Distribution of Carbonate-Rock Aquifers and the Potential for Their Development, Southern Nevada and Adjacent Parts of California, Arizona, and Utah

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 91-4146

Prepared in cooperation with the
STATE OF NEVADA,
LAS VEGAS VALLEY WATER DISTRICT, and
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By Michael D. Dettinger, James R. Harrill, and Dwight L. Schmidt,
U.S. Geological Survey, and John W. Hess, Desert Research Institute

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Carson City, Nevada
1995

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

U.S. GEOLOGICAL SURVEY
GORDON P. EATON, Director

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre	0.4047	square hectometer
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
cubic foot (ft^3)	0.02832	cubic meter
cubic mile (mi^3)	4.168	cubic kilometer
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second
gallon per minute per foot [(gal/min)ft]	0.2070	liter per second per meter
inch (in.)	25.4	millimeter
inch per year (in/yr)	25.4	millimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Temperature: Degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) by using the formula °F = [1.8(°C)]+32. Degrees Fahrenheit can be converted to degrees Celsius by using the formula °C = 0.556(°F-32).

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929, formerly called "Sea-Level Datum of 1929"), which is derived from a general adjustment of the first-order leveling networks of the United States and Canada.

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By Michael D. Dettinger, James R. Harrill, *and* Dwight L. Schmidt, U.S. Geological Survey, *and* John W. Hess, Desert Research Institute

ABSTRACT

In 1985, the State of Nevada entered into a cooperative effort with the U.S. Department of the Interior to study and test the State's carbonate-rock aquifers. The work was funded by several agencies and done by the U.S. Geological Survey, the Desert Research Institute, and the Bureau of Reclamation. The studies were focused on southern Nevada, mostly north of Las Vegas and south of Pioche and Tonopah, and were intended to address the following basic concerns:

- Where is water potentially available in the aquifers?
- How much water potentially can be withdrawn from aquifers?
- What effects might result from development of the aquifers?

Several types of basic hydrologic data were collected in eastern and southern Nevada, including measurements of (1) precipitation at high-altitude sites; (2) discharge at representative springs; (3) water levels in wells open to the carbonate-rock aquifers; and (4) meteorological conditions used to estimate evapotranspiration rates by native plants. Geology was mapped in an area of about 1,800 square miles north of Las Vegas and centered on the Sheep Range, emphasizing carbonate rocks and younger sediments. Surface geophysical measurements were made to estimate thicknesses of basin-fill aquifers overlying the carbonate-rock aquifers and to locate faults deep beneath land surface. Water samples were collected and analyzed to characterize ground-water quality, to delineate flow paths, to update water budgets, and to identify flow and mixing rates in six parts of southern Nevada, including the Spring Mountains, Las Vegas Valley, the Ash Meadows area, and the Muddy River Springs area. Nine wells were drilled (a total of about 4,500 feet in basin fill and 5,500 feet in carbonate rocks) and two abandoned wells in key locations were rehabilitated. Borehole-geophysical logs were collected from selected depth intervals in all these wells and in four wells drilled during the MX-missile siting investigation. The aquifers were tested at three of the new wells and at three of the MX wells during 1985-88 to determine transmissivity. Results from reports of drill-stem tests in 13 petroleum-exploration wells and aquifer tests at 33 other wells in the carbonate-rock aquifers of Nevada were compiled. Finally, these results were synthesized to answer the three basic concerns listed above.

The carbonate rocks of southern Nevada were deposited as layers of ancient marine sediment that cumulatively were as much as 40,000 feet thick. The carbonate-rock layers—because of their brittleness and tendency to dissolve into flowing water—are believed to be the principal water-bearing (or aquifer) zones within these ancient sediments.

Although the carbonate rocks were deposited as widespread layers, geologic forces subsequently deformed the rocks into innumerable blocks and folded rock masses of all sizes.

Because of this deformation, rocks of widely differing geologic age are intermingled, and the distribution of rocks that constitute aquifers is greatly complicated. Also, as a result of the action of those forces, much of southern Nevada is underlain by areas where the carbonate rocks remain only as isolated blocks. In contrast, the central third of southern Nevada is underlain by north-south corridors of thick, laterally continuous carbonate rocks. North of Las Vegas, within the central corridor, two areas are underlain by thick and relatively continuous carbonate rocks that are connected to a similarly thick carbonate-rock mass farther north. The thick carbonate rocks probably contain the principal conduits for regional flow from east-central Nevada into southern Nevada, with the flow ultimately discharging at Ash Meadows and Death Valley, and at the Muddy River Springs. Farther south, the thick carbonate rocks underlie the Spring Mountains-Pahrump Valley area. Water flowing through these rocks at this latitude is derived mostly from recharging snowmelt in the Spring Mountains, which flows radially away to discharge near Tecopa, in Pahrump Valley, at Indian Springs, and (in the past) at Las Vegas Springs.

Some zones within the central corridor are highly transmissive, and the present study developed the hypothesis that these zones function as large-scale drains, collecting water from less transmissive rock that underlies most of the study area. The drains probably conduct much of the flow that discharges at large regional springs. The present study also hypotheses that such zones stay highly transmissive only if large volumes of water continue to flow through them. Otherwise, openings in the rock gradually close and the rock reconsolidates. The practical implication of these hypotheses is that wells that tap conduits of concentrated regional flow probably will be most productive.

Natural recharge in the mountains of southern Nevada has been estimated to total about 140,000 acre-feet annually, of which about 110,000 acre-feet is from within the central corridor of thick carbonate-rock aquifers. In addition to ground-water recharge in southern Nevada, geochemical balances computed in the present study indicate that another 21,000 acre-feet per year is supplied to southern Nevada by inflow through carbonate-rock aquifers from east-central Nevada.

Discharge at regional springs and by flow out of the study area through carbonate rocks that extend into California totals about 77,000 acre-feet from carbonate-rock aquifers of the central corridor. The remaining water either leaks upward into the basin fill or directly recharges the basin fill, and ultimately discharges at local springs, playas, meadows, and streams. Previous studies have estimated that the natural discharge from basin-fill aquifers in the central corridor is about 50,000 acre-feet per year. A review of aquifer conditions within and along the boundaries of the central corridor indicates that only along the California border are the carbonate-rock aquifers continuous enough to transmit large quantities of water to areas where its discharge at land surface could have been overlooked in this study.

The perennial yield of the carbonate-rock aquifers cannot exceed the total flow through them. However, part of this flow discharges by leaking into adjacent basin-fill aquifers. The perennial yield of the carbonate-rock aquifers of southern Nevada, as a result, is defined in terms of the remainder of the total flow, which is no more than the combined rates of discharge at regional springs in southern Nevada and at discharge areas in the Death Valley region (total, about 77,000 acre-feet per year).

The other component of the carbonate-rock water resources is the large volume of water stored in the rocks. Because of the areal extent and great thickness of the carbonate rocks in the central corridor, the total volume of rock is enormous. Assuming that about 0.01 cubic foot of recoverable water is stored in each cubic foot of aquifer, the total quantity of water stored in the carbonate rocks south of Pioche and Tonopah would be on the order of 800 million acre-feet. For practical purposes, not all this water can be extracted. However, if an average of 100 feet of the aquifer's thickness could be dewatered, the central corridor could yield a volume of stored water on the order of 6 million acre-feet; once depleted, however, that resource would be replenished only by the equivalent of decades or centuries of recharge.

Ultimately, long-term development of the carbonate-rock aquifers would result in depletion of stored water, or in the capture of water that otherwise would discharge from the aquifers of southern Nevada and vicinity, or both. Possible effects of developing the carbonate-rock aquifers include declining water levels, decreasing springflow rates, drying up of some streams, playas, and meadows, and changing water quality.

Sustained effects within the carbonate-rock aquifers resulting from development of those aquifers have not been observed to date (1989). Hydraulic calculations indicate that water-level declines in extensive, unconfined carbonate-rock aquifers commonly would be less than 70 feet at distances beyond 1 mile from a production well after 10 years of pumping at 1,000 gallons per minute. In a confined part of the aquifer, calculated water-level declines of similar magnitude would spread as far as 10 miles from the pumped well. These calculations are, however, based on many idealized simplifying assumptions. Currently (1989), data that allow a realistic representation of the complexities of the aquifers are not available; however, several previous studies have included computer models that provide insight into the problems of prediction. Regardless of whether the effect of pumping near Devils Hole is being modeled or whether regional flow toward Death Valley is being simulated, the geologic complexity of southern Nevada has been shown to be hydrologically important. This requires (1) that detailed aquifer descriptions be available before accurate site-specific predictions can be made and, probably, (2) that those predictions be based on effective use of sophisticated computer models.

The potential for adverse effects in adjacent aquifers resulting from development of the carbonate-rock aquifers is another concern. Historical experience with such conditions is available at two areas in southern Nevada that have undergone development of basin-fill aquifers adjacent to carbonate-rock aquifers: Ash Meadows and Muddy River Springs. At Ash Meadows, direct connections between pumping from basin-fill aquifers and water-level declines in the carbonate rocks were demonstrated. Around the Muddy River Springs, in contrast, development of basin-fill aquifers has resulted in minimal changes in water levels of the carbonate-rock aquifers. The difference between responses at these areas probably could not have been predicted before the aquifers were pumped and early effects observed.

The effects of depletion of stored water and capture of water that otherwise would discharge from the aquifers would depend on site-specific conditions around areas where the water is withdrawn. Confidence in predictions of the potential effects of development of the carbonate-rock aquifers will remain limited until observations become available that document changes as the aquifers respond locally to long-term pumping stresses.

INTRODUCTION

Rocks that formed from ancient marine sediments underlie much of a 50,000 mi^2 area of southern and eastern Nevada referred to as the carbonate-rock province (fig. 1) that also extends into western Utah, eastern California, and southeastern Idaho. These rocks are dominated by limestone and dolomite, two common carbonate-rock types, and are commonly associated with large springs, most with discharges greater than 1,000 gal/min. Several wells drilled into fractured zones in these carbonate rocks have been pumped at high rates with little water-level decline. The large area underlain by the rocks, together with their demonstrated capacity to transmit large volumes of ground water, has long indicated that the carbonate rocks of Nevada comprise aquifer systems of regional scale and significance. A problem exists in that although some data could indicate a favorable potential for development, the current (1989) understanding of the distribution and hydrologic properties of these rocks and of the regional-scale aquifers that they form is not adequate to determine their overall potential for development and the probable effects of development. This information is needed to support wise development and management of the State's water resources and to ensure optimum utilization of the carbonate aquifers as a significant component of the overall resource.

Nevada is the most arid State in the Nation, and faces rapid population growth and increasing demands for water. These increasing demands have sparked considerable interest in the largely unexplored carbonate-rock aquifers as a future water supply. Historic sources of water—surface water (streams and lakes) and ground water in localized sand-and-gravel aquifers—are used or appropriated nearly to (and in some valleys, beyond) their estimated sustainable yield in many areas, and thus, without stricter resource management or new sources of water, expectations of continued growth in some parts of Nevada may be limited.

The State of Nevada passed Senate Bill 277 in 1985 and entered into a cooperative effort with the Federal Government for the study and testing of the carbonate-rock aquifers of eastern and southern Nevada. The overall study plan (U.S. Department of the Interior, 1985, p. 4 and 9) called for a 10-year program to systematically study the 50,000 mi^2 of Nevada underlain by the carbonate-rock province. The southern part was studied during the first 3 years of the program and the results of that effort are the topic of this report.

Funds supplied by the State, the Las Vegas Valley Water District, and the City of North Las Vegas were matched by Federal funds supplied by the U.S. Geological Survey and the Bureau of Reclamation. Technical work has been done by a study team consisting of personnel from the U.S. Geological Survey, the Desert Research Institute, and the Bureau of Reclamation.

Purpose and Scope

Each 3-year study proposed in the overall program is designed to address the following three questions:

1. Where is water potentially available in the aquifers?
2. How much water potentially can be withdrawn from the aquifers?
3. What effects might result from development of the aquifers?

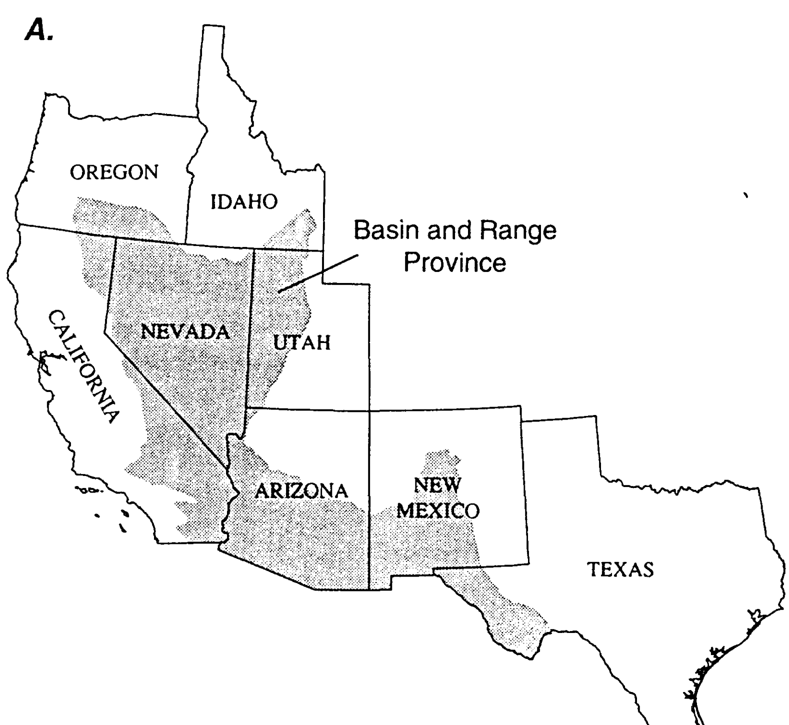
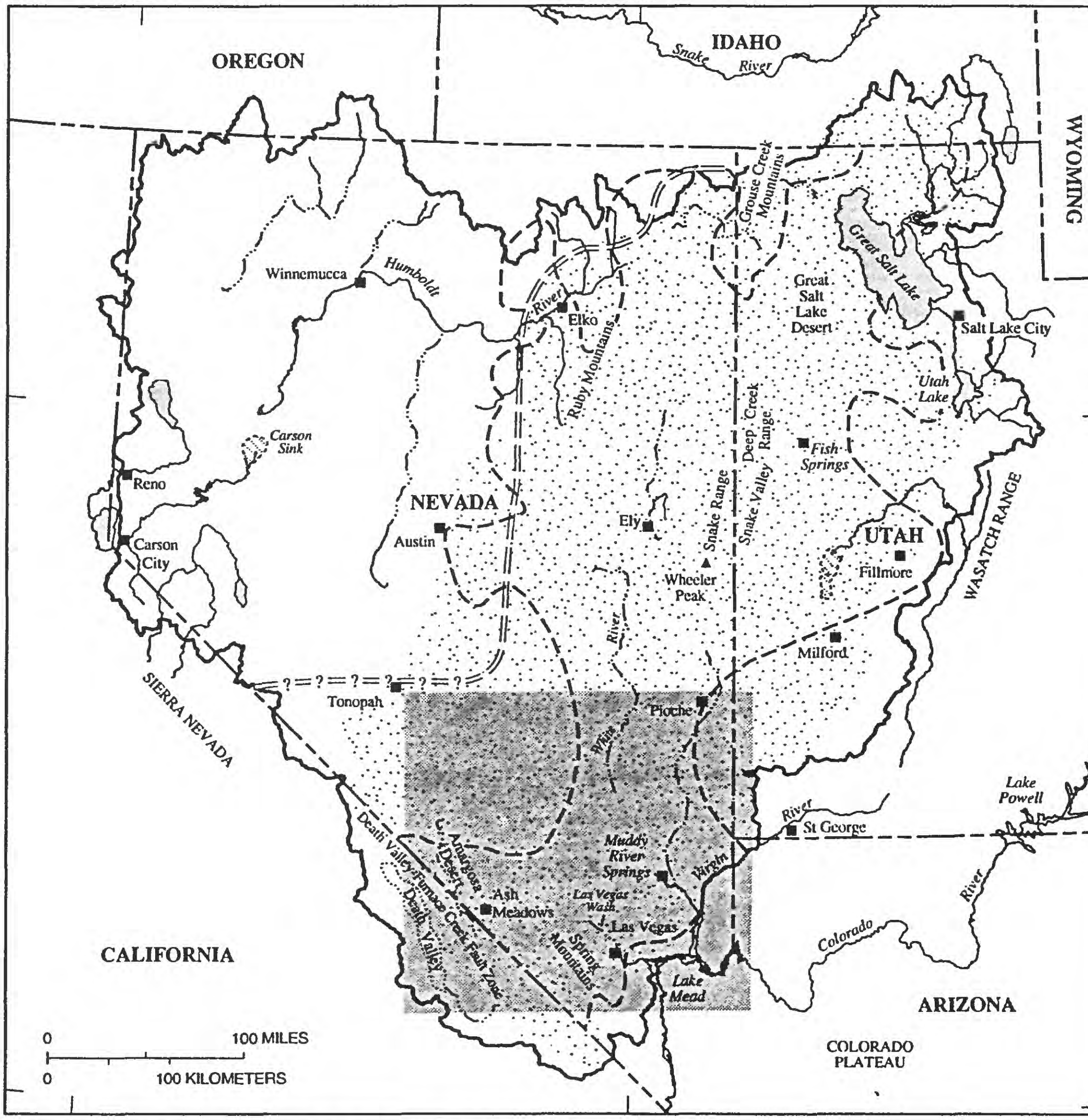


Figure 1. Location and general extent of (*A*) Basin and Range Province, and (*B*) Great Basin and carbonate-rock province. Figure 1*A* modified from Bedinger and others (1983); figure 1*B* modified from Harrill and others (1983, fig. 8).

B.



Base modified from U.S. Geological Survey digital data, 1:100,000 and 1:250,000
Albers Equal-Area Conic projection
Standard parallels 29°30' and 45°30', central meridian -114°

EXPLANATION

- Study area
- **Carbonate-rock province as used in this study** — From Thomas and others (1986, sheet 2)
- **Boundary of Great Basin Regional Aquifer-System Analysis (RASA) study area**
- **Approximate boundary of carbonate-rock province of Mifflin and Hess (1979)** — Within province, at least 80 percent of measured sections are composed of more than 50 percent carbonate rock
- **Approximate boundary of Roberts overthrust belt** — Queried where uncertain

Note: Lakes and rivers dashed where ephemeral

Figure 1. Continued

The purpose of this report is to summarize results of specific activities and studies in southern Nevada during the first 3-year study (1985-88). Regional-scale analyses have been made to improve understanding of the carbonate-rock aquifers at a large scale and to provide information applicable to specific areas. Detailed studies and analyses have been made in specific areas chosen for their relevance to the development of carbonate-rock aquifers to meet water demands in Las Vegas Valley, as well as for extending conclusions to all parts of southern Nevada. This report is intended to answer the three basic questions presented above as they apply in general in southern Nevada, within the limits of our current (1989) understanding. The scope includes summary of the findings of specific studies done in support of this project and incorporating the results into an overall regional synthesis for southern Nevada.

Activities summarized in this report extend to areas as far north as about 40°N. latitude, but are generally focused in southern Nevada, south of 38°N. latitude (that is south of Pioche, Tonopah, and vicinity). The studies and conclusions include areas of Utah and Arizona west of the Beaver Dam and Virgin Mountains and areas in California in and around Death Valley. Plate 1 shows the southern Nevada study area and many locations discussed later in this report.

Related Publications

This report is one of a number of products resulting from this study. A brief summary of findings (Dettinger, 1989b) presents the overall results of the study for the non-technical reader. Data and analysis that support the more detailed summary presented in this report are in 20 reports that were prepared as part of the overall program for the study and testing of carbonate-rock aquifers in eastern and southern Nevada. These reports are listed in the References Cited section of Dettinger (1989b) in bold type. The Bureau of Reclamation evaluated the relative economic feasibility of several alternative sources of water, including carbonate-rock aquifers, to supply water to meet peak demands for Las Vegas in the near future (Bureau of Reclamation, 1988).

