1985. Each stream was divided into three sections, with the uppermost section beginning where the stream was entrenched in consolidated rock, and the lower section generally ending at the western boundary of the primary recharge area (fig. 4). Measurable losses in flow in all three streams occurred only in the middle section, generally between altitudes of about 4,800 and 4,600 feet. Losses were fairly consistent, ranging from about 10 to 20 percent of the discharge. For the measured streams, channels above an altitude of about 4,800 feet generally had been scoured of most unconsolidated sediments by stream erosion, and the streams flow over bedrock, which probably limits seepage losses.



Base from U.S. Geological Survey 1:125,000 quadrangle, Great Salt Lake and vicinity, Utah, 1974

0 1 2 MILES

0 1 2 KILOMETERS

CONTOUR INTERVAL, IN FEET, VARIABLE
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

PRIMARY RECHARGE AREA

SECONDARY RECHARGE AREA

FAULT--Dashed where approximately located; bar and ball on downthrown side (Adapted from Davis 1983, 1985)

3

LINE OF CROSS SECTION FOR COMPUTATION OF SUB-SURFACE INFLOW AND LINE-SEGMENT NUMBER--Arrows indicate direction of ground-water flow

Figure 4.--Recharge areas, major fault zones, and computation lines for subsurface inflow.

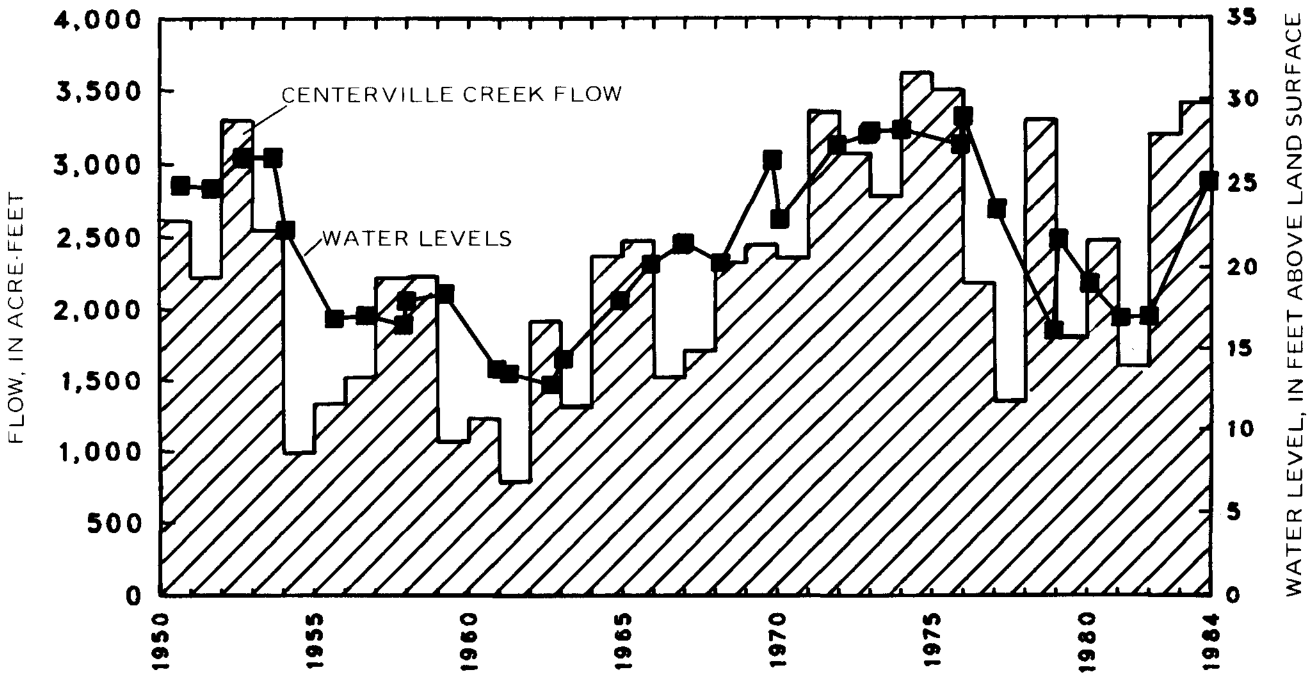


Figure 5.--Relation between annual flow of Centerville Creek and highest water levels in well (A-2-1)18abd-12, water years 1950-84.

Average annual recharge for 1969-84 from Mill Creek was calculated to be 1,800 acre-feet by assuming a seepage loss of 15 percent at high flow based on measurements, and a maximum of 50-percent loss during low flow based on information from local residents and observations. Total annual recharge is estimated to be about 25 percent of the total annual flow on the basis of available flow records, a 15-percent loss during high flow, and a 50-percent loss during low flow.

Using similar procedures, the average annual recharge was estimated to be 430 acre-feet from Parrish Creek and 750 acre-feet from Holbrook Creek. Total annual seepage losses are about 25 percent of the total annual flow of these two streams. Estimates of the average annual recharge from other streams for 1969-84, based on a 25-percent seepage loss are: Ricks Creek, 580 acre-feet; Centerville Creek, 680 acre-feet; and Stone Creek, 880 acre-feet.

Recharge from smaller ungaged perennial, intermittent, and ephemeral streams is generally by seepage into alluvial fans near the mouths of canyons and is estimated to be about 2,000 acre-feet per year. No accurate estimates of losses are available for most of these streams. Seepage measurements from nearby streams indicate larger losses in the primary recharge area than in the secondary area. Therefore, streams that cross only the secondary recharge area were assumed to have no more than a 25-percent loss; whereas, most streams that cross the primary recharge area were assumed to have an annual loss of 50 percent of their total flow. All of the smaller streams, except Holbrook Creek, which was estimated separately, were estimated to recharge 50 percent of their annual flow or 2,000 acre-feet.

Canals and ditches in the recharge area of the Bountiful area are either lined and have small or no seepage losses, or they are small, unlined ditches that carry a minimal quantity of water. Losses from these canals were assumed to be minimal when compared to losses from applied irrigation water and were not estimated.

Infiltration from Irrigation

The average annual recharge from irrigation of crops and lawns and gardens in the primary and secondary recharge areas is estimated to be 3,700 acre-feet. Annual recharge ranges from 2,000 to 5,000 acre-feet.

Much of the irrigation water applied to the urban areas after 1960 was supplied by surface water from the Weber River by way of the Gateway Tunnel and the Davis Aqueduct, with some additional water from treated municipal supplies. The quantity of water diverted from the Weber River and used exclusively for irrigation in the Bountiful area was estimated from records of the Weber Basin Water Conservancy District and from total flow through the Gateway Tunnel (Johnson, 1969-85). Estimates of diversions for irrigation use in the Bountiful area from 1960 to 1985 averaged about 17,000 acre-feet per year and ranged from about 10,000 to 25,000 acre-feet per year, depending on the quantity of water available in the Weber River.

The quantity of recharge by infiltration from irrigation depends on several factors including the quantity of water applied, the type of application, the consumptive use of the plants, and the permeability of the soils. Average recharge from infiltration of irrigation was estimated in areas with similar factors to be 25 percent of the applied irrigation water for the East Shore area of Great Salt Lake (Feth and others, 1966, p. 43) and 33 percent for an area near Utah Lake (Clark and Appel, 1985, p. 29, and the U.S. Bureau of Reclamation, 1967, 1968, and 1969). For the purpose of this study it was estimated that in the primary recharge area, about 30 percent of the applied irrigation water recharged the aquifer system in the Bountiful area. An estimated 43 percent of the total irrigated acres, or 1,700 acres, are in the primary recharge area. If 30 percent of the 7,200 acre-feet of water diverted for irrigation in the primary recharge area (43 percent of 17,000 acre-feet) infiltrated to the aquifer system, then about 2,200 acre-feet of water was recharged. Similarly, if 15 percent of the applied irrigation water infiltrated to the aquifer system in the secondary recharge area where clay comprises a larger proportion of the surface materials, then 1,500 acre-feet of water was recharged.

Infiltration from Precipitation

The average annual recharge by infiltration of precipitation in the primary and secondary recharge areas is estimated to be about 1,400 acre-feet, but it may vary considerably from one year to the next depending on quantity, intensity, season, and type of precipitation. The average annual precipitation in the recharge area is estimated to be about 20 inches per year based on records at the Ogden Pioneer Powerhouse station (National Oceanic and Atmospheric Administration, 1983b). The recharge area includes about 5,500 acres, of which 2,900 acres are in the primary recharge area and the remaining

2,600 acres are in the secondary recharge area. Infiltration of precipitation in these areas is estimated to be 20 percent for the primary recharge area and 10 percent for the secondary recharge area.

Subsurface Inflow

Subsurface inflow to the aquifer system in the Bountiful area from consolidated rocks is estimated to be about 14,000 acre-feet per year. Most of the inflow is inferred to be the result of water movement through fractures and joints and along fault zones in the consolidated rock of the Wasatch Range to the unconsolidated basin-fill deposits (fig. 2). The Wasatch Range adjacent to the study area is composed primarily of thick sequences of Precambrian metamorphic rocks and Tertiary sedimentary rocks, which, in some areas, have been extensively faulted and fractured. Snowmelt probably enters the consolidated rock by infiltration through the mountain soils into fractures or into the weathered surface of the rock.

The occurrence of subsurface inflow cannot be directly measured, and estimates are based on limited available data and assumptions; however, indirect evidence exists of subsurface inflow from consolidated rock to the basin-fill deposits. The indirect evidence includes data from wells completed in consolidated rock, springs in consolidated rock areas, and comparison of hydraulic head values among wells completed in consolidated rock and in basin fill where there are only small quantities of recharge from other sources (Clark and others, 1990, p. 31).

Wells have been completed at or near the surface contact between the basin fill and consolidated rock. Data from these wells indicate that in some areas the rock is permeable and that water does move from consolidated rock to alluvium. Some wells finished in rock near the mountain front discharge fresh water at rates of about 50 gallons per minute by artesian flow, indicating that some of the consolidated rock is capable of transmitting substantial quantities of water.

Wells finished in rock near Bountiful generally are more productive when finished in fractured rock or near faults, which indicates that the fractured rock is transmitting water that may be recharging the downgradient basin fill. Water levels fluctuate seasonally in some wells that are completed in the alluvium near the mountain front, yet distant from sources of surface water. These fluctuations probably are in response to recharge by infiltration of snowmelt moving into the alluvium from consolidated rocks.

The following variation of the Darcy equation was used to estimate subsurface flow from the consolidated rock to the unconsolidated basin fill from all sources topographically higher than a given cross section through which flow occurs.

$$Q = TIL \qquad (2)$$

where Q = discharge, in cubic feet per day;
T = transmissivity, in feet squared per day;
I = hydraulic gradient (dimensionless); and
L = length, in feet, of the cross section through which the flow occurs.

On the basis of available water-level and well data, flow was computed through a cross section along the eastern flank of the valley close to the contact of the basin fill and consolidated rock. The cross section was segmented into three subsections on the basis of differences in estimated transmissivity values and hydraulic gradients from wells near the cross section. The location of the subsections is shown in figure 4; the estimated inflow across those subsections, and the hydraulic gradients and transmissivity values used to compute the inflow, are given in table 5.

Table 5.--Estimated annual subsurface inflow from consolidated rock to basin fill
[Clark and others, 1990, table 7]

Subsection numbers for cross section (see fig. 4)	Transmissivity (T) (feet squared per day)	Hydraulic gradient (I) (dimensionless)	Length of subsection (L) (feet)	Discharge (Q) Cubic feet per day (rounded)	Discharge (Q) Acre-feet per year (rounded)
1	1,000	0.03	15,500	460,000	3,900
2	2,000	.06	12,900	1,500,000	13,000
3	500	.06	20,800	620,000	5,200
			Total		22,000

Less recharge within the recharge areas upgradient from cross section (fig. 4)

Streams	7,100
Direct precipitation	400
Lawns and gardens	500
Subtotal	8,000
Total subsurface inflow from consolidated rock	14,000

The total annual flow of about 22,000 acre-feet computed across the cross section includes about 8,000 acre-feet per year of recharge from other upgradient sources. It is assumed that about 7,100 acre-feet of flow from stream channels recharges the aquifer in the Bountiful area near the mouths of the canyons, generally near or upgradient from the cross section. On the basis of land use upgradient from the cross section, about 400 acre-feet of precipitation and 500 acre-feet of irrigation from lawns and gardens is assumed to recharge the aquifer system in the Bountiful area upgradient from the cross section. Thus, the adjusted total recharge from subsurface inflow from bedrock is estimated to be about 14,000 acre-feet per year. If part of the recharge from streams occurs downstream from the cross section, the total recharge could be larger.

Movement

Ground water in the aquifer system in the Bountiful area generally moves westward from the mountain front toward Great Salt Lake. A downward component of movement exists throughout the recharge area near the mountain front (fig. 2) where hydraulic head values decrease with depth. An upward component of movement exists away from the mountain front where water is confined and head values increase with depth; water moves upward through confining beds from deeper to shallower parts of the aquifer system. The hydraulic connection within the aquifer system depends on the thickness of the clay layers and other fine-grained sediment layers. Generally, where the clay or other fine-grained deposits are thick, hydraulic connection within the aquifer system is less.

A potentiometric-surface map was prepared for the aquifer system in the Bountiful area on the basis of water levels measured in March 1985 (fig. 6). Movement of ground water generally is perpendicular to the contours. The shape of the contours, which generally bulge westward from the mountain front, reflect recharge from Mill and Holbrook Creeks and recharge by subsurface inflow from consolidated rock. The contours also indicate possible movement of water into the Jordan River and Farmington Bay.

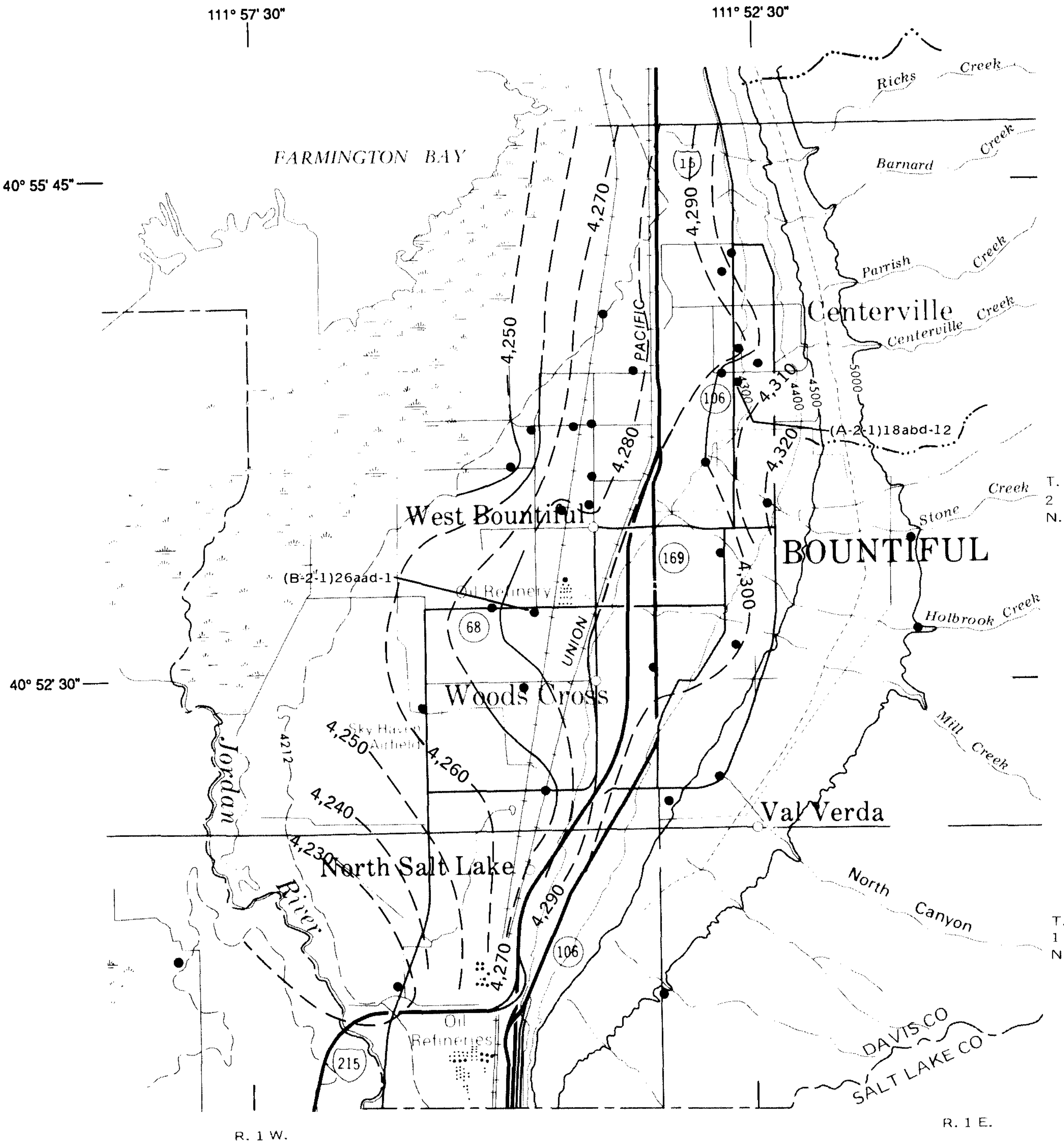
Unconfined ground water occurs locally in perched zones in the bench areas on the eastern side of the study area. Water in these areas probably moves toward the edge of the bench where it discharges by evapotranspiration, springs, seeps, or into drains. Some of the water moves into surface deposits in the valley lowlands, and minor quantities of perched water may move downward to the aquifer system.

