# Determination of Hydraulic Characteristics and Yield of Aquifers Underlying Vekol Valley, Arizona, Using Several Classical and Current Methods

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# Determination of Hydraulic Characteristics and Yield of Aquifers Underlying Vekol Valley, Arizona, Using Several Classical and Current Methods

By JAMES R. MARIE and KENNETH J. HOLLETT

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2453

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director



UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1996

For sale by the
U.S. Geological Survey
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Box 25286, Federal Center
Denver, CO 80225

**Library of Congress Cataloging in Publication Data**

Marie, James R.
Determination of hydraulic characteristics and yield of aquifers underlying Vekol Valley, Arizona, using several classical and current methods / by James R. Marie and Kenneth J. Hollett.
p. cm.—(U.S. Geological Survey water-supply paper ; 2453)
Includes bibliographical references.
Supt. of Docs. no.: I 19. 13:2453
1. Aquifers—Arizona—Vekol Valley. 2. Groundwater flow—Arizona—Vekol Valley. I. Hollett, Kenneth J. II. Title. III. Series.
GB1199.3.A7M37 1996
553.7'9'0979173—dc20 96–15542
CIP

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## CONVERSION FACTORS AND VERTICAL DATUM

| Multiply | By | To obtain |
|---|---|---|
| inch (in.) | 25.4 | millimeter |
| foot (ft) | 0.3048 | meter |
| mile (mi) | 1.609 | kilometer |
| square foot ($ft^2$) | 0.0929 | square meter |
| square mile ($mi^2$) | 2.59 | square kilometer |
| acre-foot (ft) | 0.001233 | cubic hectometer |
| million gallons (Mgal) | 3785.0 | cubic meter |
| gallon per minute (gal/min) | 0.06309 | liter per second |
| gallons per day (gal/d) | 0.003785 | cubic meters per day |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second |
| gallon per minute per foot [(gal/min)/ft] | 0.207 | liter per second per meter |
| foot squared per day ($ft^2/d$) | 0.0929 | meter squared per day |

**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.

# Determination of Hydraulic Characteristics and Yield of Aquifers Underlying Vekol Valley, Arizona, Using Several Classical and Current Methods

*By* James R. Marie *and* Kenneth J. Hollett

## Abstract

Extensive hydrologic investigations were conducted in south-central Arizona during the late 1970's and early 1980's pursuant to the Ak-Chin Indian Community Water Rights Settlement Act, Public Law 95-328. The Act directed the Secretary of the Interior to deliver a permanent water supply of 85,000 acre-feet annually to the Ak-Chin Indian Reservation no later than 25 years from the date of the enactment—July 28, 1978. The Act further directed that if sufficient ground water was available beneath Federal Lands near the Reservation to meet the emergency needs of the Community, a well field and pipeline would be constructed to deliver 30,000 acre-feet of water annually. Initial studies by the U.S. Geological Survey indicated that the emergency supply could be obtained from several large tracts of nearby Federal land. The Secretary selected Vekol Valley as the area to be developed and directed that the well field and pipeline be built.

The investigation to obtain the required information to construct the well field and pipeline in Vekol Valley began during 1981 and was conducted in two phases. The first phase was limited to the north part of the valley, which is closer to the Reservation, to determine if the total amount of water required could be produced from that area. The investigation included an extensive well-drilling program. Nineteen boreholes, including two continuous-core holes, ranging in depth from about 200 to 3,000 feet were drilled at 10 sites. Most of the holes were drilled through the entire aquifer system and into the underlying bedrock. Three of the holes were completed as 18-inch production wells, fourteen as smaller-diameter water-level observation wells, and two as heat-flow monitoring wells. Tests were conducted on all wells, including one 23-day aquifer test. A ground-water recharge experiment was conducted in conjunction with this aquifer test.

Analysis of test information for the upper, unconfined aquifer gave hydraulic property values for transmissivity of about 13,500 feet squared per day, specific yield of about 0.12, and a ratio for vertical to horizontal hydraulic conductivity of about 1:12. For the most conductive zone in the lower, confined aquifer, the analysis gave a transmissivity of about 2,000 feet squared per day and a storage coefficient of about $4 \times 10^{-4}$. Analysis of data obtained during the recharge experiment produced infiltration rates for an ephemeral channel that ranged from about 0.64 to 1.09 cubic feet per second per 1,000 feet of channel length. Vertical hydraulic conductivity values calculated for the underlying material using these steady, channel-infiltration rates ranged from about 2.9 to 7.1 feet per day. The value calculated from the aquifer test data was about 2.2 feet per day. Time required for water to move vertically through the underlying 330-feet thick unsaturated zone to the water table was about 4 days. The results obtained from all these tests were used in a ground-water flow model to evaluate various well-field designs and pumping scenarios. A description of the model and the results of the

evaluations were published in an earlier, companion report by Hollett and Marie, 1987. During the evaluation, it was determined that the entire emergency water supply of 30,000 acre-feet could not be obtained from the northern part of Vekol Valley; consequently, the investigation was expanded to include the southern part.

The investigation of south Vekol Valley also included an extensive well-drilling program. Twenty-one holes ranging in depth from about 200 to 2,000 feet were drilled at 14 sites. Six continuous-core holes were drilled, two through the entire aquifer system and into the underlying bedrock. Most of the other holes also were drilled through the entire aquifer system. Thirteen wells, including four large-diameter production wells and nine water-level observation wells, were installed. These wells ranged from 2 to 26 inches in diameter and from about 200 to 2,000 feet deep. Two vertical extensometers were installed to measure anticipated compaction of the aquifer system that would be caused during the planned 30-year pumping period. Tests were conducted on all wells installed, including two aquifer tests, one for about 9 days of pumping and the other for 21 days. All available wells were used to monitor water-level changes during the aquifer tests. Analyses of the tests show that the aquifer system underlying south Vekol Valley has a transmissivity of about 9,000 feet squared per day and a storage coefficient of about $3x10^{-4}$. The test results exhibit characteristics of a leaky, confined aquifer system with a ratio of vertical to horizontal hydraulic conductivity of about 1:60. The 21-day test created locally unconfined conditions in the aquifer system, and a specific yield of about 0.12 was estimated. Pumping from the proposed well field also will cause the conversion from confined to unconfined conditions. On the basis of the results of investigations of Vekol Valley, it was concluded that the 30,000 acre-feet of water required annually to meet the emergency needs of the Ak-Chin Indian Community could be obtained from the aquifer system underlying the valley.

# INTRODUCTION

The Ak-Chin Indian Community Water Rights Settlement Act, Public Law 95-328, enacted by the Congress of the United States on July 28, 1978, directed the Secretary of the Interior to deliver a permanent water supply of 85,000 acre-ft/yr of water to the Ak-Chin Indian Reservation no later than 25 years from the date of the enactment. The Settlement Act further directed the Secretary of the Interior to determine if sufficient ground water was available beneath Federal Lands near the Reservation to meet the interim, emergency needs of the community—about 30,000 acre-ft/yr—until the permanent supply could be provided. The Settlement Act also stated that if sufficient quantities of ground water were available that a well field and pipeline would be constructed to deliver the emergency supply.

Initial work to determine if the interim, emergency supply could be obtained near the Ak-Chin Community was started in late 1978 and the resulting studies by Wilson (1979) and Matlock (1981) indicated that the emergency supply could be obtained. On the basis of these studies and other information, the Secretary of the Interior selected Vekol Valley as the area to be developed and directed that the well field and pipeline capable of delivering the emergency supply be constructed. The tests described in this report were conducted in Vekol Valley, Arizona, by the U.S. Geological Survey in cooperation with the U.S. Bureau of Indian Affairs and the Ak-Chin Indian Community to fulfill part of the requirements of the Ak-Chin Indian Community Water Rights Settlement Act.

## Purpose and Scope

To fulfill the Secretary of Interior's directive, work was begun during 1981 to design and construct the well field and pipeline to develop and deliver the emergency water supply. To determine whether sufficient water could be developed to satisfy the entire emergency supply from the aquifer systems underlying Vekol Valley, a series of carefully designed and planned aquifer and well tests were conducted in the valley. These tests were used to determine, as accurately as possible, the hydraulic characteristics of the units that comprise the two aquifer systems underlying the valley. These tests and their results are documented in this report.

The objectives of the initial phase of this investigation were to: (1) determine the geologic and hydraulic characteristics of the aquifer systems underlying Vekol Valley to determine whether the emergency supply could be developed in the valley, (2) develop and test preliminary well designs that would efficiently produce the maximum quantity of water consistent with the hydraulic characteristics of the aquifer system, (3) provide the information necessary and then actually construct a ground-water flow model that would be used to show the effects of various alternative well-field designs, and (4) complete the preliminary design of the well field and pipeline that could produce and deliver the amount of water required to satisfy the emergency needs of the Ak-Chin Community.

This investigation of Vekol Valley was conducted in two phases. The first phase was limited to the northern part of the valley, which is closer to the Ak-Chin Reservation, to determine whether the aquifer system underlying this area could be developed to supply the emergency water needs of the Community. When it was determined that the entire, emergency supply could not be developed from the northern part of Vekol Valley, the study was expanded to include the southern part of the valley.

The results obtained from test drilling and aquifer tests, combined with information gained from a concurrent recharge experiment, also described in this report, provided the basic hydraulic information essential to defining the extent of the aquifer systems underlying Vekol Valley and their capability to supply the water required to meet the stipulations of the Ak-Chin Indian Community Water Rights Settlement Act. The results described in this report were also used in a companion study and report describing the ground-water flow simulations of the aquifer-system response to the planned pumping in the northern part of Vekol Valley (Hollett and Marie, 1987).

## Study Area

Vekol Valley is in south-central Arizona about 40 mi south of Phoenix and 30 mi east of Gila Bend (fig. 1). The north-trending valley is about 25 mi long and extends from the Cimarron Mountains on the south to the Booth Hills on the north. The valley is bounded on the east by the Table Top and Vekol Mountains and on the west by the Maricopa and Sand Tank Mountains. The mountains average about 2,500 ft in altitude and have isolated peaks that exceed 4,000 ft. Vekol Wash, an ephemeral stream, flows from south to north through the valley.

Vekol Valley is divided into two distinct areas by a low, east-west ridge that extends partly across the middle of the valley. South of the ridge, the valley is a broad, flat, almost circular basin about 12 mi in diameter. This southern part lies at an altitude of about 2,000 ft and slopes gently to the north at less than 10 ft/mi. The center of the basin generally is covered with low grass. The side slopes are covered by sparse desert vegetation. North of the ridge, the valley is only about 5 mi wide, and the valley floor has a steeper slope to the north of about 35 ft/mi. Desert vegetation, although sparse, is much more abundant in the northern part of the valley. About one third of the southern part of the valley is part of the Tohono O'Odham (previously named Papago) Indian Reservation. Most of the remaining land in the valley is Federally owned.

The climate of the valley is semiarid with precipitation about equally divided between local, summer thunderstorms and regional winter storms. The annual precipitation averages about 7 in. The potential evaporation rate is about 10 times that amount. Runoff occurs mainly as sheetflow and floods of short duration.

## Geologic Framework

Vekol Valley is a north-south trending structural trough bounded by block-faulted mountains and partially filled with sediment that was eroded from the mountain blocks (fig. 2). The valley is divided into two distinct areas by a low, east-west-trending ridge that lies across the middle of the valley. This low ridge is the surface expression of several smaller uplifted structural blocks comprised of early Proterozoic metamorphic rocks that crop out near the center of the valley (fig. 1). On the basis of geologic mapping, core and drill-hole information, and geophysical information, several significant differences exist between the northern and southern parts of the valley.

North of the ridge, the structural trough is composed of many relatively small blocks that form a stair-step surface that deepens from north to south (figs. 3 and 4). Near the northern end of the valley, several of the blocks are exposed at the surface along

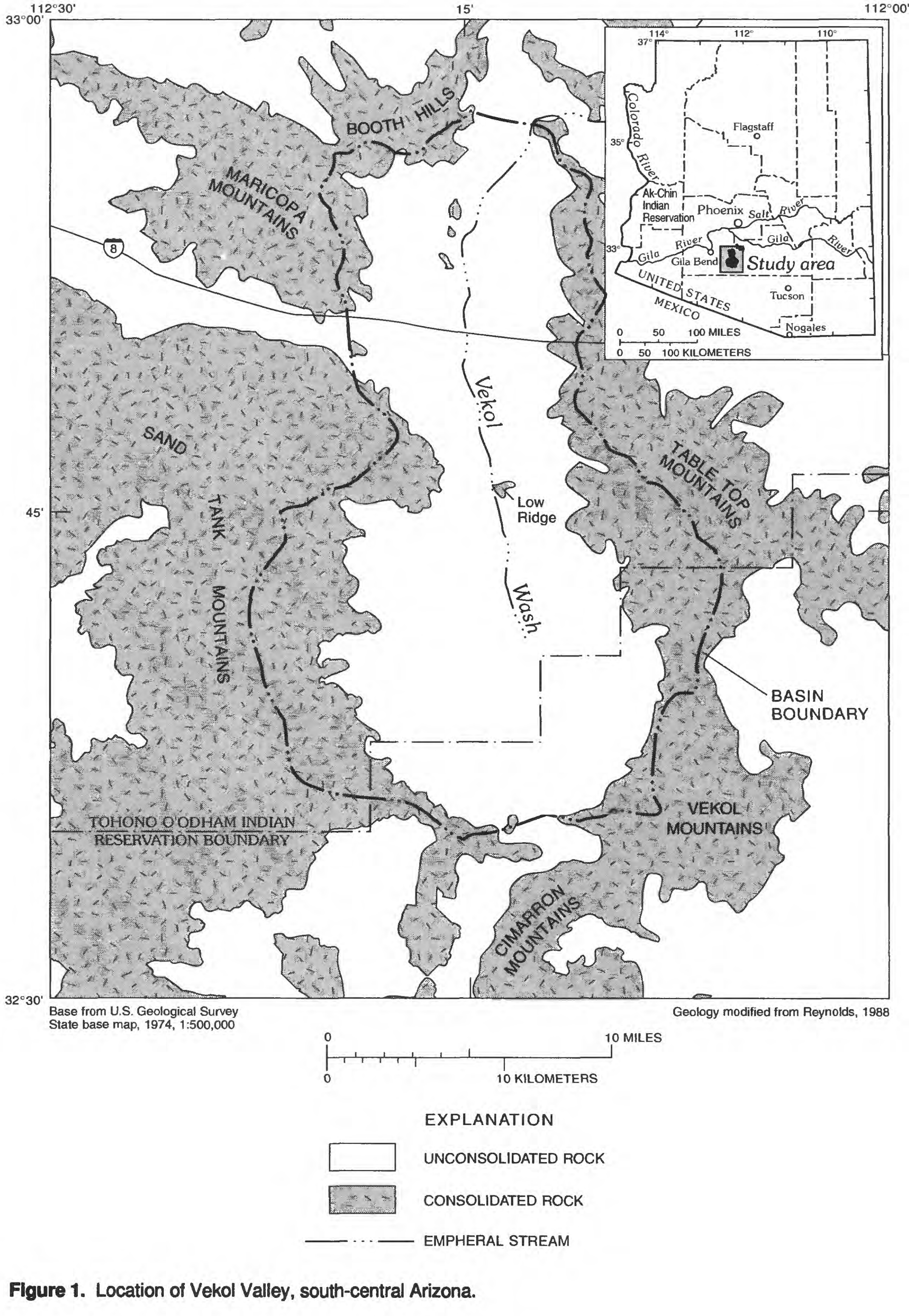



**Figure 1.** Location of Vekol Valley, south-central Arizona.

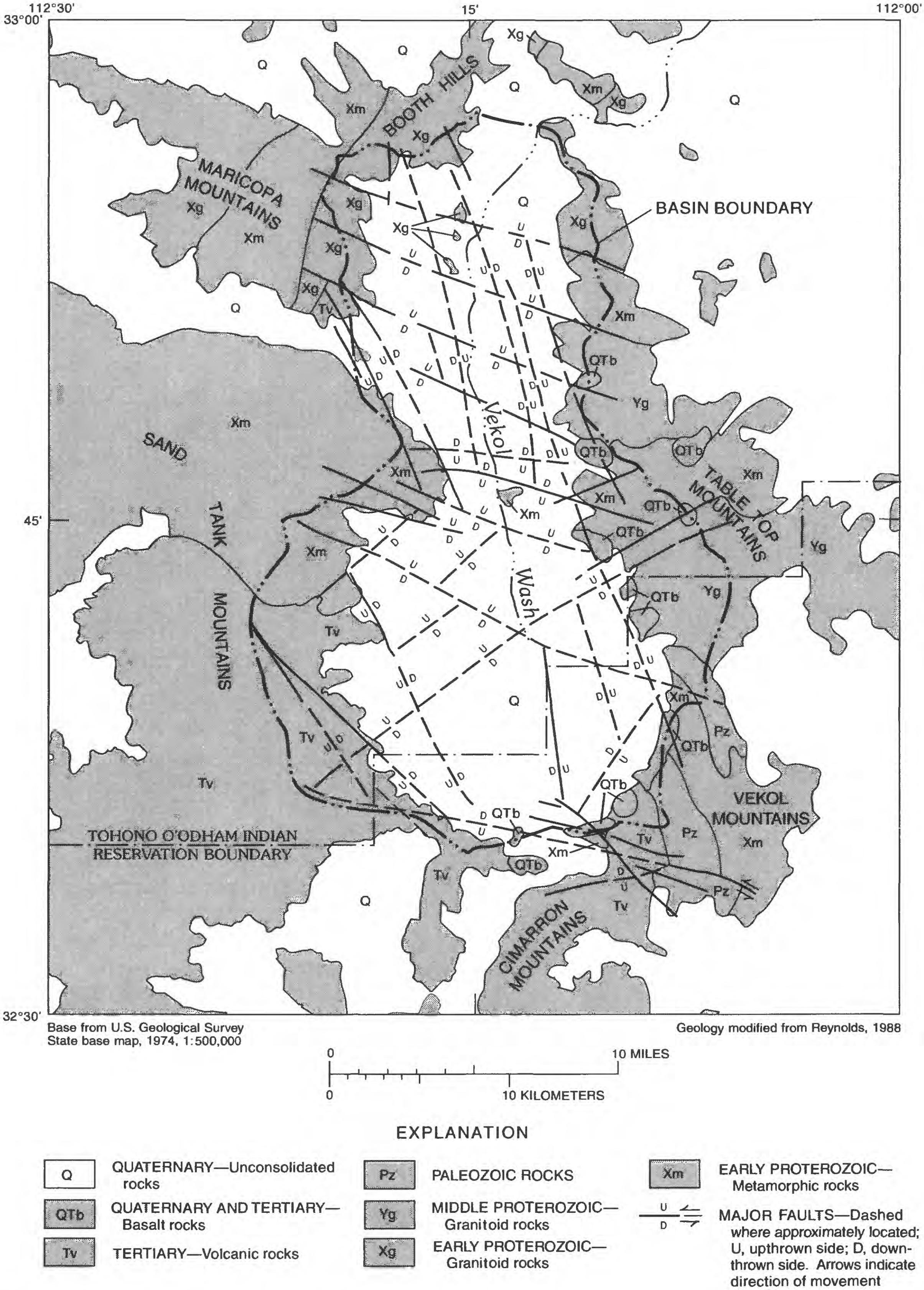



**Figure 2.** Generalized geology of Vekol Valley.

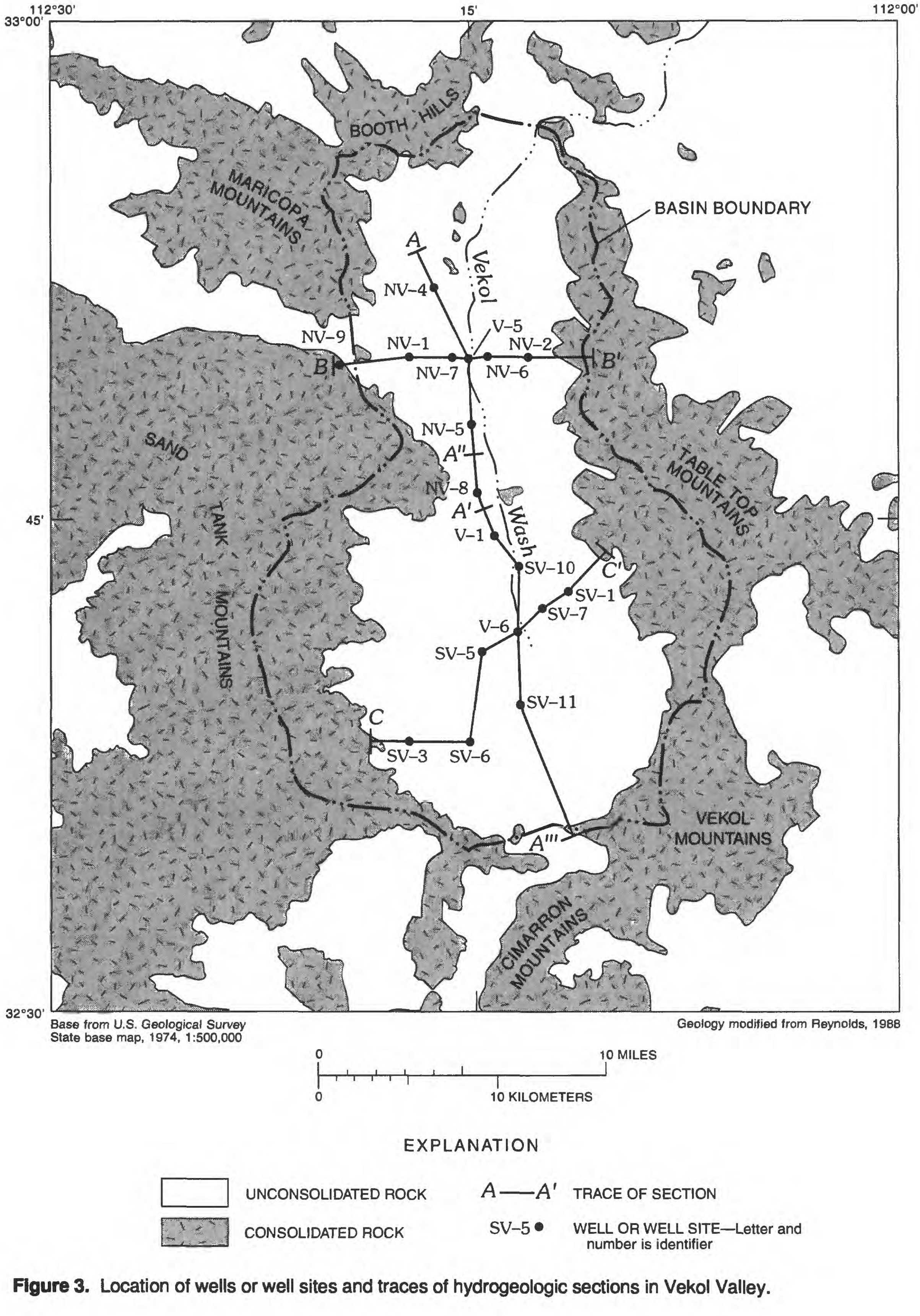



**Figure 3.** Location of wells or well sites and traces of hydrogeologic sections in Vekol Valley.

the center of the valley. However, immediately north of the low ridge, the tops of the down-faulted blocks lie at a depth of about 3,000 ft. South of the low ridge, the trough is almost circular and appears to be composed of fewer, but larger blocks that are progressively deeper from the edge of the trough toward its center. The tops of the deeper blocks were not encountered during drilling in the southern part of the valley. On the basis of these drill-hole data, however, it is inferred that the depth to the tops of these blocks exceeds 2,000 ft. Interpretation of geophysical data (Davis, 1984) indicate that the depth to the tops of the blocks that underlie the south-central part of the valley is at least 3,000 ft.

North of the low ridge, the basin-fill deposits (figs. 4*A* and 4*B*) are composed of a thick sequence of unconsolidated sand and gravel that grades to a well-cemented conglomerate with depth (Hollett and Marie, 1987). A sequence of volcanic rocks is intercalated with the conglomerate that overlies the older sedimentary, igneous, and metamorphic rocks. The total thickness of these sedimentary and intercalated volcanic rocks is about 3,000 ft in the area immediately north of the low ridge (fig. 4*A*). These younger rocks can be divided into four units (figs. 4*A* and 4*B*). Unit 1 is composed of unconsolidated sand and gravel that ranges in thickness from about 400 ft on the north to about 1,400 ft on the south. Unit 2 is a moderately to well-consolidated conglomerate that ranges in thickness from 0 to about 400 ft. Unit 3 is an unconsolidated to moderately consolidated silty sand, sand, and gravely sand with intercalated conglomerate that ranges in thickness from 0 to about 400 ft. Unit 4 is a thick sequence of conglomerate and intercalated volcanic rocks that ranges in thickness from 0 to about 1,800 ft. The wide range in thickness of some of these units is due to the faulting and subsequent, complex erosion and deposition that characterizes this area of the Basin and Range province.

South of the low ridge, the basin-fill deposits include a thick sequence of silt, sand, and gravel units (figs. 4*C* and 4*D*) deposited in a structurally controlled trough. These deposits also were divided into four units. Unit A is a thin, less than 200-foot thick, silty to sandy gravel. Unit B is a silt to sandy silt that ranges from a few feet thick around the perimeter of the basin to about 600 ft thick near its center. Unit C is a sequence of sand-and-gravel units that grades from unconsolidated to well cemented with depth similar to those units in the northern part of the valley. Unit C has a maximum thickness of about 1,200 ft. Unit D is a gravel and conglomerate that is about 1,000 ft thick in the central part of the valley. Unit D is not present in the northern and northwestern parts of the southern valley. Underlying Unit D in much of the southern valley and, at least in part contemporaneous with it, is a sequence of volcanic rocks that are as much as 900 ft thick. The volcanics, like the overlying conglomerate are not present in the northern part of the southern valley. In the northwestern part of the valley, however, the volcanic rocks are about 700 ft thick where the conglomerate is not present.

At several sites in the southern part of Vekol Valley, various rock units of Paleozoic age were encountered during drilling. Rocks of Paleozoic age were not found in the northern part of the valley.

## AQUIFER SYSTEM UNDERLYING NORTH VEKOL VALLEY

The aquifer system underlying the northern part of Vekol Valley exists primarily in the thick sequence of sand-and-gravel units. The ground-water resource of the area is the water stored in these units. Compared to the amount of recoverable ground water in storage—about 350,000 acre-ft—the annual average amount of water that enters, moves through, and leaves the aquifer system is small—only about 1,200 acre-ft (Hollett and Marie, 1987, p. 20).

The sand, gravel, and conglomerate units grade from unconsolidated to well cemented with depth in the trough. The upper units contain two aquifers: (1) an upper, unconfined aquifer that ranges in thickness in the central 12-square-mile area of the valley from about 550 to 650 ft; and (2) the most productive zone in the lower, confined aquifer that ranges in thickness from about 50 to 300 ft. These aquifers are separated by a well-cemented conglomerate that ranges in thickness from about 210 to 300 ft.

Depth to ground water in the northern part of the valley ranges from about 270 to 430 ft. The direction of ground-water movement generally is from the mountains surrounding the valley on the east and west toward the center of the valley and then toward the north along the axis of the valley to the outflow area between the Booth Hills and the Table Top Mountains (fig. 5). Water level in the upper aquifer is a few feet higher than in the lower aquifer around the edge of the valley, showing downward movement of water from the upper to the lower aquifer in these areas. Water levels are about the same in both aquifers in the central part of the valley. Water level in the lower aquifer is slightly higher than it is in the upper aquifer in the northern part of the valley, showing upward movement from the lower aquifer in the outflow area.

## TEST HOLES AND WELLS INSTALLED IN NORTH VEKOL VALLEY

From 1978 to 1984, an extensive well-drilling program was undertaken in Vekol Valley. Nineteen holes that ranged in depth from about 200 to 3,000 ft

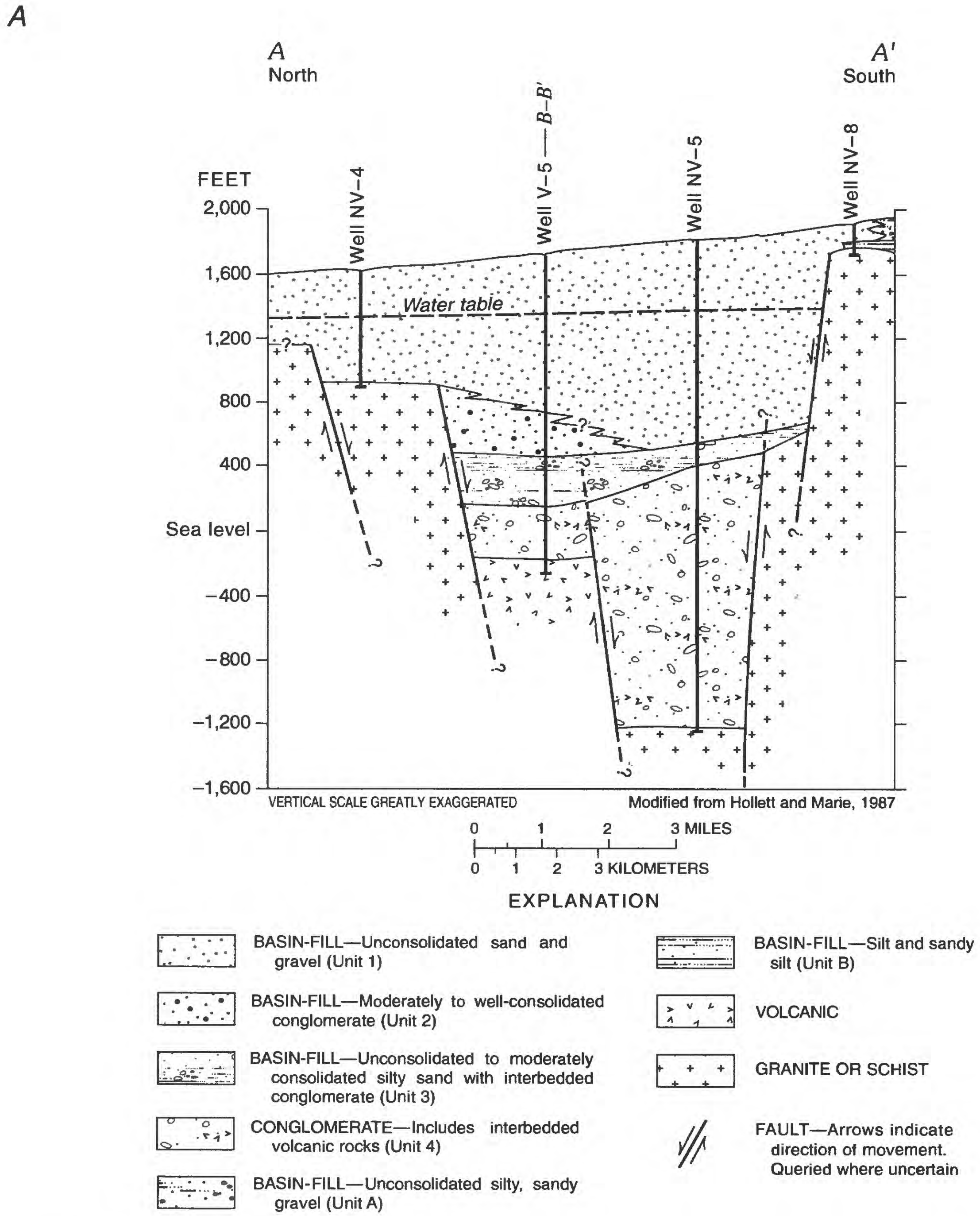



**Figure 4.** Hydrogeologic sections of Vekol Valley. *A*, Section *A–A'*; *B*, Section *B–B'*; *C*, Section *A''–A'''*; *D*, Section *C—C'*. (Traces of sections shown on fig. 3.)

were drilled at 10 sites in or near the northern part of the valley (fig. 6). The 19 holes included 2 core holes that were drilled through the entire aquifer system and into the crystalline basement rock—one to a depth of 1,553 ft, and the other to a depth of 2,000 ft. The core holes were drilled using continuous wireline coring tools and a combination of biodegradable polymer and bentonite mud. Core recovery from these holes was better than 90 percent. All holes for observation wells (table 1) were drilled using rotary methods and biodegradable polymer mud. All production wells (table 1) were drilled in stages using rotary methods and biodegradable polymer mud or using compressed air and foam for the initial stages and biodegradable polymer mud for the final stages.

