GROUND-WATER STORAGE DEPLETION IN PAHRUMP VALLEY, NEVADA-CALIFORNIA, 1962-75

U.S. GEOLOGICAL SURVEY

Open-File Report 81-635

Prepared in cooperation with the
NEVADA DIVISION OF WATER RESOURCES

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

GROUND-WATER STORAGE DEPLETION IN PAHRUMP VALLEY, NEVADA-CALIFORNIA, 1962-75

By James R. Harrill

Open-File Report 81-635

Prepared in cooperation with the
NEVADA DIVISION OF WATER RESOURCES

Carson City, Nevada

1982

UNITED STATES DEPARTMENT OF THE INTERIOR

JAMES G. WATT, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

U.S. Geological Survey
Room 229, Federal Building
705 North Plaza Street
Carson City, NV 89701

Copies of this report may be
purchased from:

Open-File Services Section
U.S. Geological Survey
Box 25425, Federal Center
Denver, CO 80225

Call (303) 234-5888 for
ordering information

CONTENTS

Page

ILLUSTRATIONS

[All plates in pocket at back of report]

Page

TABLES

CONVERSION FACTORS

Only the "inch-pound" system of measure is used in this report. Abbreviations and conversion factors from inch-pound to International (metric) units are listed below.

Multiply	*By*	*To obtain*
Acres	4,047	Square meters (m^2)
Acre-feet (acre-ft)	1,233	Cubic meters (m^3)
Cubic feet per second (ft^3/s)	0.02832	Cubic meters per second (m^3/s)
Feet (ft)	0.3048	Meters (m)
Feet per day (ft/d)	0.3048	Meters per day (m/d)
Feet squared per day (ft^2/d)	0.0929	Meters squared per day (m^2/d)
Gallons per minute (gal/min)	0.06309	Liters per second (L/s)
Miles (mi)	1.609	Kilometers (km)
Square miles (mi^2)	2.590	Square kilometers (km^2)

ALTITUDE DATUM

The term "National Geodetic Vertical Datum of 1929" (abbreviation, NGVD of 1929) replaces the formerly used term "mean sea level" to describe the datum for altitude measurements. The NGVD of 1929 is derived from a general adjustment of the first-order leveling networks of both the United States and Canada. For convenience in this report, the datum also is referred to as "sea level."

GROUND-WATER STORAGE DEPLETION IN

PAHRUMP VALLEY, NEVADA-CALIFORNIA, 1962-75

By James R. Harrill

ABSTRACT

During the 13-year period, February 1962 to February 1975, about 540,000 acre-feet of ground water was pumped from Pahrump Valley. This resulted in significant water-level declines along the base of the Pahrump and Manse fans where pumping was concentrated. Maximum observed net decline was slightly more than 60 feet. Much smaller declines occurred in the central valley, and locally, water levels in some shallow wells rose due to recharge derived from the deep percolation of irrigation water. The pumping resulted in about 219,000 acre-feet of storage depletion. Of this, 155,000 acre-feet was from the draining of unconsolidated material, 46,000 was from compaction of fine-grained sediments, and 18,000 acre-feet was from the elastic response of the aquifer and water. The total storage depletion was equal to about 40 percent of the total pumpage. The remaining pumped water was derived from the capture of natural ground-water discharge and reuse of pumped water that had recirculated back to ground water.

Natural recharge to and discharge from the ground-water system is estimated to be 37,000 acre-feet per year. Of this, 18,000 acre-feet per year leaves the area as subsurface outflow through carbonate-rock aquifers which form a multivalley flow system. The extent of this system was not precisely determined by this study. The most probable discharge area for this outflow is along the flood plain of the Amargosa River between the towns of Shoshone and Tecopa. This outflow probably cannot be economically captured by pumping from Pahrump Valley. Consequently, the maximum amount of natural discharge available for capture is 19,000 acre-feet per year. This is larger than the 12,000 acre-feet per year estimated in a previous study; the difference is due to different techniques used in the analysis.

As of 1975, pumping was causing an overdraft of 11,000 acre-feet per year on the ground-water system. No new equilibrium is probable in the foreseeable future. Water levels will probably continue to slowly decline until the pumping is reduced. The moderate rates of decline and very large amounts of ground water stored in the valley-fill reservoir suggest that a long time will be required before the valley-wide depletion of ground-water storage becomes critical. Problems involving water quality, land subsidence, and well interference will probably occur first.

INTRODUCTION

This study, made in cooperation with the Nevada Department of Conservation and Natural Resources, evaluates effects of ground-water withdrawals during the period February 1962 through February 1975 on depletion of storage in Pahrump Valley. The study updates an earlier report by Malmberg (1967) which indicated an overdraft on the ground-water system of about 13,000 acre-ft/yr during the 4-year period 1959-62. Since that time, pumping has increased substantially and large tracts of former agricultural land are being subdivided for residential development. Concern about effects of sustained overdraft on a valley that contains permanent residential development is the basic reason for this study.

Purpose and Approach

The objectives of this study are: (1) To determine or estimate, for the period 1962 through 1975, the areal extent and amount of water-level decline, the magnitude of ground-water storage depletion, and the annual pumpage; (2) to evaluate any additional impacts of development, to date, on the hydrologic system; and (3) to the extent possible, demonstrate some general long-term effects likely to occur if pumping is maintained at the 1975 rate.

In scope, the study included the Pahrump Valley and part of the mountainous area on three sides. Considered were water levels, pumpage, well records, and aquifer hydraulics. A digital ground-water flow model provided insight into long-term pumping effects.

Work began early in 1975. Principal work items included (1) review of published information; (2) compilation of available well-construction, water-level, and pumpage information; (3) a field canvass of selected wells; (4) collection of a fairly comprehensive set of water-level measurements in February 1976; (5) drilling 11 small-diameter water-level observation wells; (6) conducting short-term pumping tests on 5 wells; (7) evaluation and analysis of the information obtained; and (8) use of a digital ground-water flow model to test and refine the analysis of the ground-water system and to gain insight into possible long-term effects if pumping is continued at the 1975 rate. Most of the field work was done between early 1975 and June 1976.

The net effect of seasonal pumping during the 14 irrigation seasons starting in 1962 and continuing through 1975 was evaluated by water-level measurements made between February 1962 and February 1976. An evaluation of net changes in the ground-water levels was based on measurements made when conditions are least affected by pumping, usually in late winter of each year. For example, the change in water level from February 1975 to February 1976 largely reflected the residual effects of pumping during the previous spring, summer, and fall (1975).

Location and General Features

Pahrump Valley encompasses about 1,050 square miles in Nye and Clark Counties, Nev., and Inyo and San Bernardino Counties, Calif. The area discussed in this report conforms with boundaries of the Pahrump Valley hydrographic area designated by Rush (1968) and also conforms with the area used by Malmberg (1967) in his earlier study. Boundaries and general features of the study area are shown in figure 1.

The Spring Mountains form the northeast border of the area and are the dominant topographic feature. They are the source area for virtually all the area's water supply.

Charleston Peak (altitude 11,918 feet) is the highest point in the area. Altitude of much of the valley floor is between 2,500 and 2,800 feet, so the maximum topographic relief is more than 9,000 feet. For most of the area, however, topographic relief between the valley floor and adjacent mountains is between 2,000 and 6,000 feet.

The southwest side of the Spring Mountains is characterized by large alluvial fans that head high in the canyons leading from Mount Charleston. The most prominent of these fans have coalesced to form the major fans called the Pahrump and Manse fans (Malmberg, 1967, page 8).

Pahrump Valley is part of an intervalley ground-water flow system which contributes ground water to low areas adjacent to Death Valley. The closest major areas of ground-water discharge downgradient from Pahrump Valley are between the towns of Tecopa and Shoshone, Calif., 10 to 15 miles southwest of the topographic boundary of Pahrump Valley (figure 1).

Previous Work

About 20 previous studies deal with various aspects of the hydrology and geology of Pahrump Valley. Most of these studies are evaluations of larger areas and either include only descriptive information about Pahrump Valley or include quantitative information about only parts of the area. Only two studies contain detailed information which deals specifically with the hydrology of Pahrump Valley (Maxey and Jameson, 1948, and Malmberg, 1967). The following paragraphs outline the general scope of the principal existing studies.

Mendenhall (1909) made a reconnaissance of the water resources of southwestern Nevada and southeastern California which included information on some springs in Pahrump Valley. This constituted one of the first investigations of the valley's water resources.

Waring (1921) studied the water resources of Pahrump, Mesquite, and Ivanpah Valleys in more detail. This report included data on wells and springs in Pahrump Valley and discussed the source and occurrence of ground water.

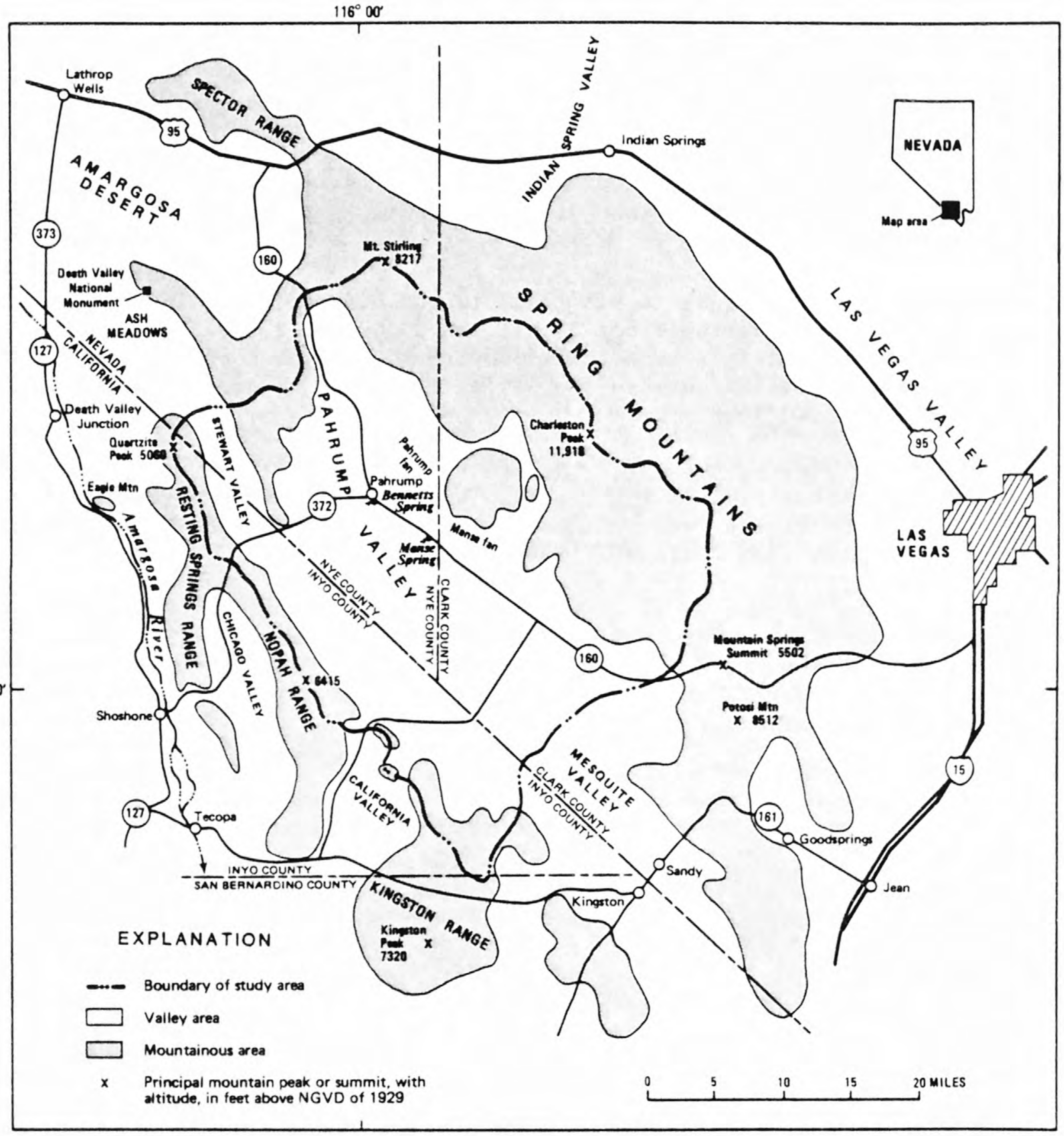


FIGURE 1. — Location and general features of the Pahrump Valley area.

During the period 1922-36, the University of Nevada Agricultural Experiment Station at Las Vegas studied the occurrence and utilization of ground water in Las Vegas and Pahrump Valleys (Hardman and Miller, 1934, and Hardman and Mason, 1949) and collected data on well and spring discharges, water levels, and chemical quality.

In 1944, a reappraisal of the ground-water resources of Pahrump Valley (Maxey and Jameson, 1948) was made which summarized all available information at that time. This study also included the first quantitative estimates of recharge to and discharge from the ground-water reservoir. Two other reports (Robinson and others, 1947, and Maxey and Robinson, 1947) contain additional data compiled during this evaluation.

Data on wells in the California part of the valley are summarized in an office report by the California Division of Water Resources (1956).

A comprehensive evaluation of the hydrology of the study area was made by Malmberg (1967). This study included a reappraisal of the hydrology of the valley, documentation of the extent of development as of 1962, and a first evaluation of cause-effect relationships associated with pumping ground water. Three major contributions of this study were: (1) Detailed mapping of the surficial geology of the valley fill which included mapping of faults that affect ground-water flow; (2) demonstration that appreciable subsurface outflow occurs through consolidated rocks beneath the Nopah Range; and (3) formulation of a reasonably balanced ground-water budget that allows better estimates to be made of the long-term yield of the basin. Geology of the valley has been mapped at 1:250,000 scale (Jennings, 1958 and 1961; Longwell and others, 1965; and Cornwall, 1972). Gravity studies by Healey and Miller (1965), Kane and Carlson (1964), Chapman, Healey, and Troxel (1971), Healey (1973), and Nilsen and Chapman (1971) provided additional information about the structural basin. A regional study by Winograd and Thordarson (1975) which evaluated the hydrologic and hydrochemical framework of the south-central Great Basin provided information about flow characteristics of consolidated rock units and the regional structural framework.

The U.S. Bureau of Reclamation has included Pahrump Valley in one of the areas encompassed by the Inland Basins Project (U.S. Bureau of Reclamation, 1969, 1972). These reports contain summaries of hydrologic and other information about the valleys and evaluate the feasibility of large-scale pumping projects in selected areas.

Hydrologic studies of adjacent areas (Glancy, 1968; Hughes, 1966; Malmberg, 1965; Malmberg and Eakin, 1962; Harrill, 1976; and Dudley and Larson, 1976), provided supplemental information that has transfer value for some areas and conditions in Pahrump Valley.

Numbering System for Wells and Springs

Pahrump Valley straddles the Nevada-California State line. A different well-numbering system is used in each State; both systems are used in this report to permit each well to be numbered compatibly for the State in which it is located.

Nevada System

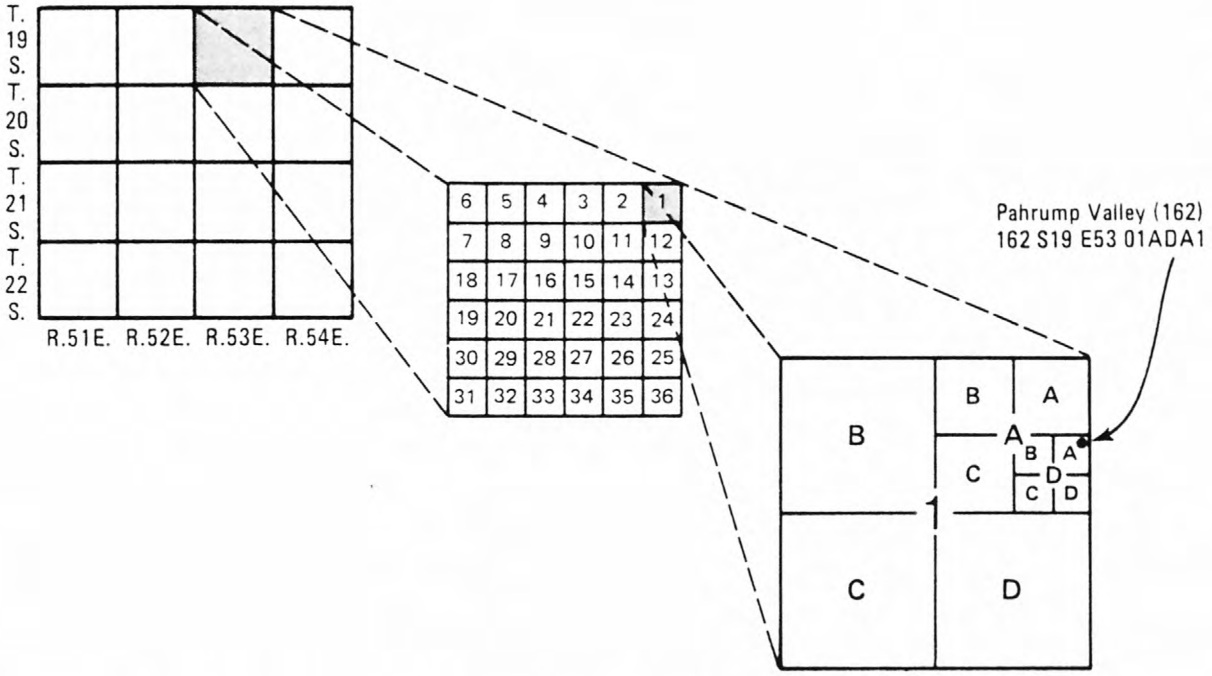
The numbering system used for Nevada is based on an index of hydrographic areas (Rush, 1968) and the rectangular subdivision of the public lands referenced to the Mount Diablo base line and meridian or, in one small area, the San Bernardino base line and meridian. Each number consists of five units separated by spaces: The first unit is the hydrographic area number. The second unit is the township, preceded by an N or S to indicate location north or south of the base line. The third unit, preceded by an E, is the range east of the meridian. The fourth unit consists of the section number. Quarter sections are designated in the fifth segment counterclockwise "A" through "D", beginning with "A" for the northeast quarter section. Where field maps are sufficiently accurate, additional letters "A" through "D" are also assigned in counterclockwise sequence to further subdivide the quarter sections into 40- or 10-acre tracts. The letters are followed by a number indicating the order in which the well was recorded in that particular tract. For example (see figure 2), well 162 S19 E53 33ADA1 is in Pahrump Valley (hydrographic area 162), and it is the first well recorded in the NE$\frac{1}{4}$SE$\frac{1}{4}$NE$\frac{1}{4}$, sec. 33, T. 19 S., R. 53 E., Mount Diablo base line and meridian. Wells located in Nevada between the Von Schmidt line and the State line, and west of R. 53 E., are referenced to the San Bernardino base line and meridian. This is indicated by an S in front of the township designation. For example, well 162 SN24 E08 26BAB1 is in the NW$\frac{1}{4}$NE$\frac{1}{4}$NW$\frac{1}{4}$, sec. 26, T. 24 N., R. 8 E., referenced to the San Bernadino base line and meridian.

California System

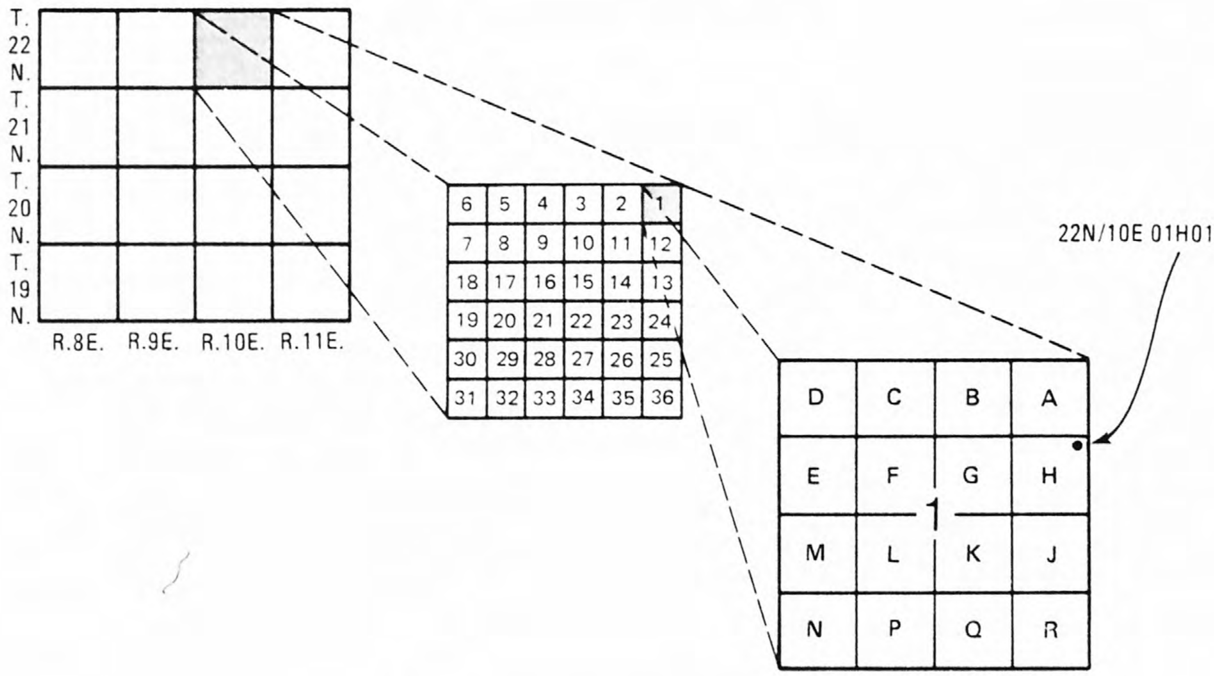
Wells in the California part of Pahrump Valley are numbered according to their location in the rectangular system for subdivision of public land, referenced to the San Bernardino base line and meridian. For example, in the well number 22N/10E-1H1, the number and letter preceding the slash indicate the township (T. 22 N.); the number and letter following the slash indicate the range (R. 10 E.); the number following the hyphen indicates the section (sec. 1); and the letter following the section number indicates the 40-acre subdivision of the section, according to the lettered diagram in figure 2. The final digit is a serial number for wells in each 40-acre subdivision.

Basic Data

The basic data on water wells and ground-water levels collected during this study are stored in the ground-water site inventory files of the U.S. Geological Survey WATSTORE data base. Retrievals of this information may be obtained through the U.S. Geological Survey District Office in Carson City, Nev., or through any designated NAWDEX assistance center.



A. Numbering system used by Nevada



B. Numbering system used by California

FIGURE 2. – Numbering systems for wells and springs, Nevada and California.

Acknowledgments

Acknowledgment is made of the cooperation of residents of the valley in supplying data and permitting the use of their wells in the course of this investigation. Considerable information on historical water-level measurements, pumpage, and other well data was provided by Messrs. Francis Thorne and Keith Cutler of the Nevada Division of Water Resources Office in Las Vegas. Most of the drillers' logs and detailed data on well construction used in this investigation were furnished by the Nevada Division of Water Resources in Carson City, Nev. The Valley Electric Association furnished information on power consumption for irrigation and public-supply pumpage.

GEOLOGIC FRAMEWORK

The geologic framework determines many characteristics of the ground-water flow system. The processes of structural deformation and erosion determine the location, orientation, and altitude of mountain masses and also the extent and depth of structural basins. The rock type or lithology strongly affects water-bearing properties of consolidated rocks and valley-fill deposits. These factors can be related to the hydrology as follows:

(1) The altitude and area of the mountains determine, to a large extent, the amount of precipitation that will be available to recharge the ground-water reservoir. The precipitation that falls on the mountains, primarily from winter storms, generally exceeds 15 inches per year in the higher mountain areas. This water provides virtually all natural recharge to the ground-water reservoir.

(2) The amount of ground water that is stored in saturated materials is largely a function of the extent, thickness, and lithology of unconsolidated deposits that occupy the structural depression which typically underlies a valley in the Great Basin region.

(3) Lithology may strongly affect the hydrologic regimen of a valley, particularly if a certain lithology predominates. For example, thick sequences of permeable carbonate rocks may transmit water well enough to cause a topographically closed basin to be either drained or recharged by subsurface flow, depending on the direction of hydraulic gradients between adjacent areas.

In this study, the geologic framework is evaluated in terms of the lithology of the consolidated rocks and unconsolidated deposits and the character of the structural basin which underlies the valley.

Lithologic Units

For purposes of this report, the principal lithologic units in Pahrump Valley are grouped into two general categories: (1) Unconsolidated and partly consolidated deposits, which form the valley fill and are generally highly porous (coarser-grained deposits of this group generally transmit water readily), and (2) consolidated rocks which compose the mountains and underlie the valley fill (commonly they have low porosity and permeability and do not readily transmit water except where highly fractured or where fractures in carbonate rocks have been enlarged by solution).

Each major group has been subdivided into several subcategories on the basis of lithologic and water-bearing properties. Nine lithologic units are described in table 1; descriptions are adapted from Longwell and others (1965), Cornwall (1972), Malmberg (1967), Winograd and Thordarson (1975), Jennings (1958 and 1961). Distribution of these units is shown on plate 1.

The valley-fill deposits and the consolidated-rock aquifers form the two principal ground-water reservoirs in the area. They will be discussed in greater detail in a later section of this report.

Structural Features

Longwell and others (1965, page 60) state that major orogenic, or mountain building, activity in southern Nevada began in the late Mesozoic Era and continued into the Cenozoic Era. They list a number of events that relate to southern Nevada in general; however, two appear to have had the most direct effects on the ground-water regimen in Pahrump Valley. These are large-scale thrust faulting with associated folding in the late Mesozoic Era and normal faulting in the Tertiary Period of the Cenozoic Era.

Several large thrust faults are exposed in the Spring Mountains and at the north end of the Nopah Range (plate 1). In some places, low-permeability clastic sedimentary rocks have been thrust above or adjacent to water-bearing carbonate rocks and restrict ground-water movement. Also, under some conditions, brecciated zones along fault planes may be conduits for ground water. Folding, which also occurred at this same general time, promotes development of sets of joints which can result in significant secondary permeability under the right conditions.

Normal faulting in Cenozoic time, associated with the development of the Basin and Range province, formed the structural depression underlying Pahrump Valley and the adjacent mountain masses. Normal faults of large displacement are inferred to be present along the margins of Spring Mountains and Nopah Range. Stewart Valley (figure 1) occupies a narrow structural trough; Malmberg (1967, plate 1) mapped a fault (shown on plate 1 as a lineament) in the valley fill that extends southeast from Stewart Valley parallel to the State line for about 15 miles. Springs and stands of mesquite along the upthrown (northeast) side of this feature suggest that it forms a partial barrier to ground-water flow.