Water-Level Changes

Water levels change in response to changes in the quantity of ground water in storage, which varies according to the quantity of water added to or removed from the aquifer system. The changes can be short-term, diurnal, seasonal, and long-term. Long-term changes in water levels generally reflect either long-term trends in precipitation or changes in discharge from wells or both. A comparison of water levels in well (B-2-1)26aad-1, annual withdrawal from municipal and industrial wells, and the cumulative departure from average annual precipitation is shown in figure 7.

In the Bountiful area, long-term water-level trends generally followed the trend of cumulative departure from normal precipitation from 1935 until about 1962. In about 1962, water levels began to rise. The rise was the result of nearly normal precipitation with smaller withdrawals of water from wells from 1960 to 1962 when compared to withdrawals from 1955 through 1959. The smaller withdrawals were the result of importation of Weber River water by the Davis Aqueduct.

Water levels generally declined from 1965 to 1968 in response to an increase in withdrawals of water from wells. From 1970 to 1975, precipitation was slightly greater than normal while withdrawals remained fairly stable; thus, water levels remained fairly stable. In the late 1970's, withdrawals again increased, causing water levels to decline. Water levels generally have risen since 1978 in response to an increase in precipitation despite a slight



Base from U.S. Geological Survey 1:125,000 quadrangle,
Great Salt Lake and vicinity, Utah, 1974

0 1 2 MILES

0 1 2 KILOMETERS

CONTOUR INTERVAL, IN FEET, VARIABLE
NATIONAL GEODETIC VERTICAL DATUM OF 1929

EXPLANATION

—4,250— — POTENTIOMETRIC CONTOUR--Shows altitude of the potentiometric surface, March 1985, in the Bountiful aquifer system, in feet above National Geodetic Vertical Datum of 1929. Dashed where approximately located. Contour interval 10 feet

(A-2-1)18abd-12● OBSERVATION WELL FINISHED IN BASIN-FILL--Well numbers shown for selected wells. See text for explanation of well-numbering system

Figure 6.--Potentiometric surface of the aquifer system in the Bountiful area, March 1985.

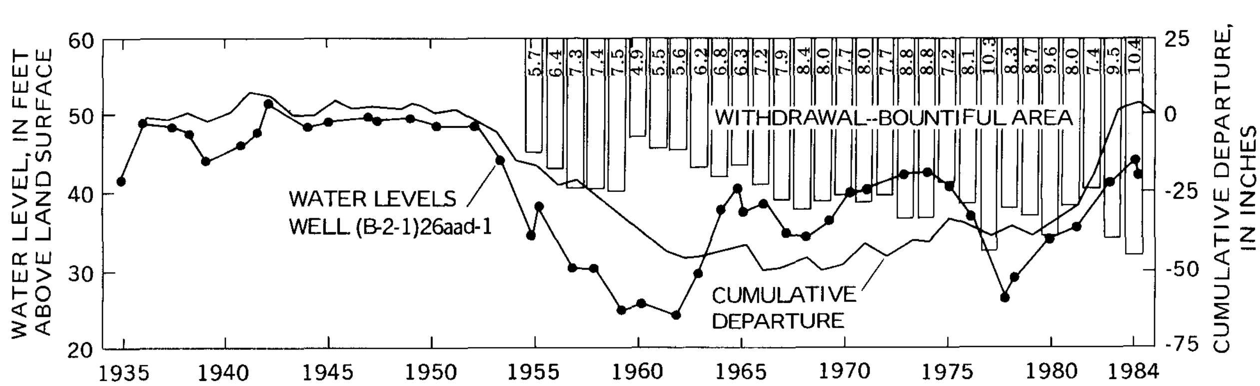


Figure 7.--Cumulative departure from the average annual precipitation at the Ogden Pioneer Powerhouse, water levels in well (B-2-1)26aad-1, and withdrawal from wells for municipal and industrial use in the Bountiful area, 1935-84. [Number inside withdrawal histogram is discharge, in thousands of acre-feet.]

increase in withdrawals. The slight decline in water levels in 1984, however, was caused by a large increase in withdrawals in 1983 and 1984. Water levels fluctuated from 1962 to 1985 depending on changes in withdrawals and precipitation.

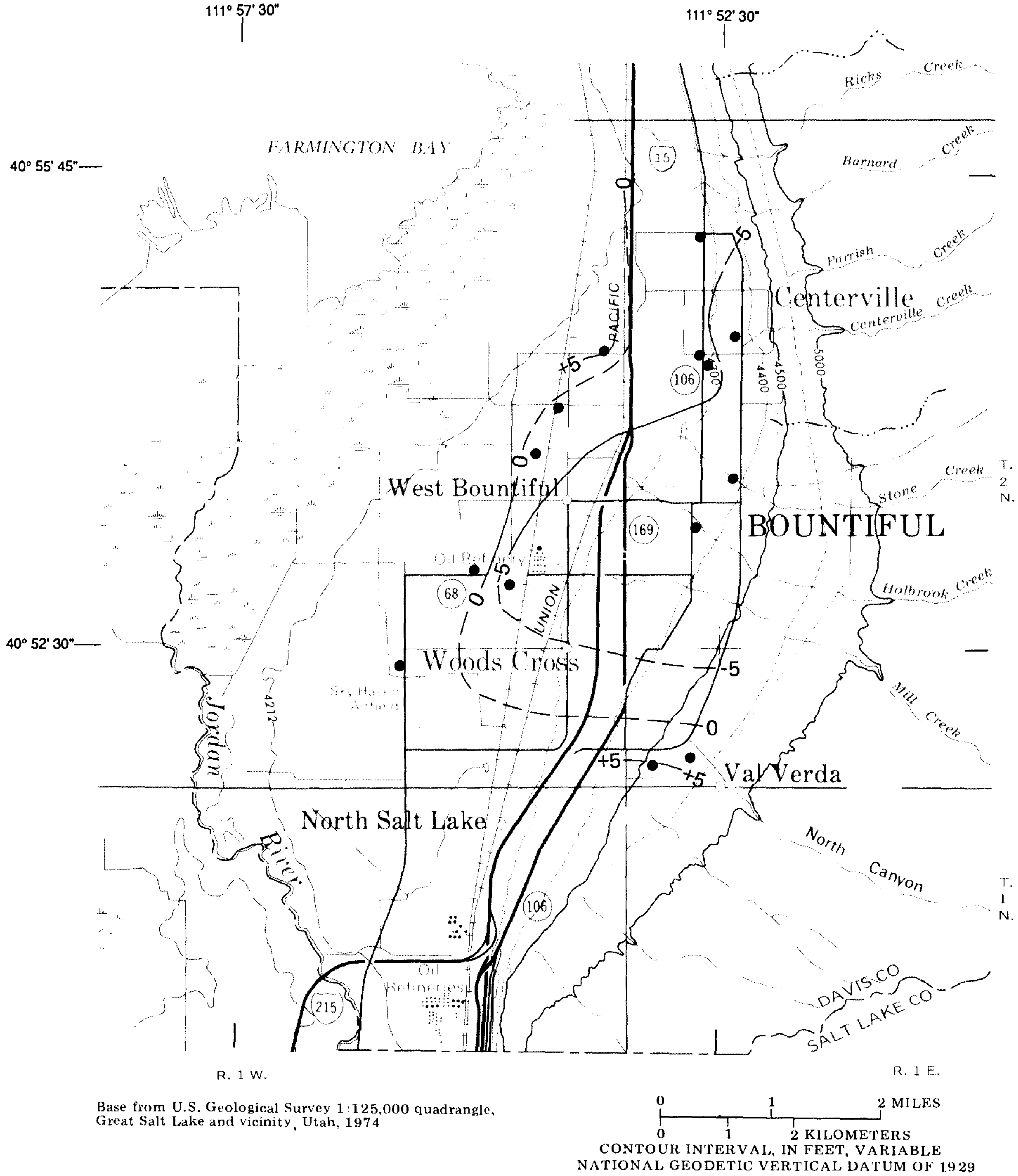
A water-level-change map (fig. 8) that shows the distribution and magnitude of water-level changes in the aquifer system in the Bountiful area was constructed for 1946-47 to 1985. Water levels in wells declined in most of the Bountiful area from 1946-47 to 1985 based on measurements in 14 wells. The water-level changes ranged from a rise of 5.4 feet west of Val Verda, to a decline of 9.1 feet northeast of Woods Cross. Declines are probably the result of increased withdrawals for municipal use; whereas, the rises are probably the result of importation of water and distance of a well from wells withdrawing substantial quantities of water.

Discharge

Discharge from the aquifer system in the Bountiful area is to wells, waterways (drains, ditches, and streams), springs and seeps, evapotranspiration, and diffuse seepage to Great Salt Lake. The average annual discharge for 1947-85 was estimated to range from about 26,000 to 30,000 acre-feet.

Wells

About 1,200 wells were constructed in the Bountiful area by 1947. These wells discharged more than 10,000 acre-feet per year (Thomas and Nelson 1948, p. 186), and discharges were estimated to range from about 13,000 to 17,000 acre-feet per year during 1969-85. According to available records, 230 wells were constructed during 1947-59, 70 wells were constructed during 1960-68 (Bolke and Waddell, 1972), and an additional 90 wells were constructed during 1969-85, for a total of about 1,600 wells. Many of the older wells have since been destroyed, abandoned, or replaced; therefore, the exact number of usable, existing wells is unknown. The wells vary from large-diameter municipal wells to small-diameter flowing wells used for domestic and stock water.



EXPLANATION

—— -5 — — — LINE OF EQUAL WATER-LEVEL CHANGE, IN FEET--Dashed where approximately located. Contour interval 5 feet. + indicates rise in water level, - indicates decline in water level

● OBSERVATION WELL

Figure 8.--Change in ground-water levels in the aquifer system in the Bountiful area, 1946-47 to 1985.

Most well discharge in the Bountiful area is from municipal and industrial wells. Annual withdrawal of ground water for municipal and industrial use increased from less than 7,500 acre-feet before 1960 to more than 10,000 acre-feet in 1980 to supply a population that increased from about 23,000 in 1960 to about 54,000 in 1980 (table 1). The annual discharge from wells during 1969-85 averaged about 8,700 acre-feet and ranged from about 7,000 acre-feet in 1975 to about 12,000 acre-feet in 1985. The discharge from about 30 municipal and industrial wells was determined from records, beginning in 1955, provided by the owners and by Weber Basin Water Conservancy District, which supplies water for municipal and industrial use.

The approximate boundary of flowing wells in 1954 and 1985 is shown in figure 9. The flowing-well boundary fluctuates seasonally and over periods of several years; thus, it is only an approximate boundary. The total percentage of wells that are within the area of flowing wells was determined from drillers' logs of wells, previously published data, and data collected at wells during 1985. According to Smith and Gates (1963, plate 2), about 900 wells flowed in 1954. Since 1954 about 400 wells have been drilled in the Bountiful area and an estimated 75 percent, or 300, of those wells flowed at land surface.

Estimates of discharge from flowing wells primarily were determined from data collected from 249 wells within the entire East Shore area. Most of the 249 wells are in five sections inventoried by Bolke and Waddell (1972, p. 7), and more than 100 of those wells are in the Bountiful area in section (B-2-1)26 (fig. 9). Of the 249 wells, 39 percent were valved or pumped, 27 percent were flowing continuously, 16 percent no longer flowed, and 18 percent were plugged or unused. These percentages, the total number of wells in the flowing-well area, and estimates of discharge based on well type (Clark and others, 1990, p. 66), were used to estimate total discharge from the flowing-well area.

EXPLANATION FOR FIGURE 9

EXPLANATION

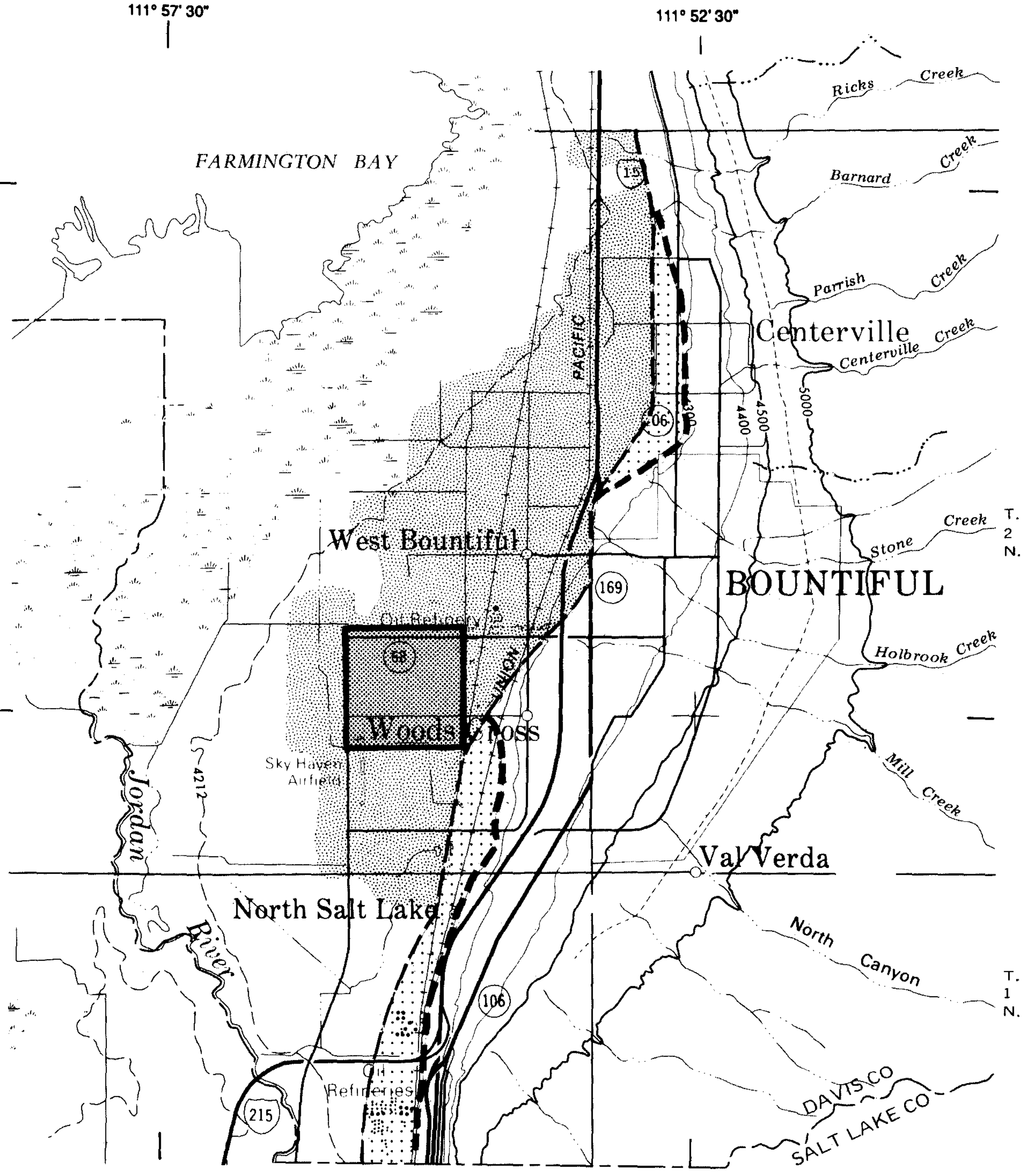
APPROXIMATE AREA IN WHICH WELLS WERE NOT FLOWING DURING THE SUMMER OF 1985 BUT WERE REPORTED TO HAVE BEEN FLOWING IN 1954

SECTION (B-2-1)26 USED TO ESTIMATE DISCHARGE FROM FLOWING WELLS

AREA IN WHICH WELLS WERE FLOWING IN 1985

BOUNDARY OF FLOWING WELLS IN 1954

BOUNDARY OF FLOWING WELLS IN 1985



Base from U.S. Geological Survey 1:125,000 quadrangle, Great Salt Lake and vicinity, Utah, 1974

0 1 2 MILES
0 1 2 KILOMETERS

CONTOUR INTERVAL, IN FEET, VARIABLE
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Figure 9.--Location of section used to estimate discharge from flowing wells and approximate boundary of flowing-well area, 1954 and 1985.

Discharge from valved or pumped flowing wells was estimated to average 1,000 acre-feet per year, and discharge from continuously flowing wells was estimated to average 4,000 acre-feet per year. An estimated 300 small-diameter wells are used for domestic, stock, and irrigation purposes outside the flowing-well area, and discharge from these wells was estimated to average 500 acre-feet per year. The total annual discharge from all wells not used for municipal or industrial use is estimated to average about 5,500 acre-feet per year; however, the discharge may vary considerably from year to year.