Core hole NV–6c was completed as a water-level observation well and as a heat-flow monitoring tube. Core hole NV–7c was designed specifically as a heat-flow monitoring tube by cementing 1,981 ft of sealed, 1–3/4-inch-diameter pipe into the hole. Wells

*B*

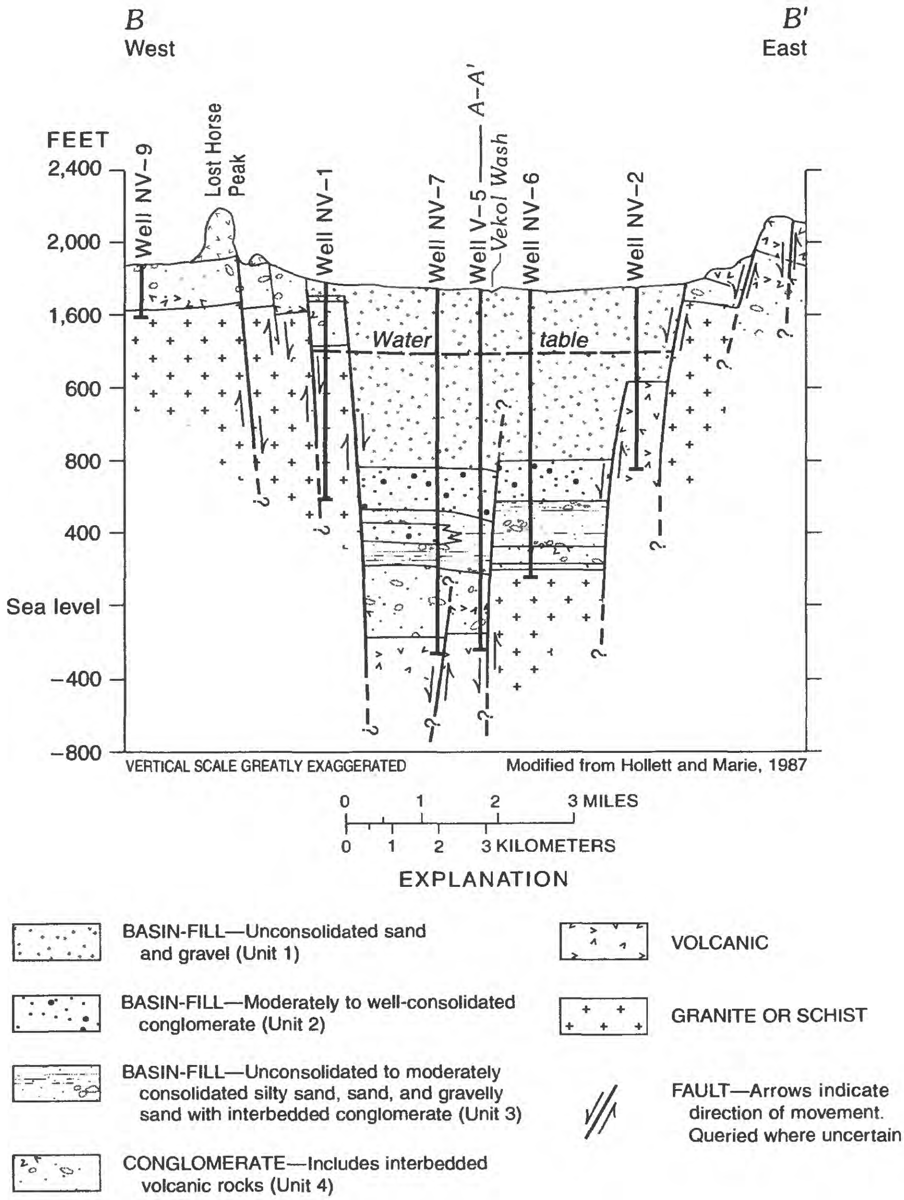



**Figure 4.** Continued

installed in the remaining 17 holes were fully developed and tested and included 4 production wells and 13 observation wells. Some of the wells are screened throughout the aquifer system, and some are screened only in specific aquifers. Most of the wells were finished using wire-wrapped, high-flow, stainless-steel screen and gravel packs. The wells ranged in diameter from 2 to 26 in. and in depth from about 200 to 2,000 ft. An aquifer test was conducted using well NV–6p as the pumping well. All other available wells (fig. 6) were used as water-level or heat-flow observation wells during this test. The well numbers

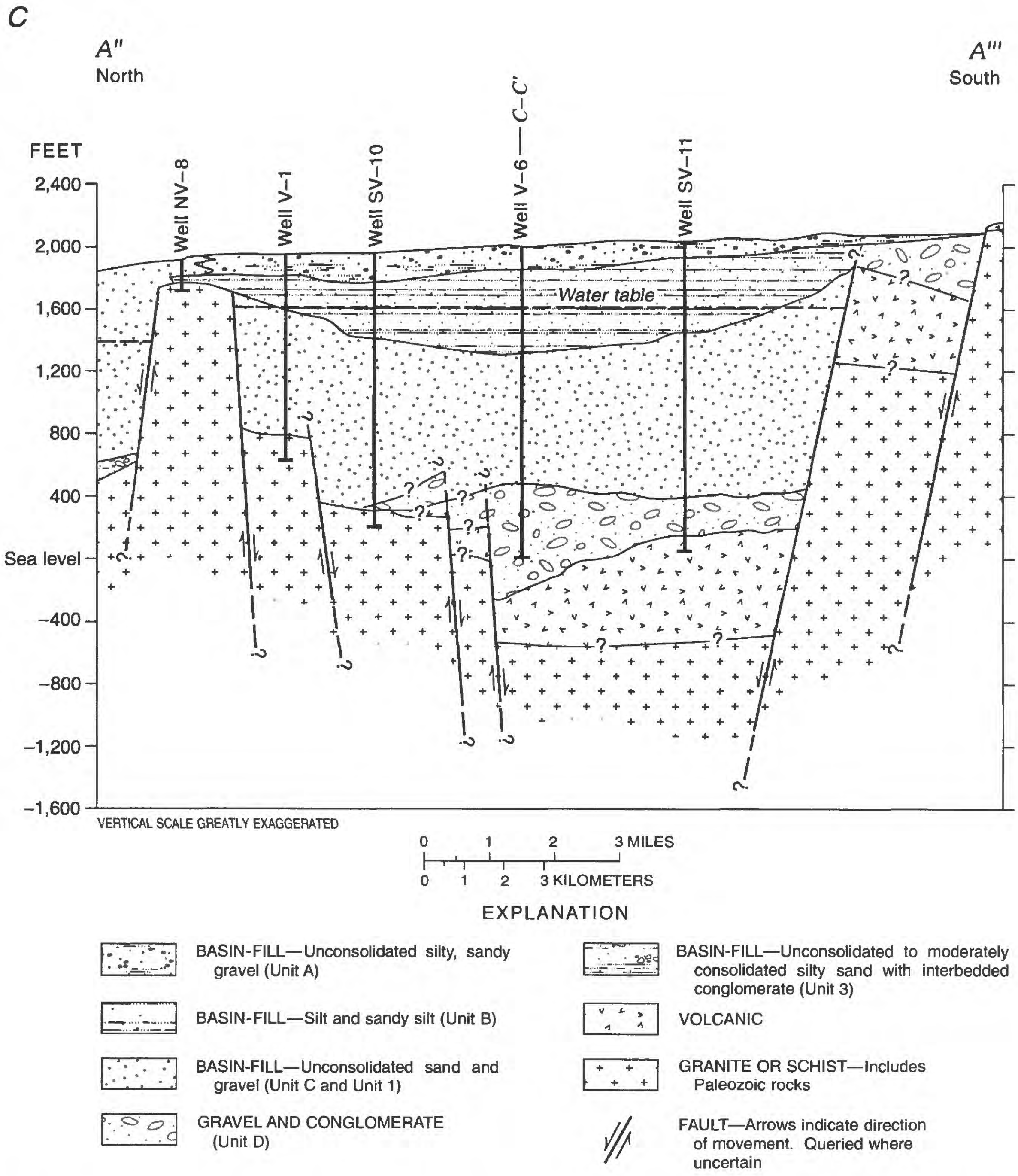



**Figure 4.** Hydrogeologic sections of Vekol Valley. *A*, Section *A–A'*; *B*, Section *B–B'*; *C*, Section *A''–A'''*; *D*, Section *C–C'*. (Traces of sections shown on fig. 3.)

and descriptions of the wells and the heat-flow tube are listed in table 1, locations of the 10 drill sites are shown on figure 6, and construction information for 11 selected wells is shown in the section entitled "Well-Construction Information" at the back of this report.

## WELL DEVELOPMENT AND TESTS

All wells installed in the northern part of Vekol Valley were developed shortly after construction using a combination of jetting, surging, and pumping. Acceptance tests were then performed on all of the

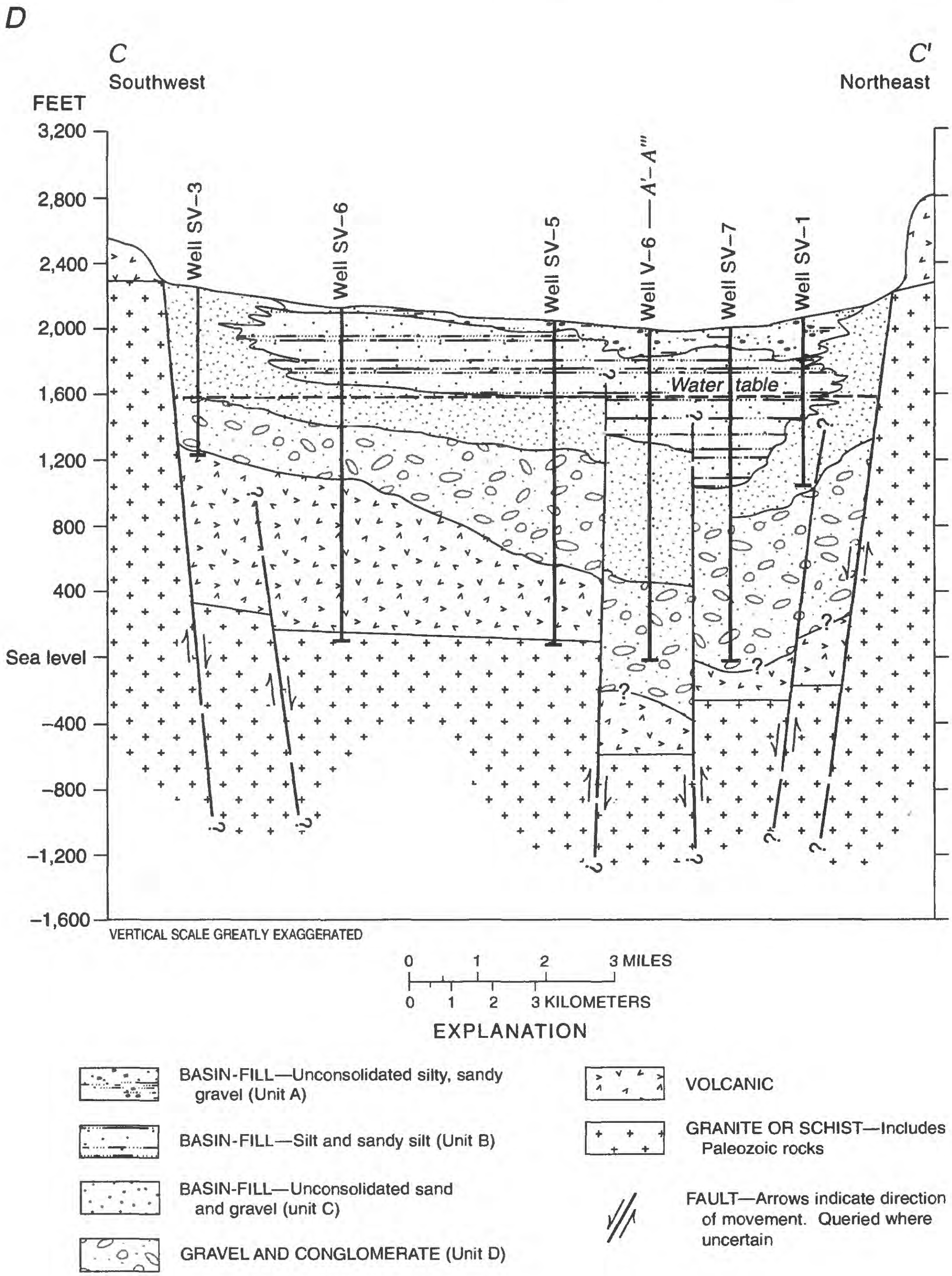



**Figure 4.** Continued

observation wells to ensure that each was open to the aquifer and would produce a specified, minimum quantity of clear water.

Additional tests consisting of a constant-discharge drawdown and recovery test or, in selected cases, a step-discharge drawdown and recovery test were then performed on all observation wells except NV–2. These tests were conducted to determine the specific capacity of each well, to estimate the efficiency of selected wells, and to estimate aquifer transmissivity. Well NV–2 was not tested because the aquifer underlying the site was too thin to provide useful information. All other observation wells, except NV–3, were tested using a submersible

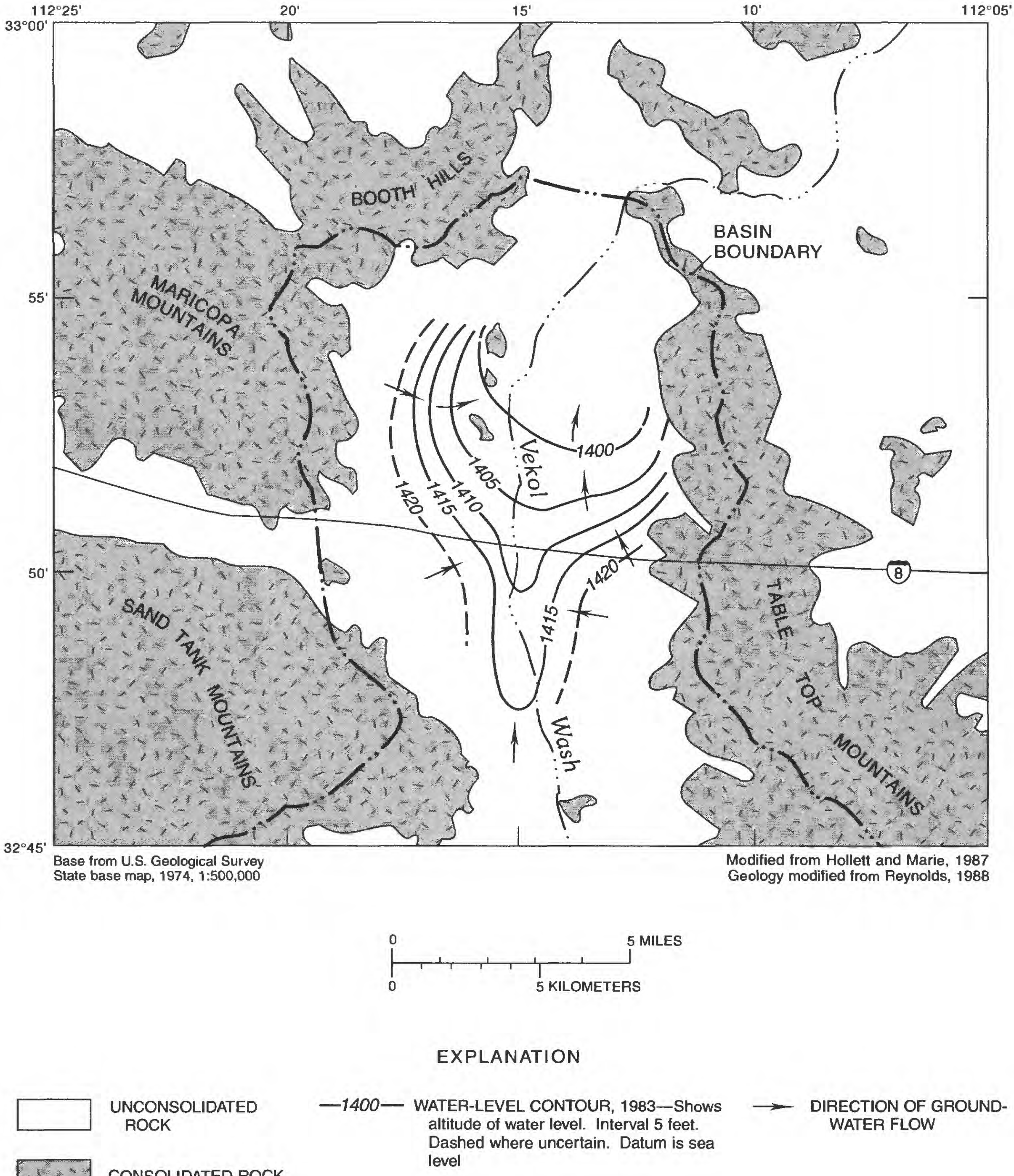



**Figure 5.** Configuration of the water table in north Vekol Valley, 1983.

pump rated at about 250 gal/min against a head of 600 ft. Well NV–3 was tested using a pump rated at 35 gal/min against a head of 500 ft. The actual pumping rates attained for these tests ranged from about 10 to 260 gal/min, and the tests ran from about 25 to 200 minutes depending on the depth to water, the diameter of the well, and the aquifer in which the well was completed. Water levels were measured during these tests using an electric sounder. Discharge rates were measured using an orifice plate or a calibrated orifice bucket.

The three large-diameter production wells (NV–5, NV–6p, and NV–7) were tested using a diesel-driven multistage turbine pump rated at 3,500 gal/min against a head of 600 ft. The tests of each of these wells consisted of a 4- or 5-step discharge drawdown test and a constant-discharge drawdown and recovery test. Discharge rates during

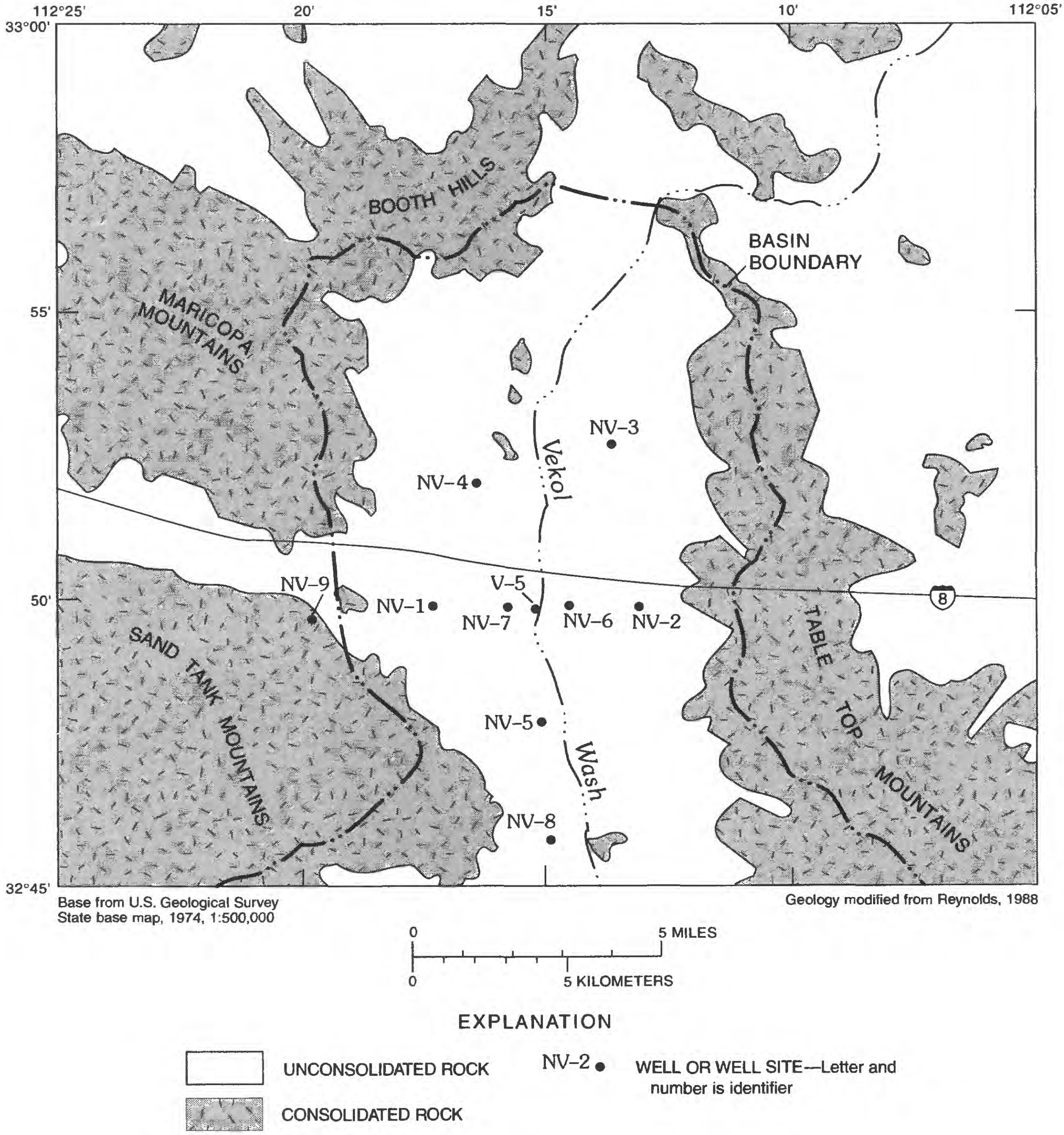



**Figure 6.** Location of selected wells and well sites in north Vekol Valley.

pumping were measured using a circular orifice weir and (or) a totalizing flowmeter. Water levels were measured in the pumping wells with an electric sounder. Water levels in all observation wells were measured with float- or pressure-sensor-activated recorders and (or) electric sounders.

## AQUIFER TESTS IN NORTH VEKOL VALLEY

The first drawdown test conducted in north Vekol Valley was completed at site V–5 during 1979 (fig. 6). This test was conducted during the first phase of the USGS studies but was not completely analyzed until 1982 during the second phase of the work. The test at site V–5 consisted of pumping well V–5 at a rate of 2,000 gal/min for about 6 days with drawdown and recovery water levels being measured in the pumped well and in observation well V–4, which was 155.5 ft from the pumped well. A vertical-velocity log of flow in the well also was made earlier at well V–5 as it pumped 1,100 gal/min and after the drawdown had stabilized and was changing slowly. In 1982, the first aquifer test in north Vekol Valley was conducted at site NV–6 (fig. 6). The test design was based on the known geology, the estimated hydraulic properties, and the anticipated response of the aquifer system to the designed pumping rate. The test consisted of pumping from well NV–6p at a rate of 2,450 gal/min for about 23 days. Water levels were measured in the

**Table 1.** Test holes drilled and wells installed in north Vekol Valley

[Dashes indicate no data]

| Well number | Location | | | Land-surface altitude, in feet above sea level | Depth, in feet below land surface | Screen, in feet below land surface | | Water level above sea level | |
|---|---|---|---|---|---|---|---|---|---|
| | Township | Range | Section | | | From | To | Feet | Date |
| **Production** | | | | | | | | | |
| V–5 | 7S | 1E | 10 | 1,755 | 2,000 | 616 | 1,719 | 1,408.2 | 12-79 |
| NV–5 | 7S | 1E | 22 | 1,830 | 2,000 | 466 | 1,782 | 1,408.5 | 9-82 |
| NV–6p | 7S | 1E | 10 | 1,756 | 1,534 | 392 | 1,510 | 1,411.4 | 10-82 |
| NV–7 | 7S | 1E | 9 | 1,763 | 2,000 | 447 | 1,499 | 1,416.1 | 7-82 |
| **Observation** | | | | | | | | | |
| V–4 | 7S | 1E | 10 | 1,755 | 1,994 | 478 | 1,874 | 1,409.2 | 11-79 |
| NV–1 | 7S | 1E | 8 | 1,798 | 2,009 | 395 | 1,200 | 1,415.7 | 6-82 |
| NV–2 | 7S | 1E | 12 | 1,797 | 1,067 | 396 | 1,057 | 1,416.8 | 7-82 |
| NV–3 | 6S | 1E | 26 | 1,668 | 674 | 368 | 608 | 1,399.6 | 6-82 |
| NV–4 | 6S | 1E | 32 | 1,695 | 592 | 445 | 455 | 1,407.9 | 10-82 |
| NV–5ob1 | 7S | 1E | 22 | 1,833 | 3,014 | 401 | 1,984 | 1,408.7 | 6-82 |
| NV–6c | 7S | 1E | 10 | 1,756 | 1,590 | 508 | 518 | 1,410.9 | 7-82 |
| NV–6ob1 | 7S | 1E | 10 | 1,756 | 1,532 | 320 | 1,486 | 1,411.2 | 7-82 |
| NV–6ob2 | 7S | 1E | 10 | 1,758 | 550 | 529 | 549 | 1,411.7 | 8-82 |
| NV–6ob3 | 7S | 1E | 10 | 1,761 | 550 | 529 | 549 | 1,411.8 | 8-82 |
| NV–6ob4 | 7S | 1E | 10 | 1,743 | 506 | 486 | 506 | 1,411.0 | 7-82 |
| NV–6ob5 | 7S | 1E | 10 | 1,741 | 507 | 486 | 506 | 1,411.0 | 7-82 |
| NV–7c-hft | 7S | 1E | 9 | 1,762 | 2,000 | ([1]) | ([1]) | --------- | ------ |
| NV–8 | 8S | 1E | 3 | 1,935 | 200 | 159 | 179 | ([2]) | ------ |
| NV–9 | 7S | 1W | 11 | 1,882 | 340 | 205 | 215 | 1,628.7 | 9-82 |

[1]None. [2]Dry.

pumped well and in 12 observation wells during both the drawdown and recovery periods.

## Methods Used for Analyses

The aquifer-test data obtained from sites in north Vekol Valley were analyzed using the curve-matching technique by Boulton (1954, 1955, and 1963) and by Neuman (1972, 1973, 1974, and 1975). This technique is applicable to the analysis of the unconfined aquifer underlying the northern part of the valley.

Two separate approaches of this technique were used to determine transmissivity (*T*) and specific-yield ($S_y$) values. The first approach used the standard curve-matching procedure to calculate the *T* and $S_y$ values at each observation well for that part of the drawdown (*s*) and time (*t*) plots after any partial-penetration effects had disappeared. The second approach then used these *T* and $S_y$ values, along with several other calculated and measured values, to generate a site-specific type curve for the actual observation and pumped-well configurations to reanalyze for *T* and $S_y$ using the complete *s* and *t* data plot. This method (Neuman, 1974) calculates the effects on water levels observed in any partially or fully penetrating observation well caused by a partially or fully penetrating pumped well. The computer code used to produce the type curves for each individual observation well was provided by S.P. Neuman. An improved computer code (Moench, 1993) also was used.

In addition, a technique, commonly referred to as a continuity test, was used to corroborate that previously calculated *T* and $S_y$ values for all data sets were consistent and reasonable. The continuity test is a curve-matching technique using a plot of drawdown (*s*) and the ratio of time (*t*) to distance from the pumped well to the observation well squared ($r^2$) to calculate *T* and $S_y$ or storage coefficient (*S*). The semilogarithmic method of Cooper and Jacob (1946) also was used to obtain transmissivity values for each aquifer to corroborate those previously obtained values.

### Partial-Penetration Effects

Some wells installed in Vekol Valley were, for various reasons, constructed so that the screen installed in the well is not open to the entire aquifer. When these partially penetrating wells are pumped, water moving through the aquifer converges as it moves toward the well screen. This convergence of flow causes vertical-flow components in the aquifer near the pumped well. If these vertical-flow components are large, analytical methods developed for fully penetrating wells may produce inaccurate values for the aquifer characteristics. The applicability of these solutions is complicated further and generally denigrated if the observation wells used to record water-level changes due to the pumping also are partially penetrating.

Techniques have been developed that allow adjustments to be made that account for the inaccuracies of these analytical methods. Hantush (1962, 1964) presented a technique that allowed adjustment to the Theis (confined) solution to account for the effects of partial penetration and vertical leakage that could be applied to determine properties of unconfined aquifers. Stallman (1965) published the results of electric-analog model studies for various partial penetrations of both pumped and observation wells. The principal results of Stallman's studies are presented as type curves on his figures 10 and 12. Neuman (1974) presented a technique that allows the effects of partially penetrating pumped and observation wells in an unconfined, anisotropic aquifer to be determined. Moench (1993) again improved the method. Although a complete discussion of these techniques is beyond the scope of this report, a brief description of their application to the tests conducted in Vekol Valley is presented below.