TABLE 1.--*Principal lithologic units and their hydrologic properties*

	Age		Unit	Thickness (feet)	Lithology	Occurrence	General hydrologic properties
QUATERN.	Holocene and Pleistocene	Valley fill	Playa deposits	0–50	Unconsolidated; clay, silt, and fine sand.	Playas in Stewart Valley and southwestern Pahrump Valley.	High porosity and very low permeability. Deposits function as confining beds and do not readily yield water to wells.
TERTIARY AND QUATERNARY	Holocene and Pleistocene at and near surface to Pliocene or Miocene at depth	Valley fill	Lacustrine and associated fine-grained deposits	0–5,000	Predominantly clay, silt, and some fine sand. Some mudflow debris and beds of caliche. Youngest deposits typically calcareous.	Occupies valley floor at surface and at depth. Includes medial lacustrine deposits and older lacustrine deposits as mapped by Malmberg (1967).	Fine-grained materials generally have high porosity and low permeability. Beds of fine sand may yield moderate amounts of water to wells. Deposits at depth presumably more compacted, with lower porosity and permeability.
TERTIARY AND QUATERNARY	Holocene and Pleistocene at and near surface to Pliocene or Miocene at depth	Valley fill	Fanglomerate and associated coarse-grained deposits	0–5,000	Unconsolidated to cemented alluvial-fan deposits and mudflow debris composed of boulders, sand, silt, and clay. Contains stringers lenses of relatively clean well-sorted sand and gravel.	Occurs over margins of valley. Occupies areas of intermediate slope between comparatively flat valley floor and mountains. Deposits at depth occupy same general position, and interfinger with lacustrine and associated fine-grained deposits toward center of valley. Includes some surficial deposits, younger fan deposits, medial fanglomerate, and older fanglomerate as mapped by Malmberg (1967).	Highly permeable lenses of gravel and sand readily yield water to wells, and are the most productive aquifers in the valley.
TERTIARY	Pliocene or Miocene	Valley fill	Tuff		White and light-yellow to light-green beds of thinly laminated tuff; extensively faulted or folded.	Exposed at the base of the upthrown fault block along the Nevada-California border; may be interbedded with other valley-fill deposits at depth.	Consolidated and partly to highly indurated; has very low permeability. Would yield virtually no water to wells.
	Tertiary or Cretaceous		Megabreccia		Landslide blocks of monolithologic dolomite breccia from Bonanza King Formation.	Occurs along south end of ridge between Pahrump Valley and Stewart Valley. Unconformably overlies Stirling Quartzite in this area.	May transmit significant amounts of water along fractures and breccia openings enlarged by solution.
	Cretaceous to Triassic	Consolidated rocks	Continental deposits	1,500±	Sandstone, shale, and conglomerate. Some interbedded limestone and gypsum.	Exposed in the Spring Mountains in southeastern part of the study area. Includes Chinle and Moenkopi Formations.	Generally low permeability; may transmit small to moderate amounts of water along fractures. Gypsum may increase sulfate content of ground water.
	Permian	Consolidated rocks	Limestone and fine-grained clastic rocks	800±	Limestone, dolomite, shale, conglomerate, and sandstone. Sequence contains significant gypsum.	Exposed in the Spring Mountains in southeastern part of the study area. Includes Kaibab Limestone, Toroweap Formation, and red beds.	Generally impermeable; may transmit moderate amounts of water where fractured or where fractures have been enlarged by solution. Gypsum may increase sulfate content of ground water.
	Permian to Cambrian	Consolidated rocks	Carbonate sedimentary rocks	18,000±	Limestone, dolomite with medial shale, sandstone, and quartzite.	Exposed in Spring Mountains; in Nopah and Resting Spring Range, along southwest side of area; and in mountains at northwest end of Pahrump Valley. Also underlies valley-fill deposits in parts of area. Includes Bird Spring Formation, Monte Cristo Limestone, Devils Gate Limestone, Nevada Formation, Sultan Limestone, Lone Mountain Dolomite, Ely Springs Dolomite, Eureka Quartzite, Pogonip Group, Nopah Formation, Bonanza King Formation, and the upper part of the Carrara Formation.	Generally impermeable except where fractured. Where solution has caused secondary enlargement of joints and fractures, rocks may be highly permeable. This unit acts as an aquifer, and transmits significant subsurface outflow from Pahrump Valley.
	Cambrian and Precambrian	Consolidated rocks	Clastic sedimentary rocks	10,000±	Sandstone, shale, siltstone, quartzite, minor limestone, and dolomite.	Exposed in Spring Mountains at north end of valley; in Resting Springs Range at west end of area; and probably at north end of Kingston Range at south end of valley. Includes the lower part of the Carrara Formation, Zabriskie Quartzite, Wood Canyon Formation, Stirling Formation, and Johnnie Formation.	Generally impermeable; may transmit moderate amounts of water where fractured. Unit acts as an aquitard.

GROUND-WATER RESERVOIRS

There are two distinct ground-water reservoirs in the study area. They are (1) the consolidated rocks which form the mountains surrounding Pahrump Valley and underlie the valley at depth, and (2) the unconsolidated deposits that have accumulated in the structural depression underlying Pahrump Valley.

Certain types of consolidated rocks transmit water well enough to carry significant underflow from Pahrump Valley. However, there has been virtually no development of this reservoir, and significant future development is improbable. Consequently, the consolidated-rock reservoir will be evaluated primarily in terms of its effect on the flow regimen of the valley-fill reservoir.

The valley-fill reservoir contains the most productive known aquifers in the area and supports virtually all existing development. It is the most feasible source for future development. Consequently, the analysis presented in this report will be made largely in terms of the hydrology of the valley-fill reservoir.

Consolidated-Rock Reservoirs

Carbonate-Rock Aquifers

The carbonate-rock aquifers are composed primarily of carbonate sedimentary rocks from Cambrian to Permian age that crop out in the Spring Mountains, underlie the valley fill of Pahrump Valley, and extend westward through the Nopah and Resting Springs Ranges into California and Chicago Valleys (table 1, figure 1, and plate 1). These aquifers are roughly equivalent to the lower and upper carbonate aquifers as defined by Winograd and Thordarson (1975, pages C14-C31) in their evaluation of regional flow systems in the south-central Great Basin.

No wells in the study area penetrate the carbonate aquifers, so their properties must be inferred from information available in other areas. The aggregate stratigraphic thickness of this sequence of rocks may be as much as 18,000 feet; however, these rocks have been complexly faulted and folded and the aggregate vertical thickness at any one place may be substantially more or less than this stratigraphic thickness.

Hydraulic continuity is probably achieved through extensive fractures and, to a small degree, by localized solution channels. The effective fracture porosity of the lower carbonate aquifer was estimated by Winograd and Thordarson to average probably less than 1 percent, although locally it may be much higher. If these rocks were to be dewatered by pumping or other causes, the average specific yield would be low; probably on the order of 0.5 percent.

Transmissivity is highly variable. Winograd and Thordarson (1975, page C22) computed or estimated transmissivities from the results of pumping tests of 10 wells that penetrated one or more formations in the lower carbonate aquifer. Values ranged from about 130 to 120,000 ft^2/d. They suggested that the wide range in transmissivity may not be randomly distributed but may be structurally controlled. In the vicinity of the test site, they concluded that extensive zones of above average fracture transmissivity over long distances are improbable.

They also estimated the gross fracture transmissivity of the lower carbonate aquifer at several places, using potentiometric contour maps and known or estimated amounts of flow. In areas of high fracture permeability, such as the Spector Range, transmissivity was estimated to be in the hundreds of thousands to millions of feet squared per day. In contrast, beneath Yucca Flat, (about 50 miles north of Pahrump Valley) transmissivity of the lower carbonate aquifer was estimated to average less than 1,300 ft^2/d. For purposes of this study, average transmissivity of the carbonate-rock aquifers around and beneath Pahrump Valley is estimated to be between 1,500 and 2,500 ft^2/d.

Clastic Aquitards

The term clastic aquitard was used by Winograd and Thordarson (1975) to categorize certain assemblages of low-permeability rocks in areas on and adjacent to the Nevada Test Site. The same concept is used in this report. The principal clastic aquitards in the vicinity of Pahrump Valley are a sequence of clastic sedimentary rocks of Cambrian and Precambrian age and a younger sequence of continental deposits of Cretaceous to Triassic age (table 1). In addition, there is a sequence of interbedded limestone and fine-grained clastic sedimentary rocks of Permian age which are probably more permeable than the first two units mentioned but still transmit water slowly enough to be relative barriers to ground-water flow.

The surficial distribution of these rocks is shown on plate 1. There is virtually no information about the distribution of these rocks beneath areas of valley fill. It was assumed that the rocks exposed in the mountains were general indicators of the rock type probably present beneath adjacent areas of valley fill. Thus, the northwest and southeast ends of the valley are presumed to be underlain by comparatively low-permeability rocks.

No wells in the area tap the clastic aquitards, so their hydraulic properties had to be inferred from information in nearby areas. Winograd and Thordarson (1975, pages C42-C43) evaluated the water-bearing characteristics of two units they termed the upper and lower clastic aquitards. For the lower clastic aquitard, they stated that although, where locally fractured, transmissivity may be as high as 1,300 ft^2/d, transmissivity for the bulk of the aquitard probably does not exceed 130 ft^2/d. They estimated that transmissivity was probably less than 70 ft^2/d for the upper clastic aquitard. Conditions are presumed to be similar in Pahrump Valley, and the average transmissivity of the clastic aquitards is estimated to be between 30 and 60 ft^2/d.

Valley-Fill Reservoir

The valley-fill reservoir is composed of unconsolidated alluvial, colluvial, and lacustrine deposits that partly fill the structural depression underlying Pahrump Valley. Some volcanic tuff is interbedded with the fill deposits.

Areal Extent

The approximate areal extent of the valley-fill reservoir is shown on plate 1. Total surface area is about 650 square miles, or about two-thirds of the total area of Pahrump Valley. The reservoir is bounded on the northeast, northwest, and southwest by consolidated rocks of the Spring Mountains, Resting Springs Range, Nopah Range, and Kingston Range (figure 1). The southeast end of the valley is generally continuous with the valley-fill reservoir in Mesquite Valley. For the purposes of this study, the southeast boundary of the reservoir is regarded to be coincident with the topographic divide between Pahrump and Mesquite Valleys. The topographic divide approximates a flow line along the predevelopment potentiometric surface, so there was no significant flow across this boundary under natural conditions.

Thickness

Wells drilled in the valley-fill reservoir range from several tens to more than a thousand feet deep. With the exception of one or two wells on the margins of the reservoir, they do not fully penetrate the valley fill and encounter bedrock. Consequently, it was necessary to use gravity data to obtain generalized information about the subsurface configuration of the reservoir. When the force of gravity is measured at a given point, the reading is affected in part by the density of underlying materials. Unconsolidated valley-fill deposits typically have substantially lower densities than adjacent and underlying consolidated rocks. This results in gravity anomalies, in valley areas, which are roughly proportional to the thickness of valley-fill deposits.

Several investigators, Healey and Miller (1965), Kane and Carlson (1964), Chapman, Healey, and Troxel (1971), and Healey (1973), have constructed Bouguer Gravity anomaly maps that include parts of Pahrump Valley. A composite map of the complete Bouguer Gravity anomalies for Pahrump was constructed from their work (plate 2).

Anomalies shown on plate 2(A) are affected by both regional trends and local conditions. The regional trends were eliminated from the data by drawing 20 sections and subtracting a regional gradient from the observed anomalies along each section. The residual anomalies were then plotted on a map and contoured. The resulting map is shown on plate 2(B). These anomalies give very rough approximation of the subsurface configuration of the valley-fill reservoir.

Rough quantitative estimates of the thickness of the valley-fill deposits were developed by making a two-dimensional analysis of the anomalies along four cross sections (A-A', B-B', C-C', and D-D' on plate 2(A)). The analysis was performed by using the Talwani method (Talwani and others, 1959) and a computer program developed by the Geological Survey. Density of the valley fill was assumed to average about 2.2 gm/cm^3 (grams per cubic centimeter) and density of consolidated rocks was assumed to average about 2.7 gm/cm^3, resulting in a density contrast of 0.5 gm/cm^3. These values are the same as those used by Healey and Miller (1965, page 7) in their gravity survey of the adjacent Amargosa Desert area. Profiles computed from this analysis are shown on plate 2(D). The relation between residual anomalies and computed depth along the four sections was applied to the anomalies on plate 2(B) to estimate approximate thicknesses of fill throughout the valley. The estimated thicknesses are shown on plate 2(C). Maximum computed thickness of about 4,800 feet occurred along section D-D' in the central part of the valley.

In general, the thickest accumulations of valley fill are along the axis of the valley south of State Route 52. The area of maximum thickness is offset slightly toward the south end of the valley, which suggests some structural relief in that area. Also, the shape of the structural depression changes from a broad shallow trough north of State Route 52 (section A-A') to a composite depression south of Route 52 (sections C-C' and D-D'). In this area the basin consists of (1) a broad upper trough that spans the entire width of the valley and has a maximum depth of 2,000 to 2,500 feet, and (2) a second trough 1,000 to 2,000 feet deeper occupies the central part of the first depression. This suggests that the basin probably contains significant internal structures and the history of deformation may be complex. However, since only reconnaissance-level data were available for analysis, additional field work with a higher density of gravity stations is needed before anything but generalized approximations can be made regarding subsurface structure.

An example of the inadequacy of the present information to handle details concerns the fault, mapped on plate 1, which parallels the State line in Tps. 21, 22, and 23 south. This feature has been mapped as a normal fault upthrown on the northeast side (Malmberg, 1967, plate 1). An eroded faultline scarp with a maximum relief of about 80 feet and tilted bedding on the upthrown side support this interpretation; however, sections C-C' and D-D' show no offset on the bedrock. There are a number of possible explanations for this apparent discrepancy. One of the simplest is that the structural relief was too small to register in the analysis of the available data. This emphasizes the need for additional subsurface information.

Hydraulic Properties of the Valley Fill

Hydraulic conductivity

Hydraulic conductivity is a measure of how easily a material will transmit water. Hydraulic conductivity is customarily expressed in terms of unit values for the area of aquifer through which a fluid moves under unit gradient per unit of time. Many natural materials transmit water in the horizontal direction much more readily than in the vertical direction. Approximate values of the horizontal conductivity of deposits typical of those in the valley-fill reservoir are listed below (values modified from Chow, 1964, figure 13-8).

Lithologic unit (table 1)	Typical materials	Probable range of hydraulic conductivity (ft/d)
Playa deposits	Clay and silt	0.001 to 0.3
	Very fine sand	0.1 to 1.6
Lacustrine and associated fine gravel deposits	Silt and clay	0.1 to 0.5
	Fine sand	1 to 4
Fanglomerate and associated coarse gravel	Mostly silt, sand, and gravel	0.1 to 4
	Sand	4 to 30+
	Gravel	20 to 150+

The above values illustrate that well-sorted gravel and sand are by far the most prolific water-yielding materials in the valley fill. Consequently, most of the water produced by wells which penetrate a variety of materials may be derived from only a few beds of coarse sand and gravel.

The average vertical hydraulic conductivity of a sequence of deposits typically is much less than horizontal hydraulic conductivity. The ratio between the two generally varies according to the type of material. Sequences of well-sorted sand and gravel commonly have higher vertical hydraulic conductivities than sequences which contain significant amounts of clay, silt, or cemented materials. For the latter materials, average vertical hydraulic conductivity values can be as small as a hundredth to a thousandth of the horizontal hydraulic conductivity. Figure 3 shows the estimated distribution of vertical hydraulic conductivity in the upper 500 feet of valley-fill deposits. The distribution shown was first estimated using available geologic and hydrologic information and then refined during the calibration of the aquifer model described in a later section of this report.

Transmissivity

Transmissivity is a measure of the ability of an aquifer to transmit water. Transmissivity is dependent on the hydraulic conductivity and thickness of the water-bearing material. Transmissivity may be calculated from the results of aquifer tests, estimated as the product of hydraulic conductivity and thickness of the aquifer, or estimated from specific

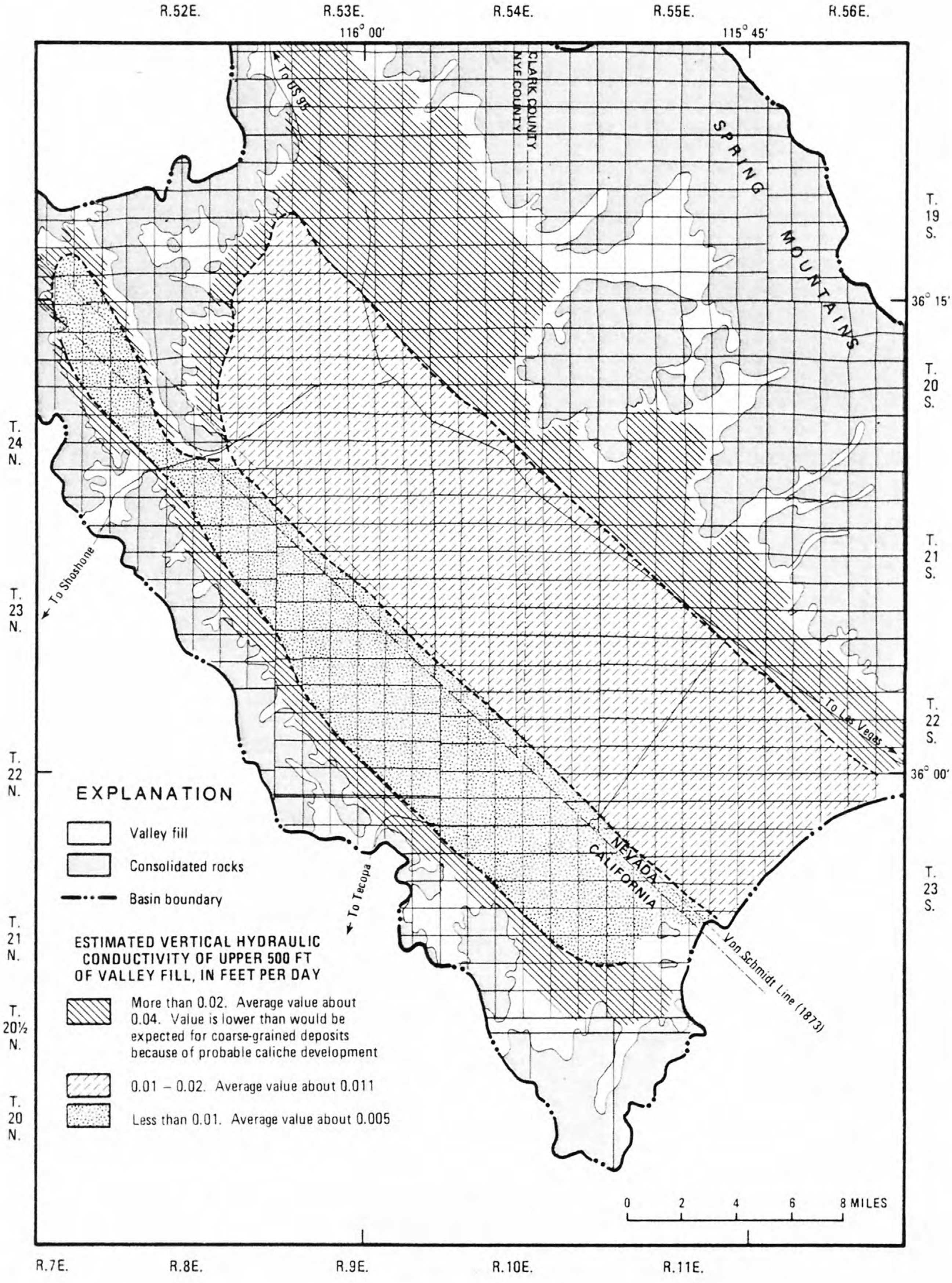


FIGURE 3. – Estimated distribution of average vertical hydraulic conductivity in upper 500 ft of saturated valley fill.

capacities of wells, provided the wells are highly efficient. Specific capacities are expressed as well yield, in gallons per minute per foot of drawdown. Properly designed wells in deposits with high transmissivity have higher specific capacities than wells tapping deposits with low transmissivity.

Figure 4 shows the approximate distribution of transmissivity of the upper 1,000 feet of saturated valley fill. This thickness was chosen because it roughly approximates the interval most affected by pumping.

Indices of ground-water storage

When the hydraulic head in an aquifer changes there is a resulting change in the amount of ground water in storage. Water can come from the draining of deposits, elastic changes in the aquifer or water, or inelastic changes in the aquifer. Water produced by these processes is described in terms of the specific yield of an unconfined aquifer, the storage coefficient of an aquifer, and the specific storage of a porous medium.

> *Specific yield* of a deposit is the ratio of (1) the volume of water which, after being saturated, the deposit will yield by gravity, to (2) its own volume, usually expressed as a percentage (Lohman and others, 1972, page 12). Specific yield of alluvial deposits ranges from about 30 percent in well-sorted sand or gravel to less than 5 percent in compacted clay or deposits with extensive caliche development. The fanglomerate and associated coarse-grained deposits shown on plate 1 typically have specific yields between about 13 and 25 percent. The higher range of specific yield is associated with well-sorted sands and gravels and the lower range with poorly sorted mudflow deposits and areas with significant caliche development. The lacustrine and associated fine-grained deposits shown on plate 1 typically have specific yields between about 5 and 15 percent depending on the degree of compaction of clay and the amount of fine sand present. The distribution of specific yield used in this study is shown in figure 5.
>
> *Storage coefficient* of an aquifer is the volume of water released from or taken into storage per unit of surface area per unit change in head. Water comes from expansion of the water and compression of the aquifer. Compression of the aquifer may be elastic or inelastic. Coarse-grained deposits such as sand and gravel are characterized by a relatively rigid framework that is supported by grain-to-grain contact; aquifer compression in these deposits is typically elastic. Fine-grained deposits, such as clay or silt, generally do not possess a rigid framework and typically both elastic and inelastic compression occur. For conditions that exist in Pahrump Valley, the quantity of water involved in inelastic compression of the aquifer is much greater than that involved

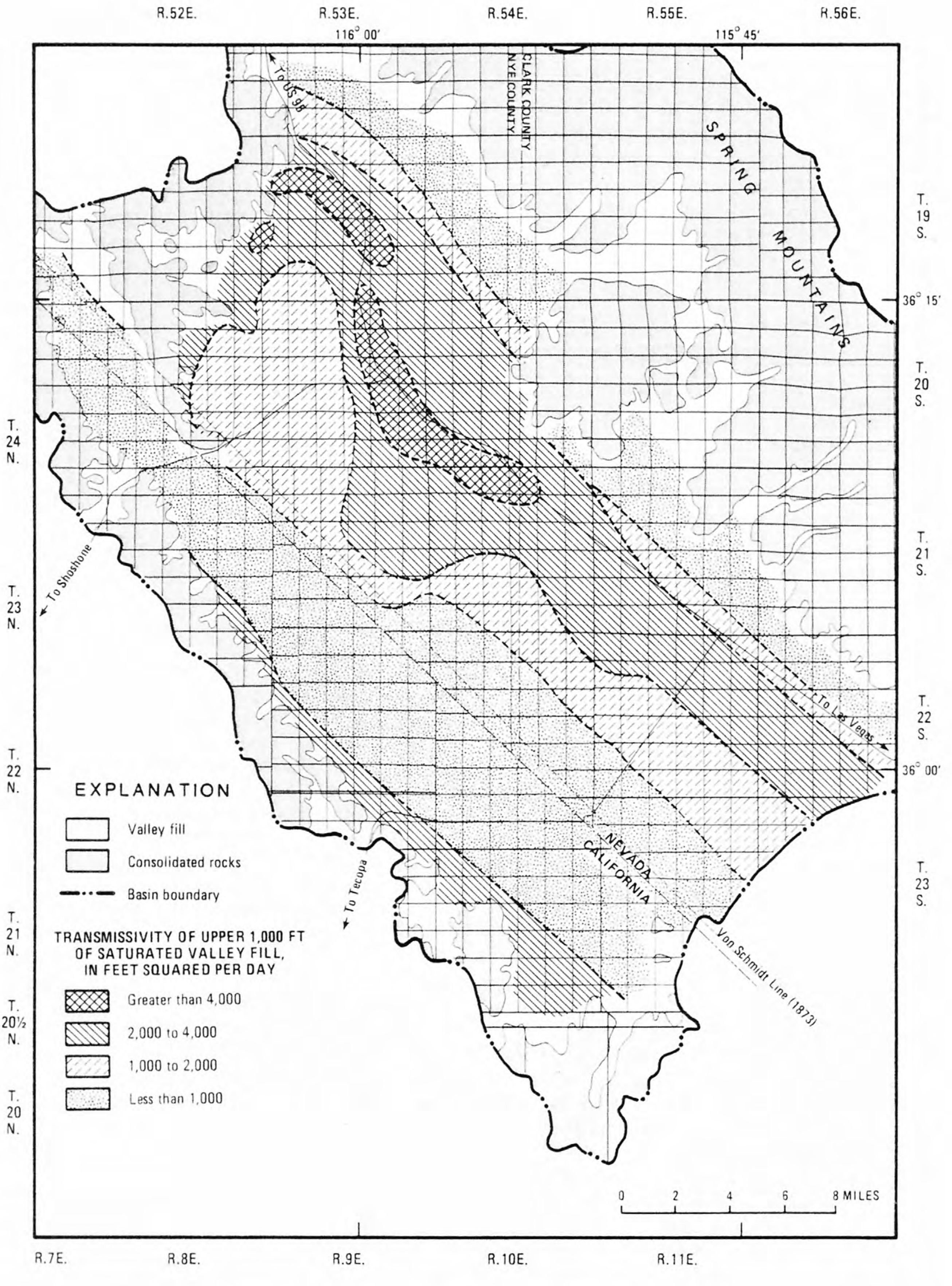


FIGURE 4. — Estimated transmissivity of upper 1,000 ft of saturated valley fill.