Waterways, Springs, and Seeps

Discharge from the aquifer system in the Bountiful area to waterways (drains, ditches, and streams) and by springs and seeps averages 10,000 acre-feet per year based on an estimated range of 7,500 to 13,000 acre-feet per year, including minor discharge to the Jordan River. The estimates of discharge are based on about 40 measurements or estimates made during the spring of 1984. The estimated average annual discharge might be greater than the actual long-term average because precipitation for 1984 and the 3 preceding years was about 150 to 200 percent of normal.

Discharge to drains in the study area ranged from 0.5 to 1.1 cubic feet per second per square mile. Measurements were made on all known drains and are assumed to represent total drain discharge within the study area. The measurements were made before the irrigation season and after the past season's irrigation water had drained off. Therefore, they were assumed to be representative of base flow conditions, which mainly include ground water derived from upward leakage from the aquifer system.

Discharge from the aquifer system in the Bountiful area varies seasonally and annually, depending on changes in the artesian pressure within the aquifer system. Many of the springs and seeps are in areas where the altitude of the potentiometric surface is slightly above land-surface altitude, generally at the headwaters of drains and ditches. The discharge by upward leakage typically is largest in the spring when ground-water levels are highest, and smallest in the fall when ground-water levels are lowest. Discharge by upward leakage to waterways and by springs and seeps generally is assumed to be greatest in areas where the confining unit overlying the aquifer system in the Bountiful area is thin and permeable.

Evapotranspiration

The Bountiful area includes about 9,000 acres of land where upward leakage from the aquifer system is a source of water for evapotranspiration. This is about 10 percent of the area where evapotranspiration occurs in the entire East Shore area. The area of evapotranspiration is about the same as the area where artesian pressure in the confined parts of the aquifer system was great enough to cause wells to flow in 1985 (fig. 9). About one half of the area is non-cropped, non-irrigated, and vegetated, and the remaining part is irrigated cropland.

Some of the shallow ground water available for evapotranspiration originates as upward leakage from the aquifer system in the Bountiful area. The leakage is taken up by plants, evaporated to the atmosphere, or discharged to drains. The remaining water consumed by evapotranspiration is supplied by local precipitation, applied irrigation from adjacent irrigated land, or from waterways.

Evapotranspiration of water by upward leakage from the East Shore aquifer system in the Bountiful and Weber Delta area (fig. 1) was estimated to range from a minimum of 4,000 acre-feet per year to a maximum of 11,000 acre-feet per year, and averaged about 8,000 acre-feet per year (Clark and others, 1990, p. 78). The estimates were based on a field inventory of phreatophytes in non-irrigated areas, evapotranspiration rates for those phreatophytes, quantity of effective precipitation, estimates of excess water from irrigation, and water in waterways (Clark and others, 1990, p. 78).

Data were not available to compute a separate estimate of evapotranspiration for the aquifer system in the Bountiful area; therefore, it was assumed that about 10 percent of the total evapotranspiration, or about 800 acre-feet per year of ground water, was discharged from the aquifer system in the Bountiful area by evapotranspiration. This estimate is based on the 10 percent of land the Bountiful area occupies in the entire East Shore area. Additional evapotranspiration in the Bountiful area is from applied water from flowing wells or surface water, return flow from upgradient irrigated areas, or from direct precipitation; however, it does not come directly from the aquifer system in the Bountiful area, and therefore, is not included in the 800 acre-feet.

Diffuse Seepage to Great Salt Lake

Ground water discharges by diffuse seepage from sediments under the east side of Great Salt Lake. The total annual ground-water discharge to the lake was estimated for the entire East Shore area, including the Bountiful area, to be 50,000 acre-feet per year (Clark and others, 1990, p. 79). The estimate was based on the average hydraulic conductivity, the hydraulic gradient at wells near the lake, the length of the cross-sectional area, and an assumed saturated thickness of the aquifer system of 1,000 feet.

An estimate of discharge from the aquifer system in the Bountiful area based on a hydraulic conductivity of 17 feet per day, a hydraulic gradient of 0.0016, and a length of 35,000 feet, is 8,000 acre-feet per year. These values are consistent with values used by Clark and others (1990, p. 79) for the East Shore area; however, some of the estimated discharge, perhaps as much as 3,000 acre-feet per year, discharges upgradient in the flatlands east of Great Salt Lake to drains, ditches, and springs. The total annual ground-water discharge from the aquifer system in the Bountiful area by diffuse seepage to the lake is estimated to be about 5,000 acre-feet per year.

Summary of the Estimated Hydrologic Budget for the Aquifer System in the Bountiful Area

The estimated hydrologic budget for the aquifer system in the Bountiful area is summarized in table 6. An estimate of the long-term average for both recharge to and discharge from the aquifer system in the Bountiful area is about 28,000 acre-feet per year (table 6).

Table 6.--Estimated hydrologic budget for the aquifer system in the Bountiful area, 1969-85

Budget component	Acre-feet per year (rounded)
Recharge	
Seepage from stream channels	7,100
Seepage from irrigated fields, lawns, gardens, and precipitation	5,100
Subsurface inflow from consolidated rocks	14,000
Total (rounded) ..	26,000
Discharge	
Wells	14,000
Waterways, springs, and seeps	10,000
Evapotranspiration	800
Diffuse seepage to Great Salt Lake	5,000
Total (rounded) ..	30,000

The budget components for recharge and discharge were estimated independently; therefore, the totals do not necessarily agree. The difference between the total estimated recharge and discharge primarily is the result of a lack of reliable, definitive data for calculating some of the individual parts of the budget, particularly subsurface inflow from consolidated rocks, discharge to waterways and springs, and diffuse seepage to Great Salt Lake, which are major parts of the total budget. The difference probably is not the result of long-term decreases in ground-water storage. If part of the recharge from streams occurs downstream from the cross section used to compute subsurface inflow from consolidated rocks, then total recharge could be larger by several thousand acre-feet per year.

SIMULATION OF THE AQUIFER SYSTEM IN THE BOUNTIFUL AREA

A principal purpose of this study was to simulate flow in the aquifer system in the Bountiful area using a computer model. The East Shore aquifer system, as described by Clark and others (1990), includes the Bountiful and the Weber Delta areas. Computer simulation of the aquifer system in the Weber Delta area, which forms the northern boundary of the Bountiful area, is described by Clark and others (1990).

The shallow water-table zone in the topographically lowest part of the Bountiful area (not included in the aquifer system in the Bountiful area as defined in this report) was included in the model because upward discharge of water into the shallow water-table zone from the aquifer system in the Bountiful area was simulated by the model. In contrast, recharge to the water-table zone by local precipitation and large quantities of seepage from excess irrigation, and subsequent discharge of this water, were not included in the model because few data on these processes were available.

The model was constructed and calibrated using available data on aquifer properties, historic water-level changes, and components of the hydrologic budget to learn more about the aquifer system in the Bountiful area and how it functions, and to improve the estimates of its hydrologic components. The calibrated model was then used to simulate changes in ground-water levels, discharge, and storage caused by projected increases in ground-water withdrawals by pumpage and possible changes in recharge.

Design and Construction of the Ground-Water Model

Data used to construct and calibrate the model were collected during hydrologic studies in the Bountiful area that span about 50 years. Data from Thomas and Nelson (1948) were used for steady-state calibration; data from Smith (1961), Smith and Gates (1963), Bolke and Waddell (1972), and Plantz and others (1986) were used for transient-state calibration; and data from previous sections of this report were used for various aspects of the model calibration.

General Description of the Model

The area simulated by the model focuses on ground-water flow in the aquifer system in the Bountiful area. The boundaries are based on the potentiometric surface as shown in figure 6 and on narrowing of the basin-fill area between the mountain front and Great Salt Lake, north of Centerville. The potentiometric contours are closely spaced at both the north and south boundaries indicating that most of the flow is directly from the mountains to the lake, and little, if any, flow crosses these boundaries.

The three-dimensional, finite-difference numerical model developed by McDonald and Harbaugh (1988) was used to simulate flow in the aquifer system in the Bountiful area. Most of the data used for the simulations were based on average conditions, or were estimated where there was a lack of measurements. Therefore, the simulations are a simplification of the natural system, and the results should be applied with discretion.

The finite-difference model uses a series of rectangular blocks in which hydraulic properties are assumed to be uniform. The model calculates the hydraulic head at the point or node that is at the center of each block. With the calculated head values, the rate and direction of ground-water flow through the system can be determined. Data used in the calculations include: boundary conditions, initial heads, hydraulic properties of the aquifers and confining units, and rates and distribution of recharge and discharge. The algorithm used as the matrix solver for the differential equations of ground-water flow in the model is SIP, or the strongly implicit procedure (McDonald and Harbaugh, 1988, p. 12-1).

Subdivision of the Aquifer System

The model consists of two layers, one representing the shallow water-table zone and the other representing the confined or unconfined intervals of the aquifer system in the Bountiful area. The layers have different lateral extents as shown in figure 10. Layer 1, which is used to simulate discharge to the shallow water-table zone from the underlying aquifer system, is simulated only where the potentiometric surface of the aquifer system is near or above land surface, roughly corresponding to the area of evapotranspiration in figure 10. Layer 1 is simulated only as it relates to the underlying layers, thus, there is no recharge to or discharge from layer 1 except the water that has moved upward from layer 2. Layer 2 represents the confined interval of the aquifer system deeper than 100 feet and the unconfined parts of the aquifer system near the mountain front. Layer 2 is simulated over the entire area of active cells shown in figure 10.

Model Grid

A block-centered grid with equal spacing was used to simulate the aquifer system in the Bountiful area. The block-centered grid was formulated by dividing the model area with two sets of parallel lines perpendicular to each other. In the block-centered formulation, the blocks formed by the sets of parallel lines are the cells and the nodes are at the center of the cells. A node represents a block of porous material within which the values of hydrologic properties are constant throughout the volume of the cell (McDonald and Harbaugh, 1988, p. 2-5).

EXPLANATION FOR FIGURE 10

EXPLANATION

GENERAL-HEAD BOUNDARY CELLS--Layer 1

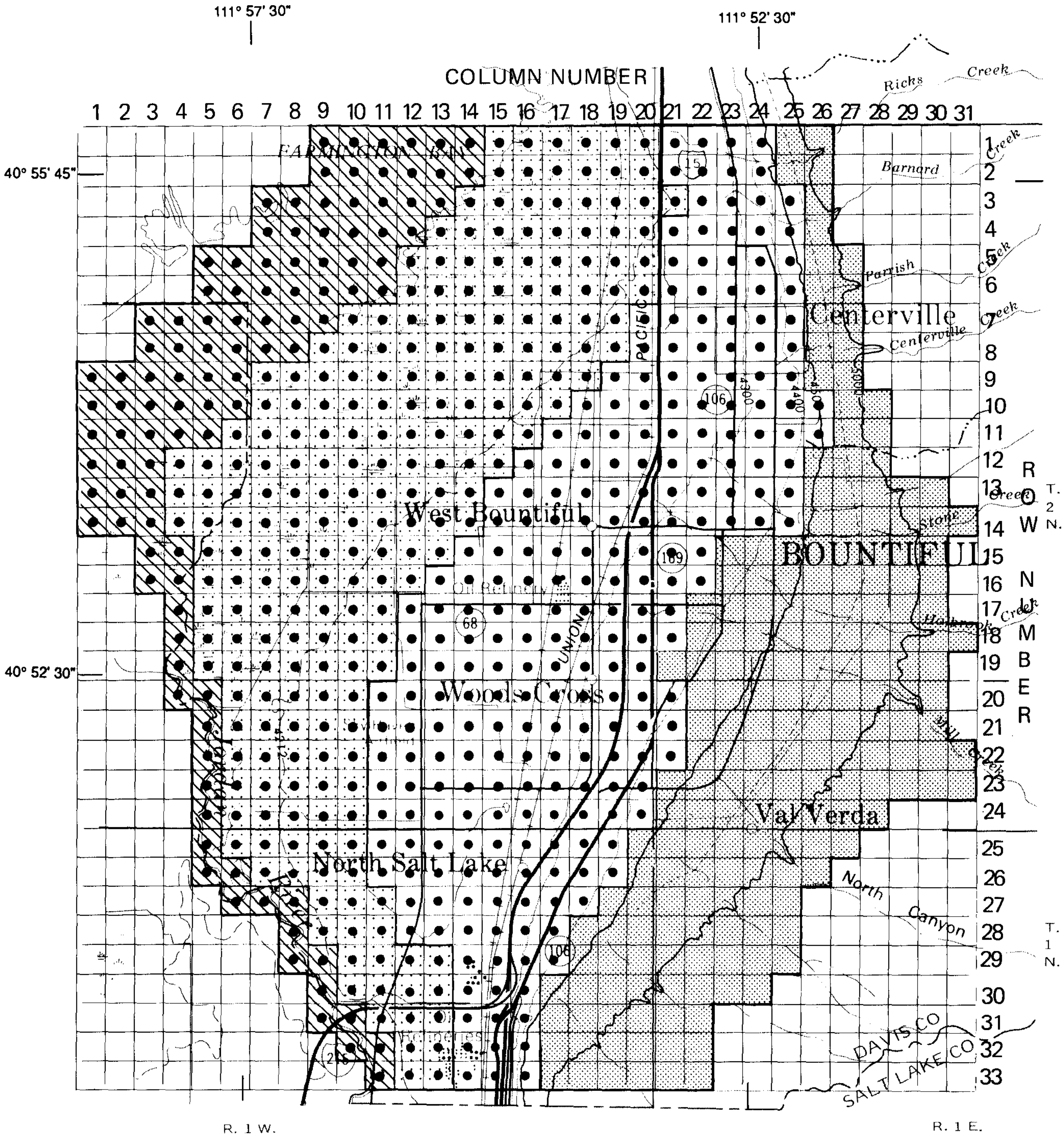
EVAPOTRANSPIRATION CELLS--Layer1

INACTIVE CELLS--Layer 1

INACTIVE CELLS--Layers 1 and 2

DOT INSIDE CELL INDICATES ACTIVE CELLS--Layers 1 and 2

BOUNDARY OF MODEL AREA



Base from U.S. Geological Survey 1:125,000 quadrangle, Great Salt Lake and vicinity, Utah, 1974

0 1 2 MILES
0 1 2 KILOMETERS

CONTOUR INTERVAL, IN FEET, VARIABLE
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Figure 10.--Location of active, inactive, evapotranspiration, and general-head boundary cells in the model of the aquifer system in the Bountiful area.

The grid consists of 31 columns and 33 rows. All cells are equally dimensioned at 0.25 mile per side with an area of 0.0625 square mile. A total of 2,046 cells were used in the model, of which 1,350 were active cells. Layer 1 has 580 active cells, and layer 2 has 770 active cells. The cells in the simulated area are shown in figure 10.

Boundary Conditions

The inactive cells illustrated in figure 10 are simulated with transmissivity values of zero, and therefore, are no-flow boundaries that surround the area of active cells. On the east, the model boundary was about one-half mile east of the contact between the unconsolidated basin-fill deposits and the consolidated rock. This boundary was chosen in order to simulate subsurface inflow from the consolidated rock. In the southwest, a no-flow boundary was placed on the western side of the Jordan River, and in the northwest a no-flow boundary was placed several miles west of the shoreline of Great Salt Lake. These boundaries were assumed to be the westernmost extent of ground-water flow from the study area. There may be some ground-water flow across this boundary toward the west; however, any flow is assumed to be negligible. A no-flow boundary under layer 2 was simulated on the assumption that there was no substantial vertical interchange of water between layer 2 and deeper strata, although minor quantities of that water may discharge along fault zones.

A general-head boundary was used to simulate inflow from the aquifer system in the Bountiful area into Great Salt Lake (fig. 10). General head-boundary cells were designated in layer 1 according to the area covered by water when the lake was at an altitude of 4,197 feet. Layer 1 in this area is assumed to represent the lake bottom, and specified heads were set at 4,197 feet for steady-state calibration. No-flow boundaries were placed at the northern and southern boundaries of the model area simulating a stream line across which there is assumed to be no flow.

During steady-state calibration, constant-head nodes were used in layer 2 (fig. 11) to simulate subsurface inflow from consolidated rocks along the Wasatch Front. Constant-head nodes were initially placed along the eastern boundary of the model area, generally near streams within the Wasatch Range. The initial head values for these nodes were estimated from water levels measured in wells completed in consolidated rock or near the boundary of the consolidated rock and basin fill. After steady-state calibration, flow rates from the constant-head nodes were used as constant-flux recharge rates during transient simulations, and the constant-head nodes were eliminated.