First, effects of partial penetration must be accounted for if:

$$\frac{r\sqrt{\frac{K_z}{K_r}}}{b} \le 1.0 , \qquad (1)$$

where

$r$ = distance from pumped well to the observation well,

$b$ = thickness of the aquifer,

$K_z$ = vertical hydraulic conductivity, and

$K_r$ = horizontal hydraulic conductivity.

However, for large values of time (*t*):

$$t > \frac{b^2 (S_y)}{2 (K_z/K_r) T} , \qquad (2)$$

where

$S_y$ = specific yield, and
$T$ = transmissivity.

The effects of partial penetration are constant in time.

The effects of a partially penetrating pumped well decrease with distance and with the ratio of $K_z/K_r$. At distances greater than:

$$r = \frac{b}{\sqrt{\frac{K_z}{K_r}}}, \qquad (3)$$

and the effects disappear when:

$$t \geq \frac{10 S_y r^2}{T} \qquad (4)$$

for a partially penetrating pumped well and a partially penetrating observation well(s).

For a partially penetrating pumped well and any fully penetrating observation wells, the effects disappear at distances greater than the distance defined by equation 3 at times greater than:

$$t = \frac{S_y r^2}{T}. \qquad (5)$$

If the pumped well and the observation well(s) fully penetrate an anisotropic, unconfined aquifer, the solution of Neuman (1975) is applicable. That is, no adjustment for well penetration is required.

For a fully penetrating pumped well in an anisotropic, unconfined aquifer where the observation well(s) are partially penetrating, the duration of the effects may be determined by using the method developed by Stallman (1965). For any value of the partial-penetration depth coefficient ($z$) for either a pumped or an observation well and for each finite value ($\beta$) of:

$$\frac{r}{b}\sqrt{\frac{K_z}{K_r}}, \qquad (6)$$

a value ($x$) is obtained for:

$$x = \frac{Tt}{r^2 S_y} \qquad (7)$$

for the amount of partial penetration of the wells. Type curves may then be drawn to account for the effects of the particular partial penetration of pumped and observation wells.

Also, specific type curves may be drawn for each individual field situation of partially penetrating pumped and (or) observation well(s) using Neuman's (1974) or Moench's (1993) method and associated computer programs. Either of these programs calculates the partial-penetration adjustment required and includes this effect in the type curve produced for a specific aquifer-test configuration. Type curves generated using either method for a particular set of field conditions allow for values of transmissivity and specific yield to be calculated directly.

## Tests at Site V–5

The first two tests conducted at site V–5 (fig. 6) included a tracer log and a flow-velocity (impeller type) log to determine the relative yield from each aquifer unit open to well V–5. These logs were made on November 28, 1979, as the well was pumped at a constant rate of about 1,100 gal/min and after the drawdown stabilized at about 111 ft. These logs support the interpretation of a heterogeneous aquifer system. Data from the logs (fig. 7 and table 2) include the distribution of discharge from each zone in the aquifer, in percent per foot at 1,100 gal/min; the total discharge for each aquifer zone, in percent; the discharge from each, in gallons per minute; and thickness of each zone, in feet. The discharge ranges from 0.019 to 0.632 percent/ft, which is a factor of about 33. About 80 percent of the water produced by the well was developed from about 30 percent (345 ft) of the total screened interval (1,104 ft) of the aquifer system.

During December 1979, the first drawdown test was conducted in north Vekol Valley. Well V–5 (fig. 6) was pumped at about 2,000 gal/min for almost 6 days. Well V–4, at a distance of 155.5 ft from the pumped well, was the only observation well. Wells V–5 and V–4 were screened only in the lower part of the unconfined aquifer; however, the wells fully penetrate the underlying confined aquifer.

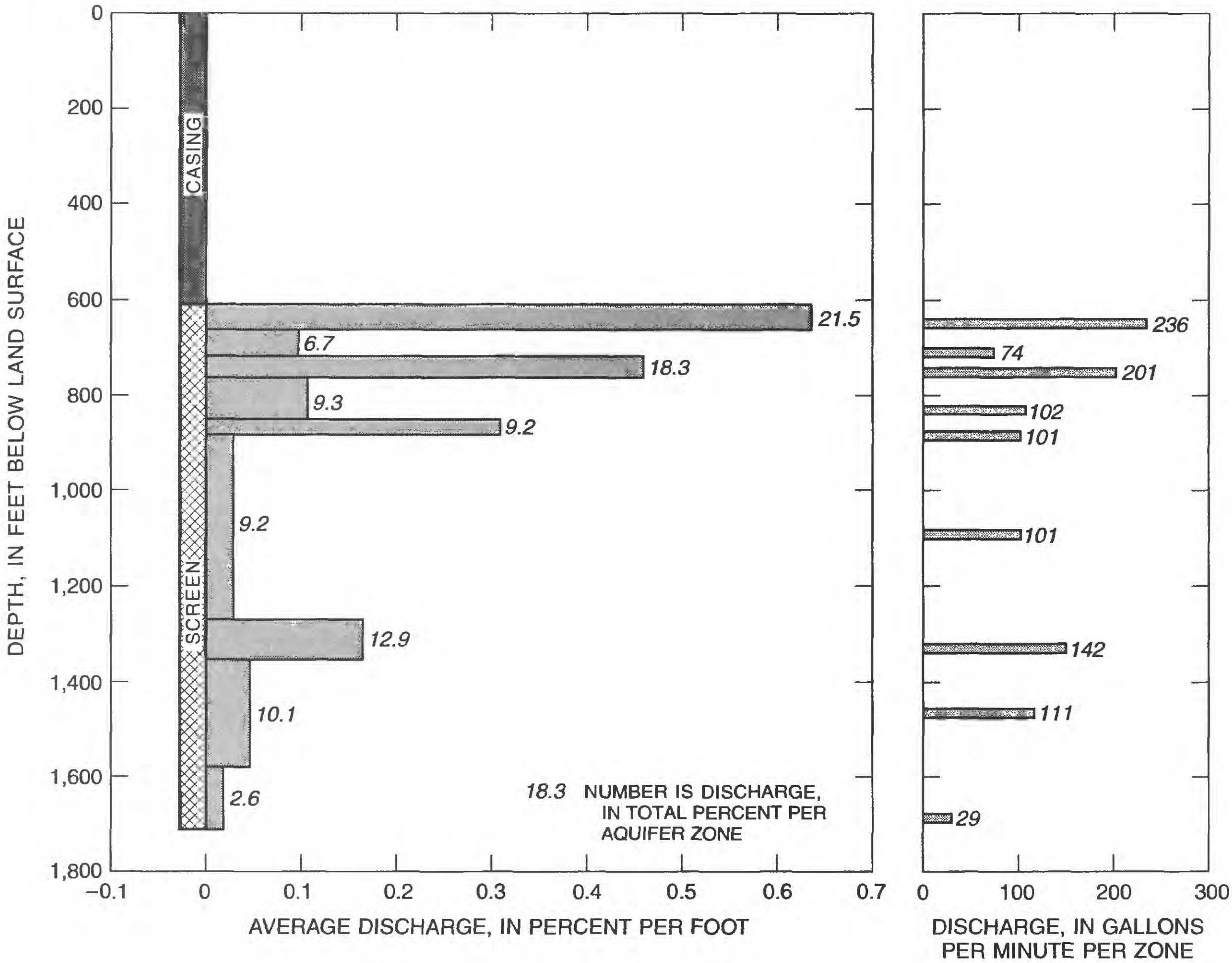



**Figure 7.** Discharge per aquifer zone in well V–5 while it was being pumped at 1,100 gallons per minute.

**Table 2.** Data obtained from velocity logs made in well V–5

| Aquifer zone | | | Discharge | | Apparent[1] | |
|---|---|---|---|---|---|---|
| Interval, in feet | | Thickness, in feet | Percent | Gallons per minute | Transmissivity, in feet squared per day[2] | Hydraulic conductivity, in feet per day |
| From | To | | | | | |
| 616 | 653 | 38 | 21.5 | 236 | 814 | 21.4 |
| 653 | 722 | 69 | 6.7 | 74 | 253 | 3.7 |
| 722 | 763 | 41 | 18.3 | 201 | 693 | 16.9 |
| 763 | 850 | 87 | 9.3 | 102 | 352 | 4.0 |
| 850 | 880 | 30 | 9.2 | 101 | 348 | 11.6 |
| 880 | 1,270 | 390 | 9.2 | 101 | 348 | .9 |
| 1,270 | 1,350 | 80 | 12.9 | 142 | 488 | 6.1 |
| 1,350 | 1,580 | 230 | 10.1 | 111 | 382 | 1.7 |
| 1,580 | 1,719 | 175 | 2.6 | 29 | 98 | .6 |
| Total | | 1,140 | 99.8 | 1,097 | 3,776 | |

[1]The values are given to the number of significant figures shown for computational purposes only and do not imply an accuracy commensurate with the number of significant figures.

[2]Transmissivity determined from aquifer test was 3,800 $ft^2/d$.

Before analyzing the drawdown-test data, the assumption was made that the analysis of the early-time drawdown data, the only data that were available from this test, would give a usable value for the transmissivity of the part of the aquifer system actually yielding the water to the well during that part of the test. The plot of the observed drawdown with time in well V–4 (fig. 8) shows that the delayed gravity response began about 85 minutes after pumping began. This delayed response indicates, considering that about 270 ft of the unconfined aquifer was not open to the pumped well and about 135 ft not open to the observation well, that the unconfined aquifer has low resistance to vertical flow. No other boundary effects were observed during the 6-day drawdown test.

As stated above, Neuman's (1975) method was used for the time-drawdown analysis of this test. Well V–5 was pumped at a rate of about 2,000 gal/min for about 6 days. The match point for the "early-time" type-A curve on the log-log plot for well V–4 was shown in figure 8. The match point is

$Wu_A$ = 1,
$1/u_A$ = 10,
$s$ = 8.0 feet,
$t$ = 8.6 minutes, and
$\beta$ = 0.002;

where

$$\beta = \frac{r^2 K_z}{b^2 K_r}. \qquad (8)$$

Solving for the properties of the apparent composite aquifer using Neuman's (1975) equations (6) and (8) gives:

$$T = \frac{Q}{4\pi s} Wu, \qquad (9)$$

and

$$S = \frac{4 T u_A t}{r^2}; \qquad (10)$$

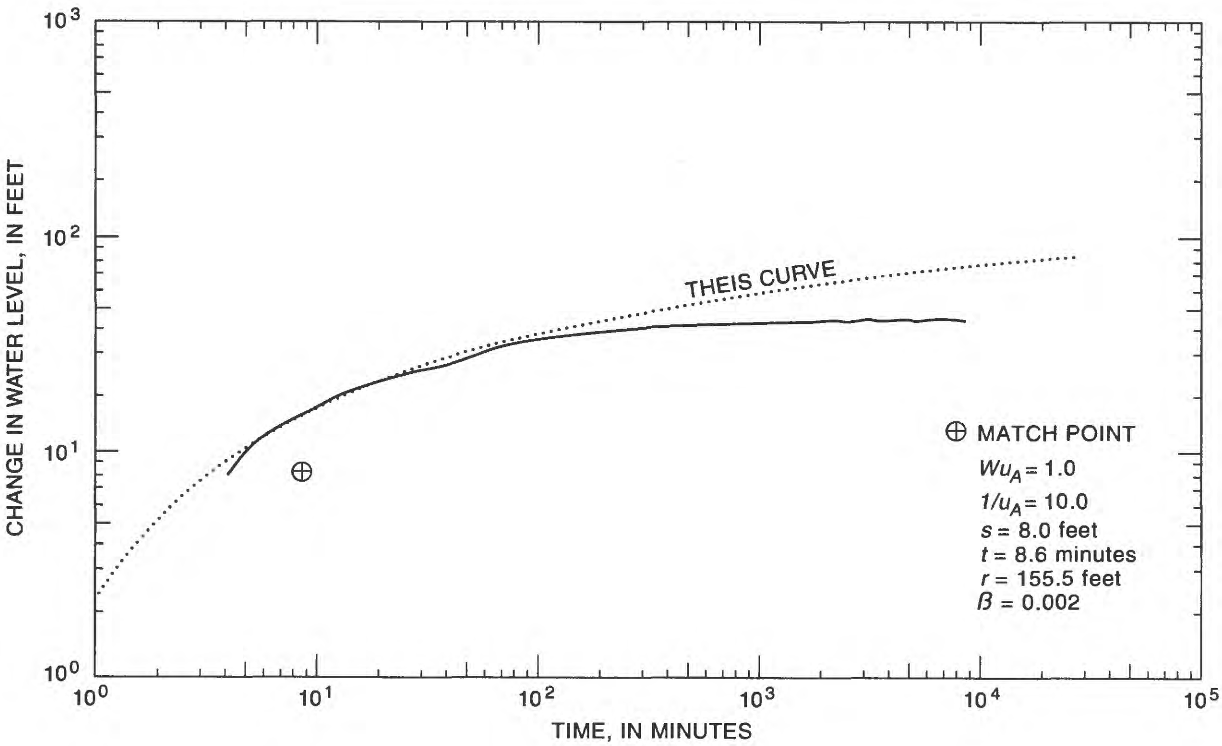



**Figure 8.** Drawdown data and type curve for well V–4 as well V–5 was being pumped at 2,000 gallons per minute.

therefore,

$$T = \frac{3.85x10^5}{4\pi(8)}(1) = 3,830\ \mathrm{ft}^2/\mathrm{d},$$

and

$$S = \frac{4(3,830)\,5.97x10^{-3}(0.1)}{155.5^2} = 3.8x10^{-4}.$$

These values for the composite aquifer are questionable for several reasons; but they are not unreasonable considering that only 345 ft of the total 1,104 ft of the aquifer system is screened or about 30 percent of the aquifer is contributing about 80 percent of water produced by the well. Also, as much as 65 percent of the water may be produced from the unconfined aquifer.

In order to obtain estimates of the transmissivity for each unit of the aquifer system, two assumptions were made. First, that the quantity of water produced from each unit of the aquifer is the same percentage of the total that was produced during the earlier test (fig. 7 and table 2). The yield of each unit is proportional to the average head change (drawdown) observed in the well. The drawdown measured in the well represents the average head change in the well bore opposite each aquifer unit. Then, using the transmissivity (3,830 ft²/d) calculated during "early time" or before the influence of the delayed gravity response, the transmissivity for each unit may be calculated from the percentage of flow from each unit. Figure 9 illustrates the results of these calculations. Using these results and the β value of 0.002 obtained from the drawdown test, the ratio of $K_z$:$K_r$ was calculated to be 1:10. The effects of the delayed gravity response observed at about 85 minutes also suggests that a value in this range is not unreasonable. In spite of the many limitations inherent in these tests, the values obtained from this analysis were used as estimates to derive reasonable hydraulic properties for the complex aquifer system underlying north Vekol Valley and subsequently to design a more definitive test at site NV–6.

## Test at Site NV–6

The aquifer test conducted at site NV–6 during August and September 1982 was the first long-term aquifer test designed and completed in Vekol Valley. The test site is underlain by a sequence of sand, gravel, and conglomerate with a thickness of about 1,500 ft. The water table is at a depth of about 345 ft below land surface in the uppermost sand and gravel. On the basis of the geology, the aquifer-system geometry, and the hydraulic properties determined at site V–5, the hydraulic properties were estimated for the aquifer system and used to design the test at site NV–6. Figure 10 shows the geology and the aquifer-system geometry along a geologic section between wells V–5 and NV–6p. Figure 11 shows hydraulic properties calculated for the aquifer units at well V–5 and the corresponding estimated hydraulic properties

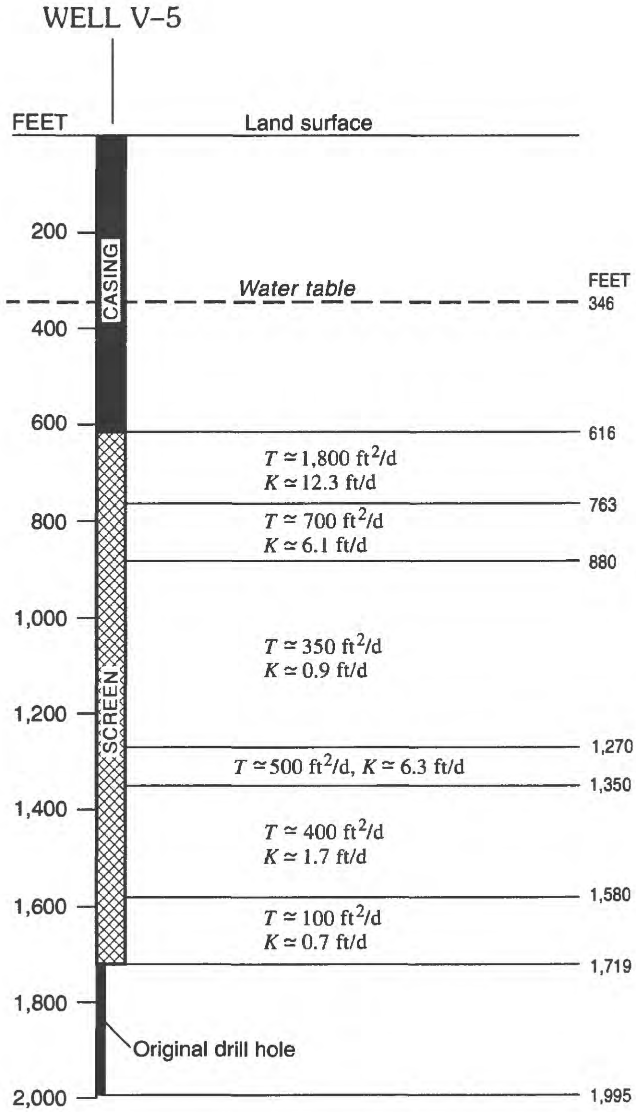



**Figure 9.** Estimated hydraulic characteristics for the aquifer system at well V–5.

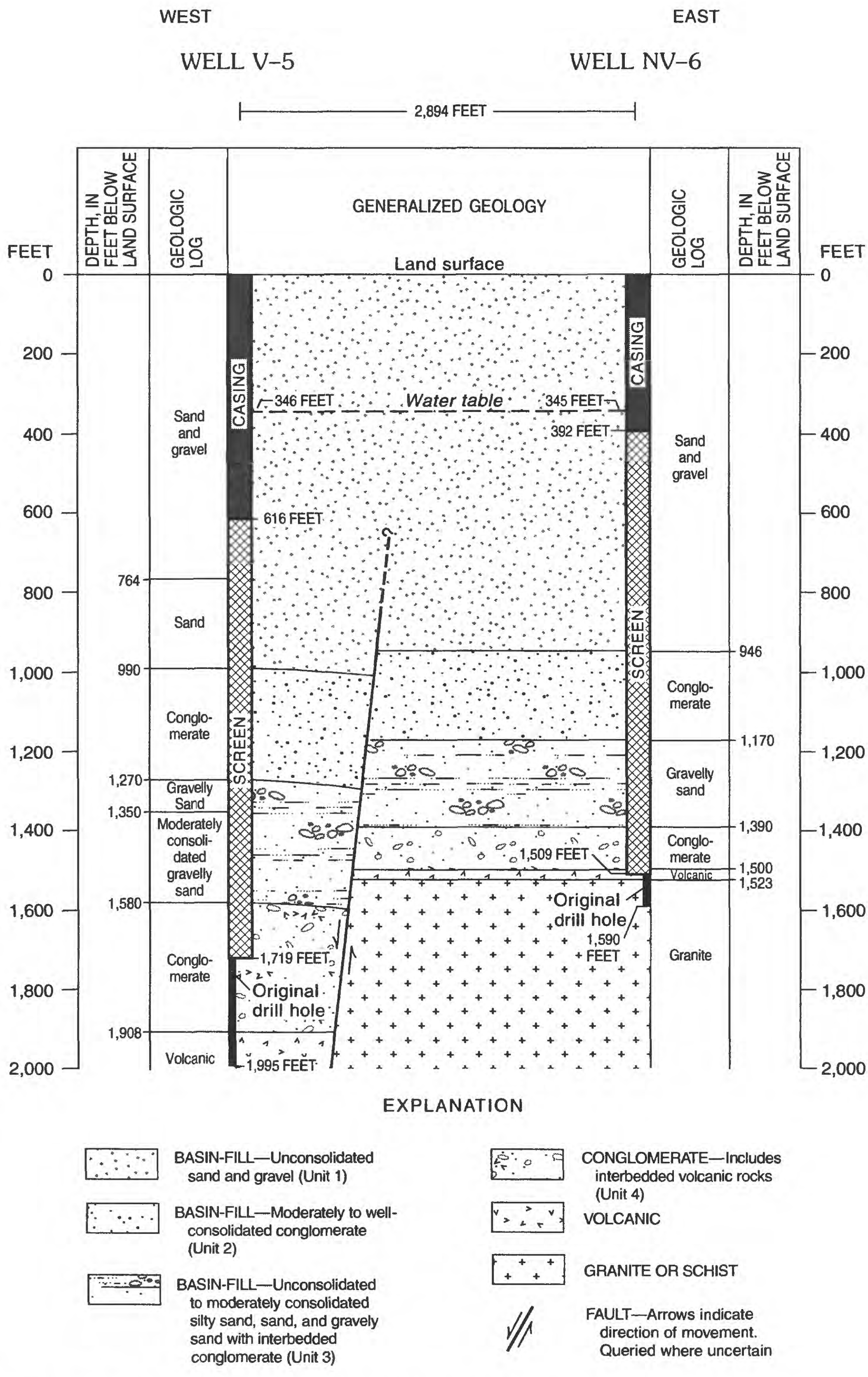



**Figure 10.** Geologic logs and generalized geologic section between wells V–5 and NV–6.

for the aquifer units at well NV–6p that were used to design the aquifer test at site NV–6. The aquifer test at site NV–6 was designed and conducted to: (1) determine the hydraulic properties of the unconfined part of the aquifer system, (2) corroborate the hydraulic properties of the confined part of the system that were determined from the tests conducted earlier at site V–5, and (3) conduct a recharge experiment. The recharge experiment was designed to (1) determine rates of recharge to the unconfined aquifer from water flowing in a natural ephemeral channel, (2) determine flow rates through the 330-foot-thick

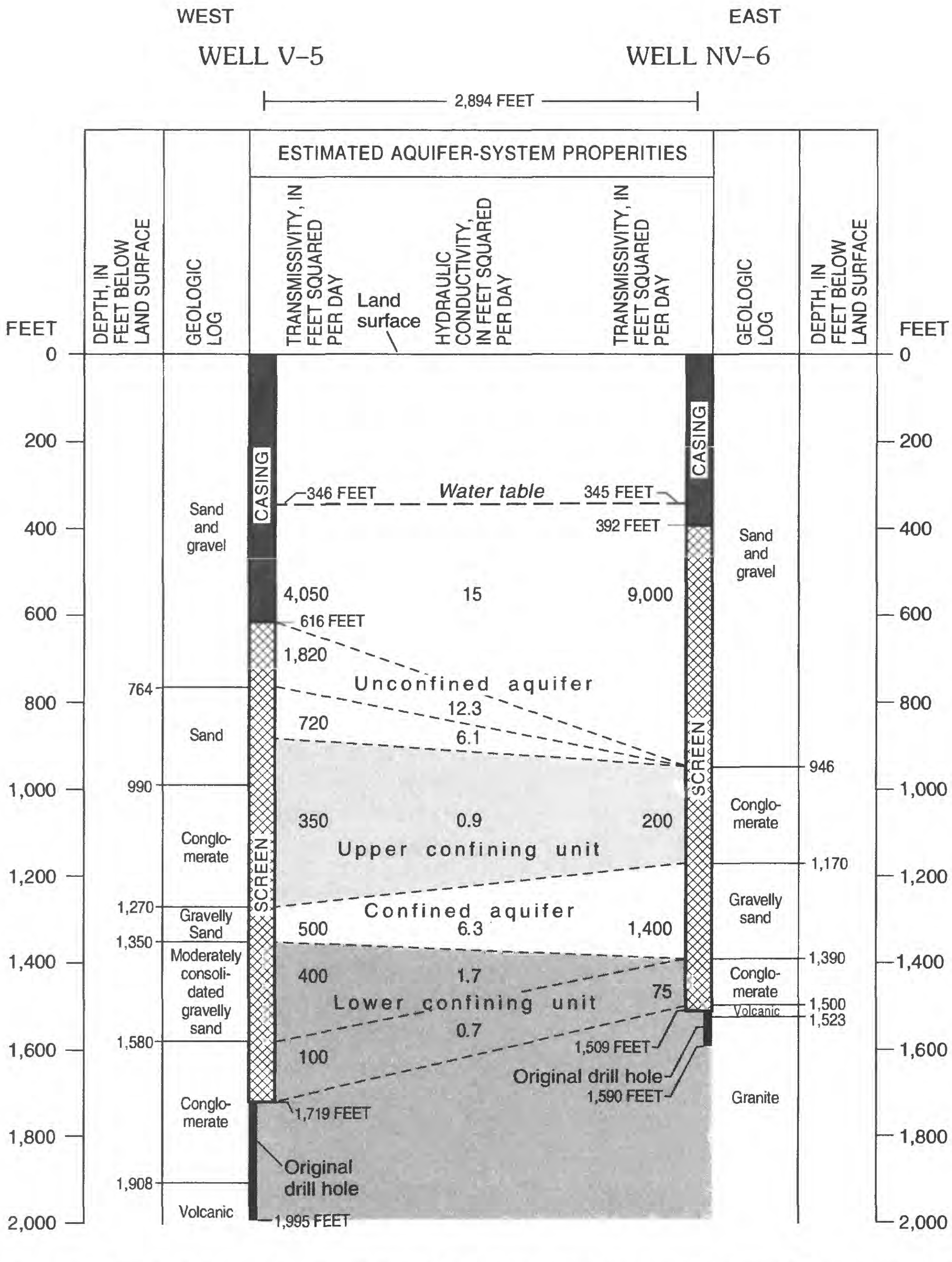



**Figure 11.** Geologic logs and estimated aquifer-system properties used to design the aquifer test at site NV–6. (See fig. 9 for changes in hydraulic characteritics.)

unsaturated zone at the experiment site, and (3) estimate the total amount and distribution of the water returning to the aquifer during the test. The locations of all observation wells and other installations used during the aquifer test are shown on figure 12.

The pumped well used for the aquifer test at site NV–6 was designed to produce 2,250 gal/min for 30 days. Actual measured discharge was 2,450 gal/min, which was maintained for 23 days. The water produced during the test was transported away from the site through a 10-inch pipeline for a distance of about 2,000 ft and discharged into a dry, ephemeral stream channel. Four weirs were installed in the channel from the outfall of the pipeline downstream for about 3,000 ft (fig. 12). Each weir was equipped with a continuous recorder. The pumping rate of the well (flow to the channel) was monitored using an in-line totalizing flowmeter and an automated, recording, circular orifice weir.

Twelve observation wells were used to monitor water-level changes and obtain other selected types of data. All observation wells were designed to provide data at specific depths, distances, and hydraulic conditions in relation to the pumped well to facilitate analysis of the aquifer test. These wells ranged in depth from about 500 to 2,000 ft (table 3). Their distance from the pumped well ranged from about 82 ft to 3.8 mi. Observation wells NV–5ob, NV–6ob1, and NV–7 fully penetrate the aquifer system. Wells NV–2ob and NV–3ob fully penetrate the upper, unconfined aquifer. Well V–5 partially penetrates the upper aquifer and fully penetrates the lower, confined aquifer. Wells NV–6c, NV–6ob2, NV–6ob3, NV–6ob4, and NV–6ob5 only partially penetrate the upper aquifer. Well NV–1ob was installed in one of the Basin and Range faults that forms the boundary of the valley. The heat-flow tube, NV–7c, which is about 100 ft from NV–7, fully penetrated the aquifer system; however, the tube was sealed and designed to provide only heat-flow data. Specific tests were conducted on all observation wells used during the aquifer test to assure adequacy as observation wells. Nine of the wells were equipped with recorders. The others were measured periodically using an electric sounder. Two recording barometers, two rain gages, and an evaporation pan equipped with a recorder also were installed. The discharge from well NV–6p was measured with an in-line flowmeter and a recording manometer. The discharge was adjusted as necessary to maintain a constant rate using a gate valve.

On August 3, 1982, a preliminary 20-minute test was run, and in this test, weirs 1 and 2 failed. All other equipment functioned properly. During the test, water moved downstream from weir 1 to weir 3. All of the weirs were reinforced with concrete for the aquifer test.

The aquifer test was started at 0832 hours, on August 9, 1982. The discharge of the pumped well stabilized at 2,450 gal/min in a few minutes. Data were collected until 0230 hours, August 10, when the engine driving the pump malfunctioned because of a fuel-flow problem. Recovery data were collected during this unscheduled shutdown. The problem with the pump was corrected, and the test resumed after 11 hours and 45 minutes at 1415 hours, August 10. The drawdown part of the test continued uninterrupted until the planned shutdown at 0830 hours, September 2, 1982, after about 23 days of pumping. During this time, the well yielded a consistent 2,450 gal/min. The recovery part of the test was continued for about 19 days.

The data collected from the aquifer test conducted at site NV–6 were analyzed using the curve-matching techniques described in the section of this report entitled "Methods Used for Analyses." The first step in the test analysis addressed the partial-penetration effects caused by well NV–6p. If the pumped well and the observation well(s) used during an aquifer test fully penetrate an anisotropic, water-table aquifer; the solution of Neuman (1972–75) is applicable, and no partial-penetration adjustment is required. For all other well penetrations, both for the pumped well and for all observation wells, adjustments must be made in order to solve for the aquifer properties.

The prepumping coefficient of penetration may be calculated using the equation:

$$Cp = \frac{b_b - Zt}{b_b - Wt}, \qquad (11)$$

where

$b_b$ = bottom of aquifer,
$Zt$ = top of well screen, and
$Wt$ = water table.