Acknowledgments

Many more people contributed to the present studies during 1985-88 and to this summary report than could be listed as authors. Michael E. Campana, Ronald L. Hershey, Brad F. Lyles, W. Alan McKay, R. Eric Noack, and Karl F. Pohlman—from the Desert Research Institute in Las Vegas and Reno—contributed activity summaries and short sections of the text. Gary Dixon of the U.S. Geological Survey, Geologic Division, in Las Vegas contributed to planning and development of the document. David L. Berger, Lori A. Carpenter, Michael J. Johnson, Kathryn C. Kilroy, Donald H. Schaefer, and James M. Thomas—all from the U.S. Geological Survey, Nevada District Office in Carson City—contributed figures, activity summaries, and short sections of the text.

GENERAL HYDROGEOLOGY

This section presents general background information describing the carbonate-rock aquifers and how water flows through them. These basic concepts are intended to serve as a foundation for understanding much of the rest of the report.

Geologic Setting

The regional geologic setting of southern Nevada can be referenced to three overlapping provinces (shown in fig. 1): the Basin and Range Province, the Great Basin "province," and the carbonate-rock province. The Basin and Range Province is a physiographic and structural province characterized by numerous north-south trending mountain ranges separated by intervening basins. This structure and topography is the result of stretching or extension of the region at various times during the past 30 million years. The Great Basin is a region characterized by internal drainage in which no surface water flows to the ocean. Much of southern Nevada fits this hydrologic description with the exception of those basins draining to the Colorado River. The carbonate-rock province is more informally defined (see fig. 1 for more details on how its boundaries have been described), but is generally described as that part of the Basin and Range Province in which ground-water flow is predominantly or strongly influenced by carbonate-rock aquifers of Paleozoic age.

The carbonate rocks that underlie much of eastern and southern Nevada are dense and brittle sedimentary rocks deposited in the shallow ocean off the west coast of the North American continent during the Paleozoic Era, between 200 and 500 million years ago, when western Utah was the west coast. These rocks are predominantly limestones and dolomites that are somewhat soluble in water. These two rock types contain an ion composed of carbon and oxygen, the carbonate ion; hence the name carbonate rocks. Other, noncarbonate sedimentary rocks—rocks that do not contain a large proportion of carbonate ions—were deposited also and today occur as subordinate layers, major sequences, and interfingering zones within the layers of carbonate rock. These noncarbonate rocks commonly are either quartzite or shale, and are lithified sand, clay, or silt. The carbonate and noncarbonate rocks were deposited in layers that totaled more than 30,000 ft thick in some areas and record temporal and spatial variations in the depositional environment from dry-land erosional surfaces to tidal flat conditions and conditions at the edge of the continental shelf (Stewart, 1980, p. 5). Figure 2 shows the sequence of rock types in an idealized Paleozoic-rock column beneath the Sheep Range (north of Las Vegas, pl. 1) and is typical of Paleozoic rocks beneath southern Nevada. See Stewart (1980, p. 16-54) for a technical overview of the sedimentary rocks deposited during this time period; a less technical history of the deposition is presented by Fiero (1986, p. 79-96). The history of these rocks subsequent to their deposition also is presented in these references.

The carbonate rocks today underlie most of the area beneath southern Nevada north of Jean (pl. 1) and eastern Nevada east of Tonopah, Austin, and Elko (fig. 1). The rocks extend beneath much of the western third of Utah, into southeastern Idaho, and south to at least Death Valley in California. The rocks originally exhibited relatively small spatial variations in thickness at local scales but, regionally, the thicknesses ranged from 4,000 ft near the present-day Muddy Mountains to 17,000 ft near the present-day Sheep Range and 25,000 ft near the Nevada Test Site (fig. 3). These thicknesses vary directly with distance from the ancestral continental coast line (located mostly in western Arizona and Utah at various times during the Paleozoic Era), and an ancestral Antler highland in central Nevada that eroded to contribute thick layers of noncarbonate rock in some places (for example, the Nevada Test Site) during the middle Paleozoic (Stewart, 1980, p. 42). The carbonate-rock section thinned eastward toward the ancient coast line, and thickened westward toward the deep edge of the ancestral continental shelf or, by middle Paleozoic time, on approaching the central Nevada highland. The mixture of carbonate and noncarbonate rocks in the Paleozoic rocks varies only slightly with distance from these boundaries and, except in the Nevada Test Site area, is about 90 percent carbonate rock and 10 percent noncarbonate rock.

The Paleozoic carbonate rocks were deposited on thick layers of older (lower Cambrian and late Precambrian age) noncarbonate clastic sediments that in turn were deposited on a complex mixture of metamorphic and igneous rocks of well over a billion years old (Precambrian age). After deposition of the Paleozoic carbonate rocks, carbonate and noncarbonate sedimentary rocks of Mesozoic age were deposited on top of the carbonate rocks (fig. 3) under both marine and continental conditions. Layered volcanic rocks (which are noncarbonate) of Cenozoic age in turn were deposited on the Mesozoic rocks as a result of volcanic activity in the region, and in some areas plutonic rocks were intruded into the pre-existing rocks. The present-day outcrops of all these various rock types are shown on plate 1.

Since deposition, the carbonate and noncarbonate rocks have been greatly deformed and, as a result, have been thickened during thrusting, compressional deformation, thinned during extension, tensional deformation, and juxtaposed against each other during both deformations. In the carbonate-rock province, Paleozoic carbonate rocks either comprise or underlie most of the ranges and lie beneath the basin fill in many basins. Figure 4 shows, in generalized form, the geometric relations of rocks that lie beneath southern Nevada. The carbonate-rock aquifers extend to great depths but also are commonly present near the surface in mountain ranges. A single continuous "layer" of carbonate rocks may underlie several basins (as shown in fig. 4) and because of this can link ground-water flow systems over large distances. Basin-fill aquifers in a given basin may or may not be in hydraulic contact with the underlying carbonate rocks. The degree of contact depends primarily on the vertical hydraulic conductivity of the deeper basin fill.

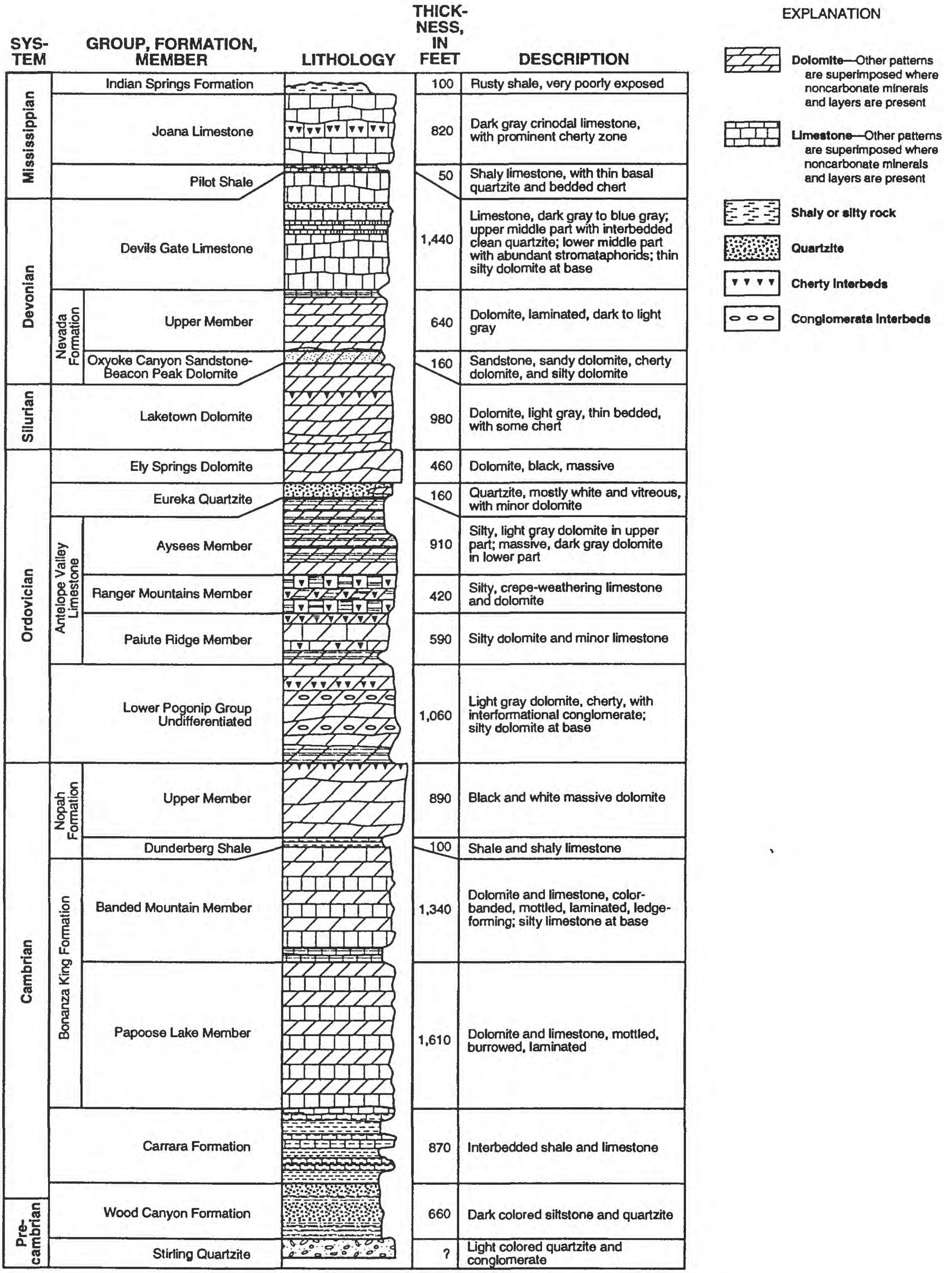
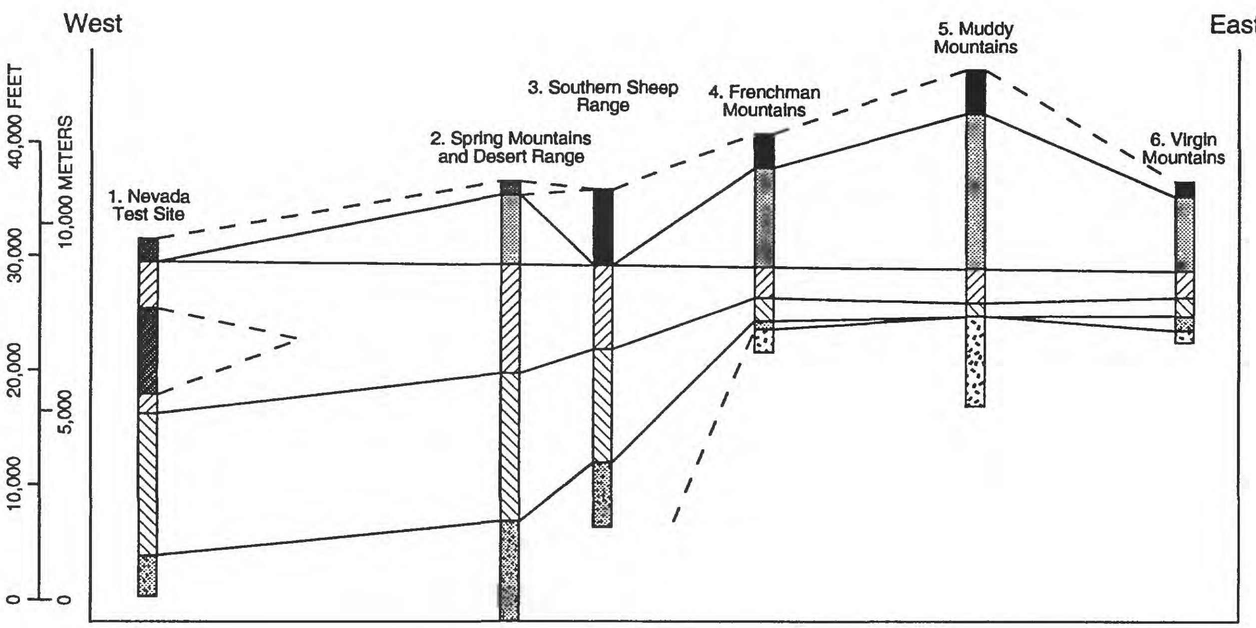
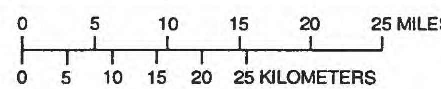


Figure 2. Paleozoic-rock section as exposed in Sheep Range (modified from Guth, 1980, pl. 3). Rocks shown range from latest Precambrian (older than 570 million years) through Mississippian (about 330 million years old).





EXPLANATION

Cenozoic sedimentary rock

Cenozoic volcanic rock

Mesozoic sedimentary rock — Carbonate and noncarbonate clastic rock containing abundant evaporitic rock. Unit includes some strata as old as Permian

Younger Paleozoic carbonate rock — Mostly limestone; shading indicates interval dominated by clastic rock, mostly shale

Older Paleozoic carbonate rock — Mostly dolomite. Both Paleozoic carbonate-rock units contain subordinate noncarbonate clastic layers, except in Nevada Test Site area, where thick clastic layer separates carbonate sections in upper unit

Older Paleozoic and younger Proterozoic sedimentary rock — Noncarbonate clastic rock (lower Cambrian and upper Precambrian)

Proterozoic cyrstalline rock — Igneous and metamorphic rock

Line connecting lithologic units between sections — Dashed where uncertain

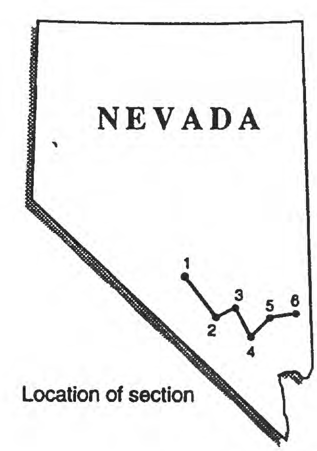


Figure 3. Stratigraphic sections showing thickness of Paleozoic carbonate rocks, overlying Mesozoic and Cenozoic rocks, and underlying Precambrian rocks beneath southern Nevada at a latitude of about 36°30′ north. Depositional thickness is shown without regard to subsequent deformation. Sources of stratigraphic data are: section 1, Tschanz and Pampeyan (1970); sections 2, 5, 6, and 7, Longwell and others (1965); section 3, Guth (1986); and section 4, Langenheim and others (1962). Index map shows location of section.

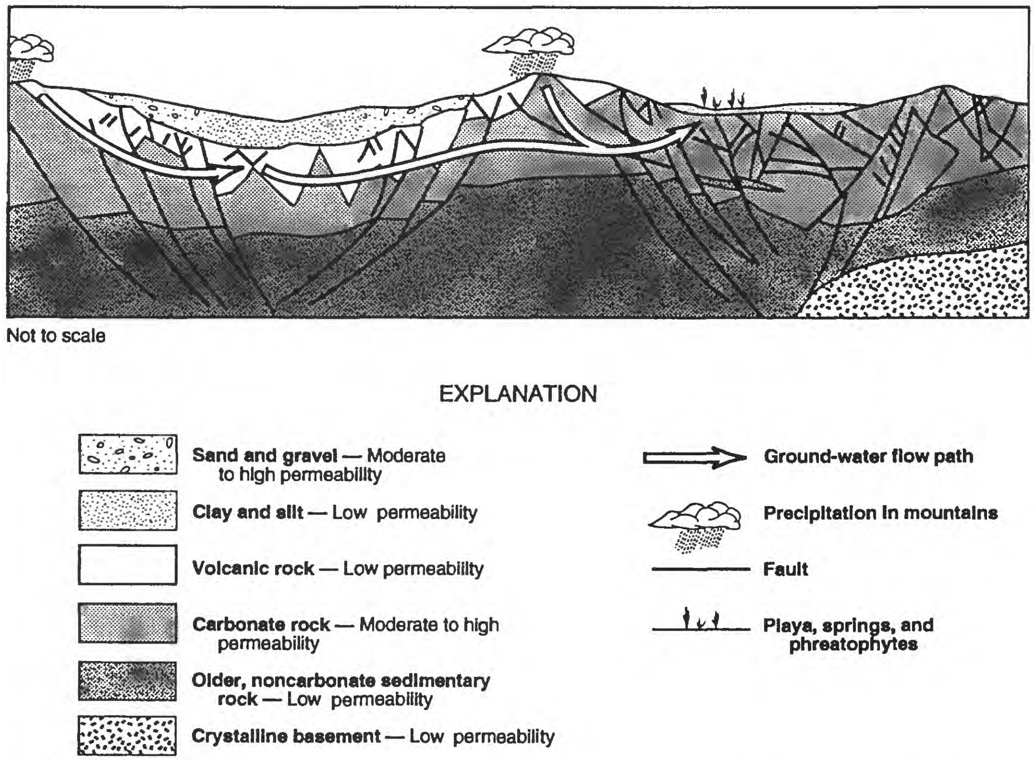


Figure 4. Schematic hydrogeologic section across basins and ranges of southern Nevada, showing hypothetical subsurface configuration of aquifers and rocks of low permeability. (Modified from Anderson and others, 1983, fig. 10.)

Deformation of the Carbonate Rocks

The carbonate rocks having depositional thicknesses as great as 30,000 ft have been deformed subsequent to their deposition, by compressional forces and by tensional forces. Beginning about 100 million or possibly as early as 200 million years ago, continental-scale forces compressed the rocks eastward against the North American continent. These forces mostly ceased about 70 million years ago (Stewart, 1980, p. 79), but while active, thick sections of the rocks were folded and thrusted over adjacent sections. The deformation created large, overlapping folds and thrusts in the previously flat-lying rocks, and in many places these repeated sections of carbonate rock remain today. For example, in parts of southern Nevada, a deep drill hole might intercept older carbonate rocks above a thrust fault and intercept younger carbonate rocks below the fault (Armstrong, 1968). Thus, the original thickness of the carbonate rocks in places was doubled by such compressional deformation.

More recently, at various times during the past 30 million years, the entire region underlying present-day Nevada was extended or pulled apart, by tensional forces. In southern Nevada, extension stretched the region between the Sierra Nevada and the Colorado Plateau by possibly more than 150 mi overall (Wernicke, Snow, and Walker, 1988, p. 256). The stretching was accommodated along both low and high-angle normal faults as well as along nearly vertical strike-slip faults (Stewart, 1980, p. 110-116). The sedimentary rocks were extended along numerous faults that transported large blocks of rock over long distances and rotated blocks of rocks to various angles. As a result, the mountain ranges were raised and tilted and the basins were depressed and filled with erosional debris from the adjacent raised ranges to give the region its characteristic Basin-and-Range topography (see fig. 1; Hamilton and Myers, 1966; Wernicke and others, 1984).

Extension of the carbonate rocks served to reverse the thickening process induced by the compressional forces by dramatic structural thinning and disruption of most of the rocks. In some areas, brittle, broken carbonate-rock layers were virtually pulled apart above deep, ductally extended crystalline rocks of Precambrian age (Wright and others, 1981; Wernicke and others, 1984, p. 488; Wernicke and others, 1985, pl. 2; Hamilton, 1988; Wernicke, Walker, and Hodges, 1988). In other areas, the carbonate rocks were removed entirely from the lower noncarbonate part of the full rock section leaving only isolated blocks of carbonate rock. In still other areas, the thick layers of the Paleozoic rock section were pulled along and deformed but remained largely intact above lower layers of carbonate rocks and the noncarbonate, Precambrian sedimentary rocks (Wernicke and others, 1984, p. 490 and fig. 9; Guth, 1988). In all these examples, depending on the juxtaposition of carbonate and noncarbonate rocks, the thinned and deformed rocks might function as barriers to flow or might function as extensive and continuous aquifers.