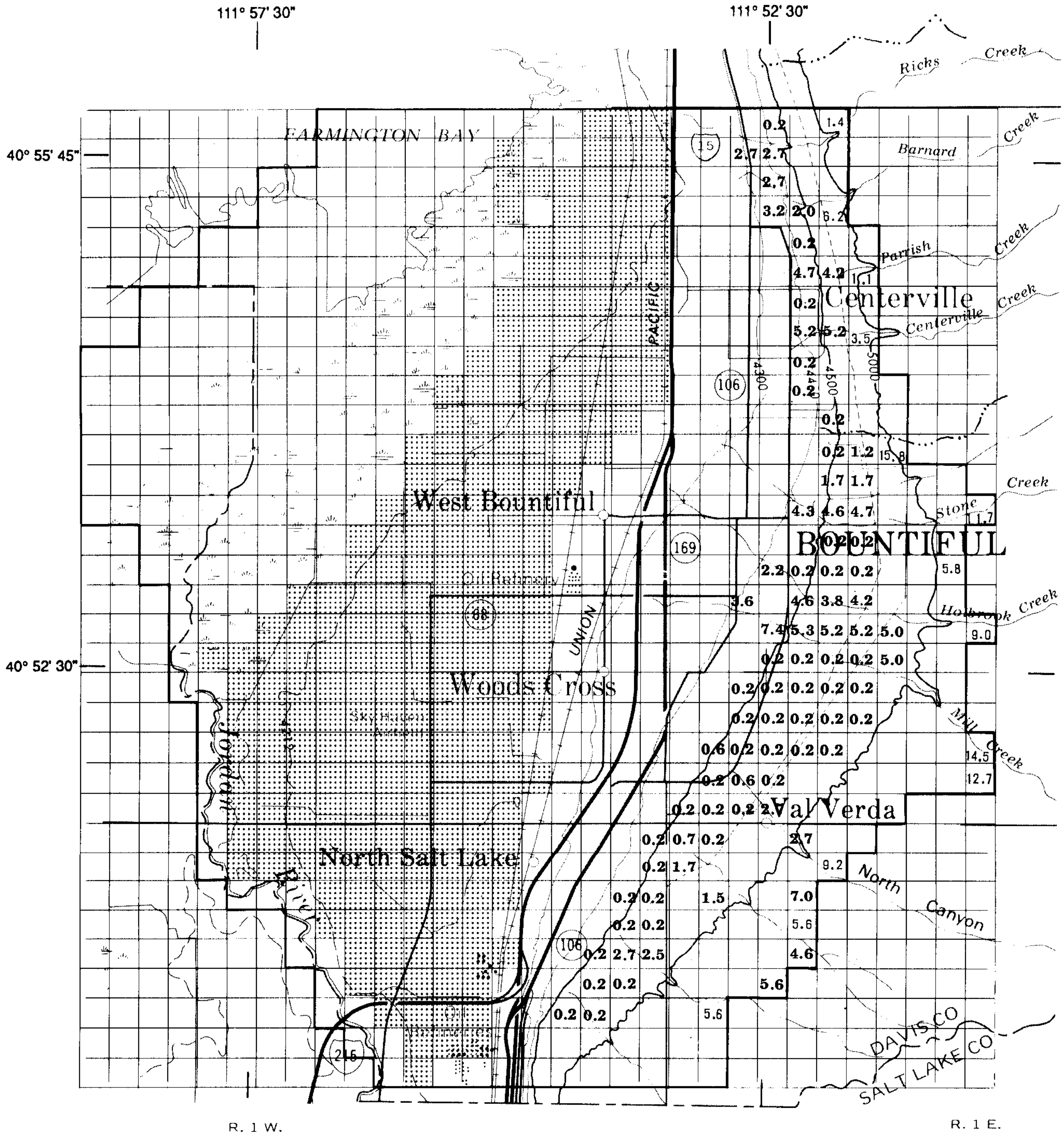
Model Parameters

Initial Conditions

Many of the initial data used for simulations of the aquifer system in the Bountiful area are from Thomas and Nelson (1948). In areas where data on historic water levels, recharge, discharge, or hydraulic properties were not available, data from this study were used to approximate initial conditions. Ground-water withdrawals prior to 1947, primarily from flowing wells, did not substantially affect water levels (fig. 7); thus, water levels measured in about 200 wells during 1946 were used as initial water levels in the areas where data were available.

EXPLANATION

0.2	CONSTANT FLUX NODE--Number indicates constant recharge in hundreds of acre-feet, layer 2
(dotted)	DRAIN CELL--Layer 1
1.4	CONSTANT-HEAD NODE--Number indicates constant recharge in hundreds of acre-feet, layer 2 for steady-state simulations
———	BOUNDARY OF MODEL AREA



Base from U.S. Geological Survey 1:125,000 quadrangle, Great Salt Lake and vicinity, Utah, 1974

0 — 1 — 2 MILES
0 — 1 — 2 KILOMETERS

CONTOUR INTERVAL, IN FEET, VARIABLE
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Figure 11.--Rate and location of constant-recharge values, and drain areas used for steady-state simulations in the model of the aquifer system in the Bountiful area.

Recharge

Recharge from seepage from streams, irrigated fields, and lawns and gardens, and from precipitation within the recharge area was simulated in the model using constant-flux nodes in layer 2 (fig. 11). Rates of recharge from sources other than subsurface inflow were based on values calculated or estimated in the ground-water recharge section of this report. The location of the constant-flux nodes required some minor adjustment during the calibration process.

Recharge by subsurface inflow from consolidated rock of the Wasatch Range to the basin-fill deposits of the aquifer system in the Bountiful area was simulated during steady-state calibration using constant-head nodes in layer 2 (fig. 11). Constant-head nodes were initially placed in most cells along the eastern boundary. However, when the calculated or estimated recharge rates primarily from seepage from streams and direct infiltration of precipitation were added to the model, the flow from many of these constant-head nodes became negligible, and the constant-head boundary at these nodes was eliminated. Following steady-state calibration, all constant-head nodes were replaced by specified flux nodes where inflow from consolidated rocks was not negligible. The constant-recharge values shown in figure 11 are the final values after steady-state calibration was complete.

Hydraulic Properties

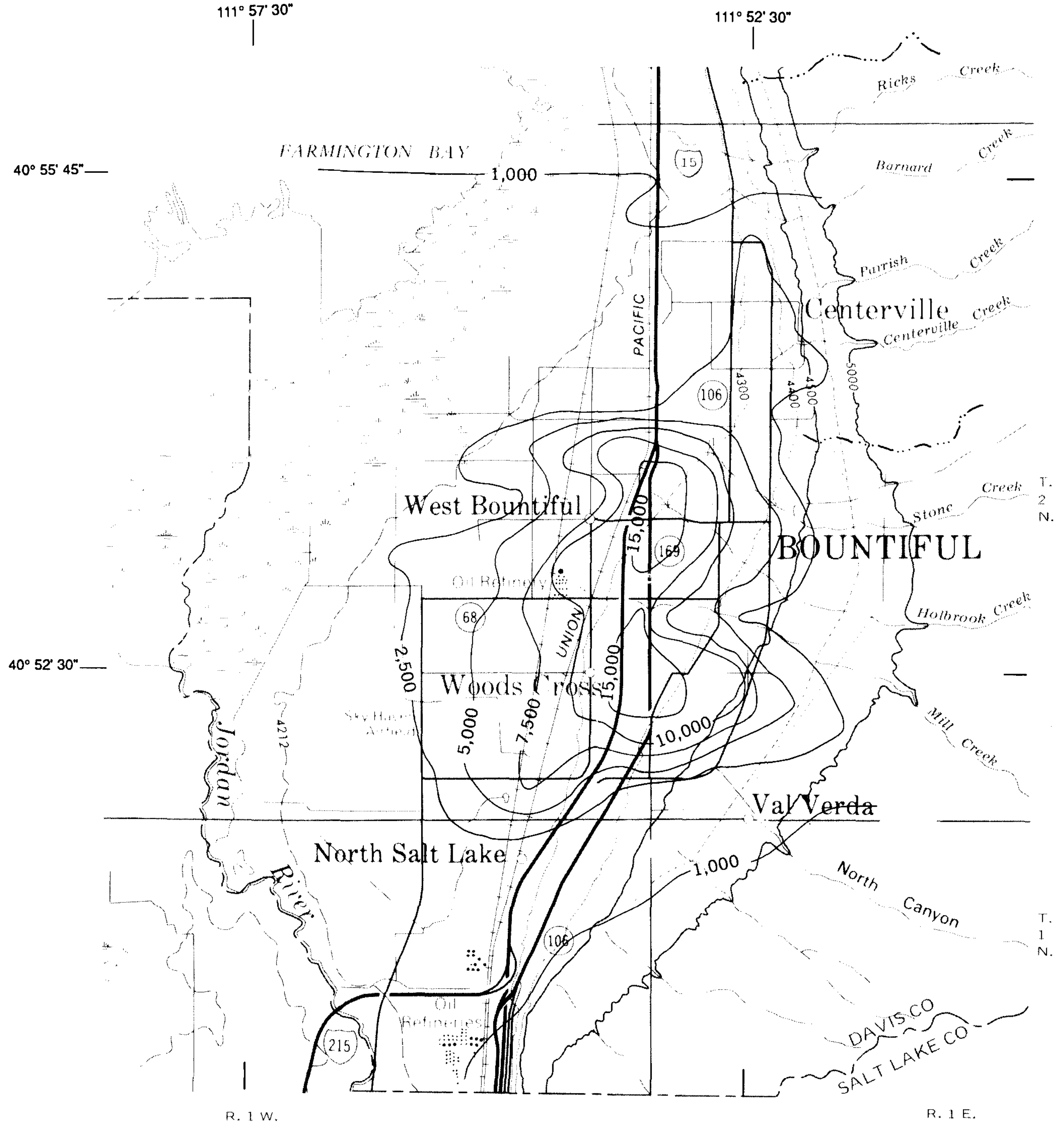
The transmissivity values of the aquifer system in the Bountiful area were estimated in part from data derived from aquifer tests (table 4); however, insufficient aquifer test data were available to adequately estimate transmissivity values over the study area. Transmissivity values were estimated from specific capacity values, average hydraulic conductivity, and aquifer system thickness.

Specific-capacity values were obtained from records of wells within the Bountiful area. These values and information about the well depth, diameter, and open intervals were used to estimate transmissivity values for the aquifer system in the Bountiful area (Theis and others, 1963).

Transmissivity values also were estimated by multiplying the thickness of sediments described in drillers' logs by the estimated hydraulic conductivity for those sediments. Values of hydraulic conductivity were from Clark (1984, p. 14), Mower (1978, p. 16), and from calculated values of transmissivity listed in table 6.

The information on hydraulic properties was used to prepare initial contour maps of transmissivity. These values were modified during the calibration process. Layer 1 was simulated with transmissivity values based on lithologies from drillers' logs of wells and an assumed thickness for layer 1 of 100 feet or less. Transmissivity values ranged from 250 feet squared per day in the valley lowlands to about 1,000 feet squared per day at the eastern boundary of layer 1.

Transmissivity values for layer 2 in the final calibrated model (fig. 12) range from less than 1,000 feet squared per day in the southern and northern parts of the Bountiful area to greater than 15,000 feet squared per day in the



Base from U.S. Geological Survey 1:125,000 quadrangle, Great Salt Lake and vicinity, Utah, 1974

EXPLANATION

——1,000—— LINE OF EQUAL TRANSMISSIVITY, IN FEET SQUARED PER DAY--Contour interval variable

0 1 2 MILES
0 1 2 KILOMETERS
CONTOUR INTERVAL, IN FEET, VARIABLE
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Figure 12.--Transmissivity of layer 2.

east-central part of the area. Values of transmissivity are largest where the basin-fill sediments are thick and relatively more permeable, primarily in the area where the sediments from Mill, Holbrook, and Stone Creeks coalesce near the city of Bountiful.

Vertical conductance between the model layers was initially estimated from equations in the model documentation (McDonald and Harbaugh, 1988, p. 5-11 to 5-18), and from calculations and estimates based on aquifer tests during this study and from nearby areas. An initial average vertical hydraulic conductivity of about 1×10^{-3} foot per day was determined from these methods. The initial value was then altered during steady-state calibration to approximately reflect the areal pattern of vertical head gradients as determined using data from Thomas and Nelson (1948, p. 166, pl. 2). Conductance values were larger in the recharge areas near the mountain front, in order to reflect the absence of confining layers in the area. The final distribution of vertical hydraulic conductivity values ranged from about 3×10^{-5} foot per day to about 3×10^{-3} foot per day.

Storage-coefficient and specific-yield values were required for the transient-state calibration. Initial values were from aquifer tests conducted in the East Shore area (Clark and others, 1990, table 5) where storage coefficient values averaged about 9×10^{-5} and specific yield values were estimated to be 0.1. These values were modified during calibration. The final values of storage coefficient ranged from 7×10^{-4} to 2×10^{-3} and the final values for specific yield ranged from 0.05 to 0.20.

Discharge

Discharge to drains, ditches, and streams was simulated in the model with the use of the 'Drain' subroutine (McDonald and Harbaugh, 1988, p. 9-1), which requires information about the altitude of the water in the drain and a conductance term for the interface between the aquifer and the drain. The altitudes used for the water in the drains were based on the altitudes of land-surface and water levels, where available, in the same area. Drain cells were used in model layer 1 and are shown in figure 11. In this application, the conductance is defined as the product of the hydraulic conductivity and the area of the drain channel, divided by the thickness of the material separating the drain from the aquifer.

Initially, a constant value for conductance was used for all drain cells; the conductance values were varied during calibration but were within a range of reasonable values to reproduce observed water levels (heads). In areas of relatively large discharge to drains, the conductance values generally were made larger. Final values of conductance ranged from 0.01 to 0.85 foot squared per second.

Simulation of discharge to drains was based on measured water levels rather than measured drain discharge, in order that values of measured and simulated total drain discharge might be compared. At the end of the steady-state calibration, the quantity of discharge to drains, as simulated by the model, was nearly equal to the discharge measured in the same area and totaled about 11,000 acre-feet per year.

Initial values for discharge from wells were derived primarily from Thomas and Nelson (1948) with the location of flowing wells from Smith and Gates (1963, plate 2). Discharge from flowing wells was based on the number of wells in a particular cell and the estimated discharge from wells in that area. Discharge from pumped wells was based on available records. The initial value for discharge from wells was about 10,000 acre-feet per year.

Part of the upward leakage from layer 2 to layer 1 discharges by evapotranspiration. Evapotranspiration from layer 1 was simulated in the model by a head-dependent option, which assumes a linear change between a maximum evapotranspiration rate, when the water level is at or above land surface, and no evapotranspiration when the water level is at or below a specified extinction depth (McDonald and Harbaugh, 1988, p. 10-1). An extinction depth of 5 feet and an evapotranspiration rate of 0.4 feet per year were used. Only a small part of the total evapotranspiration in the study area originates from the aquifer system in the Bountiful area, and at the end of steady-state calibration, this quantity was calculated by the model to be about 2,000 acre-feet per year. The cells where evapotranspiration was simulated are shown in figure 10.

Subsurface inflow to Great Salt Lake by diffuse seepage was simulated in the model with a general-head boundary (fig. 10), by assuming that discharge primarily was by upward leakage from the underlying aquifer system in the Bountiful area. It was assumed that all ground-water flow beyond the shoreline eventually discharged into the lake as diffuse seepage through the lake-bottom sediments and possibly by spring discharge under the lake. The general head-boundary was used so discharge to the entire area inundated by the lake could be simulated, and the specified heads (representing lake stage) could be changed, if necessary, as part of the transient-calibration process. The conductance values between the external specified heads (lake altitude) and the model cells were approximated based on a vertical conductance term of 5.5 feet squared per second used in simulations of areas east of the lake.

Model Calibration

The model was first calibrated to steady-state conditions which were assumed to exist in 1946. The final water levels from steady-state calibration were then used as initial heads for the transient-state calibration. Values for withdrawals from and recharge to the aquifer system in the Bountiful area were varied for the transient-calibration period from 1947 to 1985.

Steady-State Calibration

Calibration of the model to steady-state conditions involved the comparison of measured water levels for layer 2 with computer-generated water levels. The water levels generally were from 1946 when Thomas and Nelson (1948) measured water levels in about 200 wells in the Bountiful area. The mid- to late 1940's was a period of relative stability in precipitation, water levels, and well discharge, and therefore, only small changes in storage were assumed to have occurred in 1946 and preceding years (fig. 7). For the purpose of simulations, steady-state conditions were assumed to exist in 1946.

During the calibration to steady-state conditions, some values of the system characteristics were adjusted. Values most commonly adjusted were vertical conductance, drain conductance, and the starting heads for constant-head nodes. Some constant-head nodes near the eastern boundary were eliminated during calibration as flow from the nodes became negligible. Transmissivity values were changed only slightly, as they were considered to be some of the most reliable data.

As part of the calibration process, computed water levels at specified nodes were compared with water levels measured in 1946. Comparisons were made at 139 nodes in layer 2. The location of the cells associated with these nodes are shown in figure 13. The calibration cells are representative of the distribution of wells across the area. A particular node or area was considered calibrated if the model-computed water level was within a predetermined range of the measured water level. The criteria for this range were determined from the location of the measured water level in the model cell and the contoured gradient across the cell. Near the mountains, where the gradient is steep, the range was large, as much as 50 feet or even greater in a few places. Near Great Salt Lake, a computed water level needed to be within 10 feet of the measured water level to be considered calibrated.