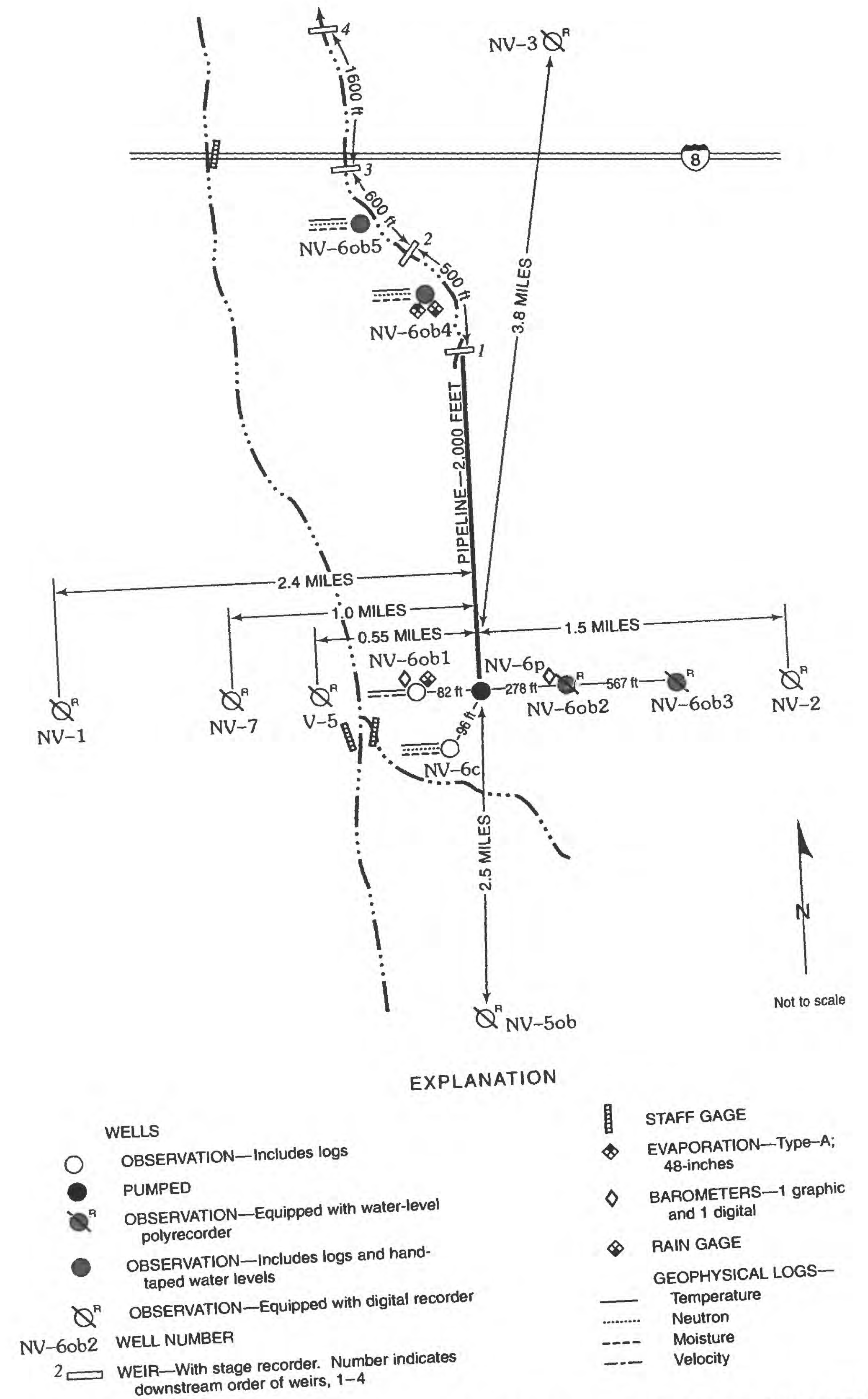



**Figure 12.** Location of wells and other equipment used for the aquifer test and recharge experiment conducted at site NV–6.

**Table 3**. Selected information from wells used during the aquifer test at site NV–6

| Well number | Radius, in feet | Altitude, in feet above sea level | Depth to bottom of casing, in feet | Screened interval, in feet, below land surface | | Method of water-level measurement |
|---|---|---|---|---|---|---|
| | | | | From | To | |
| NV–6p | 0.75 | 1,756 | 1,529 | 392 | 1,510 | Air line/tape |
| NV–6c | 96 | 1,756 | 1,395 | 508 | 518 | Tape |
| NV–6ob1 | 82 | 1,756 | 1,496 | 320 | 1,486 | Tape |
| NV–6ob2 | 278 | 1,758 | 550 | 529 | 549 | Recorder |
| NV–6ob3 | 567 | 1,761 | 550 | 529 | 549 | Recorder |
| NV–6ob4 | 1,943 | 1,743 | 506 | 486 | 506 | Tape/logs |
| NV–6ob5 | 2,407 | 1,741 | 507 | 486 | 506 | Tape/logs |
| V–5 | 2,894 | 1,755 | 1,729 | 616 | 1,719 | Recorder |
| NV–1 | 12,670 | 1,798 | 1,212 | 395 | 1,200 | Recorder |
| NV–2 | 7,920 | 1,797 | 1,057 | 396 | 1,057 | Recorder |
| NV–3 | 20,060 | 1,668 | 648 | 368 | 608 | Recorder |
| NV–5ob | 13,200 | 1,833 | 1,994 | 401 | 1,984 | Recorder |
| NV–7 | 5,197 | 1,763 | 1,519 | 447 | 1,499 | Recorder |

All values are in feet below datum. For well NV–6p:

$$b_b = 946 \text{ feet,}$$
$$Zt = 392 \text{ feet, and}$$
$$Wt = 345 \text{ feet.}$$

Using equation 11:

$$Cp = \frac{946 \text{ ft} - 392 \text{ ft}}{946 \text{ ft} - 345 \text{ ft}} = 0.92.$$

Because of this large coefficient of penetration (0.92), the assumption was made that the effects of partial penetration caused by the pumped well can be neglected for the first part of the analysis that uses the type-curve matching technique. However, the effects of partial penetration of the pumped well will be included in the second part of the analysis using Neuman's (1974) and Moench's (1993) computer programs to produce the site-specific type curves for each observation well. For the next step in the analysis, the data obtained from well NV–6ob1, the only fully-penetrating observation well, was analyzed.

#### Well NV–6ob1

Analysis of drawdown data from observation well NV–6ob1 (fig. 13), which fully penetrates the aquifer system, gives a transmissivity (using equation 9) for the "early part of the confined aquifer curve" of:

$$T = \frac{4.72x10^5}{4\pi(2)}(1) = 18,800 \text{ ft}^2/\text{d}.$$

For the "late unconfined part of the aquifer curve" using equation 9:

$$T = \frac{4.72x10^5}{4\pi(2.3)}(1) = 16,300 \text{ ft}^2/\text{d},$$

and using Neuman's (1975) equation 7:

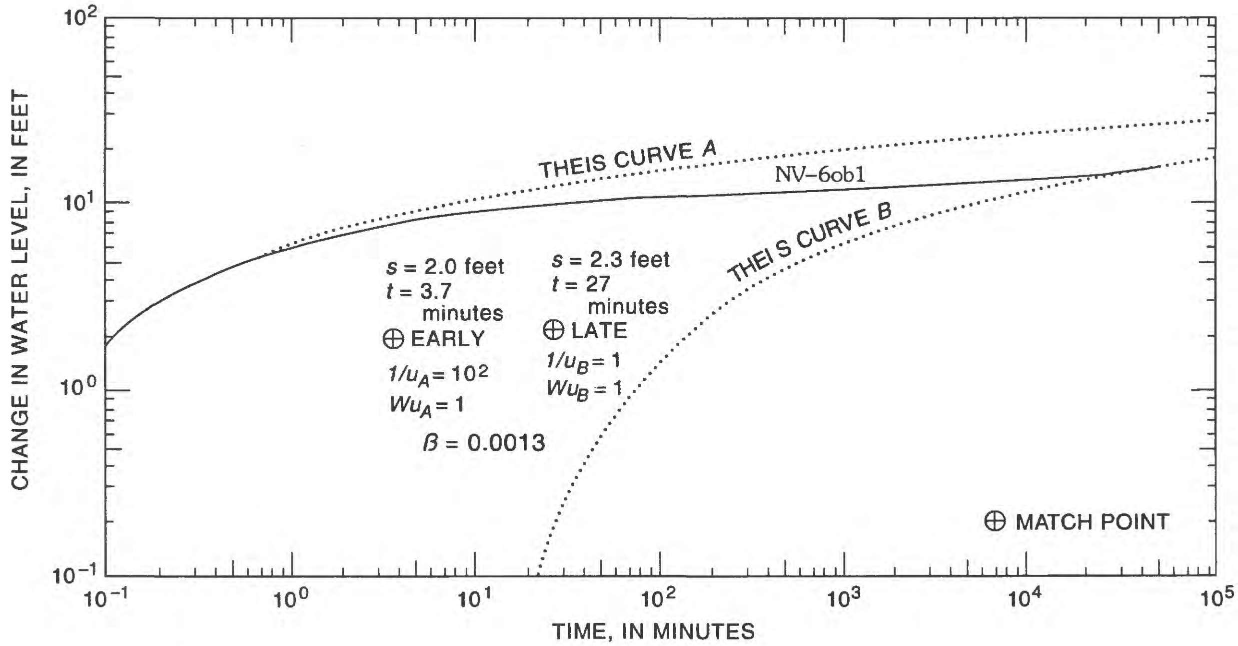



**Figure 13.** Neuman type-curve analysis for well NV–6ob1.

$$S_y = \frac{4Tu_Bt}{r^2}, \quad (12)$$

therefore,

$$S_y = \frac{4(16,300)(1)\left(\frac{27}{1,440}\right)}{82^2} = 0.18.$$

The ratio of $K_z$ *to* $K_r$ is calculated from a match of the "flat part" of the drawdown curve of β = 0.0013 and is about 0.07 or about 1:14 from equation 8:

$$\frac{K_z}{K_r} = \frac{(601)^2}{(82)^2}0.0013 = 0.07.$$

Data from these analyses of the water-level response to the pumping of well NV–6p indicate that the multiple-aquifer system exhibits the following hydraulic properties:

| | |
|---|---|
| Transmissivity | 16,300 ft²/d |
| Specific yield | 0.18 |
| $K_z$:$K_r$ | 1:14 |

On the basis of the interpretations of the geological and geophysical data available, the transmissivity value calculated for the confined, high-yielding zone in well V–5 is applied to the equivalent zone penetrated by well NV–6ob1 and gives an estimated transmissivity of about 14,500 ft²/d for the unconfined system at site NV–6. If this interpretation and extension of the *T* for the confined aquifer is valid, the analysis of data obtained for wells NV–6ob2 and NV–6ob3 that follows should corroborate these results.

### Wells NV–6ob2 and NV–6ob3

Wells NV–6ob2 and NV–6ob3 were installed in the unconfined part of the aquifer system so that the aquifer properties for that part of the system could be determined. Both wells, however, were constructed with only 20-foot screens to lessen the cost of well construction. Consequently, both wells partially penetrate the aquifer and the effects caused by this partial penetration must be considered if a realistic analysis is to be made of the hydraulic properties of the aquifer.

Knowing, for purposes of the aquifer-test analysis that NV–6p fully penetrates an anisotropic, water-table aquifer and that observation wells NV–6ob2 and NV–6ob3 only partially penetrate that aquifer, the duration that the partial penetration affects the observed response in NV–6ob2 and NV–6ob3 may be determined by using the methods by Stallman (1965) and Neuman (1974).

The method is an analysis of water-level changes caused by a partially penetrating observation well that is affected by the (1) placement of the screen of that well, (2) radial distance between the pumped well and the observation well, and (3) ratio of vertical to horizontal hydraulic conductivity. The method of calculating the partial-penetration factor (*Z/b*) caused by the placement of the screen (*z*) of an observation well in an aquifer having a thickness (*b*) is illustrated in figure 14.

Then, using Stallman's (1965) method for a fully penetrating pumped well and an observation well having a specific value of *Z/b* at a distance (*r*) from the pumped well in an aquifer, with a known or estimated ratio of $K_z$:$K_r$, a value for *y* is calculated using equation 6. Using this value of *y* and a dimensionless, partial-penetration type curve for *Z/b*, (Stallman, 1965; and fig. 10, Lohman, 1972, pl. 6), a value for *x* is obtained using equation 7.

Finally, a solution for the time when the partial-penetration effects disappear for the specific test conditions can be made by rearranging equation 7:

$$t = \frac{xr^2S_y}{T}. \qquad (13)$$

The values obtained as outlined above may then be corroborated using type curves drawn as described by Neuman (1974) and Moench (1993). This method produces type curves for specific field conditions that include the partial-penetration effects of those conditions and allows the transmissivity and specific-yield values to be calculated directly. This method was used to corroborate the values obtained using Stallman's (1965) technique.

As mentioned above, wells NV–6ob2 and NV–6ob3 were installed in the unconfined part of the aquifer system so that the properties for that aquifer could be determined. Both wells only partially penetrate the aquifer because they were constructed with only 20-foot screens set between depths of 529 and 549 ft to lessen the cost of well construction.

The water table was measured at 345 ft below land surface, and the bottom of the aquifer ($b_b$) was measured at 946 ft, which indicates that the unconfined aquifer is 601 ft thick (*b*). Because of the 20-foot lengths of screen ($Z_{os}$) installed in each well, the wells only penetrate about 3 percent of the aquifer. In order to use the observed time-drawdown information to calculate hydraulic properties of the unconfined aquifer, the time at which the effects of partial penetration will disappear must be determined.

The partial-penetration factor *Z/b* was calculated for both wells NV–6ob2 and NV–6ob3 using the midpoint of their screens.

$$Z/b = \frac{b_b - \left(d5 + \frac{Z_{os}}{2}\right)}{b}, \qquad (14)$$

and

$$Z/b = \frac{946 \text{ ft} - 427 \text{ ft}}{601} = 0.86.$$

Then, using Stallman's (1965) method for a fully penetrating pumped well and the observation wells having *Z/b* = 0.86 at distances (*r*) of 278 and 567 ft in an anisotropic aquifer where $K_z/K_r$ is in the range of 0.06 from the match of type curve B (Neuman, 1974) for NV–6ob1 using equation 6:

$$\beta = \frac{r}{b}\sqrt{\frac{K_z}{K_r}}.$$

Then, for well NV–6ob2:

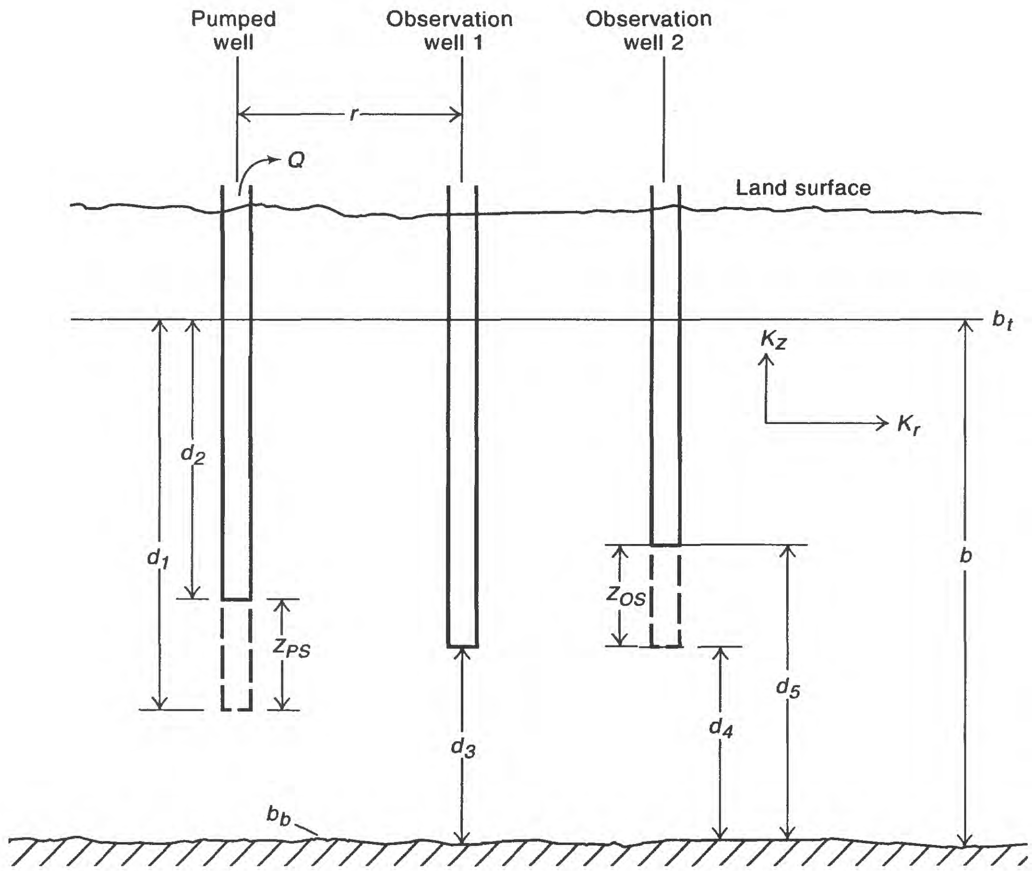
$$\beta = \frac{278 \text{ ft}}{601 \text{ ft}}\sqrt{0.06} = 0.113,$$

and for well NV–6ob3:

$$\beta = \frac{567 \text{ ft}}{601 \text{ ft}}\sqrt{0.06} = 0.231.$$

Using these values and the dimensionless, partial-penetration type curve for *Z/b* = 0.86 (fig. 15), a value for each well is obtained from the curve for equation 7. These values are 5 and 3.3 respectively for wells NV–6ob2 and NV–6ob3.

Solving for the time when the effects of partial penetration disappear at each well for well NV–6ob2 gives:




EXPLANATION

$K_z$ — Vertical hydraulic conductivity

$K_r$ — Horizontal hydraulic conductivity

$b$ — Initial saturated thickness, in feet

$b_b$ — Bottom of aquifer

$b_t$ — Top of aquifer

$d_1$ — Distance from initial water table to bottom of screen in pumped well

$d_2$ — Distance from initial water table to top of screen in pumped well

$d_3$ — Vertical distance from bottom of aquifer to bottom of open-end pipe used as observation well

$d_4$ — Vertical distance from bottom of aquifer to bottom of screen in the observation well

$d_5$ — Vertical distance from bottom of aquifer to top of screen in the observation well

$Q$ — Discharge from pumped well

$r$ — Distance from pumped well to observation well

$Z_{OS}$ — Length of screen in observation well

$Z_{PS}$ — Length of screen in pumped well

*Equations*

$PD = d_1 / b$

$DD = d_2 / b$

$ZD = d_3 / b$

$ZD_1 = d_4 / b$

$ZD_2 = d_5 / b$

$BD = b / r$

$CD = K_z / K_r$

$Z/b = (b_b) - (d_5 + Z_{OS} / 2) / b$

**Figure 14.** Relation of well-screen placement (*z*) to aquifer thickness (*b*) of pumped and obserfation wells.

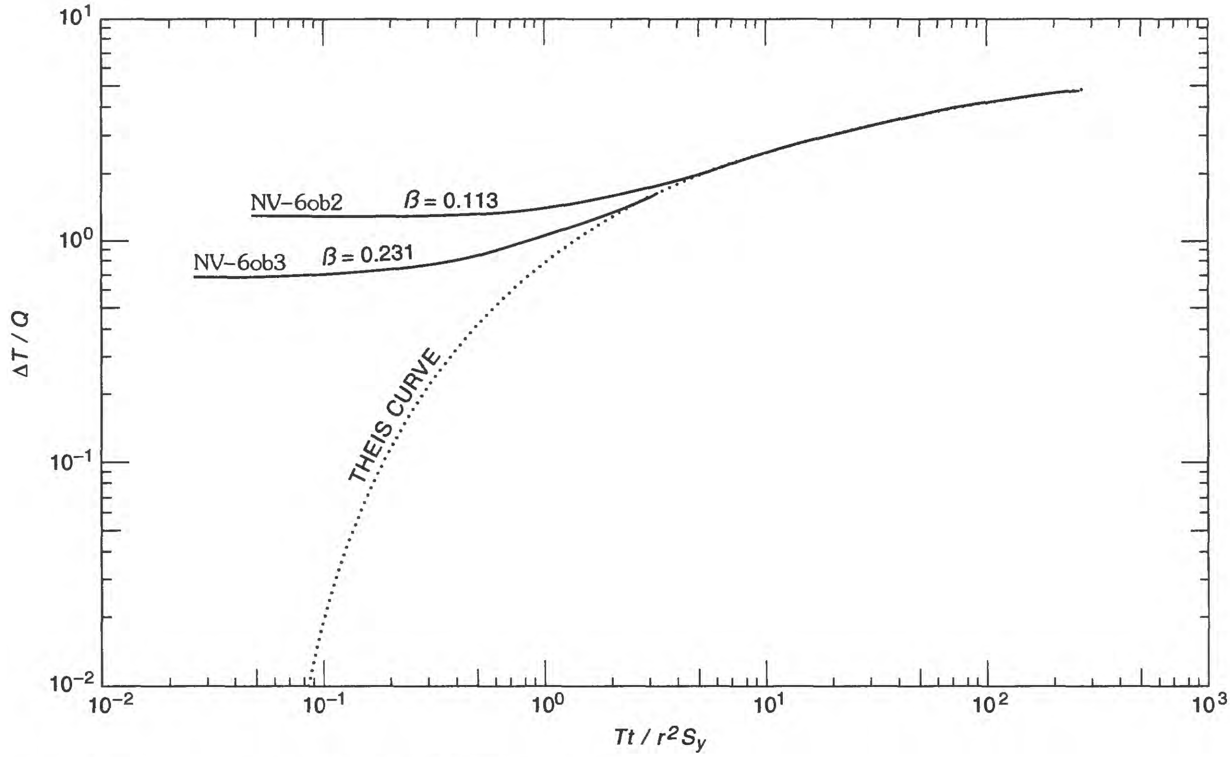



**Figure 15.** Partial-penetration type curve for *Z/b* = 0.86.

$$t = \frac{5r^2S_y}{T} = \frac{5\,(278\ \text{ft})^2\,(0.10)}{14,500\ \text{ft}^2/\text{d}} = 2.66\ \text{d} \sim 3{,}800\ \text{min},$$

and for well NV–6ob3:

$$t = \frac{3.3r^2S_y}{T} = \frac{3.3\,(567\ \text{ft})^2\,(0.10)}{14,500\ \text{ft}^2/\text{d}} = 7.32\ \text{d} \sim 10{,}500\ \text{min}.$$

The effects disappear for well NV–6ob2 at about 3,800 minutes and for well NV–6ob3 at about 10,500 minutes.

Using the observed time-drawdown data plots for wells NV–6ob2 and NV–6ob3 after the partial-penetration effects have disappeared, as shown on figure 16, gives the following hydraulic properties for the unconfined aquifer using equations 9, 12, and 8.

| Property | NV–6ob2 | NV–60b3 |
|---|---|---|
| Transmissivity | 13,000 ft²/d | 14,000 ft²/d |
| Specific yield | 0.13 | 0.08 |
| Ratio of $K_z$:$K_r$ | 1:9 | 1:12 |

These computed hydraulic properties, showing: (1) an increase in transmissivity values with radial distance from the pumped well are diagnostic of a "delayed gravity response" and (2) the decreasing specific-yield values are diagnostic of an anisotropic aquifer. These conditions are indicated by the geology at the NV–6 aquifer-test site. Then using these computed aquifer characteristics, a value for $K_z$ was calculated by the following method. First, using the equation:

$$K_r = \frac{T}{b},$$

and the aquifer characteristics obtained for well NV–6ob2:

1. $K_r = \dfrac{13{,}000\ \text{ft}^2/\text{d}}{601\ \text{ft}} = 21.6\ \text{ft/d},$

2. $K_z{:}K_r = 1{:}9$, and

3. $K_z = \dfrac{K_r}{9} = 2.4\ \text{ft/d}.$

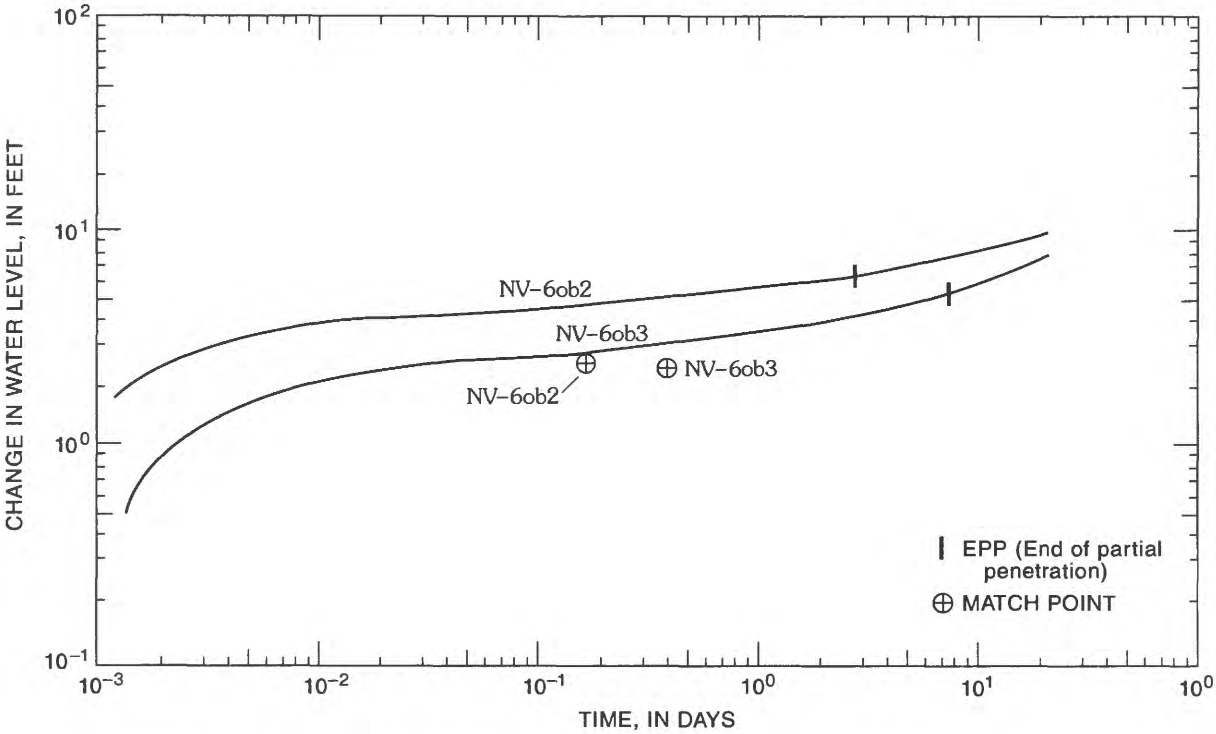



**Figure 16.** Analyses of time-drawdown data for wells NV–60b2 and NV–60b3 after partial-penetration effects disappear.

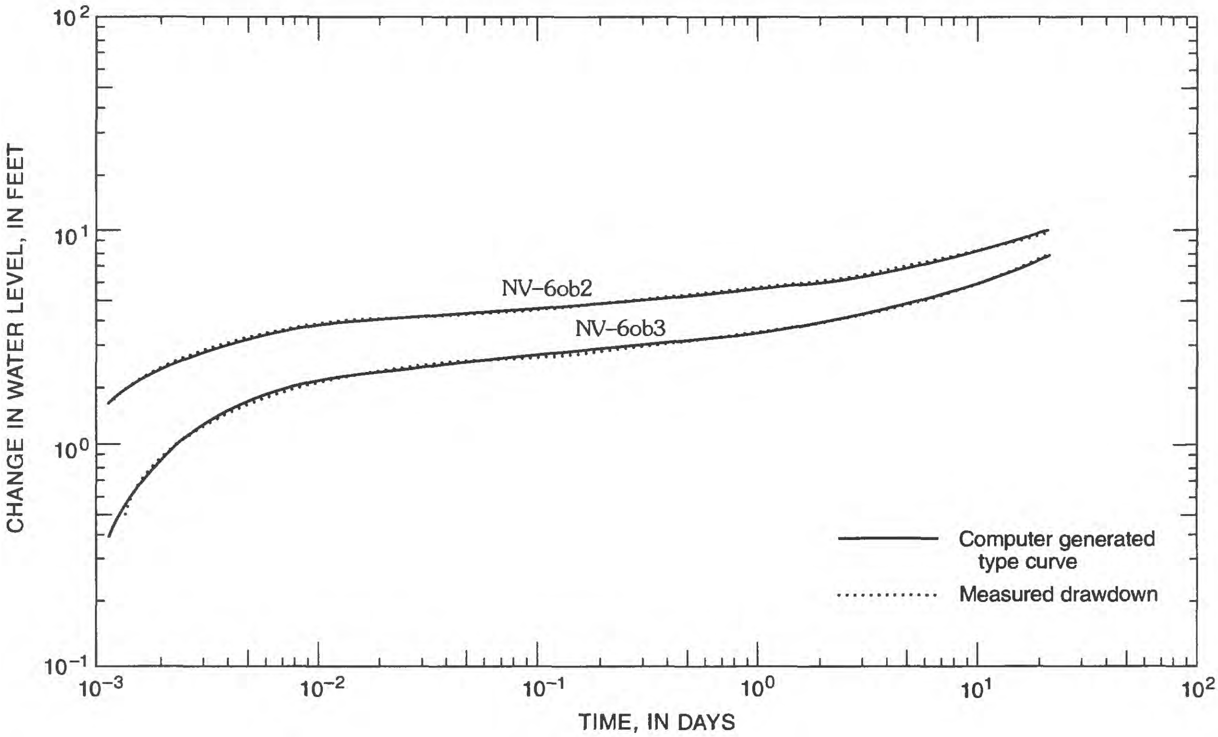



**Figure 17.** Site-specific type-curve analyses for wells NV–60b2 and NV–60b3.

Using the same method and the aquifer characteristics for well NV–6ob3 gives a $K_z$ value of 1.9 ft/d. An average value for $K_z$ is 2.2 ft/d.

The second approach to corroborate the aquifer properties used assumed aquifer-property values of $T$ = 13,500 ft²/d, $S_y$ = 0.12, and $K_z$:$K_r$ = 1:10 to 1:12 along with other calculated and measured values that characterize the system to generate a site-specific type curve for wells NV–6ob2 and NV–6ob3. These type curves then were matched to the complete data plot of $s$ and $t$ for those wells to re-evaluate the aquifer properties. The match of the site-specific type curves and the data plots are good for the entire drawdown period, especially for the $K_z$:$K_r$ value of 1:12 indicating that the computed and subsequently assumed values based on the computations above are realistic (fig. 17).