During much of the time when extension of the Basin and Range Province was taking place, volcanism was active in parts of the province (Stewart, 1980, p. 98-104). On all sides of the carbonate-rock province in southern Nevada, thick, expansive layers of volcanic rocks were deposited and in part remain today. Some volcanic rocks are permeable and constitute aquifers, whereas others are less permeable and constitute aquitards (Winograd, 1971). North of the study area and beneath the Nevada Test Site, these rocks constitute important local aquifers (Fiero, 1968; Blankennagel and Weir, 1973). Within the study area, however, volcanic rocks are generally not continuous or thick enough to form regional aquifers comparable to the carbonate-rock aquifers.

As a result of these various forces, the originally flat-lying carbonate rocks are today complexly deformed and faulted into blocks and folds wherein rocks of all ages may be intermingled. The previous depositional "layer cake" structure of the sedimentary rocks has been transformed into a complex mixture of carbonate and noncarbonate rocks that separate and underlie basins partly filled with unconsolidated sediments, and the original stratigraphic thicknesses of the rocks commonly have been greatly modified to their present-day thicknesses.

Avenues for Ground-Water Flow Through the Carbonate Rocks

The carbonate rocks are generally dense and brittle, and, where unbroken, are nearly impermeable. The unbroken carbonate rocks impede ground-water flow—because after deposition they consolidated under the great weight of sediments deposited on top of them and because, as a result, most of the original spaces between the grains or crystals making up the rocks have been compacted or sealed by cementation and recrystallization processes.

Most carbonate rocks of southern and eastern Nevada have been fractured, brecciated, and otherwise broken during the complex deformational history of the area (Hess and Mifflin, 1978, p. 16). Because the carbonate rocks are dense and brittle, many openings caused by extensional deformation are clean, smooth fractures or joints. Most of the noncarbonate sedimentary rocks, when deformed, will break into well-graded fragments (as for quartzite) that reconsolidate into impervious rock or will yield ductally (as for shale) and, in either example, will not result in significant openings through which water can flow. Some openings (fractures) that form in carbonate rocks can be excellent paths for ground-water flow. Carbonate rocks containing many fractures and interbreccia openings are commonly much more permeable than they would be if unbroken.

In addition to being brittle and subject to fracturing, the carbonate rocks have the special property of being relatively more soluble in water than most other rock types. Consequently, under the right geochemical conditions, they will dissolve when in contact with water. This is why in many parts of the world limestone terranes are riddled with caves and sink holes (Fairbridge, 1968, p. 582). The rock that once filled these large and extensive openings has simply been dissolved by water flowing through the openings. In Nevada, geochemical conditions that allow dissolution of the carbonate rocks are not common and therefore these landforms and openings are present only locally. The amount of rock that can be dissolved prior to the water becoming saturated depends on conditions that add acid to the water and make it corrosive in the rocks. The most important limiting conditions are probably the small volumes of water (relative to more humid settings) flowing through the rocks and the relatively small quantity of acid produced by the thin soils and vegetation in the ground-water recharge areas in Nevada (Fairbridge, 1968, p. 582; Winograd and Thordarson, 1975, p. C115). Both of these conditions are attributable to the aridity of the State. The relatively small quantity of water flowing through the rocks means that less water is available to dissolve the rock. As a consequence, water becomes "saturated" with carbonate ions after flowing only a short distance through the aquifers. Once saturated the water does not dissolve more rock until geochemical conditions change such that the water becomes undersaturated with respect to carbonate ions.

Regardless of these limiting conditions, some carbonate rocks of Nevada are slowly dissolved and carried away by ground water flowing through fractures. The dissolution widens the openings and allows even more water to flow through the rocks, increasing the overall permeability of the rock masses (Kemmerly, 1986). Although some dissolution occurs along fracture faces, unmodified fractures and joints are more common than solution-enlarged fractures in southern Nevada. This suggests that the dissolution process contributes to creation of large-scale permeability, but probably is not as important as simple, sustained fracturing of the rocks (Winograd and Thordarson, 1975, p. C1; Alan M. Preissler, Dwight L. Schmidt, and Gary L. Dixon, U.S. Geological Survey, written communs., 1986-87).

Hydraulic Properties of the Carbonate Rocks

Winograd and Thordarson (1975, p. C17) report that carbonate rocks in 13 cores collected at the Nevada Test Site had matrix porosities ranging from 0.4 to 12.4 percent of the total bulk rock volume, with a median value of 5.5 percent. These values are in the range suggested by borehole geophysical logs obtained during the present study (Berger, 1992). Only about 20 percent of the matrix porosity is interconnected and "effective" in allowing throughflow of water (Winograd and Thordarson, 1975, p. C17).

While most ground-water flow through the carbonate rocks of southern Nevada is assumed to be through fractures and solution openings, the amount of water actually stored in these openings is uncertain. Small, open fractures and joints generally constitute less than 1 percent of the total volume of rock (Winograd and Thordarson, 1975, p. C18; Alan M. Preissler, U.S. Geological Survey, written commun., 1987), which is less than the effective porosity of the rock matrix reported by Winograd and Thordarson (1975, p. C17). Large fractures and joints are likely to be even less common than smaller ones, and, although highly permeable, only comprise a very small volume of the aquifers. Even though water moves more easily through large open fractures near and along major fault zones, most of the water stored in the carbonate rocks is in the extensive volumes of less fractured rock between major fault zones. This water moves slowly, if at all, because of low matrix hydraulic conductivities and would be yielded to wells at only moderate rates.

The hydraulic conductivity is a measure of the capacity of a rock to allow water to move through it and is directly proportional to its permeability. Winograd and Thordarson (1975, p. C17) report that matrix or primary hydraulic conductivities of carbonate rocks in those same 13 cores range from 0.000003 to 0.01 ft/d. The median value was 0.00001 ft/d. To provide an example of how low this median conductivity is, and how impermeable the rocks are, methods described by Skibitzke (1963, p. 293-297) predict that a 12-in. diameter well that extends 500 ft beneath the water table in a water-saturated mass of unfractured carbonate rocks that is suddenly bailed dry would take more than 17 years to refill to within 1 ft of the undisturbed (static) water level.

As a result of fractures, and to an unknown extent because some of these openings have been enlarged by dissolution, the hydraulic conductivities determined in field-scale aquifer tests are much larger than reported matrix conductivities. Available measurements of hydraulic conductivity from aquifer tests at 39 carbonate-rock wells in southern and eastern Nevada are listed in table 1 with locations shown in figure 5. Of these tests, 33 are reported results and 6 are from tests made as part of this study. Another source of estimates are specialized hydraulic tests called "drill-stem tests" commonly done in oil-test wells. For completeness, table 2 is included here; it summarizes results from 13 such wells in carbonate rocks. These results were assessed for their usefulness in defining the properties of deeper parts of the aquifers (as part of the present studies and as reported in McKay and Kepper, 1988), but, at present (1989), unresolved differences have been noted between the "population" of aquifer properties determined by drill-stem tests as opposed to aquifer tests in water wells. These differences are discussed in more detail in a later section of this report, but the drill-stem test results are not included in the following statistical description of aquifer properties.

Hydraulic conductivities of the fractured rocks range from 0.01 to 940 ft/d and have a median value of 4.5 ft/d (table 1). The number of wells at which various orders-of-magnitudes of hydraulic conductivity were measured is shown in figure 5. Of the wells in table 1, the median value of hydraulic conductivities is the same as at a well near Mercury, Nev.—Army Well 1. This median hydraulic conductivity also is comparable to that of basin-fill aquifers composed predominantly of sand. Hydraulic conductivities for the most productive carbonate-aquifer wells are comparable to those for clean gravels (described by Bear, 1979, table 4-1).

Table 1. Construction data and aquifer-test results for wells in carbonate-rock aquifers and noncarbonate (clastic) rocks of Nevada

Site designation: Local name or USGS identification, preceded by: MX, constructed for studies of MX Missile-Siting Water Resources Program; NCAP, constructed for present study; NTS, constructed for studies associated with Nevada Test Site (but not necessarily located there); Prv., privately constructed.
Age: pє, Precambrian; є, Cambrian; єO, Cambrian-Ordovician; O, Ordovician; S, Silurian; D, Devonian; M, Mississippian; IP, Pennsylvanian; pIP, Permian-Pennsylvanian.
Rock-unit name: LS, limestone.
Lithology: C, predominantly noncarbonate clastics; D, predominantly dolomite; L, predominantly limestone. Multiple abbreviations are listed in order of predominance.
[--, no data available; <, less than]

Site No.	Site designation	Degrees, minutes, seconds		Rocks tested			Well construction			
							Depth (feet below land surface)		Total open interval (feet)	Casing or open-hole diameter (inches)
		Latitude	Longitude	Age	Rock-unit name	Lithology	Shallowest opening	Deepest opening		
					Wells completed in Carbonate Rock					
1	Prv. S23 E60 24BB	35 56 17	115 13 20	IP	Bird Spring	L	540	700	160	12
2	Prv. S23 E61 09BC	35 57 50	115 10 10	M	Monte Cristo	D	400	520	120	8
3	Prv. S18 E63 34CA	36 20 28	114 55 36	IP	Bird Spring	L	754	1,205	451	6
4	Prv. S17 E50 23BB2	36 27 54	116 19 02	є	Bonanza King	D	0	140	140	14
5	NCAP S16 E58 23DD (SBH1)	36 32 12	115 24 03	O	Pogonip	L	654	694	40	6
6	NTS Tracer No.1	36 32 12	116 13 47	є	Bonanza King, Carrara	D,L	625	830	205	9.9
7	NTS Tracer No.3	36 32 12	116 13 47	є	Bonanza King, Carrara	D,L	620	807	187	5.5
8	NTS Tracer No.2	36 32 12	116 13 47	є	Bonanza King, Carrara	D,L	659	828	169	6.2
9	NCAP S16 E58 14A (DR1)	36 33 32	115 24 40	D	Guilmette, Simonson	L,D	870	930	60	8
10	NTS S16 E56 08 (#2)	36 34 43	115 40 37	IP	Bird Spring	L	54	575	521	14
11	NTS TW-4 (66-75)	36 34 54	115 50 08	є	Nopah	D	737	1,490	753	7.6
12	NTS Army 1 (67-68)	36 35 30	116 02 14	є	Bonanza King, Nopah	L	785	1,946	1,161	10.7
13	NTS TW-10 (67-73)	36 35 31	115 51 04	є	Bonanza King	L	1,020	1,301	281	8.6
14	Prv. S15 E67 09DD	36 38 19	114 29 43	pIP	--	L	360	420	60	8.6
15	NTS TW-F (73-66)	36 45 34	116 06 59	S	--	D	3,137	3,400	253	8.6
16	MX CE-DT-6	36 46 04	114 47 13	IP	Monte Cristo	L	457	937	480	12
17	NCAP S13 E65 28B (CSV2)	36 46 50	114 43 20	IP	Bird Spring	L	391	480	89	8
18	MX CE-DT-5	36 47 41	114 53 28	M	Monte Cristo	L	353	628	275	20
19	MX CE-DT-4	36 47 43	114 53 31	M	Monte Cristo	L	352	669	317	10
20	NTS TW-3 (75-73)	36 48 30	115 51 26	O	Pogonip	L	1,105	1,853	748	7
21	NTS UE25P#1 (75-57)	36 49 38	116 25 21	S	Lone, Robert Mtn.	D	4,255	5,922	1,667	6.7
22	MX CE-VF-2	36 52 27	114 56 51	IP	Bird Spring	L,D,C	860	1,009	149	10
23	NTS WW-C-1 (79-69)	36 55 07	116 00 34	є	Carrara	L	1,545	1,650	105	16.7
24	NTS WW-C (79-69a)	36 55 08	116 00 35	є	Carrara	L	1,544	1,701	157	10.8
25	NTS TW-E (83-69)	37 03 21	115 59 42	O	Pogonip	L	1,780	2,620	840	10.8

Table 1. Construction data and aquifer-test results for wells in carbonate-rock aquifers and noncarbonate (clastic) rocks of Nevada--Continued

Site No.	Site designation	Degrees, minutes, seconds		Rocks tested			Well construction			
							Depth (feet below land surface)		Total open interval (feet)	Casing or open-hole diameter (inches)
		Latitude	Longitude	Age	Rock-unit name	Lithology	Shallowest opening	Deepest opening		
26	NTS U3cn-5 (84-68d)	37 03 35	116 01 30	D	--	D,C	2,821	3,026	205	6
27	NTS UE-16D	37 04 12	116 09 51	IP	Tippipah	L	753	2,119	1,366	7
28	NTS TW-D (84-67)	37 04 28	116 04 30	M	Eleana LS, Shale	L,C	1,772	1,882	110	10.8
29	NTS TW-1 (87-62)	37 09 29	116 13 23	D	Devils Gate, Nevada	D	3,700	4,198	498	7.6
30	NTS WW-2 (88-66)	37 09 58	116 05 15	O	Pogonip	L	2,550	3,422	498	6.6
31	MX DL-DT-3	38 05 31	114 53 42	M	--	L	853	2,395	1,542	8.8
32	MX-CV-DT-1	38 07 58	115 20 46	D	Guilmette	D	803	1,837	1,034	10
33	MX N07 E63 14ABC	38 28 19	114 51 58	IP	--	L	230	435	205	10.8
34	prv. N08 E43 24AA	38 32 41	117 05 41	∈O	--	L,C	160	340	180	6
35	MX SV-DT-2	38 55 21	114 50 36	IP	Ely LS, Chainman	L,C	500	2,447	1,947	6
36	Prv. Fad Shaft	39 30 20	115 59 05	∈	Hamburg LS, Shale	L,C	1,025	2,465	1,440	120
37	Prv. N22 E57 25CD	39 44 27	115 30 43	D	Devils Gate	L	480	583	103	12.8
38	Prv. N36 E62 18	41 00 13	115 00 39	D	Guilmette	L	140	220	80	6
39	Prv. N37 E63 06BA	41 07 29	114 53 56	P	Ely LS	L	555	595	40	6
	Wells completed in Noncarbonate rock (clastic)									
40	NTS TW-5 (68-60)	36 37 46	116 18 22	∈	Carrara	C	735	800	65	7
41	NTS UE16F	37 02 08	116 09 24	M	Eleana	C	1,293	1,414	121	9.6
42	NTS UE-17A (84-64A)	37 04 25	116 09 58	M	Eleana	C	745	1,190	215	4.5
43	NTS UE-15D (89-68)	37 12 33	116 02 29	p∈	Johnnie	C	1,773	5,940	4,167	4.5

Table 1. Construction data and aquifer-test results for wells in carbonate-rock aquifers and noncarbonate (clastic) rocks of Nevada--Continued

Specific capacity: Estimated by dividing constant pumping rate by final drawdown, except values estimated by Winograd and Thordarson (1975), which are based on drawdown at 100 minutes.
Estimated transmissivity: From capacity: based on specific capacity using method of Theis and others (1963). From drawdown: based on regular measurements of drawdown in pumped well using method of Cooper and Jacob (1946). From recovery: based on regular measurements of recovery in pumped well using method of Cooper and Jacob (1946). From other data: based on other methods and data noted in footnotes.
Hydraulic conductivity: Value estimated from transmissivity divided by total open interval, followed by: C, transmissivity estimated from specific-capacity data used to calculate hydraulic conductivity; D, transmissivity estimated from drawdown data used; O, transmissivity estimated from other data used; R, transmissivity estimated from recovery data used.

Site No.	Rate pumped (gallons per minute)	Draw-down (feet)	Specific capacity (gallons per minute per foot)	Test duration (minutes)	Estimated transmissivity (feet squared per day) From capacity	From drawdown	From recovery	From other data	Hydraulic conductivity (feet per day)	Reference
					Wells completed in Carbonate Rock					
1	17	90	0.19	240	32	--	--	--	0.2	(C) Driller's report dated 11/81
2	121	91	1.33	120	270	--	--	--	2.2	(C) Driller's report dated 06/73
3	72	282	.26	480	53	--	--	--	.12	(C) Driller's report, permit 50316
4	537	40	13.25	1,350	3,700	--	--	[a]3,500	25	(O) Dudley and Larson, 1976, tables 3 and 4
5	24	9	26.7	600	7,600	(b)	37,000	--	940	(R) Present study
6	100	8	13	60	2,800	--	--	--	14	(C) Johnston, 1968, p. 21-32, 44
7	100	2	60	60	16,000	--	--	--	84	(C) do.
8	94	1	140	60	36,000	--	--	--	210	(C) do.
9	14.5	11	1.3	1,638	320	450	100	--	7.5	(D) Present study
10	500	50	10	--	2,100	--	--	--	4.1	(C) U.S. Corps of Engineers, written commun., 1942
11	154	40	4.5	2,000	530	1,500	3,000	--	2.0	(D) Winograd and Thordarson, 1975, table 3
12	455	85	6	3,000	800	5,200	11,500	--	4.5	(D) do.
13	400	91	4.8	3,000	1,100	2,700	7,100	--	9.5	(D) do.
14	225	137	1.64	960	400	--	--	--	6.7	(C) Drillers report dated 11/85
15	58	2	29	--	[c]8,000	--	--	--	30	(C) Winograd and Thordarson, 1975, table 3; Thordarson and others, 1967, p. 14
16	472	42	11.4	3,963	3,200	12,600	[d]53,000	--	26	(D) Present study
17	101	30	3.4	1,320	860	1,600	7,000	--	18	(D)
18	3,400	11	309	42,441	98,000	250,000	--	[e]100,000	900	(D) Berger and others, 1988, p. 30-39; Bunch and Harrill, 1984, p. 33
19	540	3	154	4,600	45,000	200,000	--	[f]760,000	630	(D) Berger and others, 1988, p. 24-29; Bunch and Harrill, 1984, p. 33; Morin and others, 1988, p. 587
20	30	48	.7	1,000	80	510	--	--	.7	(D) Winograd and Thordarson, 1975, table 3
21	500	49	10.2	6,080	3,500	[g]1,200	--	--	0.71	(D) Winograd and Thordarson, 1975, table 3
22	77	13	5.9	830	1,600	2,800	7,800	--	19	(D) Present study
23	300	59	5.1	100	800	--	--	--	8	(C) Winograd and Thordarson, 1975, table 3
24	456	.8	570	240	130,000	--	--	--	860	(C) Claassen, 1973
25	[h]12	130	.08	340	19	--	11	--	.01	(R) Winograd and Thordarson, written commun., 1965

Table 1. Construction data and aquifer-test results for wells in carbonate-rock aquifers and noncarbonate (clastic) rocks of Nevada--Continued

Site No.	Rate pumped (gallons per minute)	Draw-down (feet)	Specific capacity (gallons per minute per foot)	Test duration (minutes)	Estimated transmissivity (feet squared per day)				Hydraulic conductivity (feet per day)	Reference
					From capacity	From drawdown	From recovery	From other data		
26	76	172	.4	3,000	90	320	--	--	1.6	(D) Winograd and Thordarson, 1975, table 3
27	570	43	13.3	1,440	3,700	--	8,600	--	6.3	(R) Dinwiddie and Weir, 1979, p. 4-6, 15
28	22	49	.45	89	80	--	11	[i]13	.11	(O) Thordarson and others, 1962, p. 31-37
29	98	135	.8	500	130	880	470	--	.94	(R) Winograd and Thordarson, 1975, table 3
30	60	180	.4	5,000	94	170	710	--	.35	(D) do.
31	106	2	53	6,400	17,000	--	--	--	11	(C) Bunch and Harrill, 1984, p. 36; Ertec Western, written commun., 1985
32	95	63	1.5	1,380	350	--	--	--	.34	(C) Bunch and Harrill, 1984, p. 32; Ertec Western, written commun., 1985
33	225	118	1.9	210	390	--	--	[j]2,400	1.7	(C) Bunch and Harrill, 1984, p. 31; driller's log 22581
34	35	4	8.75	10,080	2,700	--	--	--	15	(C) Driller's report dated 01/86
35	100	124	.8	200	190	130	530	--	.3	(R) Bunch and Harrill, 1984, p. 105; Ertec Western, written commun., 1985
36	3,600	270	13.3	43,200	3,200	2,200	2,100	[k]3,200	1.5	(D) Stuart, 1955, p. 2-4
37	550	560	.98	240	190	--	--	--	1.8	(C) Driller's log 22217
38	30	75	.4	180	80	--	--	--	1	(C) Driller's log 20511
39	15	80	.19	300	40	--	--	--	.9	(C) Driller's log 20972
Wells completed in Noncarbonate Rock (clastic)										
40	<5	126	<.04	--	<7	--	--	--	<.1	(C) Thordarson and others, 1967, p. 14
41	--	--	--	100	--	--	--	[l]1	.01	(O) Dinwiddie and Weir, 1979, p. 16-19
42	20	493	.04	120	8	--	1.2	--	.006	(R) Weir and Hodson, 1979, p. 4, 6, 8, 11
43	78	294	.27	2160	40	80	--	--	.02	(D) Thordarson and others, 1967, p. 20

[a] Estimated from drawdowns at nearby well S17 E50 23BB1.