The criteria set for calibration was not met at the end of the steady-state calibration at 13 of the 139 nodes (fig. 13). About one half of the 13 nodes are in the primary or secondary recharge areas where the gradient of the potentiometric surface is steep. The remaining uncalibrated nodes are scattered throughout the simulation area.

At the conclusion of the steady-state calibration, the flow rates for the constant-head nodes along the mountain front, as calculated by the model, were entered as recharge rates at specified-flux nodes, and the constant-head nodes were eliminated. These rates, which approximate subsurface inflow from consolidated rocks, total about 13,000 acre-feet per year. The constant recharge rates for all sources at the end of steady-state calibration are shown in figure 11. The total recharge to these nodes is about 25,000 acre-feet per year.

Constant-flux recharge values for sources other than subsurface inflow were initially placed in model cells near actual locations. During calibration procedures, it was necessary to reassign some of the rates to adjacent or nearby nodes in order to more accurately simulate measured water levels. After steady-state calibration, some of the recharge rates from seepage from stream channels were assigned to nodes farther downstream in the model grid than initially located. In some cases, the final assignment of recharge rates placed values for stream channel seepage in nodes downstream from the location of the cross section used to calculate subsurface inflow and within the secondary recharge area rather than the primary recharge area. Despite these reassignments, the total recharge simulated by the model remained similar to the total recharge calculated or estimated in this report.

Comparisons of water-level contours drawn by Thomas and Nelson (1948, fig. 17) and contours drawn using computed water levels for layer 2 at the end of steady-state calibration are shown in figure 14. The contour patterns match fairly well in areas where there is sufficient historical data.

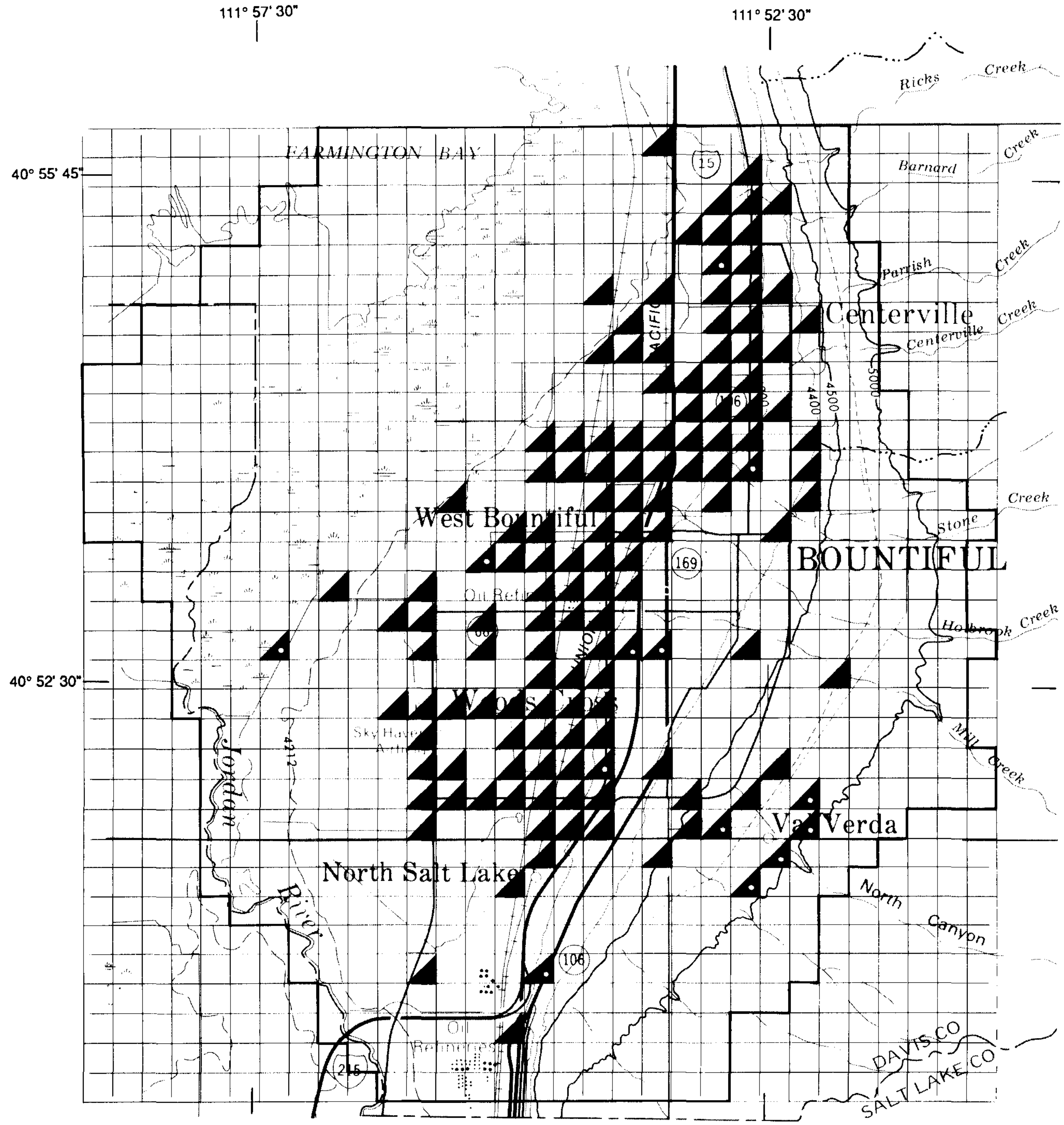
EXPLANATION

CELLS USED IN CALIBRATION

CALIBRATION CELL--Layer 2. Fit calibration criteria

UNCALIBRATED CELL--Layer 2. Did not meet calibration criteria

BOUNDARY OF MODEL AREA



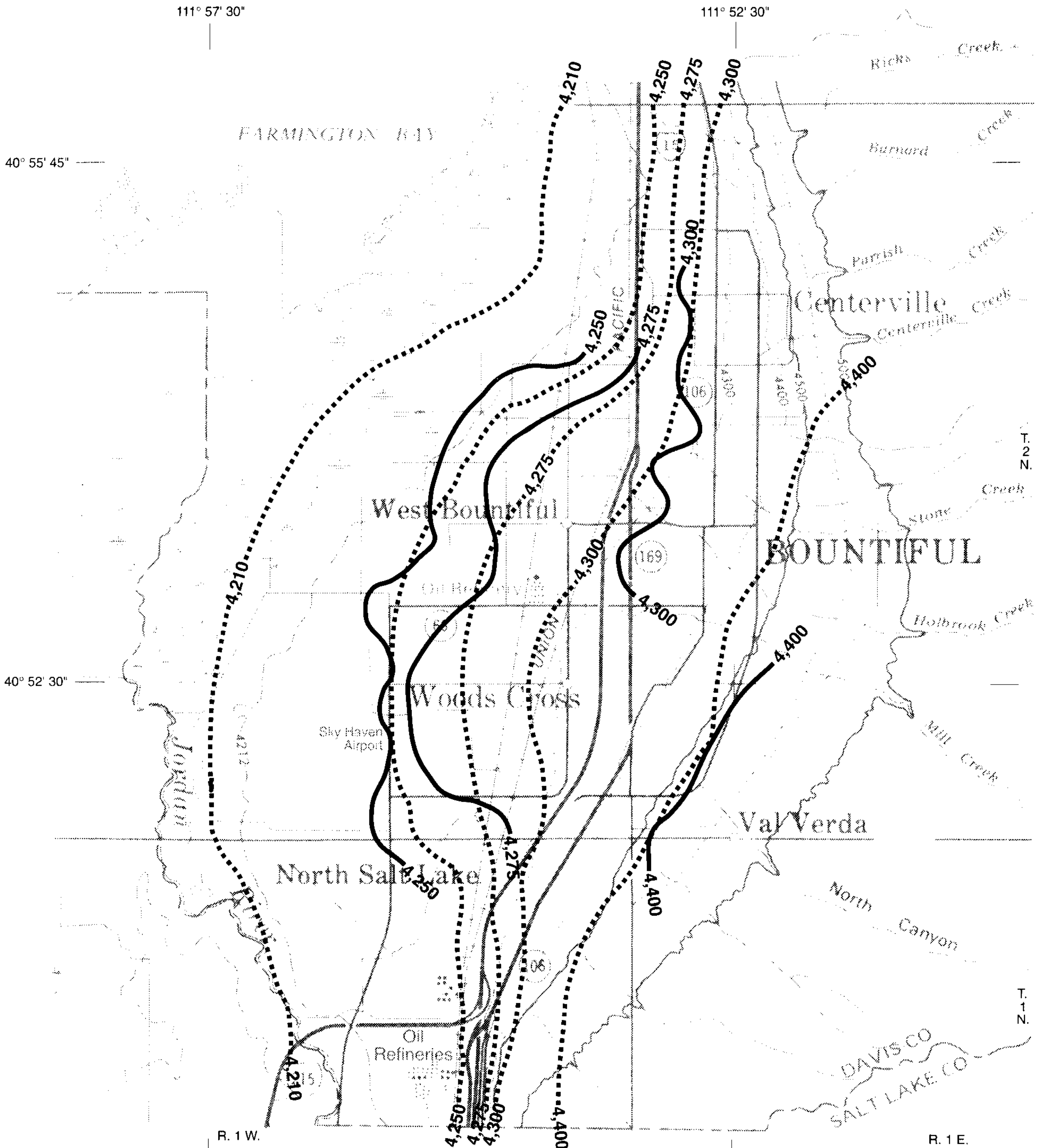
Base from U.S. Geological Survey 1:125,000 quadrangle, Great Salt Lake and vicinity, Utah, 1974

0 1 2 MILES

0 1 2 KILOMETERS

CONTOUR INTERVAL, IN FEET, VARIABLE
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Figure 13.--Location of cells used in the calibration of the model of the aquifer system in the Bountiful area.



Base from U.S. Geological Survey 1:125,000 quadrangle, Great Salt Lake and vicinity, Utah, 1974

EXPLANATION

POTENTIOMETRIC CONTOUR--Shows approximate altitude, in feet. Contour interval variable. National Geodetic Vertical Datum of 1929

— 4,300 — Contour from measured data, 1946. Contour data from Thomas and Nelson (1948, figure 17)

···· 4,300 ···· Computer-simulated contour

Figure 14.--Potentiometric contours based on measured water levels for 1946 and contours of simulated water levels, model layer 2.

Cross sections in figure 15 compare the potentiometric surface of the aquifer system in the Bountiful area based on measured water levels in 1946 and the computed water levels for layer 2. An offset of 1 year between model-simulation periods and water-level-measurement periods occurs because March water levels of a given year are used to represent water-level conditions on December 31 of the previous year. The cross sections match fairly well in most areas, with differences occurring primarily where water-level gradients are relatively steep.

Differences in the shape of water-level contours and cross sections generated from the computed and measured data are a result of simplification and errors in modeling. In general, however, the contours and cross sections are similar, indicating that the computed values are a reasonable, non-unique approximation of steady-state conditions.

Part of the steady-state calibration was the ongoing procedure of testing the sensitivity of the calibrated model. Values in some of the hydraulic-property arrays were varied within a range of values constrained by the range of known values. Transmissivity values representing the aquifer system in the Bountiful area were assumed to be fairly accurate in most areas, especially for layer 2; therefore, changes that could be made in the transmissivity values and still be within a realistic range of measured or estimated transmissivity values were relatively small. A 25-percent increase or decrease in the transmissivity value in an area resulted in relatively small changes in water levels, except in areas with steep head gradients.

The values of vertical hydraulic conductivity were not well defined, and the range of realistic values spanned at least two orders of magnitude. Changes in the vertical hydraulic conductivity within this range resulted in some large water-level changes from the calibrated results. The final distribution of vertical hydraulic conductivity ranged from about 3×10^{-3} foot per day near the mountain front to about 3×10^{-5} foot per day in some areas representing the valley lowlands.

Changes in the conductance values used in the "General-Head Boundary" subroutine (McDonald and Harbaugh, 1988) did not substantially affect either water levels or discharge from cells unless the calibrated conductance term was changed by at least one order of magnitude. In areas of large ground-water discharge to drains, however, only minor changes in drain conductance values resulted in substantial changes in the drain discharge, water levels, or both.

Transient-State Calibration

Calibration to transient-state conditions consisted of establishing data bases for the years 1947 to 1986. Data included (1) 1947-85 withdrawals from municipal, industrial, flowing, and small-discharge pumped wells and (2) 1947-86 water-level data. Transient-state calibration was initiated by simulating withdrawals from wells for 1947-85 and comparing the resultant computed water levels with water levels measured during 1947-86. Water-level changes were computed at the end of each of the 39 1-year pumping periods during the 39-year transient calibration.

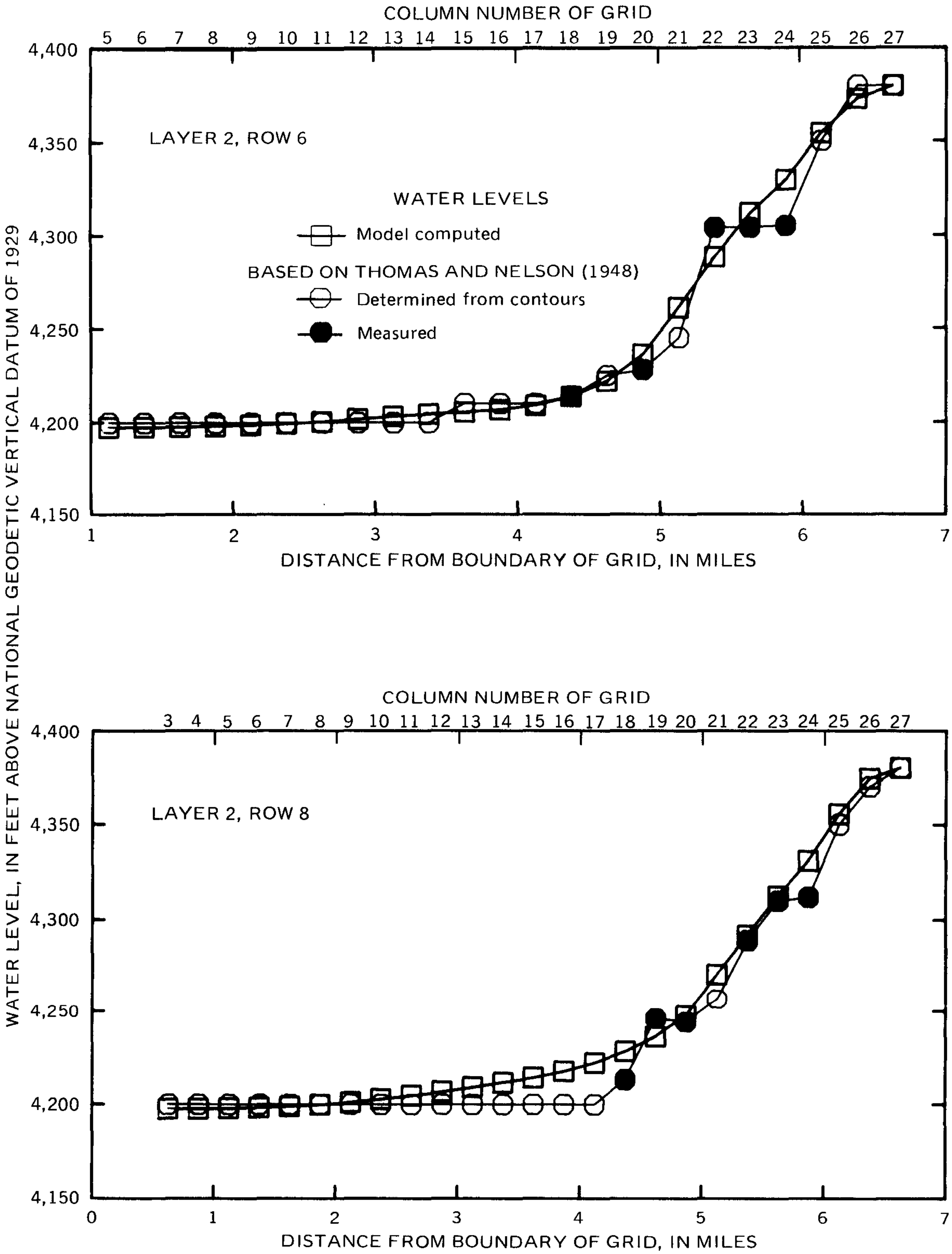


Figure 15.--Cross sections along selected columns of the model grid, showing computed and measured water levels with water levels determined from contours and measurements by Thomas and Nelson (1948).