From this analysis of the water-level response of the unconfined aquifer to the pumping of well NV–6p, the conclusion was drawn that the unconfined aquifer at the NV–6 site has hydraulic properties of:

| Property | Site NV–6 |
|---|---|
| Transmissivity | 13,500 ft²/d |
| Specific yield | 0.12 |
| Ratio of $K_z$:$K_r$ | 1:12 |

On the basis of these calculated aquifer characteristics, a value for $K_z$ was calculated using the relation $T/b = K_r$ and $K_z$:$K_r$ = 1:12. The value for $K_z$ is 1.9. In addition, another technique that employs curve matching, but using a plot of observed drawdown ($s$) and the ratio of time ($t$) to the distance from the pumped well to the observation well squared ($r^2$), commonly referred to as a "continuity test," was used to verify that previously calculated $T$ and $S_y$ values for all data sets were consistent and reasonable. Finally, the semilogarithmic method (Cooper and Jacob, 1946) was used to obtain transmissivity values that would corroborate those values previously obtained.

## Continuity Method

A continuity evaluation of aquifer-test data consists of plotting observed drawdown data against the ratio of time ($t$) to the distance from each observation well to the pumped well squared ($r^2$) for all observation wells on the same logarithmic graph. The plot illustrates the degree of areal continuity of the aquifer properties ($T$, $S_y$, $K_z$, and $K_r$) by the closeness of the fit of the data plots to the set of type curves for an aquifer having those hydraulic properties. This evaluation may be the most important analysis of the entire aquifer test because the aquifer properties that are determined can be verified as truly consistent for all observed data.

The graph for $s$ and $t/r^2$ was plotted for wells NV–6ob1, NV–6ob2, and NV–6ob3 (fig. 18). Well NV–6ob1 is included to illustrate the correspondence of the entire aquifer system with the unconfined aquifer. This correspondence would be expected to be good because of the great effect the unconfined aquifer has on the drawdown observed for the entire system.The data plots appear to be consistent (fig. 18),

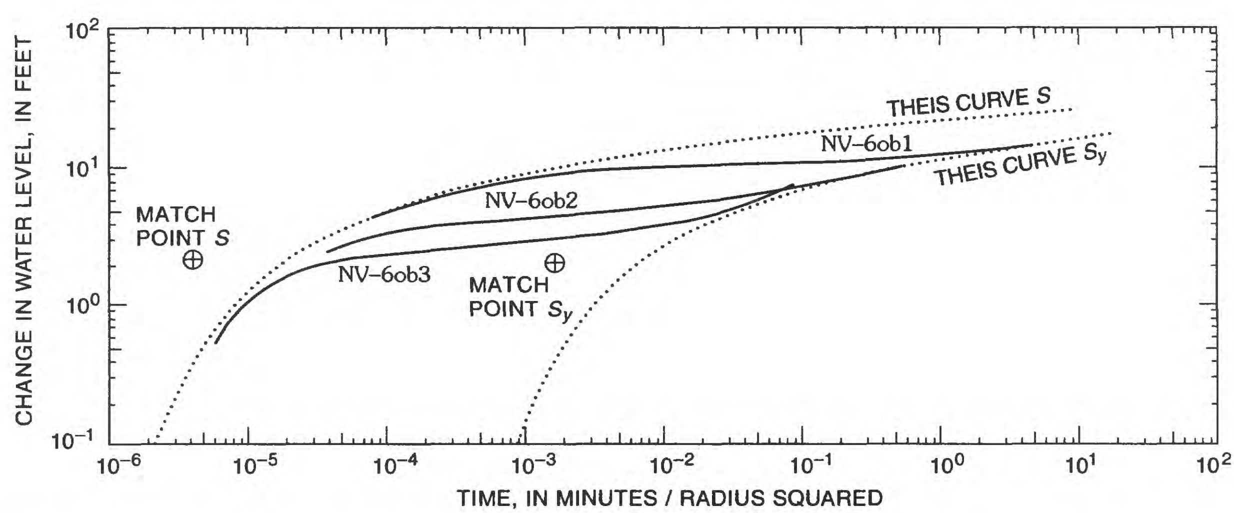



**Figure 18.** Analysis using the continuity method for wells NV–60b1, NV–609b2, and NV–60b3.

and calculations using equations 8, 9, 10, and 12 for both the "confined early" and "unconfined late" match points give values of:

| Property | Confined early | Unconfined late |
|---|---|---|
| Transmissivity | 17,500 $ft^2/d$ | 15,800 $ft^2/d$ |
| Storage ($S$ or $S_y$) | $2.0 \times 10^{-4}$ | 0.09 |
| Ratio of $K_z$:$K_r$ | ----- | 1:12 |

This evaluation of the areal continuity of the aquifer properties indicate that the observed water-level declines reasonably depict a consistent, unconfined aquifer system because the observed drawdown plots match well with the family type-curve set of the aquifer system and the computed values compare well with values computed from the individual analyses. An estimate of the average $K_z$ also was calculated and is 2.2.

### Straight-Line Method

A final technique, commonly referred to as the "straight-line method" (Cooper and Jacob, 1946) was used to calculate the aquifer-system properties for the NV–6 aquifer test. A thorough discussion of the method is beyond the scope of this report; however, Lohman (1972, p. 22–23) discusses the precautions that should be considered when applying the method. The crux of the problem in application of the method was emphasized by Neuman (1975, p. 335):

The hydrologist will do well to heed Prickett's (1965, p. 9) advice: "The effects of delayed gravity drainage must dissipate in all observation wells before using distance-drawdown data to compute the hydraulic properties of the aquifer. During the time when delayed gravity drainage is influencing drawdown in observation wells...an analysis of distance-drawdown data...will lead to erroneous results."

The drawdown data for observation wells NV–6ob1, NV–6ob2, and NV–6ob3 plot along the Theis curve for $1/u_B$ (fig. 18) of Neuman (1975) indicating that delayed gravity response has dissipated in those wells by the end of the test. Consequently, distance drawdown plots can be analyzed using the straight-line method (fig. 19). The solution for well NV–6ob1 gives a value for transmissivity of about 16,100 $ft^2/d$ for the entire aquifer system. The solution using wells NV–6ob2 and NV–6ob3 gives a value for transmissivity of 14,800 $ft^2/d$ for the unconfined aquifer. The solution for well V–5 gives a value of transmissivity of 2,500 $ft^2/d$ for the confined aquifer. These values are consistent with solutions derived earlier using the other methods.

In summary, the three techniques used to calculate the aquifer-system properties at site NV–6 gave reasonably consistent results as shown in the following table:

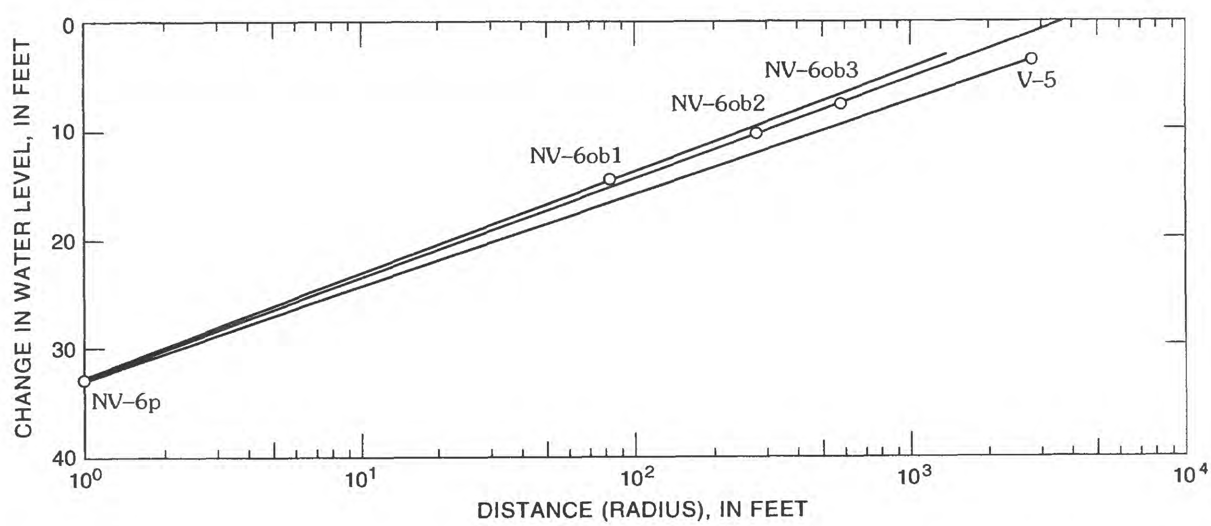



**Figure 19.** Analyses of drawdown with distance at $t$ = 32,832 minutes for selected wells at site NV–6.

| Method | Unconfined aquifer | Composite aquifer | Confined aquifer |
|---|---|---|---|
| Neuman (1975) | $T$ = 13,500 ft²/d<br>$S_y$ = 0.12<br>$K_z$:$K_r$ = 1:12 | $T$ = 16,300 ft²/d<br>$S_y$ = 0.18<br>$K_z$:$K_r$ = 1:14 | [1]2,800 ft²/d |
| Continuity | | $T$ = 15,800 ft²/d<br>$S_y$ = 0.09<br>$K_z$:$K_r$ = 1:12 | |
| Cooper and Jacob (1946) | $T$ = 14,800 ft²/d | $T$ = 16,100 ft²/d | $T$ = 2,500 ft²/d |

[1]Difference of composite minus unconfined.

## AQUIFER SYSTEM UNDERLYING SOUTH VEKOL VALLEY

Studies of the southern part of Vekol Valley that were conducted during 1979–83 show that the aquifer system underlying this part of the valley is composed primarily of a thick sequence of silt, sand, and gravel units deposited in a structurally controlled basin (fig. 20; also figs. 2–4). These units grade from a thick silt at or near the surface into underlying sand and gravel units that, in turn, grade from unconsolidated to well cemented with depth in the basin. These basin-fill sediments are intercalated with and underlain by a sequence of volcanic rocks unconformably overlying older rocks that compose the faulted blocks of the Basin and Range Province.

The upper unit of the basin-fill sedimentary deposits is comprised of silt to sandy silt that ranges from a few feet to about 600 ft thick. This unit exists in much of the central part of the southern valley; however, it is absent almost everywhere around the edge of the valley. This unit is overlain by the younger alluvium of the stream courses that is composed of thin beds of sand and gravelly sand. Underlying the upper silty unit is a sequence of sand, gravel, and conglomerate that can be divided into two aquifers. The upper aquifer consists of unconsolidated sand and gravel that ranges in thickness from a few feet near the perimeter of the basin to about 1,100 ft at site SV–11 in the central part of the valley. Underlying the upper aquifer throughout most of the southern valley is a lower gravel and conglomerate aquifer that is about 1,000 ft thick at site SV–8. The gravel and conglomerate aquifer, however, was not present in core holes to the north and northwest at sites SV–1, SV–9, and SV–10. Underlying the lower aquifer in much of the southern valley and contemporaneous, at least in part, with the lower aquifer, is a sequence of volcanic rocks that are as much as 925 ft thick at site SV–6. The volcanics, like the overlying conglomerate, are not present at sites SV–1 and SV–10; however, the volcanic rocks are about 700 ft thick at site SV–9 where the conglomerate is absent.

Depths to ground water in wells in the southern part of the valley range from about 330 to 670 ft below land surface (table 4). Outflow from the southern part of the valley cannot be determined from the water-level data for existing wells. The water-level contours indicate that the direction of ground-water movement generally is from the mountains surrounding the valley toward the center of the valley. Ground water probably does not flow northward from the southern part of the valley because the top of the buried fault block that separates the valley into two distinct aquifer systems extends more than 200 ft above the water level and probably prevents flow to the north. Only one well (X on fig. 20) is known to be drilled into the unconsolidated rocks in the extreme southern end of the valley. The water level in this well was reported to be about 300 ft higher than the water levels in wells V–2, SV–6, and SV–11 farther north. Geologic mapping by Dockter and Keith (1978) show that the southern part of Vekol Valley is completely surrounded by rocks that are nearly impermeable at or near the surface. The presence of outcropping nearly impermeable rocks and available water-level data that show a northward gradient of about 4 ft/mi toward the center of the basin and a depth greater than 400 ft indicate that the southern part of the valley may be a closed ground-water basin. Water-level data are not available to determine if vertical-head differences exist in the various aquifers underlying the southern part of the valley. Data do not indicate whether the ground water flows northward through the buried fault block or toward an exit at the southern end of the valley as hypothesized by Robertson (1991) using geochemical data or if the discharge from the southern part of the valley is by evapotranspiration or some combination of these and other conditions.

## TEST HOLES AND WELLS INSTALLED IN SOUTH VEKOL VALLEY

As part of an extensive well-drilling program that was undertaken in Vekol Valley from 1978–84,

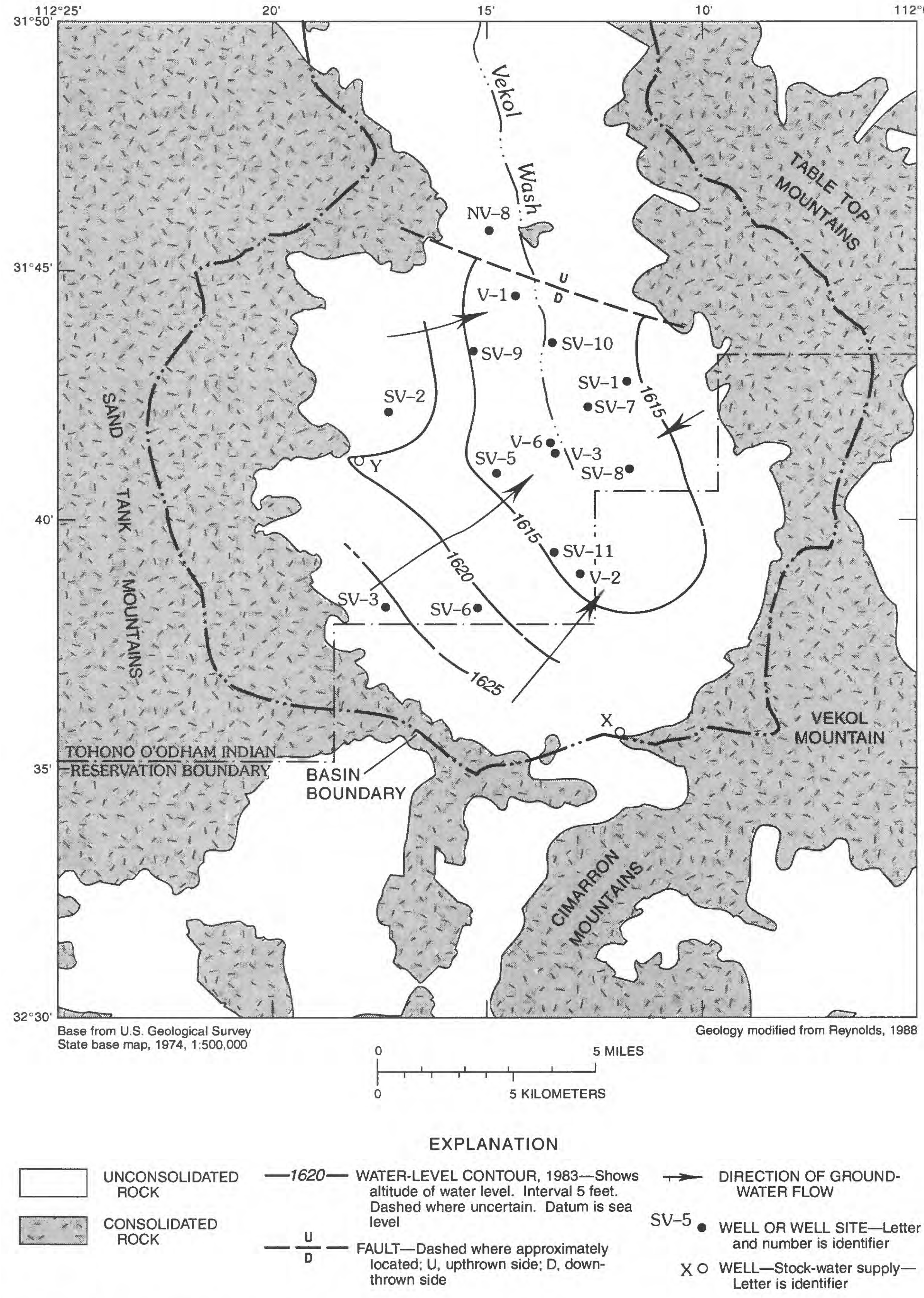



**Figure 20.** Configuration of the water table in south Vekol Valley.

**Table 4.** Test holes drilled and wells installed in south Vekol Valley

[Dashes indicate no data]

| Well number | Location | | | Land-surface altitude, in feet above sea level | Depth, in feet below land surface | Screen or open hole, in feet below land surface | | Water level, below land surface | |
|---|---|---|---|---|---|---|---|---|---|
| | Township | Range | Section | | | From | To | Depth, in feet | Date |
| **Production** | | | | | | | | | |
| V–2 | 9S | 1E | 13 | 2,048 | 1,983 | ----- | ------- | 436 | 1983 |
| V–6 | 8S | 1E | 35 | 1,002 | 1,474 | ----- | ------- | 389 | 1983 |
| SV–8 | 8S | 2E | 31 | 2,050 | 1,947 | 602 | 1,955 | 438 | 1983 |
| SV–11 | 9S | 1E | 11 | 2,050 | 1,740 | 699 | 1,720 | 436 | 1983 |
| **Observation** | | | | | | | | | |
| V–1 | 8S | 1E | 11 | 1,946 | 1,313 | ----- | ------- | 334 | 1983 |
| V–3 | 8S | 1E | 35 | 2,004 | 1,981 | ----- | ------- | 390 | 1983 |
| SV–1 | 8S | 2E | 19 | 2,092 | 1,050 | ----- | ------- | 479 | 1983 |
| SV–2 | 8S | 2E | 30 | 2,165 | 981 | ----- | ------- | 532 | 1983 |
| SV–3 | 9S | 1E | 18 | 2,296 | 960 | ----- | ------- | 669 | 1983 |
| SV–8ob1 | 8S | 2E | 31 | 2,050 | 2,000 | 657 | 1,980 | 438 | 1983 |
| SV–8ob2 | 8S | 2E | 31 | 2,050 | 2,007 | 663 | 1,987 | 438 | 1983 |
| SV–11ob1 | 9S | 1E | 11 | 2,050 | 1,979 | 406 | 1,959 | 436 | 1983 |
| SV–11ob2 | 9S | 1E | 11 | 2,050 | 1,741 | 700 | 1,720 | 436 | 1983 |
| **Core** | | | | | | | | | |
| SV–5c | 8S | 1E | 34 | 2,070 | 1,924 | 20 | 1,924 | 455 | 1983 |
| SV–6c | 9S | 1E | 15 | 2,150 | 2,000 | 20<br>871 | 261<br>2,000 | 533 | 1983 |
| SV–7c | 8S | 1E | 25 | 2,025 | 1,984 | 104<br>1,117 | 817<br>1,984 | 410 | 1983 |
| SV–8c | 8S | 2E | 31 | 2,050 | 2,000 | 30<br>1,024 | 344<br>2,000 | 438 | 1983 |
| SV–9c | 8S | 1E | 21 | 2,020 | 1,460 | 60 | 1,460 | 413 | 1983 |
| SV–10c | 8S | 1E | 14 | 1,960 | 1,747 | 60<br>1,000 | 100<br>1,747 | 349 | 1983 |
| **Extensometer** | | | | | | | | | |
| SV–11ext1 | 9S | 1E | 11 | 2,050 | 1,660 | 1,060 | 1,119 | 438 | 1983 |
| SV–11ext2 | 9S | 1E | 11 | 2,050 | 700 | 560 | 660 | 438 | 1983 |

21 test holes and wells were drilled at 14 sites in the southern part of the valley north of the Tohono O'Odham Indian Reservation (fig. 21). The test holes included two core holes that were drilled through the entire aquifer system and into the underlying granite or schist—one to a depth of 1,924 ft, the other to a depth of 2,000 ft. Two core holes—one to a depth of 1,460 ft, the other to a depth of 1,747 ft—were drilled through the aquifer system and into the underlying green shale and dolomite that is typical of rocks of early Paleozoic age. The other two core holes were terminated in the aquifer system—one at a depth of 1,984 ft in the sand and gravel of the upper alluvial aquifer, the other at a depth of 2,000 ft in the conglomerate of the lower part of the aquifer system. Core recovery from these holes, as in the northern part of the valley, was better than 90 percent. All six

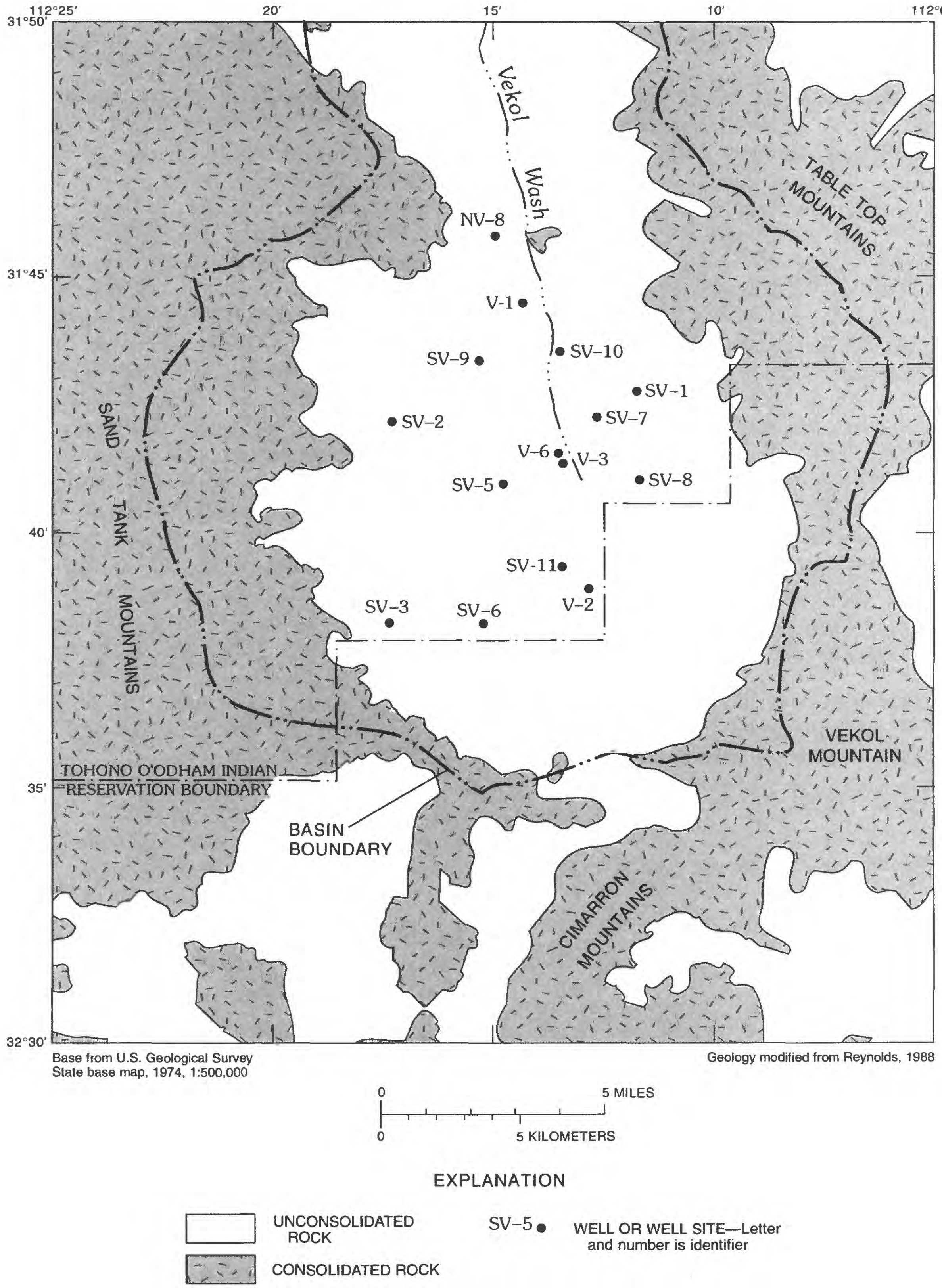



**Figure 21.** Location of selected wells and well sites in south Vekol Valley.

of the core holes were used as observation wells—two were left open; the other four holes were partially cased.

In addition to the core holes, 13 wells were drilled, cased, and (or) screened, fully developed, and tested, and included 4 production wells and 9 observation wells. Some of the wells are screened throughout the aquifer system. Others are screened only in specific aquifers. Most of the wells were finished using wire-wrapped, high-flow, stainless-steel screen. The wells range in diameter from 2 to 26 in. and in depth from 526 to 2,020 ft.

Two extensometers were constructed at site SV–11. Extensometer SV–11ext1 was designed to measure the compaction of the aquifer system. SV–11ext1 was completed at a depth of 1,660 ft on top of a 20-foot cement plug set in the top of the volcanics, which is principally basalt and underlies the aquifer system. SV–1ext1 also was designed to be used to measure heat flow in the aquifer system. Extensometer SV–11ext2 was designed to measure the compaction occurring in the silty confining unit. SV–11ext2 was completed at a depth of 660 ft on top of a 20-foot cement plug set in the top of the upper confined aquifer.

Aquifer tests were conducted using wells V–6, SV–8, and SV–11 as pumped wells. All other available wells, including the two extensometers, were used as water-level or heat-flow observation wells during these tests (table 4; fig. 21). Well-construction information is shown in table 4 and in the section entitled "Well-Construction Information" at the end of this report.

## AQUIFER TESTS IN SOUTH VEKOL VALLEY

Hydrologic information was based on exploration drilling, standard methods of estimating aquifer properties, and the results of testing similar aquifer materials in north Vekol Valley. The aquifer system underlying south Vekol Valley was expected to be a leaky, confined system with the possibility of converting to an unconfined system depending on the amount of water-level decline actually caused by the pumped wells. The pretest estimates of transmissivity and storage coefficient for well sites SV–8 and SV–11 were used to help design the aquifer tests (fig. 22).

The aquifer system at well site SV–8 is comprised of three zones. From the surface to about 800 ft is a silt to sandy silt. From about 800 to 1,000 ft is an unconsolidated sand and gravel. From about 1,000 ft to the bottom of the well at 1,955 ft is a sequence of interbedded gravel and conglomerate. The 200-foot-thick unconsolidated sand and gravel was estimated to have a transmissivity of 3,050 $ft^2/d$ and a storage coefficient of $2x10^{-4}$.

The aquifer system at well site SV–11 is much different from that underlying site SV–8. The unconsolidated sand and gravel at site SV–11 is about 1,100 ft thick; however, it is overlain by the same silt and sandy silt that is at site SV–8. The assumption was that the early-time response during the aquifer test at site SV–11 would be as a confined system and as the water level declined, the aquifer would become unconfined. The test results at SV–11 were expected to give a specific-yield value of about 0.12 or about what was calculated for site NV–6.

Before the aquifer tests, production wells SV–8 and SV–11 were tested using a 950-horsepower, diesel-driven turbine pump rated at a discharge of 4,000 gal/min against 600 ft of head. The tests in each well consisted of a three- or four-increment step-discharge, drawdown test and a short-term instrument calibration test before the long-term, constant-discharge, drawdown and recovery test was made. Discharge rates were measured using a totalizing flowmeter and an orifice plate coupled with a pressure transducer activated by a nitrogen manometer that, in turn, was coupled to a continuous recorder. All available wells were used to obtain water-level data during these tests. Drawdown and recovery water levels in the pumped wells were measured using an electric sounder. Water levels in the observation wells, including the extensometers, were measured using recorders and steel tapes.

### Methods Used for Analysis

On the basis of the geology of south Vekol Valley, aquifer tests conducted at sites SV–8 and SV–11 were expected to show that the aquifer received considerable water from the overlying silty unit and that the analysis of the tests would require that a "leaky aquifer" approach be used for the solution.