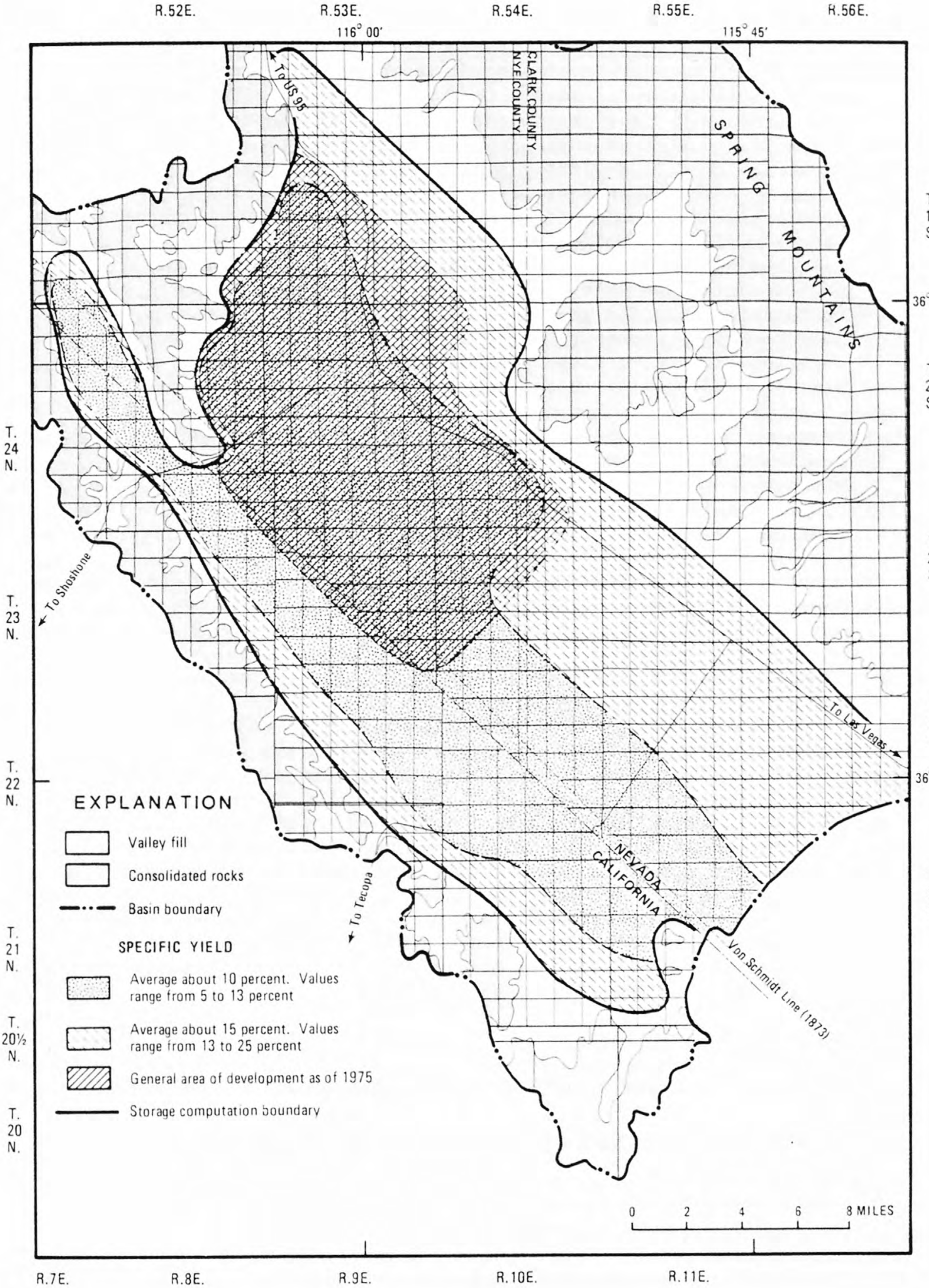


FIGURE 5. – Estimated specific yield.

in elastic compression. Consequently, for purposes of evaluating the current response to pumping in Pahrump Valley, it is satisfactory to assume that virtually all water yielded from storage by fine-grained materials is produced by inelastic compaction. Fine-grained materials form only a part of the total valley fill and their aggregate thickness varies from place to place. Consequently, it is necessary to consider water released from or taken into storage per unit volume of a porous medium. Specific storage is the volume of water released from or taken into storage per unit volume of the porous medium per unit change in head. There are no field data to describe specific storage of fine-grained deposits in Pahrump Valley; however, in adjacent Las Vegas Valley, areas underlain by fine-grained deposits generally required 20 to 80 feet of head decline to produce 1 foot of land subsidence. Comparison of these known magnitudes of land subsidence with measured head declines and the approximate thickness of the confining layer suggests that in Las Vegas Valley specific storage of the confining beds is on the order of 0.001 to 0.0001 per feet (Harrill, 1976, page 19). Lofgren (1977, page 30) states that compressible deposits may have an inelastic (largely nonrecoverable) virgin specific storage of about 0.0001 per feet. Compressible fine-grained deposits in Pahrump Valley probably have specific storage values of about the same magnitude.

In Pahrump Valley, thickness of saturated valley fill ranges from about 200 feet to 4,000 feet. If no appreciable fine-grained deposits were present the storage coefficient for these thicknesses would be 0.0002 to 0.003. The percentage of fine-grained materials present ranges from a very small amount around the margins of the valley to possibly as much as 80 in the central valley. If a change in head were uniformly distributed throughout the full thickness of the reservoir, the storage coefficient would be nearly 0.25. However, it is more probable that significant head changes would occur primarily in the most heavily pumped zones of the reservoir, for example, a 500-feet thick interval in the upper part of the reservoir. In this case, the storage coefficient would be estimated to be about 0.04. In the quantitative parts of this study values within the range 0.0002 to 0.003 were used for coarse-grained deposits around the margins of the valley and values within the range 0.001 and 0.04 were used for fine-grained deposits in the central part of the valley.

OUTLINE OF GROUND-WATER HYDROLOGY

Source, Occurrence, and Movement of Ground Water

Virtually all the ground water in Pahrump Valley is derived from precipitation that falls within the basin. Deep infiltration (recharge) occurs in the mountains where percolating water moves through bedrock fractures to the zone of saturation and on the upper slopes of the alluvial apron where streamflow percolates through unsaturated valley fill to the zone of saturation.

Recoverable ground water is primarily in the saturated parts of the valley and in fill under both water-table and confined conditions. Confined conditions occur where saturated permeable deposits are overlain by less permeable strata and where the water at the top of the aquifer is under greater than atmospheric pressure. Water-table conditions exist where the water at the top of the zone of saturation, the water table, is at atmospheric pressure. Figure 6 shows the generalized depth to ground water as of March 1976.

Ground water moves along the path of lowest resistance from areas of high hydraulic head to areas of lower hydraulic head. The rate of movement depends on the hydraulic gradient and the permeability and porosity of the material through which water is moving. Typical rates in this area range from several feet per year to several hundred feet per year.

The general slope of the ground-water surface in Pahrump Valley under predevelopment conditions (prior to 1913) is shown in figure 7. This figure shows the approximate configuration of the potentiometric surface in that part of the valley-fill reservoir penetrated by most of the high-yield wells (generally the upper 200 to 1,000 feet of saturation). It was constructed with the earliest measurements available. Ground-water flow was generally from the principal recharge areas adjacent to the Spring Mountains southwestward across the valley toward the Nopah Range. Water left the valley by evapotranspira tion in areas of shallow ground water and by subsurface outflow beneath the Nopah Range. As drawn, the contours suggest that as water flowed across the northwest border of Pahrump Valley it moved into and through projections of consolidated rocks. The final disposition of this water is not known with certainty. Hydraulic gradients exist toward both the Ash Meadows discharge area (in the Amargosa Desert north and west of Pahrump Valley) and a discharge area along the Amargosa River between the towns of Shoshone and Tecopa (south-west of Pahrump Valley). Winograd and Thordarson (1975, pages 690-692) evaluated the relation of the Ash Meadows ground-water basin to the Pahrump Valley ground-water basin and concluded that because a significant assemblage of rocks assigned to the clastic aquitards was exposed between Pahrump Valley and the Ash Meadows ground-water discharge area, at most only a small percentage of the Ash Meadows discharge can be derived from either Stewart Valley or western and northwestern Pahrump Valley.

Ground-Water Storage

The potentially recoverable water stored in the valley-fill reservoir can be estimated as the product of an area, a thickness, and a specific yield. The following procedures were used to compile estimates for Pahrump Valley:

(1) The area underlain by valley fill was divided into a number of rectangular nodes identical to those used in the ground-water model that will be described in a later section of this report (see figure 15).

(2) For each node the thickness of saturated valley fill was determined, using total thickness of fill shown on plate 2(C) and depths to water shown in figure 6; the specific yield was determined from figure 5.

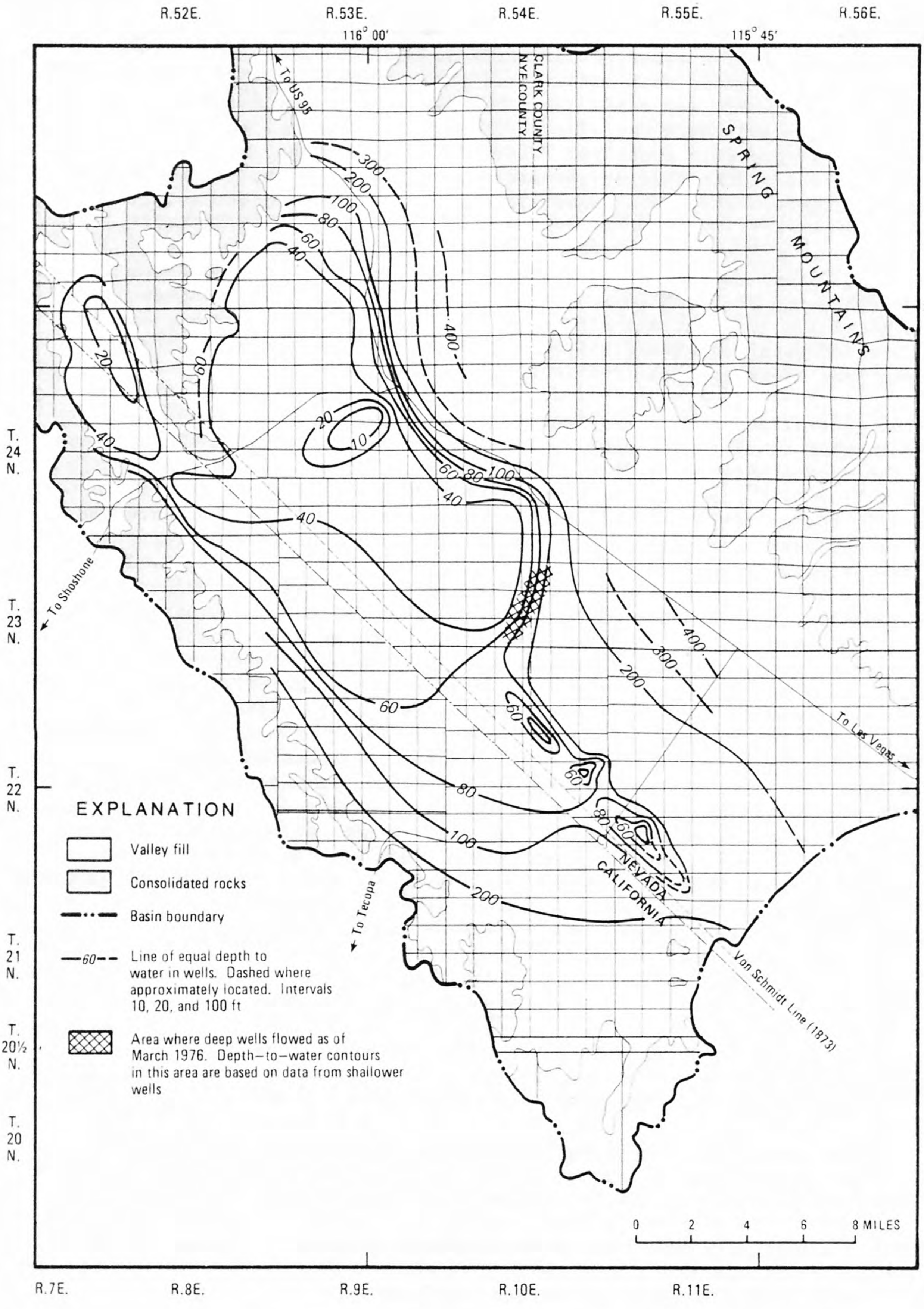


FIGURE 6. – Depth to water, March 1976.

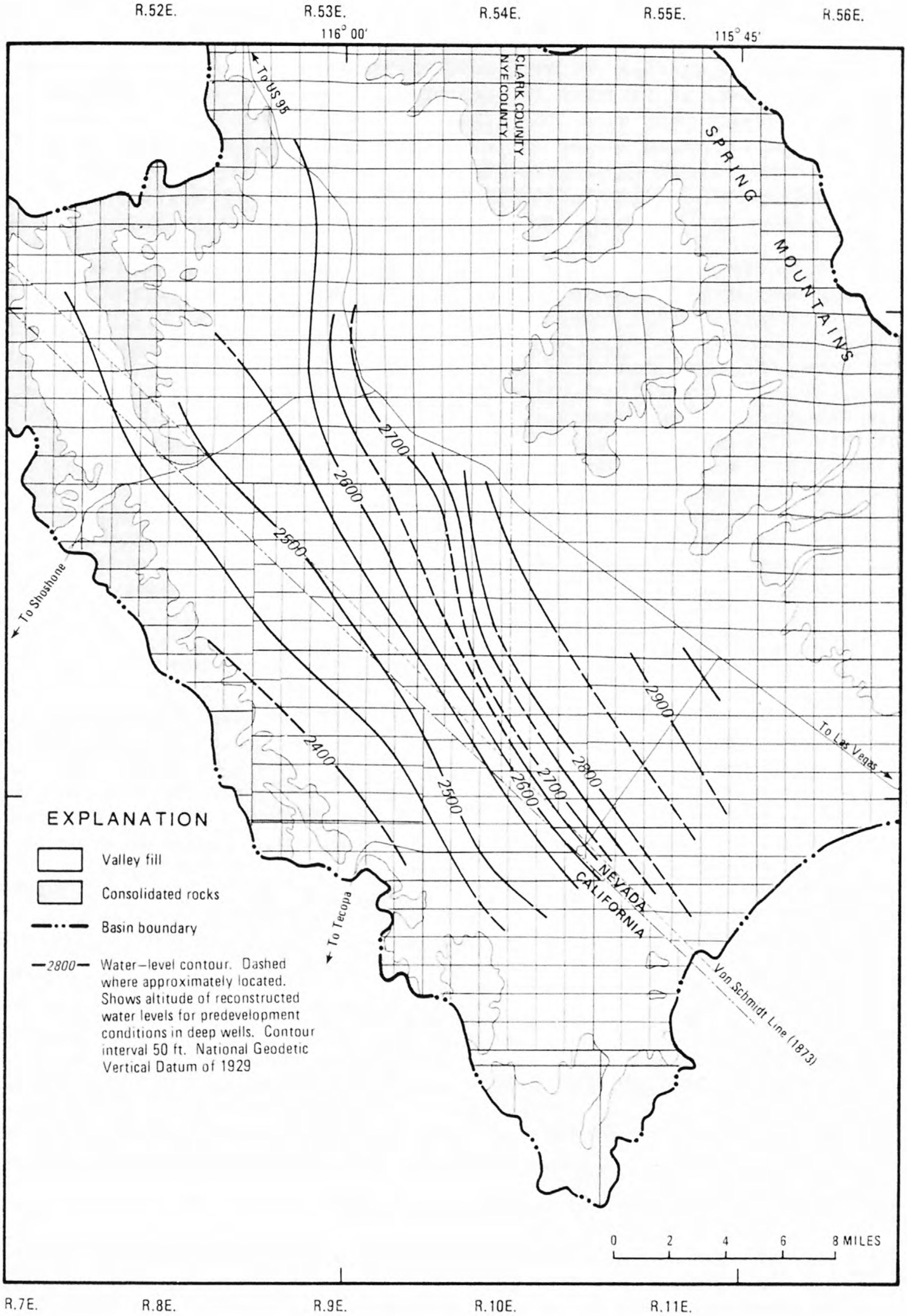


FIGURE 7. — Water-level contours for deep wells under predevelopment conditions.

(3) Recoverable storage for each node was calculated as the product of the area of the node, an interval of saturated valley fill, and a specific yield. Two intervals were used, the upper 200 feet of saturation and the remainder of the saturated valley fill. The yield of the interval below 200 feet was reduced by 5 to 15 percent (depending on the thickness of fill at each node) to account for lower yields in the older, more deeply buried deposits.

(4) Values for nodes were summed to give the results listed in table 2. Computations were made for two general areas, the developed area as of 1975 (shown in figure 5) and the remaining area of valley fill.

The estimated total amount of recoverable water stored in the valley-fill reservoir, 57 million acre-feet, illustrates the vast amounts of water stored in large valley-fill ground-water reservoirs in the Great Basin. However, much of this water cannot be practically recovered with our existing technology due to economic factors, such as high pumping lifts and environmental factors, such as land subsidence. Also, the quality of the deeper water is not known. The estimated 2.3 million acre-feet stored in the upper 200 feet of saturated valley fill in the 1975 area of development is probably within economic pumping lifts utilizing the 1975 distribution of pumpage. Even so, depletion of this amount of storage would probably cause land subsidence in the central part of the valley.

TABLE 2.--*Estimated recoverable ground-water storage*

	Recoverable ground-water storage (acre-feet, rounded)		
Location[1]	Upper 200 feet of saturation	Saturated valley fill below 200 feet	Total valley fill
Developed area as of 1975	2,300,000	17,000,000	19,000,000
Area remote from 1975 development	5,500,000	32,000,000	38,000,000
Total	7,800,000	49,000,000	57,000,000

[1] See figure 5 for location of areas.

Ground-Water Development

Development Prior to 1962

Pahrump Valley has supported agricultural development for many years. Two large springs (Bennetts Springs and Manse Spring, figure 1) provided water to early travelers and were soon developed for irrigation. Mendenhall (1909, page 91) described the level of development in Pahrump Valley shortly after the turn of the century as follows:

> "Pahrump, one of the oldest settlements in the southern part of Nevada, is about 7 miles northwest of Manse, on the road to Fairbanks Ranch. It is a large ranch in whose cultivation a number of Indians are employed. Here orchards, vineyards, and extensive fields of alfalfa flourish, and the water used in irrigation is supplied by a number of large, deep-seated warm springs similar to those at Manse. Travelers can obtain hay and grain here.
>
> "The springs at Manse have been known for years to travelers going northward from points in southern Nevada, and the place has long been the principal stopping point along this route. By the use of the water which the springs yield, this portion of the desert has been converted into a veritable oasis, and the 500 or 600 acres of alfalfa, orchards, and vineyards show the capabilities of the desert soil when water can be applied to it in sufficient quantity."

The springs described on the Pahrump Ranch were named Bennetts Springs and are reported to have flowed at about 7.5 ft^3/s in the late 1800's. Manse Spring is reported to have flowed at about 6 ft^3/s at that same time (Maxey and Jameson, 1948, page 10). The total average annual flow was about 9,800 acre-feet.

In 1910, the first well was drilled in Pahrump Valley in an attempt to obtain artesian water from wells. That attempt was unsuccessful; however, in 1913, three flowing artesian wells were successfully completed, and development of the area's ground-water resources had begun. In 1916, Waring (1921, pages 76-79) reported 28 wells in Pahrump Valley, 15 of which were flowing.

The number of new wells drilled and the annual pumpage increased slowly until the mid-1940's. At that time many wells were drilled and large capacity pumps installed. From the mid-1940's through 1962, the annual discharge from wells increased from an estimated 10,000 acre-ft/yr (acre-feet per year) to about 28,000 acre-ft/yr (Malmberg, 1967, pages 30-31). Thus, pumpage from the ground-water reservoir in 1962 was about three times greater than the reported natural flow from springs in the late 1800's.

Development 1962-75

The period 1962-75 was one of population growth and significant change in land use for Pahrump Valley. Population increased from about 250 in 1962 to nearly 1,500 in 1975. This increase in population was accompanied by conversion of land from agricultural use to real-estate development.

In the early 1960's Pahrump Valley was one of the most productive farm districts in southern Nevada. Cotton and alfalfa were the principal crops. The area remained primarily on an agriculture-based economy during most of the 1960's. In 1963, electrical power was introduced to the valley, followed by telephone service in 1965. In the late 1960's several large tracts of farmland were subdivided for real-estate development. Land sales soon became a major factor in the economy of the valley. The largest development in the valley, Calvada, is reported to have sold about 10,400 lots during the period 1970-74 and was selling an average of 300 lots per month in 1974 (Nevada West and Pahrump Valley Times, August 1974, page 11).

Ground water provides the water supply for virtually all development in Pahrump Valley. Pumpage increased rapidly between 1962 and 1968. Pumpage decreased after 1968 when some land was taken out of agricultural production and subdivided for real-estate development. If this land is fully developed, pumpage will probably return to about the same level as in 1968.

Development during the period 1962-75 is summarized in table 3, which lists estimates of population, irrigated acreage, and ground-water withdrawal. In 1975, irrigation remained the principal use of water, accounting for about 38,000 of the 40,800 acre-feet withdrawn for use. Of the remaining 2,800 acre-feet, about 800 acre-feet was used for self-supplied domestic purposes and about 2,000 acre-feet was used for public supply and commercial purposes. Part of the pumped water is recycled back to ground water. The percentage varies both with type of use and with individual systems. An average of about 25 percent of the agricultural pumpage, 70 percent of the self-supplied domestic pumpage, and 50 percent of the public supply and commercial pumpage was estimated to be recirculated back to ground water. The relative amount of water used for domestic, public-supply, and commercial purposes will probably increase substantially in the near future and the amount of water recirculated will be affected accordingly. Also, agricultural water requirements could be affected by future changes in cropping patterns. For example, population increases in both Pahrump and Las Vegas Valleys could provide a significant market for certain vegetables and other diversified crops that require much less water per acre than alfalfa. A discussion of the effects of various cropping patterns on the area's water requirements and economy is beyond the scope of this study. However, this is an alternative that should be considered when evaluating means of dealing with the overdraft on the area's ground-water resources. Figures 8 and 9 show the areal distribution of ground-water withdrawals in 1962 and 1975.

TABLE 3.--*Summary of population, irrigated-land area, and ground-water withdrawals, 1962-75*

[Populations and acreages rounded to nearest 10, withdrawals to nearest 100]

		Irrigated land (acres)[1]			Ground-water withdrawals[1] (acre-feet)		
Year	Population[2]	Cotton	Other[3]	Total	Manse Spring	Pumpage	Total
1962	250	3,320	3,170	6,490	1,400	27,600	29,000
1963	280	3,360	4,480	7,840	1,300	31,200	32,500
1964	320	3,160	4,510	7,670	1,300	36,200	37,500
1965	430	2,950	5,300	8,250	800	35,700	36,500
1966	490	2,240	5,320	7,560	1,100	37,000	38,100
1967	510	2,230	6,000	8,230	1,100	40,400	41,500
1968	570	2,310	6,070	8,380	900	47,100	48,000
1969	750	2,220	6,180	8,400	700	40,200	40,900
1970	960	1,210	3,640	4,850	400	42,200	42,600
1971	1,050	1,370	3,180	4,550	800	37,200	38,000
1972	1,230	1,200	3,120	4,320	700	35,900	36,600
1973	1,390	2,070	5,100	7,170	600	38,800	39,400
1974	1,470	1,610	5,320	6,930	400	41,000	41,400
1975	1,480	1,530	5,010	6,540	200	40,600	40,800
Total for period (rounded) --------------------					12,000	530,000	540,000

[1] From records of the Nevada State Engineer.

[2] Populations for 1975 and 1970 reported in Nevada West and Pahrump Valley Times, May 1975, page 4. Populations for other years estimated by author from home power and telephone hookups.

[3] Primarily alfalfa.

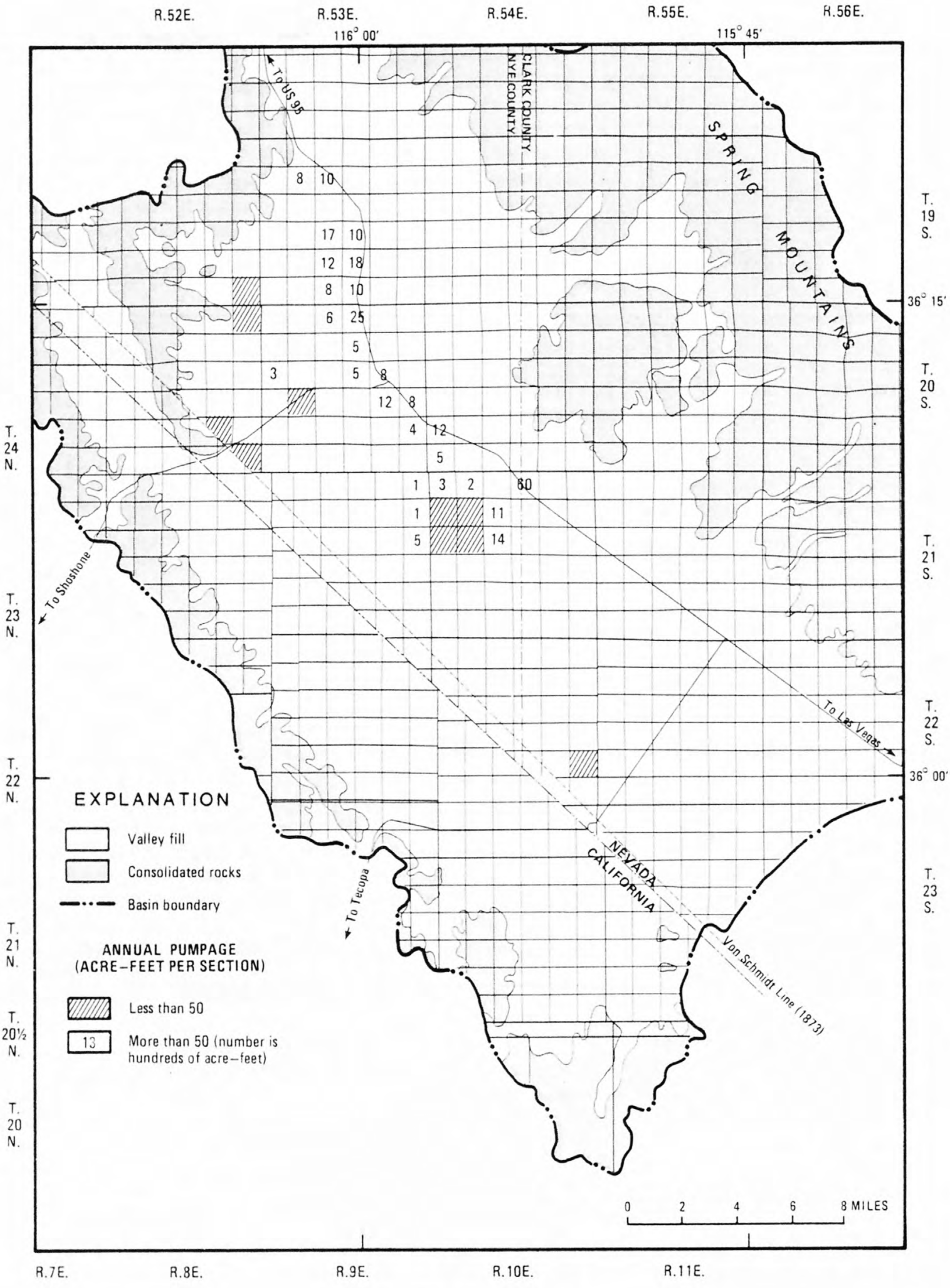


FIGURE 8. – Distribution of pumpage in 1962.