[b] Influence of barometric pressure was greater than drawdown.

[c] Estimate based on airline measurements. Estimated storage coefficient, 0.013.

[d] Pump has no foot valve, making recovery difficult to analyze.

[e] Estimated from drawdowns at MX well CE-DT-4 (site 19). Estimated from drawdowns and recoveries at several wells. Estimated storage coefficient, 0.14. Storage-coefficient estimates range from 0.0014 to 0.00075.

[f] Estimated from borehole flowmeter test during present study. Estimated from slug test. Recovery took 100 minutes.

[g] Galloway (1986) estimated storage coefficient of 0.0003 using tidal fluctuations of water levels in well.

[h] Drawdown may be influenced by caving of overlying tuffs.

[i] Estimated using method of Skibitzke (1963).

[j] Estimated from drawdown in nearby observation well.

[k] Estimated from drawdowns and recoveries at several wells. Storage-coefficient estimates range from 0.0014 to 0.00075.

[l] Estimated from slugtest. recovery took 100 minutes.

Table 2. Data from drill-stem tests on petroleum-exploration wells. Compiled from McKay and Kepper (1988, table 2, appendices A and B)

Age: ∊, Cambrian; D, Devonian; M, Mississippian; IP, Pennsylvanian; ρ, Permian; U, undifferentiated.
Lithology: C, predominantly noncarbonate clastics; D, predominantly dolomite; G, gypsum; L, predominantly limestone. Multiple abbreviations are listed in order of predominance.
Depth interval: Reported depth zone that was mechanically isolated for the test.
Duration of test: Final shut-in period. For initial shut-in time or flow times, see McKay and Kepper (1988, appendix B).
[--, no data available]

Site designation	Degrees, minutes, seconds: Latitude	Degrees, minutes, seconds: Longitude	Rocks tested: Age	Rocks tested: Rock-unit name	Rocks tested: Lithology	Depth interval tested (feet below land surface)	Duration of test (minutes)	Transmissivity (feet squared per day)	Hydraulic conductivity (feet per day)
Wells completed in Carbonate Rock									
Virgin River USA 1-A	36 38 18	114 23 42	ρ	Kaibab	L,C,G	11,764-11,814	120	0.07	0.0014
Adobe Federal 19-1	38 01 03	115 17 07	M	Joana	L	7,500-7,706	120	820	4
DOC Federal 5-18	38 17 38	115 50 22	M	Joana	L	5,671-5,725	120	84	1.6
Lone Tree 1-14-43	38 22 42	115 38 09	D	Guilmette	L,D	4,372-4,430	120	6.2	.11
Adobe Federal 16-1	38 24 15	115 50 51	D	Guilmette	L,D	3,785-3,930	90	350	2.4
Grant Canyon 5	38 27 15	115 34 49	D	Guilmette	L,D	4,548-4,648	60	460	4.6
Grant Canyon 1	38 27 19	115 34 37	D	Simonson	D	4,340-4,441	60	8.5	.085
Grant Canyon 4	38 27 32	115 34 21	D	Guilmette	L,D	4,034-4,061	62	510	19
Grant Canyon 3	38 27 45	115 34 37	D	Guilmette	L,D	3,934-3,961	60	15	.56
Bacon Flat 1	38 27 51	115 35 35	D	Guilmette	D,L	5,315-5,346	--	4.2	[a].13
Bacon Flat 5	38 27 57	115 35 10	IP	Ely	L	5,595-5,795	120	.062	.00031
White River Valley 1	38 29 09	115 06 37	IP	Ely	L	4,490-4,578	120	.077	.0087
Dobbin Creek Fed A1-6	38 59 38	116 36 49	U	--	D	(b)	1,419	6.9	.056
Wells completed in Noncarbonate Rock (clastic)									
Bacon Flat 5	38 27 57	115 35 10	M	Chain-man	C	6,228-6,276	180	.041	.0008
Soda Springs Unit 1	38 32 54	115 32 59	∊	--	C	7,699-7,796	120	0.72	.0072

[a] Transmissivity is from reservoir engineer's report. Reported hydraulic conductivity was 0.31 foot per day, but a transposition of numerals is suspected.
[b] Transmissivity and hydraulic conductivity are averages from three tests, in depth intervals 3,200-3,480, 3,600-3,660, and 3,650-4,034 feet.

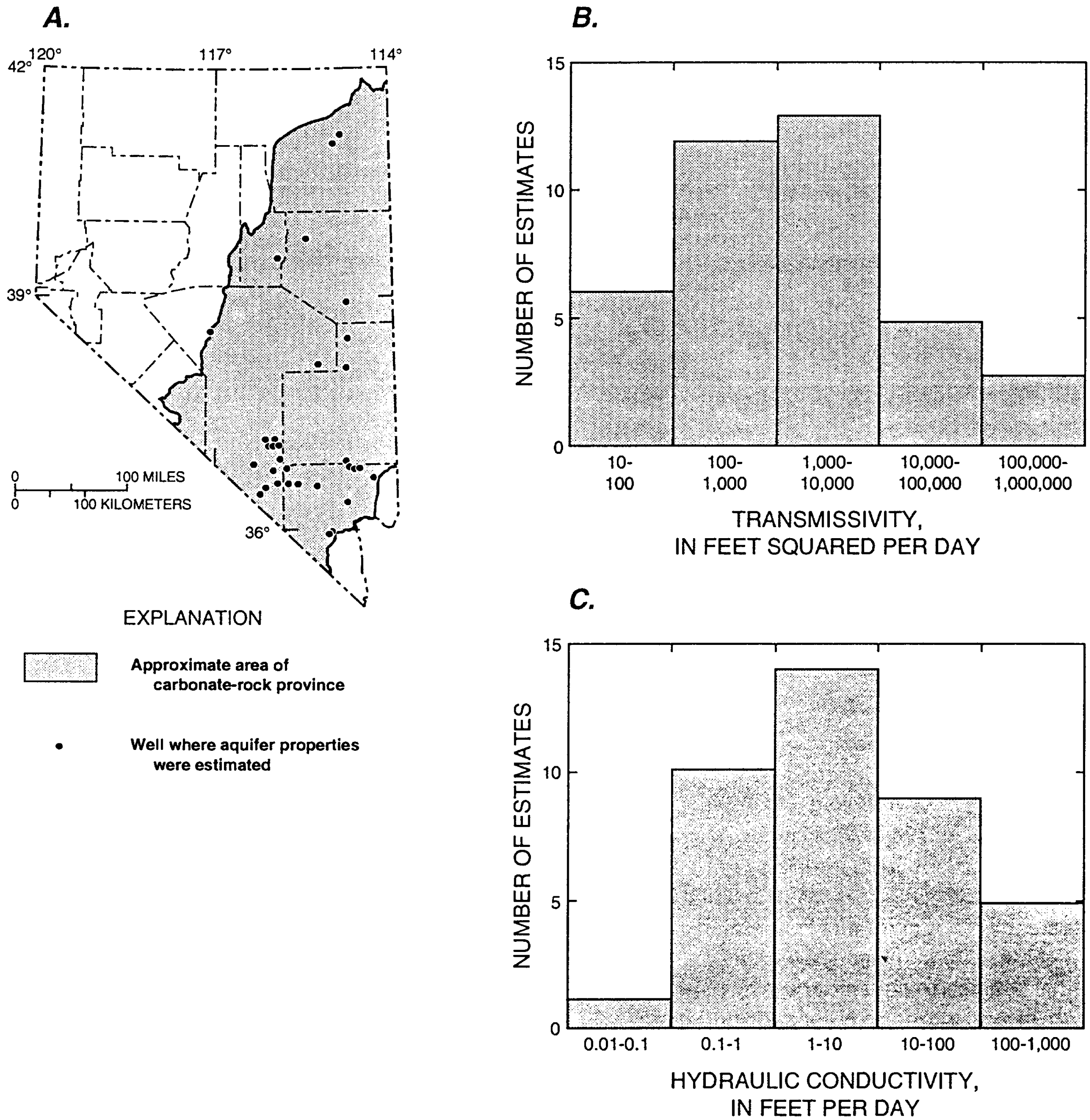


Figure 5. Estimated transmissivity and hydraulic conductivity of carbonate-rock aquifers in southern and eastern Nevada; (*A*) Location of wells at which test provide estimates of aquifer properties, (*B*) frequency distribution of estimated transmissivities, (*C*) frequency distribution of estimated hydraulic conductivities.

[Notably, the median is much less than the hydraulic conductivity at the MX wells in Coyote Spring Valley (about 900 ft^2/d), and productivity of the MX wells is correspondingly higher (3,400 gal/min pumped with only 12 ft of water-level decline compared to 455 gal/min with 85 ft of drawdown at Army Well 1). In fact, the aquifer at the MX wells has a higher hydraulic conductivity than aquifers at 38 of the 39 sites at which test results are available.]

The median value of the conductivities estimated from the water-well tests is 430,000 times greater than the matrix conductivity of the rock. The practical importance of this difference between matrix conductivities and fractured-rock conductivities is suggested by the following example: a 500-ft deep, 12-in. diameter well penetrating fractured, water-saturated carbonate rock having a hydraulic conductivity equal to the median above would take only 21 minutes to refill to within 1 ft of the static water level after suddenly being bailed dry in comparison to the long time (17 years) necessary in unfractured carbonate rocks.

Hydraulic Characteristics of Associated Noncarbonate Rocks

Aquifer properties of intervening noncarbonate sedimentary rocks are somewhat less well known. These rocks are principally shale, siltstone, and quartzite. Shale commonly is relatively soft and deforms ductilly (bending rather than breaking) or by shattering into clay size particles. Quartzite is a brittle rock and is made up of tightly cemented or recrystallized quartz sand. Observations at outcrops indicate that quartzites commonly have been broken into very small fragments (Alan M. Preissler, U.S. Geological Survey, written commun., 1987). When fractured, these rocks are believed to be much less permeable than fractured carbonate rocks (Motts, 1968, p. 289; Winograd and Thordarson, 1975, p. C40). However, there are few data upon which to base this belief. Aquifer tests have been conducted at four wells tapping noncarbonate rocks at the Nevada Test Site (table 1). The median hydraulic conductivity determined from these tests is 0.015 ft/d (300 times smaller than the median conductivity of the carbonate-rock aquifers but still 1,500 times larger than that of the carbonate-rock matrix). Winograd and Thordarson (1975, p. C43) suggest that the few, low discharge springs present in the noncarbonate sedimentary rocks in southern Nevada also may indicate lower hydraulic conductivities.

Volcanic rocks, which were deposited about the same time as the basins were forming, are an important sequence of intervening rocks between the basin-fill deposits and the carbonate rocks beneath many basins of eastern and southern Nevada. Thick layers of these rocks are exposed also in many mountain ranges. The volcanic rocks have a wide range of permeabilities depending on their depositional history and range from excellent aquifers to barriers to ground-water flow (Winograd, 1971). In southern Nevada these rocks are less common than farther north, except near the Nevada Test Site, Caliente, and just north of Lake Mead (pl. 1).

Source, Occurrence, and Movement of Water

The water moving through and stored in the carbonate rocks is derived from precipitation—rain and snow—within the carbonate-rock province and on several mountain ranges adjacent to the province. Annual precipitation ranges from less than 3 in. in some of the southern valleys (for example, the Amargosa Desert and Death Valley [pl. 1]) to greater than 30 in. in some of the highest mountain ranges (for example, the Ruby Mountains [fig. 1]), and depends primarily on altitude (Hardman and Mason, 1949, p. 10). Virtually all the precipitation on the basin floors and most of the precipitation in the mountains is evaporated or transpired (used by plants) before the remainder recharges either the basin-fill aquifers or the carbonate rocks. Some precipitation may become surface runoff, which then either infiltrates to recharge ground water or is consumed by evapotranspiration.

The process through which water enters (recharges) the carbonate-rock aquifers is not completely understood. In some areas, for example, the Ruby Mountains in northeastern Nevada (Johnson, 1980, p. 17-18) and the Spring Mountains of southern Nevada (Winograd and Thordarson, 1975, p. C92), recharge to the carbonate-rock aquifers primarily is by downward percolation of water through the thin soil zone and into the carbonate rocks within the mountains. In other areas, water enters the carbonate-rock aquifers by leaking down through basin fill. This form of recharge is difficult to delineate because it occurs at depth beneath the basin fill and depends on aquifer properties and hydrologic conditions that are not adequately defined. The water involved in this interaquifer flow can easily be "double counted" (as part of the basin-fill resource AND as part of the carbonate-rock resource) unless interchanges between basin fill and the carbonate aquifers are well understood. Geochemical tracing of water has been used to good advantage in identifying recharge source areas in selected basins in southern Nevada (Emme, 1986; Lyles and Hess, 1988; Noack, 1988). Because of the aridity of the region and the mountainous terrain of the Basin and Range Province (fig. 1), recharge to the carbonate-rock aquifers at low altitudes, from direct leakage from overlying perennial streams, is rare in southern Nevada.

Once water infiltrates into the carbonate-rock aquifers it generally will flow downgradient to one or more discharge areas at rates of flow that vary considerably in space. Because ground water flows downgradient from areas of high head to areas of lower head (Mifflin, 1968, fig. 5) at rates that depend on the permeabilities of the rocks, the rate of flow through the carbonate rocks depends on the openings in the rocks and the hydraulic gradients, that is, the gravity and pressure forcing the water along. The path that water follows as it moves downgradient may be quite circuitous owing to geologic and hydrologic barriers; however, the paths are ultimately toward some area where water is discharging from the aquifers.

Water leaves the carbonate-rock aquifers by discharging at springs, by leaking into overlying and underlying aquifers, by transpiring through plants, by evaporating from areas where the water table is near the land surface (such as playas), and by discharging into rivers or streams (such as in the middle reaches of the Amargosa River [pl. 1]; Mifflin, 1968, p. 22). In some places, water leaves the carbonate rocks of Nevada by subsurface flow into adjacent States.

SUMMARY OF PROGRAM ACTIVITIES, 1985-88

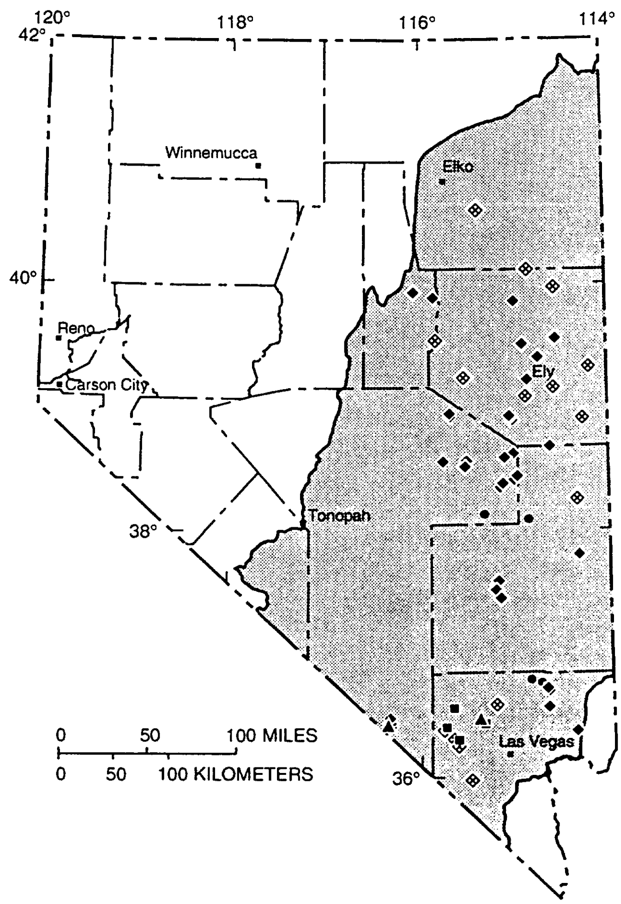
Activities during 1985-88 focused on determining the potential for development of the carbonate-rock aquifers in southern Nevada, largely north of Las Vegas. The activities included:

- **Collection of basic hydrologic data** such as high-altitude precipitation rates, ground-water levels in selected wells, and flow rates in selected springs and streams.
- **Geologic mapping** of the structure and stratigraphy of the carbonate rocks and younger basin-fill deposits.
- **Geophysical measurements and interpretations** employing measurement of the density, electrical, and magnetic properties of the rocks and sediments.
- **Geochemical sampling and inferences** characterizing ground water and flow paths using the isotopic composition and chemical constituents in the water.
- **Compilation of hydraulic properties estimated from available aquifer and drill-stem tests** in the carbonate rocks.
- **Drilling, logging, and hydraulic testing** of wells into the basin-fill and carbonate-rock aquifers.
- **Measurements of ground-water evapotranspiration rates** by native plants near key springs.
- **Synthesis** of the results of these specific activities, together with previous and concurrent studies.

Together these activities have increased our understanding of ground-water flow in the carbonate-rock aquifers of southern Nevada. This section summarizes the goals, accomplishments, and conclusions of each activity. The summaries are intended to describe the approaches and kinds of conclusions obtained by the activities. This section does not provide detailed descriptions of the work. For details or clarification, the interested reader should consult the separate reports describing these activities and results.

Basic-Data Collection

A network of gages and other monitoring sites provides information on key hydrologic parameters, and documents existing conditions in the carbonate-rock aquifers. The basic data network consists of 8 springflow gages (where flow is monitored continuously), 59 miscellaneous springflow measurement sites (where flow is monitored on a annual or semiannual basis), 4 observation-well recorder sites, 11 other wells used as observation wells for regular measurements of water level, and 15 high-altitude precipitation storage gages. Locations of all the monitoring sites are shown in figure 6. Results of this network are presented by Pupacko and others (1988, p. 45-50, 57-58, 60-61, 221, 226, 260) and Pupacko and others (1989, p. 44-47, 50, 55, 57, 187, 213-214, 216, 246). Results of monitoring spring discharge and ground-water levels in the carbonate-rock aquifers are summarized below as examples of the utility of these basic data.



EXPLANATION

- Approximate area of carbonate-rock province
- ■ Springflow gage
- ◆ Miscellaneous springflow measurement site
- ● Observation well with water-level recorder
- ◈ High-altitude precipitation storage gage
- ▲ Micrometeorological station for measurement of evapotranspiration

Figure 6. Sites where springflow, ground-water levels, high-altitude precipitation, and evapotranspiration have been monitored in carbonate-rock province of Nevada.

Spring Discharge

Continuous measurements (Pupacko and others, 1988, p. 48, 50, 61; Pupacko and others, 1989, p. 45-47, 57) indicate that the discharge from Muddy River Springs remains nearly uniform at levels reported by Eakin and Moore (1964) and Eakin (1964, p. 17) and that the discharge from Corn Creek Springs also is nearly uniform at about the rate measured during 1947-55 (Malmberg, 1965, p. 60). The locations of these springs are shown on plate 1. The observed long-term and short-term uniformity of discharge from these springs is typical of most regional springs that discharge from the carbonate-rock aquifers (fig. 7). The continuing uniformity of these discharges indicates that the springs have not been affected measurably by pumping of nearby wells. Short-term fluctuations in spring discharge are caused by changes in atmospheric pressure, earth tides, local precipitation, or other stresses. The basin-fill aquifers of the Upper Muddy River Springs area are currently (1989) experiencing increased pumping stress, and pumping from both the basin-fill and carbonate-rock aquifers in adjacent areas is expected to increase. Muddy Spring and Warm Springs West, both located in the area, have not yet shown long-term response to these pumping stresses. During the summer of 1987, discharge from Muddy Spring showed a slight decline that may or may not have been related to summer pumping. Similarly, the record of discharge from Corn Creek Ranch Spring, in northern Las Vegas Valley, indicates that the spring has not yet been affected by intensive pumping 11 mi farther south in the valley. Discharge from Rogers Spring, in a secluded part of the Black Mountains area near the Overton arm of Lake Mead, reflects only natural stresses.