A preliminary evaluation of the drawdown data confirmed this by showing the characteristic and diagnostic increasing transmissivity values for each observation well further from the pumped well when

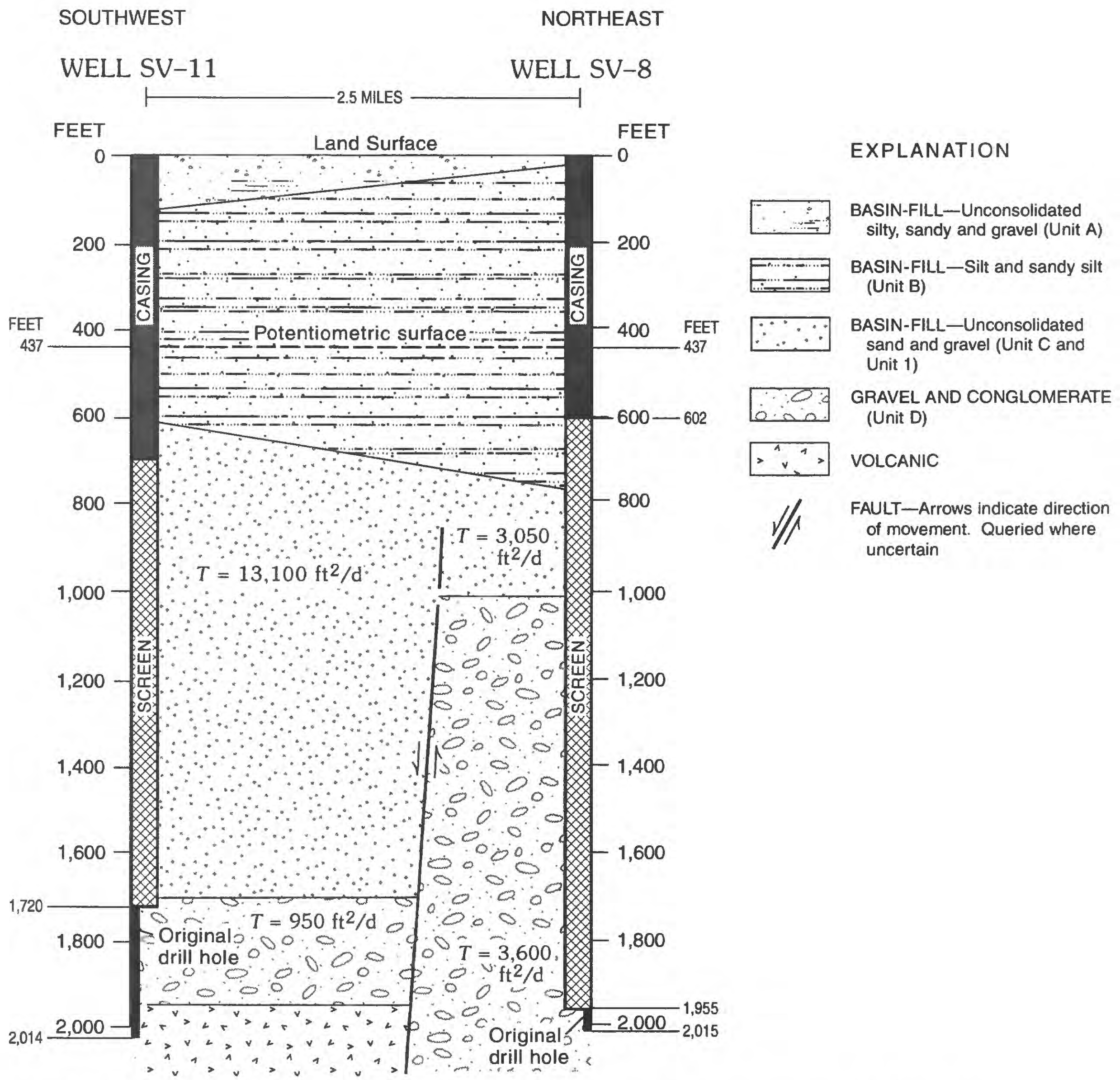



**Figure 22.** Estimated aquifer-system properties used to design the aquifer test at sites SV–8 and SV–11.

calculated using the Theis type-curve method. The values obtained from this preliminary evaluation were:

| Well number | Radial distance, in feet | Transmissivity, in feet squared per day |
|---|---|---|
| SV–8ob1 | 200 | 7,000 |
| SV–8ob2 | 500 | 7,800 |
| SV–11ob1 | 200 | 9,100 |
| SV–11ob2 | 500 | 10,300 |
| V–2 | 3,650 | 24,300 |

Consequently, the analyses of the constant-discharge drawdown tests were made using a technique that would allow solution for a "leaky artesian aquifer" to which water was contributed from an overlying confining bed. This technique is based on a combination of methods described by Cooper (1963) and Neuman (1975) that includes plotting all drawdown and recovery data for each test against $t/r^2$ on one graph. The analysis then consists of the usual observed data and type-curve matching procedure for a "continuity analysis," but uses the additional matches for each individual data curve with the flat part of the intermediate type curve to calculate the value of vertical hydraulic conductivity ($K_z$) of the confining bed using equation 8:

$$\beta = \frac{r^2 K_z}{b^2 K_r}.$$

If the geology is relatively uniform in the area of water-level decline caused by the pumping during the aquifer test, the values calculated for the $K_z$ of the confining bed for each observation well should be the same because the $K_z/b^2K_r$ part of the equation above should approximate a constant value.

After calculating values for transmissivity and storage coefficient, the values of β obtained from the matched type curve are used along with the aquifer thickness ($b$); the radial distance to each observation well ($r$); and the estimated value of $K_r$ (= $T/b$) in equation (8) to solve for the vertical hydraulic conductivity ($K_z$) of the confining bed at each observation well. As stated before, these values for $K_z$ should be approximately the same if the geology is fairly uniform.

The additional matches of the data with the family of type curves allows for the validation of the calculated values of transmissivity and storage coefficient if the expected uniformity of the vertical hydraulic conductivity of the confining bed is found. In addition, an evaluation of the leakage from the overlying confining bed in response to the withdrawal from the confined aquifer also can be made.

## Test at Site SV–8

Two constant-discharge, drawdown and recovery tests were conducted at well site SV–8. The first test was run for about 22 hours at 3,770 gal/min to test all equipment and obtain preliminary data. The main test was run for about 9 days at 3,400 gal/min. All available wells in south Vekol Valley (fig. 23), including the pumped well, were used to collect water-level data during the tests. However, in addition to the pumped well, only observation wells SV–8ob1 and SV–8ob2 showed water-level changes caused by pumping from well SV–8.

The aquifer test conducted at site SV–8 was expected to show that the aquifer received large amounts of water from the overlying silty unit. The preliminary evaluation of the drawdown data did show the characteristic increasing transmissivity values for each observation well that is further from the pumped well, which is diagnostic of leaky conditions. The values obtained from this preliminary evaluation were:

| Well number | Radial distance, in feet | Transmissivity, in feet squared per day |
|---|---|---|
| SV–8ob1 | 200 | 6,500 |
| SV–8ob2 | 500 | 7,700 |

The analysis of the 9-day, constant-discharge test was made using the technique based on a combination of methods described individually by Cooper (1963) and Neuman (1975). Again, the method consists of plotting all drawdown and recovery data for the test against $t/r^2$ on one graph. The analysis consists of the usual data/type-curve matching procedure and calculations of transmissivity and storage coefficient and then uses the additional match of each individual data curve with the flat part of the intermediate type curve to obtain an β value and to calculate the $K_z$ for the overlying confining bed at each observation well. The calculated $K_z$ values for each observation well should be the same, that is the value for:

$$\frac{\beta}{r^2} = \frac{K_z}{b^2 K_r} = \text{Constant.} \qquad (15)$$

The data obtained are plotted on figure 24 along with the type curves. Analysis of drawdown and recovery data using equations 6 and 8 and the match points shown on figure 24 are given below. Well SV–8 was pumped at 3,770 gal/min on October 26, 1983, and at 3,420 gal/min on November 9, 1983. The match points and calculations for well SV–8ob1 ($r$ = 200 ft) are as follows:

| Well | Date of drawdown | Match points and calculations |
|---|---|---|
| SV–8ob1 | 10–26–83 | $t$ = 7.2 min<br>$s$ = 8.3 ft<br>$1/u_A$ = 10<br>$Wu_A$ = 1 |

$$T = \frac{Q}{4\pi s} Wu_A = \frac{7.26x10^5}{4\pi\,(8.3)} = 6,960\,(7,000)\ \text{ft}^2/\text{d},$$

and

$$S = \frac{4Ttu_A}{r^2} = \frac{4\,(6,960)\,(5x10^{-3})\,(0.1)}{200^2} = 3.48x10^{-4}.$$

| Well | Date of recovery | Match points and calculations |
| --- | --- | --- |
| SV–8ob1 | 11–9–83 | $t = 12.5$ min<br>$s = 8.0$ ft<br>$1/u_A = 10$<br>$Wu_A = 1$ |

$$T = \frac{Q}{4\pi s} Wu_A = \frac{6.58x10^5 (1)}{4\pi (8.0)} = 6,549\,(6,500)\ \text{ft}^2/\text{d},$$

and

$$S = \frac{4Ttu_A}{r^2} = \frac{4\,(6,549)\,(8.7x10^{-3})\,(0.1)}{200^2} = 5.7x10^{-4}.$$

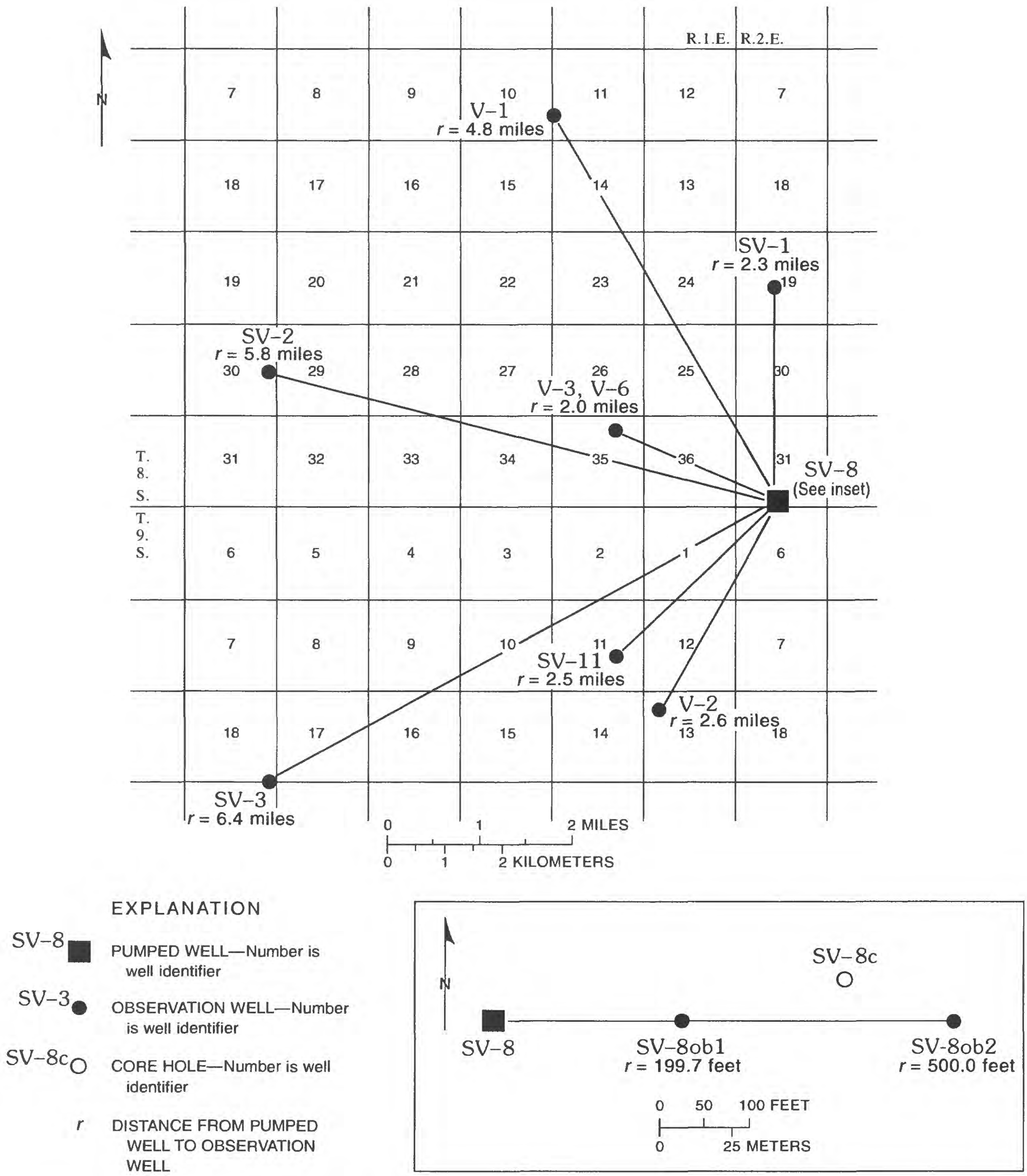



**Figure 23.** Layout for aquifer test at site SV–8. (Source: Modified from the Bureau of Indian Affairs, 1984.)

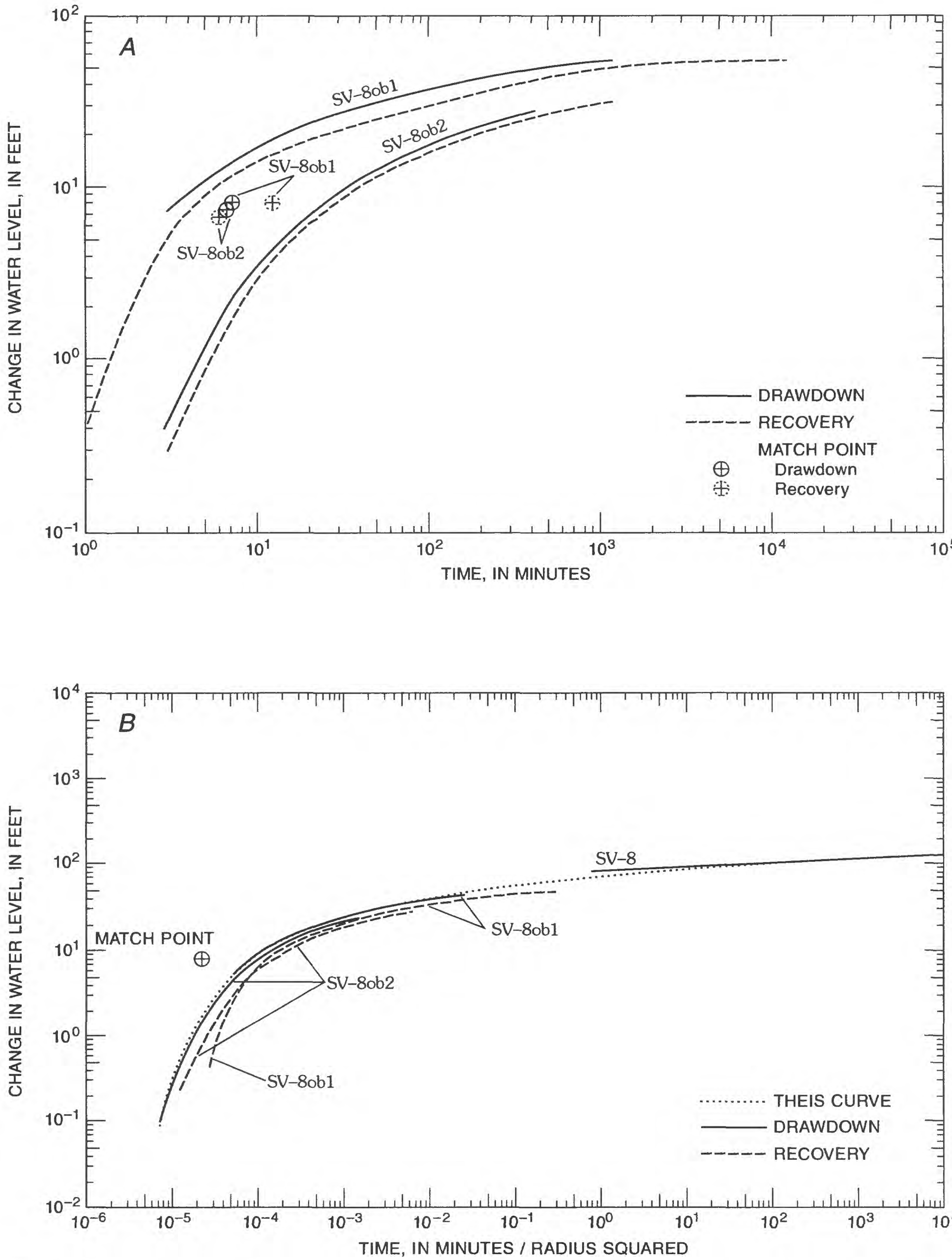



**Figure 24.** Analyses of aquifer-test data at site SV–8. A, Drawdown and recovery and match points for solution of Theis equation; B, Drawdown and Theis type curve and match point for the continuity method.

The match points and calculations for well SV–8ob2 ($r$ = 500 ft) are as follows:

| Well | Date of drawdown | Match points and calculations |
|---|---|---|
| SV–8ob2 | 10–26–83 | $t$ = 5.8 min<br>$s$ = 7.4 ft<br>$1/u_A = 1$<br>$Wu_A = 1$ |

$$T = \frac{Q}{4\pi s} Wu_A = \frac{7.26x10^5 (1)}{4\pi (7.4)} = 7,807\,(7,800)\ \mathrm{ft}^2/\mathrm{d},$$

and

$$S = \frac{4Ttu_A}{r^2} = \frac{4\,(7,807)\,(4.03x10^{-3})\,(1)}{500^2} = 5.03x10^{-4}.$$

| Well | Date of recovery | Match points and calculations |
|---|---|---|
| SV–8ob2 | 11–9–83 | $t$ = 6.0 min<br>$s$ = 6.8 ft<br>$1/u_A = 1$<br>$Wu_A = 1$ |

$$T = \frac{Q}{4\pi s} Wu_A = \frac{6.58x10^5 (1)}{4\pi (6.8)} = 7,700\,(7,700)\ \mathrm{ft}^2/\mathrm{d},$$

and

$$S = \frac{4Ttu_A}{r^2} = \frac{4\,(7,700)\,(4.2x10^{-3})\,(1)}{500^2} = 5.17x10^{-4}.$$

The match points and calculations for the continuity method are as follows:

| Well | Match points and calculations |
|---|---|
| Continuity method | $t/r^2 = 2.2x10^{-5}$ min/ft$^2$<br>$s$ = 8.3 ft<br>$1/u_A = 1$<br>$Wu_A = 1$ |

$$T = \frac{Q}{4\pi s} Wu_A = \frac{7.26x10^5 (1)}{4\pi (8.3)} = 6,960\,(7,000)\ \mathrm{ft}^2/\mathrm{d},$$

and

$$S = \frac{4Ttu_A}{r^2} = \frac{4\,(6,960)\,(2.2x10^{-5})\,(1)}{1,440} = 4.25x10^{-4}.$$

| Well | Drawdown | Recovery | Continuity |
|---|---|---|---|
| SV–8ob1 | $T$ = 7,000 ft$^2$/d<br>$S = 3.48x10^{-4}$ | $T$ = 6,500 ft$^2$/d<br>$S = 5.7x10^{-4}$ | $T$ = 7,000 ft$^2$/d<br>$S = 4.25x10^{-4}$ |
| SV–8ob2 | $T$ = 7,800 ft$^2$/d<br>$S = 5.03x10^{-4}$ | $T$ = 7,700 ft$^2$/d<br>$S = 5.17x10^{-4}$ | |

The transmissivity values calculated using these methods are within 10 percent of the average value (7,200 ft$^2$/d). On the basis of the analysis outlined above, the following properties can be assigned to the aquifer underlying site SV–8:

| | |
|---|---|
| Transmissivity | 7,200 ft$^2$/d |
| Storage coefficient | $5.5x10^{-4}$ |
| Ratio of $K_z$:$K_r$ | 1:63 |
| Thickness of the high transmissive zone | 220 ft |
| Given a maximum aquifer thickness | 1,260 ft |
| Average aquifer hydraulic conductivity, $K_r$ | 5.6 ft/d |
| $\beta$ | 0.0004 |
| Constant | $1.0x10^{-8}$ |
| $K_z$ | 0.09 |

The storage coefficient calculated for the aquifer underlying site SV–8 is $5.5x10^{-4}$ and is only slightly higher than that calculated for the expansion of water in an aquifer that has a porosity of 30 percent. The value calculated for the expansion of water is $5.04x10^{-4}$.

## Test at Site SV–11

A constant-discharge drawdown and recovery-aquifer test was conducted at site SV–11 during December 1983 and January 1984. Well SV–11 was pumped at a constant rate of 4,450 gal/min for about 21 days. All available wells in south Vekol Valley (fig. 25), including the pumped well, were used to collect water-level data. In addition to the pumped well, only wells SV–11ob1, SV–11ob2, and V–2 and extensometers SV–11ext1 and SV–11ext2 showed water-level changes caused by pumping from well SV–11. Well V–2, about 3,600 ft from SV–11, was the farthest well from SV–11 that showed water-level responses to the pumping.

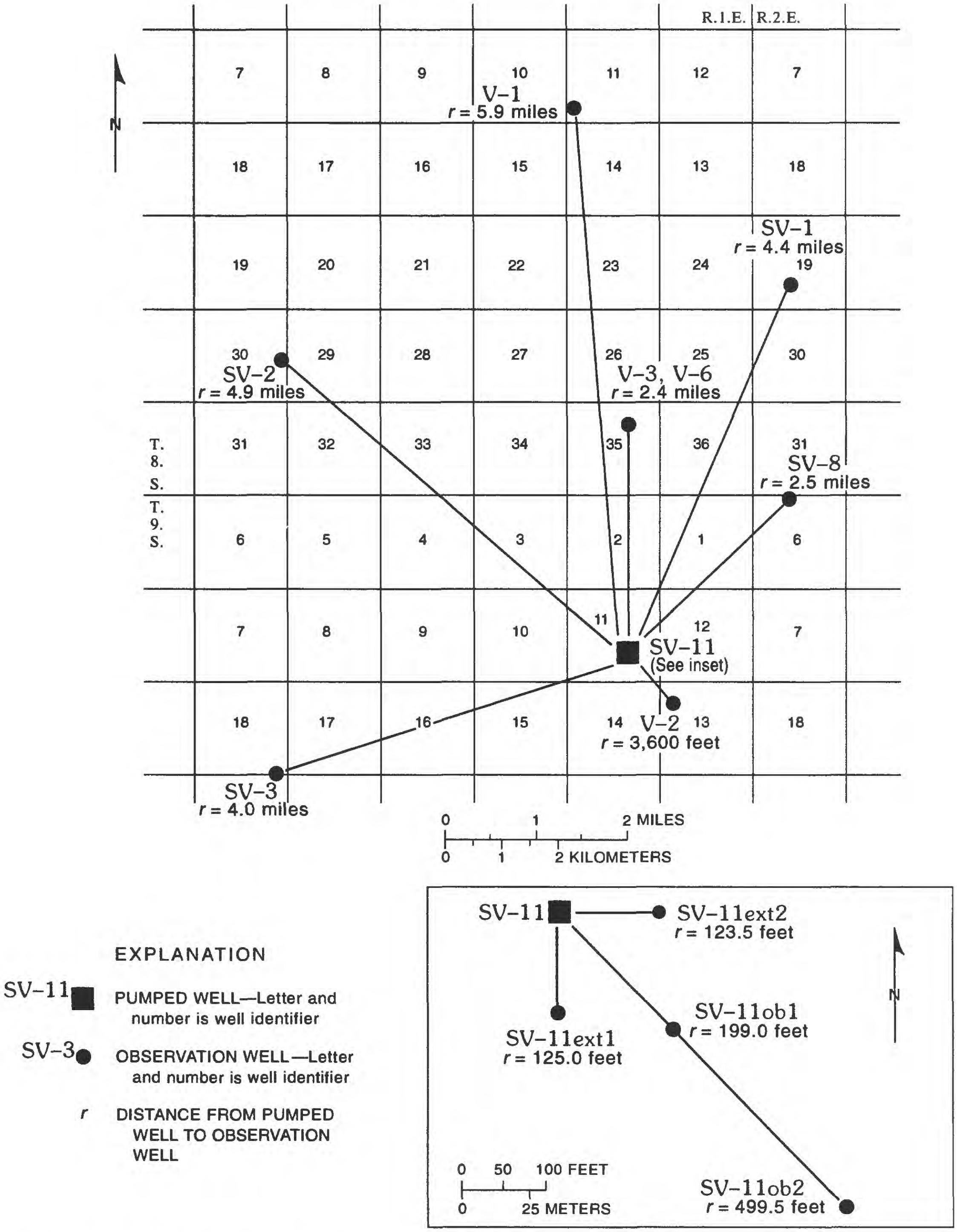



**Figure 25.** Layout for aquifer test at site SV–11. (Source: Modified from the Bureau of Indian Affairs, 1984.)

As at site SV–8, the aquifer test conducted at site SV–11 was expected to show that the aquifer received considerable water from the overlying silty unit and that it would convert from confined to unconfined during the pumping period. A preliminary evaluation of the data did show the characteristic increasing transmissivity values for each observation well further and further from the pumped well that is diagnostic of leaky conditions. The values obtained from this preliminary evaluation were as follows:

| Well number | Radial distance, in feet | Transmissivity, in feet squared per day |
|---|---|---|
| SV–11ob1 | 200 | 9,100 |
| SV–11ob2 | 500 | 10,300 |
| V–2 | 3,650 | 24,300 |

As at site SV–8, the analysis of the aquifer-test data was made using the technique based on a combination of methods described individually by Cooper (1963) and Neuman (1975) as discussed in the section entitled "Methods Used for Analysis for South Vekol Valley." The data/type-curve plots are shown on figure 26. The analysis was done in the same manner as was the analysis for SV–8 and produced the following results:

| Well number | Radial distance, in feet | Transmissivity, in feet squared per day | Storage coefficient |
|---|---|---|---|
| SV–11 | ([1]) | 8,960 | 0.12 |
| SV–11ob1 | 200 | 9,100 | $1.9 \times 10^{-3}$ |
| SV–11ob2 | 500 | 10,300 | $4.8 \times 10^{-4}$ |
| V–2 | 3,650 | 24,300 | $9.1 \times 10^{-4}$ |

| Well number | β | Constant | $K_z$ |
|---|---|---|---|
| SV–11 | -------- | ------------- | ------- |
| SV–11ob1 | 0.0004 | $1.000 \times 10^{-8}$ | 0.113 |
| SV–11ob2 | .0026 | $1.040 \times 10^{-8}$ | .121 |
| V–2 | .1400 | $1.051 \times 10^{-8}$ | .123 |

[1]Pumping well.

On the basis of this analysis, the following properties can be assigned to the aquifer system underlying site SV–11:

| | |
|---|---|
| Transmissivity | 9,000 $ft^2/d$ |
| Storage coefficient (before conversion) | $3 \times 10^{-4}$ |
| Specific yield (after conversion) | 0.12 |
| Ratio of $K_z$:$K_r$ | 1:56 |
| Given an aquifer thickness of | 1,320 ft |
| Average aquifer hydraulic conductivity | 6.8 ft/d |

## RECHARGE EXPERIMENT

A recharge experiment was conducted in conjunction with the 23-day aquifer test at site NV–6 to determine: (1) water loss from a natural channel, (2) flow rate through the 330-foot-thick unsaturated zone, and (3) the quantity of water reaching the unconfined aquifer. The recharge experiment (fig. 27) used the 2,450 gal/min (5.46 $ft^3/s$) of water pumped from well NV–6p during the aquifer test. The water was transported through a 2,000-foot pipeline and discharged into a dry, ephemeral channel. A recording circular orifice weir was installed at the end of the pipeline to record discharge. Four Cipolletti weirs with recorders were used to monitor flow in the channel. The channel was about 4 to 12 ft wide and 2 to 7 ft deep and had a thin layer, less than 1 ft, of alluvial sand and gravel covering the bottom of the channel. The basin-fill material underlying the alluvium is a poorly consolidated, silty to gravelly sand. In addition to the weirs, two wells were installed adjacent to the channel and downstream from the first weir in which borehole-geophysical logs (neutron, natural gamma, and temperature) and water-level measurements were made. Flow had not occurred in the ephemeral channel for at least 30 days before the experiment, except for the short-term pumping of well NV–6p during the equipment test.

The discharge records showed that water losses increased steadily to a maximum but a lower rate for each successive channel reach. The water losses decreased in succession from the upstream reach, which stabilized at 1.09 $ft^3/s$ per 1,000 ft of channel length after 14 days, to the downstream reach, which stabilized at 0.64 $ft^3/s$ per 1,000 ft after 20 days. These flow losses were directly related to flow depth and channel geometry. Flow extended for about 7,000 ft downstream from the end of the pipeline. The flow widened the channel for about 900 ft, removed most fine-grained alluvial material for about 3,500 ft, and

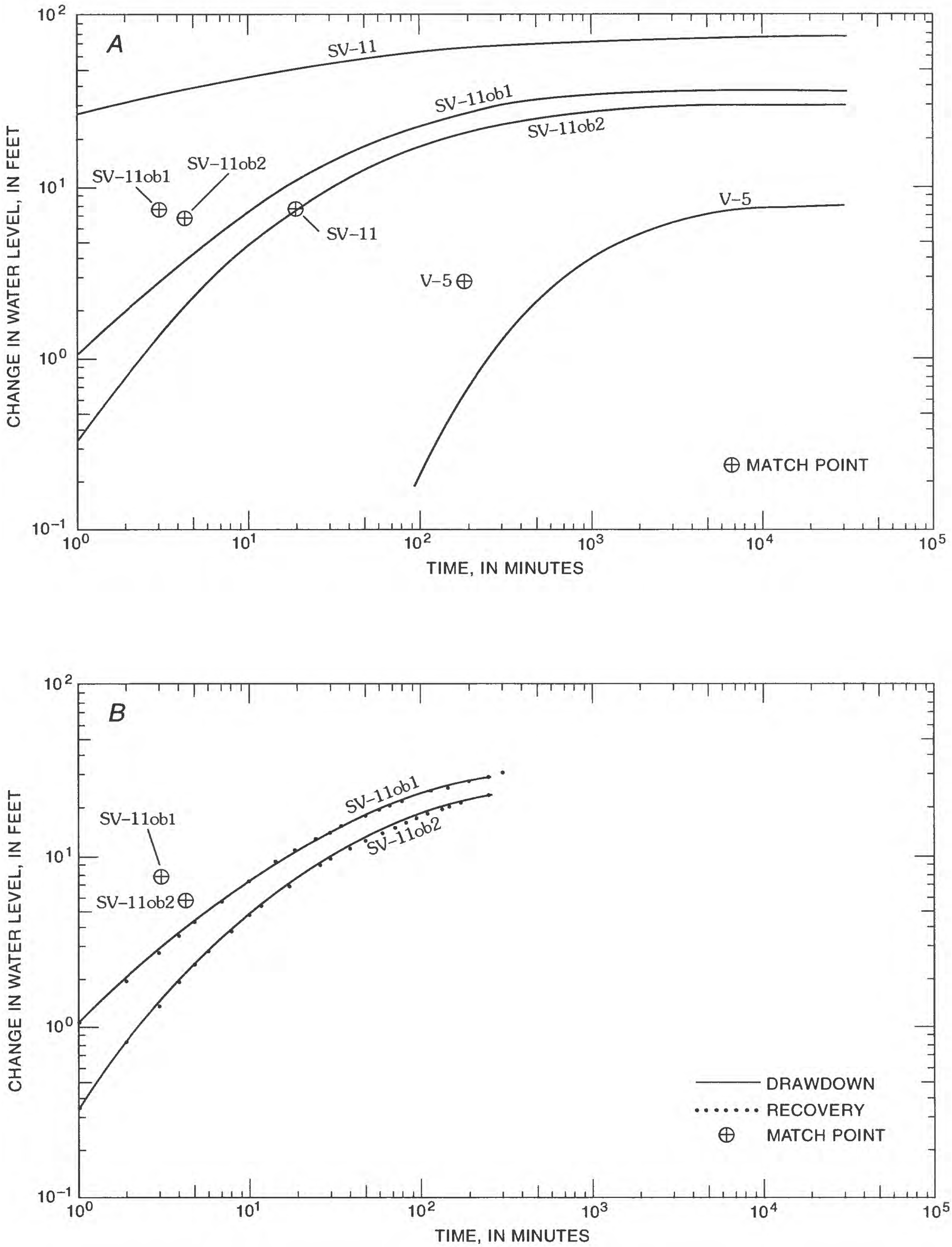



**Figure 26.** Analyses of aquifer-test data at site SV–11. A, Drawdown at wells SV–11p, SV–11ob1, SV–11ob2, and V–2; B, Drawdown and recovery at wells SV–11ob1 and SV–11ob2; C, Drawdown and Theis type curve and match point for the continuity method.