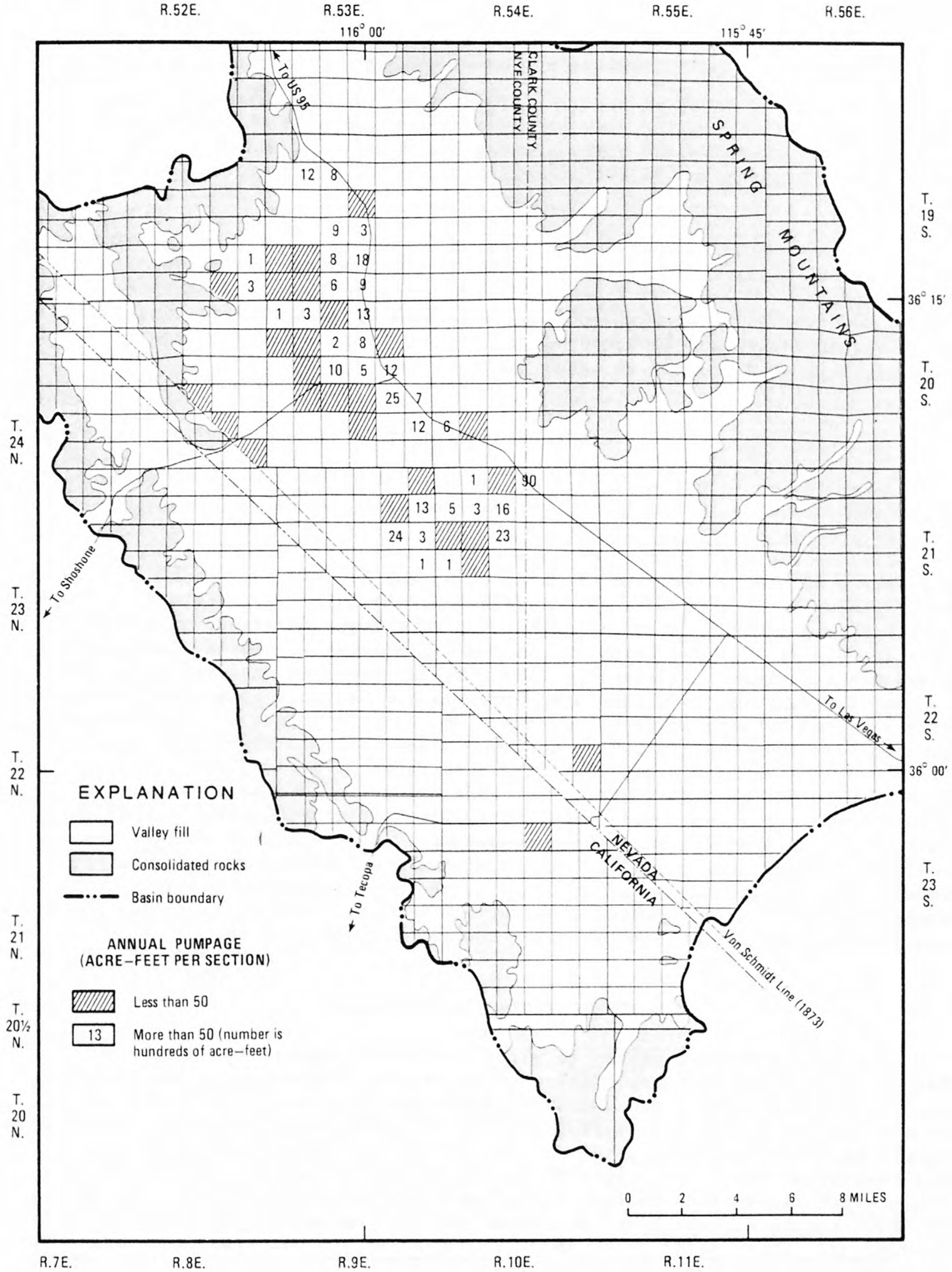


FIGURE 9. – Distribution of pumpage in 1975.

Effects of Development

As of 1975, a total of nearly 700,000 acre-feet of pumpage and about 550,000 acre-feet of spring flow had been discharged from the valley-fill reservoir in Pahrump Valley since pumping began in 1913. Of this, 530,000 acre-feet of pumpage and 12,000 acre-feet of spring flow occurred during the period 1962-75.

Response of the ground-water system to withdrawals was complex. The two most apparent effects were large water-level declines and cessation of most spring discharge. These will be discussed in the following paragraphs. Some of the more subtle responses, such as variations in ground-water evapotranspiration, probable land subsidence, and probable diminished subsurface outflow, will be discussed in later parts of this report.

Water-Level Changes

Water levels in wells generally have been declining since the first wells were constructed in 1913. The annual rate of decline and the net change between predevelopment and 1975 water levels vary at different locations, depending on the distribution of pumping (figures 8 and 9), hydraulic properties of the valley fill (figures 3, 4, and 5), and the depth of the well being measured. Hydrographs of water-level changes in six wells were prepared to illustrate typical rates and magnitudes of change in various parts of the valley. Figure 10 shows locations of the six observation wells, and figure 11 shows the hydrographs. Generally, the greatest declines occurred along the base of the Pahrump and Manse fans where maximum declines of about 100 feet were observed between predevelopment and February 1976 levels. The two wells located away from the fan in the central valley (162 S20 E53 06CDA1 and 162 S22 E53 01AA1) exhibit substantially lesser rates of water-level decline. An exception to the generally declining trend occurs in some shallow wells located near irrigated areas. Some irrigation water recharges the shallow part of the valley-fill reservoir; consequently, water levels in some shallow wells on or near irrigated land may be higher than under predevelopment conditions. Additional information about the areal distribution of water-level changes is presented on net-change maps, located in a later section that deals with simulation of the response to pumping.

Declines in Spring Discharge

Pumping in Pahrump valley is well situated to capture the discharge of Bennetts and Manse Springs. Consequently, spring flow began to decrease shortly after pumping began and continued to decrease until 1975, when it ceased to flow during the pumping season. In 1959, Bennetts Spring ceased to flow. As of 1975, Manse Spring was dry during the summer irrigation season but discharged about 200 acre-feet during the winter months. Figure 12 is a graph which illustrates changes in spring discharge through 1975. The amount by which spring discharge has decreased is also the amount of water captured by pumping. Thus, as of 1975, about 10,000 acre-feet per year of spring discharge had been captured by pumping.

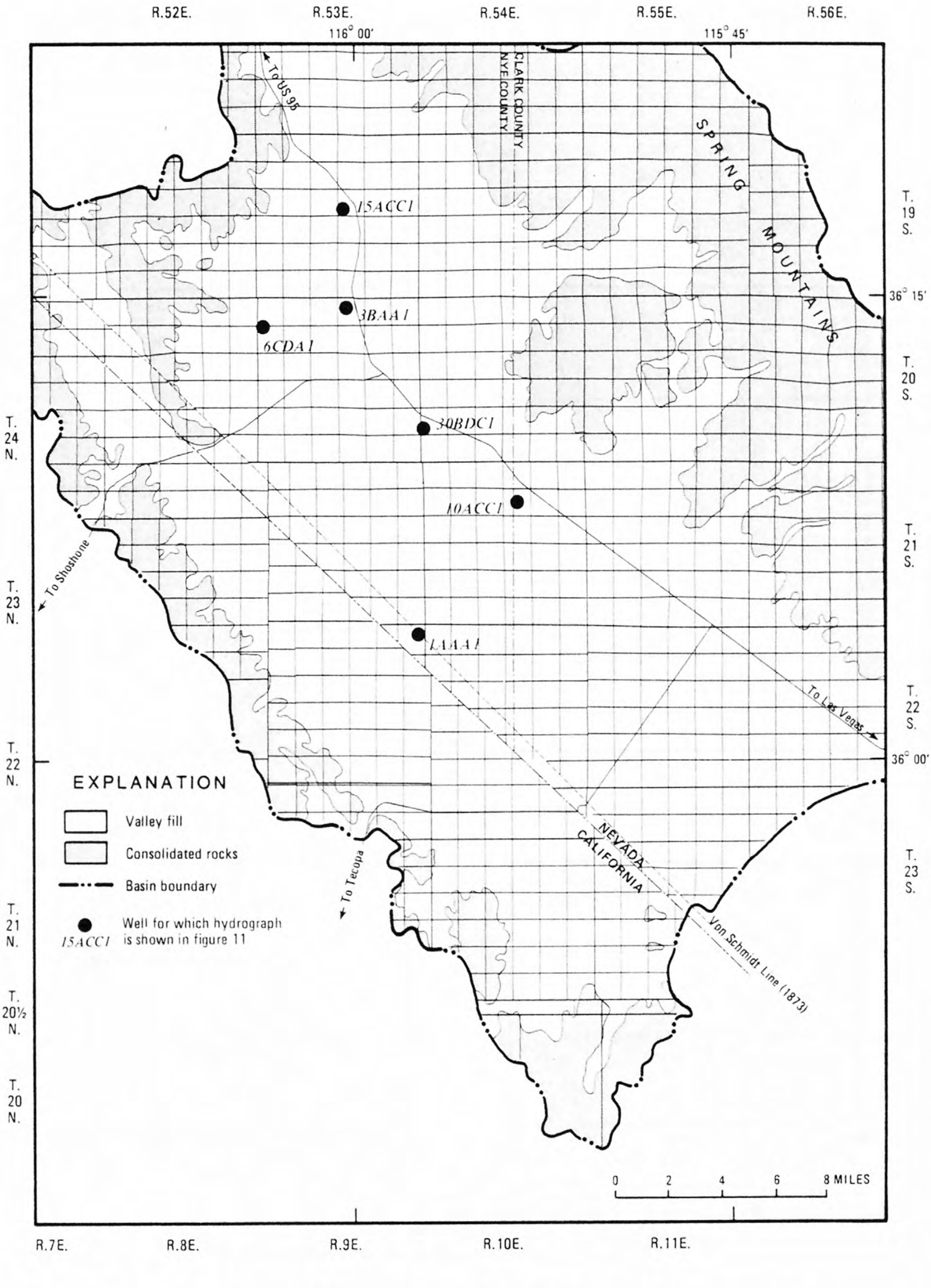


FIGURE 10. – Location of selected observation wells.

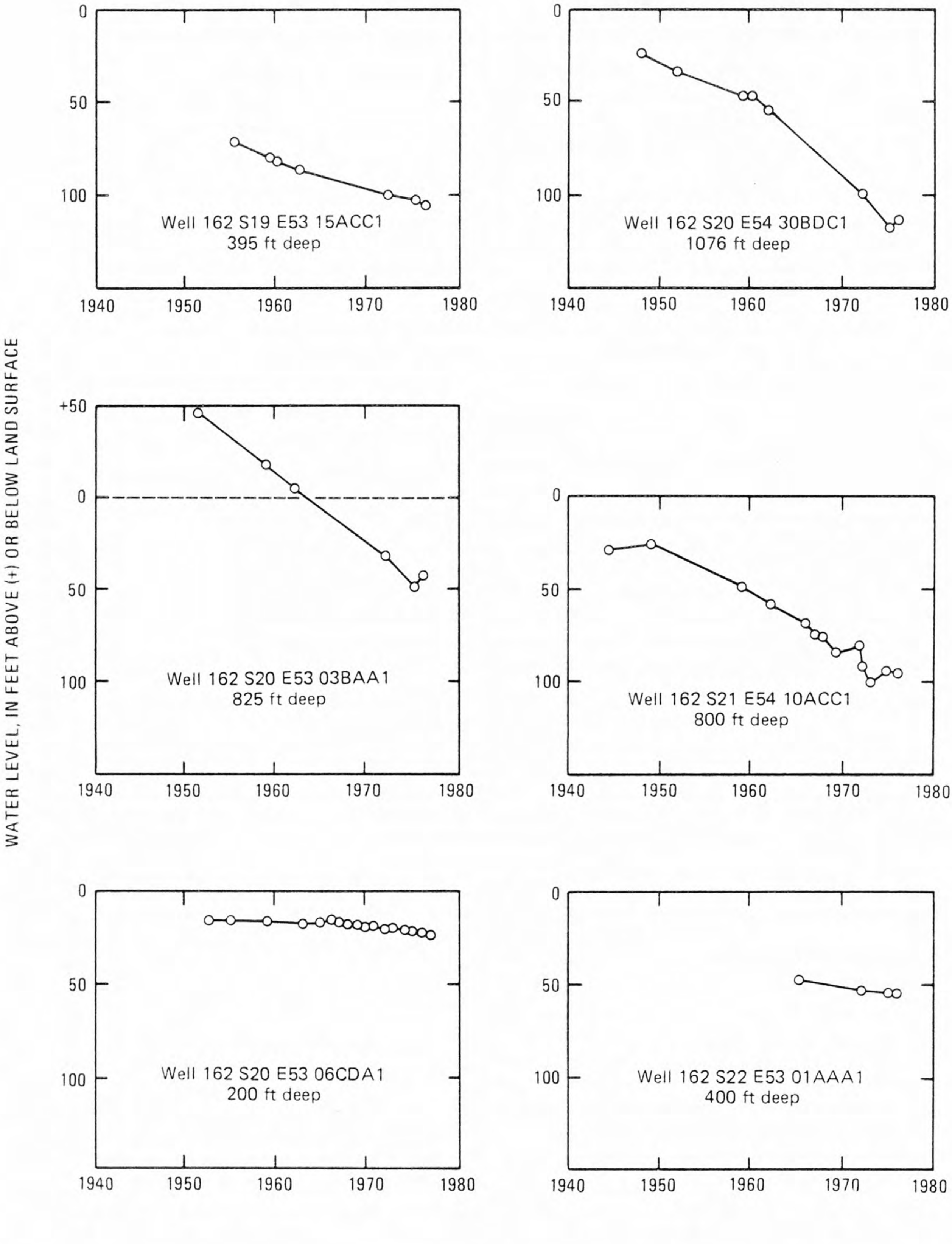


FIGURE 11. — Water-level changes in six observation wells.

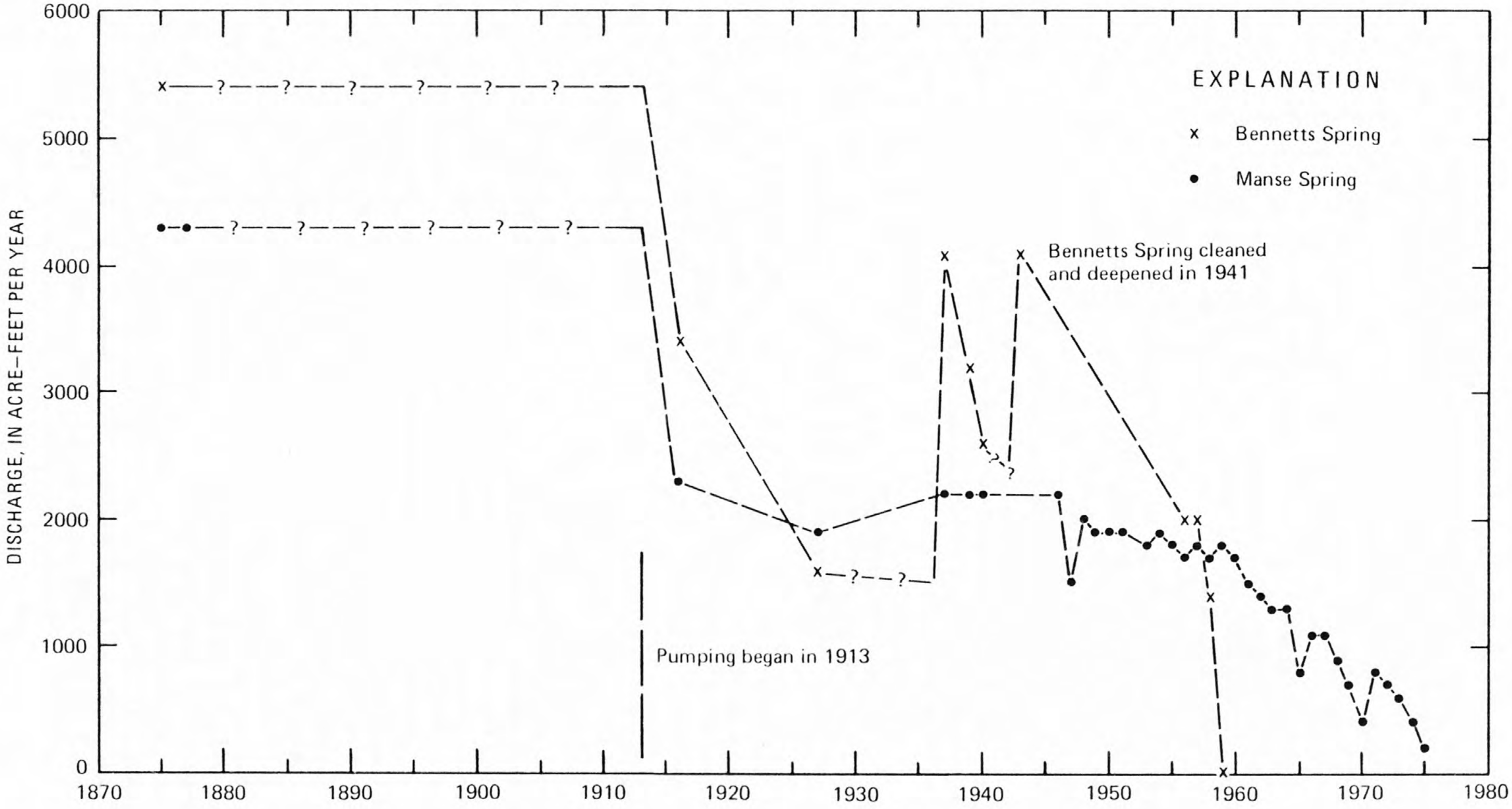


FIGURE 12. – Annual discharge of Bennetts and Manse Springs, 1875 – 1975.

GROUND-WATER RECHARGE AND DISCHARGE

Estimates of ground-water recharge and discharge for predevelopment conditions have been developed by Malmberg (1967, page 56). In this study it was not necessary to develop completely new estimates but only to evaluate the existing ones to see if any revisions are warranted in light of other information and experience gained since the mid-1960's. In the Pahrump Valley area, virtually all inflow consists of recharge from precipitation that falls within the basin. Natural discharge consists of evapotranspiration and subsurface outflow. Spring discharge is either consumed by evapotranspiration or some may return to ground water and be discharged as subsurface outflow.

Malmberg (1967, page 26) used a method described by Eakin and others (1951, page 26, 27) to estimate recharge in Pahrump Valley to be about 22,000 acre-ft/yr. This method is based on the assumption that a fixed percentage of a given average annual rate of precipitation ultimately recharges the ground-water reservoir. However, during the 1960's and early 1970's this same technique was applied to some other areas in Nevada where investigators used higher precipitation rates on the sides of mountains facing the prevailing storm tracks and also used higher percentages of recharge where there are significant areas of higher altitude. These variations could be roughly applied to Malmberg's estimates (1967, table 4) by changing average precipitation and assumed percentage of precipitation in the zone above 8,000 feet from 1.75 feet and 20 percent to 2.0 feet and 25 percent, respectively. The resulting revised estimate of recharge is about 26,000 acre-ft/yr.

There are insufficient data to define which set of assigned values is best, so this technique will be considered to produce results ranging from 22,000 to 26,000 acre-ft/yr, depending on the particular set of assumptions and assigned values used.

Malmberg (1967, page 29) estimated the annual evapotranspiration by mapping areas and densities of phreatophytes present in 1961 and multiplying the areas by assigned use rates. Areas associated with spring discharge and irrigation tail water were separated from other areas of evapotranspiration. The total evapotranspiration estimated in this way was 10,000 acre-ft/yr (Malmberg 1967, table 5). Estimates based on the 1961 distribution of phreatophytes include the assumption that there had been no significant change in areas or rates of evapotranspiration from the natural conditions. But, if pumping or clearing land for irrigated crops has reduced phreatophyte areas or discharge, then the estimate of discharge under natural conditions is too low. An alternate approach would be to assume that virtually all the natural spring discharge was ultimately consumed by evapotranspiration. Total evapotranspiration could be estimated as the sum of estimated predevelopment spring discharge (10,000 acre-ft/yr) and natural evapotranspiration outside of areas where evapotranspiration is supported by spring discharge. The resulting total of 13,000 acre-ft/yr is larger than the original estimated 10,000 acre-ft/yr but is still of the same order of magnitude. Both approaches are dependent on assumptions that cannot be completely verified by existing data. The earliest estimates of discharge from Bennetts and Manse Springs were reported by the owners (Maxey and Jameson, 1948, page 10). The earliest measurements were made in 1916 and were about 40 percent lower than the initial values reported by Maxey and Jameson. It could not be determined with certainty if the earliest measurements represented reduced spring discharge caused by nearby flowing wells or if the earliest reported estimates were in error. Consequently, in this study, natural evapotranspiration is estimated to be between 10,000 and 13,000 acre-ft/yr.

During field work conducted in 1975 and 1976, shad scale (atriplex) was observed growing in comparatively shallow ground-water areas near irrigated land in the north-central part of the valley. Some species of shad scale are phreatophytes and consume ground water. It was not determined if there were substantial stands of shad scale in the valley prior to development or if the shad scale seen today has developed as a result of the availability of irrigation tail water. If significant shad scale was present prior to development, then natural ground-water evapotranspiration probably is greater than the range indicated above.

Malmberg (1967, page 30) estimated subsurface outflow from the southwest edge of the valley-fill reservoir on the basis of computations using transmissivity, ground-water gradients, and width of flow section. The range of transmissivity that he used (134 to 668 ft^2/d) gives a range of outflow estimates from 1,000 to 4,000 acre-ft/yr. Within this range, Malmberg chose 2,000 acre-ft/yr as his best estimate of the outflow. Because of the uncertainties involved in estimating transmissivity, the range of 1,000 to 4,000 acre-ft/yr will be used for this estimate of outflow.

It was not possible to make a credible direct estimate of subsurface outflow through the carbonate-rock reservoir. Malmberg (1967, page 32) estimated this quantity as the difference between the other items of recharge and discharge. The same approach was used in this study and a range of 5,000 to 15,000 acre-ft/yr was obtained. Thus, total subsurface outflow through both valley fill and consolidated rocks is estimated to range from 6,000 to 19,000 acre-ft/yr.

Table 4 summarizes the various estimates of recharge and discharge. Ranges of estimates are given because of the uncertainties involved in assumptions for a given technique or because of varying results obtained when slightly different techniques were used to estimate the same parameter. Values estimated by Malmberg (1967, page 36) are within the general range of estimates and generally fall in the lower part of the range. These estimates will be further evaluated in a later section of this report by using a computerized mathematical model of the flow system. The values listed in table 4 (which were based on field and empirical techniques) were used as input values for the initial computer runs, and where the model results differ they provide a basis for comparison.

TABLE 4.--*Summary of estimates of recharge and discharge for natural conditions*

[Acre-feet per year]

Recharge	22,000 - 26,000
Discharge	
Evapotranspiration	10,000 - 13,000
Subsurface outflow from valley fill	1,000 - 4,000
Difference (recharge minus discharge)	5,000 - 15,000[1]

[1] Difference is assumed to be outflow through carbonate-rock reservoir. Calculated as maximum recharge minus minimum discharge for high end of range and minimum recharge minus maximum discharge for low end.

Conceptualization of the Ground-Water System

The ground-water system, as described in the preceding sections of this report, is a thick reservoir of unconsolidated deposits bounded on its sides and bottom by consolidated rocks, some of which are permeable enough to transmit significant regional ground-water flow. Water-bearing properties of the valley fill vary from place to place. Generally, the most productive deposits are along the lower parts of alluvial fans on the northeast side of the valley. Deposits in the central part of the valley are predominantly finer-grained materials and are much less productive. Ground water in the valley-fill reservoir is both confined and unconfined. Water is unconfined at and near the upper surface of saturation (the water table). Interbedded silt and clay in the central valley and caliche horizons and cemented zones around the margins of the valley inhibit vertical movement, and ground water in most of the deeper valley-fill deposits is under leaky confining conditions. Water levels in the deeper wells generally are assumed to represent composite heads typical of conditions in the upper 1,000 feet of saturation. Heads in deeper parts of the valley-fill reservoir and underlying consolidated rocks are not known.

The ground-water reservoir underlying Pahrump Valley functions as a three-dimensional system. Generally water flows from recharge areas in and near the Spring Mountains southwestward toward the Nopah Range where it leaves the area as subsurface outflow. There is a downward vertical component of movement in the recharge areas and an upward vertical component of movement in discharge areas. Consequently, head varies both areally and with depth, and a multiple-layer concept is required to give a reasonable representation of the system.

The ground-water system in Pahrump Valley is evaluated as a three-layer system. The top layer approximates the water table and underlying adjacent material in which water is unconfined. It is assumed to be about 50 feet thick. The middle layer represents that part of the valley-fill reservoir most affected by pumping. This is assumed to be generally the zone from 50 to 1,000 feet below the water table. The bottom layer consists of the valley fill not included in the overlying layer and the consolidated rocks that underlie the valley-fill reservoir and transmit significant subsurface flow.

Figure 13 illustrates the conceptualization of the ground-water system in Pahrump Valley. The southwest edge of the system has been extended approximately 15 miles southwest of Pahrump Valley to include probable discharge areas of the subsurface outflow from the valley.

Development of the Mathematical Model

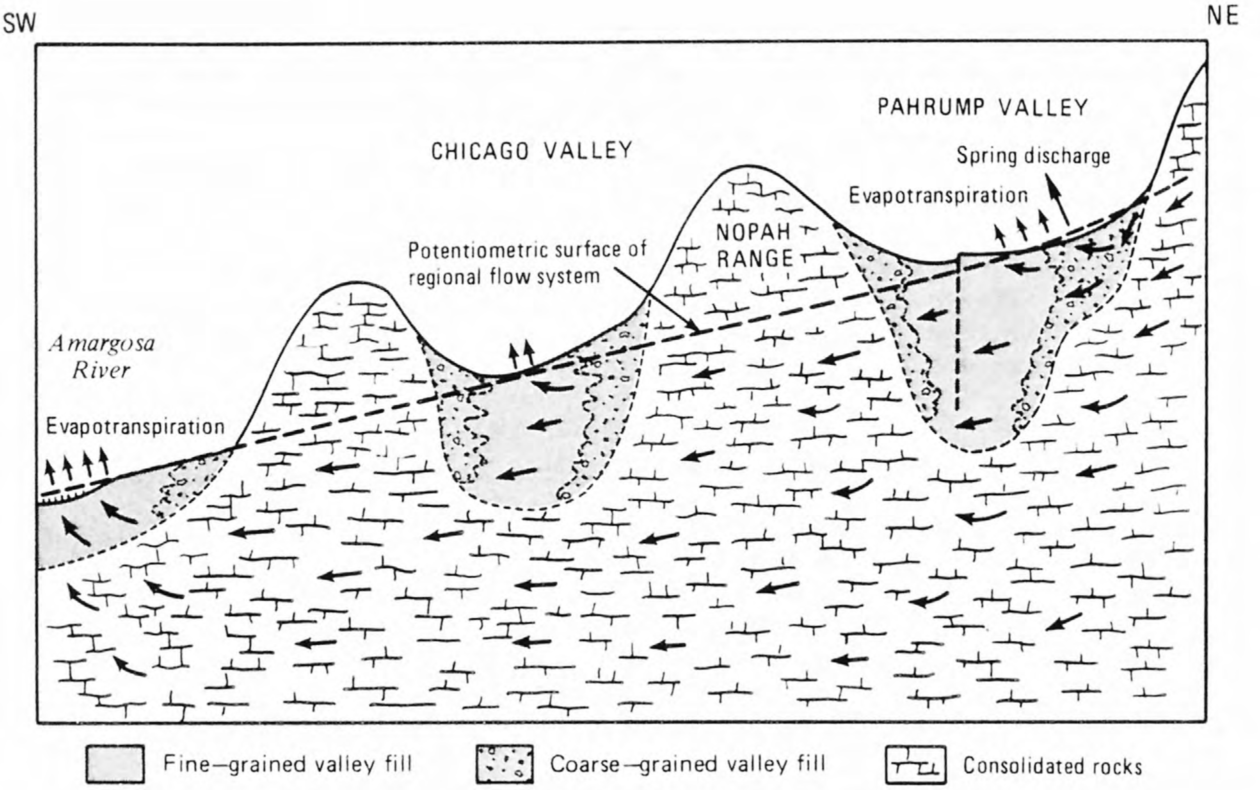
The preceding sections have developed qualitative and quantitative information that describes the ground-water system and its current state of development. A mathematical model is used in the following sections to simulate the natural conditions and response to development of the ground-water system. If a reasonable match between observed and simulated conditions can be obtained, then the model can provide useful information about the available ground-water supply and probable responses to development.

