Geohydrology of the Basalt and Unconsolidated Sedimentary Aquifers in the Fallon Area, Churchill County, Nevada

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Prepared in cooperation with the Nevada Division of Water Resources

Aerial view of Rattlesnake Hill and Fallon, looking southwest
on August 5, 1980.

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By PATRICK A. GLANCY

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Geohydrology of the Basalt and Unconsolidated Sedimentary Aquifers in the Fallon Area, Churchill County, Nevada

By Patrick A. Glancy

Abstract

Aquifers near Fallon, Nev., all belong to a large interdependent system that can be subdivided into four subsystems on the basis of hydrologic characteristics. They are (1) a hydraulically complex, shallow, unconsolidated sedimentary aquifer containing water of variable chemical character, (2) an intermediate-depth, unconsolidated sedimentary aquifer locally containing large quantities of freshwater, (3) a deep, generally unconsolidated sedimentary aquifer that probably contains mostly saline water, and (4) a highly permeable basalt aquifer that stratigraphically transects all three sedimentary aquifers.

Electrical-resistivity data suggest that the basalt aquifer is generally mushroom shaped; characteristically, much of it overlies the deep sedimentary aquifer and is interbedded with the intermediate aquifer. It is recharged mainly by freshwater from the intermediate aquifer but apparently contains a blend of freshwater and some saline water. Water from the basalt aquifer in areas of large withdrawals contains chemical evidence of modern (post-1953) recharge from surface sources. Prepumpage basalt recharge is supplemented by pumpage-induced recharge proportionate to annual pumpage rates. The basalt aquifer is highly transmissive and exhibits a nearly flat potentiometric surface.

The shallow sedimentary aquifer is inherently susceptible to pollution and contains mainly hard water, the salinity of which is influenced by irrigation recharge. In the intermediate sedimentary aquifer, known reserves of freshwater are expanding with continued exploration activity. In contrast, water sampled to date in the deep sedimentary aquifer is too salty for most uses. Water from all aquifers, including the basalt, commonly contains greater-than-normal concentrations of dissolved arsenic.

INTRODUCTION

The modern era of ground-water development and its inherent problems in Nevada desert valleys was anticipated more than 60 years ago by Oscar E. Meinzer, widely acknowledged as the "father of ground-water hydrology." Some of Meinzer's introductory comments in his 1916 report on the water resources of Big Smoky Valley in central Nevada seem appropriate to the need for scientific knowledge in Nevada, and particularly in the Fallon area, during the period of intensive population growth in the 1970's. Meinzer (1916, p. 86–88) wrote as follows:

"The ground waters underlying the Nevada deserts will certainly receive more attention in the future than they have in the past, and costly projects for their recovery will be undertaken. * * * So great is the eagerness for land that the report of a single flowing well or the skillful advertisements of a promoter may at any time start a stream of home seekers, ignorant of the actual conditions and difficulties, into almost any of the desert valleys of the West.

"It is very desirable that the possibilities of these valleys should be thoroughly investigated before they are invaded by home seekers. * * * To begin to develop the ground-water supply of a valley without first investigating its ground-water conditions is as unwise as it would be to start to build a railroad without first having the route surveyed, and the financial results are likely to be no less disastrous."

Purpose and Scope of Investigation

The results of a water-resources appraisal of the Carson River basin during the early 1970's (Glancy and Katzer, 1975) suggested the existence of several ground-water aquifers in the Carson Desert. Unconsolidated sedimentary aquifers and a consolidated rock (basalt) aquifer were being tapped for potable water, but, because of the limited data available, aquifer locations and characteristics were defined poorly, and the existence of as yet undiscovered aquifers was only a possibility.

The 1970's marked a period of rapid population growth in the Carson Desert that caused an increased demand for potable water. As a result of the increased demand and the uncertainty of limits of the water supply, the Nevada Department of Conservation and Natural Resources joined with the U.S. Geological Survey to investigate the ground-water resources of the Fallon area.

The study area covers about 270 square miles (mi^2), or roughly 13 percent of the 2,016-mi^2 Carson Desert Hydrographic Area (fig. 1). The investigation emphasized the aquifers near Fallon, the principal population center in the study area.

The initial objectives of the investigation were (1) to determine the extent of the basalt aquifer, its source of supply, its relation to enclosing valley-fill sedimentary deposits that contain water of varying salinity, and the source of

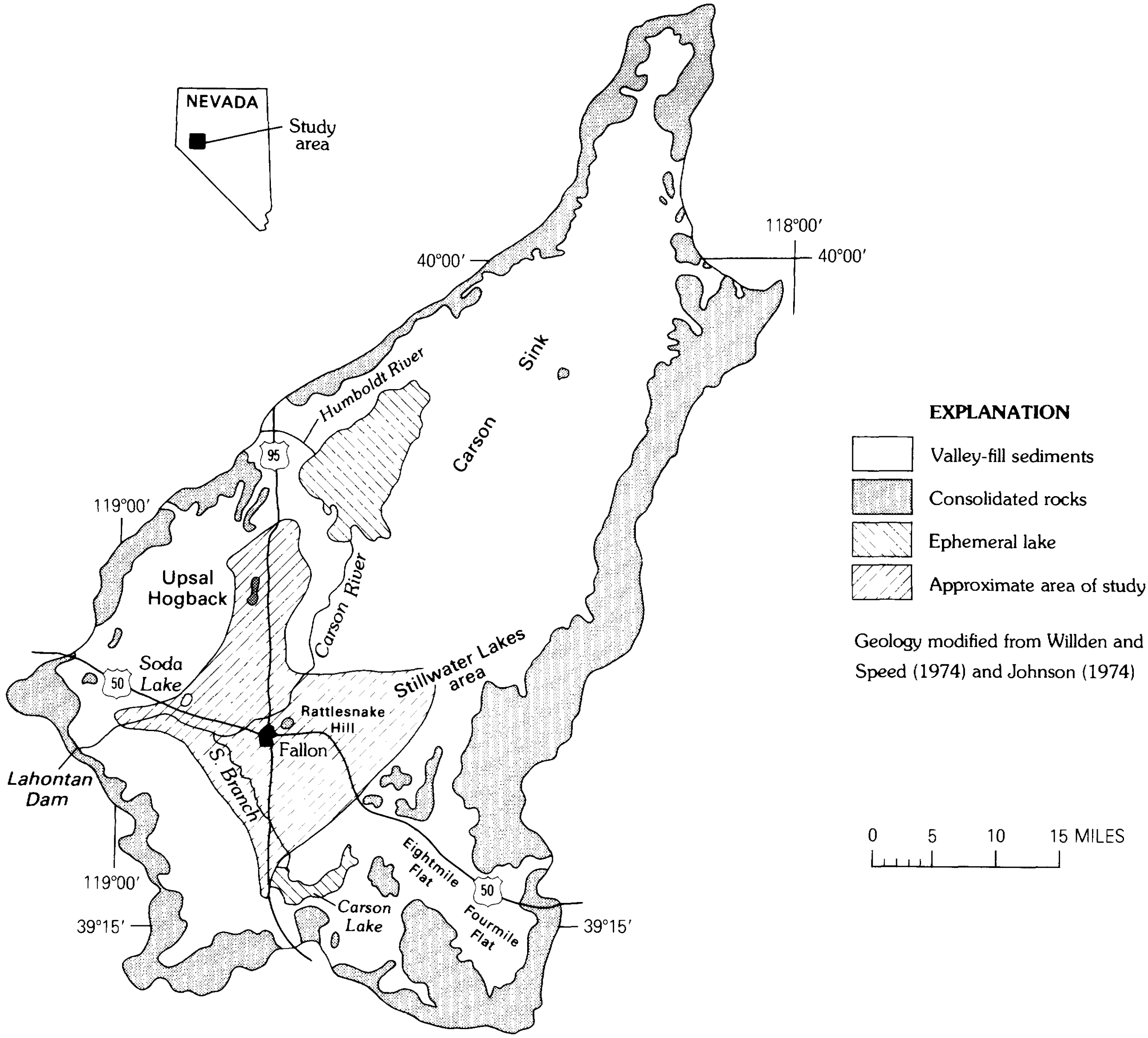

Figure 1. Generalized geology of the Carson Desert and location of the study area.

arsenic in the basalt ground water and (2) to ascertain the extent of the shallowest sedimentary aquifer, which contains potable water, and to evaluate its dependability as a water supply under present and future conditions of irrigation practice. The objectives were broadened during the investigation to include studies of the intermediate-depth and deep sedimentary aquifers as well.

Study Techniques

Few data were available for the basalt aquifer at the onset of the investigation. During a reconnaissance study, drillers' logs were collected (Glancy and Katzer, 1975) for nine wells penetrating basalt and for about six deep wells near Fallon that did not intercept basalt. Some chemical data were available for the water from Fallon city and U.S. Naval Air Station wells in the basalt; however, all of these wells tapped only the southern part of the aquifer. The three-dimensional size and shape of the basalt aquifer and the source of its water were unknown. Data on hydraulic characteristics of the aquifer were few, and the accuracy of the available data were unverified.

Geophysical techniques were used to delineate the basalt aquifer. Detailed chemical analyses of water from all available wells tapping the basalt aquifer were made to characterize the system. The water samples were filtered through 0.45-micrometer (μm) filters at the collection sites and were preserved as appropriate for later analysis according to standard methods. Aquifer tests at principal wells improved knowledge of the basalt's hydraulic characteristics. A nearly flat potentiometric surface, confirmed by periodic water-level measurements, contributed to the uncertainty regarding the direction and the rate of ground-water movement through the basalt. Radiochemical dating of the basalt water was attempted to improve understanding of the directions and the movement rates and, consequently, the nature of recharge to and discharge from the basalt. Long-term pumping records of production wells were assembled or synthesized to add knowledge regarding historical trends of water demand and to assist in understanding the recharge-discharge nature of the aquifer.

Numerous drillers' logs and chemical analyses of ground water from the shallow sedimentary aquifer were available at the onset of the study. A water-level observation-well network was designed that utilized preexisting wells and wells drilled expressly for the study. The older wells, drilled for a Geological Survey study of geothermal resources in the Soda Lake–Upsal Hogback and Stillwater areas, were used to monitor water-level changes in unpopulated areas. Additional wells were drilled in or near areas of surface-water irrigation to monitor water-level changes influenced by agriculture.

Many chemical analyses of ground water in the shallow sedimentary aquifer, obtained from files of the Nevada Consumer Health Protection Services, had been assembled and catalogued by the Churchill County District Health Department. As part of the Geological Survey study, most of the data were field located on 7.5-minute orthophotoquad maps according to street and road addresses. Data for each site were screened to eliminate analytical results of questionable accuracy (those for which the mathematical imbalance between total positive and negative ions exceeded 5 percent). The surviving data comprised analyses for about 480 well waters. A cursory review of the data showed that chemical characteristics of the shallow-aquifer water differed extensively from place to place, often between sites that were close together. The data were analyzed statistically for seasonal variability and for areal variation using computer techniques. Lines of equal concentration for dissolved solids, water hardness, and arsenic were machine interpreted and drawn by a Cal-Comp plotter.[1]

At the inception of the study (1975), evaluation of available drillers' logs and chemical data suggested that a sedimentary aquifer containing potable water existed beneath the shallow aquifer within a restricted geographical area in and around Fallon. A substantial amount of additional data was added during the period of study as exploration successes in valley fill beneath the shallow aquifer prompted more deep-drilling ventures. Thus, by autumn 1978, nearly 100 wells had been drilled into sedimentary deposits below the shallow aquifer, and many of the wells had penetrated sources of potable water. Water levels and chemical data for many of these wells were collected and analyzed as part of this investigation.

Much of the information on water wells collected during this study is 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 in Carson City, Nev., or through any designated NAWDEX assistance center. In addition, field data are available for inspection in the Carson City office.

Numbering System for Wells

The well numbering system used is based on the rectangular subdivision of the public lands referenced to the Mount Diablo base line and meridian. Each number consists of four units. The first is a township number ("N" indicates that the township is north of the base line); the second unit is the range number ("E" indicates east relative to the meridian); and the third unit includes the section number, followed by letters designating the quarter section, quarter-quarter section, and so forth (A, B, C, and D indicate northeast, northwest, southwest, and southeast quarters, respectively), followed in turn by a sequence number; for example (see table 1), well N19 E28 22DAAC1 is the first well recorded in the SW 1/4 NE 1/4 NE 1/4 SE 1/4 of section 22, township 19 north, range 28 east as referenced to the Mount Diablo base line and meridian.

Acknowledgments

Many people provided valuable assistance during this investigation. Special acknowledgment is offered with appreciation to the following: Adel Zohdy, R. J. Bisdorf, and staff, U.S. Geological Survey, Denver, Colo., for substantial geophysical assistance in the collection and interpretation of electrical-resistivity data; T. B. Coplen, Bruce Hanshaw, Joseph Pearson, T. A. Wyerman, Laurie Campbell, F. L. Leighty, and Jessica Hopple, U.S. Geological Survey, Reston, Va., for extensive support with analyses and interpretations of chemical-isotope water samples; Churchill County office staff, for sharing their water-quality files; James Regan, D. S. Pursel, D. A. Fields, and Charles Driver, Public Works staff, Fallon U.S. Naval Air Station, for assistance with well information and pumpage data; Ben T. Bartlett, Fallon City Engineer, and his staff, including Clifford Parsons, Alvin Perrier, Sonny Richards, and Roy Zaugg, for assistance with aquifer tests, well records, pumpage data, and general ground-water information; Fallon City Electrical Utility staff for assistance with aquifer tests; J. W. Biffle and J. B. "Tex" Reynolds, Fallon area well drillers, for countless items of well data, advice, and drilling recollections; T. J. Durbin, David Wood, Susan Mathews, E. L. Mathews, Nyle Pennington, and Alan

[1]The use of trade names in this report is for identification purposes only and does not imply endorsement by the U.S. Geological Survey.

Welch, U.S. Geological Survey, Carson City, Nev., for extensive assistance with field chores and computer processing of data; J. D. Frank and Willis Swan, Kennametal, Inc., and Ronald Albaugh, Clyde Bray, Ben Peck, Bernard Ponte, and Howard Wolf, well owners, who allowed data collection from their wells; and numerous Fallon area residents who allowed access to their property and furnished much helpful information about their wells and water systems.

GEOHYDROLOGY

Geology

The Carson Desert Hydrographic Area is an intermontane valley almost completely bounded by mountains. It is one of the largest such valleys in northern Nevada and is the terminal sink for the Carson and Humboldt Rivers. The mountainous boundary is composed mainly of a variety of consolidated rocks of igneous, sedimentary, and metamorphic origin that range in age from Triassic to Quaternary. The consolidated rocks are described in detail and shown on a map by Willden and Speed (1974). In addition, Morrison (1964) described the consolidated rocks in and surrounding the study area and discussed their geologic history. Consolidated rocks also underlie the valley fill and are probably of similar character and origin to those forming the surrounding mountains. The configuration of the upper bedrock surface throughout the valley is largely a product of basin-and-range normal faulting and evolved structurally during the Cenozoic Era. Faulting in the Carson Desert and nearby Fairview Valley during the 1950's suggests that structural evolution is continuing. Development of the intermontane valley was accompanied by deposition of sediments in some areas to depths of several thousand feet.

The area of this study composes about 13 percent of the total Carson Desert Hydrographic Area and is wholly on the valley floor in the southwestern part (fig. 1). Exposed sediments in the study area consist almost exclusively of Quaternary valley fill, which includes mainly river-laid alluvium, alluvial-fan deposits, lacustrine sediments including beach deposits, and eolian deposits. Rattlesnake Hill, a volcanic cone composed of basaltic ejecta, occupies less than 1 mi^2 of surface area and protrudes about 200 feet (ft) above the sedimentary plain just northeast of the town of Fallon (fig. 1). Morrison (1964, p. 23) considered the basalt to be probably of Quaternary age. His conclusion has been supported by recent radiochemical age dating; a rock sample collected by Sibbett (1979, p. 6) from the high point of Rattlesnake Hill has been dated at 1.03 ± 0.05 million years—mid-Quaternary—by Evans (1980, p. 20) on the basis of a whole-rock potassium-argon analysis.

Detrital materials composing the valley fill were derived mainly from the following sources: (1) upstream valleys of the Carson River drainage, (2) upstream valleys of the Humboldt River basin, and (3) products of mechanical and chemical weathering of consolidated rocks in the Carson Desert itself. Most of the fill underlying the study area probably was transported into the valley by the ancestral Carson River.

The depositional character of the valley-fill sediments was determined by a variety of factors. One of the chief influences was the presence of a lake or lakes in the valley. The study area is in the heart of the region occupied by ancient Lake Lahontan (boundaries not shown in fig. 1), a Quaternary lake that was subjected to numerous cycles of expansion and recession. The dynamic history of the lake is related to regional climatic changes that caused dramatic oscillations of lake shorelines and numerous fluctuations of lake stage throughout the Pleistocene Epoch. Subsurface stratigraphic evidence also suggests the existence of pre-Quaternary lakes in the valley; thus, the pluvial influences on sediment deposition were extensive and probably varied over a substantial part of Cenozoic time. The alternating influences of flowing water, standing water, wave action, and wind on the sediment moved into the valley by the Carson and Humboldt Rivers resulted in a very complex sequence of interbedded and interfingered deposits of fluvial, deltaic, lacustrine, and eolian sediments. Morrison (1964) described the sediments and differentiated several stratigraphic units; reconstructed geologic history of sediment deposition, reworking, and redeposition; and developed a comprehensive body of knowledge on the geology of the deposits in the study area. Morrison's work confirms the complexity of the deposits, and reference to his text and maps suggests that deposits of gravel, sand, silt, and clay are not segregated simply into horizontally layered strata throughout the study area. Instead, the hydraulically transmissive deposits (gravel and sand) seem to occur commonly as longitudinal stringers that interlace with one another and with the less transmissive (finer grained) deposits. Thus, ground water moves laterally and vertically, mainly along tortuous paths defined by the restricted geometric limits of the coarse-grained deposits.

Settlement of the area, beginning in the mid-19th century and accelerating greatly during the 1970's, has modified the surficial geology to varying degrees in the study area. Irrigation canals and drains of the Newlands Irrigation Project crisscross the area, natural drainage patterns have been altered, and extensive land-surface leveling to facilitate irrigation has modified severely the natural topography. Former natural bodies of standing water have been isolated from inflowing water, and temporary bodies of standing water have been created in areas that were naturally dry. These manmade changes strongly altered the natural geomorphic environment and modified greatly the hydrologic regime.

Regional Hydrology

West-central Nevada, which includes the study area, has a dry climate. Most precipitation occurs during the winter, usually as the result of moist air masses moving generally eastward from the Pacific Ocean. The most intense precipitation from the eastward moving storms falls on the Sierra Nevada of eastern California and western Nevada. The Sierras, by triggering large amounts of precipitation from the moist air masses, create a rain shadow along the eastern slopes that contributes largely to the aridity of the entire Great Basin, including the Carson Desert to the east. The heavy winter snowfall in the Sierras is the source of most runoff that feeds the major eastward flowing rivers of the region—the Carson, the Truckee, and the Walker; these rivers drain into intermontane valley sinks where the runoff is dissipated by evaporation. Large mountain masses in Nevada east of the Sierra Nevada also receive appreciable amounts of precipitation at higher altitudes, but most do not drain to any major river. A substantial number collectively feed one major river system, the Humboldt, which integrates drainage from a number of intermontane valleys in the north-central and northeastern parts of the State. Evaporation potential is high throughout the region because air masses blanketing the landscape are generally deficient in moisture; brisk winds are commonplace, and summer temperatures are high.

The extensive masses of valley fill in the many intermontane valleys provide voluminous underground reservoirs that readily receive, transmit, and store substantial volumes of water. The valley-fill reservoirs are being replenished continually in their upgradient areas by freshly infiltrating water derived from precipitation and streamflow; likewise, they continually discharge ground water by evapotranspiration in their downgradient areas. These naturally recharging and discharging valley-fill systems are assumed to be in a state of hydrologic equilibrium over a period of decades, wherein quantities of natural recharge and discharge are equal. The natural state of equilibrium is upset when man begins to extract ground water from the reservoir system, and the degree of disequilibrium is dependent on the intensity and location of pumping. Generally speaking, the ground-water reservoirs, because of their large volumes of stored water, are the most dependable sources of water supply in the region. Their dependability in the future will be determined largely by man's knowledge of the hydrologic system and the wisdom and discipline he uses in managing this resource.

Local Hydrology

Hydrology of the study area is influenced mainly by the following factors: Climate, including local precipitation and evapotranspiration rates; seasonally variable inflow of Carson River water and imported Truckee River water, which is controlled by releases from Lahontan Reservoir; surface-water irrigation of large tracts of land and the canals and drains associated therewith; pumping from the highly transmissive basalt aquifer and from overlying sedimentary aquifers; and the presence of large volumes of valley fill of widely differing porosity and transmissivity, which are saturated nearly to the land surface. All these factors interact with one another in varying combinations and to varying degrees to make the hydrologic system function.

Over a period of several decades, before the first arrival of settlers in the mid-1800's, the hydrologic system is assumed to have been in a natural state of equilibrium, which was not greatly upset until irrigation farming became extensive. During the first half century of settlement, agricultural activities were modest, and the overall population was relatively small. The most dramatic changes in farming came shortly after the turn of the century when the Newlands Irrigation Project was constructed and massive farming activity began. Canals and drains were dug, fields were leveled, natural vegetation was removed and replaced by farm crops, river water was spread over the land surface rather than left in natural channels, the population increased dramatically, numerous domestic and stock wells were drilled, and local states of hydrologic disequilibrium quickly evolved. A particularly great hydrologic change in the general study area resulted when the importation of Truckee River water for farming began by way of the Truckee Canal in 1905 (Townley, 1977, p. 33). Average annual streamflow in the lower Carson River increased by about 60 percent because of the imports. The combined flow was spread, for the most part, over the land surface miles above the terminal sink areas of the natural drainage system. Thus, water inflows were increased greatly by the imports, and some major centers of evapotranspiration (outflow) were shifted upstream from the terminal sink areas.

The population of the study area has increased sporadically over the years, and these increases have accelerated ground-water demand. The increased demand was met in rural areas by drilling shallow domestic wells in the valley fill. Increased municipal demand also was met through well drilling and eventually satisfied by the discovery and exploitation of the basalt aquifer system. The progressively increasing ground-water pumping tends to retard the hydrologic system from attaining a new state of equilibrium.

Water Inflow

The Carson Desert receives water from direct precipitation, Carson River inflow, water imported from the Truckee River basin by way of the Truckee Canal, and Humboldt River inflow. The major inflow to the Carson Desert Hydrographic Area, an estimated annual average of 660,000 acre-feet (acre-ft), is from local precipitation. However, only about 0.2 percent [1,300 acre-feet per year (acre-ft/yr)] of that amount is believed to recharge the ground-water system (Glancy and Katzer, 1975, p. 48). Most of the local precipitation is quickly lost by natural evapotranspiration before it can be captured by man or stored by nature for any prolonged period of time. An unknown, but probably small, part of that 1,300 acre-ft/yr contributes to aquifers in the Fallon area. Average annual precipitation on the study area itself is only about 5 inches (in).

The average annual contribution by the Humboldt River is estimated to be about 2,600 acre-ft (Glancy and Katzer, 1975, p. 66), and it flows directly into the Carson Sink where it is dissipated by evapotranspiration; it, therefore, has little or no effect on the hydrology of the study area.

The average annual inflow of the Carson River, including Truckee Canal imports, is about 390,000 acre-ft (Glancy and Katzer, 1975, p. 66). This inflow component, although only about 60 percent as great as the estimated direct precipitation, is concentrated on less than 15 percent of the total land area and, therefore, has a greater potential for recharge of the valley fill than does direct precipitation. Thus, for practical purposes, streamflows of the Carson River and the Truckee Canal dominate the inflow to the ground-water system in the Fallon area.

From a hydrologic budget standpoint, total inflow currently available for man's use during an average year (exclusive of rapidly dissipated local precipitation) is the summation of ground-water recharge (1,300 acre-ft), Humboldt River inflow (2,600 acre-ft), and Carson River inflow (390,000 acre-ft), or 393,900 acre-ft/yr; rounded to two significant figures, the total is 390,000 acre-ft/yr.

Water Outflow

Outflow from the valley is assumed to be equal to inflow. Because no surface-water outflow and probably little or no ground-water outflow occur, practically all water leaves the Carson Desert in vapor form through the processes of evaporation and transpiration. Thus, total outflow exclusive of quickly dissipated local precipitation averages an estimated 390,000 acre-ft/yr. Most of that quantity is believed to move through the study area.

Within the study area, outflow occurs as evaporation from exposed water surfaces and from bare soil, vegetal transpiration, ground-water and surface-water flow from the study area to downgradient areas of the Carson Desert outside the study area, and pumpage consumed within the study area. Because of the complex state of hydrologic disequilibrium now prevailing in the study area and uncertainties of the magnitudes of flow at the study-area boundaries, no attempt was made in this investigation to quantify each item of either inflow to or outflow from the study area.

Aquifer Systems

This investigation developed knowledge of valley-fill aquifers in the Fallon area but did not address the subject of ground water in underlying basement rocks or adjacent consolidated rocks. Valley-fill aquifers consist mainly of unconsolidated sedimentary deposits that represent a mixture of fluvial, pluvial, and eolian detritus. For purposes of writing simplicity in this report, however, the transmissive zones of these sedimentary deposits are hereafter frequently referred to as "alluvial aquifers."

The Fallon area valley-fill aquifers have been grouped into the following general hydrologic systems: (1) a shallow alluvial aquifer system extending from near land surface to a depth of about 50 ft, (2) an intermediate-depth alluvial aquifer system underlying the shallow system and extending from about 50 ft to depths that may be as great as 500 to 1,000 ft in some areas, (3) a basalt-aquifer system that is as shallow as 200 ft (except at Rattlesnake Hill where it is surficially exposed) and may be as deep as 1,000 ft in places, and (4) a deep alluvial aquifer system underlying the intermediate alluvial and basalt systems, generally below depths of 500 to 1,000 ft.

The alluvial aquifer systems consist mainly of sand and gravel zones in the valley fill. Morrison's (1964) descriptions of the valley-fill deposits, well-drillers' logs, and the inherent nature of the sedimentary processes that deposited the valley fill all suggest that the coarser grained sediments composing the most transmissive zones of the valley fill are interbedded complexly with zones of less transmissive (finer grained) sediments. Thus, the valley fill is interlaced with numerous shoestringlike aquifers, some of which are interconnected. The three alluvial aquifer systems each contain many water-bearing zones with varying hydraulic characteristics that, over a short period of time, appear to behave independently of each other hydrologically; however, over the long term, these units are hydrologically interdependent because of the interconnected nature of their transmissive zones. The major alluvial aquifers technically should be classified as "aquifer systems" because of their short-term hydraulic independence; however, for simplicity in discussion, the three alluvial aquifer systems described above are referred to as shallow, intermediate, and deep alluvial aquifers throughout this report.

The basalt-aquifer system is composed of the basaltic mass of Rattlesnake Hill and related volcanic rocks that are surrounded, for the most part, by valley fill. As in the case of the alluvial aquifer systems, the basalt system is referred to simply as the basalt aquifer. This consolidated rock mass is highly variable in its fluid transmissivity from place to place. Some of its transmissive zones are undoubtedly in partial contact with some of the highly transmissive zones of the valley fill; thus, the basalt aquifer is not hydraulically separated from the alluvial aquifers. However, comparisons of hydraulic and water-chemistry data for the basalt aquifer with those for adjacent alluvial aquifers suggest that the basalt aquifer is somewhat hydraulically independent of the alluvial aquifers over the short term. Major stresses on either the alluvial or the basalt aquifers, or on both types of aquifers, over the long term should be expected, nonetheless, to cause them to hydraulically interact with each other.

HYDROLOGY OF THE BASALT AQUIFER

General History of Discovery

The basalt aquifer is one of the most productive sources of water in the Fallon area, yet it was probably discovered by accident. Before this investigation, little was known about its size, shape, or geographical extent. Apparently, the aquifer was penetrated originally about 1920 by wells drilled near the Carson River in the southern part of T. 20 N., R. 29 E. A local well driller, J. B. Reynolds (oral commun., 1978), worked on several of those drilling jobs and recalled that two wells penetrated consolidated rock, probably basalt, about 300 ft below land surface. Table 1 summarizes data for wells that penetrate basalt near Fallon, and table 2 summarizes data for deep wells that apparently did not intercept hard basalt. Locations of the wells in both tables are shown in figure 2. Reynolds apparently worked on the Les Hiibel and Ronald Albaugh No. 1 wells. The Albaugh No. 1 was known originally as the Sagouspe well, the name of the ranch owners at the time the well was drilled. Reynolds recalled that the driller removed at least some casing from the Hiibel well shortly after drilling because of a dispute with the original owner; in 1977, the well, with 8-in. steel surface casing, was 41 ft deep and was flowing water of a chemical character unlike that of the basalt aquifer. The Albaugh No. 1 well appeared to have retained its original 4-in. steel casing; although it measured only 118 ft deep in 1978, it yielded water chemically like that of the basalt aquifer and also had a hydraulic head compatible with the aquifer, as is discussed later in the section titled "Hydraulic Characteristics" of the basalt aquifer.

The Gummow oil test well drilled in 1921 (table 1, fig. 2) also reportedly penetrated basalt but at about twice the depth of other nearby wells that tap the basalt aquifer. Nothing is known about the present depth of the Gummow well nor the depth or condition of its casing; however, it flows water that is chemically unlike that of the basalt aquifer. The basalt reportedly encountered by the Gummow well probably is not part of the basalt aquifer tapped by the other wells.

The history of basalt-aquifer development by the city of Fallon is most meaningful when viewed from the perspective of historical development of the municipal water supply. The following chronology was compiled from numerous articles published in the Fallon *Standard* and *Eagle* newspapers between 1928 and 1948. Fallon derived its water supply from wells tapping the shallow alluvial aquifer during the 1920's. Locations of Fallon wells, drilling tests, and pumping facilities referred to below are shown in figure 3. The shallow wells were north of town, mainly along the Carson River, and some of the wells were in the riverbed itself at the Carson River pumping plant. Yields of the shallow wells were often undependable, particularly during midsummer when riverflows were minimal and municipal demand was highest. Also, State health authorities frequently complained to the Fallon Water Department regarding the objectionable taste of the water and the high potential for contamination of the shallow aquifers by pathogenic organisms. These factors largely influenced the city council's decision to embark on a deep-well drilling program in 1930.