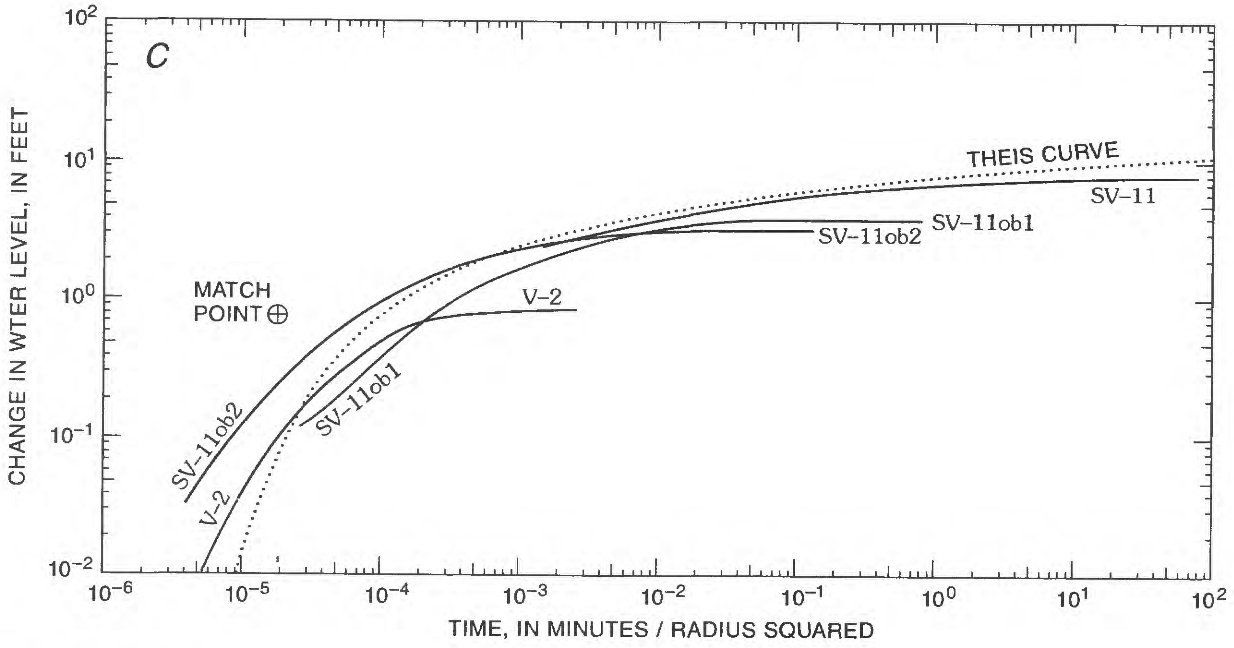



**Figure 26.** Continued

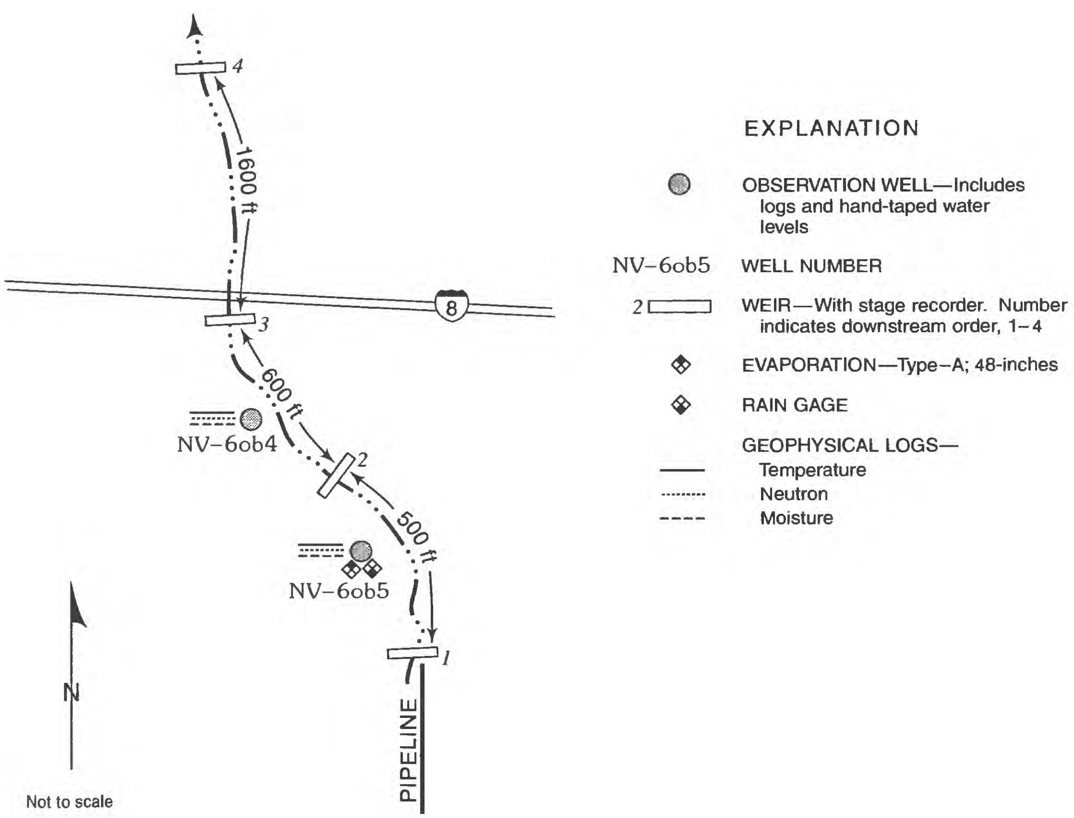



**Figure 27.** Recharge experiment conducted during the aquifer test at site NV–6.

deposited intermittent layers of sand and silt farther downstream. These channel changes were related to the water discharge and velocity in each reach.

Values calculated for vertical hydraulic conductivity using steady, channel-loss rates for each reach ranged from 2.9 to 7.1 ft/d. The average value calculated from the aquifer test was 2.2 ft/d.

Two sets of neutron logs were made before the tests at site NV–6 were started to document the relative moisture content between the saturated material (aquifer) and the overlying 330-foot-thick unsaturated zone (fig. 28). Dates of the logs were July 26 and 29; August 12, 17, 26, and 31; and September 7 and 23. The second set of neutron logs, made after the short-term equipment tests, showed a slight increase in relative moisture content in several individual beds between the surface and a depth of about 70 ft. Subsequent logs showed a moisture increase in the unsaturated zone progressing from the surface toward the water table and a mound of water (almost to saturation) developing above the water table. This mound expanded to a thickness of about 50 ft between the eighth and seventeenth day of the test. During the next 5 days, the mound continued to expand and was about 100 ft thick on the twenty-second day (fig. 28). Meanwhile, on the fourth day of the experiment, the ground-water level began to rise under the channel in response to the water being recharged through the unsaturated zone. By the tenth day, the ground-water level increased 1.04 ft. By the sixteenth day, an additional 0.07-foot rise had occurred. After pumping was stopped, the mound of water dissipated in less than 5 days, and the relative moisture content of the entire unsaturated section returned to almost pre-experiment conditions in 20 days.

Figure 29 shows the observed water-level response in wells NV–6ob2 and NV–6ob3 along with the measured water elevation at weir 3 during part of August and September 1982. Using these observed water levels and assuming that the aquifer underlying the area is an ideal, homogeneous, and isotropic medium, the theoretical drawdown that would have occurred in well NV–6ob5 under these conditions and without any recharge reaching the water table was calculated. This ideal response of well NV–6ob5 is shown on figure 29 along with the observed response. Drawdown in well NV–6ob5 caused by the pumping of well NV–6p was measurable at about 2 days (point A). The water-level response in NV–6ob5 to the pump failure in NV–6p (point B) and the restart of

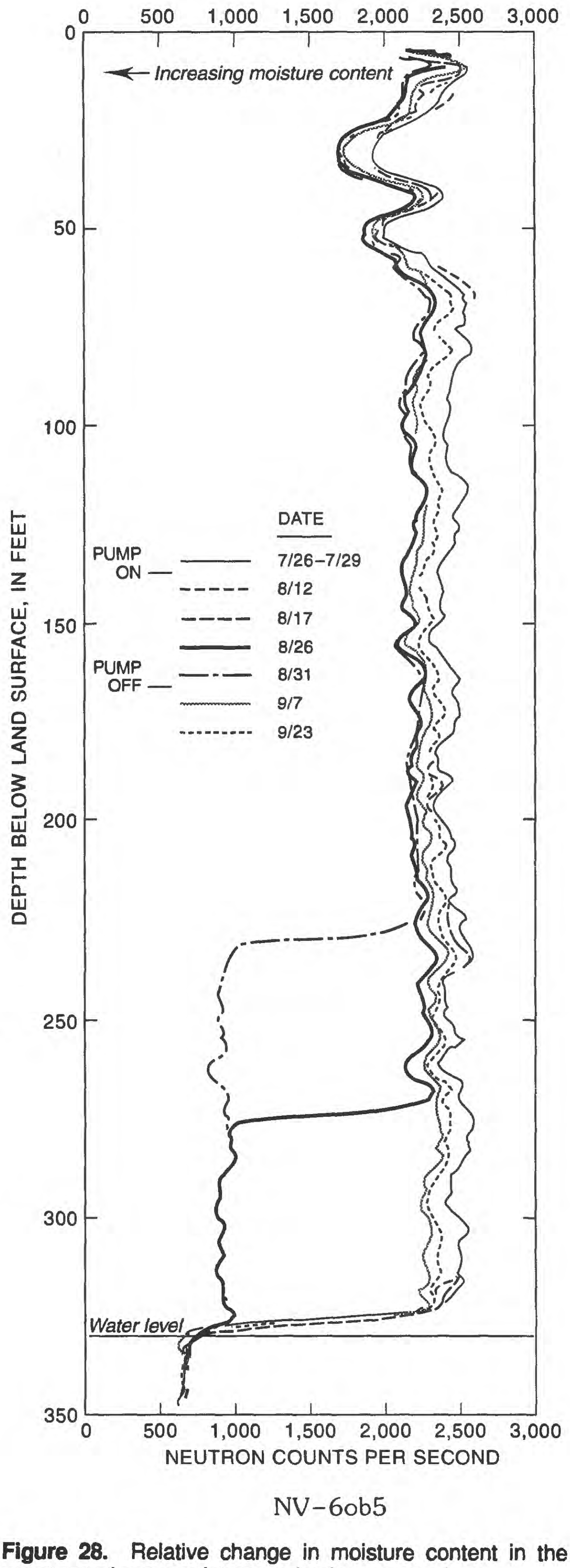



**Figure 28.** Relative change in moisture content in the unsaturated zone as interpeted using neutron logs.

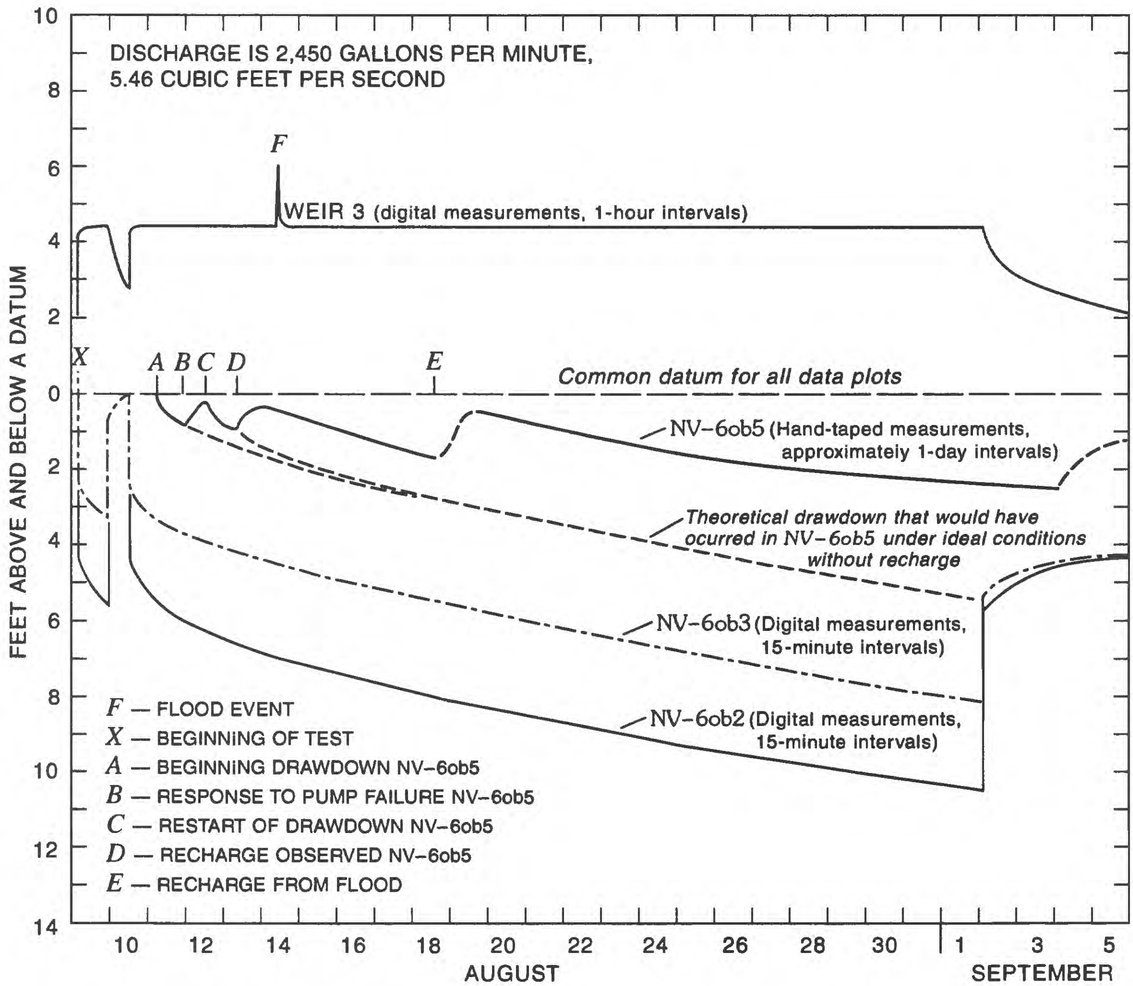



**Figure 29.** Wells and weirs used during the recharge experiment during 1982.

the pumping in NV–6p (point C) also are shown. The water-level rise in well NV–6ob5 (point D) was not observed in wells NV–6ob2 and NV–6ob3 and is attributed to recharge reaching the water table from the flow in the ephemeral channel caused by the discharge from well NV–6p. This water-level rise occurred in just over 4 days on August 13. On August 14, an intense thunderstorm caused flooding in this area of the valley. The flood peak (point F) was measured as it overtopped weir 3. The water level in well NV–6ob5 rose sharply (point E) in just over 4 days after the flood. This water-level rise is attributed to the recharge from the flood.

The movement of water from the land surface to the water table through the 330-foot-thick unsaturated zone and the consequent water-level rise shows that recharge can occur much more quickly than commonly estimated for Basin and Range unconsolidated, valley-fill deposits. Typically, estimates of downward velocity had ranged from 20 to 40 years for water to reach the water table at depths of 400 ft (Bouwer, 1980, p. 17). Estimates of 50 years/100 ft were common (Evans and Warrick, 1980, p. 58). Results from this recharge experiment drastically alter previously estimated vertical-flow velocities by documenting that water moved from the surface to the water table at a depth of about 330 ft in less than 5 days and that the moisture content increased throughout the unsaturated section and then returned to almost pre-experiment conditions in about 20 days.

## SUMMARY AND CONCLUSIONS

The Ak-Chin Indian Community Water Rights Settlement Act directed the Secretary of the Interior to deliver a permanent water supply of 85,000 acre-ft/yr of water to the Ak-Chin Indian Reservation no later than 25 years from the date (July 28, 1978) of the enactment. The Settlement Act further directed the Secretary of the Interior to determine if sufficient ground water was available beneath Federal Lands near the Reservation to meet the interim emergency needs of the community and, if sufficient quantities of ground water were available, to construct a well field and pipeline to deliver the emergency supply.

Initial studies indicated that the emergency supply could be obtained near the Ak-Chin Community. On the basis of these studies and other information, the Secretary of the Interior selected Vekol Valley as the area to be developed. The Secretary directed that a well field and pipeline capable of delivering the interim emergency supply of 30,000 acre-ft of water annually to the Ak-Chin Indian Community be constructed and work began in 1981 and was conducted in two phases. Vekol Valley is naturally divided into two distinct areas by a low, bedrock ridge that extends across the valley at about its mid-point. Consequently, a study of the northern part of the valley, which is closer to the Ak-Chin Reservation, was undertaken to determine if the ground-water resource underlying this area could be developed to supply the emergency water needs of the Community. When it was determined that the entire emergency supply could not be developed from the northern part of Vekol Valley, the study was expanded to include the southern part of Vekol Valley.

Study of the aquifer system underlying the northern part of Vekol Valley included drilling 19 boreholes at 10 sites and constructing 17 wells, three of which were high-capacity production wells designed as part of the proposed well field. The results of the study show that the aquifer system underlying the valley is composed of a thick sequence of sand and gravel units deposited in a structurally controlled basin. These sand and gravel units grade from unconsolidated to well cemented with depth in the basin. The upper units contain two aquifers: an upper, unconfined aquifer that ranges in thickness from about 550 to 650 ft in the central 12-square mile area of the valley and a lower, confined aquifer that ranges in thickness from about 50 to 300 ft. These aquifers are separated by a well-cemented conglomerate that ranges in thickness from about 210 to 300 ft.

Depth to ground water in the northern part of the valley ranges for about 270 to 430 ft. The direction of ground-water movement generally is from the mountains surrounding the valley on the east, south, and west toward the center of the valley, and then toward the north along the axis of the valley to an exit point at the north end of the valley. The water level in the upper aquifer is a few feet higher than in the lower aquifer around the edge of the valley and indicates downward movement of water in these areas. The water levels are about the same in the central part of the valley, and the water level in the lower aquifer is slightly higher than it is in the upper aquifer in the northern part of the valley. This difference in water levels indicates upward movement of water from the lower aquifer in the discharge area in the north end of the valley.

Analysis and evaluation of the data obtained during the aquifer test conducted in the northern part of Vekol Valley indicate that the aquifer system underlying the area has the following hydraulic characteristics.

| | | | |
|---|---|---|---|
| Upper unconfined aquifer | $T$ | = | 13,500 $ft^2/d$ |
| | $S_y$ | = | 0.12 |
| | $K_z:K_r$ | = | 1:12 |
| Lower confined aquifer (most productive zone) | $T$<br>$S$ | =<br>= | 2,000 $ft^2/d$<br>$4x10^{-4}$ |

A recharge experiment conducted in conjunction with the aquifer test used the 2,450 gal/min (5.46 $ft^3/s$) of water pumped during the test. The water was transported from the test site through a 2,000-foot pipeline and discharged into a dry, ephemeral channel. Water discharge was measured using a recording orifice-manometer installed at the end of the pipeline and four Cipolletti weirs with recorders along the channel. The channel was about 4 to 12 ft wide, 2 to 7 ft deep, and had a thin layer—less than 1 ft—of alluvial sand and gravel. The basin-fill material underlying the alluvium is a poorly consolidated, silty to gravelly sand. Two wells were installed adjacent to the channel and downstream from the first weir in which geophysical logs and water-level readings were made. Natural flow had not occurred in the channel for at least 30 days before the experiment.

The results of the experiment indicated that water losses increased steadily to a constant rate. Each successive downstream channel reach had a lower loss rate. The water losses decreased in succession from the most upstream reach, which stabilized at 1.09 $ft^3/s$ per 1,000 ft of channel length after 14 days, to the most downstream reach, which stabilized at 0.64 $ft^3/s$ per 1,000 ft after 20 days. These flow losses were directly related to flow depth and channel geometry. Flow extended for about 7,000 ft downstream from the end of the pipeline. The flow widened the channel for about 900 ft, removed most fine-grained alluvial material for about 3,500 ft, and deposited intermittent layers of sand and silt farther downstream. These channel changes were related to the discharge and velocity in each reach.

Several sets of water levels and two set of geophysical logs were made before the experiment was started and daily water levels and six additional sets of logs were made during the experiment to document water-table changes and moisture changes in the 330-foot thick unsaturated zone. The second set of logs showed a slight increase in moisture in several individual beds between the surface and a depth of about 70 ft. This slight increase in moisture is attributed to the short-term pumping of well NV–6p for the equipment test. Subsequent logs made during the aquifer test showed moisture increases in additional beds between the surface and the water table and a mound of moisture (almost to saturation) developing above the water table. This mound expanded to a thickness of about 50 ft between the seventh and sixteenth days of the experiment. During the next 5 days, the mound continued to expand and was about 100 ft thick on the twenty-first day.

Meanwhile, on the fourth day of the experiment, the ground-water level began to rise in response to the water being recharged through the unsaturated zone. By the tenth day, the ground-water level increased 1.04 ft. After pumping was stopped, the high moisture content above the water table dissipated in less than 5 days and the moisture content in the entire unsaturated section returned to about pre-experiment conditions in 20 days.

The movement of water from the land surface to the water table through the 330-foot-thick unsaturated zone shows that recharge can occur much more quickly than commonly estimated for Basin and Range, unconsolidated, basin-fill deposits. Typically, estimates of downward velocity had ranged from 20 to 40 years for water to reach the water table at depths of 400 ft. Estimates of 50 years/100 ft were common. Vertical velocities of about 65 ft/d were observed during the recharge experiment.

Values calculated for vertical hydraulic conductivity ($K_z$) using steady, channel-loss rates for each reach ranged from 2.9 to 7.1 ft/d. The value calculated from the aquifer test was 2.2 ft/d. Values calculated using the average vertical velocity observed during the recharge experiment ranged from 6 to 11 ft/d.

The results of the tests conducted in the northern part of Vekol Valley were used to construct a numerical ground-water flow model of that area to evaluate well-field design and projected water-level declines caused by the proposed long-term pumping to supply the Ak-Chin Community's water needs (Hollett and Marie, 1987).

The study of the southern part of Vekol Valley included drilling 21 test holes at 14 sites and constructing 13 wells, 4 of which were high-capacity production wells designed as part of the proposed well field. The results of the study show that the aquifer system underlying south Vekol Valley is composed primarily of a thick sequence of silt, sand, and gravel units deposited in a structurally controlled basin. These units grade from a thick silt at the surface into sand and gravel units, which in turn, grade from unconsolidated to well cemented with depth in the basin. These basin-fill sediments unconformably overlie various rocks of Tertiary to Precambrian age that comprise the faulted blocks of the Basin and Range province. The upper unit is comprised of silt to sandy silt that ranges from a few feet to about 600 ft thick. This unit forms an effective, leaky confining unit in much of the southern part of the valley. The sequence of sand, gravel, and conglomerate that underlie the silty unit can be divided into two aquifers: an upper, unconsolidated sand and gravel aquifer that ranges in thickness from a few feet near the perimeter of the basin to about 1,100 ft in the central part of the valley. Underlying the upper aquifer in most of the southern valley is a lower gravel and conglomerate aquifer that is about 1,000 ft thick in the center of the valley but was not present in the north and northwest. Underlying the lower aquifer in much of the southern valley and possibly, at least in part, contemporaneous with it, is a sequence of volcanic rocks that are as much as 925 ft thick in the southwestern part of the valley. The volcanics, like the overlying conglomerate is not present in the northeast; however, the volcanic rocks are about 700 ft thick in the northern part of the valley where the conglomerate is not present.

Depths to ground water in the southern part of the valley range from about 330 to 670 ft where measured. Analysis of available hydraulic data indicate that the southern part of Vekol Valley may be a closed ground-water basin. Data are not available to show vertical-head differences in the aquifer system underlying the southern valley. Analysis and evaluation of the two aquifer tests conducted in the thicker part of the aquifer system in the southern part of the valley give similar aquifer-system characteristics.

| Property | Site SV–8 test | Site SV–11 test |
|---|---|---|
| Transmissivity | 7,200 $ft^2/d$ | 9,000 $ft^2/d$ |
| Storage coefficient | $5.5x10^{-4}$ | $3x10^{-4}$ |
| Specific yield | Not applicable | 0.12 |
| Hydraulic conductivity | 5.6 ft/d | 6.8 ft/d |
| Ratio of $K_z$:$K_r$ | 1:63 | 1:56 |

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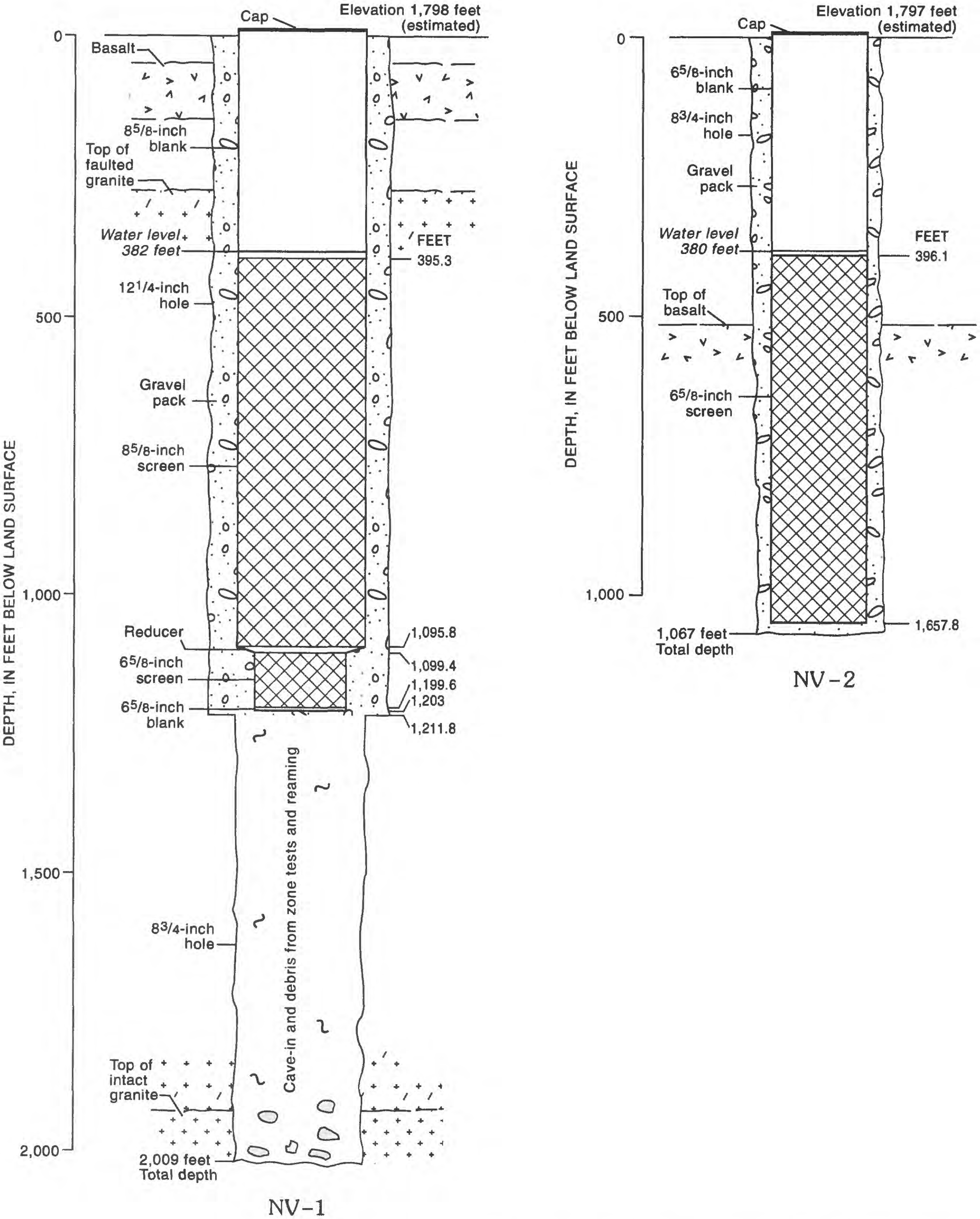
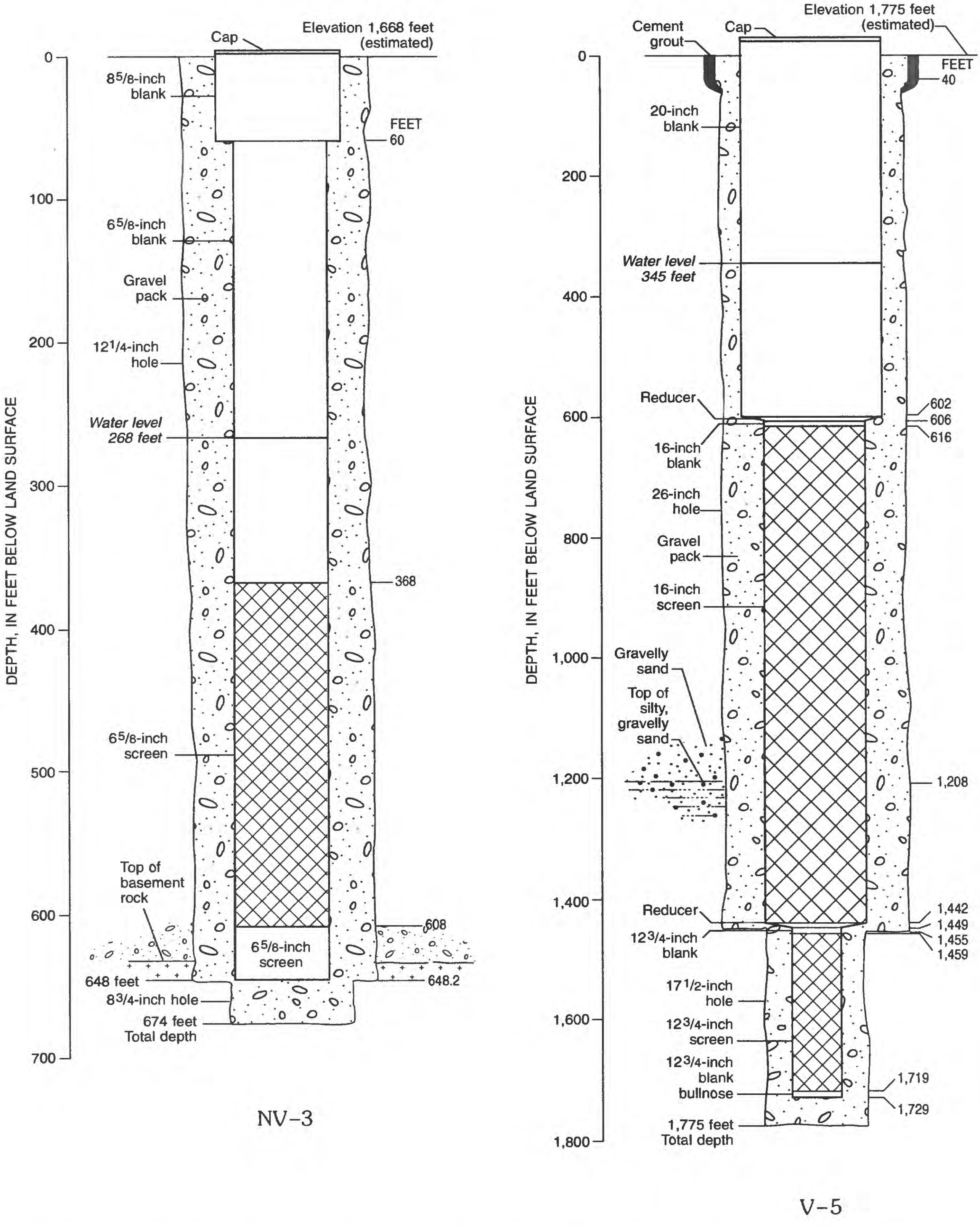
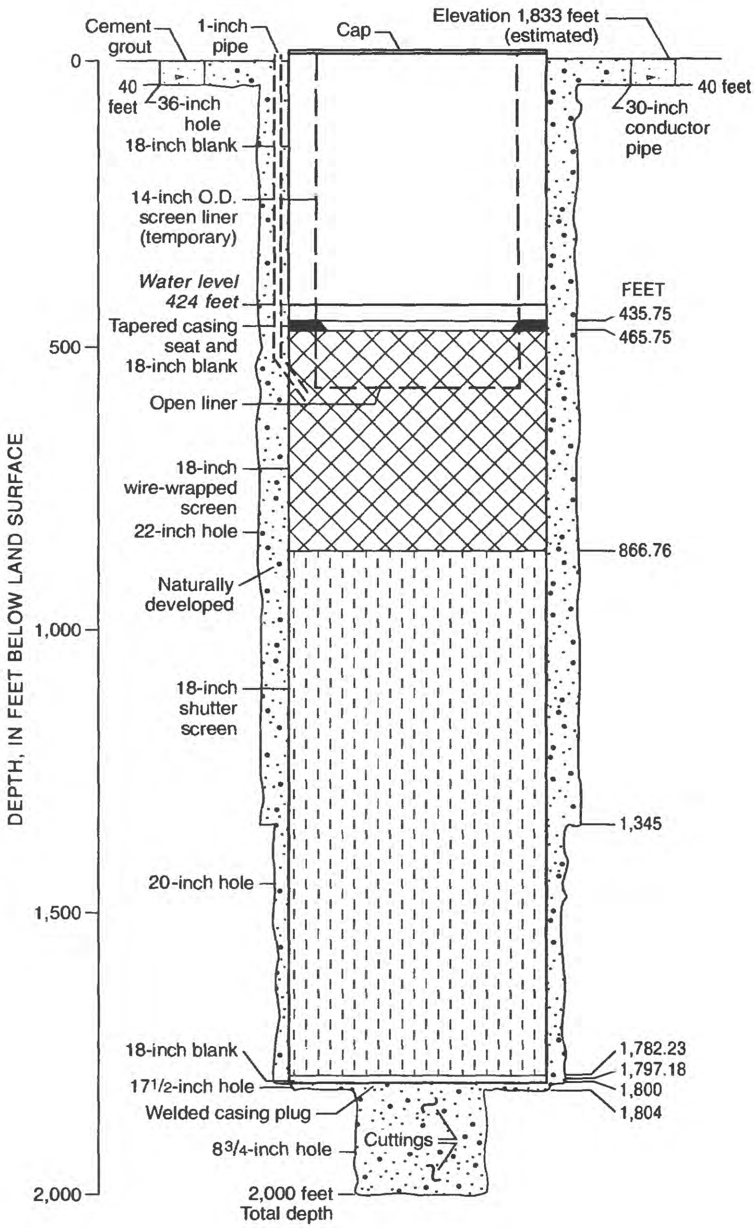
# WELL CONSTRUCTION INFORMATION