Mathematical models are tools that increase an investigator's capability to formulate and test hypotheses about a ground-water system and to predict generalized responses to a given scheme of development.

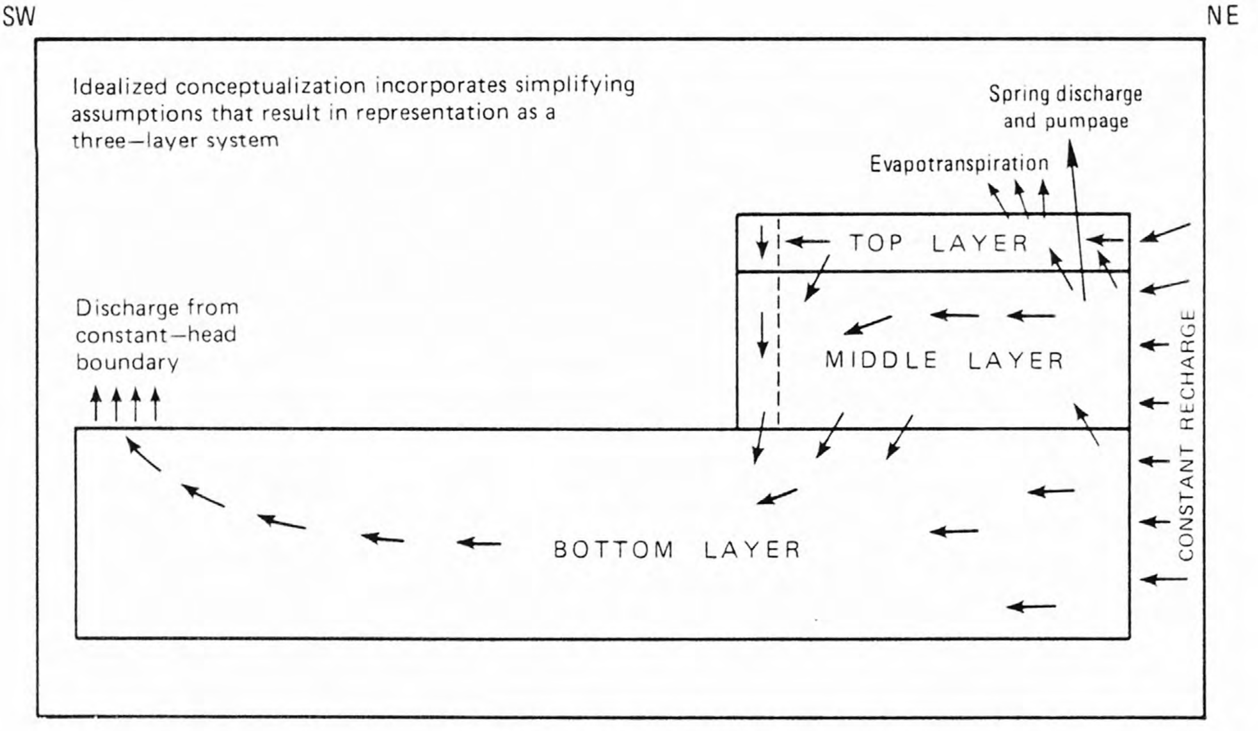
Any attempt to simulate a ground-water flow system is subject to limitations inherent in the particular technique used. The model itself is essentially a set of equations which describe an idealized system with properties similar to a real ground-water system. If the model adequately describes a real ground-water system then the response of the model to imposed stresses, such as ground-water pumpage, will be very close to the response of the real system if it were to undergo the same stress. The degree of exactness with which a model can describe a natural system is limited by characteristics of both the particular model used and the particular system being described. Examples of three types of limitations in most models are:

1. The inability of a model to handle all the complexities of a natural system. The simplifying assumptions and generalizations that are incorporated into a model affect the output. If a model is designed to perform a specific task, then the simplifying assumptions can be made so the effects on a particular type of prediction are minimal. If the model is used to make predictions other than originally designed, then the generalizations and assumptions used could significantly effect the results.

2. The inadequacy of existing data to describe the system. Most valleys have development localized in a comparatively small area. Reasonably good data on water levels and aquifer properties may be available in the vicinity of the development; however, away from developed areas, information is generally sparse and aquifer properties and hydraulic heads must be estimated on the basis of what little information is available. Errors in these estimates may significantly effect the results. The severity of these adverse



A. Generalized section across Pahrump Valley and basins to the southeast



B. Idealized ground-water flow

FIGURE 13. – Conceptualization of the ground-water flow system in and downgradient from Pahrump Valley. Arrows show direction of ground-water movement.

effects varies with the intended uses of the model. For some purposes, the probable errors associated with data deficiencies in areas remote from the existing development may have very little effect on the results. For other purposes, it may be necessary to collect additional data before an adequate model can be constructed.

3. The problem of nonunique solutions. Most ground-water models are calibrated by comparing model output with observed changes such as hydraulic heads or water-level changes and then adjusting model parameters, within limits, until a reasonable agreement between observed and computed values is obtained. However, in some cases it is possible to obtain identical water-level configurations with numerous different combinations of parameters. Consequently, computed solutions are not unique and a match between observed and modeled conditions does not guarantee that the model parameters and the parameters of the real system are identical. It guarantees only that the combination of parameters used will reproduce the observed conditions. If the parameters used are generally compatible with known information then the model will constitute a best fit of the data and errors caused by nonuniqueness are minimal.

The above examples illustrate several factors that can limit the accuracy of model results. Generally, if the intended uses of a model are carefully considered prior to its formulation, then it can be constructed so that adverse effects of these and other factors will be minimal. It was not possible to determine the absolute accuracy of results obtained from the model used in this study. Few data were available to describe the materials underlying the valley fill and if the estimates used for these materials are reasonably accurate, then model results are considered by the author to be accurate to within about 30 percent of the real values.

Governing Equations of Ground-Water Flow

The flow of ground water in a porous medium in three dimensions (Jacob, 1950; Cooper, 1966) may be expressed as follows:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = \frac{S_s}{K}\frac{\partial h}{\partial t} , \qquad (1)$$

in which h is hydraulic head, in feet,
S_s is specific storage, in 1/feet,
K is hydraulic conductivity, in feet per unit time, and
t is time.

Permitting hydraulic conductivity to be heterogeneous and anisotropic and adding a source term, equation 1 becomes:

$$
\begin{aligned}
&\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x} + Kxy\frac{\partial h}{\partial y} + K_{xz}\frac{\partial h}{\partial z}\right) \\
&+ \frac{\partial}{\partial y}\left(K_{yx}\frac{\partial h}{\partial x} + K_{yy}\frac{\partial h}{\partial y} + K_{yz}\frac{\partial h}{\partial z}\right) \\
&+ \frac{\partial}{\partial z}\left(K_{zx}\frac{\partial h}{\partial x} + K_{zy}\frac{\partial h}{\partial y} + K_{zz}\frac{\partial h}{\partial z}\right) = S_s\frac{\partial h}{\partial t} + W(x,y,z,t) \ , \qquad (2)
\end{aligned}
$$

in which $W(x,y,z,t)$ is a volumetric flux per unit time,
K_{ij} is the hydraulic conductivity that produces flux along axis i caused by the component of hydraulic gradient on axis j, and
$i, j = x, y, z$.

Assuming that the coordinate axes x, y, and z are alined with the principal directions of the hydraulic conductivity tensor, the cross-product terms drop out of equation 2 and it becomes, in expanded form:

$$
\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) = S_s\frac{\partial h}{\partial t} + W(x,y,z,t) \ , \qquad (3)
$$

in which K_{xx}, K_{yy}, and K_{zz} are the principal components of the hydraulic conductivity tensor, in feet per unit time.

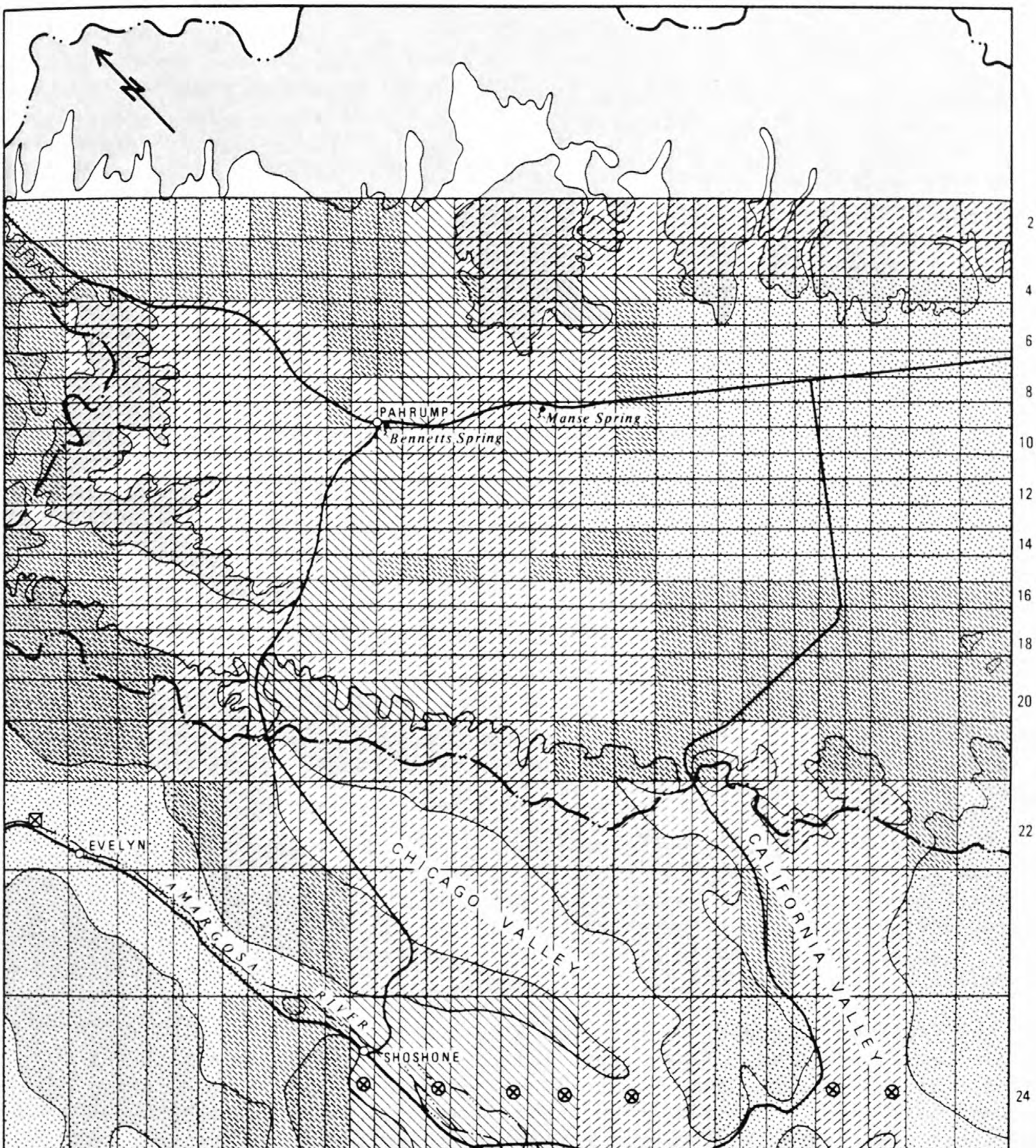
In the finite-difference simulator, it is often convenient to represent a hydraulic unit by one layer of nodes. For this approach, equation 3 is multiplied by b, the thickness of the hydraulic unit, giving:

$$
\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial x} b\left(K_{zz}\frac{\partial h}{\partial z}\right) = S\frac{\partial h}{\partial t} + bW(x,y,z,t) \ , \qquad (4)
$$

in which T_{xx} and T_y are the principal components of the transmissivity tensor, in feet squared per unit time, and
S is the dimensionless storage coefficient.

Application of Flow Equations to a Finite-Difference Model

A computer algorithm for the model was developed by P. C. Trescott (1975) of the U.S. Geological Survey. The program is written to solve finite difference approximations of the differential equations of ground-water flow (as expressed in equation 4). The version used in this study allows for a multilayer heterogeneous aquifer with irregular boundaries, numerous wells, and evapotranspiration from the upper layer in areas of shallow ground water. Flow between layers is treated as vertical flow through confining layers using the quasi-three-dimensional option of the program where no horizontal flow or storage of water is allowed in the confining beds. Program output was modified to enable evaluation of the areal distribution of evapotranspiration. In this study, the ground-water system is represented by three layers of the variable-space finite-difference network shown in figure 14. A finite-



EXPLANATION

Valley fill

Consolidated rocks

Boundary of Pahrump Valley

Finite difference grid used to model ground-water flow system. (Only bottom layer of model extends beyond Pahrump Valley)

⊗ Constant-head node used to simulate discharge from lower end of system

⊠ Constant-head node used to simulate inflow from Amargosa Desert

TRANSMISSIVITY USED IN BOTTOM LAYER OF MODEL IN FEET SQUARED PER DAY

0 – 500

500 – 1500

1500 – 2500

More than 2500

FIGURE 14. – Finite-difference grid and transmissivity used in bottom layer of the model (materials underlying upper 1,000 ft of saturated deposits).

difference representation for the ground-water-flow equation is written for each node in the network. This results in a series of simultaneous equations which are solved by the strongly implicit procedure. The reader is referred to Trescott (1975) and Trescott and Larson (1976) for detailed information about the model.

Parameter Values Used and Assumptions Made

Assumptions made and parameters used in this model are briefly outlined in the following paragraphs:

Boundary conditions

The boundary condition of a model must be specified before satisfactory solution of the finite-difference flow equation can be obtained. When an area of interest is near model boundaries, the solution obtained is generally quite sensitive to the boundary conditions specified. Consequently, adequate evaluation and proper specification of appropriate boundary conditions is an important step in adjusting a mathematical model to be representative of a given area.

The northeast boundary of the model is recharged by inflow from the Spring Mountains and is treated as a constant-recharge boundary. The recharge is simulated by wells situated along the northeast margin of the model that inject water at a constant rate.

The northwest and southeast boundaries of the model approximately coincide with ground-water flow lines under predevelopment conditions. Moreover, low-permeability bed rock belonging to the clastic aquitards is present just beyond the northwest edge of the model, and the southeast edge is remote from any heavy pumping. Consequently, these boundaries were specified as no-flow boundaries in the model.

The southwest boundary is assumed to be the discharge area of a multivalley flow system. Heads along this boundary are the lowest in the system. Discharge along this border is represented by flow into a series of constant-head nodes. Heads at these nodes have been set at altitudes comparable with the potentiometric surface in the vicinity of the Amargosa River. It was assumed, for the time periods and rates of pumping used in this simulation, that pumping in Pahrump Valley would have no significant effect on the water levels along the flood plain of the Amargosa River, some 25 miles away. The effects, if any, would most probably be small reductions in discharge. These changes would be roughly approximated by variations in flow to the constant-head nodes.

The lower part of the multivalley flow system also receives some inflow from the Amargosa Desert in the vicinity of the Amargosa River. Walker and Eakin (1963, page 23) estimated that in the vicinity of Eagle Mountain there was subsurface flow of about 500 acre-ft/yr from the Amargosa Desert toward Shoshone. It is beyond the scope of this study to attempt to simulate the multivalley flow system; however, one constant-head node was placed along the northwest boundary of the model (figure 15) where most of the inflow from the Amargosa Desert was assumed to occur. The head was varied until the amount of water added to the system from the node was about equal to the amount estimated by Walker and Eakin (1963). This same water was discharged from constant-head nodes near Shoshone, so there was little net effect on conditions in Pahrump Valley.

The bottom surface of the model was specified as a no-flow boundary. The upper surface was specified as a variable-flow boundary where discharge (if any) depends on the depth that the head in the upper layer is below land surface. This condition will be more fully described in the section on evapotranspiration.

Initial conditions

For each simulation the model must have the head at each node set to an initial value. For transient-state simulations these values should represent a set of equilibrium conditions for the entire model; otherwise, simulated head changes may represent response to the initial conditions rather than to any imposed stress such as pumping.

The predevelopment water levels were assumed to represent equilibrium conditions. Figure 7 shows the predevelopment water levels representative of conditions in the middle layer of the model. Similar maps were prepared for the top and bottom layers. These values were used as the initial condition for the steady-state calibration of the model. The results of the steady-state calibration of the model produced a set of head values, recharge rates, and discharge rates that were at equilibrium. These values were used as the initial condition for the transient-state simulation runs which began with the year 1913.

Transmissivity

The distribution of transmissivity used for the top and middle layers of the model is similar to that in figure 4. It is apportioned between the two units on the basis of their relative thickness (5 to 10 percent to the top layer and 90 to 95 percent to the middle layer). Both the top and middle layers do not extend beyond Pahrump Valley. Consequently, vertical hydraulic conductivities along the downgradient margins of each layer were adjusted to insure adequate continuity with the more extensive bottom layer.

There is no direct field information on which to base the exact distribution of transmissivity in the bottom layer of the model. It was assumed that rock types in areas overlain by valley fill would be generally the same as those exposed in adjacent mountains. Using this assumption and the transmissivity values listed on page 12, a preliminary distribution of transmissivity was prepared. Adjustments were made to also allow for accumulations of saturated valley fill greater than 1,000 feet in parts of Pahrump Valley. This initial distribution was subsequently refined during calibration of the model. The final distribution used is shown in figure 15. One of the adjustments made during the calibration was to assume two southwest-northeast trending linear zones of higher permeability in the vicinity of Bennetts and Manse Springs (figure 14). Orientation of the thrust faults shown on plate 1 and steep gravity gradients shown on plate 2 provide some indirect support for this assumption. However, the principal reason that these zones were added is that their presence was necessary to obtain an adequate model calibration. Additional information is needed to confirm or deny their existence.

Evapotranspiration of ground water

Evapotranspiration of shallow ground water is approximated as a linear relationship between a maximum, when depth to water in the top layer is at land surface, and zero when the water table reaches the depth at which significant evapotranspiration ceases. The value used for maximum evapotranspiration, 6.3 ft/yr (feet per year), is slightly higher than the probable average annual lake evaporation in the area (Meyers, 1962, plate 3) but less than the probable maximum of about 8 ft/yr that might occur if shallow ponds of water were maintained on a year-round basis. In actuality, the relationship between rate of annual ground-water evapotranspiration and depth to water table is probably not linear. The relation selected is considered to give a better approximation of the actual relationship at the depths to water table most commonly encountered in areas of evapotranspiration (generally between 10 and 20 feet). Under natural conditions phreatophytes were not commonly found where depth to water table exceeded 20 feet. Consequently, that depth was selected as the maximum effective depth at which significant ground-water evapotranspiration occurred.

Vertical hydraulic conductivities

Vertical hydraulic conductivites used to represent confining beds between layers are those in figure 3. The model allows only vertical flow and no storage of water in the confining layers. Before being placed into the model, values were adjusted for thickness to more accurately represent the resistance to flow between midpoints of the various layers.

Storage coefficient

The storage coefficients used for the upper layer approach the specific yield values shown in figure 5. They are generally 1 or 2 percent lower to allow for slow drainage and local retention of some water above impermeable clay beds and caliche layers. Storage coefficients used in the middle layer ranged between 0.0008 and 0.002 for coarse-grained valley-fill deposits around the margins of the valley. A higher storage coefficient was used for finer-grained deposits in the central valley to account for water released by compaction associated with head declines. In reality, water yielded by compaction varies with time and is produced only during periods when water levels decline below the level which previously produced permanent deformation in the system. It is almost entirely a one-way process, and when water levels rise, the amount of water returned to the aquifer per unit of water level rise is much less than was originally released as a result of compaction. These refinements are beyond the scope of this study. The approximation made by increasing the coefficient of storage to between 0.01 and 0.04 is satisfactory for the purposes of this study; however, the model cannot be used to accurately simulate the response to sustained cutbacks in pumping or other conditions that would result in rising water levels. The storage coefficient used for the bottom layer was 0.002.

Method of Analysis

The system and its response to development were simulated in three phases: (1) The natural condition prior to 1913, (2) the response through 1975, and (3) probable future response assuming that pumpage remained the same as in 1975. Analysis of the first two phases provided insight about the nature of the system and was a means of evaluating parameters used in the model. The model was calibrated so that computed heads, water-level changes, and distribution of evapotranspiration agreed reasonably well with observed and estimated values. Transmissivity, vertical hydraulic conductivity, recharge and subsurface outflow were adjusted mostly during the first phase of calibration and distribution of storage coefficient and recirculation of pumpage was adjusted mostly during the second phase. Once a reasonable fit between observed and computed value was obtained, model output for the period 1962-75 was used to supplement the other analyses done during this study. Finally, a run was made for the period 1975-2040 to roughly determine the magnitudes of future change if the amount and distribution of pumping stays the same as in 1975.

Simulated Natural Conditions

Figure 7 shows the approximate predevelopment potentiometric surface in that part of the valley fill tapped by deep wells and figure 15 shows the steady-state potentiometric surface generated for the middle layer of the model. These results were obtained using parameters already described and an average annual recharge of about 37,000 acre-ft/yr. The distribution of recharge and computed subsurface outflow (18,000 acre-ft/yr) is shown on figure 15. The area of most concentrated gorund-water recharge (22,600 acre-ft/yr) is located upgradient from Bennetts and Manse Springs. Plate 1 shows this area to be underlain by carbonate sedimentary rocks which have been deformed by several thrust faults. The transmissivity of these rocks may have been substantially increased by this structural deformation. This coupled with the fact that this area is situated on the side of the Spring Mountains most exposed to major storms which move in from the southwest may account in part for the exceptionally high recharge indicated.

Values of recharge and discharge developed by the model are higher than those estimated by using empirical techniques. However, they provide a reasonable fit with known information and if assumptions made about the deeper

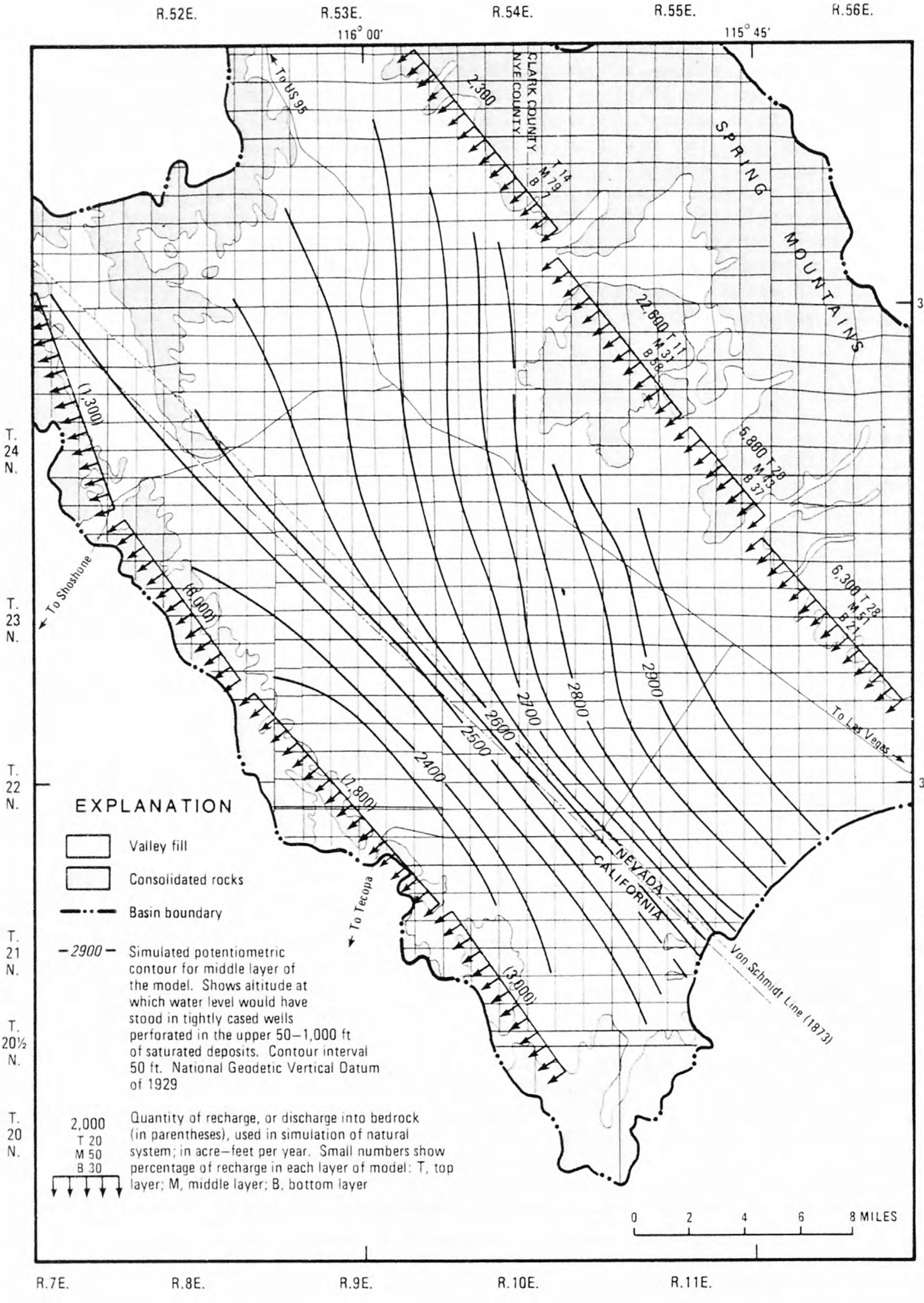


FIGURE 15. – Contours of simulated potentiometric surface for natural conditions.

parts of the valley-fill reservoir and the underlying bedrock are adequate, then the model should provide reasonably accurate quantitative results. Figure 16 illustrates the agreement obtained between "observed" and simulated head for all nodes in the model where there was adequate information to make a reasonably accurate estimate of the head.