The first deep-well exploration, by driller Jack Phelps, was just north of the Carson River pumping plant in T. 19 N., R. 29 E., sec. 19 (fig. 3). Phelps contracted to drill a 400-ft test hole and began work during spring 1930. He reportedly drilled into "bedrock" of unknown type and thickness at a depth of about 210 ft. Attempts were made to produce adequate water from a 23-ft zone of sand, gravel, and boulders immediately above the "bedrock"; this zone was overlain by 45 ft of clay. Production tests failed, and the well was abandoned in August 1930 at an unknown depth. R. L. Pennington, a Carson City driller reputed to have a professional background in geological engineering, encouraged Fallon authorities to again explore for a deep ground-water supply. Pennington contracted with Fallon to drill exploration holes for a nominal fee (about $1.00 per foot). Pennington's first drilling venture was in October 1930, a "deep" test hole at the Wingfield Ranch pumphouse away from the river (fig. 3); the drilling encountered rock described as lava 170-180 ft below land surface. The drill reportedly penetrated 8 ft of "lavalike" material, and the hole was abandoned because of the difficulty and expense of drilling through the rock. In November 1930, Pennington tried another "deep" test on the John Oates Ranch just south of the Wingfield Ranch. Water-bearing strata were penetrated at about 200 ft beneath a thick stratum of clay, but the test drilling terminated at 236 ft because of drilling problems again caused by "hard rock." Pennington characterized the rock as buried lavas related to lavas of Toyeh Hill (now

Table 1. Data for wells that penetrate basalt

Location	Well name or owner	Date drilled	Land-surface altitude (feet above sea level)	Total depth (feet)	Depth to top of basalt (feet)	Basalt thickness (feet)	Remarks
N19 E28 22DAAC1	Clyde Gummow	1921	[1]3,975	1,150±	1,050	—	Oil exploration well.
36AABC1	Fallon-Mori	9–21–69	3,962.23	813	520	69	Well completed to depth of 540 ft.
36DAAA1	Fallon-Taylor Addition.	11–05–65	[1]3,960	558	510	—	
N19 E29 8BCDD1	Harold Chisholm	3–23–74	[1]3,945	580	580	—	Test hole.
18DCBB1	Kennametal, Inc.	3–07–74	3,956.59	510	452	—	
29BACB1	U.S. Indian Health Service.	2–29–80	3,973.09	95	30	—	
30CBAD1	Fallon No. 3	12–28–70	3,959.55	484	404	—	
30CCAB1	Fallon-Laverne and B Streets.	10–28–70	[1]3,960	510	462	—	
30CDBC1	Fallon No. 1	7–41	3,959.44	506	448	—	Preceded by a test hole in 1931.
30CDBC2	Fallon No. 2	1948	3,958.63	521	455	—	
31BABC1	I. H. Kent Co.	1960	[1]3,960	444	418	—	
33CBBB1	U.S. Navy No. 2	2–61	3,950.7	530	500	—	
33CBBB2	U.S. Navy No. 3	4–21–62	3,950.7	531	500	—	
33CBBC1	U.S. Navy No. 1	5–22–62	3,950.7	540	496	—	
N20 E29 22CBCA1	Les Hiibel	1920	[1]3,910	41(1977)	300±	—	Basalt reportedly penetrated at about 300 ft during drilling.
34BBAC1	Howard Wolf	8–01–77	3,923.64	343	240	—	
34CBDC1	Ronald Albaugh No. 2.	12–16–78	[1]3,930	205	175	30	
34CCDC1	Ronald Albaugh No. 1.	1920	3,929.72	118(1978)	300±	—	Do.

[1]Altitude estimated from topographic maps (scale, 1:62,500, contour intervals 10, 20 ft). Other altitudes determined by field leveling from established benchmarks.

known as Rattlesnake Hill). This is the first recorded recognition of a subsurface mass of basalt believed to be genetically related to volcanic rock exposures of Rattlesnake Hill (frontispiece). Pennington believed deep exploration success could be achieved if a well could be drilled that would not intercept "Toyeh Hill lavas" and recommended another test near the site of City Hall (not shown in fig. 3).

The city council, however, had lost interest in deep drilling and reinvested in a "shallow well" at the Wingfield Ranch pumphouse site (fig. 3). In June 1931, a citizen filed

Table 2. Data for deep wells that probably do not penetrate the basalt aquifer

Location	Well name or owner	Date drilled	Land-surface altitude (feet above sea level)	Total depth (feet)	Remarks
N18 E29 3CCCB1	U.S. Navy test No. 1	8–09–58	[1]3,940	602	No consolidated basalt mentioned in driller's log.
4BDBA1	U.S. Navy test No. 3	10–20–58	[2]3,946.70	776	Basalt detritus penetrated below 706 ft. Possibly 3-ft-thick basalt flow from 706 to 709 ft.
5AAAA1	U.S. Navy test No. 2	9–26–58	[1]3,950	626	Possibly 19-ft-thick basalt flow from 593 to 612 ft. Detrital basalt from 612 to 626 ft.
23CABC1	U.S. Navy (earliest test).	2–44	[3]3,930	1,755	No consolidated basalt mentioned in driller's log.
N19 E29 11CDCC1	U.S. Indian Health Service.	12–05–79	[3]3,925	545	Test hole; no basalt penetrated.
12	--------do--------	12–02–79	[3]3,910	550	Do.
N19 E30 17BCCC1	--------do--------	11–22–79	[3]3,915	550	Do.
N20 E28 1ABB1	Kennametal Upsal well.	4–30–68	[3]3,960	627	Basalt of Upsal Hogback from 357 to 382 ft; not part of Fallon basalt aquifer.
N20 E29 30CCCC1	U.S. Army Corps of Engineers test well.	10–15–59	[3]3,970	692	No consolidated basalt mentioned in driller's log.

[1]Altitude reported by Kingman (1959).
[2]Altitude determined by field leveling from established benchmark.
[3]Altitude estimated from topographic maps (scale, 1:62,500, contour intervals 10, 20 ft).

a complaint with the Nevada Public Service Commission, alleging bad taste and bacterial contamination of Wingfield Ranch well-field water that was being pumped from the shallow alluvial aquifer. This reignited the city's interest in "deep drilling," and Pennington again promoted such plans.

After extended negotiations regarding possible prospecting sites and an order from the Nevada Public Service Commission to launch a deep-well testing program, two tests were begun almost concurrently during late summer and early autumn 1931. One test explored rumors of potable artesian water in alluvial aquifers at depths between 200 and 300 ft on the Rice Ranch (T. 19 N., R. 28 E., center of sec. 24), which was the site of a 1920's oil test well that reportedly discovered high yields of flowing artesian water.

The second test site was on property owned by I. H. Kent at the southeast corner of the intersection of Maine and B Streets in Fallon (SW 1/4 sec. 30, T. 19 N., R. 29 E). This site was in the general locality that Pennington recommended as one of several promising exploration sites. Kent offered the city rent-free exploration rights and an option to purchase the land for $550 within 6 months of completion of test drilling. The site is the location of the present (1981) Fallon No. 1 production well. Pennington hoped this site was far enough southwest of Rattlesnake Hill to be beyond the subsurface extension of Rattlesnake Hill lavas.

During a city council meeting in late July 1931, C. A. Wilber stated that he had "traced" the water strata supplying the Sagouspe well (Albaugh No. 1) almost to Lovelock and that he believed a good supply of water could be developed at Toyeh Hill (Rattlesnake Hill) from a depth of about 480 ft. Wilber's comment represents the first known recorded statement alluding to the existence of a basalt-aquifer system. He was apparently incorrect in extending the system to Lovelock [about 50 miles (mi) north-northeast of Fallon] but was remarkably prophetic in

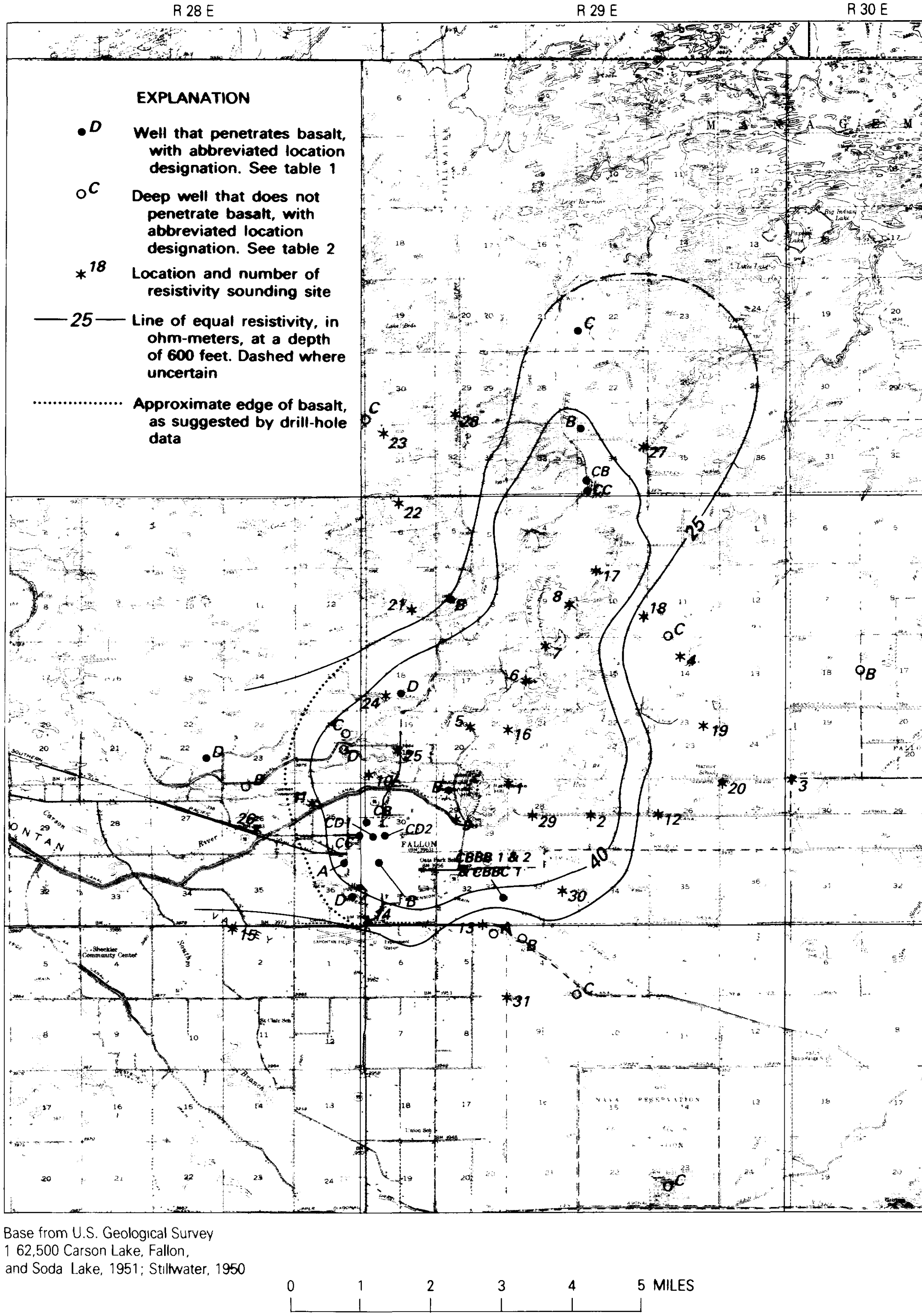

Figure 2. Location of deep wells that do and do not penetrate basalt, and selected electrical-resistivity data that suggest lateral limits of the basalt aquifer.

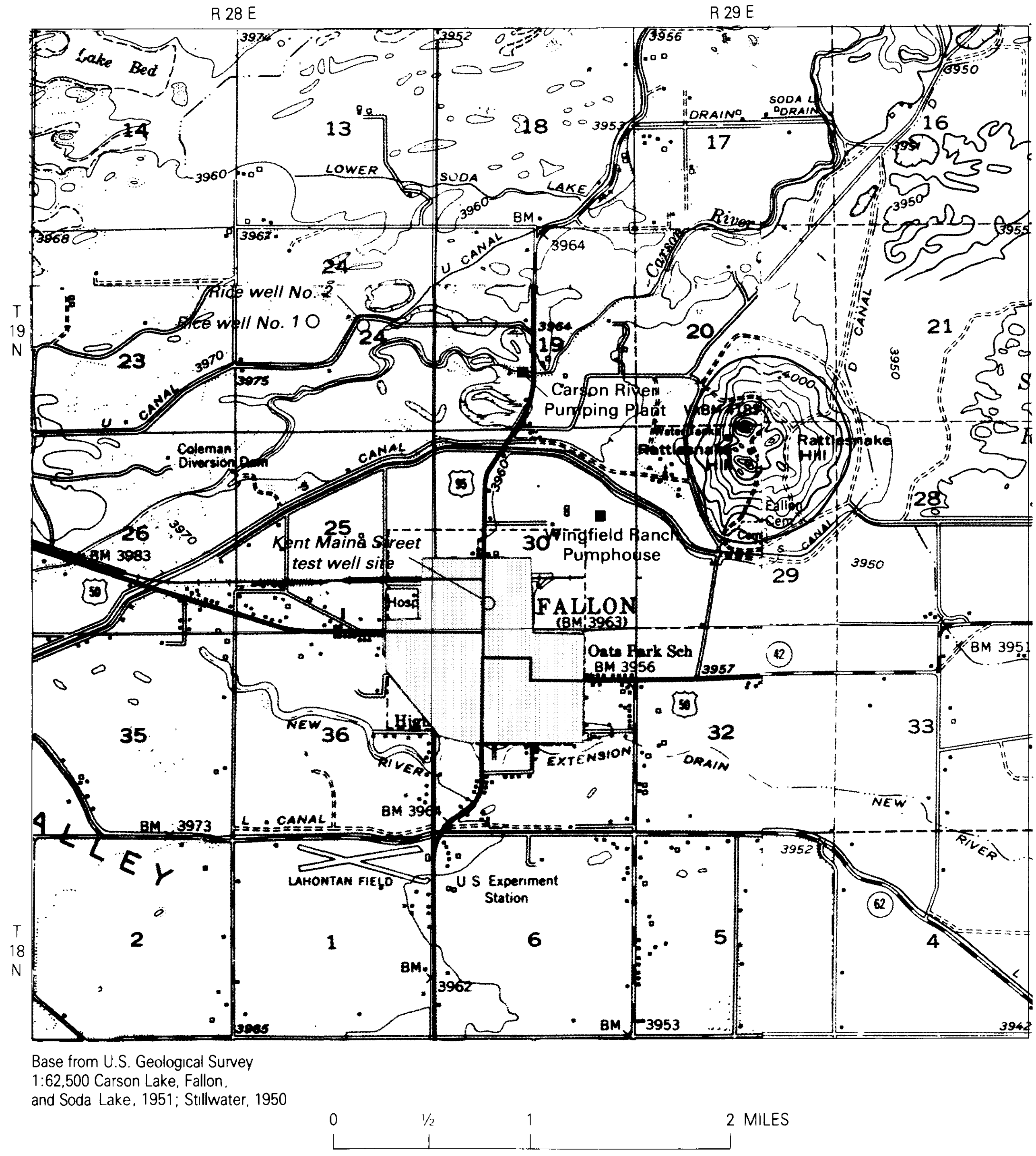

Figure 3. Sites of historical significance with regard to Fallon municipal water supply before 1941.

his assessment of required drilling depth in the general vicinity of Fallon. He was also hydrologically ahead of his time in correlating water production from the Sagouspe well to the basalt aquifer.

The Kent-Maine Street test well was drilled by the firm of Underwood and Adams to a depth of 513 ft, after reportedly encountering hard rock (lava) at 464 ft. In spite of the encounter with lava, Pennington apparently changed his philosophy and predicted "good water" beneath the rock. As it turned out, "good water" was encountered in the lava itself; several chemical analyses suggested a dissolved-solids concentration of between 500 and 600 milligrams per liter (mg/L).

Meanwhile, the Rice Ranch test produced an unquantified yield of potable water (dissolved-solids concentration of about 250 mg/L) from alluvial strata at a depth between 250 and 300 ft below land surface.

Pennington examined the data from both test wells; he estimated production costs and concluded that yields of the Rice well were less than hoped for and that the plant construction costs, because of pipeline length, slightly exceeded those for the Kent property site. However, the dissolved-solids concentration of Rice well water was notably less than that from the Kent site, and, on that basis, he favored production from the Rice well rather than from the Kent well. He also recommended drilling additional wells on the Rice property along the pipeline to supplement any deficient yields. The city council accepted Pennington's advice and also exercised the purchase option on the Kent property to preserve that site for future production if the Rice well field proved deficient. Rice No. 1 well was put into production in late 1931 or early 1932, and water was piped about 2 miles (mi) to a reservoir on Rattlesnake Hill. A second well (Rice No. 2) was drilled on the Rice Ranch in 1934 by J. B. Reynolds, and the yield of that well supplemented Rice No. 1 to adequately supply Fallon's needs for about a decade.

The quality and serviceability of the Rice well field declined with time. Rice No. 2 yielded water that occasionally tasted and smelled bad (particularly during summer months) because of escaping hydrogen sulfide gas. Both Rice wells pumped sand at times, which caused problems in the distribution system. The pipeline deteriorated with time and caused serious maintenance problems. Also, increasing demand for water surpassed the combined yield of the two wells. The cumulative effect of these problems diverted city officials' interest back to the successful test well at the former Kent property at Maine and B Streets.

The city publicized plans to increase the water supply in early September 1940. Production-well drilling began near the southeast corner of Maine and B Streets in February 1941. The Shuey Drilling Company hoped to obtain an adequate supply from alluvium above the basalt, but, if unsuccessful, the company was prepared to drill into the lava. The well was completed in the basalt in July 1941 (Fallon No. 1, table 1), and hydraulic testing showed that the well's yield of more than 1,000 gallons per minute (gal/min) exceeded expectations; in fact, it exceeded the combined yield of the two Rice wells. Fallon's needs at the time were met adequately by this single well. Production pumping began in late July or early August 1941. Rice No. 2 was abandoned hastily because of the sulfurous odor and taste of its water, and Rice No. 1 was maintained only as an emergency standby for Fallon No. 1.

Municipal water demand increased during the 1940's, as did the population (fig. 9), and, by the latter part of the decade, the deteriorating yield of Rice No. 1 (to about 250 gal/min) was deemed inadequate as an emergency backup supply. Also, the pipeline from Rice No. 1 to the reservoir on Rattlesnake Hill had deteriorated further. The city announced plans in February 1948 to drill another production well into the basalt near Fallon No. 1. The new well, Fallon No. 2, was in production by late October or early November 1948. Rice No. 1 was subsequently abandoned, along with its pipeline, and, from that time until the present, Fallon has derived its municipal water supply exclusively from the basalt aquifer.

The U.S. Navy established the U.S. Fallon Naval Auxiliary Air Station (fig. 2) in 1944 and drilled a test well 1,755 ft deep in the SW 1/4 sec. 23, T. 18 N., R. 29 E. (table 2, fig. 2) at that time. The well which did not penetrate consolidated rock, yielded saline water unfit for human consumption (dissolved solids, about 1,900 mg/L). For many years thereafter, the Air Station utilized irrigation water purchased from the Truckee-Carson Irrigation District. A variety of supply problems and increasing demand prompted the Navy to contract, in 1958, with Dean S. Kingman, a consulting engineer, for a study that would address immediate- and long-term water-supply problems. The study (Kingman, 1959) included a test-well drilling program designed to find the nearest location of the basalt aquifer. Three test holes were drilled in secs. 3, 4, and 5, T. 18 N., R. 29 E. (table 2, fig. 2) to depths of 602, 776, and 626 ft, respectively. Although the holes in secs. 4 and 5 reportedly penetrated "a very hard stratum consisting chiefly of basalt" (Kingman, 1959, p. 20), the driller's logs do not document convincingly a penetration of the basalt aquifer (table 2). The test well in sec. 4 (N18 E29 4BDBA1) was pumped for hydraulic and chemical-quality testing as part of Kingman's study. A drawdown of about 70 ft while pumping about 400 gal/min (Kingman, 1959, p. 18) is not characteristic of wells tapping the prolific zones of the basalt aquifer. A chemical analysis of water pumped during the test showed a dissolved-solids concentration of 950 mg/L (almost twice that of the Fallon wells). However, measured water-surface altitudes of about 3,922 ft in the sec. 4 well during late 1979 and early 1980 were compatible with concurrent water-surface altitudes of the basalt aquifer. Later data (1980–81) show that water levels in the well rose and declined out of phase with those of the basalt aquifer. This suggests the Kingman test well was not tapping the basalt aquifer.

The Kingman report recommended that the Navy drill production wells slightly closer to Rattlesnake Hill than Kingman's test wells in secs. 4 and 5. The Navy followed the recommendations in 1961 and 1962, resulting in development of the well field that presently (1981) produces the Navy's entire water supply from the basalt aquifer (table 1).

During 1974, test drilling at Kennametal, Inc., and Harold Chisholm wells confirmed the presence of the basalt aquifer several miles north-northeast of Fallon (table 1). Drilling at Wolf well in 1977 and Albaugh No. 2 well in 1978 confirmed the presence of the basalt several miles farther north-northeast; indeed, the Wolf and Albaugh No. 2 wells confirmed J. B. Reynolds' recollections of the 1920's discoveries in the same general area.

The chronology of basalt-aquifer discovery and development outlined above documents a growing awareness, by Fallon area residents and others, of the basalt aquifer as a major source of water supply. However, the drilling history also depicts a series of sporadic exploration ventures that ranged from random drilling to systematic exploration for the basalt aquifer. The exploration was not coordinated by any centralized authority, and, as a result, knowledge of the aquifer generated through exploration was fragmentary and often loosely recorded.

Location and Extent

The more-or-less haphazard development of the basalt aquifer yielded some knowledge about its location and extent. Unfortunately, at the onset of this investigation, drilling had not yet been geographically extensive enough to accurately outline the lateral extent of the aquifer. Also, most of the wells that penetrated the basalt were drilled only deep enough to achieve an acceptable yield of water; thus, little was learned about the thickness of the basalt. By the mid-1970's, therefore, available information did not allow reasonable estimation of (1) the area where wells might be expected to penetrate basalt, (2) the storage capacity of the reservoir system, (3) the movement of water into and through the aquifer, and (4) the response of the aquifer to pumpage.

An understanding of the general three-dimensional shape and areal extent of the basalt aquifer was critical to evaluating its volume of water and its source of supply. As a result, development of such knowledge was assigned a high priority among the several study objectives.

The first prospecting attempt involved a land surface magnetic survey. This geophysical technique, however, proved unsuccessful because of an apparent lack of detectable differences in magnetic character between valley-fill sediments and basalt. Surface electrical-resistivity soundings using the Schlumberger array were selected as an alternative investigative tool because they offered reasonable promise at moderate cost to delineate relatively high-resistivity basalt containing high-resistivity freshwater from conductive clays and silts, particularly those containing conductive saline water. The soundings proved largely successful in delineating the vertical and areal extent of the basalt. Two wells drilled into the basalt after the resistivity study was completed supported the interpretive results by confirming the presence of the basalt aquifer several miles northeast of previously confirmed locations. Three deep wells, which were later drilled near, but outside, the interpreted basalt boundaries, failed to penetrate basalt.

The electrical-resistivity survey made in May 1976 comprised 31 soundings (Zohdy and others, 1977). The sounding sites, numbered in chronological order, are shown in figure 2. The resistivity data were analyzed by computer to develop interpreted resistivity-depth curves using the technique presented by Zohdy (1973). Specific resistivity data were then picked from the interpreted curves for specific depths and were used to produce machine-generated lines of equal resistivity for those depths.

Figure 2 shows the 25- and 40-ohm-meter resistivity lines at a depth of 600 ft below land surface. These two lines are considered significant with regard to the presence or absence of basalt. The basalt has an excellent chance of being present in areas with resistivities equal to or greater than 40 ohm meters; the chances are increased even further if the basalt contains fresh, rather than saline, water. Chances of basalt in areas where the resistivity is between 25 and 40 ohm meters are also favorable, particularly if basalt and freshwater coexist. If the basalt contains saline water, the resistivity could be at or near 25 ohm meters. Similarly, very fresh water in sand or gravel might be characterized by resistivities on the order of 25 ohm meters. Thus, the 40- and 25-ohm-meter lines have been used as general indicators of the location of the basalt aquifer and related freshwater zones.

The data in figure 2 are compatible with the physical information listed in tables 1 and 2. The interpretation probably does not delineate solely the basalt extremities; it more likely delineates basalt and associated freshwater. Figure 4 shows a series of four interpreted planimetric (horizontal plane) sections, similar to that of figure 2, depicting locations of the 40- and 25-ohm-meter resistivity lines at specific depths below land surface. Similarly, figure 5 shows selected vertical cross sections within the same geographic area as figure 4. The combination of both figures provides an interpreted three-dimensional conception of the system. The vertical sections suggest that the upper part of the basalt is commonly overlain by or in contact with freshwater.

The geophysical and hydrologic interpretation presented here implies that the basalt aquifer is related directly to a volcanic eruption or series of eruptions that also created Rattlesnake Hill, a semiconical physiographic feature that protrudes about 200 ft above the valley-fill plain just northeast of Fallon (frontispiece). If this interpretation is correct, the hill provides land-surface exposures of the material that, at least in part, composes the aquifer. The hill consists principally of extrusive basaltic igneous rock that ranges from rather dense, blocky, and moderately fractured lava flows to porous and moderately consolidated, interbedded, lower density deposits of cinders (Morrison, 1964, p. 23). The hydraulic characteristics of this type of consolidated rock mass are discussed in the next section of this report.

The three-dimensional shape of the basalt system, as suggested by the resistivity data, is that of an asymmetrical, northeast-trending, mushroom-shaped mass that is almost

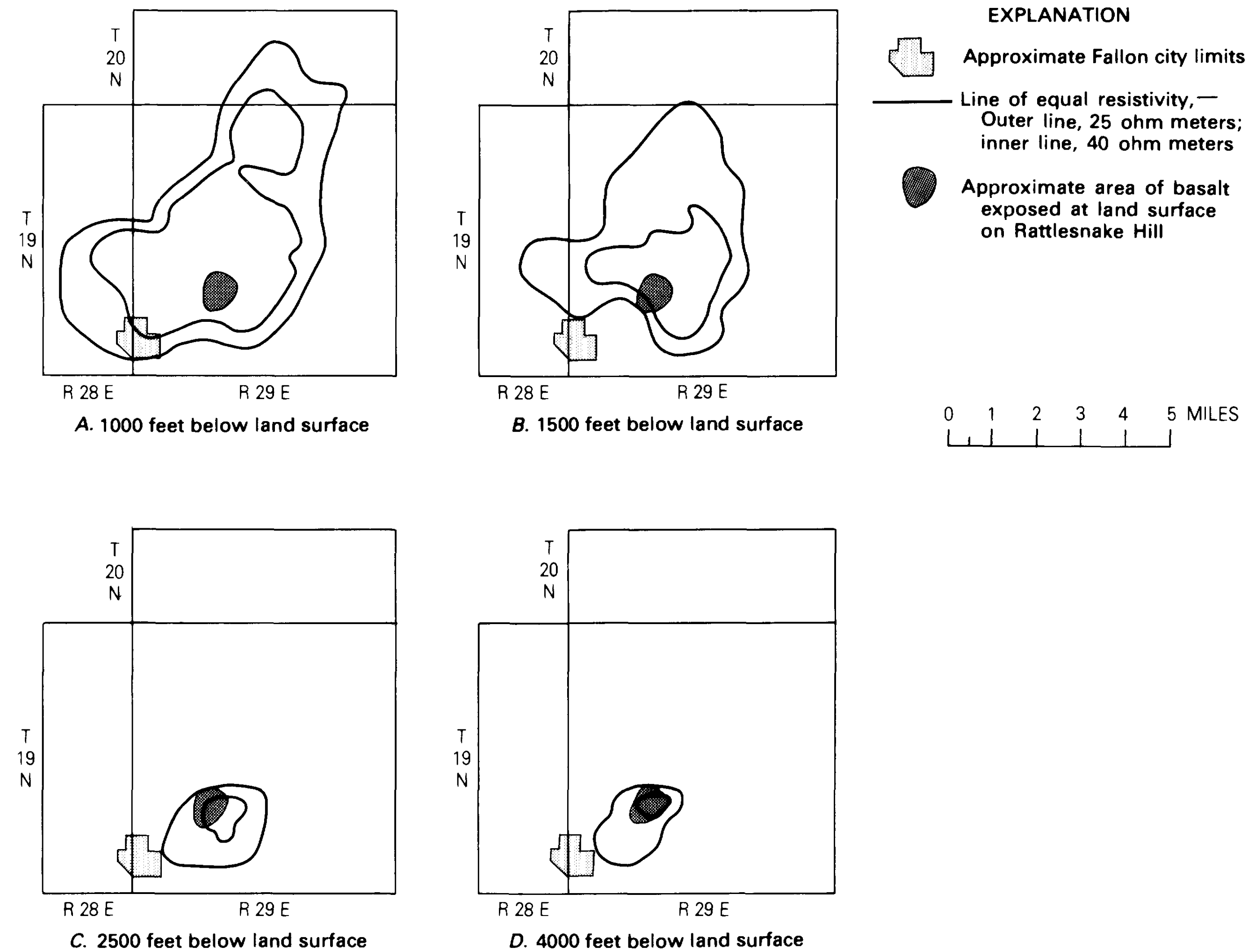

Figure 4. Electrical resistivity at 1,000, 1,500, 2,500, and 4,000 feet below land surface, as interpreted from resistivity soundings.

completely enclosed by unconsolidated sediments. The mushroom-shaped canopy of the basalt appears to constrict at depth to form a relatively thin stock that also is elongated slightly in a general northeast direction.

Although drill-hole data (table 1) show that the top of the basalt generally lies 400–600 ft below land surface in a semicircular arc south, west, and northwest of Rattlesnake Hill, they also show the top of the basalt to be several hundred feet shallower about 4.5 mi to the northeast. The apparent presence of high-resistivity freshwater within moderately high-resistivity sand and gravel aquifers in the upper several hundred feet of sediment overlying the basalt results in only a slight electrical contrast between the basalt and overlying detritus. Thus, interpretations of the depths to the top of the basalt were uncertain for many of the soundings. As a result, estimates of the location of the upper basalt surface in figure 5 were based mainly on drill-hole data. The upper basalt surface might be better distinguished from the overlying sediments by using gravity measurements or seismic techniques; however, employment of these techniques was beyond the limits of this investigation.

The shallower occurrence of basalt northeast of Rattlesnake Hill may be the result of one or more of the following possibilities: (1) additional buried basalt fed by as yet undiscovered stocks in that area, (2) faulting northeast of Rattlesnake Hill, or (3) a buried ridge of basalt trending northeastward from Rattlesnake Hill. Interpretations of the resistivity data did not suggest additional feeder stocks necessary for the emplacement of additional lava flows. If a northeastward-trending basalt ridge exists, it could not be distinguished from the highly resistive shallow freshwater in coarse-grained sediments by using the resistivity data. Again, gravity or seismic studies might provide the answers, as would test drilling.

The high-resistivity, near-vertical basaltic stock underlying the mushroom-shaped canopy of Rattlesnake Hill may be too dense and unfractured to contain water. Freshwater, which is a characteristic component of the basalt-aquifer system, may not occur below a depth of 1,000 ft in most places and probably does not occur below 2,000 ft in the study area.

The lateral extent of the basalt is most uncertain at the northeast and southwest extremities of the system. The resistivity sounding pattern did not extend far enough to the northeast to allow confident closure of the 25-ohm-meter contour at a depth of 600 ft (fig. 2). Similarly, the profusion of freshwater in sand and gravel zones to depths of several hundred feet in the areas west of Rattlesnake Hill and along the Carson River makes delineation of the westward edge of the basalt difficult with resistivity data. However, the Fallon-Mori well (table 1) completely penetrated a rather thin (about 70-ft) section of basalt; this evidence suggests that the edge of the basalt-rock unit may not extend much farther west.

The combination of resistivity-data interpretations and drill-hole data have improved substantially the knowledge of the location and extent of the basalt aquifer. However, additional refinements would be possible through the use of other geophysical techniques and additional drilling.

Hydraulic Characteristics

All available hydraulic data indicate that the basalt aquifer is highly transmissive. The physical character of the buried basalt can be inferred from the material exposed on Rattlesnake Hill and from characteristics of similar basaltic rocks that form highly transmissive aquifer systems in other areas. The basalt of the Fallon area appears to be a texturally heterogeneous mass that laterally and vertically ranges from congealed dense and impermeable lava flows to highly porous zones of loosely consolidated scoriaceous cinders. Permeable zones consisting of masses of basalt rubble probably exist on some lava-flow surfaces that are, in turn, overlain by subsequent flows or sediments. The dense lava flows, which have low primary permeability, probably are fractured, resulting in a secondary permeability that may be high. The fracture systems probably interconnect with the highly permeable rubble and cinder zones. Thus, the rock mass, with its widely ranging primary permeability interlaced with secondary fracture permeability, tends to be highly transmissive. As a result, hydraulic stresses imposed on the confined basalt aquifer are transmitted quickly beyond the point of application and are neutralized just as quickly by the rapid hydraulic reaction of the overall system.