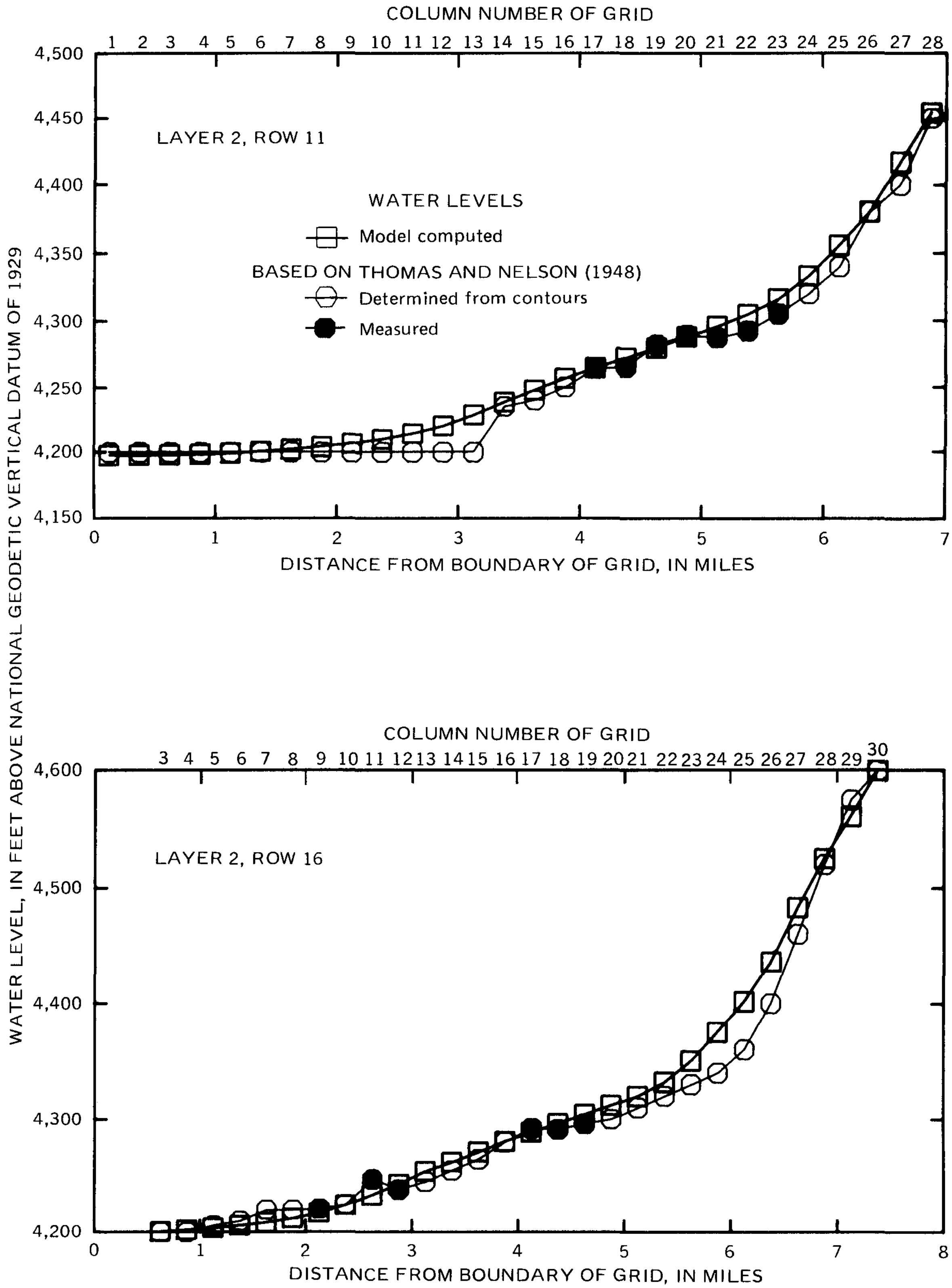


Figure 15.--Cross sections along selected columns of the model grid, showing computed and measured water levels with water levels determined from contours and measurements by Thomas and Nelson (1948)--Continued.

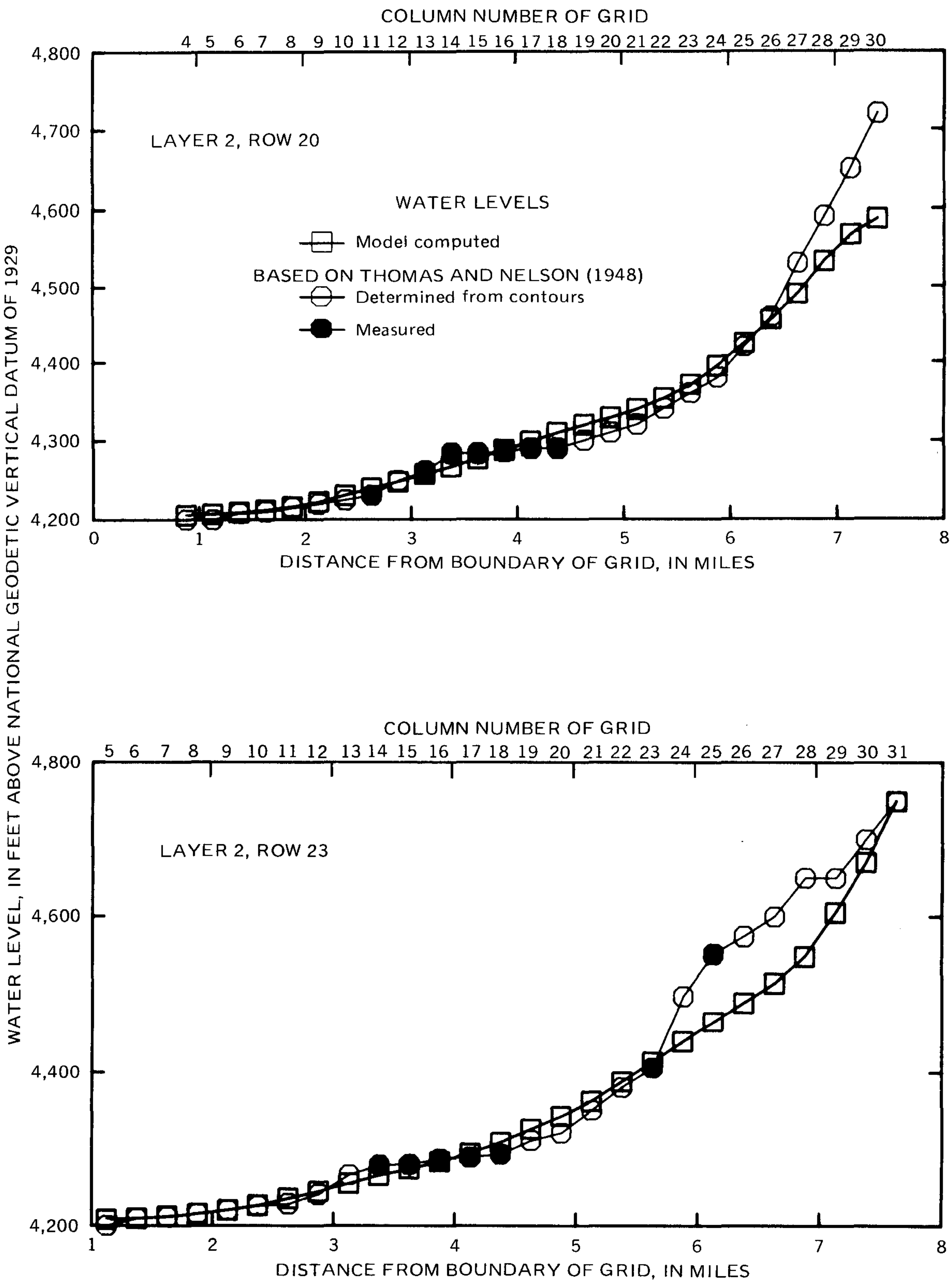


Figure 15.--Cross sections along selected columns of the model grid, showing computed and measured water levels with water levels determined from contours and measurements by Thomas and Nelson (1948)--Continued.

Records of withdrawals for municipal and industrial use are fairly complete from 1955-85; however, there is little information on pumpage prior to 1955. Most withdrawal records are given as a total for a user; therefore, it was necessary to assume that total pumpage was divided equally among all wells owned by the user, unless information was available for individual wells. In the case of wells drilled during a year in which pumpage was estimated, it was assumed that the well went into production the following year.

Annual discharge from municipal and industrial wells ranged from about 4,900 acre-feet in 1960 to about 12,000 acre-feet in 1985, and averaged about 7,800 acre-feet during 1955-85. Discharge from flowing wells and small-discharge pumped wells was estimated as described earlier in this report. Total annual withdrawal from wells during 1955-85 averaged about 15,000 acre-feet and ranged from about 12,000 acre-feet in 1960 to about 19,000 acre-feet in 1985.

The cells where discharge by municipal and industrial, flowing, and small-discharge pumped wells was simulated during transient-state calibration are shown in figure 16. All wells were simulated in at least one pumping period, but not necessarily in all pumping periods. The flowing-well area is essentially the same as that simulated during steady-state calibration with the addition of a few cells where wells were drilled after 1946.

As part of the calibration, total recharge to the aquifer system in the Bountiful area was assumed to vary from periods of less-than-average precipitation to periods of greater-than-average precipitation. In addition, water imported from the Weber River affected the total recharge to the system. During the late 1950's and early 1960's, precipitation was much less-than-average (fig. 7), and water levels declined because of a decrease in recharge and an increase in withdrawals. A decrease in withdrawals and the beginning of the importation of Weber River water in the early 1960's caused water levels to rise. Water levels in wells fluctuated from 1965 to 1985 in response to increased withdrawals, changes in recharge, or both. When a constant recharge rate was used during transient calibration, it resulted in water-level changes that compared poorly with measured changes of water-level declines in the area. As a result, it was necessary to simulate yearly changes in the total quantity of recharge for the 39 stress periods.

The changes in yearly recharge rates initially were derived by methods used for the computer model of the adjoining Weber Delta aquifer system (Clark and others, 1990, p. 119). The methods were based on the assumption that when annual flow in the Weber River was less than average, ground-water recharge was also less than average. The changes in the recharge rates were then adjusted for the aquifer system in the Bountiful area on the basis of the average annual flow in Centerville Creek during 1950-80 and on the substantial quantity of recharge related to surface water imported from the Weber River. The simulated total annual recharge rates varied from 20,600 acre-feet in 1954, before the importation of surface water, to 32,000 acre-feet in 1983, a year with much greater-than-average precipitation.

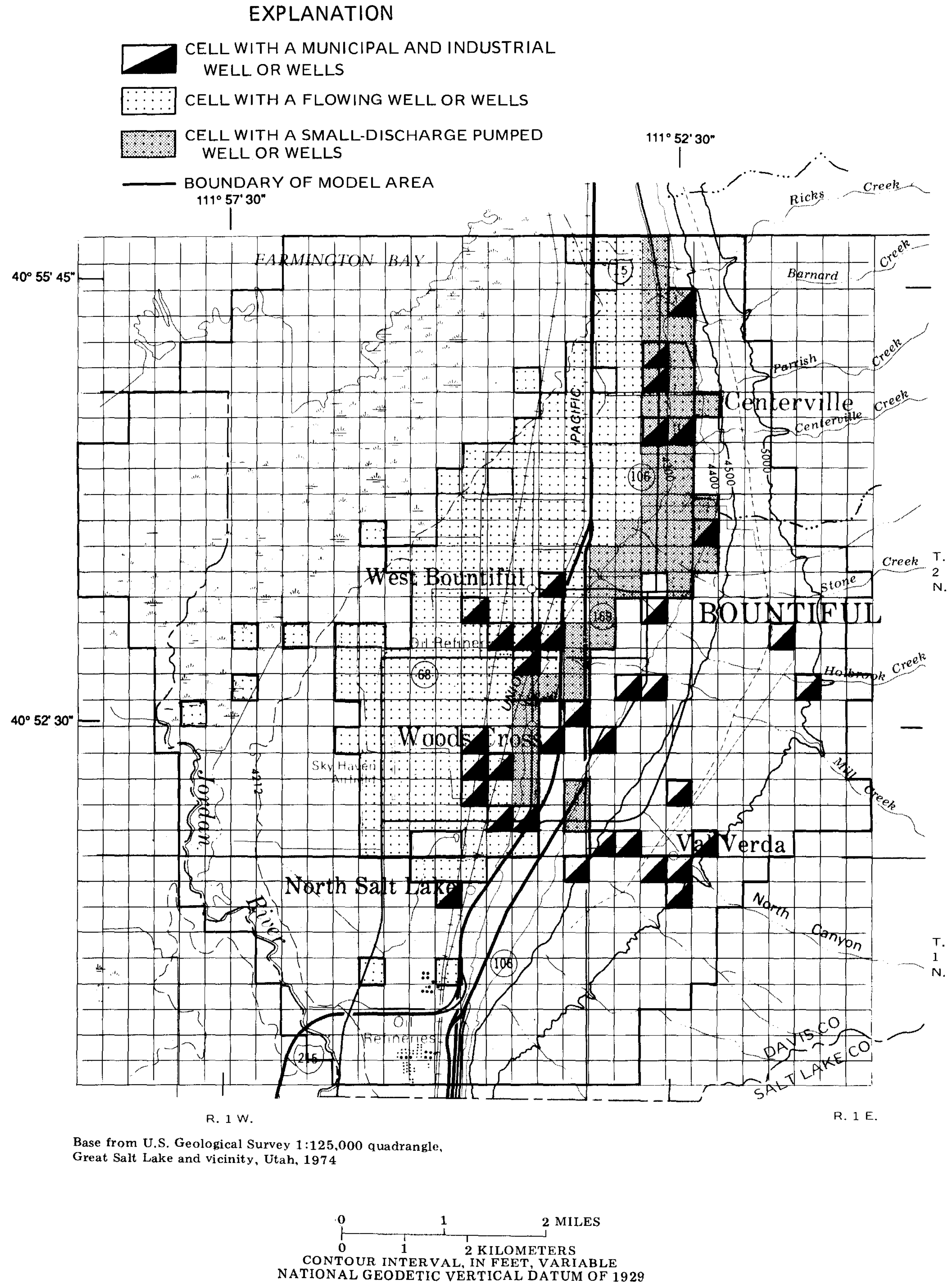


Figure 16.--Location of cells containing municipal and industrial, flowing, and small-discharge pumped wells.

During transient-state calibration, changes to the storage coefficient array had little effect on the model results. A constant value of 7×10^{-4} was used for the confined parts of the aquifer system simulated by layer 2. A storage coefficient value of 2×10^{-3} was used for layer 1 where upward leakage from layer 2 was simulated in the valley lowland plain. Where parts of the aquifer system simulated by layer 2 are unconfined near the mountain front, specific-yield values of 0.05 to 0.2 were used, and in the easternmost cells representing layer 1, a value of 0.2 was used. About 28,000 acre-feet was simulated as being removed from ground-water storage between 1947 and the introduction of imported surface water in the early 1960's, which accompanied an increase in annual precipitation. From the early 1960's until the end of transient-state calibration in 1985, simulated ground-water storage increased about 19,000 acre-feet, for an overall simulated decrease in ground-water storage of about 9,000 acre-feet.

The ground-water budget resulting from the steady-state and transient-state calibrations, changes in total recharge, and the various types of discharge for 1947-85 are shown in table 7. Total recharge generally decreases, with some fluctuations, until 1962. After 1962, simulated recharge increases and remains greater than pre-1962 values. Discharge to drains and evapotranspiration generally decrease until 1963, and then fluctuate through 1985.

As part of the transient-state calibration process, measured and computed water-level changes for 7 observation wells were compared with data for all or some of the 39-year simulation period (figs. 17-19). Most of the hydrographs show that the model-computed water levels are close approximations to the measured levels, especially in the areas of water-level declines (fig. 8) resulting from increased withdrawals of ground water. Measured and computed water levels could not be matched in some wells near the recharge areas because actual water levels in these areas change rapidly with changes in recharge.

At the completion of transient-state calibration, the 1947-85 period was simulated again, using a change in the level of Great Salt Lake to test the effect of changing lake levels on ground-water levels and budget components. The actual level of the lake fluctuated about 1 to 1.5 feet annually during 1947-82 and then rose about 10 feet during 1982-85.

During the simulation, the water-level altitude in the general-head boundary cells that represented Great Salt Lake was raised from 4,200 feet in 1982 to 4,210 feet during 1985. This simulated change in the lake level resulted in water-level rises of 5 feet or less in layer 2 near the lake. Water-level changes were negligible in the rest of the study area. Simulated annual discharge to the lake in 1985 decreased slightly. Discharge by evapotranspiration deceased by 50 percent because the area of evapotranspiration decreased as a result of inundation by the rising lake. Discharge to drains increased by about 1,000 acre-feet, and there was a total increase in ground-water storage of about 10,000 acre-feet. The lake level receded to 4,193 feet in 1961, which probably resulted in a larger percentage of the total ground-water discharge moving by upward leakage into the lake.