The quantity and distribution of evapotranspiration were one of those parameters evaluated by the model. Comparison of the modeled distribution of evapotranspiration and the mapped distribution of phreatophytes provides an additional check on the ability of the model to simulate the ground-water system. The mapped distribution of phreatophytes is shown on plate 3(A) and the modeled distribution of evapotranspiration is shown on plate 3(B).

Response through 1975

Changes in the hydrologic system which occurred as a result of development prior to 1962 are not directly within the scope of this study; however, simulation of the entire period after 1912 provides additional information about the degree to which the model can reproduce changes in the natural system. The interval 1913 through 1975 was divided into 10 pumping periods. This was considered to be the minimum number of steps needed to approximate variations in pumpage that occurred during the 63-year period. Figures 8 and 9 show distribution of pumping in 1962 and 1975. A similar distribution of pumping was prepared for each period. All pumpage was assumed to be from the middle layer of the model. A percentage of the pumpage was assumed to be recirculated back to the water table (top layer of the model) by deep percolation of irrigation water. An initial value of between 20 to 30 percent was selected and then adjusted during the calibration of the model. A comparatively high percentage of recirculation was used for the first pumping period for areas of pasture subirrigated by recirculated spring discharge. The lower percentage for periods 2, 3, and 4 allow for some recirculated water on newly irrigated land to become stored as soil moisture. Results from individual pumping periods were grouped for the longer periods 1913-61 and 1962-75. Table 5 summarizes pumpage data used in each period of the simulation.

The model contains sufficient computational power to allow the response to development to be evaluated in terms of water-level changes, variations in natural discharge, and ground-water storage depletions. These items will be discussed in moderate detail in the following sections. One important item that was beyond the scope of this study, but should be considered, is possible changes in the chemical quality of ground water as a result of development activities.

Water-level changes

Figure 17 shows simulated net changes in the water table during the period 1913-76. There are not adequate data from shallow wells for a detailed comparison of observed and simulated water-table fluctuations. However, information available indicates changes of the same general magnitude as shown in figure 17. Also, water levels in some shallow wells near irrigated areas were reported to have risen slightly. The model produces similar results.

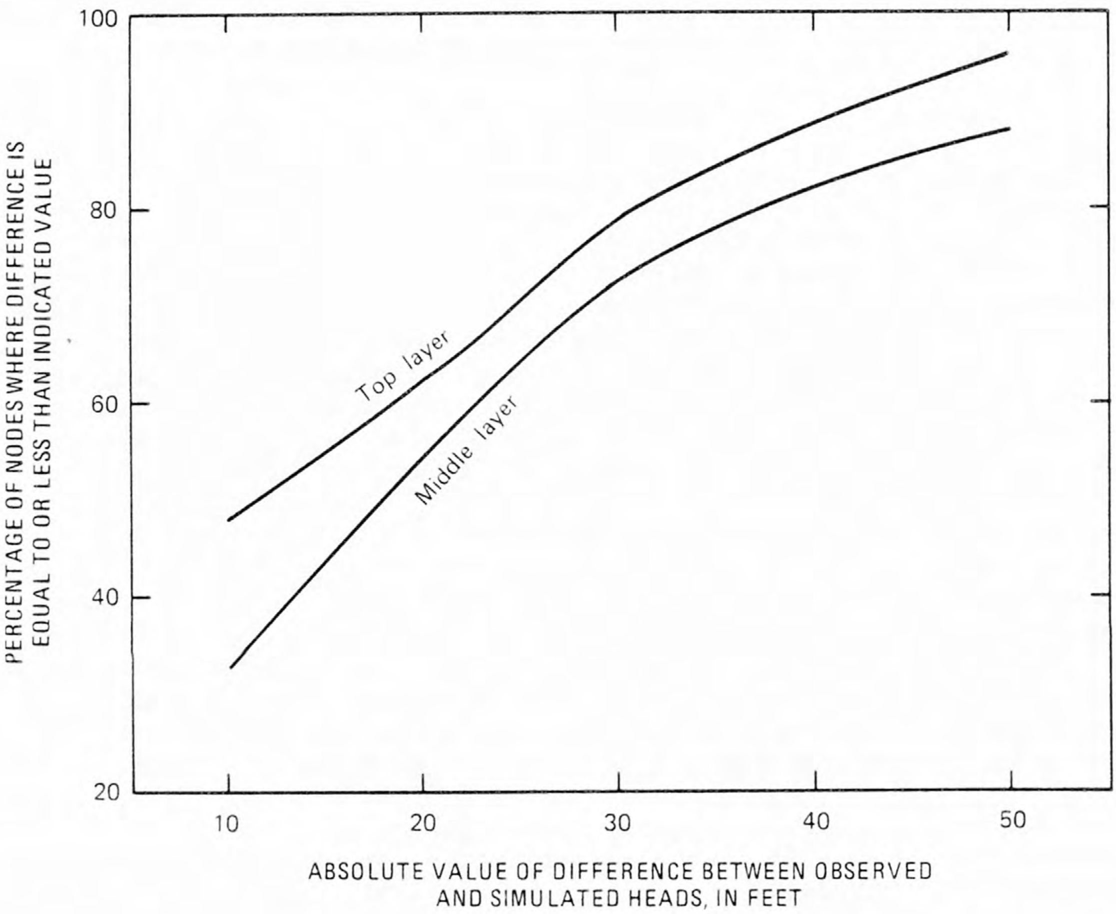


FIGURE 16. — Relation between observed and simulated heads for natural conditions. Number of nodes used for calibration: Top layer, 299; middle layer, 242; bottom layer, 0. Nodes used in calibration were those for which data were adequate to evaluate pre—development heads.

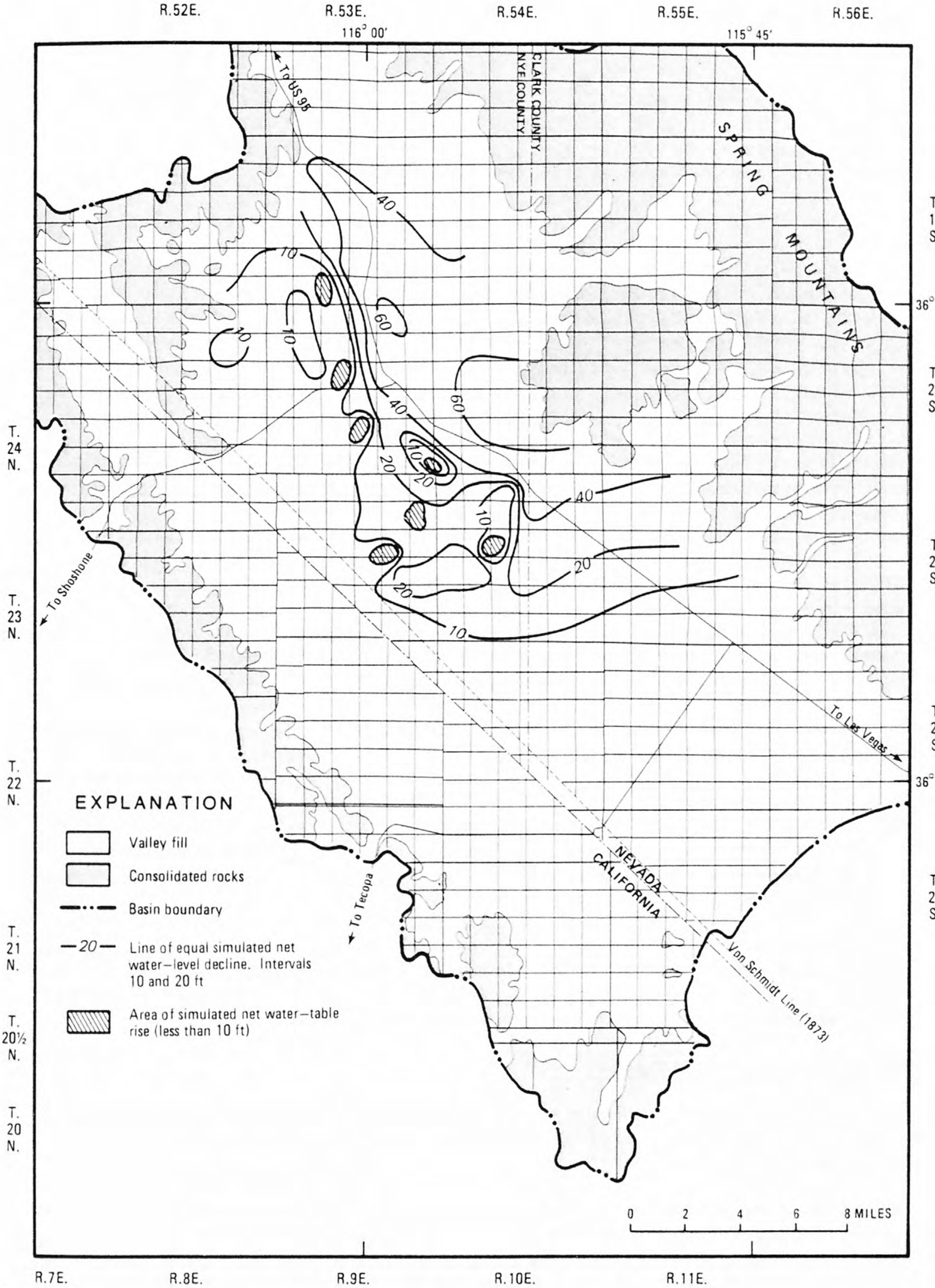


FIGURE 17. – Simulated net changes in the water table, February 1913 – February 1976.

Water levels in deeper wells declined significantly more than those in shallow wells. Figure 18(A) shows the observed distribution of water-level declines in deeper wells and figure 18(B) shows the simulated head declines in the middle layer of the model during the period 1913-76. There is a reasonable agreement between the observed and simulated distribution of water-level declines; however, there are two significant differences.

The first difference is that simulated declines along the base of the Pahrump fan were less than the observed values. The exact reason for this is not known; however, the three most probable causes are: (1) The amount of recharge assigned to nodes upgradient from this area may be more than that which occurs in the natural system. The resulting capture of discharge by pumping would cause water-level declines to be less than the observed values. (2) The assumption that the distribution of recharge does not change may not be valid. Heavy pumping in the vicinity of Manse Springs may have altered heads in nearby carbonate rocks sufficiently to induce water that formerly flowed towards Bennetts Springs to move toward Manse Spring instead. During the last calibration run of the model a total of about 0.8 ft^3/s (580 acre-ft/yr) of recharge was gradually shifted from a recharging node upgradient from Bennetts Spring to a recharging node upgradient from Manse Spring. The response was a somewhat better agreement between the observed and simulated heads. (3) Modeled pumpage estimates may be smaller than the true values. Many pumpage estimates for individual wells were compiled by using an average discharge rate and an estimated or reported duration of pumping. More widespread use of meters and timing devices or site-specific determination of electrical consumption and wire-to-water pump efficiencies may be required before the absolute accuracy of existing pumping records can be determined.

The second difference is that small areas with rapidly changing rates of decline tend to be smoothed out over a slightly larger area in the model. This is largely a result of the grid size selected for the model. A smaller grid size would produce more detailed results, but the larger number of nodes required would make the simulation more expensive. Results obtained with the existing grid are adequate for the purpose of this study; however, if there is a need to simulate detailed changes over localized areas of the valley, a much smaller grid size will be required.

Figure 19 shows the observed water-level declines in deeper wells and the simulated head declines in the middle layer of the model for the period 1962-76. There is a general overall agreement, but the differences noted for the longer period are present in this shorter period also.

Variations in natural discharge

Changes in natural ground-water discharge include decreases in spring discharge, evapotranspiration of ground water by phreatophytes, and possible changes in subsurface outflow.

Spring discharge was located near areas where heavy pumping centers developed. Consequently, this type of natural discharge was most readily captured by pumping. Spring discharge decreased from nearly 10,000 acre-ft/yr under natural conditions to about 1,400 acre-ft/yr in 1962 (Malmberg, 1967, page 31) and to about 200 acre-ft/yr in 1975.

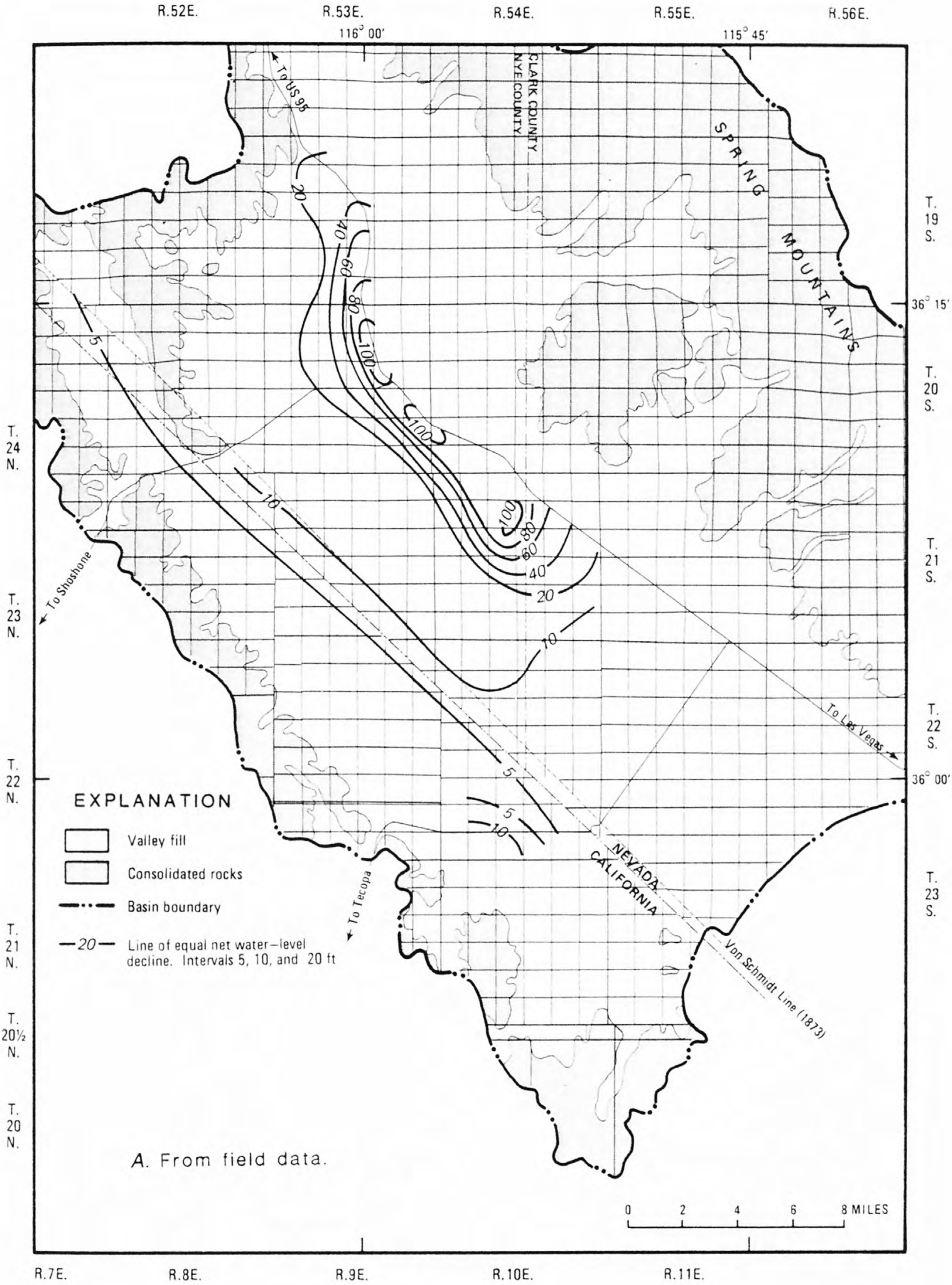


FIGURE 18. – Net water-level declines in deep wells, 1913–76, (A) from field data and (B) simulated by the model.

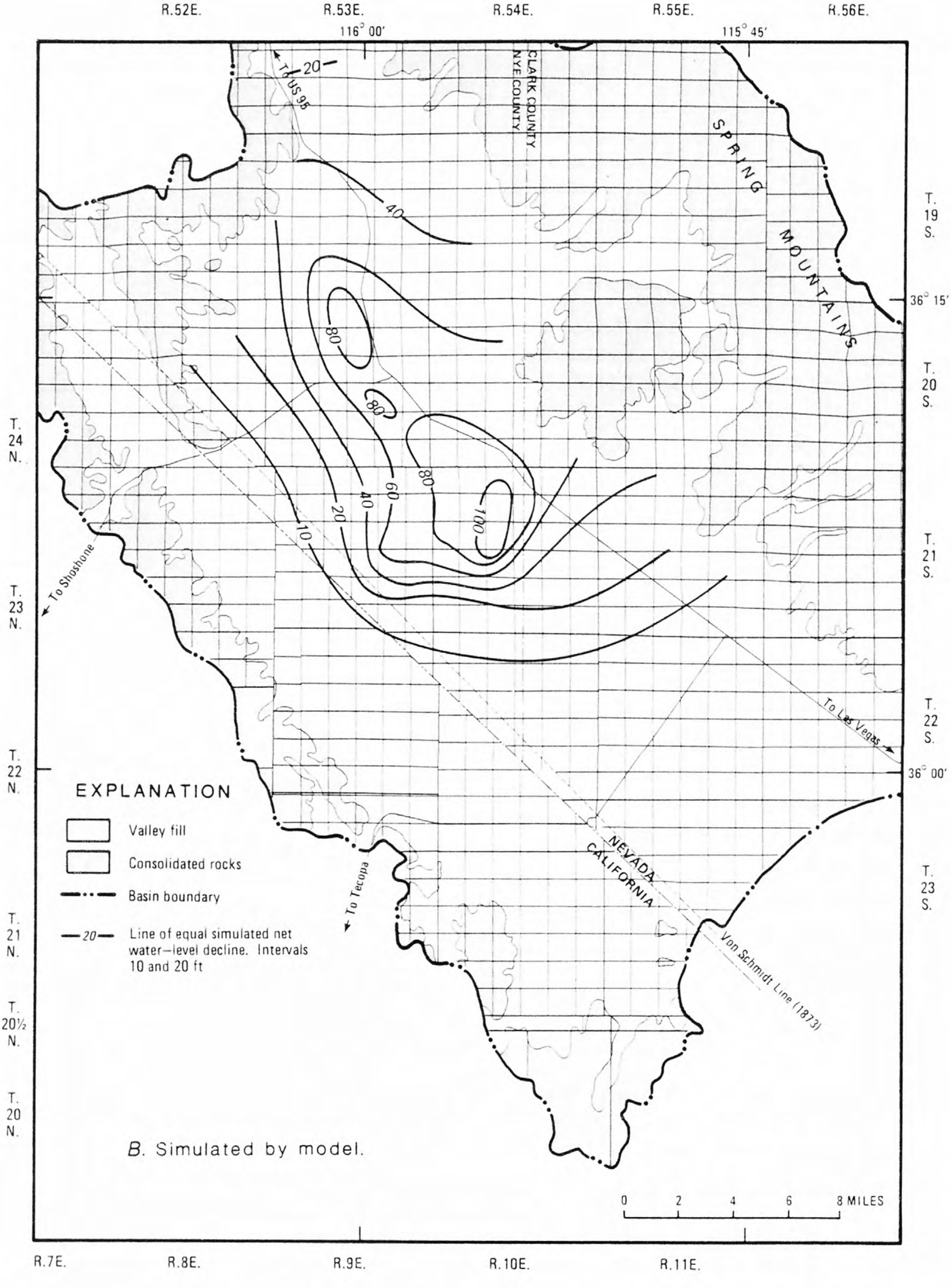


FIGURE 18. – Net water-level declines in deep wells, 1913–76, (A) from field data and (B) simulated by the model.

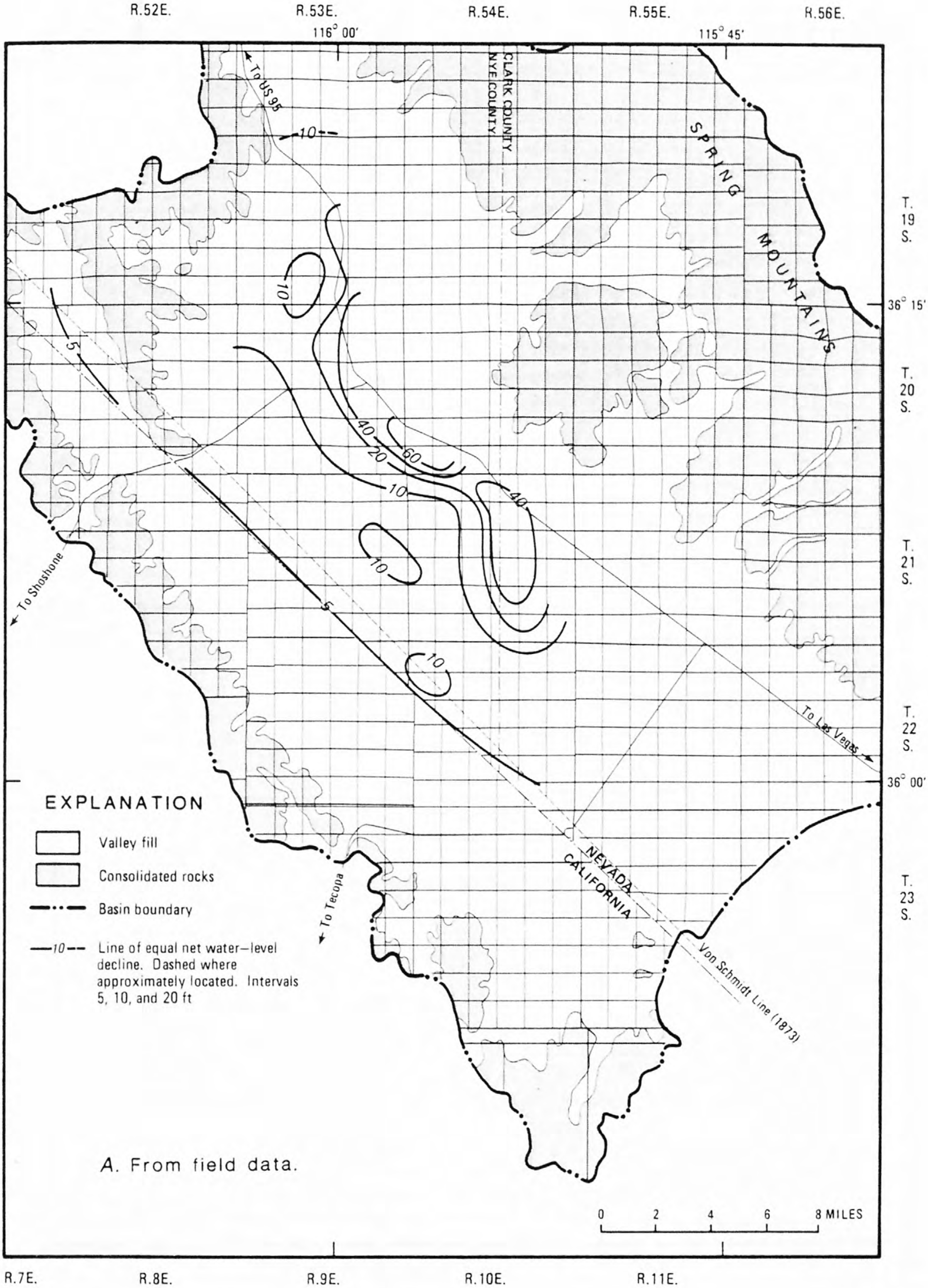


FIGURE 19. – Net water-level declines in deep wells, 1962–76, (A) from field data and (B) simulated by the model.

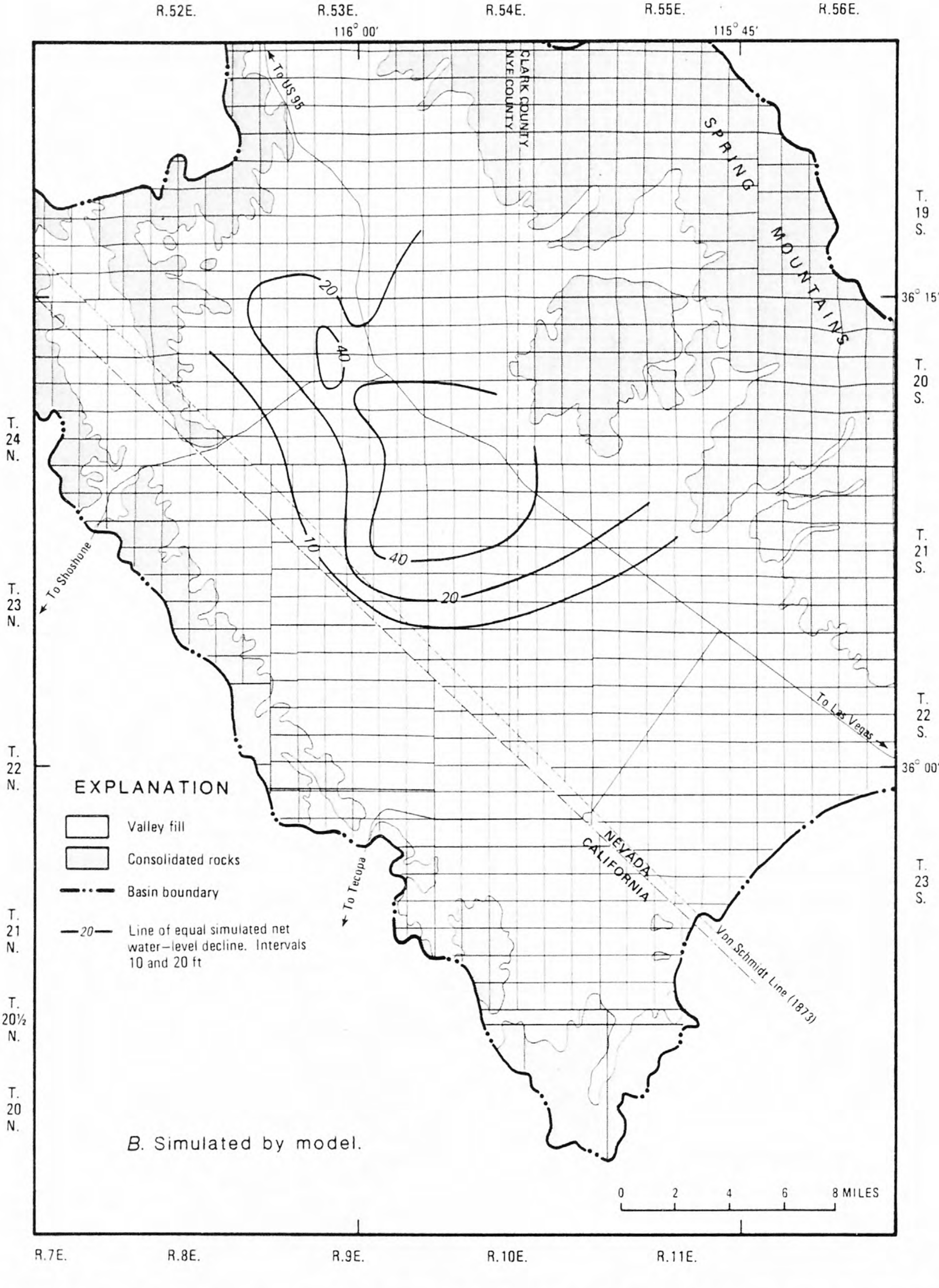


FIGURE 19. – Net water-level declines in deep wells, 1962–76, (A) from field data and (B) simulated by the model.