Several aquifer tests were made of basalt production wells during the course of this investigation, and the results, which generally agree with other scanty existing aquifer test data, are summarized in table 3. The test results, including details not listed in table 3, show that under heavy pumping stress (hundreds of gallons per minute), the basalt aquifer generally reacts as follows: (1) a small drawdown (generally less than 3 ft for pumping rates of about 1,000 gal/min) occurs in the pumped well within a few minutes after the onset of pumping, (2) only a minimal drawdown (a few hundredths of a foot) occurs thereafter, and (3) measurable drawdown apparently ceases within 1–2 hours after the start of pumping. Following cessation of pumping, water levels recover about as abruptly as they declined during pumping. Pumping of basalt-aquifer wells for as long as 24 hours at rates of about 1,000 gal/min appear to have little or no measurable effect on nearby basalt-aquifer observation wells. Thus, the aquifer test data substantiate the earlier characterization of high transmissivity. The absence of measurable water-level drawdowns in nearby observation wells during the test pumping and the nearly instantaneous drawdown in the pumping well prevented the assessment of a storage coefficient for the basalt aquifer. However, hydraulic data from the Columbia River Plateau area in eastern Washington suggest storage coefficients ranging from 0.00007 to 0.002 for confined basalt aquifers in that area (U.S. Geological Survey, 1975, p. 62). Therefore, a storage coefficient for the Fallon basalt aquifer is probably not greater than 0.001.

The pumping-drawdown characteristics summarized above suggest that the basalt aquifer is connected hydraulically to a quick-acting source of replenishment that functions efficiently when the system is pumped. The Theis nonequilibrium formula (Ferris and others, 1962, p. 92–98) was employed, using varying combinations of aquifer test data from table 3 and an assumed range of aquifer-storage coefficients shown above, to investigate whether downward leakage of water from the Carson River or the S Irrigation Canal (fig. 3) should be considered as a direct source of replenishment to the basalt system. The Carson River and S Canal are about 1 and 0.5 mi, respectively, north of the pumped aquifer test wells (Fallon Nos. 1 and 3 wells). The Theis results did not rule out the river and canal as vertically leaking sources of recharge to the basalt system. Unfortunately, the available data are not adequate to accurately assess basalt-aquifer transmissivities or storage coefficients and, thus, do not allow the pinpointing of specific recharge sources or areas. The river and canal, as well as surface irrigation flooding, undoubtedly contribute water to underlying sedimentary aquifers that seem to be leaking mainly vertically into the cones of depression created by pumping. Chemical evidence favoring vertical leakage of water from the valley-fill sediments to the basalt are described in the following report section titled "Hydrochemical Characteristics" of the basalt aquifer.

Depth-to-water data were collected periodically during the course of this investigation from most wells penetrating the basalt and were translated into water-level altitudes. Table 4 shows a summary of selected water-level altitudes for the basalt aquifer. The data portray a nearly flat potentiometric surface throughout the basalt aquifer. The featureless character of that surface suggests that water movement through the aquifer may be sluggish. The lack of a well-defined and persistent hydraulic gradient (data of table 4

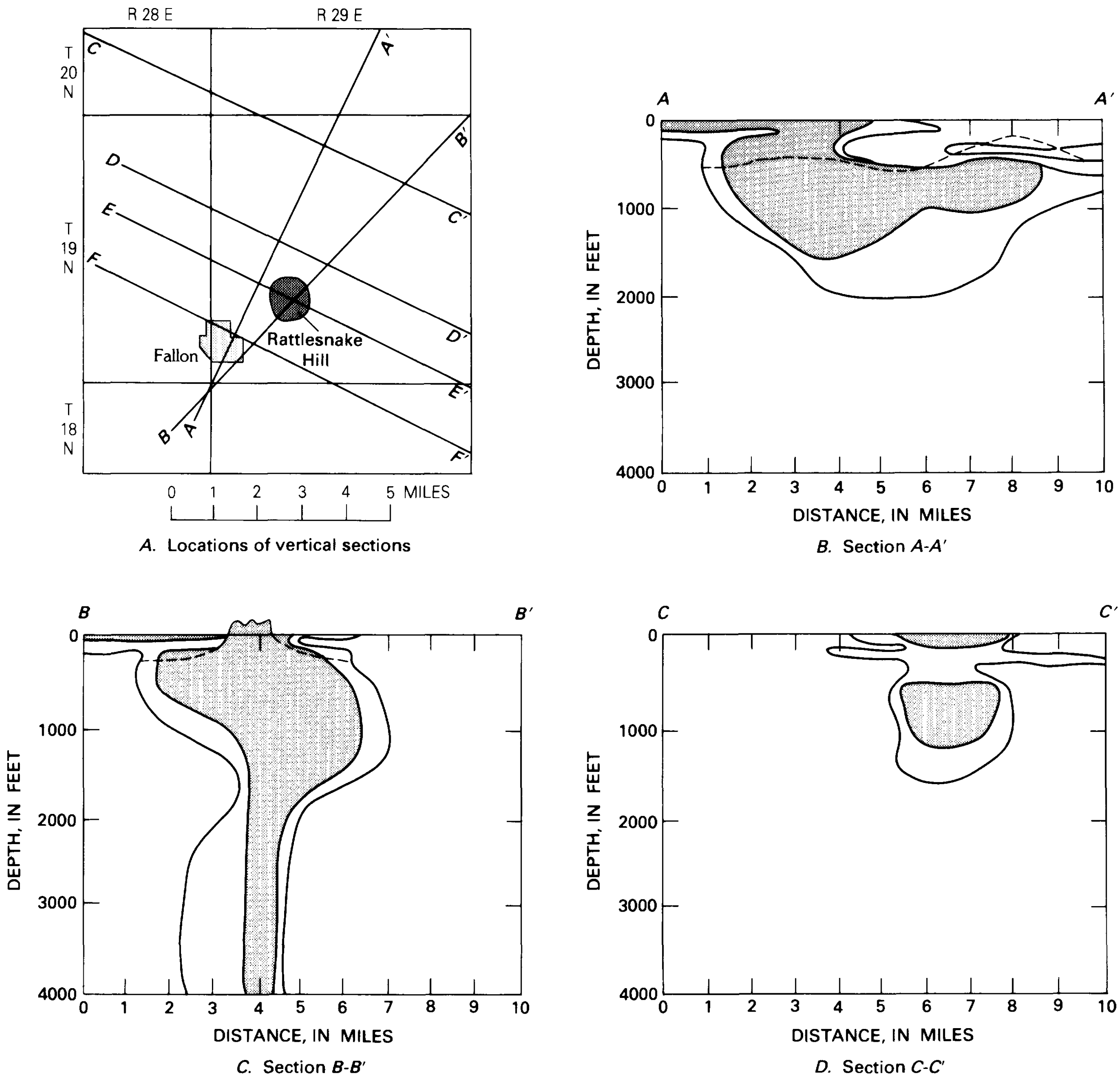

Figure 5. Vertical sections showing interpreted variations in electrical resistivity.

suggest a very slight northeastward gradient) inhibits understanding of the direction and rate of movement of water through the system. Chemical and isotopic evidence regarding movement of water through the aquifer sheds more light, as is discussed later in the report sections titled "Hydrochemical Characteristics" and "Isotopic Evaluation of Recharge and Flow" in the basalt aquifer.

Water-level fluctuations in the basalt aquifer during the course of the investigation are shown in figure 6. The hydrographs show general seasonal trends that document a decline in the aquifer's potentiometric surface during periods of heavy pumping in the summer and a rebound during periods of reduced pumping in the winter. The transmissive character of the basalt and its homogeneous response to seasonal stress is verified further by the similar shapes of the water-level curves of figure 6; particularly convincing evidence is furnished by the curves of the Kennametal, Albaugh No. 1, and Wolf wells, which tend to replicate those of the Fallon No. 1–3 and Navy No. 1–3 wells even though these three wells produce little water and are far removed from the centers of intensive pumping. The direct relation between seasonal water-level fluctuations and intensity of pumping is clearly shown by figure 7. The annual water-level trend of the Fallon-Mori well (fig. 7) suggests an annual net decline of up to about one-third of a foot as the pumpage increased during the study period.

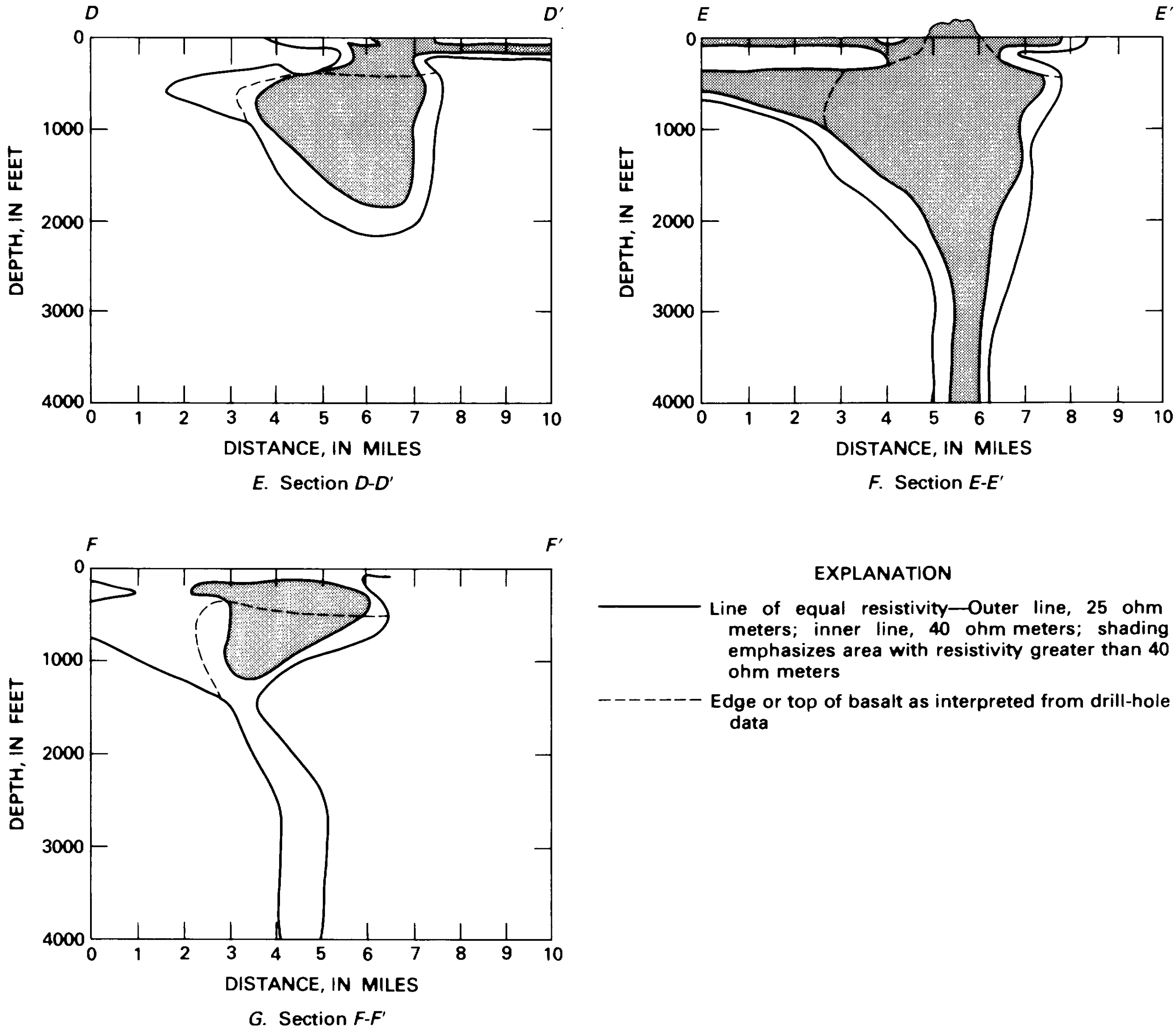

Figure 5. Continued.

Hydrochemical Characteristics

Chemical characteristics of water in the basalt aquifer are distinctively different from those of water in the alluvial aquifers. Waters from seven basalt-aquifer wells were sampled for chemical analyses during this investigation (table 5). The data generally depict the aquifer as the container for a relatively homogenous body of water. The order of analyses in table 5 is based on the geographic locations of the wells from southwest to northeast, which is similar to the flow direction of the regional ground-water system in this part of the Carson Desert.

With the exception of data for the Fallon-Mori well, the analyses show that (1) the dissolved-solids concentrations increase by about one-third from southwest to northeast, (2) the water is uniformly and remarkably soft throughout the system, (3) the net increase in sodium concentration from southwest to northeast also is about one-third, (4) the net increase in alkalinity from southwest to northeast is about one-half, (5) the sulfate concentrations range from 65 to 94 mg/L and average 82 mg/L but do not persistently increase or decrease from southwest to northeast, (6) the chloride concentrations increase by a little more than one-half from southwest to northeast, (7) the fluoride concentrations vary irregularly from southwest to northeast, but none exceed the maximum allowable drinking-water limit of 1.8 mg/L (U.S. Environmental Protection Agency, 1975, p. 59570; based on 68°F for the average of maximum daily air temperatures), (8) the nitrate concentrations, although low, are noticeably higher in water from the heavier producing wells (Fallon Nos. 1 and 3 and Navy No. 3), (9) the

Table 3. Summary of aquifer-test data from the basalt aquifer[1]

Location	Well name or owner	Date(s) of test	Pumping rate (gallons per minute)	Pumping duration (hours)	Total drawdown (feet)	Specific capacity (gallons per minute per foot)	Estimated transmissivity[2] (square feet per day)
N19 E28 36AABC1	Fallon-Mori	10/4–6/78	27.7	49.7	1.8	15	4,100
N19 E29 18DCBB1	Kennametal, Inc.	3/6–7/74	330±	20.8	about 1	330	88,000
30CBAD1	Fallon No. 3	3/7–8/77	990	21.6	[a]1.6	620	170,000
30CDBC1	Fallon No. 1	2/28–3/1/77	1,120	21.0	[b]2.8	400	110,000
33CBBB2	U.S. Navy No. 3	9/9/77	1,150	0.5	[c]3.2	360	96,000
N20 E29 34BBAC1	Howard Wolf	5/1/78	430	4	8.9	48	13,000

[1]All wells cased (unperforated) through sediments, with casings cemented into top of basalt (except Wolf well) to retard leakage into wells from overlying sediments; production through bottom of casing from open holes drilled into basalt.

[2]Rapid drawdown and stabilization of water levels during pumping prohibited determinations of transmissivity by using graphical techniques. Transmissivities (T) were calculated from specific capacity (SC) by using the following approximation: $T \cong 267\ (SC)$. This assumes wells to be fully efficient and fully penetrating.

[a]Fallon Nos. 1 and 2, 1,250 and 1,350 ft from Fallon No. 3, respectively, showed possible maximum drawdowns of 0.04 and 0.08 ft, respectively. Observation wells 12 and 68 ft deep and less than 100 ft from Fallon No. 3 showed no measurable drawdown.

[b]Fallon Nos. 2 and 3, 200 and 1,250 ft from Fallon No. 1, respectively, showed possible maximum drawdowns of 0.07 and 0.05 ft, respectively.

[c]U.S. Navy No. 2, 50 ft from U.S. Navy No. 3, showed possible maximum drawdown of 0.02 ft. U.S. Navy No. 1, 100 ft from U.S. Navy No. 3, showed no measurable drawdown.

Table 4. Selected water-level data for the basalt aquifer

Location	Well name or owner	Date						
		11–29–78	1–19–79	2–20–79	3–23–79	12–29–79	1–30–80	3–03–80
		Water-surface altitude (in feet above 3,900 ft[1])						
N19 E28 36AABC1	Fallon-Mori	[a]21.78	21.78	21.81	21.62	21.26	21.38	21.47
N19 E29 18DCBB1	Kennametal, Inc.	21.79	21.79	21.85	21.75	Pumping	Pumping	21.51
30CBAD1	Fallon No. 3	21.79	21.78	21.87	21.70	21.42	21.56	21.66
33CBBB1	U.S. Navy No. 2	21.61	21.63	21.78	21.43	[b]21.17	21.27	21.37
N20 E29 34BBAC1	Howard Wolf	20.45	21.79	20.62	Pumping	21.04	20.13	20.24
34CCDC1	Ronald Albaugh No. 1	20.59	20.76	20.90	21.75	20.34	20.40	20.53
Range		1.34	1.03	1.25	0.32	1.08	1.43	1.42

[1]Datum is sea level.

[a]Measurement on 12–1–78.

[b]Measurement for U.S. Navy No. 3; U.S. Navy No. 2 pumping.

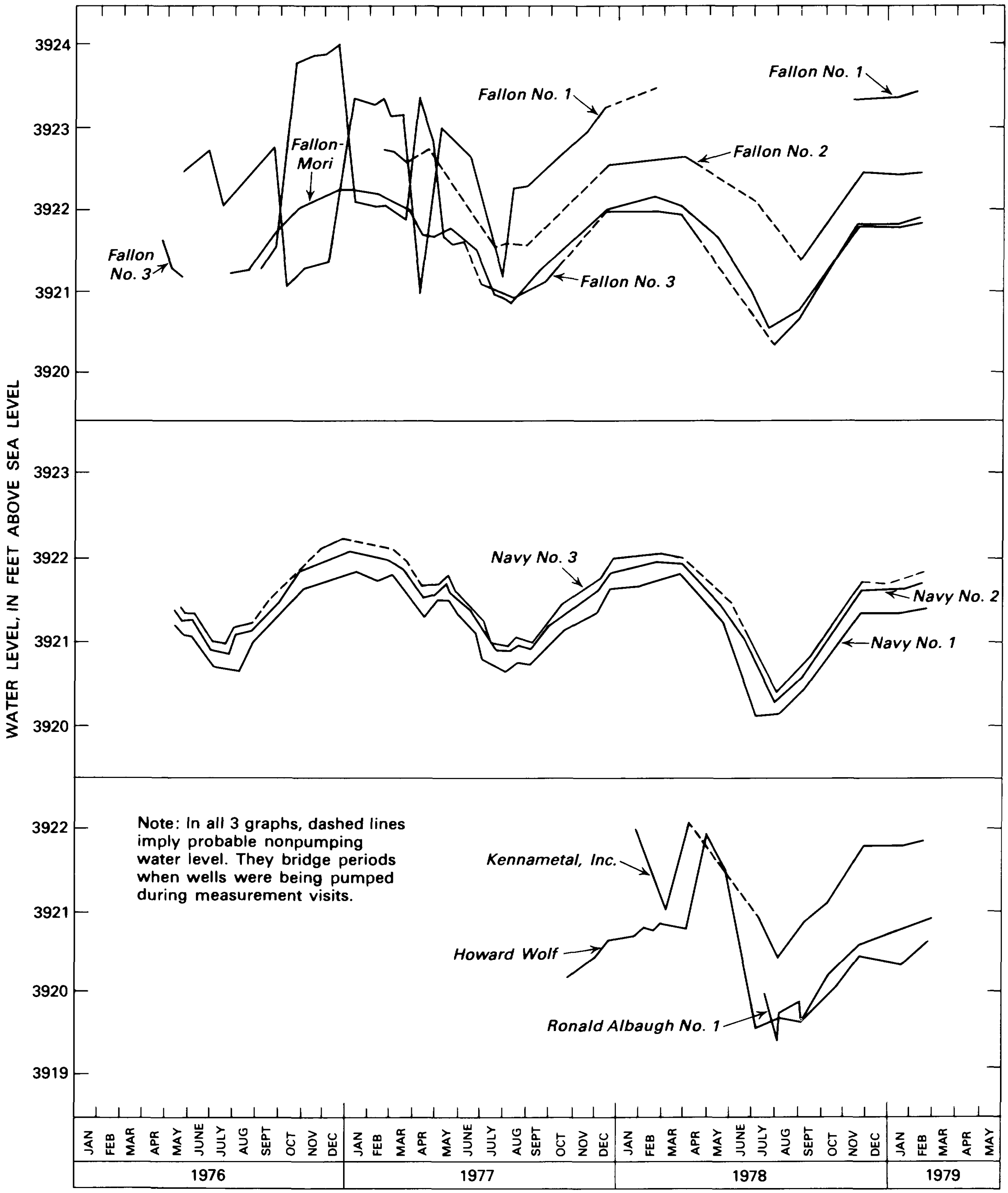

Figure 6. Water-level fluctuations in wells tapping the basalt aquifer, 1976–79. Well data are listed in table 1. Note correspondence between curves for Fallon and Navy wells which are more than 1 1/2 miles apart.

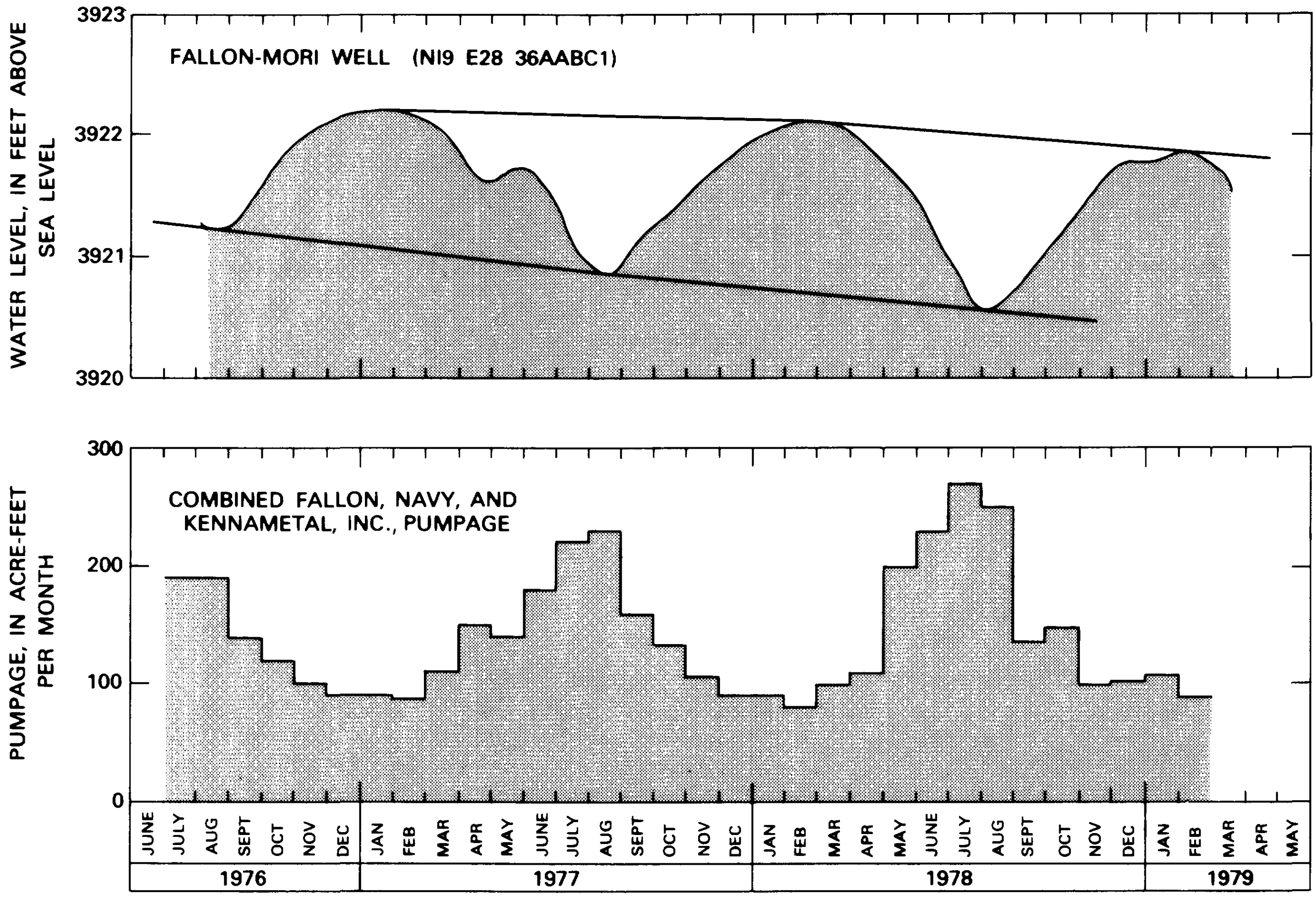

Figure 7. Relation between water levels in a nonproducing basalt-aquifer well and pumpage from the aquifer, 1976–79. Lines connecting tops and bottoms of water-level curve show net water-level decline.

arsenic concentrations exceed the allowable drinking-water limit of 50 μg/L (U.S. Environmental Protection Agency, 1975, p. 59570) in all wells, but no directional trend of change is apparent, (10) the concentrations of potassium and silica are generally uniform throughout the system, (11) the boron concentrations more than double from southwest to northeast, and (12) the concentrations of heavy metals are generally low and do not exceed allowable drinking-water limits (U.S. Environmental Protection Agency, 1975, p. 59570; 1977, p. 17146).

The apparently persistent increase of dissolved solids, sodium, alkalinity, chloride, and boron from southwest to northeast and the lack of other directional trends suggest that water quality deteriorates mainly toward the northeast; this, in turn, suggests a northeastward flow direction for water in the basalt aquifer, similar to that of the regional flow system in the overlying valley-fill sediments. However, available hydraulic head data, as discussed in the preceding report section titled "Hydraulic Characteristics" of the basalt aquifer, weakly suggest a northeasterly flow direction through the basalt system.

The Wolf well was pumped several times for extended periods during this investigation. Concurrent monitoring of specific conductance showed that salinity increased during pumping; however, conductance tended to stabilize after a few hours during each test. The sample of May 1, 1978 (table 5), was collected after conductance stabilized, and the water as sampled was assumed to be reasonably representative of the basalt aquifer at that site. The causes of salinity increases during pumping are not known but may be the result of the well's location near the edge of the basalt aquifer or leakage of shallow water into the well casing because of the absence of a concrete seal between the top of the basalt and overlying sediments.

The Fallon-Mori well reacted similarly, except that specific conductance did not stabilize during pumping. Milton Lakey, Fallon City Engineer's staff (oral commun., 1979), observed the drilling of the Mori well and concluded that the grout seal at the upper basalt-sediment contact probably was defective. Nonetheless, the water was sampled after pumping about 30 gal/min for 48 hours. The sample was less saline than other water from the basalt aquifer; its chemical character is similar to potable water of the intermediate alluvial aquifer in the same geographic area (table 12). The Fallon-Mori and Wolf wells are at opposite geographical extremities of the basalt, but whether this marginal position is a factor in the observed chemical peculiarities described above is unknown. The hydraulic connection of both wells with the basalt aquifer is verified by their hydraulic compatibility with other wells tapping the system (figs. 6, 7); however, as described above, both wells may be receiving water from sediments overlying the basalt because of defective casing seals. Temperatures of water from these wells also generally agree with temperatures expected from the indicated depths of production at the two sites.

The Fallon-Mori and Wolf wells share the following characteristics with Navy test well N18 E29 4BDBA1 drilled by Kingman (table 2; discussed on p. 12): (1) they all apparently were drilled near the edge of the basalt aquifer, (2) water levels in all three wells are very similar to water levels of other basalt wells, and (3) water from all three wells exhibits chemical characteristics different from those of other basalt water. This apparent chemical anomaly may result from the wells' location at or near the outer limits of the basalt aquifer, where nearby mixing of fresh and saline water from one or more of the alluvial aquifers could be influential.

To discern whether chemical character changed during short periods of pumping, water from Fallon Nos. 1 and 3 wells was sampled near the beginning of pumping tests and again about 15 hours later; no distinct changes were apparent (table 5).

Water from Fallon No. 1 well was sampled for chemical analysis in 1948 and 1958 as well as during the current study (table 5). Comparison of the data does not suggest any noteworthy changes in chemical character during the past three decades. This particular well, because of its longevity, high yield, and persistent use, has undoubtedly produced more water from the basalt than any other well. Thus, the data suggest that the overall chemical character of water in this part of the basalt aquifer probably has not changed markedly during nearly four decades of pumping.

Comparisons of chemical characteristics of basalt-aquifer water with those of the overlying intermediate alluvial aquifer, deeper than 50 ft below land surface, show that the basalt-aquifer water is generally about 2.5 times more saline. To what extent the higher salinity of basalt water is caused by dissolution of the basalt itself or by mixing with saline water from other sources is unknown. No chemical data for water directly underlying the basalt are available; however, results of the electrical resistivity study suggest that water in the deep alluvial aquifer underlying the basalt is consistently more saline than that in the basalt. The saline water in the deep alluvial aquifer may have a higher artesian head than that within the basalt and thus may be naturally contributing recharge to the basalt. Indeed, the chemical makeup of basalt water suggests that it represents a blend of overlying freshwater and underlying saline water. Prolonged and increased pumping stresses may change the chemical blend of saline water and freshwater in the basalt.

Estimates of hypothetical blends of freshwater and saline water were made on the basis of firm knowledge regarding the salinity of water from the basalt and from the overlying intermediate alluvial aquifer. In contrast, estimates require liberal assumptions regarding the salinity of water from the deep alluvial aquifer. Equating basalt-aquifer water having an average dissolved-solids concentration of 575 mg/L (average of all wells except the Fallon-Mori well in table 5) and overlying water having a concentration of about 230 mg/L with deep alluvial aquifer water having a possible concentration of 5,000 mg/L (p. 56–57). The following blend would result:

$$230X + 5{,}000\,(1-X) = 575\ ,$$

where $100X$ = percentage of freshwater and $100\text{-}100X$ = percentage of saline water. Solving the equation for X gives a value of 0.93, which indicates a mixture of 93 percent freshwater and 7 percent saline water. Likewise, assuming dissolved-solids concentrations of 1,500 and 10,000 mg/L in the deep alluvial aquifer, the following blend percentages would result: at 1,500 mg/L, 73 percent freshwater and 27 percent saline water and, at 10,000 mg/L, 96 percent freshwater and 4 percent saline water. Thus, for a reasonable range of salinity for the water underlying the basalt, the resultant blend would probably consist of more than three-fourths freshwater.

The above exercise suggests that the recharge for the basalt system comes mainly from the freshwater in the intermediate alluvial aquifer overlying the basalt, which agrees with other hydraulic and isotopic evidence relating to basalt aquifer recharge.