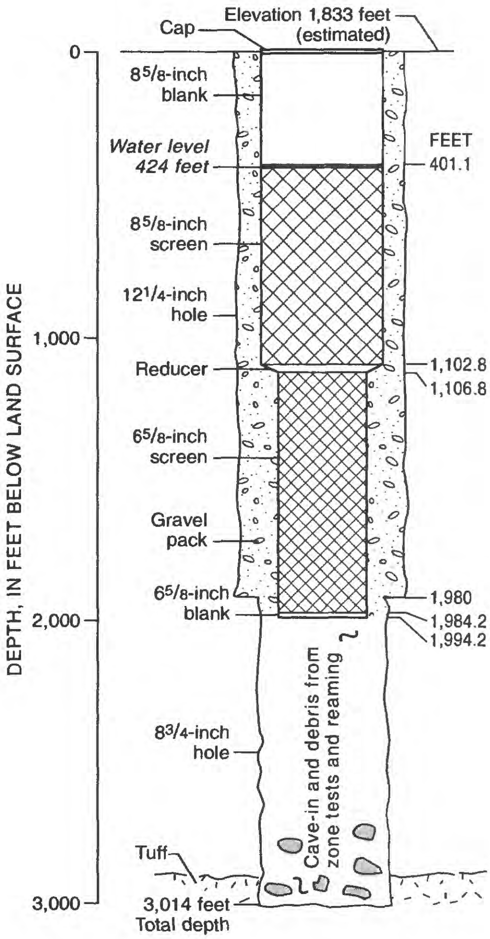

Construction information for wells NV–1 and NV–2 installed in north Vekol Valley. (Source: Modified from Bureau of Indian Affairs, 1983.)




Construction information for wells NV–3 and V–5 installed in north Vekol Valley. (Source: Modified from Bureau of Indian Affairs, 1983.)




NV-5




NV-5ob1

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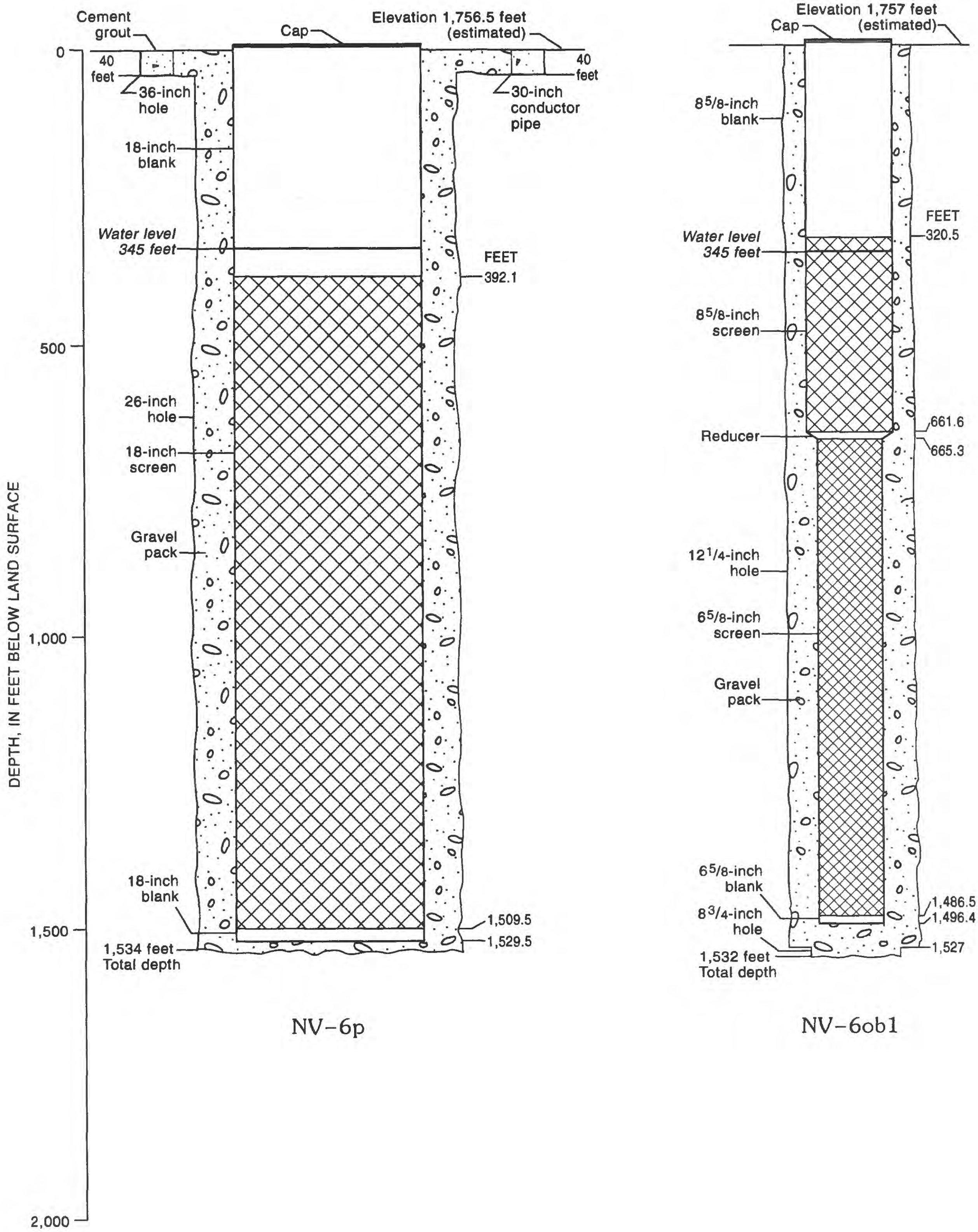
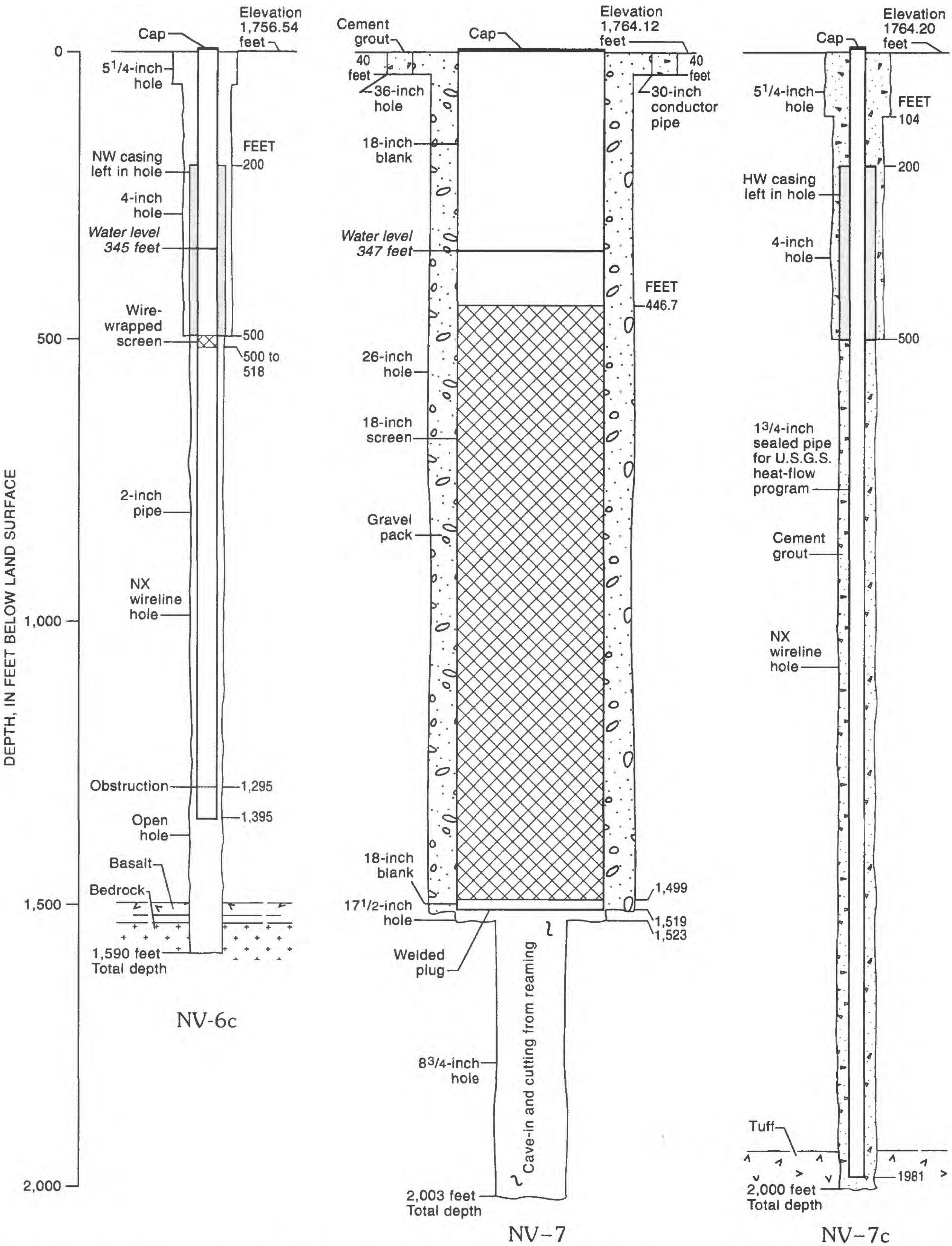
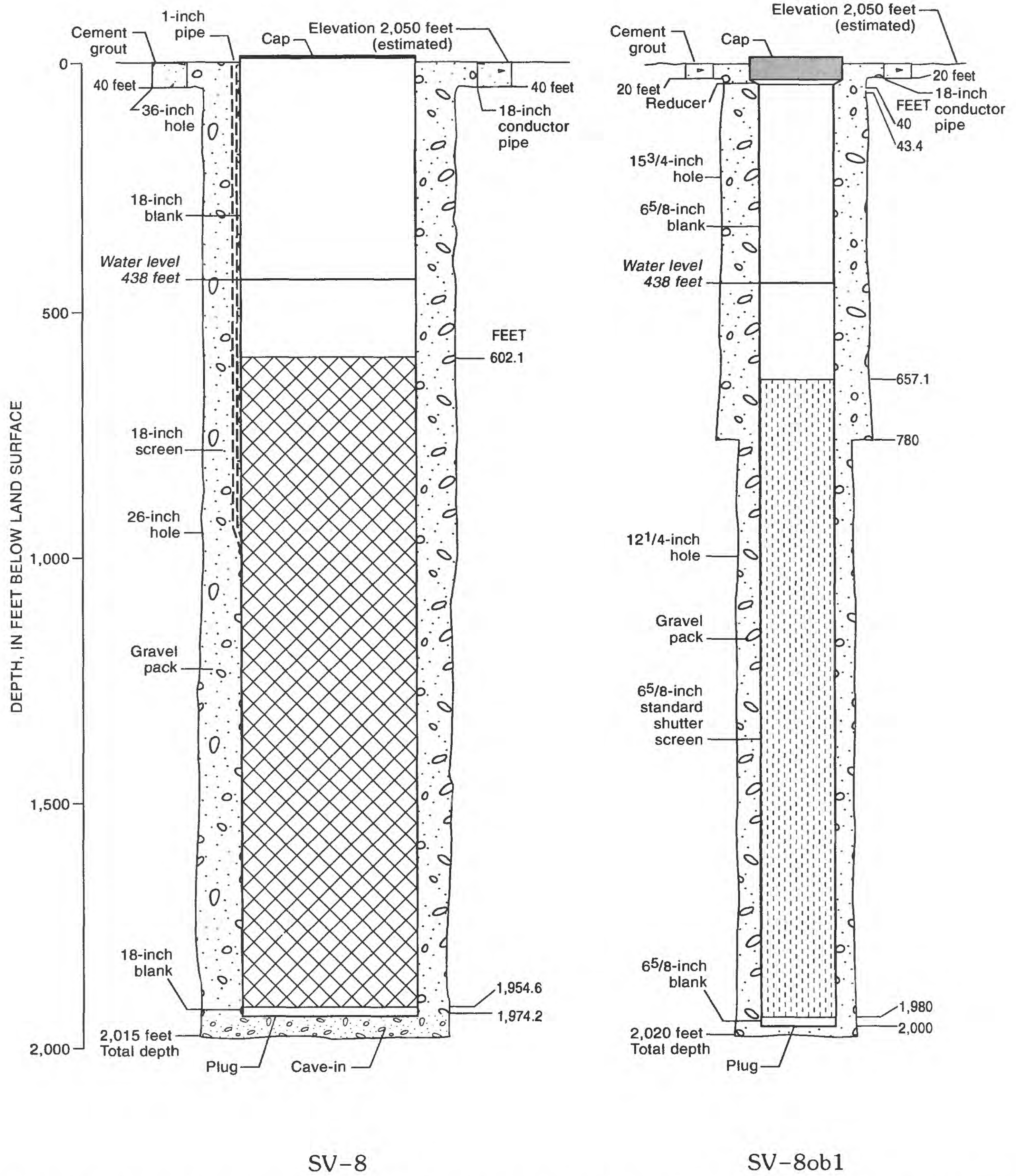


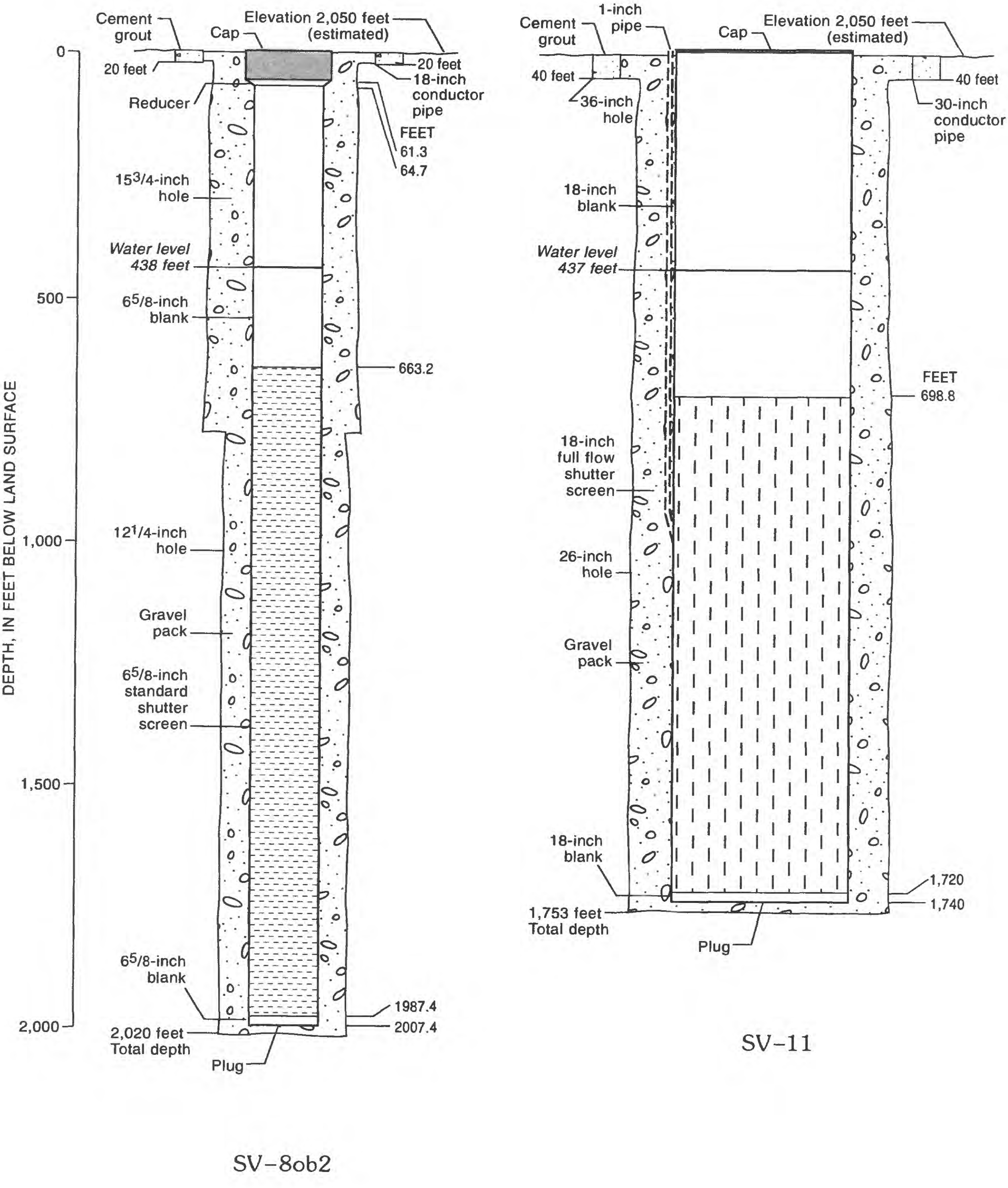

Construction information for wells NV–6p and NV–6ob1 installed in north Vekol Valley. (Source: Modified from Bureau of Indian Affairs, 1983.)



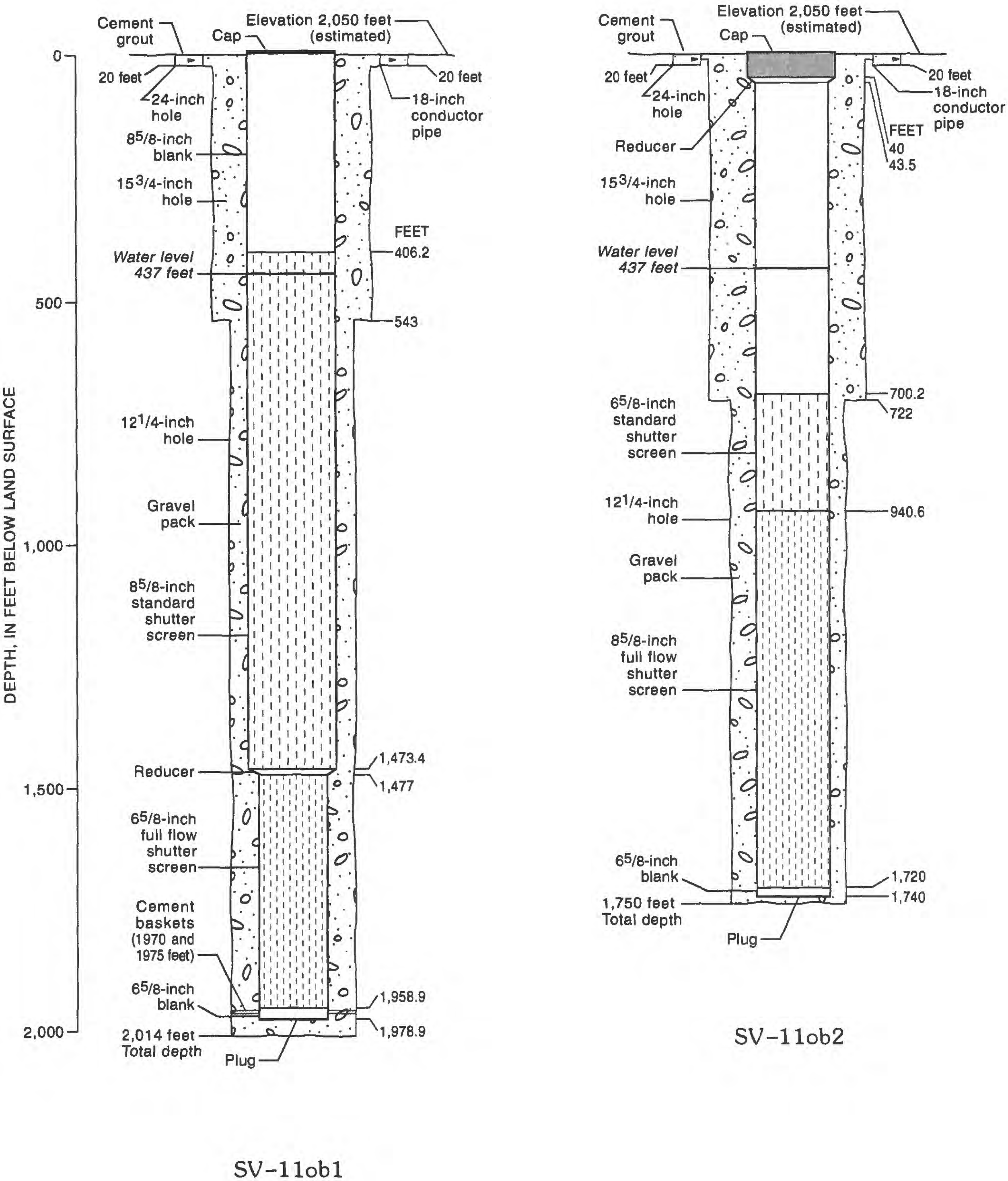

Construction information for wells NV–6c, NV–7, and NV–7c installed in north Vekol Valley. (Source: Modified from Bureau of Indian Affairs, 1983.)



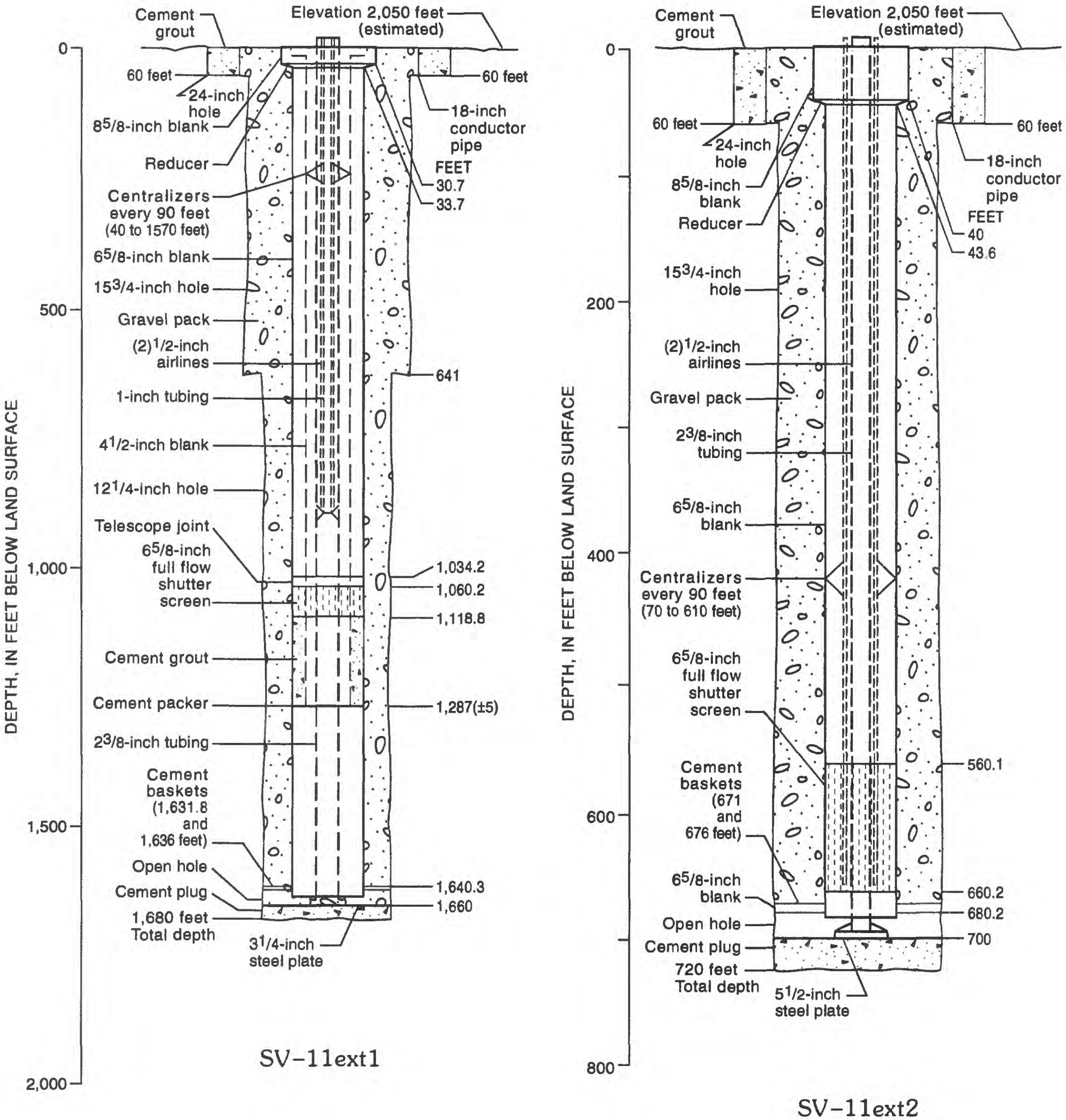

Construction information for wells SV–8 and SV–8ob1 installed in south Vekol Valley. (Source: Modified from Bureau of Indian Affairs, 1984.)




**Construction information for wells SV–8ob2 and SV–11 installed in south Vekol Valley. (Source: Modified from Bureau of Indian Affairs, 1984.)**




**Construction information for wells SV–11ob1 and SV–11ob2 installed in south Vekol Valley. (Source: Modified from Bureau of Indian Affairs, 1984.)**




Construction information for wells SV–11ext1 and SV–11ext2 installed in south Vekol Valley. (Source: Modified from Bureau of Indian Affairs, 1984.)

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