TABLE 5.--*Pumpage data used in simulation*

Pumping period	Period	Number of nodes used as pumping centers	Average annual spring discharge and pumpage: Spring discharge (acre-ft/yr)	Average annual spring discharge and pumpage: Pumpage (acre-ft/yr)	Spring discharge and pumpage recycled back to ground-water system (acre-ft/yr)
1	1913-44	2	6,000	4,000	4,300
2	1945-51	10	5,200	13,000	3,500
3	1952-58	26	4,000	23,000	5,000
4	1959-61	29	1,600	25,400	5,000
5	1962-63	35	1,200	29,000	7,600
6	1964-67	39	1,200	37,400	9,700
7	1968-68	39	900	47,900	12,600
8	1969-70	42	700	41,900	11,300
9	1971-72	41	600	37,600	9,900
10	1973-75	54	400	41,200	11,200

	Total acre-feet (rounded): Spring discharge	Pumpage	Recycled
Period 1913-61	260,000	460,000	210,000
Period 1962-75	12,000	[a] 540,000	140,000
Entire period 1913-75	270,000	1,000,000	350,000

[a] Pumpage higher than 530,000 acre-feet shown in table 3 because of (1) minor increases made during model calibration and (2) rounding of values selected to represent average rates for each pumping period.

Changes in ground-water evapotranspiration were evaluated by the model. Simulated ground-water evapotranspiration (not including direct evapotranspiration of about 5,000 acre-ft/yr of spring discharge from the soil or open-water surfaces) declined from about 14,000 acre-ft/yr under natural conditions to about 4,500 acre-ft/yr in 1962 and to about 2,600 acre-feet in 1975. The capture of this amount of natural discharge has been a significant factor in limiting water-level declines to the values shown in figures 17, 18, and 19.

Plate 3 shows the simulated distribution of evapotranspiration of ground water by phreatophytes under natural conditions and in 1962 and 1975. Areas and rates of evapotranspiration near centers of heavy pumping (figures 8 and 9) have experienced the greatest changes, while there have been only minor changes in areas remote from pumping. Plate 3(D) indicates large areas where simulated evapotranspiration was eliminated when the water table declined to more than 20 feet below the land surface. In actuality, changes are not so clearly defined. Phreatophytes attempt to adjust to declining water levels by growing deeper tap roots, by developing a shallow root system to better utilize soil moisture, and by becoming established where they can utilize irrigation tail water. Consequently, residual stands of phreatophytes may survive for a number of years after declining water tables have virtually eliminated ground water as a source of supply.

Changes in subsurface outflow were evaluated by using the model. The amount of subsurface outflow captured by pumping was considered equal to the net decrease in flow to constant-head nodes along the southwest boundary of the model (figure 14). As of 1976, only about 200 acre-ft/yr of the total outflow of 18,000 acre-ft/yr had been captured.

Ground-Water Storage Depletion

Ground-water storage depletion is primarily the result of drainage of unconsolidated porous materials as the water table is lowered. However, consolidation of fine-grained deposits and the elastic response of water and the aquifer also account for small but significant quantities of water. These processes are discussed in more detail in the following paragraphs.

Water derived from the drainage of unconsolidated materials is evaluated in the model as the product of a storage coefficient, a change in head, and an area. The storage coefficients used for the top layer of the model were generally 1 to 3 percent less than the specific yield values shown in figure 5, to allow for delayed drainage and impermeable lenticular deposits and caliche layers. The head changes used are those shown in figure 17, and the areas are the area of each node (figure 14). The maximum water-table declines shown in figure 17 occurred along the lower parts of the Pahrump and Manse fans. This area also coincides with the area of highest specific yield shown in figure 5. Consequently, most of the ground-water storage depletion was derived from the dewatering of deposits along the lower parts of the Pahrump and Manse alluvial fans.

The release of water from storage in confining beds causes consolidation of these deposits and commonly results in subsidence of the land surface. There are no data on reported leveling of benchmarks in critical areas of the valley to establish the magnitude and rate of land subsidence, if any, in the area. During the spring of 1972, a small ground fissure and some casing protrusion was observed in a localized part of the NE$\frac{1}{4}$ of sec. 15, T. 20 S., R. 53 E. This suggests that land subsidence is active in at least parts of the area. Additional indirect arguments for the presence of active land subsidence were developed during the calibration of the model.

During calibration, the storage coefficient of the middle layer was initially assigned values on the order of 0.001 or 0.002. These values are representative of the confined aquifer where water is derived mainly from the elastic response of water and the aquifer. Reasonable agreement between served and computed values was obtained around the margins of the valley; however, where heavy pumping coincided with areas where significant fine-grained material was present in the valley fill, computed changes were much greater than observed changes. Attempts were made to improve agreement by increasing the vertical leakage, but this resulted in large head declines in the top layer that did not agree with available field data. The best agreement was obtained when the storage coefficient of the middle layer was increased to 0.02 or 0.03 in areas containing significant fine-grained material (see plate 1). Theoretically, storage changes in a confined aquifer much in excess of the initial values used would have to be derived from the consolidation of fine-grained materials. Crude estimates of probable land subsidence were made by assuming that the amount by which the storage coefficient of the middle layer of the model exceeded 0.002 would represent water being derived from the consolidation of fine-grained materials. The volume of subsidence can be estimated as the residual of the storage coefficient times the drawdown times an area. The amount of land subsidence can be estimated as the product of the residual of the storage coefficient times the decline in a given area. Figure 20 shows areas of possible land subsidence estimated in this way. The total volume of subsidence was inferred to be about 68,000 acre-feet. This inference is based on adjustments made during the calibration of the model and consequently is only an indicator of the possible extent and magnitude of land subsidence. However, it points out the need for additional field information.

Under confined conditions both the water and aquifer undergo small elastic changes in volume in response to changes in artesian head. Although the amount of change is small when evaluated on a unit basis the total changes in confined systems cover large areas and involve significant amounts of water. Both the middle and bottom layers of the model were considered to be under confined conditions. Storage depletions due to elastic response were evaluated as the product of change, area, and 0.002.

Table 6 summarizes estimates of storage depletion by all processes for the periods 1913-61 and 1962-75. The total storage depletion of about 375,000 acre-feet at the end of 1975 was equal to 38 percent of the total pumpage of about 1,000,000 acre-feet since 1913 (table 5).

TABLE 6.--*Summary of estimates of storage depletion*

[Acre-feet]

Period	Type of depletion: Drainage of unconsolidated deposits	Consolidation of fine-grained deposits	Elastic response of aquifer and water	Total depletion
1913-61	120,000	22,000	14,000	156,000
1962-75	155,000	46,000	18,000	219,000
1913-75	275,000	68,000	32,000	375,000

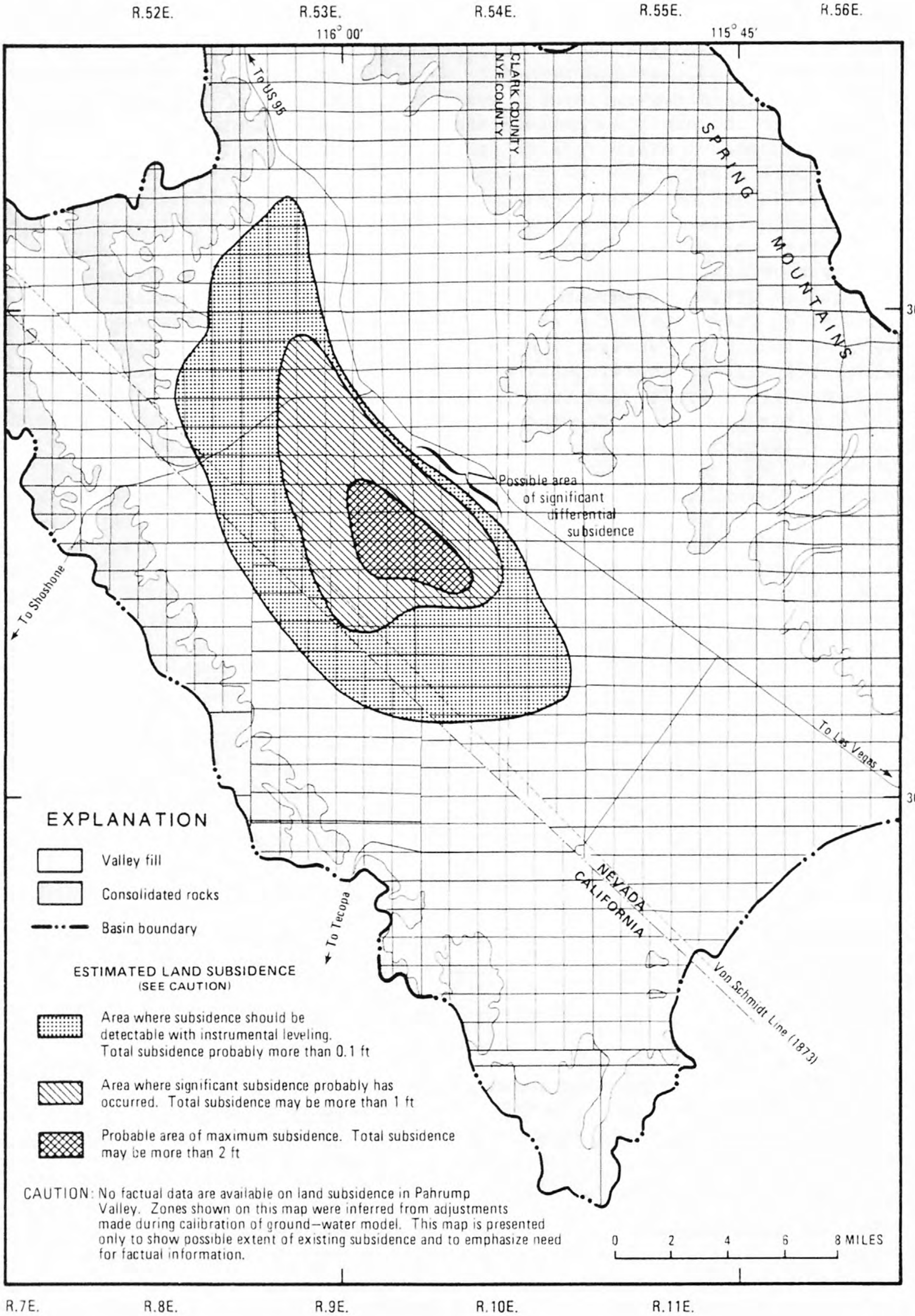


FIGURE 20. — Estimated land-surface subsidence.

Future Response

It is difficult to predict future responses to pumping because magnitude, distribution, and use of the pumped water changes with time. However, generalized information about how the ground-water system is likely to respond in the future can be obtained by assuming that future pumping will remain at about the 1975 level. This assumption was incorporated into the model, and probable system response to the year 2040 was simulated. This long period was selected only to allow a crude quantitative evaluation of trends likely to be present in the future. Precise prediction is beyond the scope of this study, and this limitation should be kept in mind while evaluating the results presented in the following paragraphs.

Simulated future response is summarized in terms of two types of parameters. The first comprises rates of flow that represent the total pumpage, spring discharge, ground-water evapotranspiration, and storage depletion at a given time. These factors provide insight as to the state of the system. The second type of parameter comprises water-level changes in different parts of the valley. Flow quantities listed as the first type of parameter tend to react with each other and the system in a complex manner. However, the net result is integrated into a simple change in water levels which provides an indication of the net response of the system. Three areas were selected, and computed water-level changes at nodes within each area were averaged to provide generalized indications of water-level trends. The areas are: (1) A zone, C, along the base of the Pahrump and Manse fans where historical pumping has been concentrated, (2) a zone, B, along the axis of the Nevada part of the valley which contains some development, and (3) a zone, A, along the Nevada side of the State line that is southeast of any significant development. Location of these areas is shown in figure 21.

Figure 22 is a graph which shows plots of the various parameters against time. The illustration shows results for the entire period of simulation (1913-2040). This was done because future trends tend to have more significance when viewed in terms of the perspective provided by historical information.

The following statements are based on information shown in figure 22:

1. Spring discharge was virtually all captured by pumping prior to 1976. Consequently, future water-level declines will not be moderated by additional capture of spring discharge.

2. Ground-water evapotranspiration was captured more slowly by pumping than was spring discharge. As of 1976, about 2,600 acre-ft/yr of ground-water evapotranspiration remained. Capture of all ground-water evapotranspiration by pumping probably will not occur in the foreseeable future because some remaining areas of active evapotranspiration are too remote from pumping.

3. It is very difficult to capture appreciable amounts of subsurface outflow from Pahrump Valley. As of 1976, only about 200 acre-ft/yr of the total of 18,000 acre-ft/yr had been captured. By the year 2040, a total of only 600 to 700 acre-ft/yr may be captured.

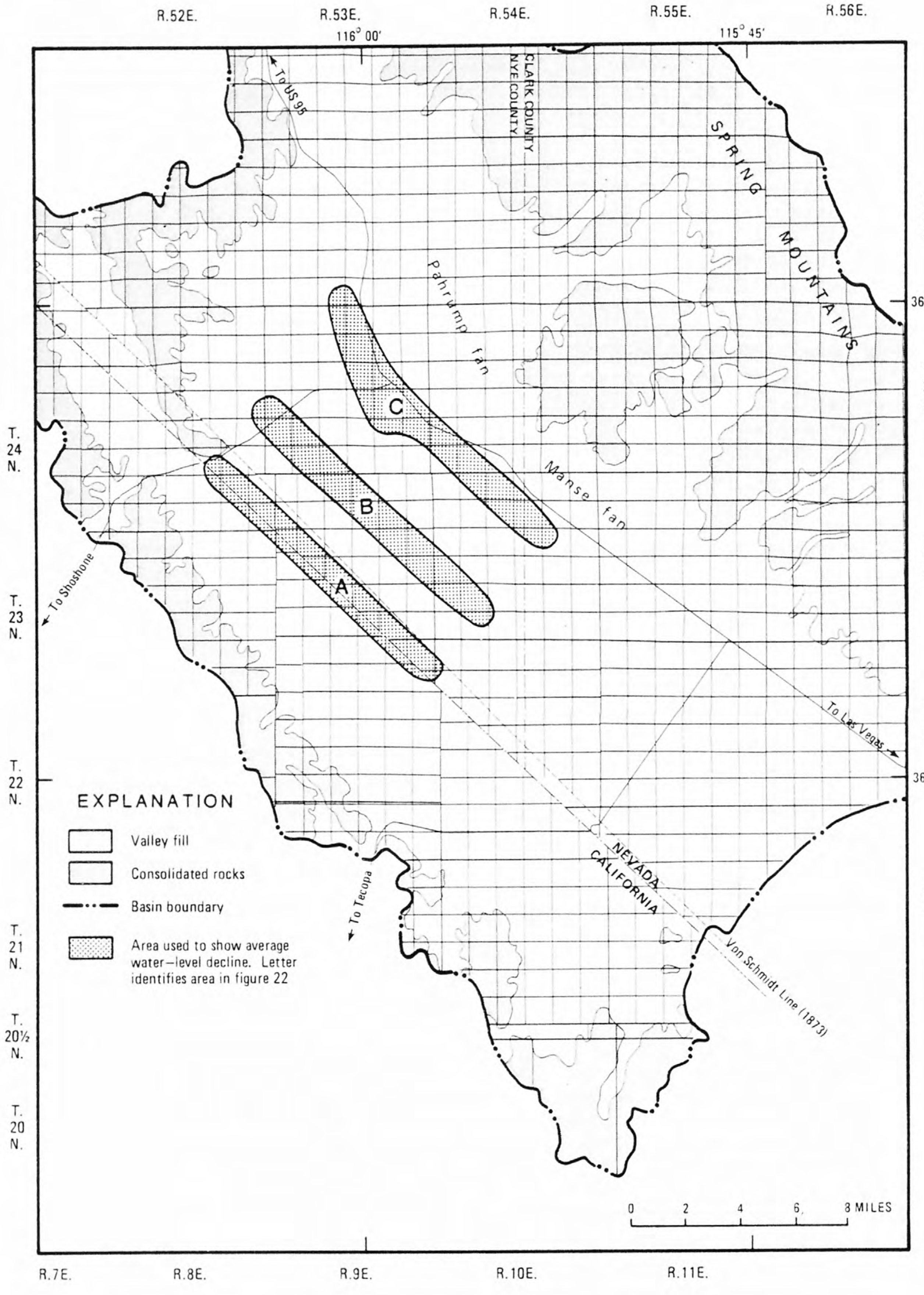


FIGURE 21. – Areas used in figure 22 to indicate simulated long-term water level declines.

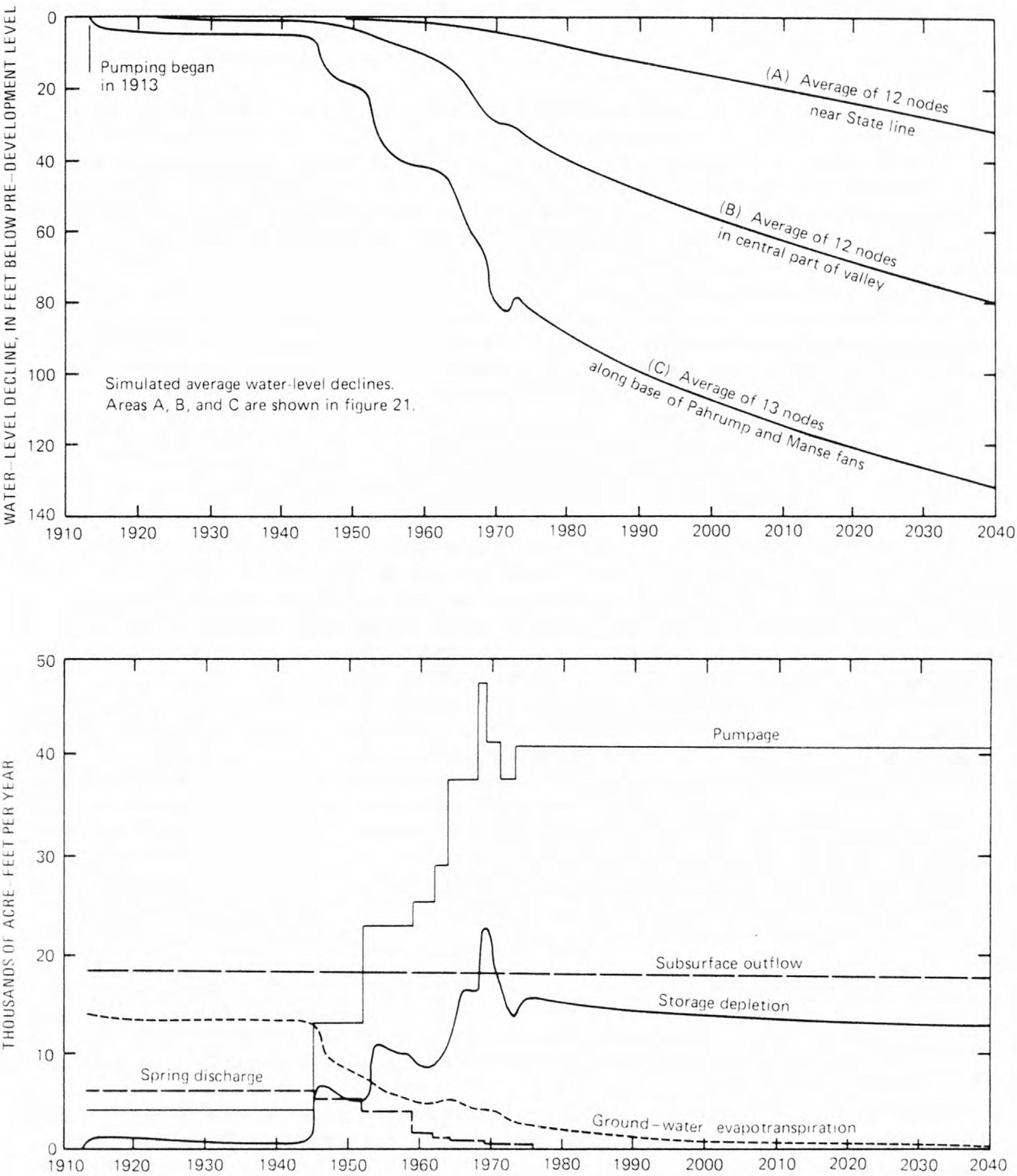


FIGURE 22. – Simulated long-term trends in selected hydrologic parameters.

4. Ground-water storage depletion and water-level declines will continue at fairly constant rates until 2040, and the system will remain in nonequilibrium conditions as long as pumping is maintained at the 1975 rate.

Accuracy of Model Results

Calculations performed by the model produce precise results. However, accuracy of the computer output depends on the validity of simplifying assumptions used in the formulation of the model and the accuracy of the concept of the hydrologic system.

In Pahrump Valley, hydrologic conditions in the deeper valley fill and underlying bedrock must be inferred. Consequently, the assumptions made about these areas introduce a comparatively large degree of uncertainty into the model results. Moreover, because the boundary conditions and transmissivity of the lower layer are not precisely defined, the problem of nonunique solutions, which has already been mentioned (page 39), also introduces uncertainty in results that give a reasonable match to observed conditions. More specifically, the fact that a reasonably good fit between observed and simulated heads for natural conditions was obtained by using 37,000 acre-ft/yr of recharge and the distribution of transmissivity and vertical hydraulic conductivity shown in figures 3, 4, and 14 does not preclude that matches equally as good could be obtained by using other values of recharge and transmissivity. In theory, identical head distributions could be obtained by multiplying all the variables by a constant factor.

In this study the range of uncertainty of the final steady-state solution was evaluated by keeping the evapotranspiration function constant and multiplying other model parameters by a constant. When model parameters were increased by 30 percent (multiplied by 1.3) the agreement between observed and simulated heads was not as good as that shown in figure 16 (the difference was probably due to the increase in heads needed to cause additional evapotranspiration). However, the model parameters were decreased by 30 percent multiplied by 0.7) the agreement between observed and simulated heads was almost as good as that shown in figure 17. The area of evapotranspiration was about the same as that shown on plate 3(B) but the rates were substantially less. The exact areas and rates of evapotranspiration that existed under natural conditions are not known, but further decreases probably would not produce representative results. Thus, analysis of the steady-state model results indicates a possible range in recharge of 37,000 to 26,000 acre-ft/yr.

It was necessary to evaluate the transient-state simulations where pumping was introduced into the model in order to determine a rate of recharge and the associated parameters that would give the best overall fit. Model parameters compatible with 37,000 acre-ft/yr of recharge produced the best fit between observed and simulated drawdowns. Consequently, 37,000 acre-feet is used as the best estimate of recharge generated by the model. When evaluating the accuracy of recharge estimates generated by the model, the possible range of 37,000 to 26,000 acre-ft/yr should be kept in mind.

THE AVAILABLE WATER SUPPLY

Ground-Water Budget

Under natural conditions, the ground-water flow system was in a state of dynamic equilibrium where over the long-term average annual recharge was equal to the discharge and there was no net change in ground-water storage. Development by pumping ground water created an imbalance where the total discharge (natural discharge plus pumpage) exceeded the total recharge (natural recharge plus recirculated pumpage).

The system responds to pumping by the removal of ground water from storage and the subsequent capture of natural discharge in an attempt to establish a new equilibrium where recharge (natural recharge plus recycled pumpage) again equals discharge (pumpage plus the reduced natural discharge). If pumpage exceeds the recharge to the system, a new equilibrium is not possible. Water will continually be withdrawn from storage, and ground-water levels will decline as long as pumping exceeds recharge.

Table 7 lists a ground-water budget which summarizes the various items of inflow to and outflow from the ground-water system (1) under predevelopment natural conditions, (2) as of spring 1962, and (3) as of spring 1976. The varying quantities listed can be compared with the graphical information shown in figure 23 to obtain a feel for the state of the system at times other than the three times selected for a budget analysis. The simulated areal distribution of evapotranspiration for the three times when budgets were formulated is shown on plate 3. Two budgets are shown in table 7 for natural conditions. One is based on estimates derived by using field and empirical techniques and the other summarizes the items of inflow and outflow used in the calibrated steady-state version of the model. The estimates generated by field and empirical techniques are less than those generated using the model. Determination of which of the two techniques provides the most accurate information is difficult. Credibility of the lower set of values is limited because of (1) the empirical nature of the techniques used, (2) the assumption that the distribution of evapotranspiration in 1962 was very close to that under natural conditions (see plate 3), and (3) the necessity to estimate subsurface outflow by difference. On the other hand, credibility of the precise computations performed by the model is limited by the accuracy of the information input to the model (see previous discussion on accuracy of model results). Budget values generated by the model are considered slightly better because they represent a set of data where individual elements are internally compatible and because the assumptions used represent the best approximations that could be made at this time. However, the relatively wide range between results obtained by using both techniques where the range of natural recharge is 37,000-26,000 acre-ft/yr, provides an indication of the uncertainties in the estimates.

Under natural conditions the general level of net inflow to and outflow from the ground-water system is estimated by the model to be about 37,000 acre-ft/yr. In 1962 and 1976, when the system was not in equilibrium, the difference between inflow and outflow agrees closely with the calculated rates of storage depletion.

TABLE 7.--*Ground-water budgets*

[Acre-feet per year, rounded to two significant figures]

	Natural conditions: Based on field and empirical techniques	Natural conditions: Based on steady-state simulation	Spring 1962	Spring 1976
INFLOW				
Natural recharge	22,000-26,000	37,000	37,000	37,000
Recirculated pumpage and spring discharge	([a])	[b] 4,600	5,900	11,000
Total inflow	22,000-26,000	[c] 42,000	43,000	48,000
OUTFLOW				
Evapotranspiration	10,000-13,000	[d] 14,000	4,900	2,600
Pumpage	0	0	27,000	42,000
Spring discharge	([a])	9,800	1,400	200
Subsurface outflow	6,000-19,000	18,000	18,000	18,000
Total outflow	16,000-32,000	[c] 42,000	51,000	63,000
DIFFERENCE	6,000-10,000	0	8,000	15,000
STORAGE DEPLETION	0	0	[e] 8,600	[e] 16,000

[a] Spring discharge under natural conditions was about 9,800 acre-ft/yr. All of this quantity is included in the estimate of evapotranspiration and is not repeated in order to avoid double counting.

[b] Amount of spring discharge recirculated back to top layer of model to produce distribution of evapotranspiration shown on plate 3(B).