Mechanisms of Recharge and Discharge

The depth of the basalt-aquifer system is a factor affecting recharge to and discharge from the system. Drill-hole data suggest that the top of the basalt generally ranges from 200 to 600 ft below land surface (table 1), except in the immediate vicinity of Rattlesnake Hill where it protrudes as much as about 200 ft above land surface. The basalt does not directly contact surface water and is virtually insulated from surface water by a generally thick overburden of water-saturated sediments. This isolation from surface-water flow inhibits the postulation of a simple recharge-discharge model to explain the mechanisms through which the basalt aquifer is replenished naturally or flushed. The inability to

Table 5. Analyses of water from the basalt aquifer

	Reporting units	Wells, from southwest				
		Fallon-Mori[2]	Fallon No. 1[3]	Fallon No. 1	Fallon No. 1	Fallon No. 1
Date	M–D–Y	10–6–78	7–13–48	5–8–58	2–28–77	3–1–77
Time	24-hours	1530	—	—	2100	1245
Approximate depth to water-bearing zone	feet	505	480	480	480	480
Pumping rate	gallons per minute	28	—	—	1,130	1,130
Time of sample collection after start of pumping	hour	49.2	—	—	1.5	17.2
Specific conductance	micromhos	445	902	—	840	840
Temperature	degrees Celsius	23.0	—	—	20.0	20.0
Hardness as $CaCO_3$	milligrams per liter	33	—	11	6	5
Calcium (Ca)	do	10	—	2.0	1.4	1.4
Magnesium (Mg)	do	1.9	—	1.4	.6	.4
Sodium (Na)	do	80	—	175	180	180
Percent sodium	percent	80	—	93	96	96
Sodium-adsorption ratio (SAR)	units	6.1	—	23	32	35
Potassium (K)	milligrams per liter	9.4	—	8.4	7.4	7.4
Alkalinity as HCO_3	do	160	330	270	269	269
Sulfate (SO_4)	do	53	72	75	[c]84	78
Chloride (Cl)	do	31	82	67	70	70
Fluoride (F)	do	.4	.8	.8	.7	.7
Silica (SiO_2)	do	51	30	31	29	30
Dissolved solids, residue at 180°C	do	304	499	506	503	503
Nitrate as N	do	—	—	—	.38	.38
Nitrite as N	do	—	—	—	.00	.00
Nitrite plus nitrate as N	do	.10	—	—	.38	.38
Arsenic (As)	micrograms per liter	75	—	—	140	[d]140
Barium (Ba)	do	0	—	—	—	0
Boron (B)	do	490	—	40	—	990
Cadmium (Cd)	do	7	—	—	—	1
Chromium (Cr)	do	0	—	—	—	0
Copper (Cu)	do	1	—	—	—	0
Iron (Fe)	do	30	—	0	—	20
Lead (Pb)	do	31	—	—	—	5
Manganese (Mn)	do	20	—	0	—	10
Mercury (Mg)	do	.0	—	—	—	.0
Selenium (Se)	do	1	—	—	—	1
Uranium (U)	do	<.4	—	1.4	—	3.3
Zinc (Zn)	do	—	—	—	—	—

[1]Well locations are listed in table 1.
[2]Evidence suggests the well casing may be leaking alluvial-aquifer water (see text).
[3]Analysis by Nevada Department of Food and Drugs; all other analyses by U.S. Geological Survey.
[a]Well had been pumped extensively within the previous 24 hours.

measure directly the flow into or out of the basalt aquifer, except for pumpage, complicates development of a hydrologic budget and a quantitative understanding of the basalt-aquifer flow system. An understanding of the recharge-discharge mechanisms and the aquifer's flow system, therefore, must be developed from measurements of the aquifer's hydraulic and chemical characteristics and their responses to man-induced stresses.

Several factors suggest that the basalt acts as a rigid matrix, which is hydraulically driven by the following hydrologic characteristics prevailing within the alluvial aquifer's flow systems: (1) the high artesian heads associated to northeast[1]

Fallon No. 3	Fallon No. 3	Navy No. 3	Kennametal, Inc.	Ronald Albaugh No. 1	Howard Wolf
3–7–77	3–8–77	2–22–78	2–28–78	7–19–78	5–1–78
2200	1200	1000	1115	1430	1500
450	450	508	490	>118	260
1,000	1,050	1,000	207	5.9	425
1.5	15.5	[a].2	[a].1	1.2	4.2
853	853	995	1,010	1,070	1,140
20.0	20.0	20.5	21.0	[b]19.5	18.0
6	6	9	6	3	3
1.5	1.3	2.8	1.9	1.0	1.0
.6	.7	.6	.3	.2	.0
180	180	220	210	230	240
96	96	96	97	97	97
31	32	31	37	55	65
7.6	7.5	8.5	7.4	7.7	8.6
274	274	300	300	360	410
81	81	94	91	79	65
77	76	97	100	100	110
.7	.8	.6	.4	1.1	1.4
29	29	26	28	29	25
511	510	574	573	632	658
.43	.43	.28	.06	.05	.01
.00	.01	.02	.01	.01	.00
.43	.44	.30	.07	.06	.01
[e]90	90	80	120	96	73
0	0	9	0	9	0
—	1,000	1,200	1,400	1,600	2,100
—	0	4	0	5	1
—	0	0	10	0	10
—	0	0	1	0	0
—	10	10	10	20	20
—	5	7	9	5	0
—	0	0	0	2	20
—	.0	.0	.0	.0	.0
—	1	1	1	0	0
—	3.6	2.2	2.4	—	.6
—	—	—	—	4	—

[b]Temperature suggests water is probably coming from a depth greater than 118 ft.
[c]Results from sample collected at 2138 hours, same date.
[d]Another sample collected at 2228 hours on same date showed 140 micrograms per liter (μg/L). A sample collected 2–22–78 showed 98 μg/L.
[e]Average of two determinations (80 and 100 μg/L).

with the basalt aquifer suggest that the system is in hydraulic continuity with sources of water near the land surface, (2) the highly transmissive characteristics of the basalt (table 3) imply that the basalt aquifer offers minimum resistance to through-flowing water, and (3) the high artesian head in the downgradient (northeast) end of the basalt suggests that the duration of residence of water in the basalt is largely a function of the resistance to outflow (escape) through the enclosing sediments. The basalt is, therefore, an integral component of the overall valley-fill aquifer system. Because of its unique hydraulic characteristics, however, the basalt aquifer also takes on unique chemical characteristics. Under natural conditions, the basalt (1) receives its water from sediments surrounding it, being governed by the hydraulic restraints of the sediments, (2) chemically mixes the water from the various sediment sources, (3) transmits it efficiently within its own confines, and (4) finally discharges the water mixture back into sediments under the hydraulic controls imposed by those enclosing sediments.

Pumpage

Pumpage from the basalt aquifer may have begun in the early 1920's. However, the Albaugh No. 1 well (Sagouspe well) was apparently the only producer for about 15 years and supplied only small amounts of water for livestock and humans occupying a single ranch. Large-scale

Table 6. Pumpage from the basalt aquifer

Year[1]	Cumulative percentage of time	Pumpage (acre-feet)					Annual total as percentage of 38-year total	Cumulative percentage
		Fallon[2]	Navy[3]	Kennametal, Inc.[4]	Yearly total	Cumulative total		
1941	2.6	[a]100	—	—	100	100	0.3	0.3
1942	5.3	350	—	—	350	450	1.0	1.3
1943	7.9	370	—	—	370	820	1.1	2.4
1944	10.5	390	—	—	390	1,210	1.1	3.5
1945	13.2	410	—	—	410	1,620	1.2	4.7
1946	15.8	440	—	—	440	2,060	1.3	6.0
1947	18.4	460	—	—	460	2,520	1.3	7.3
1948	21.0	480	—	—	480	3,000	1.4	8.7
1949	23.7	510	—	—	510	3,510	1.5	10
1950	26.3	550	—	—	550	4,060	1.6	12
1951	29.0	560	—	—	560	4,620	1.6	13
1952	31.6	560	—	—	560	5,180	1.6	15
1953	34.2	570	—	—	570	5,750	1.6	17
1954	36.8	580	—	—	580	6,330	1.7	18
1955	39.5	580	—	—	580	6,910	1.7	20
1956	42.1	590	—	—	590	7,500	1.7	22
1957	44.7	600	—	—	600	8,100	1.7	23
1958	47.4	600	—	—	600	8,700	1.7	25
1959	50.0	610	—	—	610	9,310	1.8	27
1960	52.6	620	—	—	620	9,920	1.8	29

[1]Pumpage compiled on a water-year basis (October–September) from 1967 to 1978. Prior data are for calendar years.
[2]Metered pumpage records were not available from 1941 to 1966. The following summary for that period was furnished by the Fallon City Engineer's office, author unknown (B. T. Bartlett, written commun., 1978): "The years, 1939–48 show a 40 percent increase in water used. The years, 1948–50 show a 13 percent increase or 179,795,662 gallons with 911 water meters in service. The year, 1960, shows an 11.6 percent increase or 200,000,000 gallons of water used, 1,025 water services." Annual estimates were prorated using the above information. Pump-meter records were available after 1966.

extractions began with Fallon No. 1 well supplying municipal needs in late 1941. Table 6 shows estimated, reported, and metered pumpage from the basalt during the 38-year period since 1941. A graphical cumulation of pumpage is shown in figure 8. About one-half of the pumpage has occurred during the last 11 years; in contrast, only about 27 percent of the pumpage occurred during the first one-half of the period. Historical distribution of pumpage from the basalt through 1978 is approximately as follows: city of Fallon, 78 percent; U.S. Navy, 20 percent; Kennametal, Inc., 2 percent; and others, less than 1 percent.

Figure 9 shows trends in Fallon's annual municipal pumpage from the basalt aquifer and changing population with time. Calculated water-use rates by Fallon residents

Table 6.— Continued

Year[1]	Cumulative percentage of time	Pumpage (acre-feet)					Annual total as percentage of 38-year total	Cumulative percentage
		Fallon[2]	Navy[3]	Kennametal, Inc.[4]	Yearly total	Cumulative total		
1961	55.3	640	—	—	640	10,560	1.8	30
1962	57.9	660	65	—	720	11,280	2.1	33
1963	60.5	680	389	—	1,070	12,360	3.1	36
1964	63.2	700	440	—	1,140	13,500	3.3	39
1965	65.8	730	422	—	1,150	14,640	3.3	42
1966	68.4	760	483	—	1,240	15,880	3.6	46
1967	71.0	784	457	—	1,241	17,130	3.6	50
1968	73.7	853	486	—	1,339	18,460	3.8	53
1969	76.3	911	438	—	1,349	19,810	3.9	57
1970	79.0	874	438	—	1,312	21,130	3.8	61
1971	81.6	1,029	438	—	1,467	22,590	4.2	65
1972	84.2	1,179	495	—	1,674	24,270	4.8	70
1973	86.8	1,295	481	—	1,776	26,040	5.1	75
1974	89.5	1,281	460	85	1,830	27,870	5.3	80
1975	92.1	1,213	440	114	1,770	29,640	5.1	86
1976	94.7	1,224	396	114	1,730	31,370	5.0	91
1977	97.4	1,209	383	114	1,710	33,080	4.9	95
1978	100.0	1,294	323	114	1,730	34,810	5.0	100
Total (rounded)	100	28,000	7,030	540	—	35,000	100	100

[3]Pumpage compiled from U.S. Navy pump-meter records.
[4]Estimated by Willis Swan, Kennametal, Inc. (written commun., 1978).
[a]Basalt system began to furnish water about first week in August 1941 (Fallon *Standard*, July 30, 1941, p. 1). Basalt pumpage for 1941 estimated to be about 100 acre-ft (assuming that full-year total would have been 330 acre-ft).

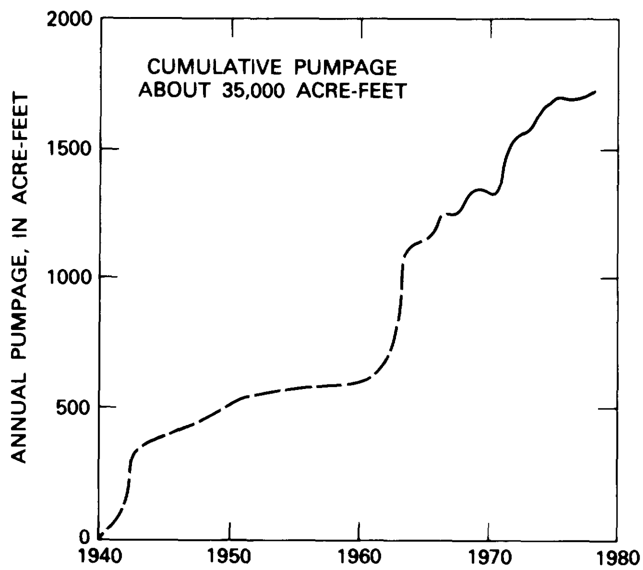

Figure 8. Pumpage from the basalt aquifer, 1941–78. Curve is dashed where annual pumping is estimated (see table 6).

during the historical period of basalt-aquifer production are listed in table 7. The tabular data suggest that average annual per-capita use has almost doubled during the four decades of basalt-aquifer pumpage.

Physical Evidence of Recharge and Discharge

Figure 10 shows interpreted head differences in the late 1970's among the potentiometric surface of the basalt aquifer (buried hundreds of feet below land surface), the potentiometric surfaces of the shallow alluvial aquifer (buried as much as 50 ft below land surface), and the upper part of the intermediate alluvial aquifer (buried mainly 90–120 ft below land surface). These contours show that the maximum potential for recharge to the basalt from the alluvial aquifers is at the southwestern extremity of the basalt (heads in alluvial aquifers are 30–40 ft higher than that in basalt). This recharge potential decays progressively in a northeasterly direction until a state of net pressure equality develops between the basalt and overlying sediments. Continuing northeastward, the hydraulic situation is reversed, with the development of a progressively increasing potential for the basalt to discharge its water into overlying and adjacent sediments (head in northeastern part of basalt aquifer is 10–20 ft higher than that in contiguous alluvial aquifers); maximum discharge potential of the basalt occurs at its northeastern extremity. These head differences were derived by relating the potentiometric-surface contours of the shallow and intermediate alluvial aquifers (figs. 17, 25) to the virtually flat potentiometric surface of the basalt aquifer (altitude during study period about 3,922 ft).

Pumpage of 35,000 acre-ft from the basalt between 1941 and 1978 represents a small, but persistent, long-term stress on the system. The hypothesized map limits of the basalt, as shown in figure 10, enclose an area of about 33 mi^2, or 21,000 acres. The cumulative historical pumpage is equivalent to a blanket of water 1.7 ft deep over the interpreted area of basalt.

The trend of water levels in the basalt during the past few years suggests that current pumping may be causing an annual net decline of the potentiometric surface from 0.1 to 0.3 foot per year (ft/yr) (fig. 7). Assuming that the basalt-aquifer storage coefficient is 0.001 and that the area of water-level decline extends uniformly over the entire 21,000 acres because of the high transmissivity of the basalt, a pumpage of only about 6 acre-ft would be sufficient to induce a 0.3-ft potentiometric surface decline, if the basalt aquifer were a hydraulically closed system (no natural recharge or discharge). In contrast, annual pumpage between 1976 and 1978 ranged from 1,710 to 1,730 acre-ft. If 1,700 acre-ft of annual pumpage causes a water-level decline of the magnitude expected from only 6 acre-ft of pumpage, it follows that most of the 1,700 acre-ft of pumpage is being replaced quickly by inflow from surrounding sediments.

Mathematical Analysis of Recharge and Discharge

Mathematical procedures suggested by T. J. Durbin (U.S. Geological Survey, oral commun., 1978) were devised to describe quantitatively some hydraulic interactions

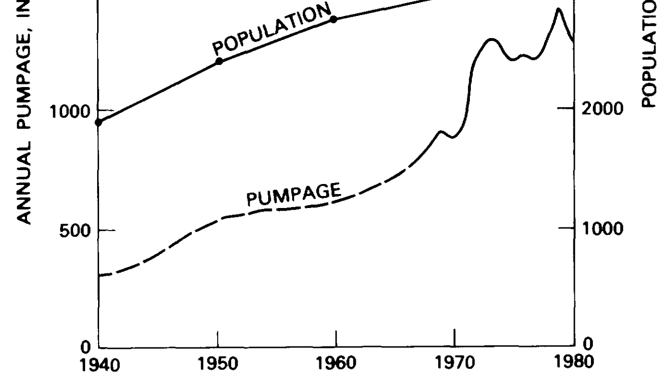

Figure 9. Fallon municipal pumpage and population, 1940–80. Curve is dashed where estimated.

Table 7. Fallon municipal water-use rates

Year	Pumpage		Population[2]	Per-capita use rates (gallons, rounded)	
	Acre-feet[1]	Gallons (rounded)		Annual	Daily average
1940	[a]310	100,000,000	1,911	52,000	140
1950	550	180,000,000	2,400	75,000	200
1960	620	200,000,000	2,734	73,000	200
1970	874	285,000,000	2,959	96,000	260
1980	1,310	427,000,000	4,262	100,000	270

[1]From table 6, except for 1980.
[2]From U.S. Bureau of Census.
[a]Pumpage during 1940 was from intermediate alluvial aquifer. All pumpage after 1941 was from basalt aquifer.

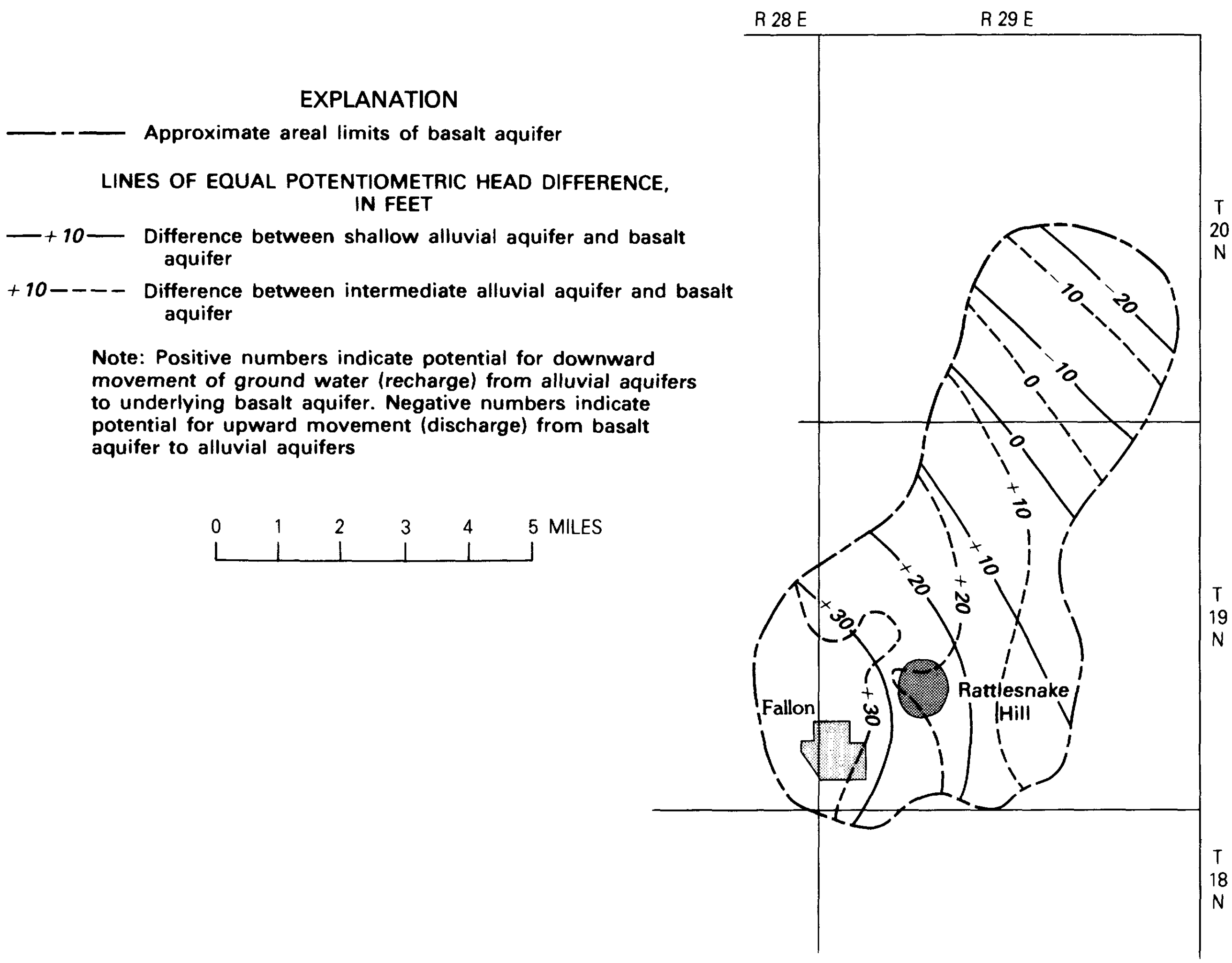

Figure 10. Recharge and discharge potential for the basalt aquifer during the late 1970's.

between the basalt aquifer and the overlying alluvial aquifers [the deep alluvial aquifer was not included in this analysis; earlier discussion ("Hydrochemical Characteristics" section) of probable chemical blends of recharge suggests most recharge is from the intermediate aquifer.] The procedures are used to quantify the hydraulic relations of the basalt aquifer with acceptable accuracy to provide a practical "first approximation" of a water budget for the basalt aquifer. The method utilizes carefully measured field data to calibrate the mathematical concept. The procedure is a steady-state solution that quantifies water inflow and outflow rates for the basalt as they relate to pumpage from the system. The assumption of "steady state," however, inherently excludes time as a parameter. Therefore, the steady-state concept is slightly modified, wherein the scheme assumes that a series of relatively rapid steps of water-level decline occur in response to incremental changes in pumpage; this results in a sequence of steady-state stages. Thus, the procedure acknowledges incremental changes in storage within the basalt related to pumpage changes.

The mathematical procedure arbitrarily divides the sediment blanket above the basalt into nine vertically sliced elements, each having a fixed map area and thickness; thus, a composite map of the sediment-element areas is congruent with the interpreted map area of buried basalt. Figure 11 shows the array of elements and relates physical and hydraulic characteristics of the elements to parameter terms used in the computations. Most of the computational parameters are constants, and only the head (pressure) and pumpage parameters vary during the calculation procedure.

As part of, and in addition to, the concept of steady state, the procedure incorporates several other assumptions: (1) flow paths of recharge to and discharge from the basalt through the overlying sediment blanket are practically vertical, (2) although flow into or out of the basalt depends specifically on head differences between the basalt and adjacent sediments, the head difference between the basalt aquifer and the shallow alluvial aquifer is the only pressure difference sufficiently defined by field measurements at this time to allow these calculations, (3) water levels in the shallow alluvial aquifer remain constant throughout time and are equal to the levels shown in figure 17, and (4) resistance to the flow of water through the basalt is negligible and, therefore, is quantitatively ignored.

These assumptions are supported by the following rationale. Results of basalt-aquifer hydraulic testing and the Theis formula exercise, discussed in the report section titled "Hydraulic Characteristics" of the basalt, suggest strong vertical leakage of water into the basalt from overlying alluvium. Higher nitrate concentrations in basalt water beneath centers of heavy pumping (p. 17) also suggest downward leakage. Recharge of modern (post-1953) ground water into the basalt near centers of heavy pumping also is suggested by tritium analyses of basalt-aquifer water (table 8). Seasonal water-level fluctuations in the shallow alluvial aquifer are documented in a later report section titled "Hydraulic Characteristics" of the shallow alluvial aquifer, but the fluctuations are slight compared to the magnitude of head differences between the shallow aquifer and the basalt aquifer. Long-term stability of shallow-aquifer water levels in sediments overlying the basalt seems reasonably well assured because the river traverses those sediments and is probably a dependable source of replenishment. Replenishment potential of the river also is supplemented by surface-water irrigation; however, that source of replenishment may not persist undiminished in the future because of changing land uses or legal water rights. Finally, although the basalt aquifer undoubtedly offers some resistance to through-flowing water, water-level and aquifer test data suggest that the aquifer is much more transmissive than the valley fill; therefore, the resistance probably can be quantitatively ignored for preliminary computation purposes.

Although none of the several above listed assumptions are completely true, they are, for practical purposes, reasonable enough in at least a semiquantitative sense to allow a first approximation of the basalt aquifer's water budget.

A mathematical statement of flow through the basalt aquifer is as follows:

$$P = Q_{net} = K \frac{\Delta h}{\Delta l} A \quad \text{or}$$

$$P = Q_{net} = K \sum_{i=1}^{n} \left(\frac{A_i \, \Delta h_i}{\Delta l_i} \right) ,$$

where

Q_{net} = difference between recharge to and natural discharge from the basalt,

K = average hydraulic conductivity of sediments overlying the basalt,

$\sum_{i=1}^{n}$ = algebraic summation of calculated values for all elements,

A_i = map area of an individual element of sediments overlying the basalt,

h_i = average head difference between the basalt aquifer and the shallow alluvial aquifer for a given element,

l_i = average thickness of saturated sediments overlying basalt for a given element (assumed equal to thickness of sediments between land surface and top of basalt), and

P = pumpage from the basalt aquifer during a specified time period.

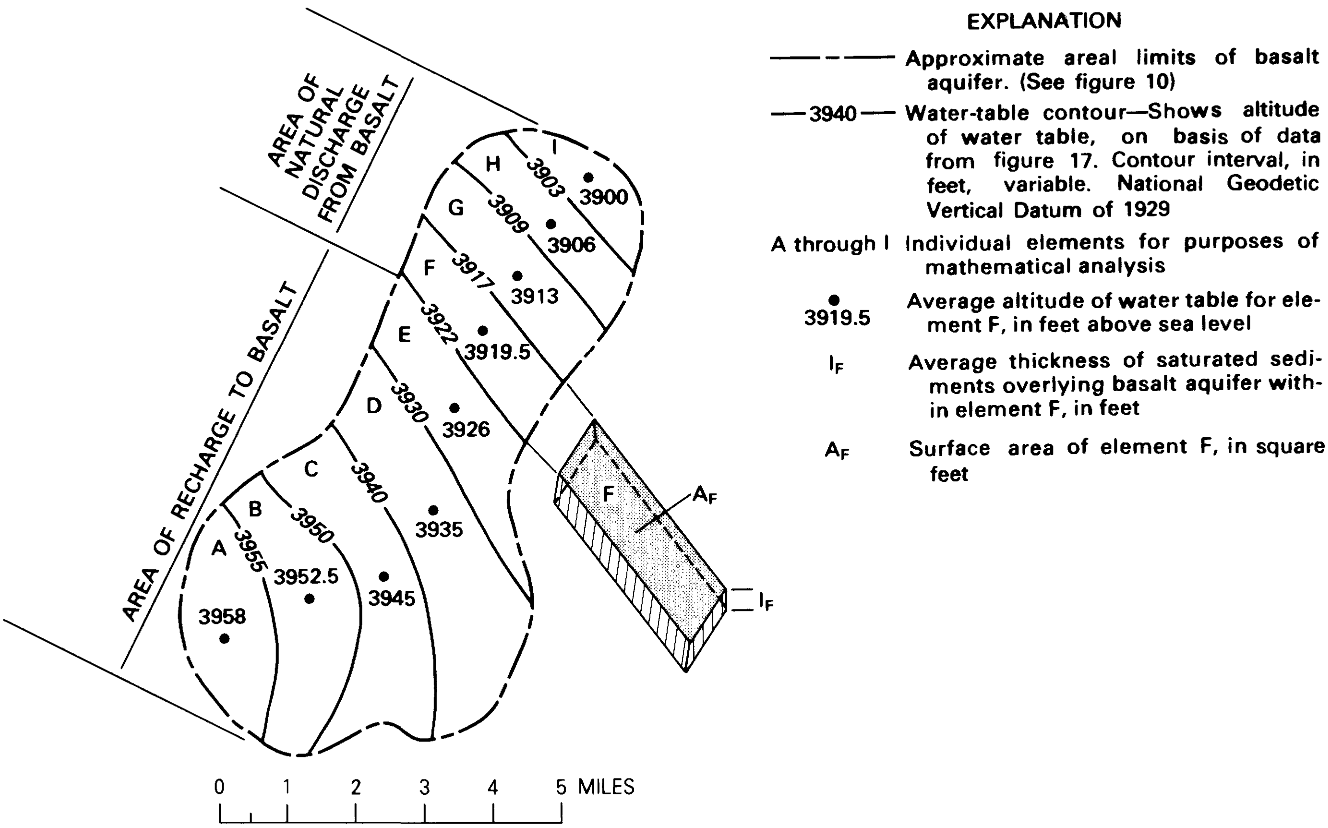

Figure 11. Physical and hydraulic parameters of saturated sediments overlying the basalt aquifer, for use in mathematical analysis of recharge to and discharge from the basalt aquifer.

Average conductivity (K) of the sediments was calculated by fitting the above equation to measured field data. The calculation involved the rearrangement of the equation terms as follows:

$$K = \frac{P}{\sum_{i=1}^{n} \left(\frac{A_i \, \Delta h_i}{\Delta l_i} \right)} ,$$

and the substitution of data determined from field measurements for the appropriate algebraic parameters, element by element. A pumpage value (P) of 1,720 acre-ft/yr represented the average for water years 1976–78 (table 6). Individual element areas (A_i) were determined by map planimetry; head differences for individual elements (Δh_i) are the algebraic differences between the appropriate study-period head in the basalt aquifer (potentiometric altitude, 3,922 ft) and the average water-surface altitudes for each element of the shallow alluvial aquifer, as shown in fig. 11. Thicknesses of sediments overlying the basalt for each element (l_i) are estimates based on information from drillers' logs. The resultant calculated K (average conductivity) is about 0.0154 foot per day (ft/d) and is assumed to be dominantly vertical in direction.

The equation

$$Q_i = K \left(\frac{A_i \, \Delta h_i}{\Delta l_i} \right)$$

was also used to define the recharge to ($+Q_i$) or discharge from ($-Q_i$) any given element for any specified head value within the basalt; K, A_i, and l_i remain constant for each element, and only the head difference (Δh_i) changes as the basalt-aquifer head varies. Thus, the sum of all positively signed values of Q_i equals the system recharge (Q_r) for a specified basalt-aquifer head, and the sum of all negatively signed values of Q_i equals the natural (nonpumpage) discharge of the system (Q_d). It follows that, for a steady-state condition, pumpage equals the algebraic sum of Q_r and Q_d, or

$$P = (+Q_r) + (-Q_d) = K \sum_{i=1}^{n} \left(\frac{A \, \Delta h_i}{\Delta l_i} \right) .$$

The mathematical relations defined by the equation were used to calculate changes in the water budget of the basalt aquifer for different rates of pumpage. Because of possible errors in assumptions, however, confidence in the accuracy of calculated responses decreases proportionately as pumpage is extrapolated from that used to calibrate the computation procedure. Figure 12 graphically portrays these responses as water-level changes in the basalt, total basalt recharge, pumpage-induced recharge, and natural (non-pumpage) basalt discharge as these quantities relate to different pumping rates. As shown, zero pumpage corresponds with virtually no change in water level; likewise, pumpage of 1,720 acre-ft/yr (average during study period; table 6) suggests a corresponding water-level decline in the basalt of 5.5 ft. Thus, the analysis suggests a prepumping water-surface altitude of about 3,927 ft for the basalt aquifer. The driller's report for Fallon No. 1 well, the first large production well, indicates an initial static water level of 33 ft below land surface (water-surface altitude, 3,926 ft). Thus the computed and driller's water-level data generally substantiate each other.

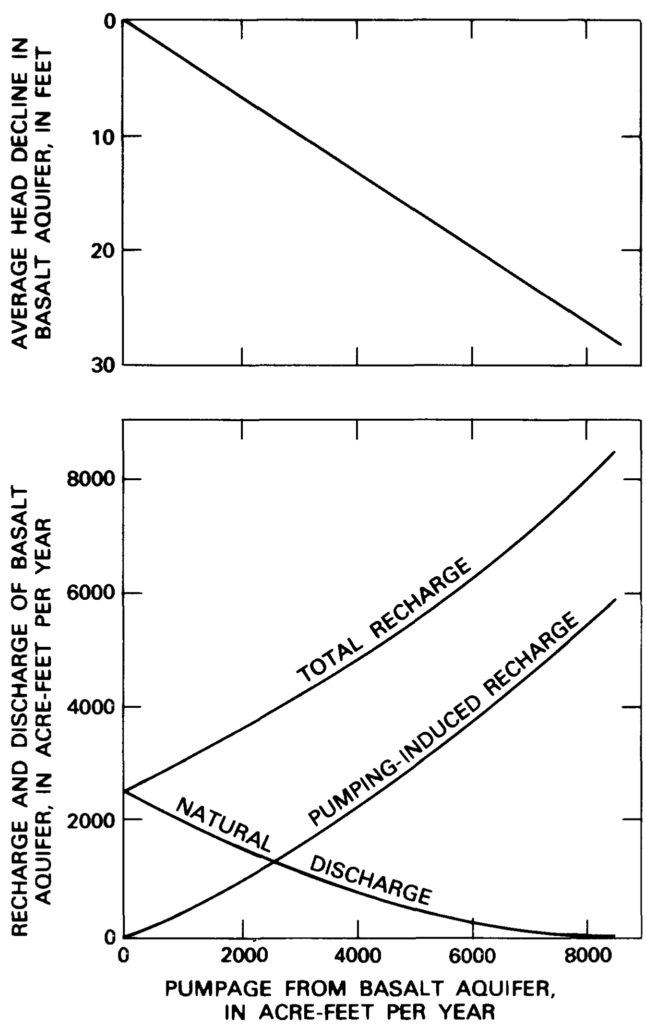

Figure 12. Relations among head decline, recharge, pumping-induced recharge, discharge, and pumpage for the basalt aquifer, on the basis of mathematical analysis.