Water Levels in Observation Wells

Measured static water levels in wells provide valuable information about conditions in an aquifer. For example, figure 8 shows water levels measured in a well (MX well CE-DT-4) that penetrates the carbonate rocks beneath Coyote Spring Valley, about 10 mi from Muddy River Springs (pl. 1). The water levels fluctuate about 0.2 ft seasonally with no apparent long-term trend of change. As of 1988, no water has been pumped from the carbonate-rock or basin-fill aquifers in the immediate vicinity, but nearby industrial pumping is planned for the near future. The nearest pumping is from another well into the carbonate rocks about 6 mi away (MX well CE-DT-6). The Moapa Valley Water Company has pumped this well during summers since 1986. More observations are needed to determine if the seasonal fluctuations measured in MX well CE-DT-4 are effects of this nearby pumping.

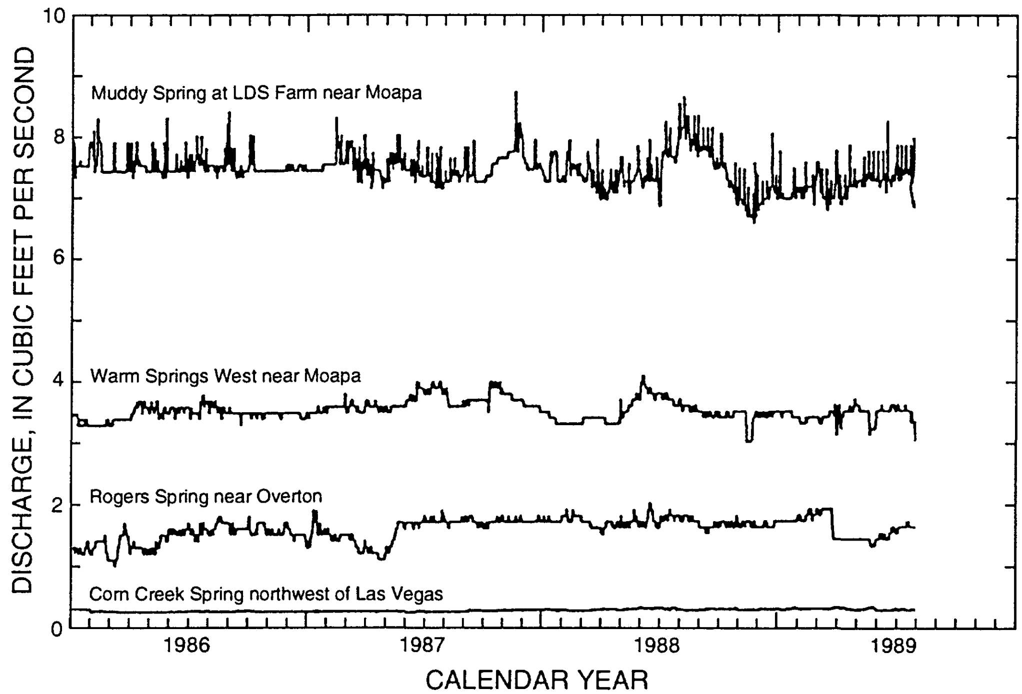


Figure 7. Flow rates of four springs that discharge from carbonate rocks in the study area, 1986-89. Spring locations are shown on plate 1.

Geologic Mapping Activities

Geologic studies in a 1,800-mi^2 area north of Las Vegas during 1985-88 included examination of the geologic literature, wide-ranging reconnaissance of the area, and detailed geologic mapping of areas selected to resolve known geohydrologic problems concerning past and present ground-water flow through the carbonate-rock aquifers. Geologic mapping and interpretations entail developing maps that show outcrops of rocks of all types and ages, together with structures that deform or disrupt those rocks. The history of the rocks and structures as well as their configurations at depth are inferred from observed field relations, previous mapping, and regional relations. Mapping is generally based on a combination of detailed field observations and correlation of observations with aerial photography and satellite imagery. Mapping was partly or fully supported throughout the area indicated in figure 9 (Guth, 1986, 1988; McBeth, 1986; Blank, 1988; Guth and others, 1988).

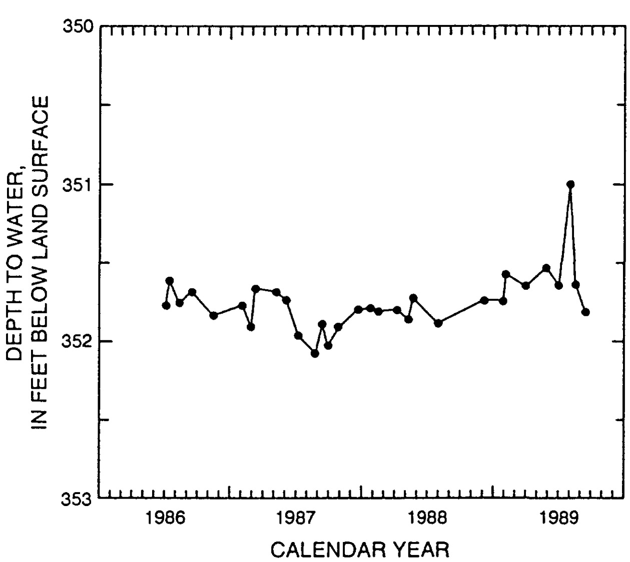
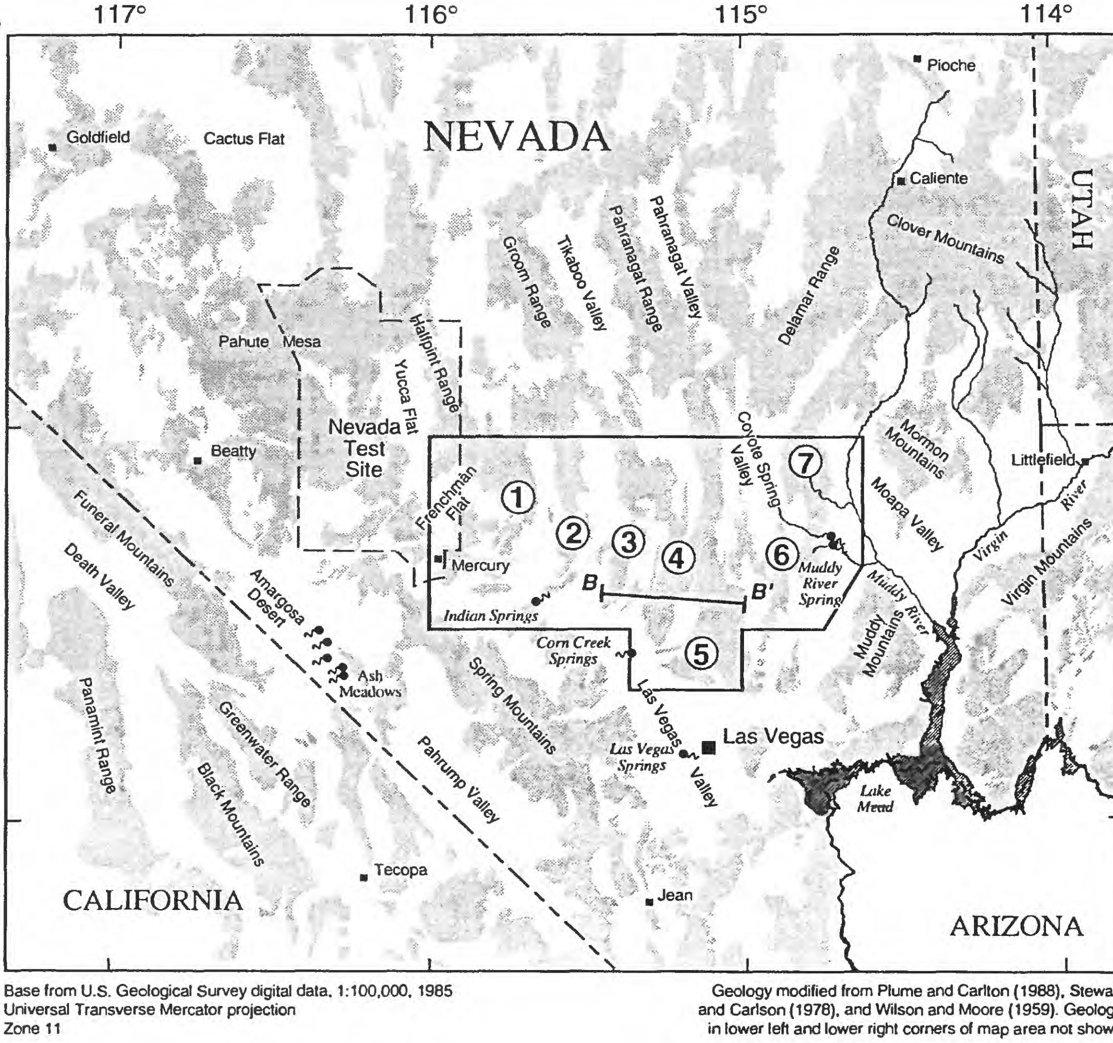


Figure 8. Water levels in MX well CE-DT-4, 1986-89. Well penetrates carbonate-rock aquifer beneath Coyote Spring Valley. Well location is shown in figure 36.

Geologic mapping with special attention to aquifer configurations has shown that structural deformation subsequent to deposition of the carbonate rocks in southern Nevada greatly complicated the originally flat-lying carbonate rocks and thereby greatly complicated the aquifer systems contained therein. Mapping west of the Sheep Range during 1986-87 indicated that many of the exposed (and buried) carbonate rocks were pulled apart along low-angle faults during the last 15 million years (Guth, 1986; Guth and others, 1988). Fault-bounded blocks of carbonate rocks have been juxtaposed against other blocks of rocks of lower



EXPLANATION

- **Basin fill**
- **Consolidated rock**
- B—B' **Approximate line of geologic section in figure 10**
- **Extent of mapping**
- ① **Mountain ranges in which mapping was fully or partly supported by this study**—1, Spotted Range; 2, Pintwater Range; 3, Desert Range; 4, Sheep Range; 5, Las Vegas Range; 6, Arrow Canyon Range; 7, Meadow Valley Mountains
- **Spring or closely spaced springs**

Figure 9. Area where geologic mapping was fully or partly supported by present study.

permeability (Guth, 1986). These forces were far more effective in pulling apart the exposed rocks in this area than in the area east of the Sheep Range (as previously noted in Wernicke and others, 1984, p. 489). The area east of the Sheep Range was mapped for this study mostly during 1985-86. The differences in extension and aquifer thickness between the highly deformed sections of rock beneath and west of Sheep Range and the less deformed sections farther east are suggested in figure 10. These differences are believed to have important hydrologic consequences (Dettinger, 1988; Dettinger and Schaefer, in press), and have been an important part of selection of sites for some of the exploratory wells drilled for this study.

The origin and configuration of individual structures also may affect ground-water flow. Extension of the rock masses resulted in innumerable small and large faults and widespread fracturing and shattering of the rocks. Field observations of fault zones and fractures in outcrops along the west side of the Sheep Range (and on Tucki Mountain in Death Valley) revealed that, in some instances, breakage of rocks was so severe that rocks were reduced to grain- to clay-size fragments, followed by alteration of the component minerals and subsequent reconsolidation of the rock along some faults. Examples of this brecciation and reconsolidation are reported by Guth (1981, p. 766). Such deformation and reconsolidation was found mostly adjacent to older, low-angle fault zones, and locally may have rendered many such fault zones impermeable to ground-water flow. Other fault zones, especially recently active, high-angle normal faults (such as those that form the steep edges of mountain ranges) were observed to form fractures that are more open and, consequently, might transmit ground-water flow more readily.

Geophysical Explorations

About 50 percent of the carbonate-rock aquifers lie buried beneath younger rocks and sediments that may be thousands of feet thick. Four kinds of geophysical measurements were made to provide information to estimate thicknesses of basin fill overlying the carbonate rocks and to locate faults deep beneath land surface. Estimates of depths to carbonate rocks and faults are helpful when choosing sites for exploratory drilling. The measurements used were gravity, seismic refraction, direct-current (DC) resistivity, and magnetotellurics. These measurements detect spatial variations in the density, strength, and electrical properties of rocks in the subsurface.

Measurements were made of Earth's gravitational field at about 200 sites on both sides of the Sheep Range. Figure 11 is a Bouguer gravity anomaly map of the area just north of Las Vegas based on these measurements. Thick sections of low-density basin fill (relative to the carbonate rocks) result in lower gravity anomalies. Thus, the areas underlain by such thick sections of basin fill are indicated on this map by gravity depressions (especially, the barbed ovals).

Seismic-refraction measurements were made at seven proposed drill sites to determine—on a local scale—the thickness of unconsolidated material overlying the carbonate-rock aquifers. Seismic waves—radiating from an explosion—travel much more slowly through basin fill than through carbonate rocks and this difference is detectable. Measurements were made of the time required for waves from an explosion to reach detectors at several distances from the explosion. The arrival times at several distances can be used to estimate the thickness and strength of the rock layers through which the waves pass.

Direct-current resistivity measurements were made at more than 60 sites on the west side of the Sheep Range. These measurements yield estimates of the electrical resistivity of rocks over a wide range of depths beneath the measurement equipment by inducing electrical currents in the Earth's crust and measuring the resulting voltage drops across the same area. Audiomagnetotelluric and magnetotelluric measurements also can be used to measure electrical resistivities of rocks at depth. These methods were applied both east and west of Sheep Range at locations shown in figure 11 (Pierce and Hoover, 1986, 1988). The methods infer electrical resistivities of buried rocks by measuring electrical and magnetic fields associated with naturally occurring electrical currents in the Earth's crust. When direct-current resistivity data are organized into a cross section such as the one in figure 12 (location shown in fig. 11) and conditioned on field geology and other geophysical measurements, variations in electrical resistivity of rocks at different depths can be inferred. Because different rock types (and different degrees of water saturation) can have different resistivities, such cross sections can be used to infer rock (and aquifer) configurations at great depths.

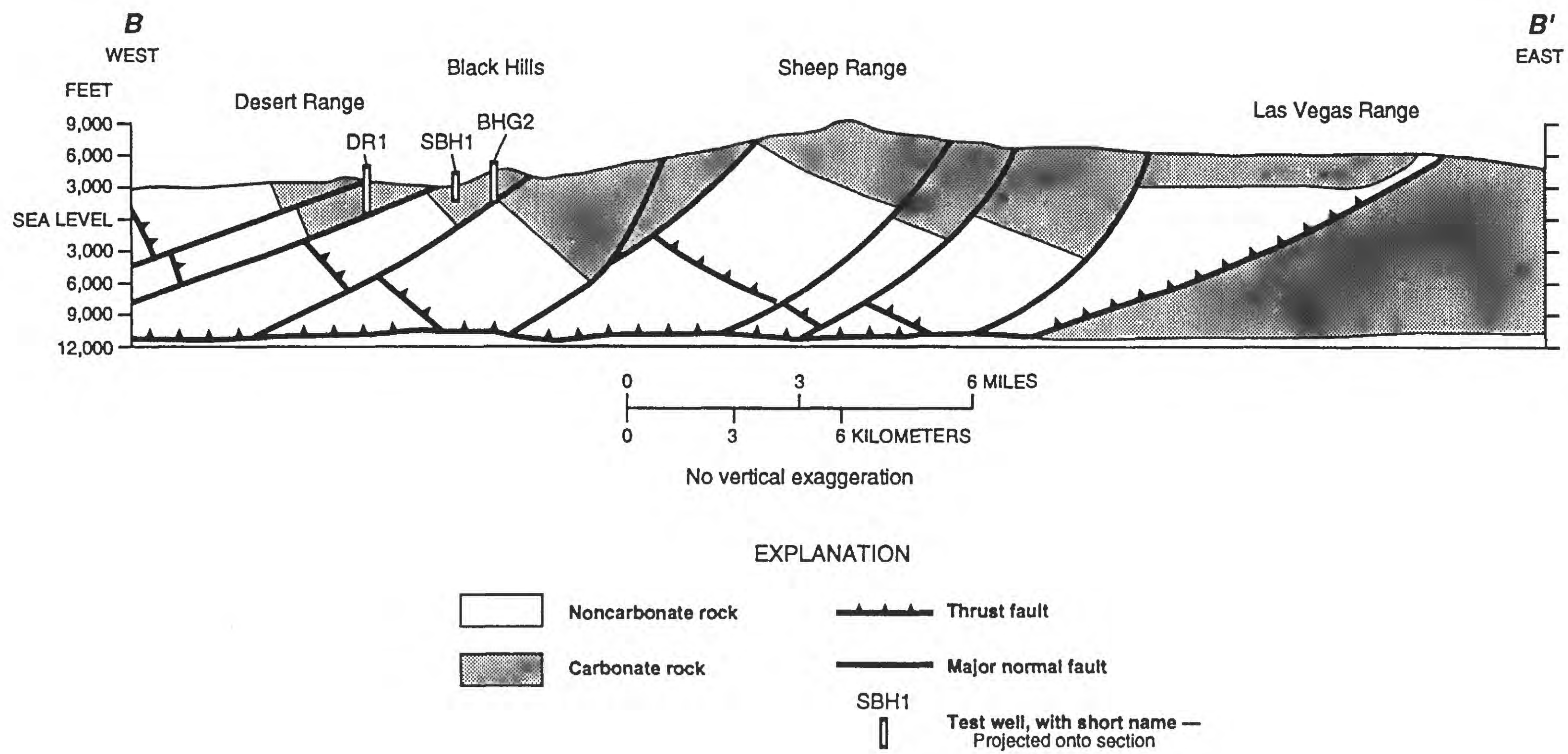


Figure 10. Schematic geologic section across Desert Range, Sheep Range, and Las Vegas Range, showing general location of test wells drilled in 1987-88. (Modified from Guth, 1981.) Line of section is shown in figure 9.