[c] Includes 4,600 acre-feet of internal recirculation. Net inflow and outflow 37,000 acre-ft/yr.

[d] Does not include direct evapotranspiration of 5,200 acre-ft/yr of spring discharge not recirculated back to ground water.

[e] Average rates for periods 1959-61 and 1973-75, respectively.

Table 8 is a cumulative mass balance which summarizes cumulative values of the budget items listed in table 7 for the periods 1913-61, 1962-75, and 1913-75. As in table 7, the differences between cumulative values of recharge and discharge are about the same as the estimates of cumulative storage depletion. In theory, they should be in exact agreement. The observed differences are due to accumulating small consistent errors and to independent rounding of large numbers. During the period 1913-61, about 34 percent of the water pumped was derived from storage as opposed to about 40 percent during the period 1962-75.

TABLE 8.--*Cumulative mass balance*

[Acre-feet, rounded]

	1913-61	1962-75	1913-75
INFLOW			
Natural recharge	1,800,000	520,000	2,300,000
Recirculated pumpage and springflow	210,000	140,000	350,000
Total inflow (rounded)	2,000,000	660,000	2,700,000
OUTFLOW			
Evapotranspiration	540,000	60,000	600,000
Pumpage	460,000	540,000	1,100,000
Spring discharge	260,000	11,000	270,000
Subsurface outflow	880,000	250,000	1,100,000
Total outflow (rounded)	2,100,000	860,000	3,000,000
DIFFERENCE	100,000	200,000	300,000
STORAGE DEPLETION	156,000	219,000	375,000

Maximum Steady-State Pumping Rates

Ground water is the source of virtually the entire water supply in Pahrump Valley. Pumped water must be derived from the capture of natural discharge, from reuse of water recycled back to ground water, or from the depletion of ground-water storage. Depletion of ground-water storage will eventually be limited by the amount of storage economically recoverable or by environmental or legal constraints. Thus, the available water supply will ultimately be limited to the amount of natural discharge that can be captured by pumping.

The preceding analysis indicates it will be very difficult to capture a significant amount of the subsurface outflow. Consequently, the maximum amount of natural discharge that feasibly can be captured by pumping is estimated as the total natural discharge (37,000 acre-ft/yr) minus subsurface outflow (18,000 acre-ft/yr), or about 19,000 acre-ft/yr. For practical purposes, this represents the maximum amount of water that can be withdrawn and consumed annually on an indefinite basis without creating a continuing draft on ground-water storage.

Generally, when water is used some of it is not consumed and ultimately recirculates back to ground water as return flow. This water is usually degraded in quality but may be suitable for some uses. If it is assumed that water quality will not be a problem or that quality problems can be handled by treatment, then the maximum steady-state pumping rate that can be sustained is a function of both the amount of natural discharge that can be captured and the amount of pumpage recycled back to ground water.

The amount of natural discharge that can be captured is virtually a fixed quantity; however, the amount of water recycled back to ground water varies with the type of use. The type of use may change as the valley develops; consequently, the maximum steady-state pumping rate may change with time. Arteaga and Durbin (1978, page 29) described a technique for estimating maximum steady-state pumping rates in Eagle Valley, Nev., which allows for different rates of return flow from various uses. The relationship that they derived includes use of both surface water and ground water and is not directly applicable to Pahrump Valley. However, the same procedures were applied to conditions for an arid desert basin with no surface supplies, and the following general relationship between the maximum steady-state pumping rate, capturable natural discharge, and net pumpage was obtained:

$$SPR = \frac{CND}{1 - [RFA(PCTA) + RFB(PCTB) + RFC(PCTC) + \ldots RFN(PCTN)]}$$

in which SPR is the maximum steady-state pumping rate,
CND is the maximum amount of natural discharge that can be captured by pumping,
PCTA is the fraction of the total pumpage used for Purpose A,
PCTB is the fraction of the total pumpage used for Purpose B,
PCTC is the fraction of the total pumpage used for Purpose C, and
PCTN is the fraction of the total pumpage used for Purpose N, where PCTA through PCTN obey the following relationship

$$PCTA + PCTB + PCTC + \ldots PCTN = 1.0 \quad ;$$

RFA is the fraction of pumpage for use A that is return flow,
RFB is the fraction of pumpage for use B that is return flow,
RFC is the fraction of pumpage for use C that is return flow, and
RFN is the fraction of pumpage for use N that is return flow.

Thus, [RFA(PCTA) + RFB(PCTB) + RFC(PCTC) + ... RFN(PCTN)] is the total annual return flow for the entire valley expressed as a decimal fraction of the total annual pumpage.

For Pahrump Valley under 1975 conditions

CND = 19,000 acre-ft/yr (page 66),
A = Agricultural use which was 0.93 of total pumpage,
B = Self-supplied domestic use which was about 0.02 of total pumpage,
C = Public supply and commercial use which was about 0.05 of total pumpage,
RFA = 0.25,
RFB = 0.70, and
RFC = 0.50.

Substituting into the equation and solving

$$SPR = \frac{19,000}{1 - [0.25(0.93) + 0.70(0.02) + 0.50(0.05)]}$$

$$= 26,000 \text{ acre-ft/yr.}$$

Thus, under 1975 conditions the maximum steady-state pumping rate for Pahrump Valley is 26,000 acre-ft/yr. This rate will undoubtably change in the future as public supply and domestic use increase and the average return flow changes. Figure 23 shows the relation between the maximum steady-state pumping rate and the average return flow. It can be used to estimate the maximum steady-state pumping rate as types of water use and the resulting return flow change in the future.

Field conditions should be carefully evaluated before the general concept of a maximum steady-state pumping rate is applied to a specific area. Items such as the maintenance of suitable water quality, the areal distribution of pumping, the degree of continuity between shallow and deeper parts of the ground-water reservoir, and the possibility of localized overpumping in areas of low transmissivity should all be considered. Problems in any of these areas could cause adverse effects at pumping rates substantially less than the maximum steady-state pumping rate.

Overdraft

When a previously stable ground-water system is developed, water is withdrawn from storage until resulting water-level declines alter the flow system sufficiently to either reduce the discharge or induce additional inflow. Eventually, water levels stablize when the system reaches a new equilibrium. Then pumpage plus the reduced natural discharge (the quantity can be reduced to zero) equals the natural recharge plus any additional recharge induced as a result of development. If ground water is withdrawn from a source more rapidly than it is replenished, an overdraft develops. Ultimately resulting water-level declines cause pumping lifts to become prohibitive or cause other undesirable results.

Two generalized types of overdraft are possible: basinwide and localized. Basinwide overdrafts occur when net ground-water pumpage exceeds inflow to the system over a sustained period of time. In this case, water

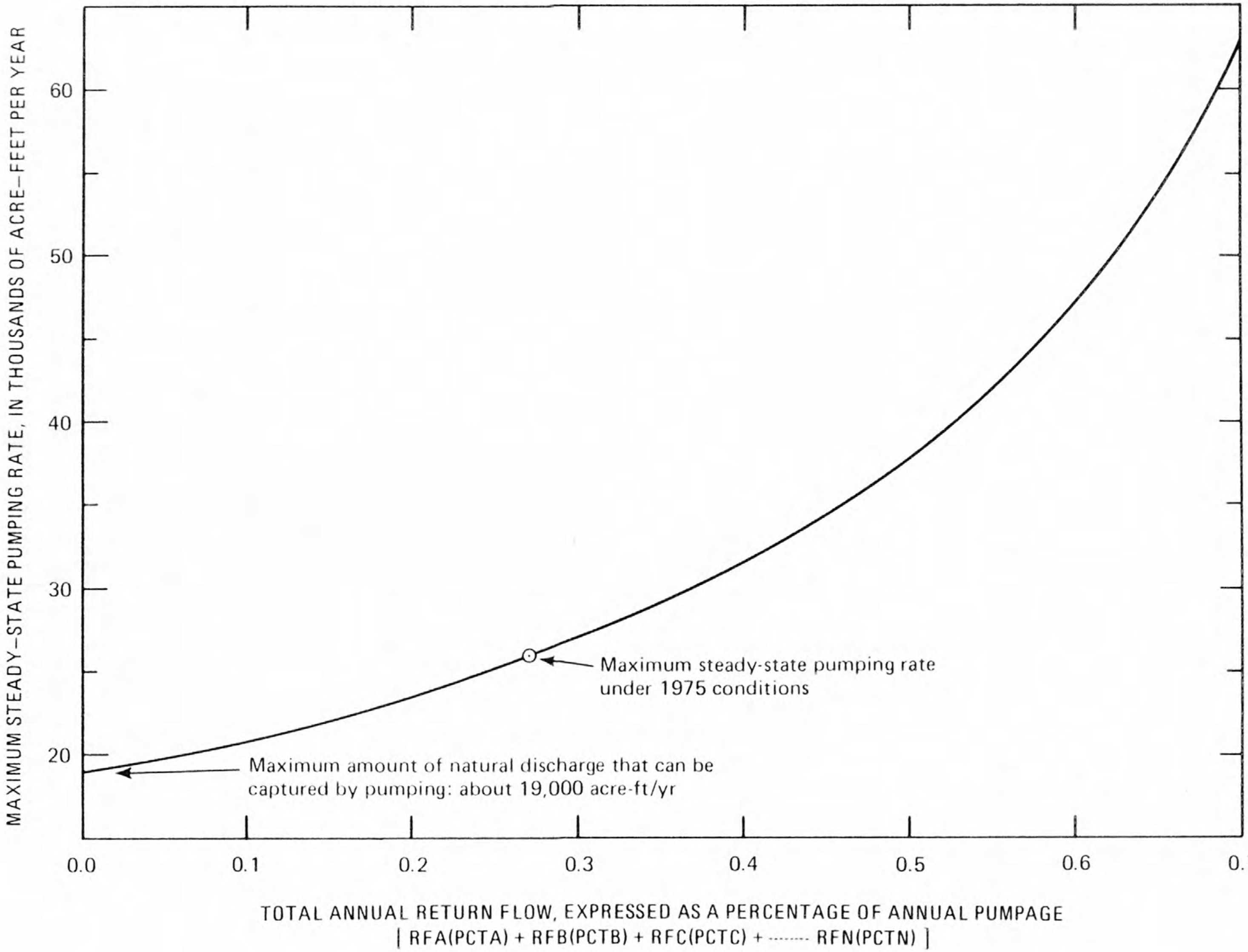


FIGURE 23. — Relation between maximum steady-state pumping rate and average return flow.

levels will continue to decline as long as pumping exceeds recharge, although the rate of decline will decrease as natural discharge is captured by pumping. Thus, even though wells may be ideally located, cumulative effects of gradual but sustained water-level declines will eventually result in excessive pumping costs or other undesirable effects. At this point, either additional water must be imported or pumping must be reduced. A more common occurrence in Nevada valleys is localized overdraft, which results from pumping being concentrated in a localized area. Water-level declines in these areas are accelerated, and pumping lifts and associated detrimental effects may become intolerable before enough discharge is captured to stabilize water levels.

The analysis made in this report indicates that it will be very difficult to capture a significant amount of subsurface outflow by pumping from the valley-fill reservoir in the general vicinity of existing areas of development. This evaluation of overdraft assumes that future pumping will be primarily from the valley fill and, for the most part, will be concentrated in the same general areas as shown in figures 8 and 9. It is beyond the scope of this report to evaluate if deep pumping located near the Nopah Range could economically capture a significant amount of subsurface outflow.

A basin-wide overdraft has existed in Pahrump Valley for many years. As of 1975 the general level of pumping of about 40,800 acre-ft/yr resulted in a net draft on the system of about 30,000 acre-ft/yr (total pumpage minus recirculation). The maximum amount of natural discharge that can be captured by pumping has been estimated as 19,000 acre-ft/yr. The difference between these two quantities (30,000-19,000, or 11,000 acre-ft/yr) is the magnitude of the existing overdraft. The magnitude of the overdraft can also be estimated from the maximum steady-state pumping rate by using the following relationship:

$$OD = \frac{(APR - SPR)\ (CND)}{SPR},$$

where OD = Overdraft rate,
APR = Actual pumping rate,
SPR = Maximum steady-state pumping rate, and
CND = Maximum amount of natural discharge that can be captured by pumping.

Using 1975 pumping conditions:

$$OD = \frac{(41,000 - 26,000)\ (19,000)}{26,000}$$

$$= 11,000 \text{ acre-ft/yr}.$$

Consequently, pumping in Pahrump Valley will eventually either have to be curtailed or additional water imported in order to alleviate the overdraft. However, at the present and probable future rates of water-level decline (figure 23) there may be considerable time before either action becomes necessary. One reason why the present rates of water-level decline have been only moderate in terms of the level of pumping and the amount of overdraft on the basin is that the existing pumping is situated to rather effectively capture spring discharge. The consequent capture of about 10,000 acre-ft/yr of spring discharge and about 6,000 acre-ft/yr of other evapotranspiration by pumping has helped to alleviate the rate of water-level decline.

CONCLUSIONS

The principal conclusions regarding the ground-water resources of Pahrump Valley are as follows:

1. The ground-water system consists of two reservoirs: (1) The valley-fill reservoir which consists of unconsolidated materials and occurs only within the study area, and (2) a consolidated-rock reservoir which is composed primarily of carbonate-rock aquifers and extends beyond the boundary of Pahrump Valley to form a multivalley flow system which partially drains the ground-water resources of Pahrump Valley.

2. Although the scope of this study did not allow detailed delineation of the consolidated-rock reservoir, two statements are supported by the result of this evaluation: (1) The system, as conceived in this study, does not contribute appreciable subsurface inflow to the adjacent Amargosa Desert; and (2) the most probable discharge area for subsurface outflow from Pahrump Valley is along the flood plain of the Amargosa River between the towns of Shoshone and Tecopa, some 12 to 15 miles southeast of Pahrump Valley. Additional field work is needed to confirm or disprove this hypothesis.

3. Analysis of the system suggests that natural ground-water recharge and predevelopment discharge are within the range of 37,000 to 26,000 acre-ft/yr. The value at the high end of the range was chosen because it provided the best fit to information available at the time of this study. About 18,000 acre-ft/yr of this quantity leaves the valley as subsurface outflow. Precise determination of these quantities is hindered by a lack of knowledge about hydrologic conditions in the consolidated-rock reservoir.

4. Ground water supplies virtually all the water used in Pahrump Valley. During the period 1962-75, ground-water withdrawals from springs or wells increased from about 29,000 acre-ft/yr in 1962 to a maximum of 48,000 acre-ft/yr in 1968 and then declined to about 41,000 acre-feet in 1975. The decrease was due primarily to the transition from agricultural to real estate development. Future pumping may again approach the maximum historical rate when land taken out of agricultural production becomes fully developed for residential purposes. As of 1975, all but a few acre-feet of pumpage was from the Nevada part of the valley.

5. Substantial water-level declines have occurred in deeper wells along the lower parts of the Pahrump and Manse alluvial fans where heavy pumping has been concentrated. Maximum observed declines since development began have been slightly greater than 100 feet in localized areas. Maximum observed declines during the period 1962-75 were slightly more than 60 feet. Water-level declines were substantially less in the central part of the valley. During the period 1962-75, water levels along the fan generally declined at rates between

1 and $4\frac{1}{2}$ ft/yr, while water levels in the central part of the valley declined less than 1 ft/yr. The rate of water-level decline in shallow wells was generally much less than in deeper wells. In some areas the water level in shallow wells rose as the result of local recharge from irrigated land.

6. There are no leveling data that will allow an accurate evaluation of amount of land subsidence; however, the analysis made in this study suggests that land subsidence is active in the valley. A network of strategically located benchmarks should be established and periodically releveled to determine the extent and rate of subsidence.

7. Pumping during the period 1962-75 has resulted in a total ground-water storage depletion of 219,000 acre-feet, which was about 40 percent of the total pumpage. About 155,000 acre-feet of this storage depletion was derived from drainage of unconsolidated deposits, about 46,000 acre-feet was probably from the compaction of fine-grained sediments, and about 18,000 acre-feet was from the elastic response of the aquifer and the water.

8. Pumpage not derived from storage was supplied by the capture of spring discharge and natural ground-water evapotranspiration and from secondary recharge that consists mainly of infiltration from irrigated fields. During the period 1962-75, spring discharge declined from 1,400 to 200 acre-ft/yr, ground-water evapotranspiration declined from 4,900 to 2,600 acre-ft/yr, and recharge from recirculated pumpage and springflow increased from 5,900 to 11,000 acre-ft/yr. Very little subsurface outflow had been captured by pumping.

9. The model analysis made during the study indicates that the maximum amount of natural discharge that might ultimately be captured by pumping is about 19,000 acre-ft/yr. This represents the amount of water that the valley could yield on a sustained basis without continually depleting ground-water storage. This amount is larger than the 12,000 acre-feet estimated by Malmberg (1967, page 39). The difference in estimates is due primarily to different techniques used in the analysis.

10. The maximum amount of water that can be pumped on a sustained basis is dependent on both the amount of natural discharge that can be captured by pumping and the amount of pumped water that is recirculated back to ground water. Under 1975 conditions, about 27 percent of the pumpage was recirculated back to ground water. Under these conditions the maximum steady-state pumping rate is 26,000 acre-ft/yr. If the type of use and amount of water recirculated back to ground water changes in the future, then maximum steady-state pumping rate will change also.

11. There is significant uncertainty in estimates which attempt to quantify the ground-water budget in Pahrump Valley; however, all estimates indicate a substantial overdraft on the ground-water reservoir. Using the estimates generated by this study, overdraft on the system in 1975 was about 11,000 acre-ft/yr. Under these conditions, no new equilibrium is possible and water levels will continue to decline as long as this high level of pumping is sustained. Results from simulated pumping of the ground-water model until the year 2040 also indicate this trend.

12. The valley-fill reservoir contains vast amounts of stored ground water. Geophysical techniques were used to estimate the total thickness of valley fill. With this information, it was also possible to estimate that there may be as much as 57 million acre-feet of recoverable ground water stored in the valley-fill reservoir. Most of this cannot be economically recovered with existing technology due to high pumping costs. There is also the environmental factor of land subsidence to be considered. The amount of water stored in the upper 200 feet of saturated valley fill in and adjacent to the area of development, as of 1975, is about 2.3 million acre-feet. This quantity probably better represents the amount of ground water stored within economic pumping lifts, utilizing the general distribution of pumping as of 1975. Depletion of even this amount of ground-water storage would probably cause significant land subsidence in the central part of the valley.

13. Ground water currently is the sole source of large-scale development in Pahrump Valley and will probably remain so for the foreseeable future. The overdraft that exists will create a sustained depletion of stored ground water, and continuing water-level declines are anticipated. However, the amount of ground-water storage is large in relation to the magnitude of the annual overdraft, and pumping can remain at the 1975 level for many years before the reservoir of stored ground water is seriously depleted. If serious problems arise they will probably not be related to running out of water on a valley-wide basis but, instead, to situations such as deteriorating water quality, land subsidence, or too closely spaced pumping.

REFERENCES CITED

Arteaga, F. E., and Durbin, T. J., 1978, Development of a relation for steady-state pumping rate for Eagle Valley ground-water basin, Nevada: Carson City, Nev., U.S. Geological Survey Open-File Report 79-201, 44 p.

California Division of Water Resources, 1956, Office report on water wells and ground-water data in Pahrump, Mesquite, Ivanpah, Lanfair, Fenner, Chuckawalla, and Jacumba Valleys: California Division of Water Resources report, 58 p.

Chapman, R. H., Healy, D. L., and Troxel, B. W., 1971, Bouguer gravity map of California, Death Valley sheet: California Division of Mines and Geology map.

Chow, Ven Te, editor, 1964, Handbook of applied hydrology: New York, McGraw-Hill, 1453 p.

Cooper, H. H., Jr., 1966, The equation of ground water flow in fixed and deforming coordinates: Journal Geophysical Research, v. 71, no. 20, p. 4785-4790.

Cornwall, H. R., 1972, Geology and mineral deposits of southern Nye County, Nevada: Nevada Bureau of Mines and Geology Bulletin 77, 49 p.

Dudley, W. W., Jr., and Larson, J. D., 1976, Effect of irrigation pumping on desert pupfish habitats in Ash Meadows, Nye County, Nevada: U.S. Geological Survey Professional Paper 927, 52 p.

Eakin, T. E., Maxey, G. B., Robinson, T. W., Fredericks, J. C., and Loeltz, O. J., 1951, Contributions to the hydrology of eastern Nevada: Nevada State Engineer, Water Resources Bulletin 12, 171 p.

Glancy, P. A., 1968, Water-resources appraisal of Mesquite-Ivanpah Valley area, Nevada and California: Nevada Division of Water Resources Reconnaissance Report 46, 57 p.

Hardman, George, and Mason, H. S., 1949, Irrigated lands of Nevada: University of Nevada, Reno, Agricultural Experiment Station Bulletin 183, 57 p.

Hardman, George, and Miller, M. R., 1934, The quality of the waters of southeastern Nevada, drainage basins and water resources: University of Nevada, Reno, Agricultural Experimental Station Bulletin 136, 62 p.

Harrill, J. R., 1976, Pumping and ground-water storage depletion in Las Vegas Valley, Nevada, 1955-74: Nevada Division of Water Resources Bulletin 44, 70 p.

Healey, D. L., 1973, Bouguer gravity map of California, Kingman sheet: California Division of Mines and Geology map.

Healey, D. L., and Miller, C. H., 1965, Gravity survey of the Amargosa Desert area of Nevada and California: Denver, Colo., U.S. Geological Survey Technical Letter NTS-99, 32 p.

Hughes, J. L., 1966, Some aspects of the hydrogeology of the Spring Mountains and Pahrump Valley, Nevada, and environs, as determined by spring evaluation: University of Nevada, Reno, unpublished M.S. thesis, 116 p.

Jacob, C. E., 1950, Flow of ground water, *in* Rouse, Hunter [ed.], Engineering Hydraulics: New York, John Wiley, p. 321-386.

Jennings, C. W., 1958, Geologic map of California, Death Valley sheet: California Division of Mines and Geology map.

-----1961, Geologic map of California, Kingman sheet: California Division of Mines and Geology map.

Jennings, C. W., Burnett, J. L., and Troxel, B. W., 1962, Geologic map of California, Trona sheet: California Division of Mines and Geology map.

Kane, M. F., and Carlson, J. E., 1964, Bouguer gravity anamoly map of Clark County, Nevada: Denver, Colo., U.S. Geological Survey open-file report, 1 sheet.

Lofgren, B. E., 1977, Changes in aquifer-system properties with ground-water depletion: Fresno, Calif., Paper presented at 11th Biennial Groundwater Conference, Sept. 15-16, 1977, typewritten report, 46 p.

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

Lohman, S. W., and others, 1972, Definitions of selected ground-water terms--revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, p. 21.

Longwell, C. R., Pampeyan, E. H., Bowyer, Ben, and Roberts, R. J., 1965, Geology and mineral deposits for Clark County, Nevada: Nevada Bureau of Mines Bulletin 62, 218 p.

Malmberg, G. T., 1965, Available water supply of the Las Vegas ground-water basin, Nevada: U.S. Geological Survey Water-Supply Paper 1780, 116 p.

-----1967, Hydrology of the valley-fill and carbonate-rock reservoirs, Pahrump Valley, Nevada-California: U.S. Geological Survey Water-Supply Paper 1832, 47 p.

Malmberg, G. T., and Eakin, T. E., 1962, Ground-water appraisal of Sarcobatus Flat and Oasis Valley, Nye and Esmeralda County, Nevada: Nevada Department of Conservation and Natural Resources Reconnaissance Report 10, 39 p.

Maxey, G. B., and Jameson, C. H., 1948, Geology and water resources of Las Vegas, Pahrump, and Indian Spring Valleys, Clark and Nye Counties, Nevada: Nevada Water Resources Bulletin 5, 292 p.

Maxey, G. B., and Robinson, T. W., 1947, Ground water in Las Vegas, Pahrump, and Indian Spring Valleys, Nevada (a summary): Nevada State Engineer, Water Resources Bulletin 6, 23 p.

Meinzer, O. E., 1923, Outline of ground-water hydrology, with definitions: U.S. Geological Survey Water-Supply Paper 494, 71 p.

Mendenhall, W. C., 1909, Some desert watering places in southeastern California and southwestern Nevada: U.S. Geological Survey Water-Supply Paper 224, 98 p.

Meyers, J. S., 1962, Evaporation from the 17 western States: U.S. Geological Survey Professional Paper 272-D, 100 p.

Nevada West and Pahrump Valley Times, 1974, Survey shows PV growth continues: v. 4, no. 8, p. 1 and 11.

-----1975, PV population is 53% above 1970's: v. 5, no. 5, p. 4.

-----1977, Home hookups up 18.5% yearly: v. 7, no. 16, p. 1.

Nilsen, T. H., and Chapman, R. H., 1971, Bouguer gravity map of California, Trona sheet: California Division of Mines and Geology map.

Robinson, T. W., Maxey, G. B., Fredericks, J. G., and Jameson, C. H., 1947, Water levels and artesian pressure in wells in Las Vegas Valley and in other valleys in Nevada, 1913-1945: Nevada State Engineer, Water Resources Bulletin 3, 77 p.

Rush, F. E., 1968, Index of hydrographic areas: Nevada Division of Water Resources Information Report 6, 38 p.

Talwani, Manik, Worzel, J. L., and Landisman, Mark, 1959, Rapid gravity computations for two-dimensional bodies with application to the Mendocino submarine fracture zone: Journal of Geophysical Research, v. 64, no. 1, p. 49-59.

Trescott, P. C., 1975, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: Reston, Va., U.S. Geological Survey Open-File Report 75-438, 32 p.

Trescott, P. C., and Larson, S. P., 1976, Supplement to open-file report 75-438, Documentation of finite-difference model for simulation of three-dimensional ground-water flow: Reston, Va., U.S. Geological Survey Open-File Report 76-591, 21 p.

U. S. Bureau of Reclamation, 1969, Inland basins projects, Pahrump-Mesquite Valleys, California-Nevada: U.S. Bureau of Reclamation Interim Report, 70 p.

-----1972, Inland basin projects, California-Nevada: U.S. Bureau of Reclamation Summary Report, 363 p.

Walker, G. E., and Eakin, T. E., 1963, Ground-water resources of Amargosa Desert, Nevada-California: Nevada Department of Conservation and Natural Resources Reconnaissance Report 14, 45 p.

Waring, G. A., 1921, Ground water in Pahrump, Mesquite, and Ivanpah Valleys, Nevada and California, *in* Contributions to the hydrology of the United States: U.S. Geological Survey Water-Supply Paper 450, p. 51-81.

Winograd, I. J., and Thordarson, William, 1975, Hydrogeologic and hydrochemical framework, south central Great Basin, Nevada-California, with special reference to the Nevada Test Site: U.S. Geological Survey Professional Paper 712-C, 126 p.

Zietz, Isidore, Gilbert, F. P., and Kirby, J. R., 1978, Aeromagnetic map of Nevada: U.S. Geological Survey Geophysical Investigations Map GP-922.