The computation predicts an overall drop of about 28 ft in the basalt water level relative to the "no-pumpage" or "predevelopment" level for an annual pumpage of 8,500 acre-ft/yr, which is five times the 1978 pumpage. At that pumping rate (8,500 acre-ft/yr), Q_d would equal zero, and most of Q_r would be pumpage-induced. Before pumpage began, $Q_r = Q_d \cong 2{,}500$ acre-ft/yr. Thus, Q_r increases as pumpage increases, and Q_d decreases; pumpage induces recharge, and increasing pumpage further increases induced recharge.

One of the assumptions of the steady-state calculations is that flow paths of recharge to and discharge from the basalt through the overlying sediment blanket are practically vertical. This assumption minimizes the effect of lateral ground-water movement through the sediments, as part of the northeastward trending regional ground-water flow system,on inflow to the basalt.

The transmissivity of an aquifer is the rate at which water would be transmitted through a unit width of the aquifer under a unit hydraulic gradient (Lohman and others, 1972, p. 13). The transmissivity (T) of the basalt aquifer can be estimated using the results of the steady-state calculation scheme and the following equation:

$$Q = WT\frac{\Delta h}{\Delta X},$$

where

Q = average prepumpage recharge to the basalt, which is estimated to have been about 3×10^5 cubic feet per day (ft^3/d) (2,500 acre-ft/yr);

W = average width of the basalt through which lateral flow occurs (derived from cross sections in fig. 5), which is about 20,000 ft (4 mi);

Δh = head difference throughout the length of the basalt mass, which is assigned a value of 0.5 ft for this calculation (the difference appeared to be virtually zero during the period of study and is assumed to be less than 1 ft for natural conditions); and

ΔX = approximate length of the basalt mass, which is about 50,000 ft (10 mi).

Solving the equation for T gives a value of 1.5×10^6 feet squared per day (ft^2/d). This calculation reaffirms the highly transmissive character of the basalt aquifer described earlier. Although this transmissivity estimate is about 10 times greater than the highest estimated transmissivity of table 3, it could be a better approximation of the true value because the pumping rates upon which the data in table 3 are based did not stress the aquifer severely enough to allow great confidence in the estimates of transmissivity calculated from the aquifer test data and also because transmissivities calculated from specific capacity data are representative only if wells are fully efficient and fully penetrating, which the pumped wells were not.

Isotopic Evaluation of Recharge and Flow

The inability to discern a strong hydraulic gradient within the basalt aquifer prompted the use of additional techniques to improve understanding of flow through the system. Isotopic determinations were made on well waters from the basalt to provide clues to flow directions and rates. Similar determinations were made on water from selected wells producing from sediments to add perspective to the sampling scheme and to provide additional insight regarding recharge. Results of the isotope determinations are summarized in table 8. It was hypothesized that age determinations of basalt-aquifer water coupled with lateral trends of changing chemical character would help define flow directions because water becomes older and matures chemically as it moves thorugh an aquifer. However, age dating of the basalt-aquifer water is complicated by several factors. As described earlier ("Mathematical Analysis of Recharge and Discharge"), assumptions and some hydraulic evidence suggest that much of the recharge to the system may be downward rather than lateral inflow; therefore, the net age of water at any specific site is influenced to some unknown degree by vertical movement and mixing of water rather than exclusively by lateral movement. Also, the hypothesis expressed above ("Hydrochemical Characteristics" of the basalt aquifer) regarding the likelihood that basalt-aquifer water represents a mixture of overlying freshwater with underlying saline water (each presumably of different age) implies that the apparent age of the basalt water at any site probably represents a "blend of ages." As a result, age relations laterally or vertically through the system probably are complex.

For this study, water dating was based chiefly on the proportions of stable and unstable (radioactive) carbon isotopes. The isotope of greatest interest is carbon-14, which decays radioactively with a half life of 5,730 years. To estimate age, the ratio of unstable carbon-14 to stable carbon-12 ($^{14}C/^{12}C$) is determined in the sampled water and then is related mathematically to the comparable ratio for a standard of known isotopic composition. By convention, the computed result is expressed as "delta carbon-14" ($\delta^{14}C$) and measured in "permil." This raw carbon-14 value then is adjusted for reactions between the water and carbonate mineral components of the aquifer, using measured and estimated data for the unstable isotope carbon-13 (^{13}C), on the basis of the following equation (Pearson and White, 1967, p. 253):

$$\delta^{14}C \text{ (adjusted)} = (\delta^{14}C, \text{ raw}) \frac{\delta^{13}C_{soil} - \delta^{13}C_c}{\delta^{13}C_{water} - \delta^{13}C_c} ,$$

where $\delta^{13}C_{water}$, the proportion of carbon-13 in the water sample, is measured; $\delta^{13}C_{soil}$, the proportion of carbon-13 in soil, is assumed to be -15 permil; and $\delta^{13}C_c$, the proportion of carbon-13 in carbonate minerals within the aquifer, is assumed to be 0 permil (B. B. Hanshaw, U.S. Geological Survey, oral commun., 1979). The age then is calculated by reexpressing the adjusted $\delta^{14}C$ as a percentage of modern (undecayed) carbon-14 and by matching that percentage with its appropriate age as determined by the formula for radioactive decay of carbon-14. An apparent age can be calculated in a similar manner using the raw $\delta^{14}C$ rather than the adjusted value. These techniques are described in more detail by Hanshaw (1969), Grove and others (1969), and Pearson (1975). Carbon-isotope data for the study area are listed in table 8.

The adjusted carbon-14 ages (table 8) suggest that water from 2 of the 10 wells is younger than today—obviously an incorrect conclusion. The two waters were from the shallowest sampled wells in the intermediate alluvial aquifer. This apparent "future age" of water may be caused by contamination of recharge as a result of atmospheric nuclear-explosive testing that began in 1952. The atmosphere during this period has shown variations in carbon-14 that suggest ages that range up to 200 percent of modern (B. B. Hanshaw, U.S. Geological Survey, written commun., 1980). However, associated tritium data do not suggest the presence of "nuclear-age" water in these samples. The correction procedure used in this report is not the current state-of-the-art technique that provides the best accuracy. However, the most precise procedure is more expensive than the study budget allowed and requires a higher degree of technology than was available during this study. Furthermore, the added precision may be unwarranted because of the factors that complicate the age dating of basalt-aquifer water, as described above. Therefore, the adjusted isotopic age estimates in table 8 are meant to serve as guides to understanding the flow system rather than as absolute ages.

The adjusted ages of water from the Fallon and Navy wells suggest that younger water is being extracted from the centers of heaviest pumping. Also, the tritium data from these wells affirm the younger age of the extracted water to the degree that they suggest a discernible component of post-1952 water in the yield of those wells. This evidence also indicates that heavy pumping stress on the basalt aquifer induces vertical recharge; the tritium data suggest that the induced recharge moves relatively quickly from the land surface to the basalt aquifer.

Chemical characteristics of water from the basalt discussed earlier suggest a chemical maturing toward the northeast, thereby inferring a northeastward flow direction. Adjusted carbon-14 ages suggest more complex relations in the basalt. Some adjusted ages suggest that the basalt water gets progressively older to the northeast beyond the Fallon-Navy center of heavy pumping. The adjusted ages of water from the Kennametal, Inc., well (4,400 years) and the Wolf well (8,800 years), coupled with the apparent chemical maturation in a northeastward direction, hint of a lateral flow system generally parallel to that of the regional ground-

Table 8. Isotope and related data for water from selected wells[1]

Well name	Location	Lithology of producing zone	Approximate depth of producing zone (feet)	Apparent (unadjusted) ^{14}C age of water (years)	$\delta^{13}C$ (permil, ±0.1, relative to PDB standard)	Adjusted ^{14}C age of water (years)		Tritium concentration (units)	δD (permil, ±1, relative to SMOW)	$\delta^{18}O$ (permil, ±0.1, relative to SMOW)	Dissolved inorganic carbon (millimoles per kilogram of sample, ±5–10 percent)
						Value	Limits				
Fallon-Mori	N19 E28 36AABC1	Basalt	505	7,600±150	−9.96	4,200	3,980–4,150	2.6±0.5	−112.5	−14.82	2.2
Kennametal, Inc.	N19 E29 18DCBB1	--- do ---	490	8,900±630	−8.72	4,400	3,680–5,420	0.8±0.2	−114.0	−14.54	2.7
Fallon No. 3	30CBAD1	--- do ---	450	5,500±600	−9.23	1,500	790–2,360	8.3±0.5	−108.0	−14.27	3.7
Fallon No. 1	30CDBC1	--- do ---	480	5,300±160	−9.41	1,500	1,200–1,840	8.1±0.5	−107.5	−14.12	3.6
Navy No. 3	33CBBB2	--- do ---	508	5,500±420	−8.85	1,100	630–1,640	6.7±0.4	−110.5	−14.12	4.2
Howard Wolf	N20 E29 34BBAC1	Basalt	260	14,000±400	−7.98	8,800	8,290–9,710	0.2±0.2	−112.5	−14.38	5.5
Ronald Albaugh No. 1	34CCDC1	--- do ---	118+	9,900±210	−6.89	3,500	3,420–3,810	0.0±0.2	−110.5	−14.32	4.8
Ponte Subdivision	N19 E28 24ADCC1	Sediment	300	4,000±420	−10.98	1,400	930–1,920	0.0±0.2	−114.0	−14.75	1.6
Ben Peck	24DABB1	--- do ---	90	1,200±170	−10.68	[a]122	[a]118–125	0.1±0.2	−110.0	−13.76	1.8
Country Club Estates	26BAAA1	--- do ---	130	1,100±160	−12.68	[a]104	[a]101–106	0.0±0.2	−111.0	−14.38	1.9

[1]Carbon-14 analyses were done at the U.S. Geological Survey Central Laboratory, Lakewood, Colo. Other isotope analyses were done at the Geological Survey isotope laboratories, Reston, Va. Abbreviations: ^{14}C, carbon-14; $\delta^{13}C$, delta carbon-13 relative to carbon-12; PDB standard, carbonate-mineral belemnite fossile from Cretaceous Peedee Formation of South Carolina; δD, delta deuterium (hydrogen-2) relative to hydrogen-1; SMOW, standard mean ocean water; $\delta^{18}O$, delta oxygen-18 relative to oxygen-16.

[a]Adjusted carbon-14 ages younger than today are expressed as percentage of modern standard.

water flow system. However, the adjusted age of water from the Albaugh No. 1 well (3,500 years) is anomalous to this apparent trend. Data are unavailable on the original completion depth and type of construction for the Albaugh No. 1 well (table 1), but the chemical character and hydraulic potential of its water are compatible with the basalt aquifer, as described earlier ("Hydrochemical Characteristics" and "Hydraulic Characteristics" of the basalt aquifer). Causes of the apparent age anomaly of the Albaugh well water are unknown.

Temporarily ignoring the Albaugh anomaly, an average lateral velocity of about 4.5 ft/yr is suggested by prorating the apparent lateral time of travel of water through the basalt between the Kennametal and Wolf wells. This rate is coincidentally similar to that suggested by prorating the unadjusted ages between the Fallon-Navy wells and the Wolf well. In any event, no known data exist that suggest an average lateral velocity through the basalt greater than 5 ft/yr.

The inferred 4.5 ft/yr average velocity can be used to approximate the lateral flow rate through the basalt system, utilizing the basic flow equation $Q = VA$, where Q is the flow rate normal to a vertical cross section through the aquifer system, in acre-feet per year; V is the average flow velocity, in feet per year; and A is the area of an average-sized cross section, in acres. The average area was derived by determining the arithmetic average of the vertical inflow and outflow sections; the maximum-sized inflow section normal to the regional valley-fill system, as interpreted from section E-E′ of figure 5, is about 25 million feet squared (ft^2), and the outflow section, as interpreted from section C-C′ of figure 5, is about 9.1 million ft^2. The resulting average cross-sectional area (A) is about 17 million ft^2, or about 400 acres. Assuming an effective porosity for the basalt of 10 percent, the average cross section of flow is about 40 acres. Using that value and the average velocity of 4.5 ft/yr, the equation gives an estimated flow rate of about 180 acre-ft/yr. This rate is less than 10 percent of the estimated 2,500 acre-ft/yr for natural recharge to the basalt aquifer before pumping, as determined by the steady-state recharge computation procedure, and suggests that vertical movement of water into and out of the basalt aquifer is greater than lateral movement through it.

Graphical relations between the isotopes deuterium and oxygen-18 are shown in figure 13*A* (the data are listed in table 8). The relatively tight cluster of data points suggests that water from all sampled sites probably was derived from a similar atmospheric source. This generic similarity between water in the sediments and the underlying basalt supports the previously stated hypothesis that the basalt aquifer can be recharged by water from the sediments. Location of the data points to the right of the "meteoric water line" of Craig (1961) is typical of ground water in desert areas (T. B. Coplen, U.S. Geological Survey, written commun., 1980).

Graphical relations between carbon-13 and dissolved inorganic carbon are shown in figure 13*B* for water from the wells of table 8. Data points for the three wells producing from sediments plot in the lower left part of the graph, whereas data for the basalt-aquifer wells farthest northeast in the study area (Albaugh No. 1 and Wolf, tables 5, 8) are segregated at the upper right corner of the graph. The chemical character of the Fallon-Mori well water (table 5) suggests that it may be a mixture of basalt- and alluvial-aquifer water, and its data point in figure 13*B* falls between those representing the alluvial and basalt waters. The remaining basalt-aquifer data points lie between the end groups on the graph; points representing the heavily pumped wells (Fallon Nos. 1, 3 and Navy No. 3) are concentrated in a group. The distribution of data points generally suggests a trend from younger alluvial ground water (lower left part of graph) to the oldest basalt water (upper right). The trend generally substantiates the hypothesis of a flow system wherein the basalt is recharged from the sediments in the southwest, and the water then moves northeastward through the basalt, discharging naturally from the northeastern part.

HYDROLOGY OF THE ALLUVIAL AQUIFERS

The three alluvial aquifer systems (p. 6) were shown in preceding report sections (chiefly "Hydrochemical Characteristics" and "Mathematical Analysis of Recharge and Discharge" of the basalt aquifer) to be the source of supply for water recharging the basalt aquifer. The shallow and intermediate alluvial aquifers also supply water directly to a substantial part of the population of Carson Desert. According to 1970 and 1980 census figures, about 60 percent of the population of Churchill County resides outside the limits of Fallon and the Fallon U.S. Naval Air Station. Few of these rural inhabitants are supplied by the basalt aquifer. During the latter part of the 1970's, this rural population numbered about 8,000 people (1980 census) and consumed more than one-half of the domestic water used in the Carson Desert. Most of this rural population derives its water supply from 3,000 to 4,000 wells tapping the shallow alluvial aquifer. A minority of the rural population is supplied by about 100 wells tapping the intermediate alluvial aquifer. The deep alluvial aquifer is tapped rarely by production wells.

Water chemistry is the chief known difference, other than depth, among the three alluvial aquifers. Gross chemical characteristics are generally distinctive enough to warrant the differentiation of the three alluvial aquifers which underlie almost the entire study area. The extent of the study area and of water-quality data for the alluvial aquifers is shown in figure 14; the study area also is shown in relation to the overall Carson Desert Hydrographic Area in figure 1.

Valley fill of the Carson Desert constitutes a vast volume of generally unconsolidated sedimentary detritus. The hydrologic character of these sediments depends to a

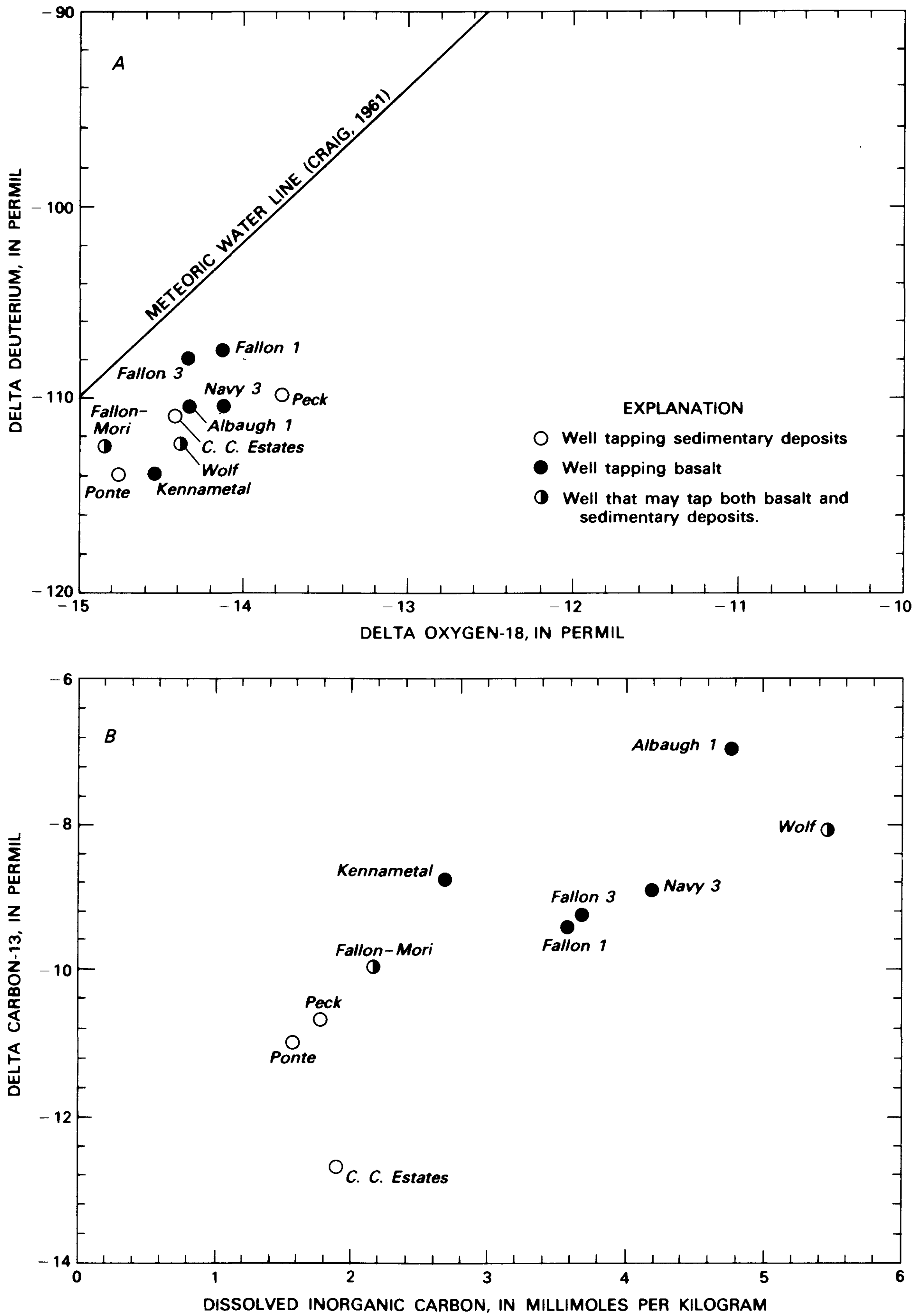

Figure 13. Graphical relations between isotopes in ground water from selected wells: *A*, Oxygen-18 and deuterium; *B*, Total dissolved inorganic carbon and carbon-13.

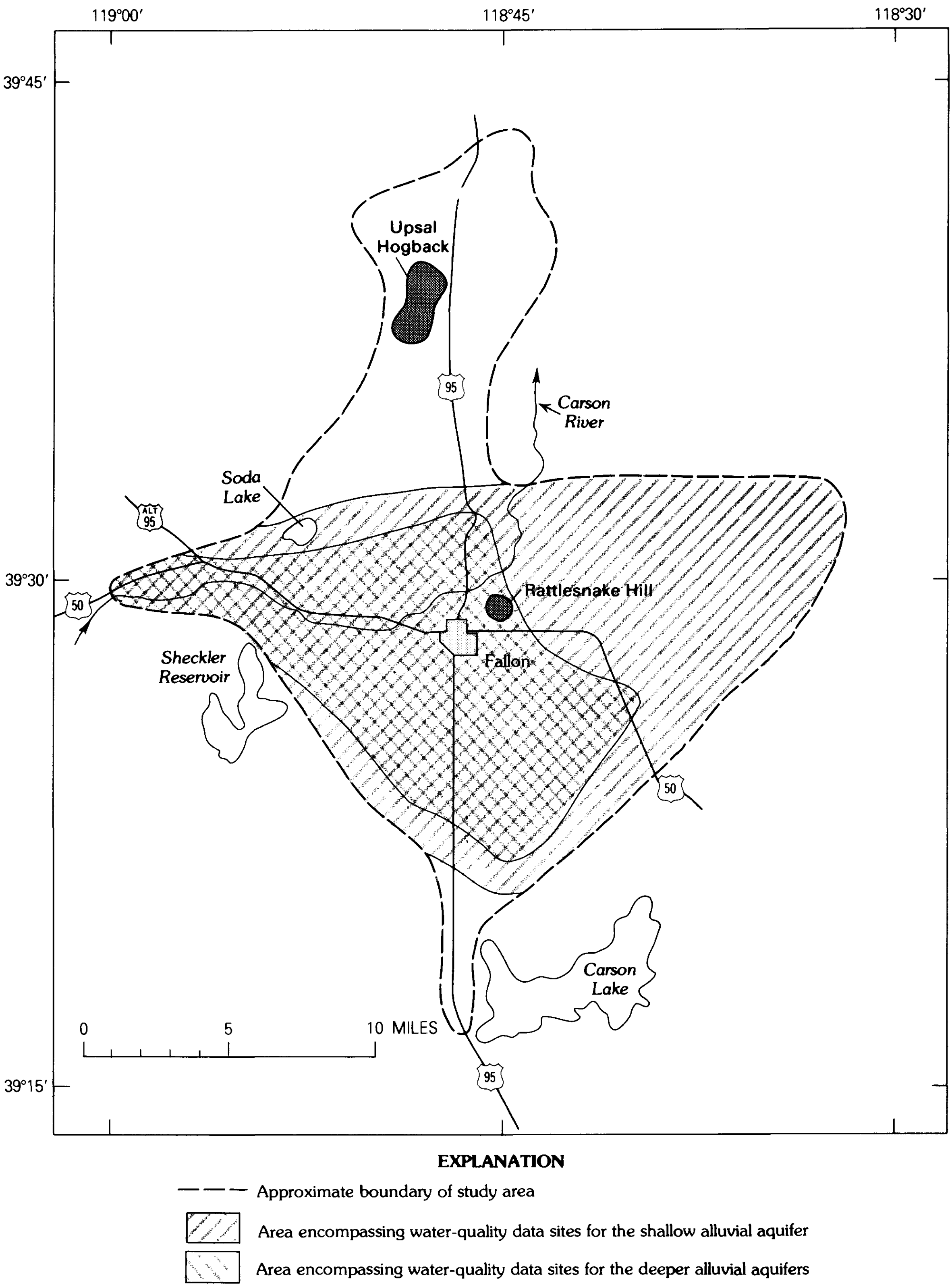

Figure 14. Distribution of water-quality data for the alluvial aquifers.

large degree on their geologic characteristics, which were discussed briefly in the "Geology" section of this report. Thickness of the valley-fill in the study area ranges from zero to at least 8,000 ft. If an average thickness of 3,000 ft and a study area of 173,000 acres (270 mi^2) are assumed, valley-fill deposits have a volume of 520 million acre-ft. Moreover, if the valley fill is assumed to be virtually saturated, with an average specific yield on the order of 10 percent, recoverable ground water in storage would represent a volume of about 50 million acre-ft. Thus, available ground water in the valley fill evidently constitutes a very large resource. The Fallon study area makes up only about one-fourth of the overall valley-fill area of the Carson Desert; therefore, recoverable water stored in the valley fill beneath the entire Carson Desert Hydrographic Area may be on the order of 200 million acre-ft.

Not all of this vast ground-water resource is easily attainable or chemically suited to all or most needs. Therefore, this large quantity of water should not be thought of as a single resource but rather as a combination of resources available to satisfy a variety of needs. Profitable exploitation for a specific purpose is subject to a variety of natural and manmade laws.

The earlier proven, or at least strongly implied, relations between alluvial aquifers and the basalt aquifer ("Hydrochemical Characteristics" and "Mathematical Analysis of Recharge and Discharge" of the basalt aquifer) suggest that activities affecting alluvial aquifers ultimately will affect the basalt aquifer. The magnitude and timing of such effects on the basalt aquifer depends to a large degree on the intensity of activity and its location relative to the ground-water flow systems of the sediments and the basalt.

Data-collection strategy during this investigation was designed to develop the most detailed information on the basalt aquifer, and a less intensive study was made of the alluvial aquifers. The following sections describe the specific findings of this investigation as they pertain to the alluvial aquifers.

Shallow Alluvial Aquifer

For the purposes of this study, the shallow alluvial aquifer is defined as water-yielding strata within unconsolidated valley-fill deposits not more than 50 ft below land surface. The aquifer is not a simple layer of permeable detritus but, instead, includes many loosely interconnected zones of variable permeability throughout the study area. It includes sediments deposited by wind, as well as those deposited in an aqueous environment.

Location and Extent

The shallow alluvial aquifer extends throughout the study area except at the relatively small outcrops of volcanic rock (less than 3 mi^2) at Rattlesnake Hill and Upsal Hogback. Generally, the water table of the shallow aquifer is less than 10 ft below land surface and occasionally is contiguous with lakes and ponds, as in the Soda Lakes volcanic craters and in numerous relatively small wind-sculptured potholes that pockmark the land surface. The vertical limits of the shallow alluvial aquifer are the water table and the 50-ft depth below land surface.

The persistence of the shallow alluvial aquifer throughout the study area has been verified by numerous wells that penetrate the water table at relatively shallow depth. Its presence also is verified by the widespread phreatophytic vegetation that it supports except where excessively saline soil or ground water, or the works of man, prevent the natural use of this easily accessible water supply by vegetation.

The approximate volume of recoverable water stored in the shallow alluvial aquifer is the product of the aquifer's area, thickness, and specific yield. That volume is estimated as follows: The saturated thickness of the storage zone is 42 ft (an average obtained from 65 measured sites scattered throughout the study area); the area of the aquifer is about equal to that of the study area, or 173,000 acres; an average specific yield of 10 percent is assumed; and the resulting recoverable ground-water storage is about 730,000 acre-ft. This is probably only about 1 to 2 percent of all recoverable water stored in valley fill of the study area (see above).

Hydraulic Characteristics

Lithologic data show that the shallow sediments mainly consist of interlayered beds of sand, silt, and clay and occasional stringers of gravel. Individual strata, particularly the coarse-grained units, are not known to be areally extensive. Morrison (1964, p. 117) characterized a part of the shallow aquifer as follows: "Stringers of alluvial sand and gravelly sand of post-Sehoo channels of the Carson River locally furnish small supplies to shallow wells, but such water is liable to pollution." [Morrison's term "Sehoo" refers to the Sehoo Formation, a lacustrine unit of Quaternary age (Morrison, 1964, p. 41–63)]. Hydraulic conductivity, which is dependent on lithology, generally tends to vary sharply, both geographically and vertically, over short distances, particularly in the western part of the study area. In spite of this pronounced variability, some generalizations are suggested by the history of sediment deposition in the area. Morrison's (1964) detailed description of Quaternary geologic history portrays the dominant influence exerted by ancient Lake Lahontan on sediment deposition in the Carson Desert. The generally continuous and sometimes wide oscillations of the lake's water surface, and thereby the varying location of its shorelines, during the past 60,000–80,000 years exerted a complex control on the deposition of sand- and gravel-sized particles from the Carson River as they entered the lake. Thus, the vertical and lateral geometric patterns of coarse-grained sediment deposits are complex, and this complexity probably is reflected by great areal variability in the transmissivity of the shallow alluvial aquifer. Regardless of lake-level fluctuations, the Carson River persistently delivered its sediment load to the lake's western shoreline; therefore, the coarse-grained sediment component of basin-fill detritus generally should increase and coarsen in a westerly direction. Likewise, overall hydraulic conductivity of the valley fill, dependent on particle-size distribution and sorting of the sediment deposits, also should increase in a westerly direction.

Pumping tests to determine hydraulic characteristics of the shallow alluvial aquifer were not made as a part of this investigation. Well-yield test data were available for about 430 shallow wells in Tps. 18 and 19 N., Rs. 28 through 30 E., in the Nevada State Engineer's files of drillers' logs. These wells probably represent 10–15 percent of the shallow wells in the study area. The aquifer test data were used to compute specific capacities (expressed as pumpage, in gallons per minute divided by drawdown in feet) for each well. Figure 15 shows a histogram of the calculated specific capacities. The data show no perceptible geographic trend of specific-capacity magnitude.

Figure 15 suggests that relatively low values of specific capacity dominate the data set. However, low specific capacities can result from inefficiently constructed wells as easily as from poorly transmissive aquifers. Figure 16 shows the distribution of maximum specific capacities, section by section, for the study area. Although geographic trends are not defined sharply, it is noteworthy that no values greater than 50 gallons per minute per foot [(gal/min)/ft] appear east of Fallon. That fact plus other more subtle areal trends suggest that specific capacities generally increase from east to west. These trends are compatible with the earlier stated reasoning regarding qualitative aspects of sediment-deposition environments.

A rough estimate that, in slightly modified form, relates aquifer transmissivity to specific capacity was described by Thomasson and others (1960, p. 222). The equation is

$$T \cong 267(SC),$$

where T is the transmissivity, in feet squared per day, and SC is the specific capacity, in gallons per minute per foot of drawdown. The computation assumes that the well for which a specific capacity is calculated is fully efficient; the degree to which the well is less than fully efficient will have a commensurate effect on the accuracy of the estimated transmissivity. On the basis of specific capacities discussed above, the equation suggests that transmissivities of the shallow alluvial aquifer may range from 2,000 to 15,000 ft^2/d or more, if the larger specific capacities accurately portray the true hydraulic conductivity of the aquifer. However, if most of the shallow wells have been constructed properly and efficiently yield water commensurate with potential aquifer yields, figure 15 suggests that transmissivities of the aquifer normally are less than 2,000 ft^2/d. The uncertainty probably cannot be resolved without extensive and expensive additional field data. In any event, transmissivities of the shallow aquifer apparently differ considerably from place to place.

Depths to water were measured in about 65 shallow alluvial-aquifer wells during the course of the investigation. Water levels in 37 of the wells were remeasured periodically to discern seasonal and annual variations. The results of this monitoring program are summarized in table 9. In most of the wells, water levels were measured periodically throughout the severe drought period between 1976 and 1977. The variability in range among the measured water levels (0.19–5.87 ft) generally attests to the hydrologic complexity of the shallow alluvial aquifer.