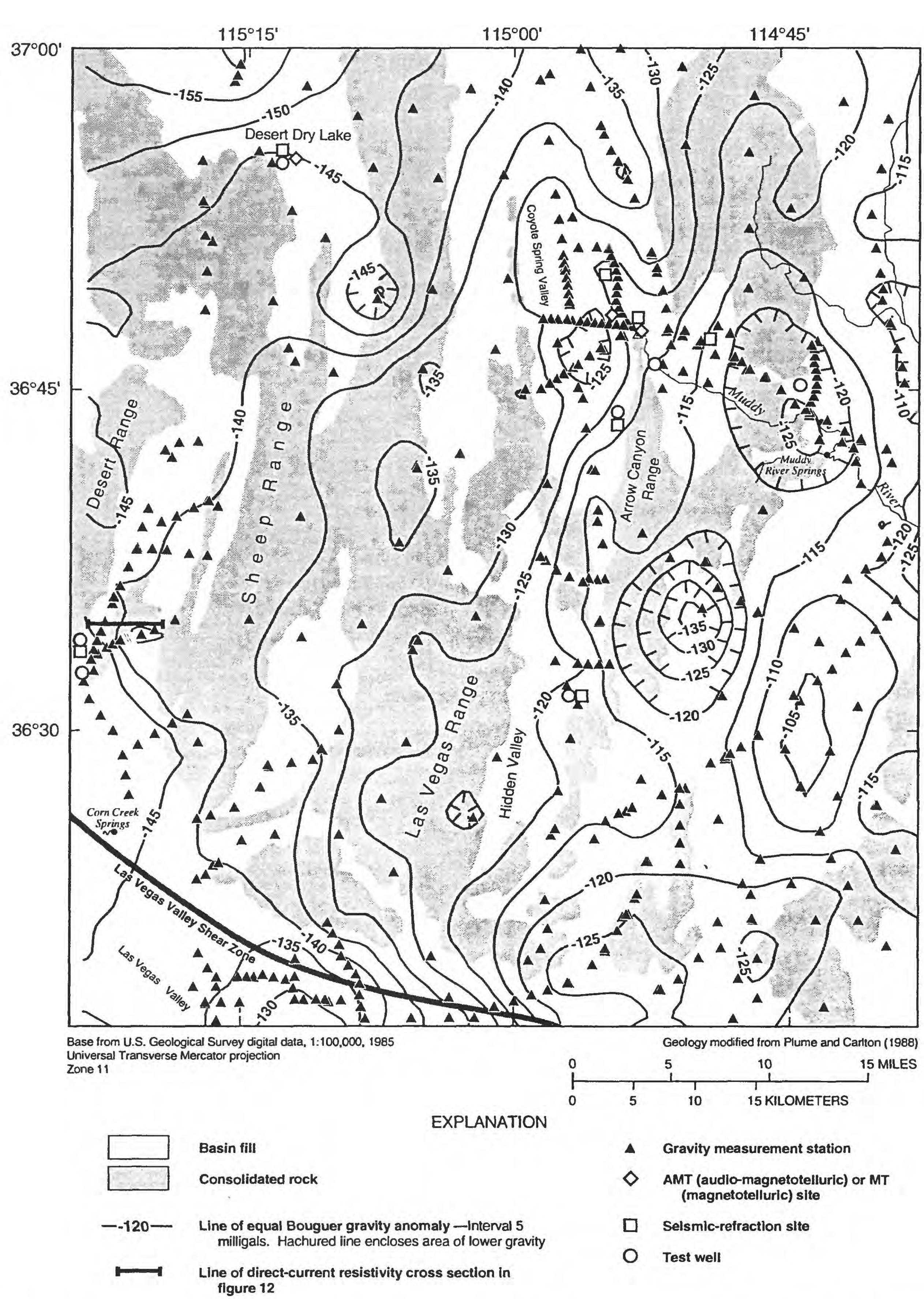
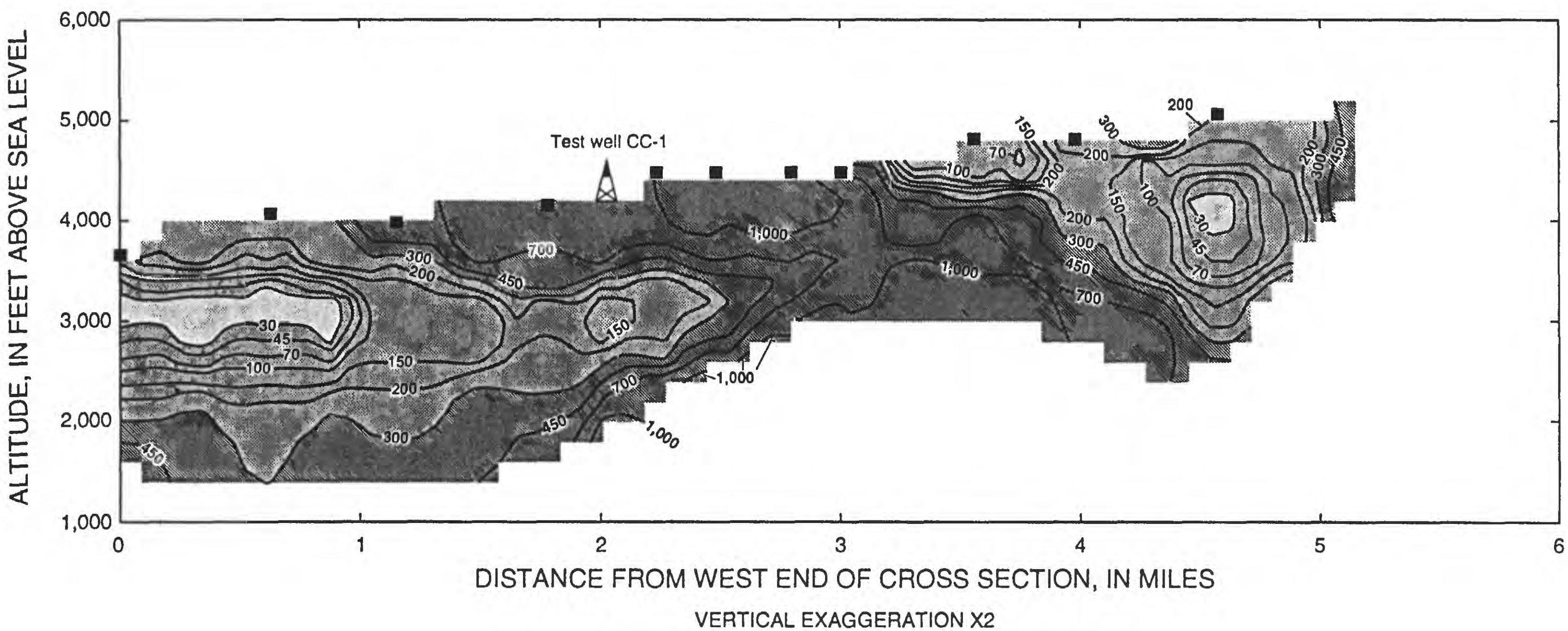


Figure 11. Bouguer gravity anomalies and location of geophysical measurement sites in south-central part of study area. Geophysics by Donald H. Schaefer, U.S. Geological Survey, Carson City, Nev.



EXPLANATION

RESTIVITY, IN OHM-METERS

1,200
300
30
0

Resistivity — Range from 300 to 1,200 ohm-meters probably is dense (unfractured and unsaturated) carbonate rock or coarse-grained, unsaturated fill. Range from 30 to 300 ohm-meters probably is highly fractured, saturated carbonate rock or basin fill (from fine-grained and unsaturated to coarse-grained and saturated). Range from 0 to 30 ohm-meters probably is saturated, fine grained basin-fill or basin fill saturated with poor-quality water

—70— **Line of equal resistivity** — Interval, in ohm-meters, is variable

■ **Direct-current measurement array**

Figure 12. Direct-current resistivity of rocks at depths between Desert Range and Sheep Range. Figure is based on direct-current geoelectrical profiles, but incorporates information from audiomagnetotelluric and magnetotelluric measurements and from geologic mapping. Line of section is shown in figure 11. Geophysics by Donald H. Schaefer, U.S. Geological Survey, Carson City, Nev.

Interpretation of a combination of these geophysical measurements indicates that thicknesses of basin fill overlying carbonate rocks range from less than 500 ft in Hidden Valley to about 1,000 ft in Coyote Spring Valley, and more than 6,000 ft beneath southern Desert Dry Lake Valley (Donald H. Schaefer and H.A. Pierce, U.S. Geological Survey, written communs., 1988). In the northernmost part of Las Vegas Valley (at the cross section in fig. 12), basin-fill deposits are probably about 2,000 ft thick (Pierce and Hoover, 1986, p. 363; Adel A.R. Zohdy, U.S. Geological Survey, written commun., 1986).

The geoelectrical measurements also showed that highly productive MX wells drilled in Coyote Spring Valley encountered a fault zone along the east edge of Arrow Canyon Range, rather than the more visible fault zone on the steep west side of the range (Pierce and Hoover, 1986, fig. 2). These measurements clarified the nature of structures that conduct water to those wells.

Geochemical Sampling and Interpretation

Water samples were collected and analyzed from 209 springs, streams, and wells in eastern and southern Nevada as a part of the carbonate-rock investigations during 1985-88. Locations of these sample sites are shown in figure 13. These new data were combined with other available data to determine sources and flow paths for water in the carbonate-rock aquifers in southern Nevada. These determinations were made using calculations of (1) chemical and isotopic mass balances, (2) the chemical saturation states of various constituents in the water with respect to minerals comprising the aquifers, (3) expected variations in chemistry of the ground water along flow paths in response to naturally occurring reactions, and (4) ground-water ages.

These geochemical efforts updated or evaluated regional-scale water balances in six parts of southern Nevada, including Las Vegas Valley, the Ash Meadows area, the Meadow Valley Wash area, and the Coyote Spring Valley-Muddy River Springs area (Emme, 1986; Hershey and others, 1987; Kirk and Campana, 1988; Lyles and Hess, 1988; Noack, 1988; Thomas, 1988). The studies (Emme, 1986; Schroth, 1987; Kirk and Campana, 1988; Thomas, 1988) generally verify the overall water budgets developed by previous investigators for regional flow beneath the White River drainage and Meadow Valley Wash area in east-central Nevada that provide inflow to southern Nevada (Rush, 1964; Eakin, 1966; Winograd and Friedman, 1972). Other results alter previous concepts of regional flow beneath southern Nevada in that most recharge from the Sheep Range is directed toward the Muddy River Springs rather than radially towards other adjacent valleys including Las Vegas (Thomas and Welch, in press).

The studies also addressed flow and recharge processes in and around the Spring Mountains that are the major local recharge area for southern Nevada (Hershey and others, 1987; Lyles and Hess, 1988; Noack, 1988; Thomas, 1988). Within the Spring Mountains, lithologic variations in the mountain block are directly associated with chemical variations in

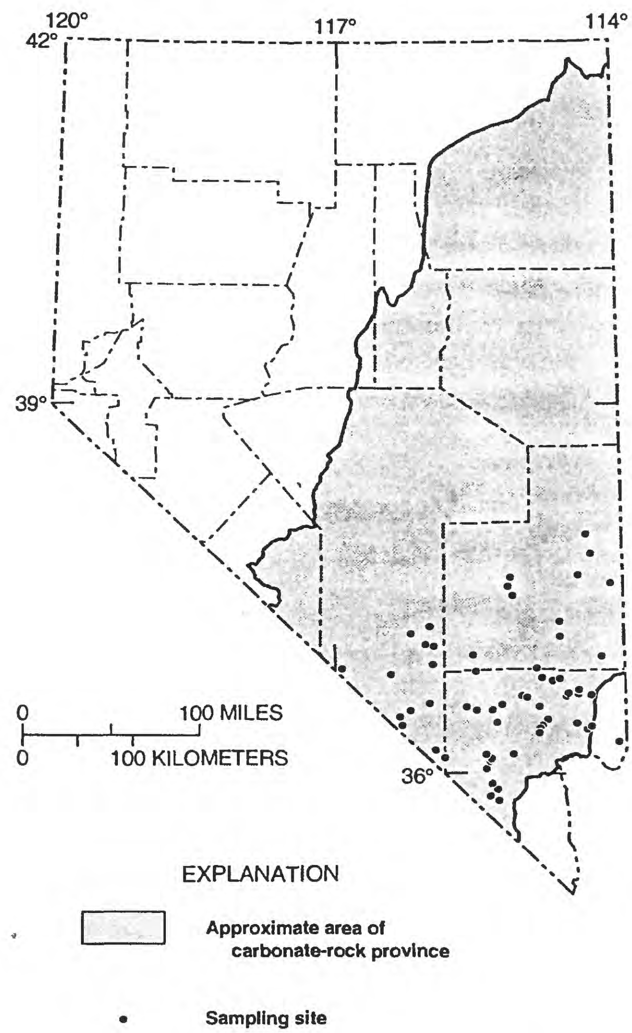


Figure 13. Springs, wells, and streams sampled for geochemical determinations in and adjacent to carbonate-rock province of southern Nevada.

ground water. Examples of this were observed in areas of dolomitized limestone (such as in Lee Canyon, pl. 1) where higher concentrations of magnesium are found in the water and near outcrops of Jurassic rocks (as in Red Rock Canyon, pl. 1) where sulfate becomes a dominant ion (Lyles and others, 1986).

Much of the effort around the Spring Mountains focused on the Las Vegas Valley shear zone—a complicated structure extending from the northeastern part to the northwestern part of Las Vegas Valley and nearly to Mercury. Flow in the basin-fill aquifers of the shear zone was shown to be impeded in some areas and enhanced in others, presumably by the influence of deeply buried geologic structures (Lyles and Hess, 1988). As a consequence, the ground water of Las Vegas Valley—in and south of the shear zone—is a mixture of water from different sources. Recharge from the Spring Mountains contributes significantly to basin-fill aquifers of Las Vegas Valley. One hypothesis developed from studies around the Spring Mountains is that, near the main well fields for the Las Vegas urban area and near the toe of Kyle Canyon alluvial fan (pl. 1), ground water may be a mixture of shallow circulating water that is clearly from the Spring Mountains and deep circulating water from areas to the north or west (including other parts of the Spring Mountains; Lyles and Hess, 1988, p. 51; Noack, 1988, p. iii). At the toe of the Kyle Canyon fan, for example, ground water is composed of a small amount of shallow circulating water discharging from Kyle Canyon and as much as 90 percent deep-circulating water (Lyles and Hess, 1988, p. 43).

The quantity of water entering southern Nevada as inflow from the carbonate-rock aquifers of east-central Nevada was addressed also in some detail. The White River regional flow system—an interbasin ground-water flow system that spans much of eastern Nevada from areas west of Ely in east-central Nevada to Moapa in southern Nevada— provides the principal (perhaps only) inflow from east-central Nevada. Kirk and Campana (1988) simulated the flow system using a "discrete-state compartment model," which is a sophisticated accounting of mixing of naturally occurring deuterium in the ground water along flow paths in the system. The model represented the flow system as two layers of mixing cells: a lower layer representing the carbonate-rock aquifers and an upper layer of basin-fill aquifers (fig. 14). The mixing of water with different isotopic compositions that results from the flow of water from cell to cell was simulated by the model. Calibrating the model allowed determinations of ranges of "reasonable" values for recharge, storage volumes, and ground-water ages in the flow system that are compatible with observed conditions (Kirk and Campana, 1988). The ranges reported are relatively large and uncertain but can be constrained somewhat by a simultaneous reevaluation of the southern White River flow system and Ash Meadows system reported by Thomas and Welch (in press). As noted previously, the efforts generally agreed with previous water budgets, but some sources of flow within southern Nevada were re-considered (notably, recharge from the Sheep Range).

Finally, a broad reconnaissance of water quality in several aquifers of southern Nevada demonstrated that aquifers beneath and east of Las Vegas Valley and elsewhere in southeasternmost Nevada are likely to contain water of a quality not suitable for public supply or most other uses (Lyles and others, 1986; Schroth, 1987, p. iii). This result will be discussed in greater detail in the section of this report titled "Where is water potentially available in carbonate-rock aquifers?"

Well Drilling, Geophysical Logging, and Aquifer Testing

Test wells were drilled to provide direct subsurface data on the carbonate-rock aquifers. Aquifer tests were done and geophysical logs collected. The wells also provided information on depths to water and chemistry of water in the aquifers. Data collected from the wells were used to test hypotheses developed in other studies and provided solid evidence—subsurface configurations of rock types and units, estimates of hydraulic properties, water levels, water chemistry, and measures of rock porosity—as to hydrologic conditions in the carbonate-rock aquifers.

The 16 wells drilled, rehabilitated, or otherwise used for collection of these kinds of data are described in table 3 and their locations are shown in figure 15. Descriptions of lithology, drilling rates, geophysical logs, and aquifer tests are described for eight of these wells by Berger and others (1988). The lithology of well BHG-2 is described by Schaefer and others (1992). Water levels in the Divide and Old Dry wells are described by Lyles (1987). Overall results of drilling, logging, and testing are summarized (with examples) in the following paragraphs.

Well Drilling and Rehabilitation

Nine wells were drilled during the studies in 1985-88. Lithologic samples, drilling records, and geophysical logs were available for five MX wells drilled during 1980-81, and were used in this study.

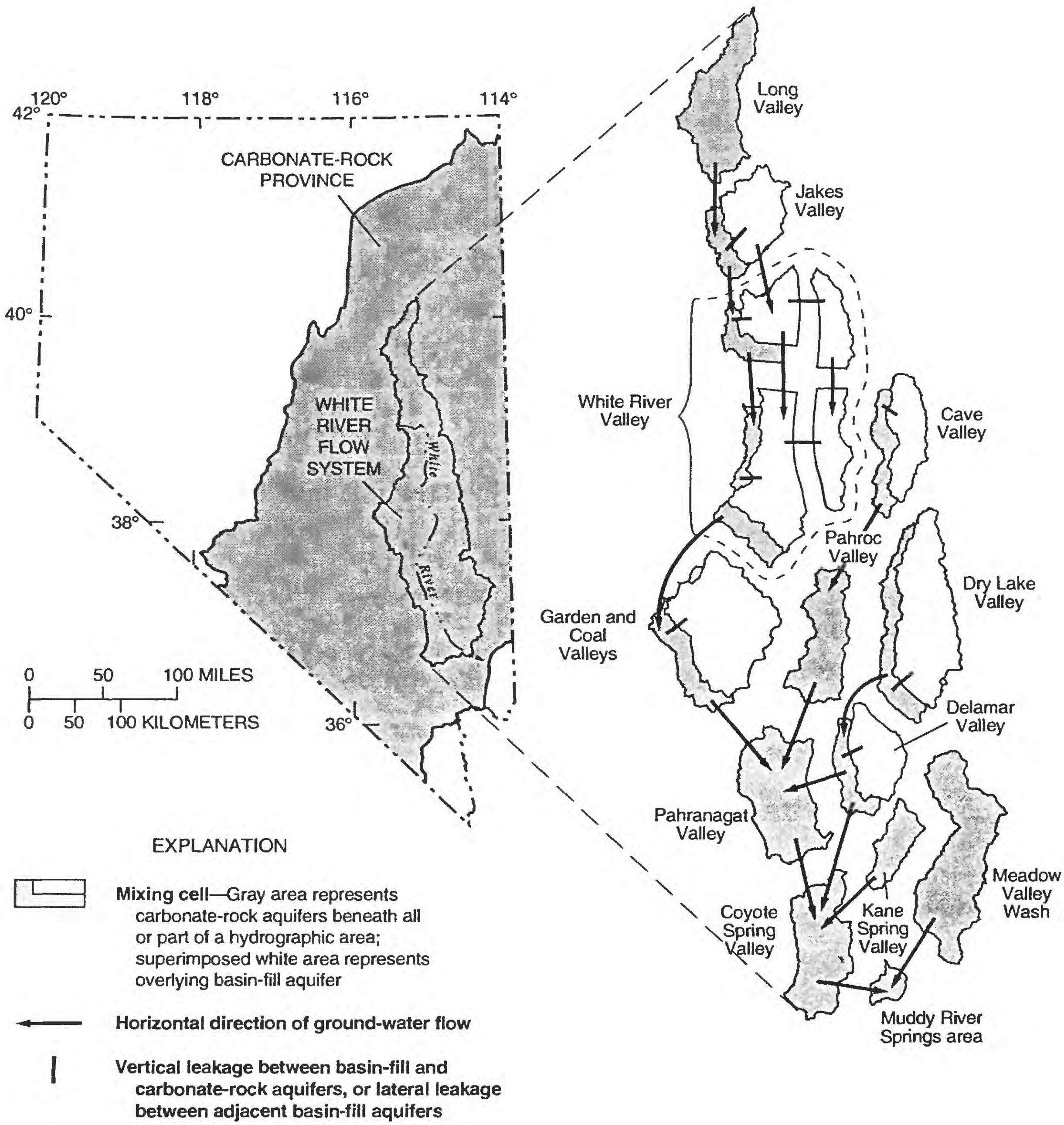


Figure 14. Schematic three-dimensional representation of mixing-cell model used to simulate flow and isotopic mixing in White River flow system (modified from Kirk and Campana, 1988, fig. 11).

Two abandoned stock wells in remote areas were reconditioned to provide inexpensive access to the subsurface. As a result, rock and sediment samples and drilling records are available from a total of 10,000 ft of drilling for this study (and the MX study) in the study area. Of this total, 4,500 ft penetrated basin fill and 5,500 ft penetrated carbonate rocks.

Some direct results from this drilling are access to the water-table for measurements of water-level altitudes and water samples that contributed to the geochemical interpretations. Zones of highly fractured carbonate rock that locally might be water-producing zones can be identified from penetration rates and rock samples collected during drilling. Finally, lithology encountered during drilling is a direct sampling of rock configurations beneath a well site, and thus might provide valuable inputs to geologic interpretations in the study area.