Table 7.--*Simulated annual ground-water budget of the aquifer system in the Bountiful area, 1947-85, in acre-feet per year*

Change in storage: Minus (-), decrease in storage; plus (+), increase in storage

Year	Recharge	Discharge					Change in storage
		Wells		Drains	Evapotranspiration	Seepage to Great Salt Lake	
		Municipal and industrial	Flowing and small-discharge pumped				
1946	24,300	[1]10,100		11,000	2,100	1,000	[2]--
1947	24,400	10,100		11,300	2,000	1,100	- 100
1948	24,400	10,100		11,300	2,000	1,100	- 100
1949	24,400	10,100		11,300	2,000	1,100	- 100
1950	24,400	10,100		11,300	2,000	1,100	- 100
1951	24,300	10,100		11,300	2,000	1,100	- 200
1952	25,100	10,100		11,300	2,000	1,100	+ 200
1953	24,100	12,500		10,300	1,900	1,100	-1,700
1954	20,600	12,500		9,800	1,800	1,100	-4,600
1955	22,000	5,700	7,700	9,600	1,800	1,000	-3,800
1956	22,000	6,400	7,200	9,400	1,800	1,000	-3,800
1957	23,300	7,300	7,200	9,200	1,800	1,000	-3,200
1958	23,300	7,400	7,500	8,800	1,700	1,000	-3,100
1959	23,200	7,500	7,900	8,500	1,700	1,000	-3,400
1960	23,000	4,900	7,000	8,500	1,700	1,000	- 100
1961	21,600	5,500	8,400	8,300	1,700	1,000	-3,300
1962	24,000	5,600	8,000	8,300	1,700	1,000	- 600
1963	25,500	6,200	7,200	8,500	1,700	1,000	+ 900
1964	31,400	6,800	7,100	9,100	1,800	1,000	+5,600
1965	29,300	6,300	7,100	9,500	1,800	1,000	+3,600
1966	27,800	7,200	7,100	9,400	1,800	1,000	+1,300
1967	28,500	7,900	6,600	9,500	1,800	1,000	+1,700
1968	29,400	8,400	6,600	9,700	1,800	1,100	+1,800
1969	29,400	8,000	6,700	9,900	1,900	1,100	+1,800
1970	29,300	7,700	6,700	10,100	1,800	1,000	+2,000
1971	30,200	8,000	7,200	10,200	1,900	1,100	+1,800
1972	29,600	7,700	7,200	10,300	1,900	1,100	+1,400
1973	29,700	8,800	7,200	10,100	1,900	1,100	+ 600
1974	30,400	8,800	7,200	10,200	1,900	1,100	+1,200
1975	30,100	7,200	7,400	10,500	1,900	1,100	+2,000
1976	27,000	8,100	8,400	9,700	1,800	1,100	-2,100
1977	22,500	10,300	8,400	8,800	1,700	1,000	-7,700
1978	28,000	8,300	8,400	9,000	1,800	1,000	- 500
1979	27,800	8,700	8,800	8,800	1,700	1,000	-1,200
1980	28,400	9,600	8,400	8,700	1,700	1,700	-1,700
1981	30,200	8,000	7,900	9,400	1,800	1,000	+2,100
1982	30,700	7,400	7,900	10,000	1,900	1,100	+2,400
1983	32,000	9,500	6,500	10,000	1,900	1,100	+3,000
1984	31,200	10,400	6,100	9,900	1,800	1,100	+1,900
1985	28,000	11,600	7,100	9,400	1,800	1,000	-2,900

[1] Well discharge from 1946-54 was not separated by type of well.

[2] Conditions in 1946 represent steady state.

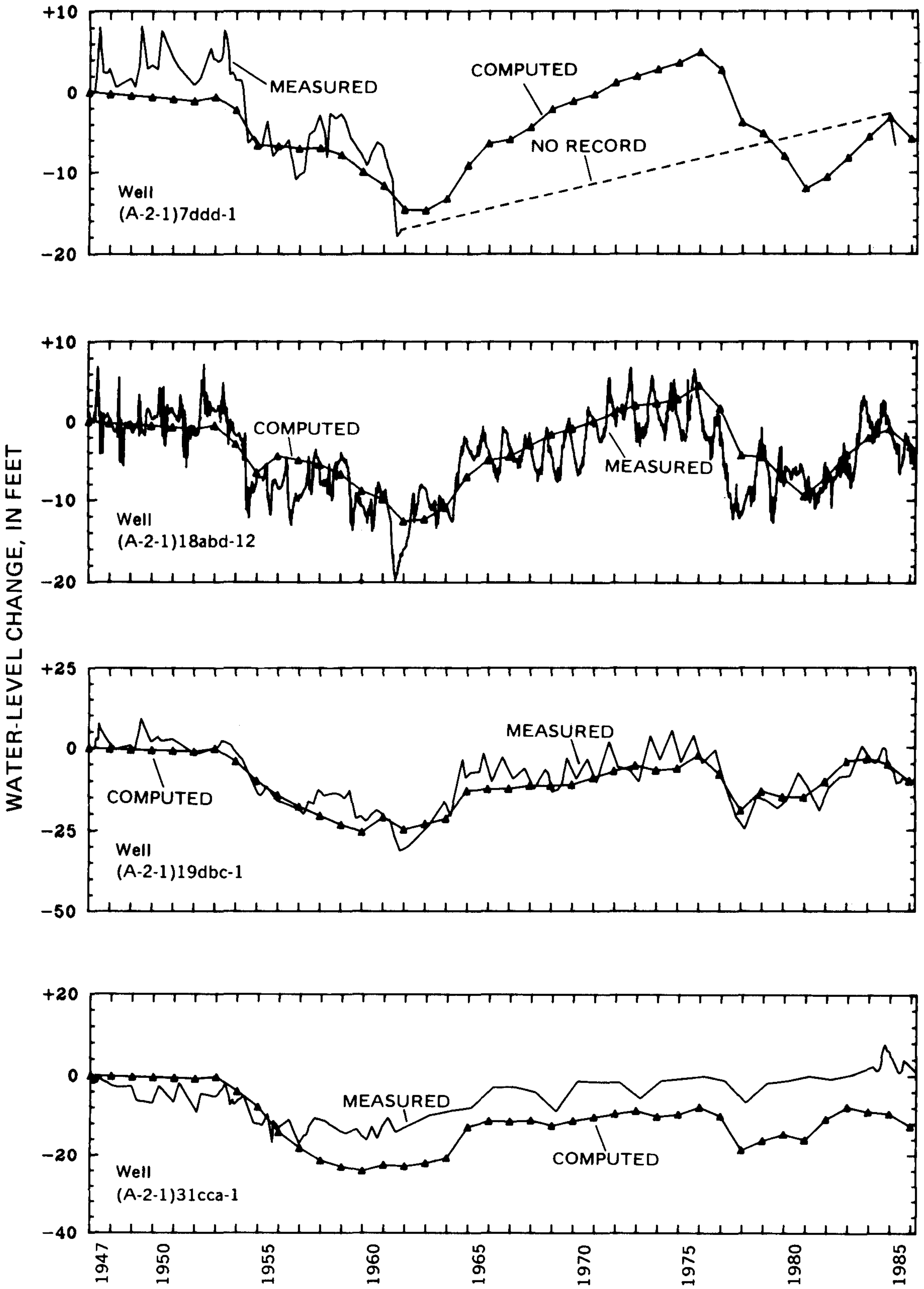


Figure 17.--Measured and computed water levels during 1947-86 for observation wells completed in layer 2.

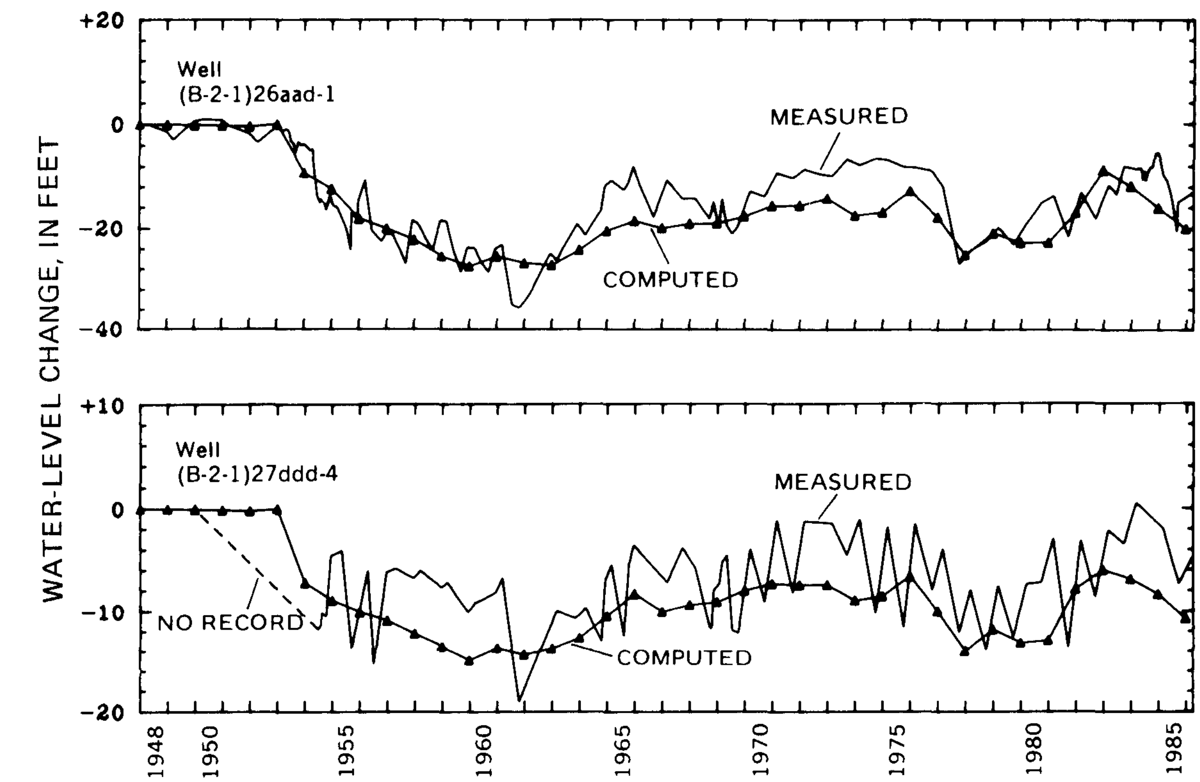


Figure 18.--Measured and computed water levels during 1948-86 for observation wells completed in layer 2.

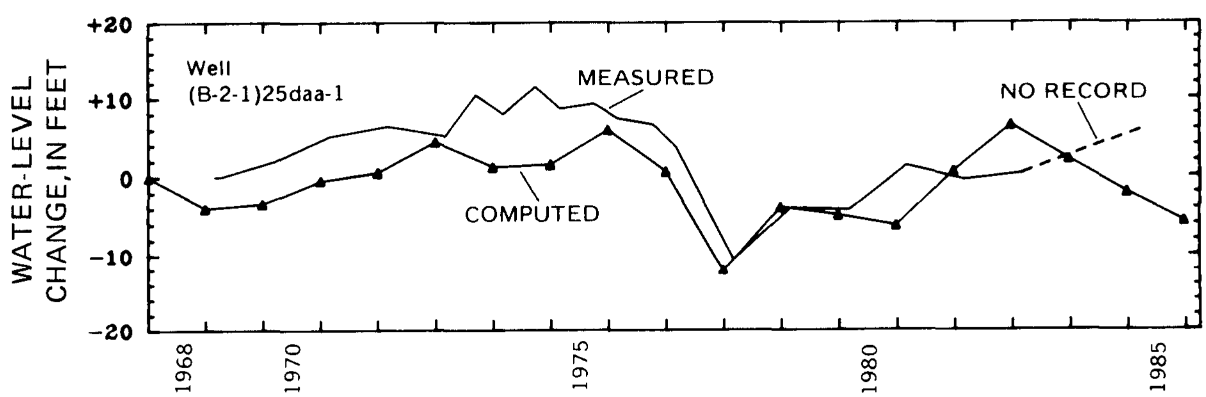


Figure 19.--Measured and computed water levels during 1968-86 for an observation well completed in layer 2.

The computed water levels and total budget were assumed to be reasonable non-unique approximations of the aquifer system in the Bountiful area at the end of the steady-state calibration. During the transient-state calibration, computed water-level changes approximated the measured changes in most of the observation wells. Therefore, the model was used with discretion to simulate changes that might occur with potential increases in pumpage or changes in recharge. Although actual altitudes of the ground-water levels might not be simulated accurately, the computed water-level changes derived from the final transient-state water levels are considered to be reasonable.

Sensitivity Analysis

A detailed sensitivity analysis was not done as part of the calibration process. Sensitivity analysis was an ongoing part of the simulation and was not conducted separately. A large quantity of data was available for the simulation of the Bountiful area, particularly water-level and discharge measurements; therefore, the range of estimates for most parameters was not large. For the hydraulic parameters for which ranges were large, primarily vertical hydraulic conductivity and storage coefficient, sensitivity analyses were conducted as part of the simulation process.

Storage coefficient values for layer 2 were varied considerably in the transient-state calibration process. The array for storage coefficient was decreased and increased by at least one order of magnitude from the calibrated array, and there was virtually no change in water levels or budget terms. The simulations probably were not sensitive to changes in storage coefficients because most of the modeled area was simulated as being under confined conditions, and water-level and storage changes were relatively small.

Simulated Effects of Increased Withdrawals

Simulations were made for a 20-year period beginning in 1986 to estimate water-level changes resulting from continued and increased ground-water withdrawals from wells. The simulations were made to estimate possible changes in water levels, water in storage, and distribution of discharge, using changes from transient-state rates for both ground-water recharge and discharge from wells.

Simulations of the effects of current withdrawals were made using the average annual rate of pumpage, about 9,400 acre-feet, from municipal and industrial wells for 1981-85, the last 5 years of the transient calibration. The first simulation used the average annual recharge rate for 1981-85, about 30,000 acre-feet. This rate includes recharge from imported surface water and is larger than the 39-year average of about 27,000 acre-feet. The result of the simulation showed an overall water-level increase of about 5 feet in layer 2 and an increase in ground-water storage of about 5,000 acre-feet.

Further simulations were conducted by increasing the pumpage from municipal and industrial wells over a period of 20 years. The actual pumpage from these wells had gradually increased by about 50 percent from the mid-1960's through the 1980's. Simulated discharge from these wells was gradually increased from 9,400 to 14,100 acre-feet per year, while discharge from other wells remained constant at 7,200 acre-feet, for a total well discharge of

21,300 acre-feet per year at the end of the simulation. Recharge was simulated at the 1981-85 average of 30,000 acre-feet per year.

The simulated changes depended on the location of the wells where withdrawal was changed and the location of the nodes where recharge was changed. As a result, well discharge was changed only in large discharge wells that were in operation in the 1980's, and recharge changes were simulated only in locations receiving recharge from perennial streams.

The simulation results indicated water-level declines of about 5 to 25 feet throughout layer 2 (fig. 20). Ground-water discharge from sources other than wells was simulated to decrease from about 13,000 to 10,000 acre-feet per year, with discharge to drains decreasing about 2,400 acre-feet per year. A simulated total of about 25,000 acre-feet of ground water was removed from storage during the 20 years.