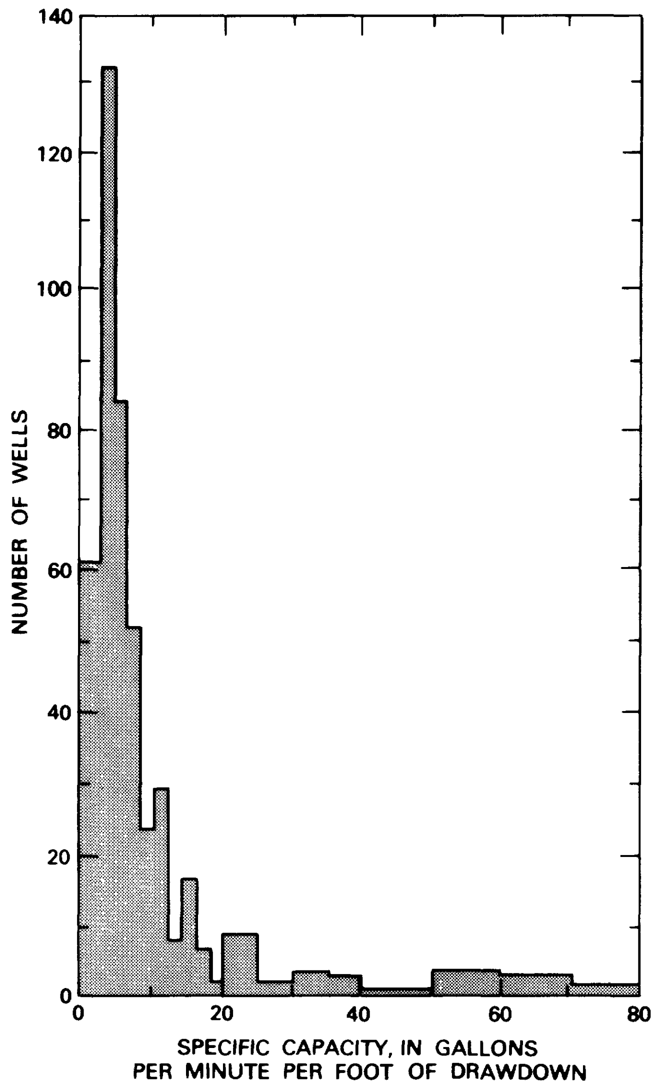

Figure 15. Specific capacities of wells tapping the shallow alluvial aquifer.

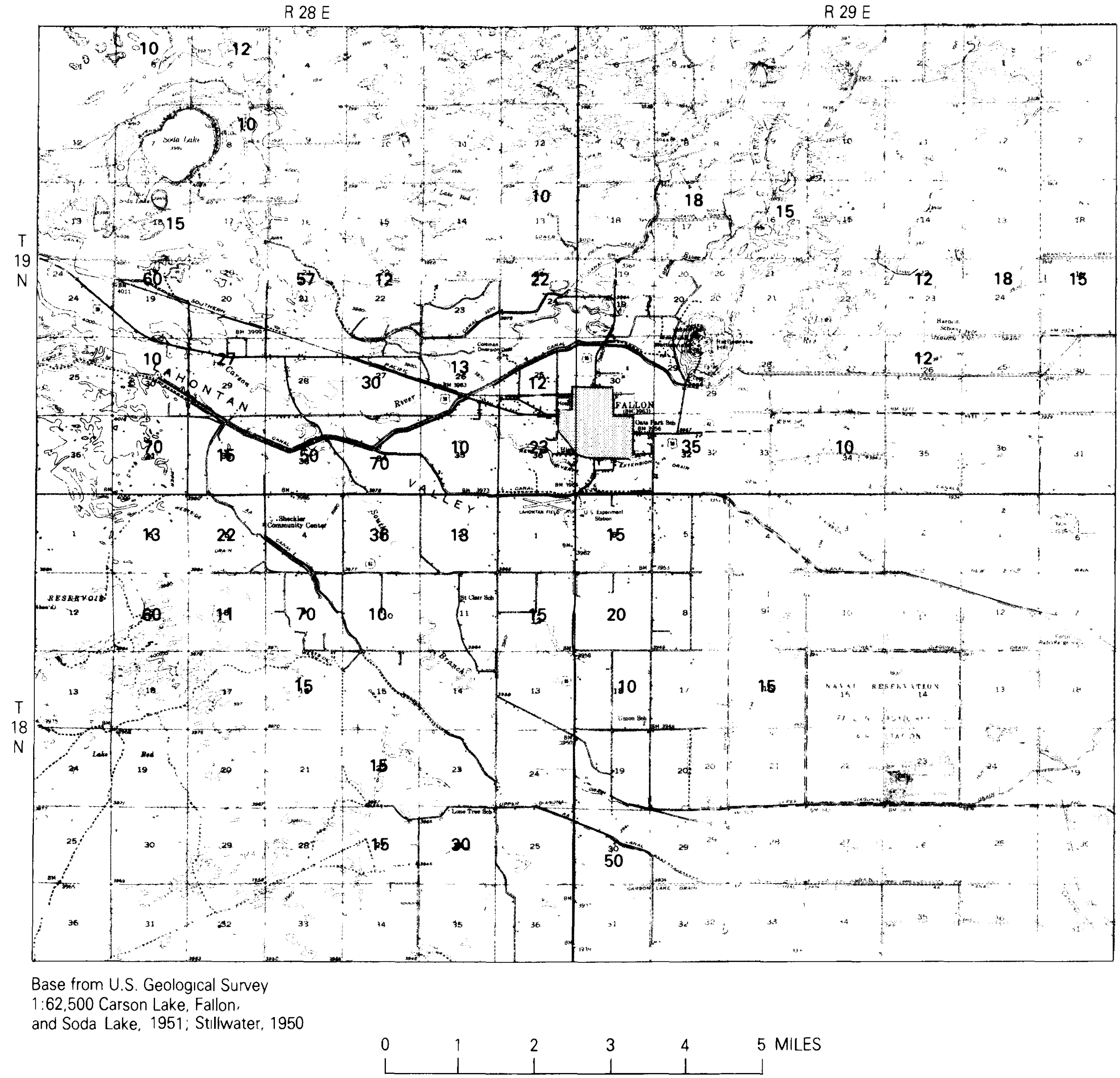

Figure 16. Maximum specific capacities of wells tapping the shallow alluvial aquifer. Number indicates maximum value, in gallons per minute per foot, determined in each section for which data are available. Maxima less than 10 not shown.

Generalized contours of water-surface altitudes are shown in figure 17. Ground-water flow directions and gradients, as inferred from the contours, have a strong eastward component. The average head gradient throughout the shallow aquifer is 7.5 feet per mile (ft/mi); directionally, the system gradients average 8.5 ft/mi to the northeast, 6 ft/mi to the east, and 7 ft/mi to the southeast. Most of the shallow-aquifer throughflow ultimately moves northeastward toward the Carson Sink and eastward toward Stillwater Lakes; lesser amounts move southeastward toward Carson Lake and the saline playa sumps of Eightmile and Fourmile Flats (fig. 1).

Water-level hydrographs for several wells were selected to show the diverse character of water-level fluctuations throughout the study area. Figure 18 shows relations between water-level fluctuations in a shallow well and in a nearby intermediate-depth well, along with concurrent fluctuations of Carson River streamflow. The wells are less than 0.5 mi from the river and about 0.25 mi from a large irrigation canal that diverts water from the river. Neither well is pumped, nor is there any pumping nearby. Water-level fluctuations in both wells are nearly in phase with riverflow fluctuations, implying a close relation between river stage, or flow, and response of the aquifer. The figure shows that water levels in the shallow aquifer (well depth, about 12 ft) have a greater amplitude of fluctuation than those in the intermediate aquifer (well depth, about 140 ft). This suggests that alluvial-aquifer responses to river and irrigation flow diminish with depth. Responses of ground-water levels appear to lag slightly behind riverflow fluctuations, but the underground and surface-flow systems generally seem to fluctuate in phase.

Figure 19 shows water-level fluctuations in two other shallow wells about 4 and 6.5 mi away from the river but within the river-supplied irrigation acreage. Generally, water levels in these wells fluctuate in response to seasonal river fluctuations and irrigation, but fluctuations are less in phase with the river fluctuations than the levels in wells of figure 18. Also, their annual cyclic curves contain many individualistic perturbations that probably are related more to local irrigation pulses than to minor riverflow fluctuations.

Water-level fluctuations in two other shallow wells, about 3 mi from the river and 4–6 mi from irrigated lands, are shown in figure 20. The degree of correlation between their water levels and riverflows, and irrigation, appears to be less than that in figures 18 and 19.

Finally, figure 21 shows water-level fluctuations in a shallow well nearly 8 mi from the river and adjacent to the downstream end of the irrigation system. Little or no correlation appears to exist between these water levels and the riverflow. Figure 21 also includes the hydrograph of a well tapping the basalt aquifer. Water-level fluctuations in the shallow well do not appear any more related to those in the basalt aquifer than to the riverflow. As shown earlier, the basalt-aquifer water levels rise and fall out of phase with seasonal increases and decreases of riverflow because they reflect mainly the effects of pumpage (outflow). Pumpage pulses in phase with riverflow, and water levels are synchronized with, but opposite to, pumpage.

Characteristics of water levels illustrated by figures 18–21 suggest that, in general, relations between the shallow aquifer's water levels and river or canal flow depend, to some degree, on the lateral distance from the river or canal. Beneath irrigated lands, seasonal water-level fluctuations are generally in phase with seasonal riverflow. Local pulses of surface flooding, either natural or caused by man (irrigation), can override local effects of short-term changes in riverflow on shallow-aquifer water levels. The combined effects of riverflow, irrigation, and areal variations in precipitation result in complex water-level responses. The irrigation drainage canals also modify the effects of this complex recharge system by attenuating recharge in some areas and probably enhancing it in others. The inflow to and outflow from the shallow aquifer also is governed by lateral and vertical variations in permeability.

Analysis of shallow water-level data collected during the study disclosed areal differences in the magnitude of water-level fluctuations. Fluctuations were generally greater beneath irrigated areas than beneath the uninhabited and undeveloped desert areas. The seasonal fluctuations commonly were more than 2 ft throughout much of the irrigated area and between 4 and 6 ft in some parts of the irrigated area. In desert areas, however, seasonal fluctuations were less than 2 ft and often less than 1 ft; in some desert areas, water levels fluctuated less than 0.5 ft/yr.

Maps depicting magnitudes of water-level fluctuation within the shallow aquifer beneath irrigated areas during the 1977 and 1978 water years are shown in figure 22. The area included within the boundaries of figure 22 is about 152,000 acres. During both years, the geographic patterns are similar, in that the largest fluctuations take place generally west and southwest of Fallon along the Carson and South Branch Carson Rivers. The greatest depths to water commonly occur during late winter, and the minimum depths occur during midsummer, suggesting that water-level buildups are a direct response to the volume of riverflow and surface irrigation. As discussed earlier, these water-level pulses beneath the irrigated lands generally tend to be in phase with riverflow and local irrigation fluctuations. Rising water levels provide a means of quantitatively assessing ground-water storage increases in the shallow aquifer caused by the infiltration of irrigation water; likewise, declining water levels can be used to quantify decreases in stored ground water.

Table 10 relates the water-level changes to estimates of water-storage change in the shallow alluvial aquifer beneath irrigated land during the 1977 and 1978 water years. Even though the patterns in figure 22 vary somewhat between 1977 and 1978, the resultant annual estimates of water-storage change are nearly the same (27,000 acre-ft in 1977 versus 26,000 acre-ft in 1978). These storage changes are believed to be roughly equivalent to the annual recharge of the shallow aquifer by irrigation and river infiltration. They also are considered equal to the annual depletion by natural and other forms of discharge. The water-storage changes represent about 7 percent of the annual flow of the Carson River below Lahontan Reservoir, which averaged nearly 370,000 acre-ft/yr between 1967 and 1978.

All the wells utilized in assessing the ground-water storage changes ranged in depth from about 4 to 32 ft below land surface; irrigation drains throughout the area ranged in depth from about 2 to 15 ft (R. G. Green, U.S. Bureau of Reclamation, oral commun., 1979). Most monitored water-level changes apparently were below the levels of nearby drains, and, consequently, most of the water-storage inputs were not quickly bled out of the shallow aquifer by the drains. Irrigation infiltration is not the sole source of water

Table 9. Summary of periodic water-level measurements for the shallow alluvial aquifer

Location	Well depth (feet)	Period of record	Depth to water (feet below land surface)		
			Maximum	Minimum	Range
N16 E28 1AAAA2	27	1-76—9-78	21.37	20.80	0.57
N17 E28 13DAA1	17	1-76—9-78	5.38	2.83	2.55
N17 E29 3CCBC1	3.9	2-76—8-78	3.75	1.99	1.76
N18 E28 10CAAB1	8	1-76—9-78	8.51	4.02	4.49
12ADA1	10.5	1-76—9-78	8.24	5.04	3.20
34ACAA1	9.5	1-76—10-78	5.68	1.96	3.72
N18 E29 15BBDB1	9.5	1-76—9-78	8.15	7.66	.49
30BCBD1	29.2	1-76—9-78	4.86	1.60	3.26
30BCBD2	4.1	1-76—9-78	>4.1	1.44	>2.66
N19 E27 13CCB2	14.4	2-76—9-78	12.62	6.75	5.87
36DDCD1	25.5	1-76—9-78	15.19	14.14	1.05
N19 E28 9DDA1	22.2	1-77—9-78	9.90	7.33	2.57
11ABB2	32.18	12-76—9-78	30.83	28.98	1.85
27BBC1	10	1-76—9-78	8.53	4.10	4.43
N19 E29 14ACB2	12	1-76—9-78	9.12	7.59	1.53
18DCBB2	10	1-76—9-78	8.47	6.92	1.55
30CBAD3	12	1-76—9-78	6.14	4.05	2.09
35DAA1	9.5	1-76—9-78	8.24	6.19	2.05
N19 E30 9ADBB1	22	1-76—9-78	5.44	3.11	2.33
20DCCC1	10	1-76—9-78	7.73	6.92	.81
35CBD1	17	2-76—9-78	9.65	9.27	.38
N20 E28 22BCA2	34	10-74—9-78	31.67	30.77	.90
24BDD2	33.4	1-75—9-78	29.88	29.63	.25
27CCA2	21.91	12-74—9-78	21.30	19.62	1.68
N20 E29 8BDC2	8.3	2-76—9-78	7.13	2.49	4.64
32CAB2	17.3	1-77—9-78	7.30	6.52	.78
N20 E30 35DDDC1	17	1-76—9-78	3.28	1.84	1.44

Table 9. —Continued

Location	Well depth (feet)	Period of record	Depth to water (feet below land surface)		
			Maximum	Minimum	Range
N21 E28 16DDD2	14.9	2–76—9–78	3.91	3.09	.82
16DDD3	5.08	2–76—9–78	4.13	3.22	.91
24BBA3	12.66	12–75—9–78	9.40	9.21	.19
N21 E29 7BAC3	15.85	12–75—9–78	10.14	9.32	.82
18DDB3	4.89	2–76—9–78	5.41	4.01	1.40
30DDC2	15	12–75—9–78	7.41	5.58	1.83
33AAA2	15.87	12–75—9–78	3.44	1.91	1.53
33AAA3	6.1	2–76—9–78	3.67	2.28	1.39
N22 E29 32CCD2	10.12	2–76—9–78	2.82	1.15	1.67
32CCD3	3.28	1–76—9–78	3.13	1.85	1.28

inflow to the shallow aquifer beneath the irrigated area; some unknown quantity of water also moves laterally into the system, mainly from the west, and out of the system to the northeast, east, and southeast. However, the volumes of lateral inflow and outflow are indeterminate without more data.

As stated earlier, the water-level measurements upon which the above calculations are based were made during and just following a period of severe regional drought. They may not portray accurately fluctuations of ground-water levels during more hydrologically normal periods.

Hydrochemical Characteristics

Water samples collected at different sites from the shallow alluvial aquifer range widely in their chemical characteristics. Indeed, numerous data suggest that chemical variability within the shallow system is probably equal to or more commonplace than the hydraulic variability discussed in the preceding report section. Standard chemical data are available for more than 1,000 ground-water samples collected from the shallow aquifer at hundreds of wells. This investigation utilized chemical data from about 480 sites. Plate 1*A* shows the approximate locations of these data sites.

The chemical data suggest general geographical patterns of salinity in the shallow aquifer; however, they also show a great likelihood that water from a specific site may not conform to the generalized pattern. Table 11 shows concentrations of common chemical constituents for water from 10 selected wells in the shallow alluvial aquifer. The wells are grouped in five pairs, with the wells of each pair in close proximity. The data were not selected to show the range in salinity throughout the aquifer; instead, they depict the substantial chemical variability of shallow-aquifer water over relatively short geographical distances.

A specific chemical characteristic was used to help differentiate the shallow alluvial aquifer from the intermediate alluvial aquifer during this study. Water from wells deeper than 50 ft commonly is very soft (hardness, usually less than 25 mg/L). This characteristic prevails generally throughout the deeper water (depth 60–300 ft) beneath the inhabited area near Fallon. In contrast, water from shallower wells typically is much harder. Some shallow wells yield very soft water, but these wells constitute a minority of those composing the shallow-aquifer data base. Likewise, some wells deeper than 50 ft, particularly west of Fallon, yield harder water, but these wells are in areas where coarse sedimentary deposits provide efficient recharge paths to depths below 50 ft or where deeper water is relatively saline and not potable. Although the arbitrary depth boundary of 50 ft does not always coincide with the apparent chemical boundary, it nonetheless applies to most known situations regarding potable water underlying areas of urban and rural development.

Plate 1*B* shows a very generalized distribution of water hardness throughout the shallow aquifer. The map was machine contoured on a rectangular grid (individual grid elements, about 1 mi^2) wherein all available hardness

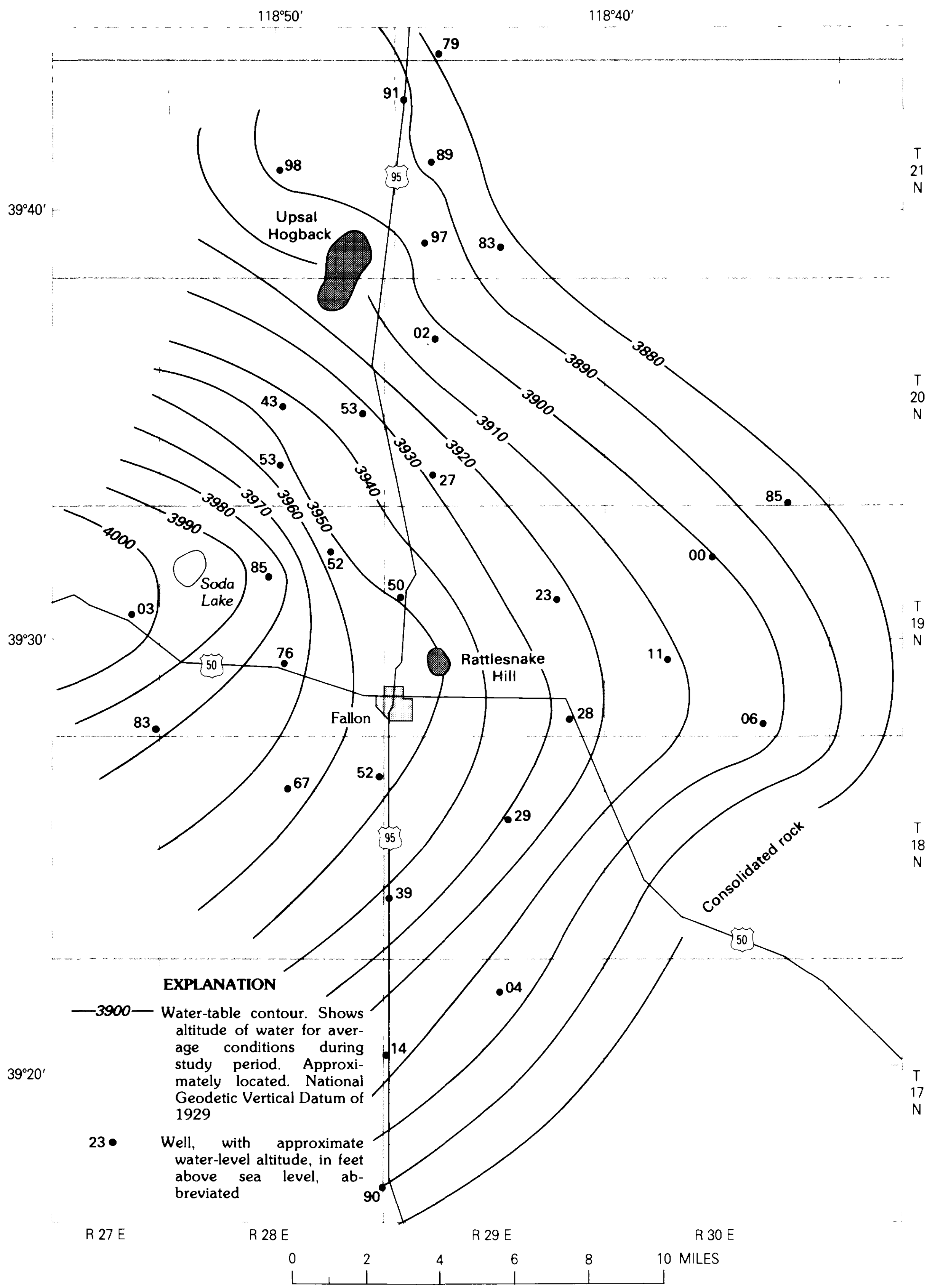

Figure 17. Generalized water-table contours for the shallow alluvial aquifer.

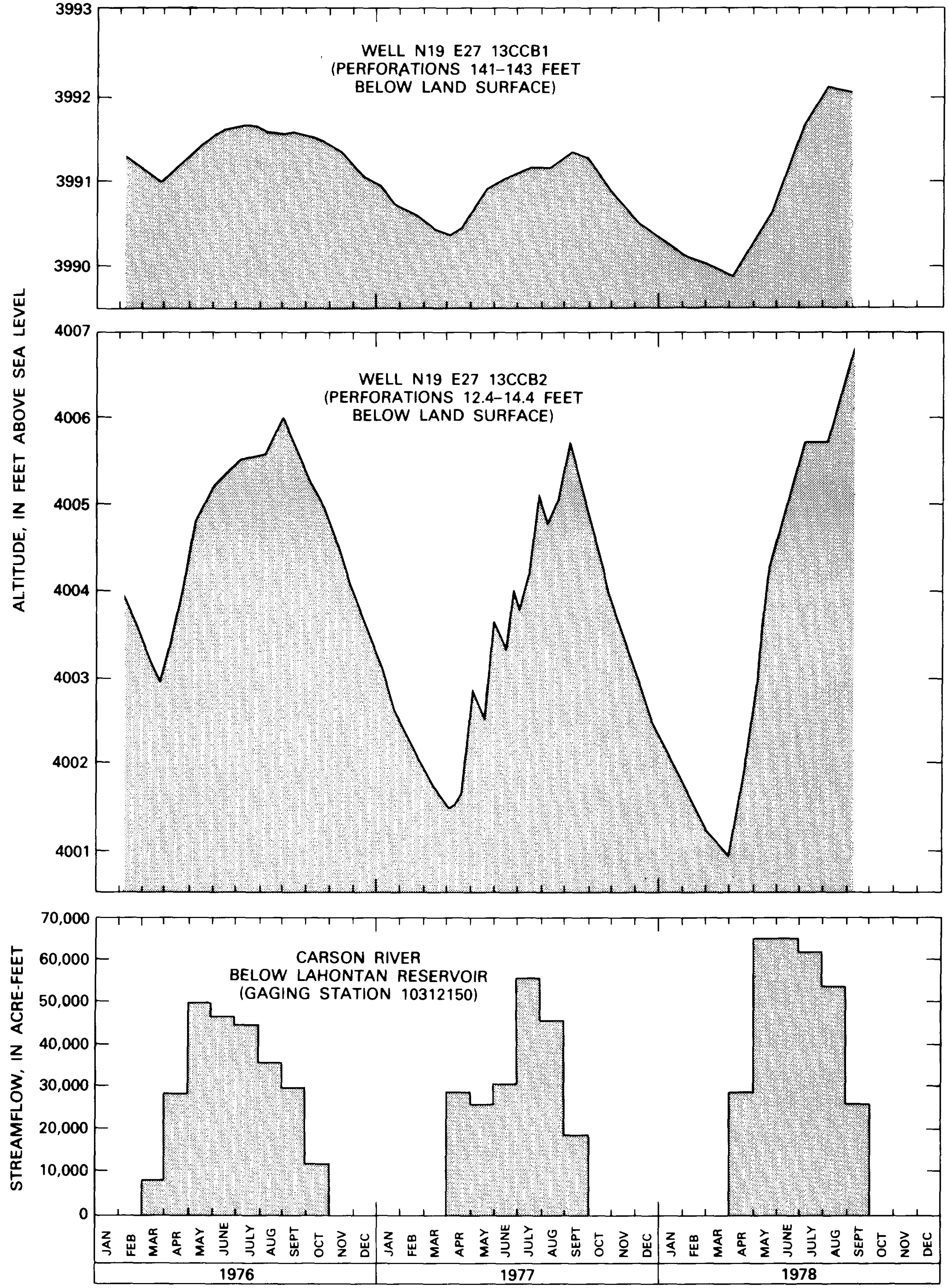

Figure 18. Relations between Carson River flow and water levels in a shallow well and an intermediate-depth well near both the river and large irrigation canals.

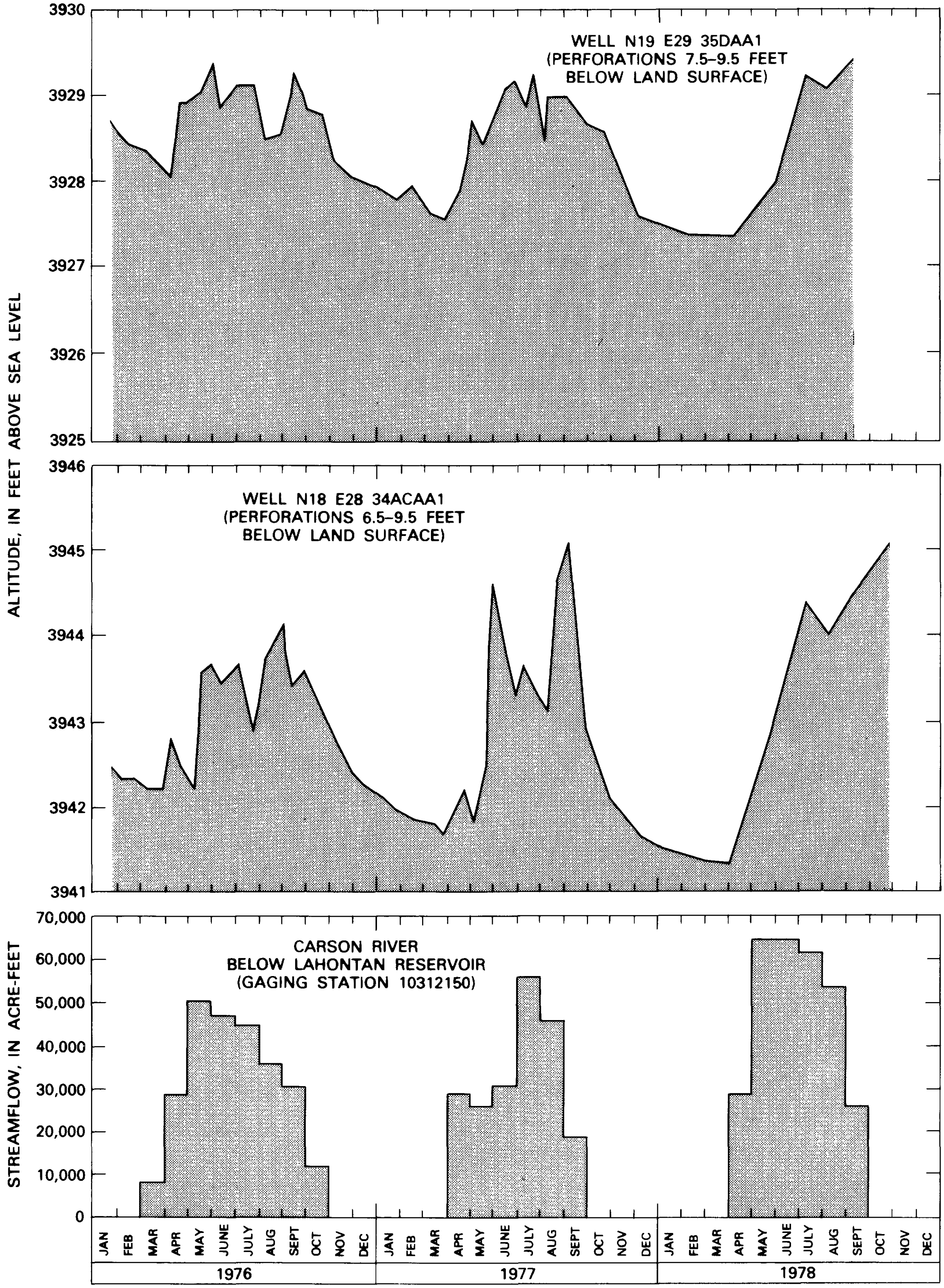

Figure 19. Relations between Carson River flow and water levels in two shallow wells remote from the river but within the irrigated area.

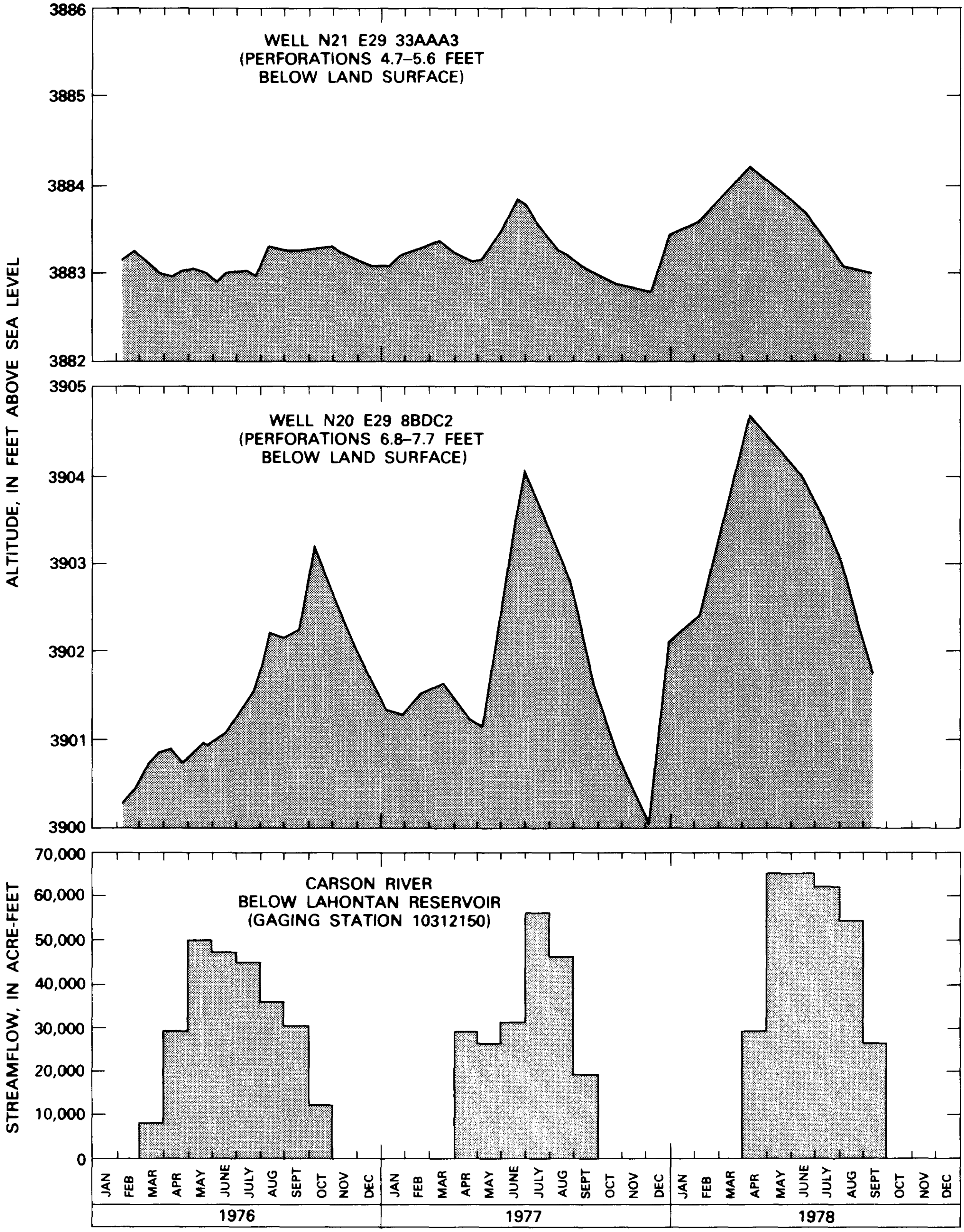

Figure 20. Relations between Carson River flow and water levels in two shallow wells remote from both the river and irrigated areas.