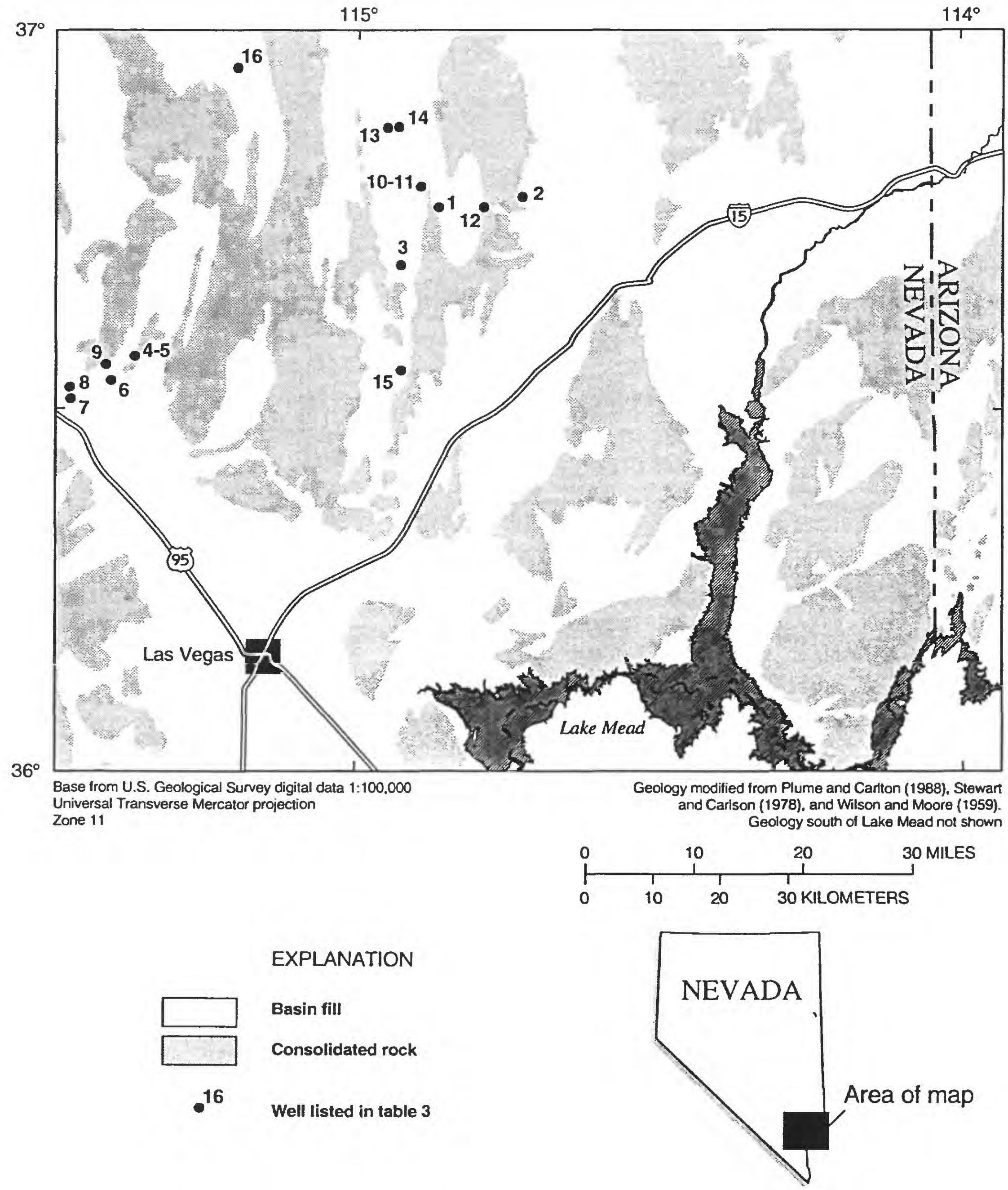


Figure 15. Wells used for measuring borehole geophysical properties, aquifer properties, water levels, and geochemical characteristics, 1984-88, in southeastern part of study area.

Borehole Logging

Geophysical logs of boreholes measure physical properties of rocks penetrated by a well as a function of depth (see descriptions of information that can be derived from logs in table 4). Zones of fractured rock commonly can be identified and hydrologic parameters can be estimated from the rock properties recorded. The several log types in different depth zones collected for this study total about 28,000 ft (Berger and others, 1988).

Geophysical logging in the wells indicated a wide range in the rock properties measured, which were dependent on primary porosity (open spaces between grains in the rocks) and secondary porosity (fractures and dissolution cavities). These porosities are important in determining the quantity of water contained in a given volume of aquifer material. The total porosities—primary plus secondary—determined from geophysical logging were in the same range as those reported from laboratory measurements of rocks

Table 3. Thickness of basin fill and carbonate rocks penetrated by selected wells

Site No. (fig. 18)	Well name	Thickness penetrated (feet) Basin fill	Carbonate rocks	Total well depth (feet below land surface)
		Wells Drilled During Present Study		
1	CSV-1	765	0	765
2	CSV-2	17	461	478
3	CSV-3	780	0	780
4	BHG-1	380	40	420
5	BHG-2	142	1,258	1,400
6	SBH-1	60	634	694
7	DIVIDE	200	0	200
8	OLD DRY	210	0	210
9	DR-1	182	768	950
		Existing Wells		
10	CE-DT-4	30	639	669
11	CE-DT-5	110	518	628
12	CE-DT-6	420	517	937
13	CE-VF-1	714	0	714
14	CE-VF-2	850	371	1,221
15	SHV-1	250	670	[a]920
16	DDL-1	420	0	420

[a] No drilling records available.

Table 4. Information acquired from various geophysical logs

[Modified from Keys and MacCary, 1971, table 1]

Geophysical log	Information acquired
Acoustic transit time	Primary porosity, fractures, lithology
Borehole televiewer	Fractures, construction of existing wells
Caliper	Diameter of hole, fractures, construction of existing wells
Electric	True resistivity, stratigraphic correlation
Gamma-gamma density	Bulk density of rocks or sediments, total porosity, water level, lithology
Natural gamma	Clay or shale content, stratigraphic correlations
Neutron	Total porosity, location of water level, lithology
Temperature	Ground-water temperature and temperature gradients, location of water level, movement of water in well

collected at the Nevada Test Site (Winograd and Thordarson, 1975, p. C17), which averaged about 5-6 percent. Secondary porosity as estimated from the logs in zones where many fractures were present locally might constitute almost half of that total (Berger, 1992).

Aquifer Testing

Properly conducted and monitored aquifer tests can provide estimates of the capacity of aquifers to transmit and store water. The hydraulic properties that characterize these capacities are the transmissivity and storage coefficient of the aquifer, respectively.

Aquifer testing involves lowering a pump into a well to a depth below the water level, pumping water from the well at a constant rate for long periods of time while recording water-level changes in the pumped well and, if available, in any nearby observation wells. As pumping continues, water levels generally decline in the well, and the rate at which the water level declines can be used to estimate the transmissivity. After the pump is turned off, measurements are made of the recovery of water levels in the wells. The rate of recovery is used to estimate transmissivity. Measurements of declining water levels in nearby wells can be used to estimate both the transmissivity and storage coefficient of the aquifer. Because of the high cost of drilling in the carbonate-rock aquifers, most aquifer tests in the carbonate-rock aquifers of Nevada lack nearby observation wells. This limits the accuracy of the estimates of transmissivity and precludes estimation of storage coefficient (Heath, 1983, p. 42).

Estimates of transmissivity (and storage coefficient for one example) calculated from aquifer tests made in some of the carbonate wells during 1985-88 are given in table 5. All estimates are based on the straight-line approximations described for well CSV-2 and data presented in Berger and others (1988) or collected since that report. To facilitate comparisons among well sites, the last column in table 5 presents a normalized response of the aquifer tested in each well to 1 week of pumping at 1,000 gal/min. The responses are normalized to reflect drawdown that would occur in a 24-in. diameter production well at each site if it tapped 500 ft of water-saturated rock. The storage coefficient is assumed to be 0.1. Projections of drawdown are made by using known and estimated aquifer properties at each well together with simple mathematical solutions for drawdown given in Theis (1935). Projected drawdowns are those that theoretically would develop in addition to the rapid drawdowns that develop in the first few minutes of pumping. These early drawdowns reflect well construction, pump configuration, and other installation specific properties and may amount to more drawdown than the long-term contributions.

Table 5. Data and results of aquifer tests done during 1985-88

[--, no estimate available]

Well	Pumping rate (gallons per minute)	Pumping duration (hours)	Maximum drawdown (feet)	Calculated transmissivity (foot squared per day)	Calculated storage coefficient (fraction)	Hypothetical drawdown (feet)
CSV-2	101	22	30.1	1,600	--	27
CE-DT-4	540	77	3.7	200,000	--	.9
CE-DT-5	3,400	326.3	11.8	250,000	0.14	.7
CE-DT-6	472	66	41.6	13,000	--	17
CE-VF-2	77	14	13.0	3,000	--	47
SBH-1	24	10	.9	37,000	--	1.6

Activities Using Data from Petroleum-Exploration Wells

As part of the studies, existing data from petroleum-exploration activities in Nevada, where applicable, were used to describe the hydrology of the carbonate rocks (McKay and Kepper, 1988). In Nevada, three types of data are available for estimating the hydraulic properties of carbonate-rock aquifers: aquifer tests at water wells, natural fluctuations of water levels in wells or flow from springs, and records from wildcat oil and gas exploration. Results from tests at 39 water wells penetrating carbonate-rock aquifers (including the aquifer tests described in the preceding paragraphs) were compiled (table 1). Only one example of the use of natural water-level fluctuations is available in the literature (Galloway, 1986). Beginning with the present study, measurements of natural water-level fluctuations were made and used to augment the aquifer tests and oil-exploration tests; see Kilroy (1992) for complete details. As of 1988, over 480 wildcat oil and gas wells have been drilled in Nevada, and many penetrate carbonate rocks. Some provide useful data about the properties of carbonate-rock aquifers.

Locations of all the oil and gas exploration wells in and adjacent to the carbonate-rock province of Nevada are shown in figure 16. Individual records for each well are on file at the Nevada Bureau of Mines and Geology. Ideally, a complete well file will contain the following: application forms and completion reports, all geophysical logs (if run), and drill-stem test (DST) reports (if run). In practice, few files are complete.

Drill-stem tests are specialized hydraulic tests used by the petroleum industry to determine aquifer properties of rocks penetrated by oil-exploration wells.

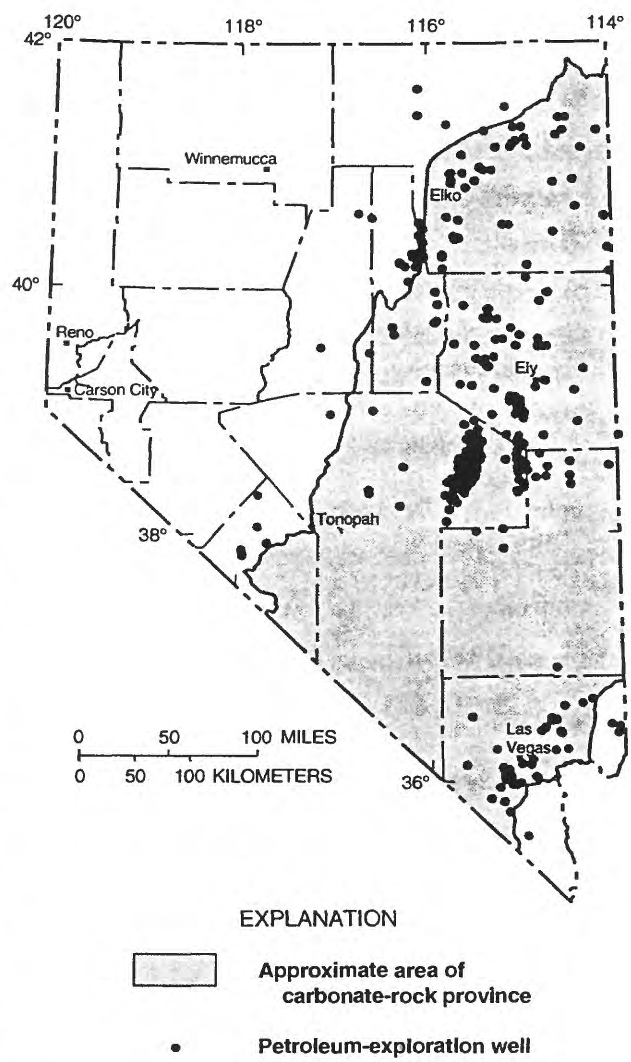


Figure 16. Distribution of petroleum-exploration wells in and adjacent to the carbonate-rock province of Nevada. Data from McKay and Kepper (1988).

By mechanically isolating a chosen interval in an oil well and then observing flow rates and pressures in the well as the isolated zone is vented to atmospheric pressure or closed off ("shut in"), three important characteristics of the subsurface formation may be obtained: pressure head, permeability, and fluid chemistry. By using a technique developed for the petroleum industry (but analogous to the Theis recovery method familiar to hydrologists [Bredehoeft, 1965]), hydraulic conductivities have thus far been estimated at 13 oil test wells drilled in carbonate rocks of Paleozoic age.

The estimates of aquifer properties derived from DST's in carbonate-rock aquifers are shown in table 2; estimates from two tests in noncarbonate rocks are shown also. The resulting conductivities are plotted against depth to the middle of the tested zone in figure 17, as are the hydraulic conductivities estimated from aquifer tests at water wells (from table 1). Note that moderate hydraulic conductivities (on the order of 4 ft/d) are estimated from tests as deep as 7,770 ft below land surface.

Combining the 13 estimates from DST's with 39 estimates from aquifer tests at water wells (table 2), the overall distribution of 52 measured hydraulic conductivities shown in figure 18 is achieved. If no distinction between DST estimates and water-well estimates is made, the 52 hydraulic conductivity estimates have a median value of 2.1 ft/d, a mean of 75 ft/d, and a standard deviation of 226 ft/d. The hypothesis that the distribution of hydraulic conductivities is a lognormal distribution (with those statistics) cannot be rejected at a 10-percent confidence level.

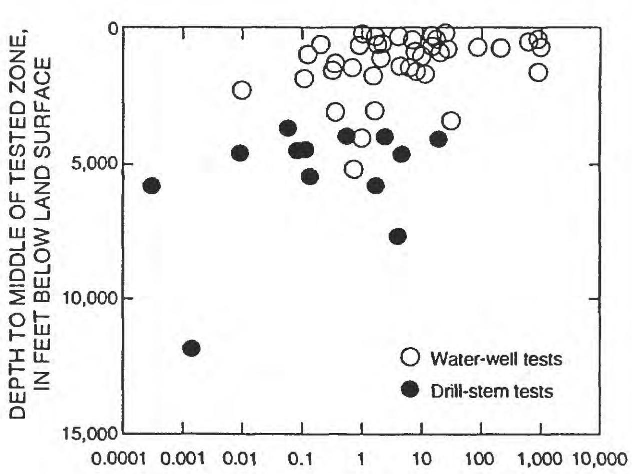


Figure 17. Relation between depth and hydraulic conductivities estimated from drill-stem tests at petroleum-exploration wells or aquifer tests at water wells in carbonate-rock aquifers of Nevada.

When the distinction is made between DST estimates and water-well estimates, DST values are as a group about an order of magnitude lower than the water-well estimates. In particular, the mean of the logarithm of the DST estimates is -0.7 whereas the mean of the logarithm of water-well estimates is +0.6. (Logarithms are used here to convert the lognormally distributed estimates to normal variates.) These two means imply that the central tendency of the DST distribution is 23 times less than the central tendency of the water-well estimates (the difference between means is significant at a 95-percent confidence level). Possible explanations for this difference between DST estimates and estimates from tests at water wells include the following:

1. DST's may have a greater tendency than the water-well tests to include insufficient flow periods during the test to allow for flushing of drilling fluids or for large parts of the aquifer to be "sampled."
2. The DST's generally test deeper rock zones than do the water-well tests and perhaps conductivities decrease with depth below land surface (although no such relation is apparent in fig. 17). For the test results in carbonate-rock

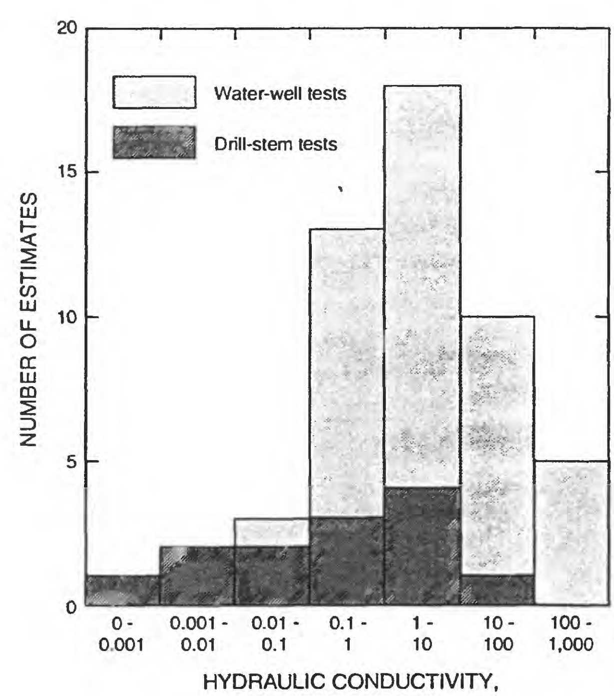


Figure 18. Frequency distribution of hydraulic conductivities estimated from drill-stem tests at petroleum-exploration wells or aquifer tests at water wells in carbonate-rock aquifers of Nevada.

aquifers (in tables 1 and 2), the median depth to the middle of the test interval for DST's is 4,500 ft; whereas, the median depth to the middle of the test interval for water-well tests is about 900 ft. The maximum depth of the middle of the interval tested by water-well tests is about 5,000 ft (minimum, 70 ft); whereas, the middle of the intervals of the DST's is about 3,600 ft (maximum, 11,800 ft). Thus, overlap in the depth distributions is relatively uncommon.

3. The DST's may more commonly test low-transmissivity zones. For example, DST locations near shale units also are common because exploration geologists often are searching for a transmissive reservoir rock (such as carbonate units) that is capped by a shaly formation to form a natural "trap" to catch oil and gas. That this placement of tests may influence the distribution of aquifer properties tested is shown by numerous outcrops in southern Nevada where fractures in the carbonate rocks have been filled with clays from nearby shale units.

4. Finally, significant violation of the assumptions underlying the mathematical interpretations of test results may be more common among the DST's (which commonly are done for much shorter periods of time than tests at water wells), and may systematically influence the general range of values estimated.

At present (1989), the difference between aquifer properties estimated from DST and water-well aquifer tests is poorly understood. More research is needed to make possible full use of the oil-industry records in studies of the carbonate-rock aquifers. Such research would be helpful because, aside from the Nevada Test Site area, oil wells commonly are the only deep wells and deep tests that have been made in the carbonate-rock aquifers. One result of uncertainty about the relation between the results of the two groups of tests is that, in this report, the distribution of conductivity estimates from water-well tests will be used wherever estimates of "characteristic" aquifer properties are required (to make estimates of drawdowns associated with development, for example). Development will cause stresses to the aquifers more like the stresses induced by water-well tests (long-term constant discharge, for instance) than like the stresses induced during DST's, and consequently the water-well estimates may be more representative of the properties that will control long-term impacts.

Evapotranspiration Measurement

Evapotranspiration (ET) is the total rate of direct evaporation from bare soil and free water surfaces plus transpiration by plants, with no attempt to distinguish between the two processes. Evapotranspiration together with springflow and subsurface leakage into other aquifers are the principal mechanisms by which water leaves the carbonate rocks. To better quantify the potential for spatially diffuse discharge of ground water from the carbonate-rock aquifers (as opposed to the localized flow of water from springs), measurements of evapotranspiration by native plants and bare soil evaporation were made during 1986 and 1987 and compared with previous studies in nearby arid regions. Previously, few measurements of actual ET (such as those of Czarnecki, 1986) had been made in the carbonate-rock province. Consequently, accurate quantification is difficult of the overall ET component in water budgets, as is quantification of that part of the ET component supplied by flow from the carbonate-rock aquifers.