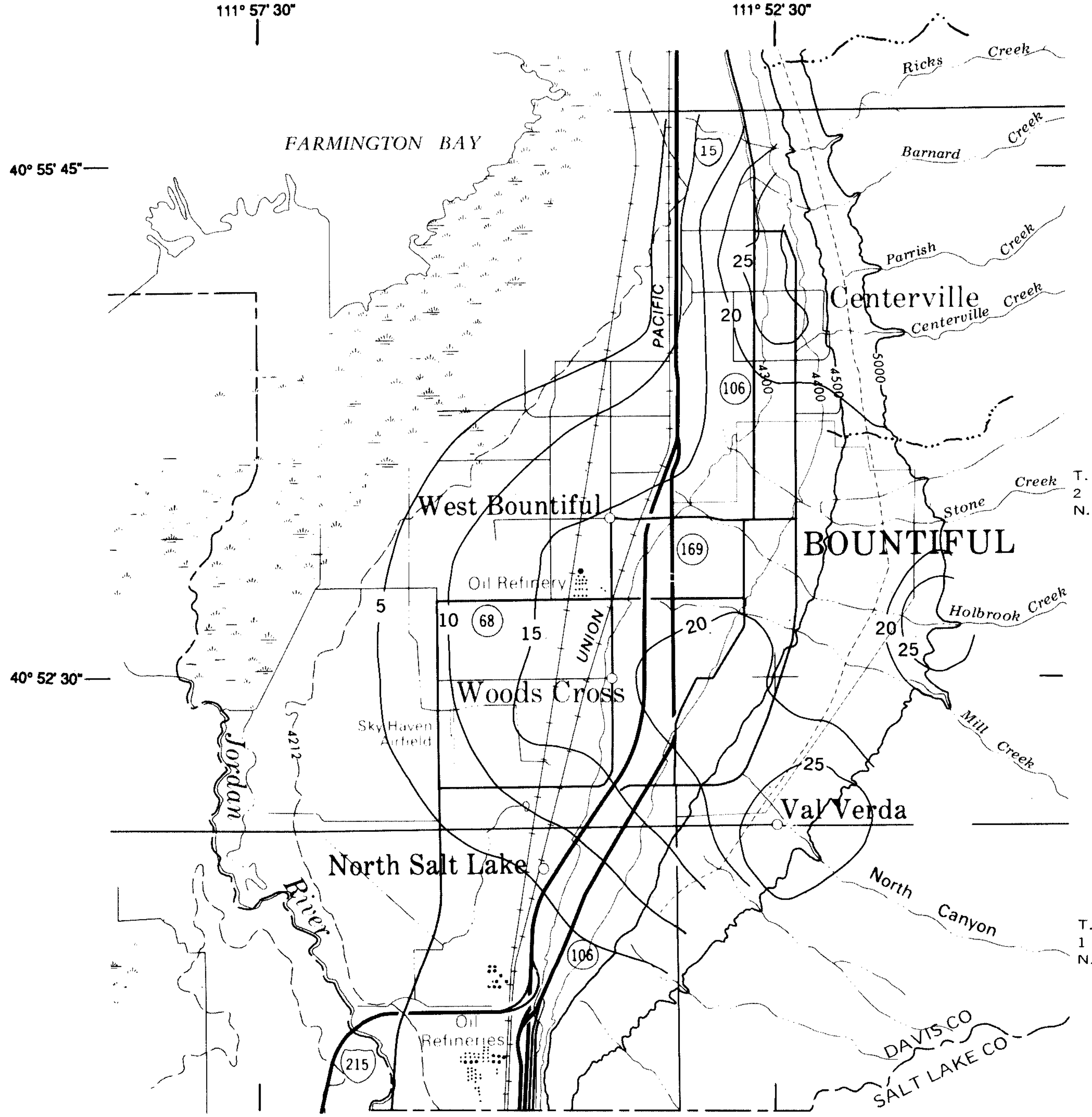
A 20-year simulation was made using the 50-percent increase in the 1981-85 pumpage rate (total well discharge of 21,300 acre-feet per year) and a recharge rate of 25,800 acre-feet per year. The lower recharge rate represents an average annual recharge rate during a period of less-than-average precipitation. This simulation represents a reasonable estimate of increased pumpage and a drier long-term weather pattern. Results of the simulation indicate (fig. 21) a 10- to 50-foot decline in water-levels across the simulated area. Flowing-well discharge was kept constant during the simulation, although it would undoubtedly decrease. A total of about 70,000 acre-feet was removed from storage during this simulation, and annual discharge to drains, evapotranspiration, and to Great Salt Lake decreased from about 13,000 acre-feet to about 7,000 acre-feet.

When the simulations were completed, water-level declines were indicated across the northern boundary of the model area, which was simulated as a no-flow boundary. The northern boundary of the model area was placed where the aquifer system narrowed between the mountain front and Great Salt Lake. In this area, the potentiometric surface has a steep gradient, and flow is directly from the mountain front to the lake indicating no flow crossing the boundary. Simulated declines across the northern boundary were probably greater than would have actually occurred because of the specified no-flow conditions; however, in the real system, if pumpage increased in the Bountiful area at the simulated rates, pumpage from wells north of the simulated northern boundary probably would increase at a similar or greater rate. As a result, the simulated declines across the northern boundary may approximate the actual conditions.

The results of the simulations indicate that continued increases in withdrawals for municipal and industrial use can cause declines in water levels, especially in areas of large withdrawals. These declines could be larger than simulated values if recharge decreased to less-than-average rates, as in 1955-64 when precipitation and streamflow were less than normal. Water-level declines of this magnitude could cause static water levels to decline below land surface in some areas, and the cessation of flow in some currently flowing wells. The declines also could cause a decrease in the rates of natural ground-water discharge to drains, by evapotranspiration, and to Great Salt Lake.

EXPLANATION

——10—— LINE OF EQUAL WATER-LEVEL DECLINE--
Contour interval 5 feet



Base from U.S. Geological Survey 1:125,000 quadrangle,
Great Salt Lake and vicinity, Utah, 1974

0 1 2 MILES
0 1 2 KILOMETERS

CONTOUR INTERVAL, IN FEET, VARIABLE
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Figure 20.--Simulated changes in water levels during 1986-2006 in model layer 2 using a recharge rate of 30,000 acre-feet per year.

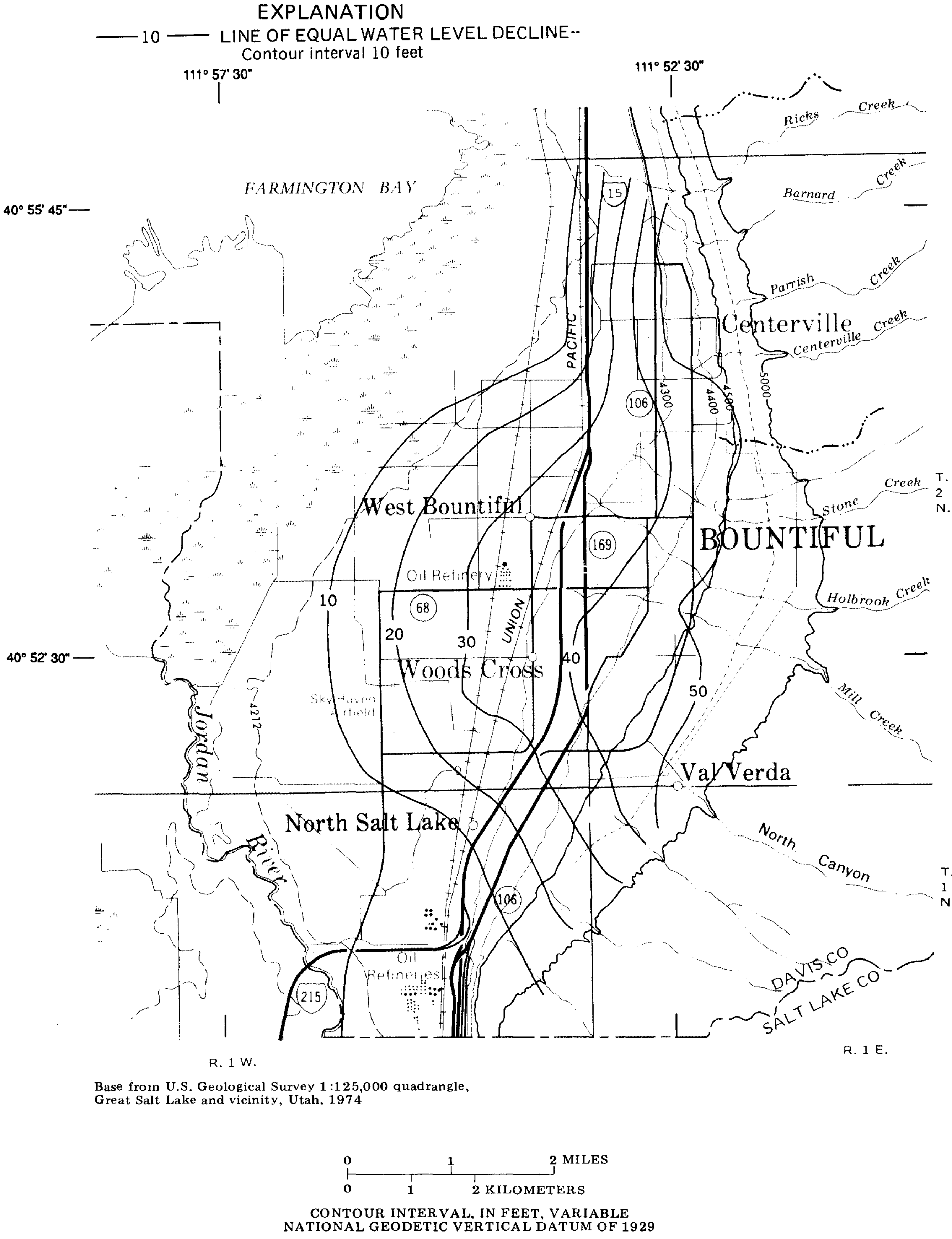


Figure 21.--Simulated changes in water levels for 1986-2006 in model layer 2 at an average annual recharge rate of 25,800 acre-feet and a 50-percent increase in the 1981-85 pumpage rate.

Results of simulations based on changes in withdrawals or recharge are probably valid over a large area; however, simulated water levels may not be accurate at a specific location because model construction requires generalizations in the values of hydraulic properties such as vertical hydraulic conductivity. Simulated water levels in recharge areas may not be accurate because changes in recharge from the transient-state calibration rates apparently have more effect than increases in withdrawals.

SUMMARY AND CONCLUSIONS

The Bountiful study area is north of Salt Lake City at the eastern edge of the Basin and Range physiographic province. Total annual surface-water inflow to the study area was estimated to average about 28,000 acre-feet during 1969-84. The aquifer system in the Bountiful area is in the basin-fill deposits of an elongate graben between the Wasatch Range and Great Salt Lake. The aquifer system is primarily a confined system with unconfined parts along the mountain front.

Annual ground-water recharge to the aquifer system in the Bountiful area averages about 26,000 acre-feet per year. The primary sources of recharge are seepage from streams, infiltration of excess irrigation water, infiltration of precipitation, and subsurface inflow from consolidated rock of the Wasatch Range to the basin-fill deposits.

Estimates of the hydraulic properties of the aquifers were made from aquifer tests, lithologic and specific-capacity data, and with the use of a computer model. Estimates of transmissivity using these methods range from about 200 feet squared per day where the sediments are predominantly fine-grained to 30,000 feet squared per day in thick, coarse-grained deposits.

Long-term water-level data from most observation wells indicate a decline in ground-water levels from 1952 to 1962. The importation of surface water for irrigation and consequent decrease in ground-water withdrawals resulted in a recovery in water levels beginning in 1962. Water levels fluctuated from 1962 to 1985, depending on changes in withdrawals and precipitation.

The average annual discharge from the aquifer system in the Bountiful area during 1947-85 was estimated to range from about 26,000 to 30,000 acre-feet, including discharge to wells, waterways, springs and seeps, evapotranspiration, and diffuse seepage to Great Salt Lake. The annual withdrawal of water from municipal and industrial wells averaged about 8,700 acre-feet during 1969-85 and ranged from about 7,000 acre-feet in 1975 to about 12,000 acre-feet in 1985. Withdrawals from these wells gradually increased to supply the 135 percent increase in population, which grew from 23,000 people in 1960 to 54,000 in 1980.

A three-dimensional, finite-difference model was used to simulate flow in the aquifer system in the Bountiful area. The model area extended from the Salt Lake County line northward to about one mile north of Centerville. The two-layer model was used to simulate effects of increased ground-water withdrawals. Layer 1 represented a shallow water-table zone and was largely used to simulate upward discharge from the aquifer system in the Bountiful area to the shallow water-table zone in the valley lowlands. Layer 2 represented the principal aquifer system in the Bountiful area, which was primarily simulated as a confined aquifer with some unconfined parts near the Wasatch front.

The model was calibrated to steady-state conditions using data for 1946, and to transient-state conditions using data for 1947-86. Values of various hydrologic properties and processes were evaluated as part of the calibration process, including transmissivity, ranges for vertical hydraulic-conductivity values, and determination of subsurface inflow from consolidated rock. Also, variations of total recharge with time, and changes in discharge to drains, evapotranspiration, and Great Salt Lake with changes in ground-water withdrawals and recharge were evaluated. Large rises in the level of Great Salt Lake in 1982-85 were simulated, with the results indicating only small rises in ground-water levels near the lake and decreased discharge by diffuse seepage to the lake.

A principal test of the simulations and the method of model calibration was to reproduce measured water-level fluctuations from 1947-86, and to simulate the effects of any future increased withdrawals from municipal and industrial wells. Simulations were based on a 50 percent increase in the 1981-85 withdrawals for municipal and industrial use over a 20-year period while using (1) the average 1981-85 recharge rate of 30,000 acre-feet per year and (2) an average recharge rate of 25,800 acre-feet per year. The results of the first simulation indicate water-level declines of 5 to 25 feet and decreases of ground water in storage of 25,000 acre-feet after 20 years. The second simulation results indicate water-level declines of 10 to 50 feet and decreases of ground water in storage of 70,000 acre-feet after 20 years. Increased ground-water withdrawals and water-level declines of this magnitude could cause some now-flowing wells to cease flowing and decrease the quantity of natural ground-water discharge to drains, by evapotranspiration, and to Great Salt Lake.

The simulations are based on a transient-state calibrated model. They are considered to be a reasonable representation of possible changes to the aquifer system in the Bountiful area given assumed increases in withdrawals and possible changes in recharge; however, the model results are general and non-unique, and should not be used to evaluate site-specific problems.

REFERENCES CITED

Bolke, E.L., and Waddell, K.M., 1972, Ground-water conditions in the East Shore area, Box Elder, Davis, and Weber Counties, Utah: Utah Department of Natural Resources Technical Publication No. 35, 52 p.

Clark, D.W., 1984, The ground-water system and simulated effects of ground-water withdrawals in northern Utah Valley, Utah: Water-Resources Investigations Report 85-4007, 56 p.

Clark, D.W., and Appel, C.L., 1985, Ground-water resources of northern Utah Valley, Utah: Utah Department of Natural Resources Technical Publication No. 80, 80 p.

Clark, D.W., Appel, C.L., Lambert, P.M., and Puryear, R.L., 1990, Ground-water resources and simulated effects of withdrawals in the East Shore area of Great Salt Lake, Utah: Utah Department of Natural Resources Technical Publication No. 93, 150 p.

Davis, Fitzhugh D., 1983, Geologic map of the central Wasatch Front, Utah: Utah Geologic and Mineral Survey Map 54-A.

Gilbert, G.K., 1890, Lake Bonneville: U.S. Geological Survey Monograph 1, 438 p.

Feth, J.H., Barker, D.A., Moore, L.G., Brown, R.J., and Veirs, C.E., 1966, Lake Bonneville: Geology and hydrology of the Weber Delta district, including Ogden, Utah: U.S. Geological Survey Professional Paper 518, 76 p.

Jacob, C.E., and Lohman, S.W., 1952, Nonsteady flow to a well of constant drawdown in an extensive aquifer: American Geophysical Union Transactions, v. 33, p. 559-569.

Johnson, E.B., 1969-85, Report of distribution of water supply entering Weber River for the water year 1969; 1970; 1971; 1972; 1973; 1974; 1975; 1976; 1977; 1978; 1979; 1980; 1981; 1982; 1983; 1984; 1985: Unpublished reports on file with Utah Division of Water Rights.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey, Techniques of Water-Resources Investigation, Book 6, chapter A1, 586 p.

Mower, R.W., 1978, Hydrology of the Beaver Valley area, Beaver County, Utah, with emphasis on ground water: Utah Department of Natural Resources Technical Publication No. 63, 81 p.

National Oceanic and Atmospheric Administration, Environmental Data Service, 1982, Climatological Data Annual Summary 1981: v. 83, no. 13, Asheville, N.C.

-----1983a, Climatological Data Annual Summary 1982: v. 84, no. 13, Asheville, N.C.

-----1983b, Climatography of the United States 1981--Monthly normals of temperature, precipitation, and heating and cooling degree days, 1951-80, Utah: Asheville, N.C.

-----1984, Climatological Data Annual Summary 1983: v. 85, no. 13, Asheville, N.C.

-----1985, Climatological Data Annual Summary 1984: v. 86, no. 13, Asheville, N.C.

Plantz, G.G., Appel, C.L., Clark, D.W., Lambert, P.M., and Puryear, R.L., 1986, Selected hydrologic data from wells in the East Shore area of the Great Salt Lake, Utah, 1985: U.S. Geological Survey Open-File Report 86-139, 75 p.

Smith, R.E., 1961, Records of water-level measurements of selected wells and chemical analyses of ground-water, East Shore area, Davis, Box Elder, and Weber Counties, Utah: Utah Basic Data Report No. 1, 35 p.

Smith, R.E., and Gates, J.S., 1963, Ground-water conditions in the southern and central parts of the East Shore area, Utah, 1953-61: Utah Geologic and Mineral Survey Water-resources Bulletin 2, 48 p.

Theis, C.V., Brown, R.H., and Meyer, R.R., 1963, Estimating the transmissibility of aquifers from the specific capacity of wells, in Bontall, Roy (compiler), 1963, Methods of determining permeability, transmissibility, and drawdown: U.S. Geological Survey Water-Supply Paper 1536-I, p. 331-341.

Thomas, H.E., and Nelson, W.B., 1948, Ground water in the East Shore area, Utah; part 1, Bountiful district, Davis County: Utah State Engineer Technical Publication 5, in Utah State Engineer 26th Biennial Report, p. 52-206.

U.S. Bureau of Reclamation, 1967 and 1968, Use of water on federal irrigation projects, 1966 and 1967 detailed reports, v. I, Eden Project, Wyoming; Strawberry Valley, Utah: Salt Lake City, Utah.

-----1969, Use of water on federal irrigation projects, 1968 detailed report, v. II, Strawberry Valley Project, Utah, West Mountain Study area: Salt Lake City, Utah.

U.S. Department of Commerce, Bureau of Census, 1971, 1970 census of population, number of inhabitants, Utah: Washington, D.C., Final Report PC(1)A46.

-----1980, 1980 census of population and housing, preliminary population and housing unit counts, Utah: Washington, D.C., Preliminary Report PHC 80-P-46.