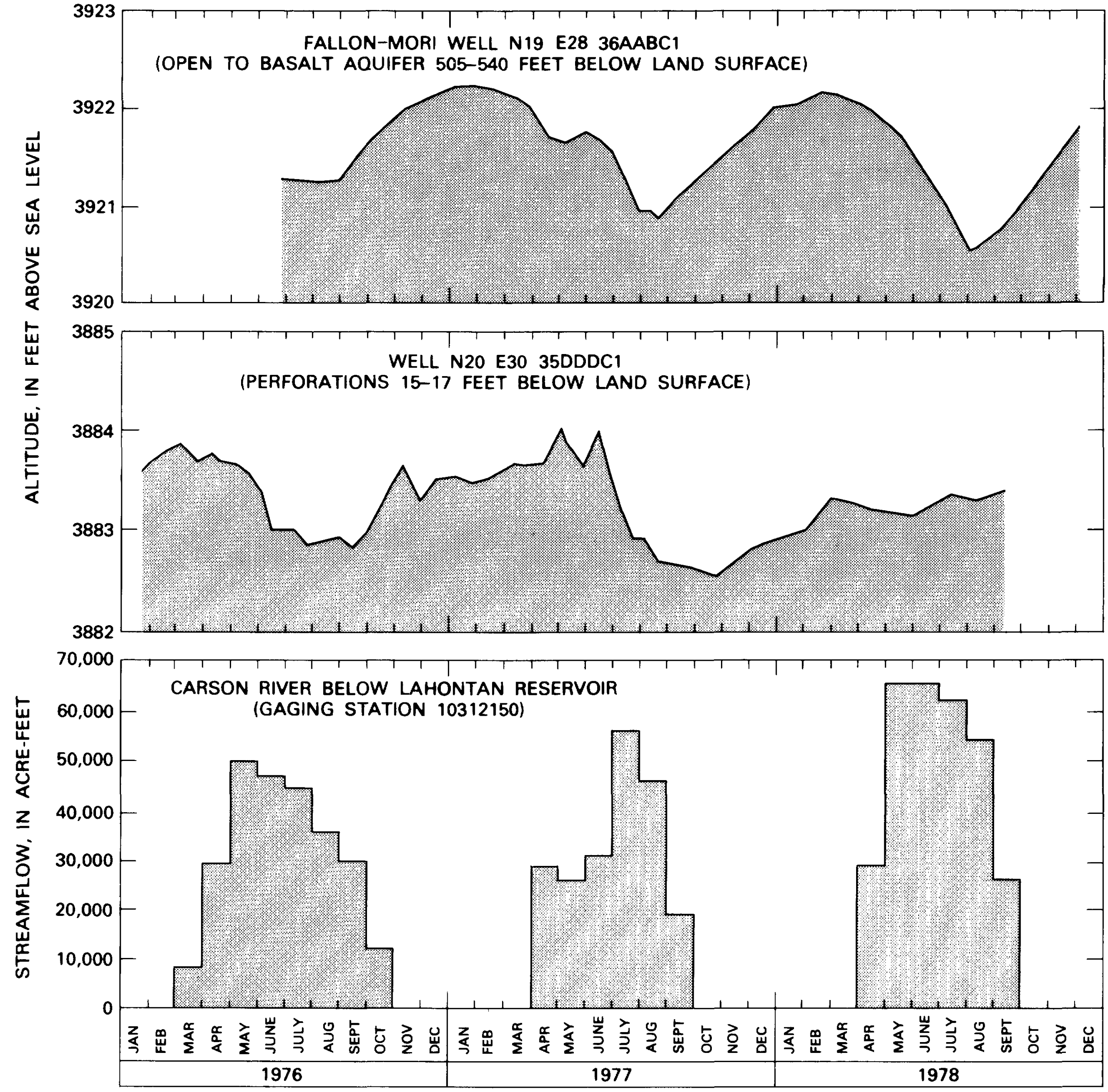

Figure 21. Relations between Carson River flow and water levels in a shallow well downgradient from irrigated areas and remote from the river, and a deep well tapping the basalt aquifer beneath Fallon.

data from sites within a particular grid element were represented by a mean hardness value at the center of the element. The resultant map, therefore, shows the generalized areal patterns of hardness throughout the aquifer but cannot be used to accurately predict the water hardness at any specific site. At best, it is a trend map. The data support the earlier cited dominance of hard water in the shallow aquifer, but the distribution suggests that the degree of hardness differs erratically within shallow-aquifer water beneath the irrigated area.

Surface inflow, the major source of ground-water recharge to the study area, almost always exhibits a hardness greater than 70 mg/L and frequently greater than 100 mg/L (Rollins, 1965, p. 29). Thus, a water hardness greater than 70 mg/L in the shallow aquifer is to be expected. The apparent softening as recharge percolates downward below the 50-ft depth represents a significant geochemical change within the ground-water flow system; it is discussed in the report section "Hydrochemical Characteristics" of the intermediate and deep alluvial aquifers.

Another feature of the shallow alluvial aquifer is the apparent extreme lateral variability of chemical character. Water of different chemical composition can be found at similar depths in lateral distances of a few tens of feet or at slightly different depths at the same site. In fact, the first attempt to machine contour the widely differing dissolved-solids concentrations for the 480 shallow-aquifer sites resulted in a confusing and uninterpretable map because of great differences in water chemistry even in adjacent wells. The second attempt, which averaged data roughly according to a 1-mi^2 grid network and which machine contoured the resulting dissolved-solids averages, attenuated some of the severe lateral variability.

Plate 1*C* shows the generalized distribution of dissolved solids throughout the shallow aquifer. Dissolved-solids concentrations of river water just below Lahontan Dam, the inflowing irrigation supply, generally ranged between 150 and 300 mg/L (Rollins, 1965, p. 29). Thus, the recharge supply is dilute with respect to sampled shallow-aquifer water. Generally, the lowest concentrations of dissolved solids in shallow-aquifer water (250–500 mg/L) are most likely west of Fallon. Concentrations tend to increase eastward (characteristic range, 500 to more than 1,000 mg/L) in the general downgradient direction of the ground-water flow system. However, exceptions to the general distributions suggested by plate 1*C* are not unusual. Because of the areal averaging technique described above, plate 1*C* should not be relied upon to locate specific sites when prospecting for chemically dilute supplies of shallow ground water.

The dissolved-solids data used for plate 1*C* have been further segregated into groups representing two periods, September to February and March to August, to ascertain the magnitude of seasonal differences (pl. 1*D*, *E*). The results suggest that the areas of more dilute concentrations generally may expand during winter and contract during summer.

Chemical data for 620 analyses of water from the approximately 480 data sites were analyzed statistically to determine whether concentrations of standard chemical constituents varied according to any seasonal pattern. A periodic regression and harmonic analysis fitted cyclic annual type curves to monthly average concentrations for each constituent. The curves suggested that maximum concentrations of almost all constituents tended to occur during the spring and summer months and that minimum concentrations were most prevalent during the autumn and winter months; however, correlations between the data and the fitted curves were poor.

The specific conductance of water samples collected periodically from a shallow domestic well at N18 E28 34ACA1 showed greater salinity in the summer than during

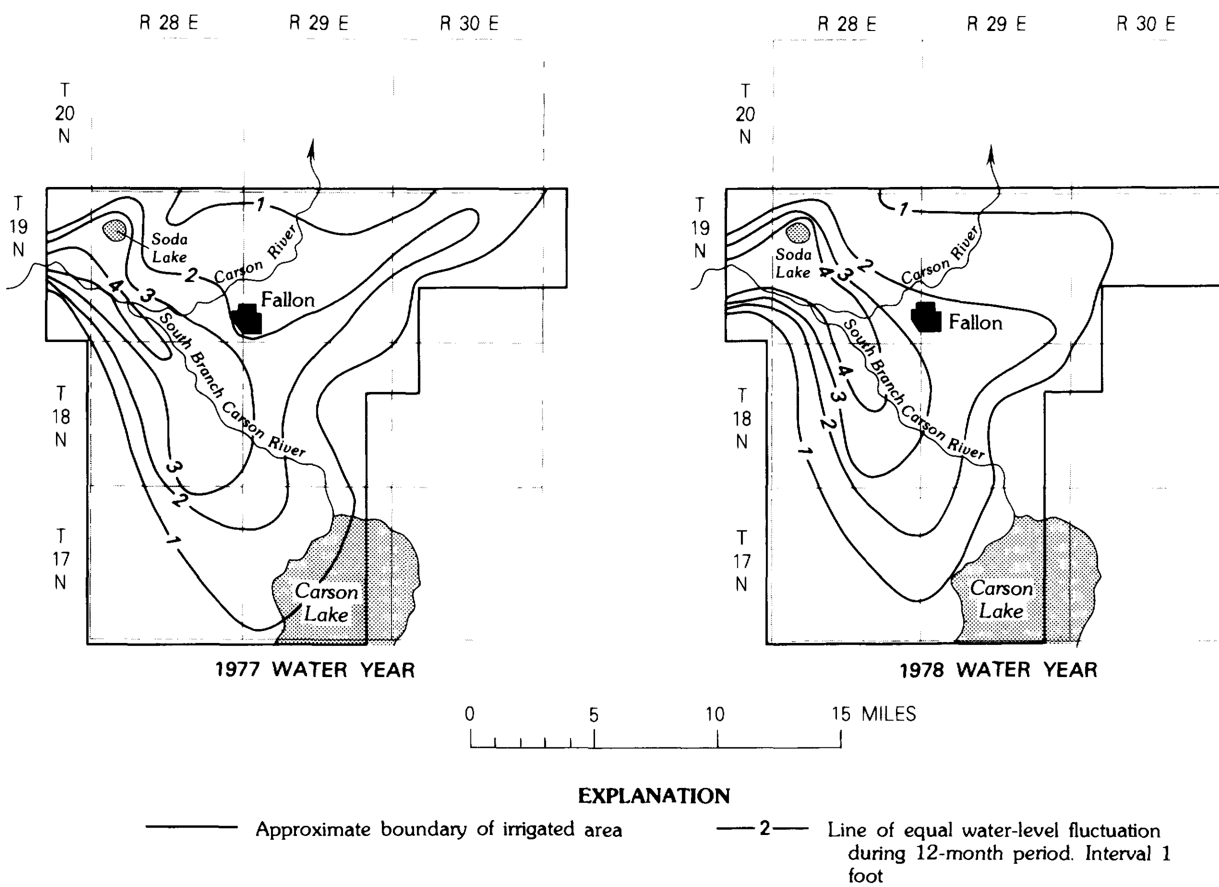

Figure 22. Range of water-level fluctuations in the shallow aquifer during the 1977 and 1978 water years.

Table 10. Estimated annual change in ground-water storage for the shallow alluvial aquifer beneath the general area of irrigation, 1977 and 1978 water years

Water-level range (feet)	Average change (feet)	Area (acres)	Aquifer volume (acre-feet)	Estimated water-storage change (acre-feet, rounded)[1]
		1977 water year		
>4	4.2	2,680	11,300	1,100
3–4	3.5	18,800	65,800	6,600
2–3	2.5	28,100	70,200	7,000
1–2	1.5	58,800	88,200	8,900
<1	.7	44,000	30,800	3,100
Total (rounded)	—	152,000	—	27,000
		1978 water year		
>4	4.8	10,800	51,800	5,200
3–4	3.5	12,400	43,400	4,300
2–3	2.5	25,400	63,500	6,400
1–2	1.5	45,900	68,800	6,900
<1	.5	57,800	28,900	2,900
Total (rounded)	—	152,000	—	26,000

[1]Assumes an average specific yield of 10 percent for the shallow alluvial aquifer.

the winter. However, dissolved-solids concentrations of water samples collected monthly for a year from a shallow domestic well at N19 E28 33 did not show a perceptible seasonal trend. Most, but not all, available data suggest that salinity fluctuates seasonally out of phase with recharge. This apparent lag in salinity might be caused by time-of-travel delays as the water moves from the surface to depths of several tens of feet. However, the great lateral and vertical variability of chemical character within the shallow aquifer suggests that widely fluctuating concentrations of different chemical constituents through time are probably the rule.

The common occurrence of dissolved-arsenic concentrations exceeding recommended health limits (0.05 mg/L) in shallow-aquifer water constitutes a serious water-quality problem in the Fallon area. The arsenic problem probably has persisted throughout the history of shallow-aquifer water use but could have been unknown to the local populace until a case of arsenic poisoning was discovered in the mid-1960's. After drinking water from a well in N19 E28 21BBCA, a girl developed severe symptoms of arsenic poisoning. Available dissolved-arsenic data for the well water showed concentrations of 1.85 and 2.75 mg/L (Nevada Bureau of Laboratories and Research and Fallon City Engineer, written commun., 1978). The well, drilled in 1963, is reportedly 36 ft deep (Mrs. M. D. Gabiola, girl's mother, oral commun., 1978). The poison victim apparently consumed normal amounts of the water over a period of 1–2 years before the progressively worsening symptoms, including fatigue, brittle hair, and severe skin discoloration (reportedly orange), were attributed to arsenic poisoning. Other family members, including other children, also consumed the water but did not exhibit the severe skin discoloration symptoms as did the confirmed poison victim. Others suffered fatigue but no other known or confirmed symptoms. A 22-ft well, only about 10 ft from the arsenic yielding well, was used by the family before 1963. Consumption of that water did not cause any known symptoms of arsenic poisoning. The 22-ft well was destroyed, and no arsenic data are available for its water; however, the apparent absence of poisoning symptoms suggests that water from the shallower well water contained considerably less arsenic

Table 11. Selected chemical analyses of water from the shallow alluvial aquifer[1]

Well location	Concentration (milligrams per liter)											
	Dissolved solids	Hardness as $CaCO_3$	Calcium	Magnesium	Sodium	Potassium	Sulfate	Chloride	Fluoride	Arsenic	Iron	Manganese
N18 E28 12AAA	429	112	34	7	[a]106	—	106	26	0.5	0.04	0.01	—
N18 E28 12AAA	854	440	120	34	103	6	189	69	.6	.005	.01	0.06
N18 E29 6DCD	604	324	92	23	92	4	99	20	.7	.02	.01	.44
N18 E29 6DDD	1,130	306	80	26	254	34	354	63	.6	.055	.07	.19
N19 E28 16AAC	369	65	21	3	94	11	60	14	.6	.015	.01	.00
N19 E28 16ABC	2,020	13	2	2	720	27	719	153	3.7	1.71	.16	.01
N19 E28 29DDD	677	204	57	15	181	5	80	15	.6	.000	1.26	.56
N19 E28 32ABA	279	144	41	10	37	3	35	12	.4	.005	.05	.01
N19 E29 23CDC	1,070	116	30	10	308	18	370	79	1.2	.48	.49	.04
N19 E29 23DBC	539	138	37	11	124	10	133	34	.6	.035	.00	.46

[1]Chemical analyses from files of Nevada Bureau of Consumer Health Protection Services.
[a]Calculated sodium plus potassium, expressed as sodium.

than water from the 36-ft well. The cumulative evidence at this site and at nearby sites suggests that arsenic concentrations have a high lateral and vertical variability in the shallow alluvial aquifer.

In contrast to the low arsenic concentrations of the Carson River (source of ground-water recharge), the widespread occurrence of high arsenic concentrations in all aquifer systems suggests that the arsenic is derived from the sediments that compose the valley fill. The distribution and source of arsenic in the sediments were not addressed by this investigation.

Available dissolved-arsenic data for water from approximately 480 shallow-aquifer wells were machine processed, plotted according to the grid-averaging scheme described earlier in this section, and machine contoured (pl. 1*F*). The map suggests great variability in dissolved-arsenic concentrations throughout the shallow aquifer.

The above discussions affirm great lateral, vertical, and probably time variability of shallow-aquifer water chemistry. Although Carson River inflow varies chemically to some degree, this variability is less than that within shallow-aquifer water. Therefore, processes within the aquifer must be responsible for much of the chemical variability of the shallow ground water. Before agricultural settlement of the study area, most of the lands now being farmed were dominated hydrologically by natural ground-water discharge. Much of the transient ground water was discharged to the atmosphere by vegetal transpiration or bare-soil evaporation, and the formerly dissolved salts remained, accumulating in the shallow soils. This accumulation of water-soluble salts was interrupted from time to time by natural redistribution, mainly by local precipitation, flooding, or wind action. The net result of those natural processes during late prehistoric times was probably a gradual, areally variable buildup of salinity within shallow soils throughout most of the study area. Agricultural developments since the turn of the century upset these natural processes to a notable degree. Although much of the farmed area continues to discharge shallow ground water to the atmosphere by evapotranspiration, the repetitive cyclic flooding of much of the area by surface irrigation has altered the disposition of salts in near-surface soils. Irrigation has tended to flush away laterally and vertically the soluble near-surface salts. The redissolved salts have moved hydraulically downgradient as both surface- and ground-water flows. One of the effects of this salt mobilization and migration has apparently been an accelerated differential deterioration of shallow ground water beneath the naturally saline surface-soil and root zones. The apparent hydraulic variability of the shallow aquifer has caused, in turn, variability in the rate and magnitude of saline migration to different depths. This is, at least partially, the cause of the uneven distribution and apparent random scattering of salinity throughout the shallow aquifer.

Changes in general salinity throughout the shallow aquifer with time have been predicted by Alan H. Welch (U.S. Geological Survey, oral commun., 1978), who used a digital two-dimensional flow model. The assessment was done to evaluate the proportional influence of several hydraulic parameters on salinity and was thus a sensitivity analysis of the several parameters. The evaluated parameters were porosity and hydraulic conductivity of the aquifer, dispersivity of the combined fluids and flow media, and rates of applied recharge to the land surface. Changes in assumed magnitudes of porosity, hydraulic conductivity, and dispersivity produced moderate changes in salinity, but the greatest potential salinity change was predicted to result from a change in the rate of applied recharge (mostly irrigation water). The model results suggest that future changes in irrigation rates should be expected to result in salinity changes in the shallow aquifer; these salinity changes might also be transmitted downward into the intermediate aquifer.

Intermediate and Deep Alluvial Aquifers

The deeper alluvial aquifers are defined as water-yielding strata in unconsolidated valley-fill deposits at depths greater than 50 ft below land surface, underlying the shallow alluvial aquifer. Almost all available hydrologic data for these aquifers were obtained from wells tapping deposits 80–150 ft below land surface (fig. 23). Data were available for about a dozen wells between 130 and about 320 ft in depth, but data for wells tapping sedimentary aquifers below 320 ft are few throughout the Carson Desert and particularly in the proximity of the basalt aquifer. As a result of these limitations, most of the discussion relating to deeper alluvial aquifers is limited to those in the 60- to 320-ft range.

The basalt aquifer, at least in its recharge areas, appears to be overlain by sediments containing dominantly

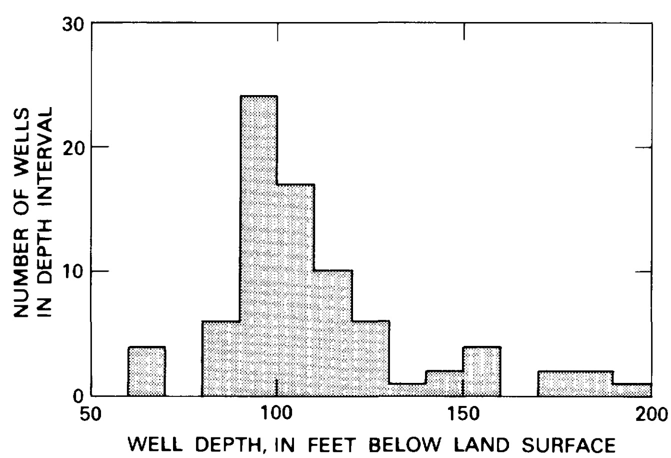

Figure 23. Depths of wells tapping the intermediate alluvial aquifer.

fresh water. This implies that sedimentary aquifers between depths of 50 and 500–1,000 ft, both above and adjacent to the basalt, are principally freshwater bearing. Also, sediments that contain freshwater to a depth of at least 150 ft extend several miles beyond the southwestern part of the basalt. For these reasons, the sedimentary deposits between 50 and about 500–1,000 ft below land surface are defined as the intermediate alluvial aquifer, and sediments below about 500–1,000 ft are defined as the deep alluvial aquifer.

Location and Extent

The intermediate and deep alluvial aquifers extend throughout the study area, except in the small areas occupied by volcanic rocks associated with Rattlesnake Hill and Upsal Hogback. Before 1974, these aquifers generally were not known to constitute a major supply of freshwater. However, drilling into the intermediate aquifer has increased during recent years and has caused a growing awareness of the presence of freshwater below the shallow aquifer in some areas. Currently (1979), about 100 wells tap the intermediate aquifer (fig. 24) and probably supply less than 1,000 people. However, drilling into this aquifer presumably will accelerate if developing knowledge continues to expand the known limits of potable water.

The deep alluvial aquifer probably extends to several thousand feet in most of the study area. However, the usable lateral and vertical limits of the intermediate and deep alluvial aquifers for potable water supplies depend on the chemical quality of their water. As mentioned earlier, a paucity of hydrologic data for depths below 320 ft severely limits knowledge of the vertical extent of currently usable water in the deeper alluvial aquifers. The presence of relatively freshwater in the basalt aquifer strongly suggests that freshwater-bearing strata extend at least to a depth of 500 ft adjacent to the southwestern part (recharge area) of the basalt. No evidence suggests that the basalt is overlain by dominantly saline water. However, the fact that basalt-aquifer water is more saline than most water from the intermediate alluvial aquifer overlying it suggests the basalt probably is underlain by saline water in the deep alluvial aquifer that mixes with the overlying dominantly freshwater to create a blend in the basalt (see p. 21). Thus, saline water may be commonplace in the sedimentary deposits at depths below about 500–1,000 ft throughout much or most of the study area. Further discussion of the chemical nature of water from the deep alluvial aquifer appears in the following section titled "Hydrochemical Characteristics."

Available data allow an estimate of the amount of generally freshwater (dissolved-solids concentration, less than about 1,000 mg/L) stored within the intermediate alluvial aquifer. The known area underlain by freshwater is about 50,000 acres. Assuming a 500-ft average thickness of saturated sediments containing freshwater and a 10-percent specific yield, the estimated recoverable freshwater in storage would be about 2.5 million acre-ft. This is more than three times the estimated amount of both freshwater and saline water stored in the shallow aquifer and thus is a significant component of the potable-water resource of the study area. Yet, it constitutes only about 5 percent of the recoverable available water stored in all valley-fill deposits throughout the study area (p. 36).

Hydraulic Characteristics

Available lithologic data show that the intermediate alluvial aquifer, above a depth of 320 ft, consists of interbedded and possibly interconnected deposits of clay, silt, and sand, with occasional stringers of gravel. It is similar in overall lithologic character to the shallow alluvial aquifer.

The depth distribution of about 80 of the approximately 100 wells tapping the intermediate aquifer was evaluated to ascertain the possibility of lateral continuity of some transmissive strata. Figure 23 shows the distribution of wells according to their depths; about two-thirds of the 80 wells are between 90 and 120 ft deep, and about four-fifths are between 80 and 130 ft. This distribution suggests that significant water-yielding deposits occur in these depth ranges and that measured water-surface altitudes for many of these wells should define the potentiometric surface of the upper part of the intermediate alluvial aquifer.

Contours based on water-surface altitudes for about 35 selected privately owned wells and about 30 U.S. Geological Survey geothermal exploration wells of similar depth (fig. 25) show the generalized potentiometric surface for the upper part of the intermediate alluvial aquifer. The contours indicate that the ground-water flow is dominantly eastward and progressively changes to northeastward in the northern part of the study area and southeastward at the southern extremity of the study area. Thus, the flow system is similar to that of the shallow aquifer (suggested by water-level contours in fig. 17) and compatible with the assumed directions of the regional ground-water flow. The average head gradient throughout the intermediate aquifer is about 6.5 ft/mi; directionally, the gradients are about 8 ft/mi to the northeast, 5 ft/mi eastward, and 6 ft/mi to the southeast. Further comparison of figures 17 and 25 shows that the overall gradients (from the known limits of inflow to the known limits of outflow) in the shallow aquifer are consistently steeper than those of the intermediate aquifer, as follows: Toward the northeast, about 20 percent steeper; toward the east, about 30 percent steeper; and toward the southeast, about 50 percent steeper. The practically flat gradient in the basalt aquifer contrasts sharply with those of the overlying shallow and intermediate alluvial aquifers.

Differences in water levels between the shallow aquifer and the upper part of the intermediate aquifer are

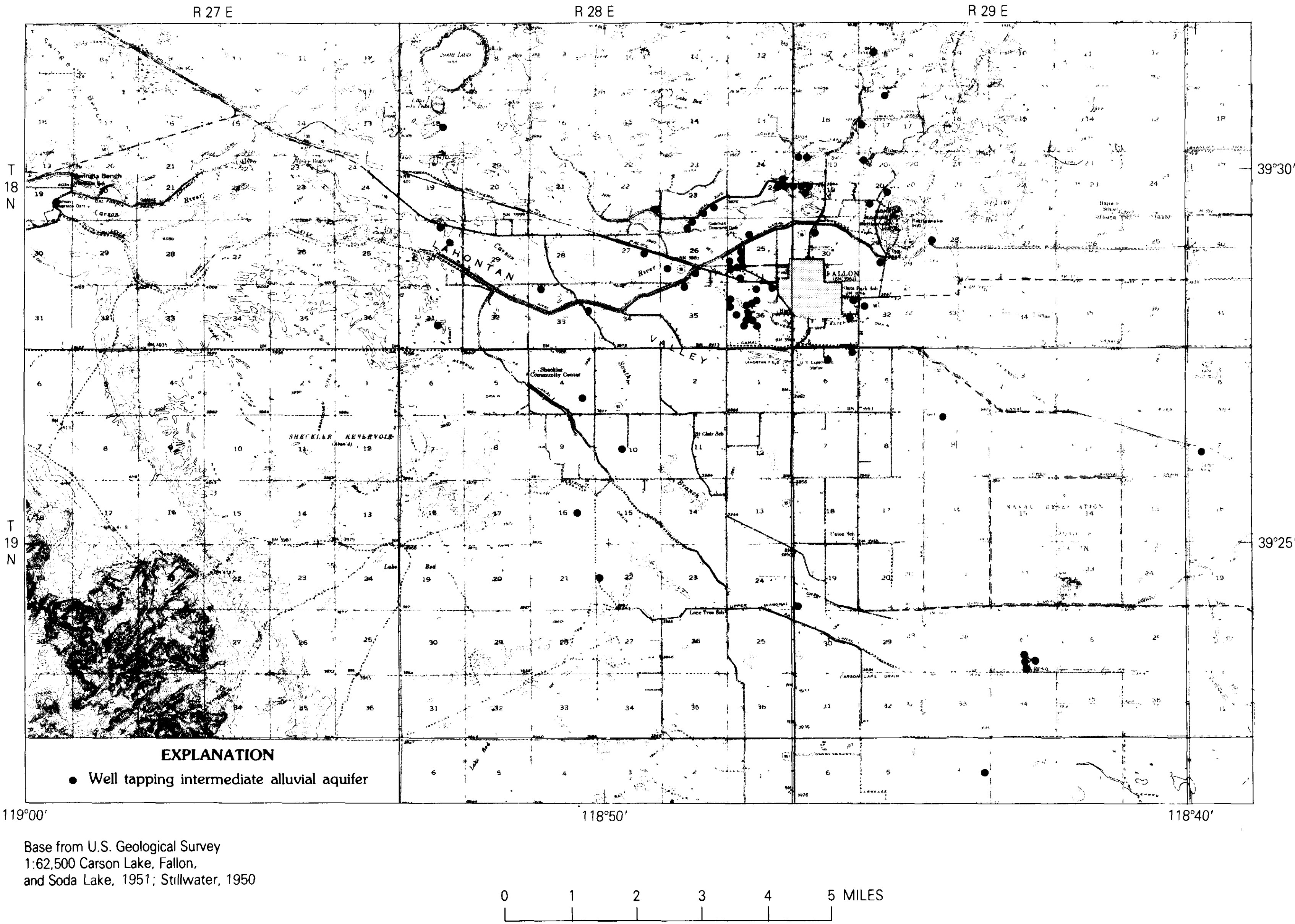

Figure 24. Wells tapping the intermediate alluvial aquifer in inhabited areas.

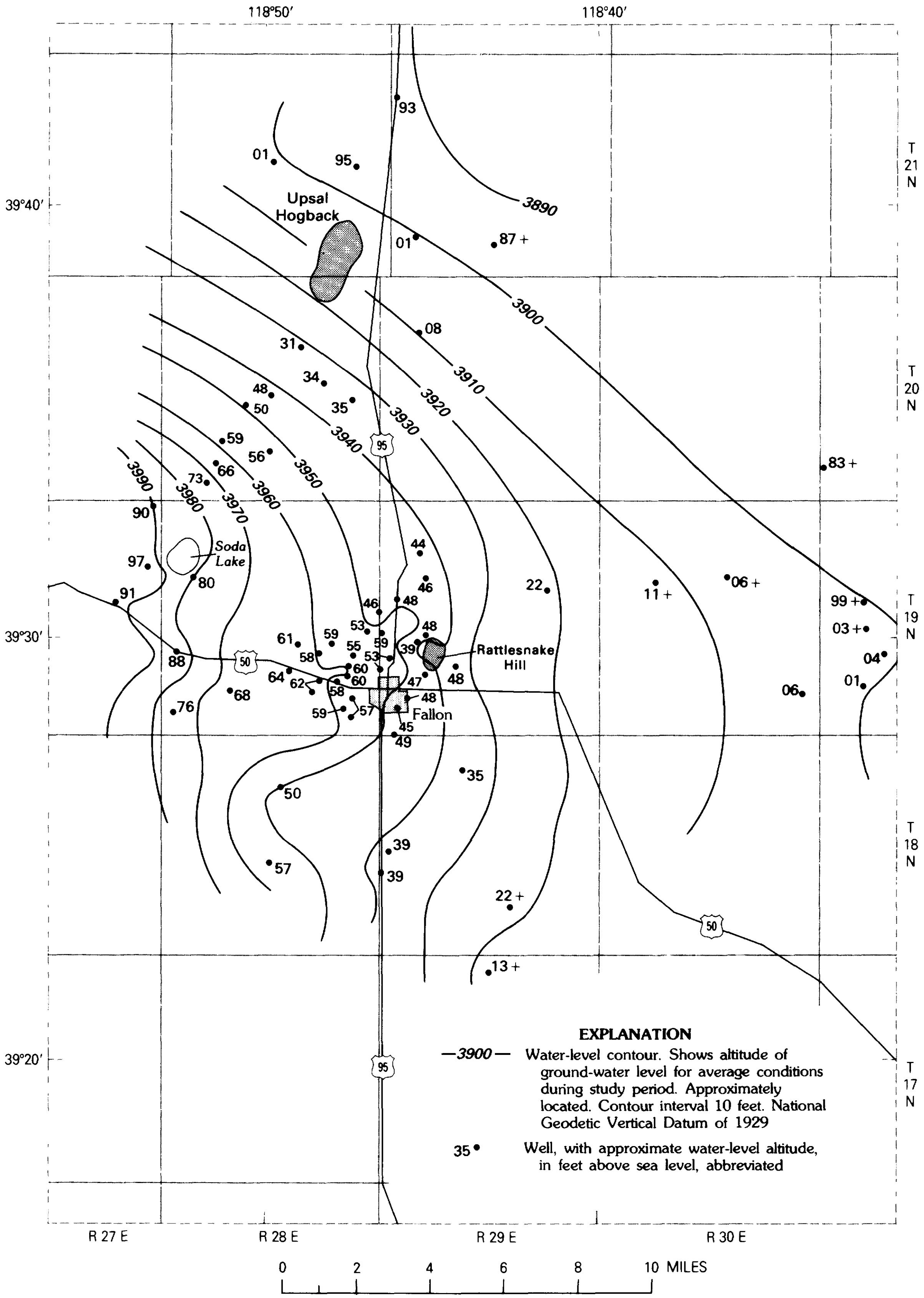

Figure 25. Generalized water-level contours for the upper part of the intermediate alluvial aquifer.

shown in figure 26. In areas of positive head difference (that is, water levels higher in the shallow aquifer than in the intermediate aquifer), the potential exists for downward recharge to the intermediate aquifer from the shallow aquifer. The overall area where such a potential exists exceeds 100 mi^2. Northeast, east, and southeast of the recharge area defined by figure 26, the intermediate aquifer exhibits a potential to discharge ground water upward into the overlying shallow aquifer. The sharp southwesterly indention of the zero contour, which is near Fallon and is roughly parallel to the present Carson River channel, suggests the presence of permeable sediments—perhaps paleoriver-channel deposits—interconnecting the two aquifers.

The demonstrated and implied hydraulic relations among the various aquifers of the study area depict a hydraulic system wherein aquifer components display hydraulic characteristics suggesting that the individual aquifers may be hydraulically independent; over the long term, however, the individual aquifers are hydraulically interdependent.

Time constraints of this study did not allow a hydraulic testing program for the intermediate or deep alluvial aquifers. Only about 15 drillers' logs contain hydraulic test data for the intermediate alluvial aquifer. They show specific capacities ranging from 0.5 to 12 (gal/min)/ft of drawdown. The available data, although possibly not representative of overall aquifer character, suggest that transmissivities are generally less than 2,000 ft^2/d, which is similar in magnitude to many of those cited above for the shallow aquifer ("Hydraulic Characteristics" of the shallow alluvial aquifer). The upper 150 ft of the intermediate alluvial aquifer exhibits many hydraulic characteristics similar to those of the shallow aquifer.

The preponderance of wells producing from the 90- to 120-ft depth zone (fig. 23) over an extensive area suggests some stratigraphic continuity over the area. The scope of this study did not allow stratigraphic correlation of drillers' logs with the several stratigraphic units defined by Morrison (1964). However, Morrison's correlations (1964, p. 148, 149) of five logs (N18 E28 4DC, N19 E27 24BB, N19 E28 33AD, N19 E29 17CB, and N19 E29 30CD) suggest that sand and gravel zones between 90 and 120 ft below land surface commonly are part of Morrison's Wyemaha Formation. The wells that Morrison correlated are scattered widely in the area encompassed by this investigation; thus, many of the wells in at least the upper part of the intermediate aquifer probably are producing from various sand and gravel zones in the Wyemaha Formation. Since Morrison's study, the large number of wells drilled that produce potable water, apparently from Wyemaha deposits, adds credibility to Morrison's (1964, p. 117) statement

> "The principal aquifer throughout the basin interior is the Wyemaha Formation, and the yields and quality of the water vary with facies changes in this formation. The most copious yields and those of the best quality are obtained within a few miles of the Carson River west of Fallon, where the Wyemaha contains many stringers of gravel and sandy gravel. Farther in the interior of the basin moderate yields of fair quality commonly are obtained from beds of lake sand in the upper part of this formation, but locally the only water either has a strong hydrogen sulfide or organic odor, or it is too saline to be potable. In some parts of the basin, notably near Carson Lake and Stillwater Slough, the Wyemaha Formation is mostly silt and clay, yields little or no water, and the water generally is highly saline."

Hydrochemical Characteristics

Knowledge of the chemical characteristics of water in the deeper alluvial aquifers is limited mostly to those of the upper part of the intermediate aquifer, with only a few scattered data for greater depths. These characteristics are notably different from those of water in the basalt aquifer and most water in the shallow alluvial aquifer. Chemical data are available for 71 wells having depths ranging from 65 to about 310 ft. These data form the basis for interpretation of the chemical composition and chemical trends of water in the intermediate aquifer. Locations of the well sites are among those shown in figure 24.

Chemical data for water from seven selected wells of the intermediate alluvial aquifer are shown in table 12. Potable water from depths of 95–312 ft is depicted chemically by analyses of water from four nearby wells in T. 19 N., R. 28 E. just west of Fallon. Nonpotable water from depths of 97–186 ft is represented by the other three sets of analytical data; these areally separated wells are several miles southeast of Fallon.

Salinities of water from the intermediate aquifer are generally areally predictable. Water from only 4 of the 71 wells (about 6 percent) showed salinities above the recommended limit of 1,000 mg/L of dissolved solids (Nevada Bureau of Consumer Health Protection Services, 1977, p. 9). Three of these four wells (the first three locations shown in table 12) are more than 5 mi east or south of Fallon and hydraulically downgradient from the natural or man-caused recharge areas. The remaining well is near Soda Lake where considerable ground-water discharge by evapotranspiration may be responsible for high salinities to depths of several tens of feet.

The remaining 94 percent of the wells yielded freshwater, with salinities as low as about 200 mg/L. This suggests that ground-water salinity in the intermediate aquifer beneath the inhabited areas near Fallon is commonly low and probably well within potable limits. This area of predictable potability extends at least 12 mi west-northwest of Fallon along the Carson River. It also may extend at least 10 mi north-northeast of Fallon along the lowermost Carson River. The distance to nonpotable water areas southeast of

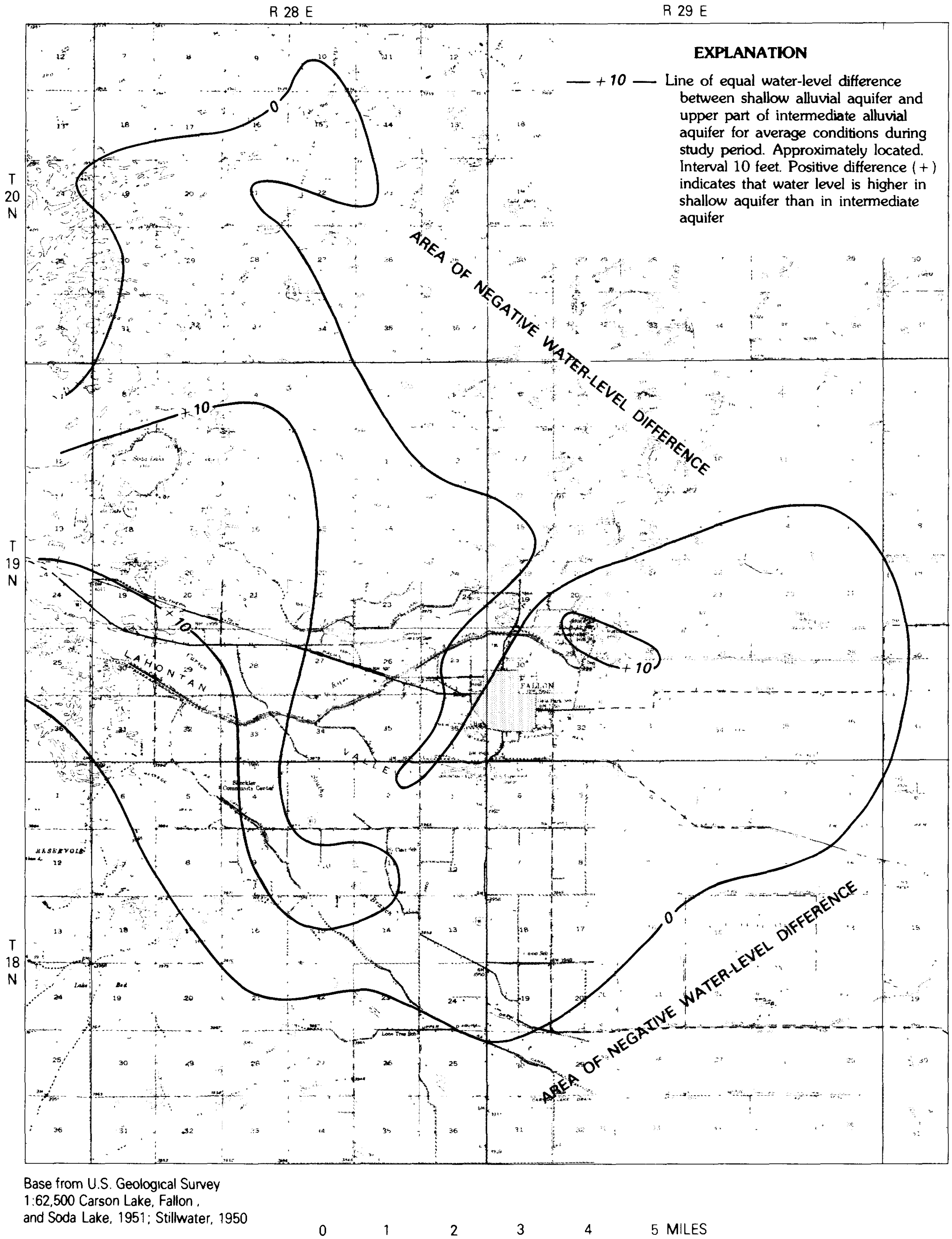

Figure 26. Differences in water level between the shallow aquifer and the upper part of the intermediate aquifer.

Fallon is much less. Plate 2*A* shows the known distribution of salinity in the intermediate alluvial aquifer.

Low to moderate hardness is a diagnostic characteristic of ground water below the shallow aquifer throughout most of the study area. The radically changing hardness of ground water within a rather narrow depth range may be explained by cation exchange, whereby calcium and magnesium ions are exchanged for sodium ions, resulting in a natural softening as the water filters both vertically and laterally through clays. The probability of contact between water and clay would be a function of distance traveled by ground water moving downward and laterally through the generally clay-rich sediments that were deposited in a dominantly fluvial-lacustrine environment. Comparisons of chemical composition of Carson River inflow with typically hard waters of the shallow alluvial aquifer and soft waters of the intermediate alluvial aquifer support the hypothesis of possible natural cation exchange as an explanation. Some other geochemical process, of course, may cause this phenomenon; however, resolution of the question probably requires additional geochemical data and additional study, which were beyond the scope of this investigation.

Plate 2*B* is a machine-contoured map showing hardness distribution within the intermediate alluvial aquifer. Of the available data for the aquifer, about three-fourths of the 71 sites yielded soft water having a hardness less than 25 mg/L, about 60 percent were less than 10 mg/L, and about 90 percent were less than 100 mg/L. Of the 19 sites having water hardness greater than 25 mg/L, 14 are west of Fallon. As generally documented by drillers' logs, sediment facies become coarser in a westward direction. If decreased hardness is a result of cation exchange between water and clay, as was hypothesized above, then the preponderance of coarser sediment facies to the west would decrease the likelihood of contact between water and clay, which, in turn, would reduce the efficiency of this natural water-softening process. Among intermediate-aquifer wells in the western part of the study area that yield hard water, about one-third are less than 90 ft deep. In contrast, only about 10 percent of the intermediate-aquifer wells are less than 90 ft deep. Thus, the preponderance of hard water to the west may be a statistical function of depth of sampling as well as decreased contact with clay. Greater hardness also tends to occur in highly saline water at the eastern extremity of the inhabited part of the study area. Thus, the soft water in the intermediate aquifer apparently occurs within only a few miles of Fallon. It is noteworthy, however, that soft water is also characteristic of the basalt aquifer.

No data were available for wells deeper than about 310 ft (that is, near the buried mass of basalt) in the sedimentary deposits near Fallon. Chemical data are available for a well 1,700 ft deep at the Fallon U.S. Naval Air Station, about 6 mi southeast of Fallon. In May 1978, the dissolved-solids concentration of that water was about 1,900 mg/L, and its hardness was 10 mg/L. During late 1977 and early

Table 12. Selected chemical analyses of water from the intermediate alluvial aquifer

Well location	Producing zone or total depth (feet)	Date sampled	Concentration (milligrams per liter)											
			Dissolved solids	Hardness as $CaCO_3$	Calcium	Magnesium	Sodium	Potassium	Sulfate	Chloride	Fluoride	Arsenic	Iron	Manganese
N17 E29 04DAAA1[a]	97	10–12–78	2,550	12	3	1	923	21	8	730	4.1	0.41	0.50	0.01
N18 E29 27DCBB1[a]	186	10–12–78	1,510	16	3	2	555	8	32	425	3.0	.33	.15	.02
N18 E30 07CBA1[a]	100	4–22–76	7,060	53	8	8	2,520	52	3	3,000	2.1	.16	.26	.05
N19 E28 24ADCC1[b]	284–312	3–08–78	188	23	7.7	.8	49	7.3	36	7	.4	.025	.23	.03
N19 E28 25CBAD1[a]	176–182	9–22–78	258	19	6	1	75	7	45	9	.4	.020	.07	.06
N19 E28 26BAAA1[b]	134	7–21–78	272	5	1.5	.3	75	6.2	65	12	.2	.031	.05	.04
N19 E28 26DDAB1[a]	95	9–28–78	212	3	1	0	66	3	38	5	.4	.040	.12	.02

[a]Chemical analysis from files of Nevada Bureau of Consumer Health Protection Services.
[b]Chemical analysis by U.S. Geological Survey.

1978, three wells were drilled for the Nevada Department of Fish and Game 15–20 mi east-northeast of Fallon. The well casings reportedly were perforated from 120 to 710 ft, 120 to 670 ft, and 120 to 680 ft below land surface. Thus, they all produce water from a thick sequence of sediments in the intermediate and deep alluvial aquifers. Salinities of the water from those wells range from about 4,000 to about 10,000 mg/L, and the water is moderately hard (about 100 mg/L). The Kennametal Upsal well (N20 E28 1ABB1, table 2, fig. 2), which produces mainly from consolidated sedimentary material between depths of 520 and 607 ft, yields water having a dissolved-solids concentration of about 5,100 mg/L and hardness of 290 mg/L.

Plate 2*C* shows the distribution of dissolved arsenic in water of the intermediate aquifer. Of 69 sites for which dissolved-arsenic data were available, water from 45 percent had concentrations equal to or less than the recommended health limit of 0.05 mg/L; water at about three-fourths of the sites had concentrations of less than 0.15 mg/L. Known concentrations do not exceed 0.42 mg/L. Thus, on the basis of these limited data, dissolved-arsenic concentrations in the intermediate aquifer may stand about an even chance of exceeding recommended drinking-water limits and roughly a 25-percent chance of exceeding maximum known concentrations in the basalt aquifer (about 0.15 mg/L). On the basis of geographical distribution of the available data, plate 2*C* generally outlines areas where acceptable concentrations of dissolved arsenic most likely would be found. As might be expected, the best prospecting area is along the river west of Fallon, in the general areas of natural recharge to the aquifer.

One chemical problem associated with the intermediate aquifer that can be perceived readily is a commonplace "swampy" odor or taste. No quantitative data were collected to evaluate this problem, but the author received many complaints from well owners and was able to qualitatively test, by odor and taste, numerous samples from wells in widely ranging locations in the study area. Although not all the wells were sampled and reports varied regarding the severity and frequency of recurrence of the problem, at least one-half of the wells tapping the system were affected adversely from time to time. The unpleasant odor and taste probably are mainly esthetic, rather than a health hazard, but the characteristics nonetheless degrade the quality of water extracted from a well for drinking purposes.

The source of the odor and taste is believed to be the release of hydrogen sulfide gas as water is pumped to the land surface; the released gas formerly was dissolved in the water under the natural temperature and pressure conditions in the aquifer. Thus, a logical solution to the problem would be to remove the gas by heating, aerating, or chemically stripping.

The hydrogen sulfide gas annoyance will probably increase as use of the aquifer accelerates. Most complainants who experience seasonally fluctuating problems with the "swamp" gas commonly note that the severity increases during periods of heavy pumping. This probably is because increased local or regional pumping decreases hydraulic pressures in the aquifer; as aquifer pressures decrease, the pressure disequilibrium accelerates recharge from adjacent, less permeable strata. The less permeable recharging strata of the Fallon area are usually lacustrine clay beds that commonly contain appreciable amounts of decomposed organic material rich in hydrogen sulfide decomposition products. Thus, the recharging water commonly contains dissolved hydrogen sulfide of organic origin that contaminates the less concentrated aquifer water.

Increased tapping of deeper aquifers, notably the basalt aquifer, was earlier shown ("Mathematical Analysis of Recharge and Discharge" of the basalt aquifer section of this report) to induce recharge from overlying strata. The same result should be expected when the intermediate alluvial aquifer is increasingly stressed by accelerated pumping. Descending recharge water, mainly from the Carson River by way of the shallow aquifer, will bring in a dissolved chemical load. Man's historical influence on shallow-aquifer chemistry, namely the downward mobilization of soluble salts by infiltrating irrigation water, was discussed in the report section titled "Hydrochemical Characteristics" of the shallow alluvial aquifer. Increased saline input to the deeper aquifers is likely because numerous data depict the shallow-aquifer water as commonly more saline than much of the intermediate-aquifer water. If salinity of inflowing river water increases because of upstream pollution, the chemical deterioration of the shallow and deeper aquifers will be further compounded.

CONCLUSIONS

In the Fallon area, the ground-water reservoir, which extends to a depth of several thousand feet, can be subdivided, for purposes of water-resources development, into four major aquifers: basalt, shallow alluvial, intermediate alluvial, and deep alluvial aquifer (see p. 6 for discussion of the term "alluvial"). The principal features of each aquifer are described below.

Basalt Aquifer

The basalt aquifer, which is the most prolific in the Fallon area, mainly supplies the city of Fallon and the U.S. Naval Air Station nearby and, during 1978, yielded about 1,720 acre-ft. It consists mostly of buried basaltic lava flows and cinders deposited by volcanic eruptions that ultimately produced Rattlesnake Hill. The basalt aquifer has supplied municipal water demands since 1941; through the 1978 water year, it had yielded a total, for all uses, of about 35,000 acre-ft of water.

Electrical-resistivity soundings and well drillers' data helped to physically characterize the basalt aquifer as follows: The upper basalt surface, excluding the Rattlesnake Hill protrusion, ranges from about 200 to about 600 ft below land surface. The map area of buried basalt appears to be about 33 mi^2, is elongate in shape, alined in a northeasterly direction from Fallon, and is about 10 mi in length and averages roughly 3.5 mi in width. In the subsurface, it appears to have the general shape of an asymmetrical, northeast-southwest-alined, mushroom-shaped body spread laterally over the deep alluvial aquifer and perched on top of a basaltic stock that descends to an ancient magma chamber below the valley fill. The basalt mass is capped near its southwest extremity by the peaked volcanic cone of Rattlesnake Hill, which protrudes about 200 ft above the surrounding land surface. The basalt aquifer is encased mainly by fluvial and lacustrine sediments of the intermediate and deep alluvial aquifers.

The basalt aquifer is highly transmissive to the extent that only minor head differences exist in its potentiometric water surface throughout its areal extent. Transmissivity of the aquifer may be as much as 1.5 million ft^2/d.

The basalt aquifer is recharged by infiltration of water from surrounding sediments. Under current municipal pumping stresses, it evidences strong vertical recharge from overlying sediments and minor recharge from deeper sediments. Isotopic evidence suggests that some recharge has transited from the land surface to a depth of at least 500 ft during the past 25 years. The rate of vertical movement of water downward from the land surface appears to be related to the degree of pumping stress. The principal and long-term source of recharge to the basalt is the Carson River. Calculations suggest a current recharge rate to the basalt of about 3,400 acre-ft/yr. Prepumping recharge is suggested by the calculation to have been about 2,500 acre-ft/yr. The difference, about 900 acre-ft/yr, presumably was induced by pumping. Calculations suggest, and historical water-level data generally verify, that historical pumping from the basalt aquifer has lowered the artesian head 4–5.5 ft. The calculations predict that a pumping rate of 8,500 acre-ft/yr will cause a net lowering of the artesian head of about 28 ft; at about that stage, the nonpumping discharge from the basalt aquifer should cease.

Chemical data characterize basalt-aquifer water as soft and quite homogeneous, having a dissolved-solids concentration of 500–660 mg/L throughout. The chemical quality of the aquifer's water appears to deteriorate somewhat in a northeasterly direction. Limited data suggest that no perceptible chemical change has occurred throughout the basalt aquifer during the historical period of pumping. Isotopic and standard chemical data suggest that water flows from southwest to northeast through the system, congruent with the regional ground-water flow through the overlying valley-fill deposits. Arithmetic comparisons of the dissolved-solids concentrations of water from the basalt aquifer (average, 575 mg/L), from the overlying intermediate alluvial aquifer (average, 230 mg/L), and from the underlying deep alluvial aquifer (range of hypothetical values, 1,500–10,000 mg/L) suggest that the basalt-aquifer water represents a blend of 73–93 percent overlying freshwater and 7–27 percent underlying saline water. The concentration of arsenic in basalt water (commonly ranging from 0.08 to 0.15 mg/L) is believed to be mainly indigenous to the recharge water from surrounding sediments.

Shallow Alluvial Aquifer

The shallow alluvial aquifer (transmissive zones to a depth of 50 ft below land surface) currently supplies more than one-half of the population of the Fallon area with an aggregate pumpage that represents more than one-half of the total ground water annually pumped in the area. This pumpage is supplied by 3,000–4,000 wells. The part of the shallow aquifer containing potable water generally underlies or is adjacent to the irrigated acreage of the Fallon area. The estimated ground water stored in the shallow aquifer within the 270-mi^2 study area is about 730,000 acre-ft. Not all of this water is potable.

Hydraulic characteristics of the shallow aquifer appear to vary greatly from place to place and with depth. This variation is largely the result of complex stratigraphic relations and rapidly changing sedimentary facies. Water-table gradients of the shallow aquifer average a little more than 7 ft/mi. Specific-capacity data for wells in the shallow aquifer also vary greatly, but geographic trends are apparent. Highest specific capacities, and thus highest transmissivities, probably occur in the hydraulically upgradient, western parts of the study area along geologically recent routes of the Carson River. Highest transmissivities may be as much as 13,000 ft^2/d, but values more commonly may be less than 2,000 ft^2/d.

Irrigation is related seasonally to river flows, and shallow-aquifer water levels fluctuate in response to changing riverflows and rates of irrigation. The phase relations between water-level rises or falls in the shalllow aquifer and increases or decreases in irrigation or surface-water flows depend, to a large degree, on the lateral proximity of wells to the river, canals, or irrigated fields. Seasonal water-table fluctuations of the shallow aquifer commonly ranged from more than 2 ft throughout much of the irrigated area to as much as 6 ft locally. In contrast, they often fluctuated less than 1 ft and, in desert areas, less than 0.5 ft. Seasonal water-table fluctuations indicate changes in ground-water storage within the shallow-aquifer system; the estimated annual storage changes, in turn, approximate annual recharge to and discharge from the shallow aquifer. During the study period, the recharge and discharge each ranged from 25,000 to 30,000 acre-ft/yr, which is 7–8 percent of the average annual flow rate of river and canal water into the study area.

Chemical characteristics of water in the shallow aquifer are as diverse and variable as the hydraulic characteristics. Salinities range from that of inflowing river water (150–300 mg/L) to thousands of milligrams per liter. Diversity and variability are interpreted to result, at least partly, from the mobilization of soluble salts near the land surface by irrigation water and the nonuniform downward movement of these redissolved salts by infiltration of the irrigation water. Although water salinities in the shallow aquifer beneath irrigated lands are erratic and generally unpredictable, the salinity characteristically tends to increase downgradient geographically, and potable shallow ground water is uncommon beneath the downstream extremities of irrigated lands or beneath unirrigated desert areas. Statistical manipulations of large amounts of shallow-aquifer chemical data weakly suggest seasonal fluctuations in concentrations of most chemical characteristics and also suggest that those fluctuations are out of phase with apparent recharge pulses. This apparent phase difference is interpreted as a time-of-travel lag of recharge to deeper parts of the shallow aquifer.

Water of the shallow aquifer is dominantly hard. It is not commonly softer than inflowing river water (generally greater than 70 mg/L).

Concentrations of dissolved arsenic in shallow-aquifer water are commonly greater than the recommended drinking-water limit, and at least one case of arsenic poisoning is known. Arsenic concentrations generally are believed to be impossible to predict at specific sites when prospecting for potable water in the shallow aquifer. This study, however, suggests general geographic trends in arsenic concentration throughout the shallow-aquifer system. The absence of deleterious concentrations of dissolved arsenic in inflowing surface water that recharges the system, and the erratic, but widespread, occurrences of high concentrations in shallow ground water suggest that the arsenic is being derived in large part from the sediments composing upper layers of valley fill.

The proximity of the shallow aquifer to the land surface renders it particularly vulnerable to pollution by man. This pollution poses the further hazard that deeper aquifers, in turn, will become polluted.

Intermediate and Deep Alluvial Aquifers

The shallow alluvial aquifer is underlain by deeper alluvial aquifers generally to depths of about 3,000 ft and possibly locally of more than 8,000 ft. The volume of recoverable water stored in the valley-fill sedimentary deposits beneath the study area to a depth of 3,000 ft is roughly estimated to be about 50 million acre-ft; in contrast, the volume stored in valley fill beneath the entire Carson Desert may be approximately 200 million acre-ft. The deeper aquifers can be subdivided into an intermediate-depth alluvial aquifer that contains freshwater near Fallon and a deep alluvial aquifer that is believed to be largely saline.

Intermediate Alluvial Aquifer

An intermediate-depth, predominantly freshwater aquifer underlies an area with a radius of probably not less than 3 mi surrounding Fallon and extends up to 12 mi west of Fallon. Its southwestern limits are unknown but appear to be at least 6 mi from Fallon. The freshwater may extend more than 10 mi north-northeast of Fallon along the course of the Carson River. The intermediate, freshwater alluvial aquifer probably extends from a depth of 50 ft (base of the shallow aquifer) to a depth of at least 500 ft at Fallon, but its thickness elsewhere is generally unknown. The quantity of recoverable water stored in the intermediate aquifer is roughly estimated at about 2.5 million acre-ft on the basis of its currently known areal limits and assumed thickness and specific yield. Knowledge gained from recent drilling activity has been expanding the known geographic limits of the aquifer.

The average potentiometric gradient of the intermediate aquifer is about 6.5 ft/mi, similar to that of the shallow alluvial aquifer and the general land surface. Limited data suggest that transmissivities of the system are commonly less than 2,000 ft^2/d. The shallow alluvial aquifer has the potential to recharge the intermediate aquifer over an area of at least 100 mi^2. Most of the wells producing potable water from the intermediate aquifer seem to be tapping transmissive zones in the Pleistocene Wyemaha Formation.

The intermediate aquifer system commonly contains soft water east of a zone a few miles west of Fallon; west of that zone, the water is notably harder. The extreme softness of water in the Fallon area probably results from cation exchange processes as the water comes in contact with lacustrine clay during its downward and eastward movement. The chemical character of the intermediate depth water is laterally and vertically more stable and predictable than that of the shallow-aquifer water. Arsenic concentrations exceeding the recommended limit for municipal supply are common in water of the intermediate aquifer. Risk of encountering high concentrations of arsenic tends to decrease generally westward from Fallon. Arsenic is believed to be derived from the recharging shallow-aquifer water and may be increased by the pickup of more arsenic from intermediate-depth sediments.

Water from the intermediate-depth aquifer near Fallon commonly smells bad and tastes "swampy." The odor probably is imparted to the water by hydrogen sulfide gas associated with decaying organic materials trapped in lacustrine clays. Increased pumping probably will increase the release of hydrogen sulfide, but the problem may be alleviated by mechanically or chemically treating the water.

The intermediate aquifer receives its recharge from the shallow aquifer and is thus subject to pollution from that source. Likewise, the intermediate aquifer recharges the basalt aquifer and thereby potentially transmits pollutants to it.

Deep Alluvial Aquifer

The deep alluvial aquifer probably extends beneath the entire study area and directly underlies the basalt aquifer. Locally, it may range in thickness from a few hundred feet to more than 8,000 ft. Its hydraulic characteristics are generally unknown, and its water probably is too saline to be potable in most places. Little is known about the chemical character of deep-aquifer water, but a few data suggest that dissolved-solids concentrations everywhere probably exceed 1,000 mg/L, may average around 5,000 mg/L, and locally may greatly exceed 5,000 mg/L.

FUTURE STUDY NEEDS

This study shows that aquifers of the Fallon area are interdependent parts of a ground-water reservoir that depends mainly on the inflow of the Carson River from Lahontan Reservoir for its replenishment and maintenance. The investigation did not attempt to assess quantitatively the effects on individual aquifer-system components caused by chemical and physical changes within other interactive system components nor to quantify the effects of changes in riverflow. Future studies will need to address quantitatively these interactions. The present state of hydrologic technology suggests that these interactive processes might be understood, and cause-and-effect relations might be best predicted, by using the techniques of digital modeling.

Knowledge is needed regarding a number of hydrologic parameters to ensure that an accurate and efficient digital-modeling program can be realized. Some of the more important data needs are as follows:

1. A quantitative assessment of the Truckee Canal and adjacent areas on Swingle Bench to evaluate diversion rates, seepage losses, irrigation infiltration, and details of water quality for these surface flows and the infiltrating water.
2. A water-quality assessment of outflows from Lahontan Reservoir to ascertain in detail the chemical characteristics of the major inflow to the Fallon area.
3. Accurate quantitative information on the distribution, application, and drainage of irrigation water throughout the Carson Desert, including an areal and time-related evaluation of water-quality differences.
4. Additional quantitative data on the hydraulic characteristics of all four aquifers—particularly, accurate pumpage-drawdown data for the alluvial aquifers and time-related water-level changes in the individual aquifers.
5. Borehole geophysical data for selected wells in all aquifers to help delineate aquifer lithologies and the three-dimensional extent of water-bearing zones.
6. Geophysical data that will determine accurately depths to the top and bottom of the basalt, check the accuracy of the electrical-resistivity thickness interpretations of this investigation, and develop knowledge relating to the natural ground-water discharge processes.
7. Geophysical data that will allow reasonably accurate contouring of the consolidated rock floor of the basin and provide knowledge of the stratigraphy of the thick valley-fill deposits.
8. Data that will properly characterize ground-water hydrology of the Stillwater area.
9. Data from wells drilled through the basalt that will properly characterize the physical and chemical hydrology of underlying sediments in contact with the basalt.
10. Additional aresenic data, including multiple samples from individual wells to evaluate changes in arsenic concentrations with time at a specific site. These data are needed particularly for the intermediate alluvial aquifer.
11. Pesticide and herbicide data for ground water of all aquifers.

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CONVERSION FACTORS AND ABBREVIATIONS

Except for water-quality units of measure, only the inch-pound system is used in this report. Abbreviations and conversion factors from inch-pound to International System (SI) units are listed below.

Multiply	By	To obtain
Acre-feet (acre-ft)	0.001233	Cubic hectometers (hm^3)
Acres	0.4047	Hectares (ha)
Feet (ft)	0.3048	Meters (m)
Feet per mile (ft/mi)	0.1894	Meters per kilometer (m/km)
Feet squared per day (ft^2/d)	0.0929	Meters squared per day (m^2/d)
Gallons (gal)	3.785	Liters (L)
Gallons per minute (gal/min)	0.06309	Liters per second (L/s)
Gallons per minute per foot [(gal/min)/ft]	0.2070	Liters per second per meter [(L/s)/m]
Inches (in.)	25.40	Millimeters (mm)
Miles (mi)	1.609	Kilometers (km)
Square feet (ft^2)	0.09290	Square meters (m^2)
Square miles (mi^2)	2.590	Square kilometers (km^2)

Water-quality units of measure used in this report are as follows:

For concentration, milligrams per liter (mg/L) and micrograms per liter (μg/L), which are equivalent to parts per million and parts per billion for dissolved-solids concentrations less than about 7,000 mg/L.

For isotope ratios, permil (‰).

For temperature, degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by using the formula °F = [(1.8)(°C)] +32.

For specific conductance, micromhos per centimeter at 25°C (μmho).

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."