Evapotranspiration rates have been calculated from data collected at special micrometeorological stations (fig. 6) at Ash Meadows and Corn Creek Springs. Data collected at the two sites between October 1, 1986, and September 30, 1987, included regular measurements or samples of air temperature, windspeed, relative humidity, precipitation, solar radiation, net radiation, soil heat flux, sensible heat flux, and latent heat flux. ET was calculated using two methods: the eddy-correlation method (Brutsaert, 1982) and the Penman combination method (Campbell, 1977, p. 138). The data collected (and some calculated results) are described by Johnson (1993), and summarized in the following paragraphs.

Typical conditions during 24-hour periods during summer 1987 at the two sites are shown in figure 19. The amount of solar radiation reaching the two sites was similar, but the fate of that energy differed depending on the hydrologic conditions at each site. Under relatively moist conditions at Ash Meadows, most of the total available radiation went to convert water to vapor.

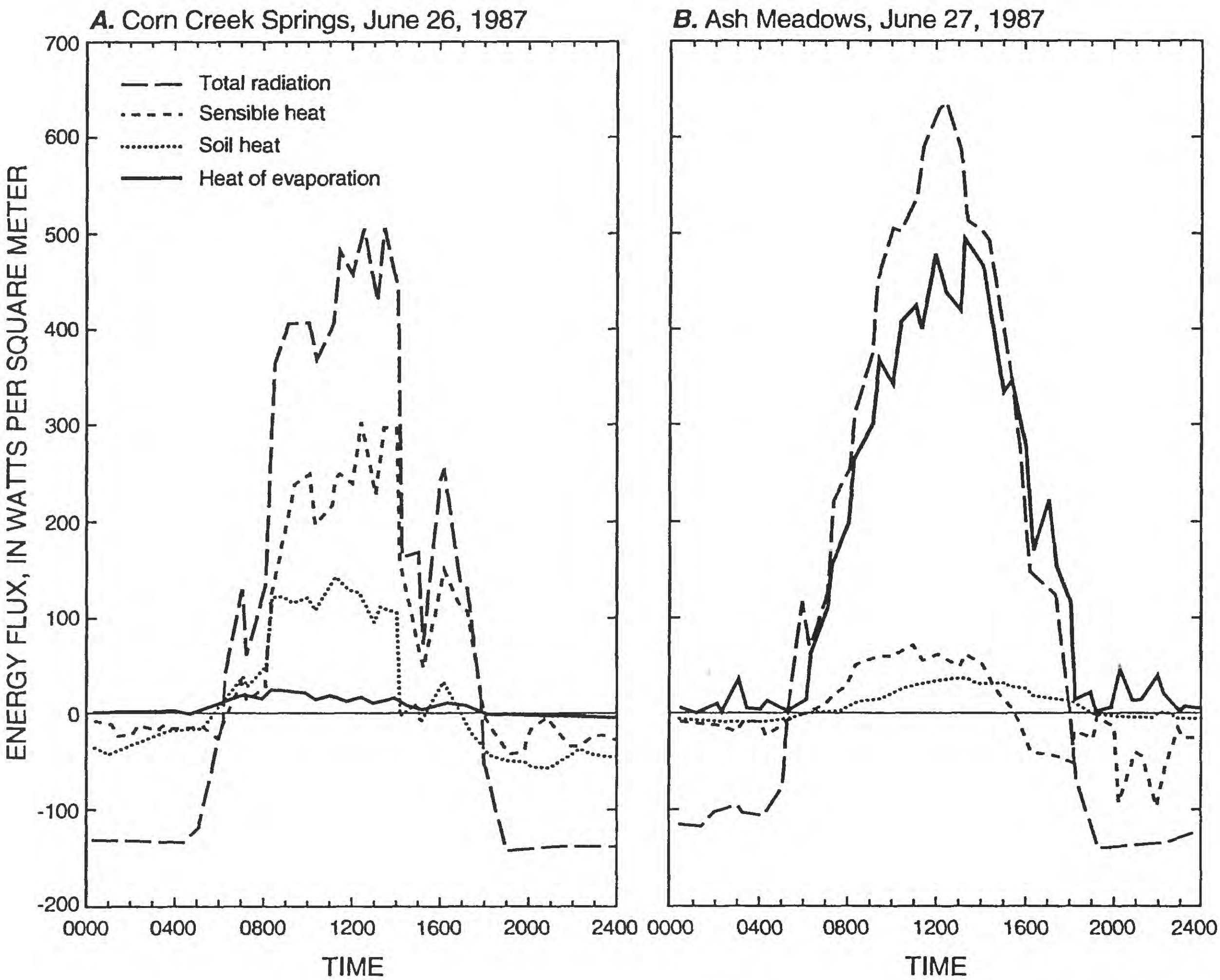


Figure 19. Energy flux during typical 24-hour, mid-summer periods at (*A*) Corn Creek Springs and (*B*) Ash Meadows. Micrometeorology by Michael J. Johnson, U.S. Geological Survey, Carson City, Nev.

At Corn Creek Springs, moisture was not as readily available for evaporation and so the available heat went mostly to raise soil and air temperatures.

The Ash Meadows ET station was located in a large meadow containing moist sub-soils; sparse, low-standing shrubs; and a dense, short grass ground cover. Depth to ground water generally was 4 to 8 ft. Ash Meadows is a regional spring discharge area with an estimated annual discharge of 17,000 acre-ft, and moist subsoils or shallow water tables are common within a radius of several miles from the springs. The measured daily rates (Johnson, 1993) imply an interstorm ET rate of about 30 in/yr.

In contrast, the Corn Creek Springs ET station was on bare, dry soils with a 25 percent coverage of low-standing shrubs. Depth to ground water is about 27 ft below land surface. Corn Creek Springs, with an annual discharge of about 220 acre-ft, discharges ground water that is recharged in the nearby Sheep Range (Thomas and Welch, in press). The small spring center at this site has an effect on ET only within a radius of about a quarter to half mile from the springs. Calculated daily ET rates for the area farther from the springs imply an interstorm ET total at this site of about 3 in/yr.

Synthesis

The preceding activities provided useful information describing how and where water is moving beneath specific areas of southern Nevada, but individually do not address some of the regional concerns that motivated the study. These regional concerns are addressed by synthesizing results from all parts of the present study, as well as from other ongoing (and many previously completed) hydrogeologic investigations in the area.

The following sections report on that synthesis in terms of the three basic concerns listed earlier: the location of water in the aquifers, the quantity of water in the aquifers, and the potential effects of development.

WHERE IS WATER POTENTIALLY AVAILABLE IN THE CARBONATE-ROCK AQUIFERS?

This question is best answered at two different scales or focuses. Regionally, the question "Where are the carbonate rocks present?" is not trivial and is basic to finding where water is in the rocks. More locally, the question "Where is the water concentrated within the rocks?" is also not trivial, and is basic to siting of exploratory wells and production wells. In addition, delineation of where the water in the carbonate-rock aquifers is likely to be of usable chemical quality is basic to determining where development may be pursued. This section will address each of these topics in turn.

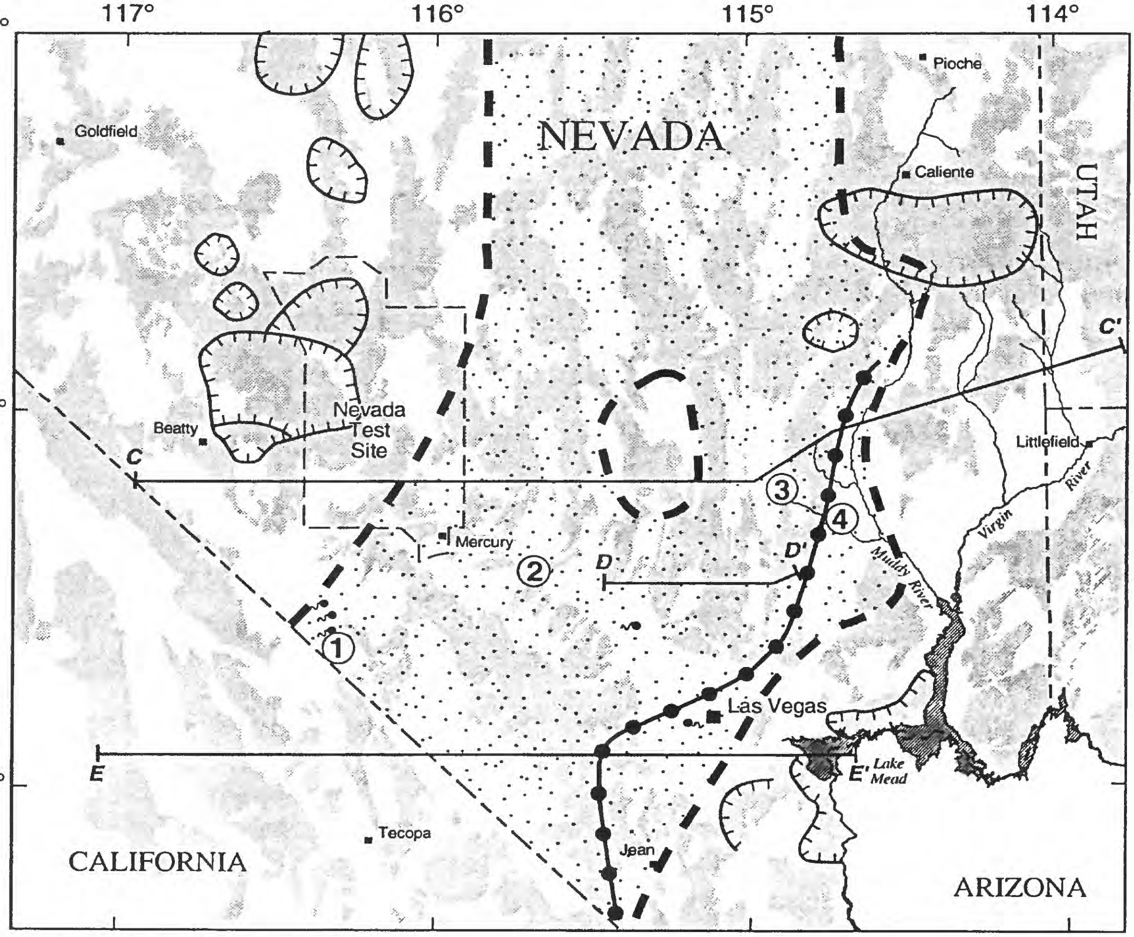
Distribution of Regional Carbonate-Rock Aquifers

In southern Nevada, over time, all geologic processes acting in the carbonate rocks including initial deposition and subsequent deformation have resulted in a broad zone of thick, laterally continuous carbonate rocks containing regionally significant aquifers (Dettinger and Schaefer, in press). This zone we refer to as the "central corridor" of the carbonate-rock province. Figure 20 shows the general boundaries of the central corridor south of 38°N. latitude.

On the east, the corridor is bounded by thin carbonate rocks east of Delamar Valley and the Meadow Valley Mountains. The carbonate rocks in these areas are thin as a result of original depositional thinning near the ancient seashores, extensional thinning, and erosion of much of the original sequence (Bartley and others, 1988). A large caldera (a volcanic collapse structure) and volcanic-rock complex protrudes into the eastern boundary in the vicinity of present-day Caliente (Ekren and others, 1977). Southward, the boundary probably runs west of the Mormon Mountains and east of Northern Muddy Mountains (Axen and Wernicke, 1989).

In the Mormon Mountains area (fig. 21, section *C-C'*), extension was extreme and results in thin, scattered, isolated blocks of carbonate rock lying on Precambrian igneous and metamorphic rocks at shallow depth (Wernicke and others, 1984, pl. 2; Smith and others, 1987, p. 386; Axen and Wernicke, 1989, p. 22-23). This shallow level of crystalline basement rock requires the corridor boundary to be west of the Mormon Mountains. The eastern boundary of the corridor continues along and around the north and west side of Lake Mead and then through the southeast quadrant of Las Vegas Valley and on past Jean toward the California border. North and west of Lake Mead, the carbonate rocks are overlain by Mesozoic sedimentary rocks containing evaporite minerals (gypsum, halite, and other natural salts) that render some unknown part of the ground water unsuitable for human consumption (more on this topic later in this section). The region south of the Muddy Mountains and east of Las Vegas and Jean contains few carbonate rocks (fig. 21, section *E-E'*); in fact, volcanic rocks mostly lie directly on crystalline rocks of Precambrian age (Bohannon, 1984, pl. 1b; Smith and others, 1987, p. 388 and 391). Although ground water has been inferred to flow through the volcanic rocks, flow rates and volumes are small (McKay and Zimmerman, 1983, p. 10-12).

The west side of the corridor (fig. 20) is positioned to coincide with a belt of Precambrian noncarbonate sedimentary rocks on the surface. Carr (1984) and Wernicke and others (1988) have suggested a thrust structural origin to bring these clastic rocks to and near the surface, but extreme extensional thinning of the Paleozoic carbonate rock section seems more likely to us. The belt largely isolates the locally thick carbonate rocks to the west from those of the central corridor. The area was greatly extended and the thickly deposited carbonate rocks (fig. 3, Nevada Test Site column) were greatly thinned (Maldonado, 1985, 1988; Carr, 1988a; Carr and Monsen, 1988, p. 50; Guth, 1988; Hamilton, 1988; Scott, 1988). A thick extensive cover of volcanic rocks and associated intrusive rocks west of the central corridor (Ekren and others, 1971; Byers and others, 1976; Carr and others, 1986) makes interpretation of the complex faulting of the carbonate rocks difficult. However, the low permeability of the Precambrian sedimentary rocks in the belt and the extensively thinned carbonate rocks probably constitute an effective western border to the central corridor along the Groom, Papoose, and Halfpint Ranges.



Base from U.S. Geological Survey digital data, 1:100,000, 1985
Universal Transverse Mercator projection
Zone 11

Geology modified from Plume and Carlton (1988), Stewart and Carlson (1978), and Wilson and Moore (1959). Geology in lower left and lower right corners of map area not shown

0 20 40 60 MILES
0 20 40 60 KILOMETERS

EXPLANATION

- **Basin fill**
- **Consolidated rock**
- **Central corridor of carbonate-rock aquifer in Nevada** — Area is underlain by thick sequences of carbonate rock; outside corridor, carbonate rock is thin, or present as isolated bodies
- **Outer margin of caldera or volcanic center** — From Ekren and others (1971), Stewart and Carlson (1976), Ekren and others (1977), Carr and others (1986)
- **Western limit of ground water generally too mineralized for most uses**
- C—C' **Location of hydrogeologic section in figure 21**
- (1) **Other locations discussed in text** — 1, Ash Meadows; 2, Indian Springs; 3, MX wells in Coyote Spring Valley; 4, Muddy River Springs
- **Spring or closely spaced springs**

Figure 20. Central corridor of thick carbonate-rock sequences in Nevada part of study area that probably contains water of suitable quality for domestic and municipal use.

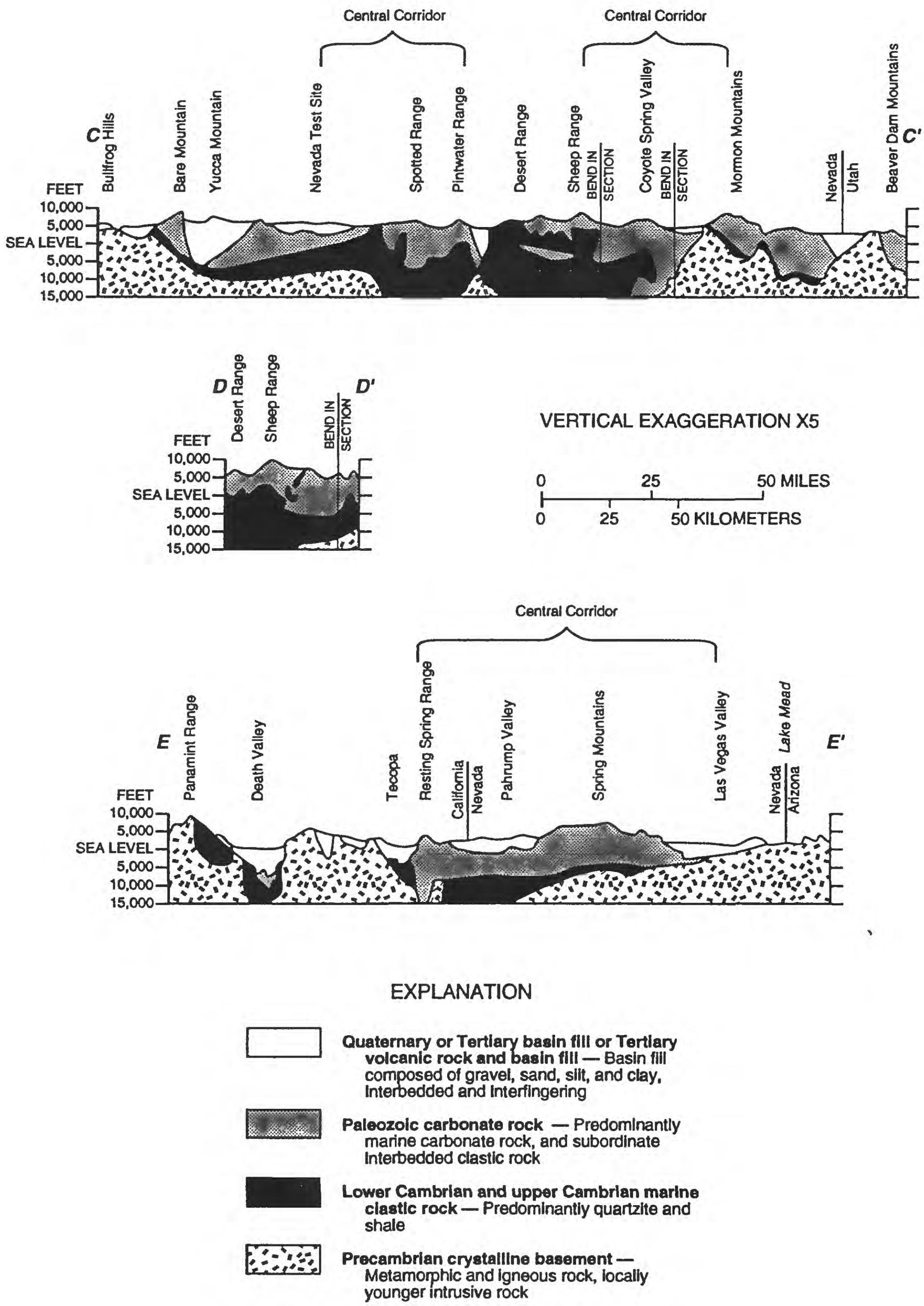


Figure 21. Hydrogeologic sections across southern Nevada. Section *C-C'* is based on work of Scott and Whitney (1987), Guth (1988), P.L. Guth (U.S. Naval Academy, written commun., 1988) and G.L. Axen (Harvard University, written commun., 1988). Section *D-D'* is modified from Guth (1980) and D.L. Schmidt (U.S. Geological Survey, written commun., 1986). Section *E-E'* is modified from Wright and others (1981) and Smith and others (1987). Lines of section are shown in figure 20.

South of the Nevada Test Site, the position of the western boundary of the corridor is uncertain but is assumed to run near the settlement of Amargosa Valley (Lathrop Wells) and west of Ash Meadows beneath the Amargosa Desert. The boundary then continues south along the western front of the Resting Spring Range in California and then east to the northern and eastern edges of the Kingston Range (Wright and Troxel, 1973, fig. 6; Wright and others, 1981; Burchfiel and Davis, 1988, figs. 9, 15, and 16). West of the southern part of the western boundary (fig. 21, section *E-E'*) are many complicated and hydraulically isolated blocks of carbonate rock, ranging from a veneer on the eastern slopes of the Panamint Range (Wright and others, 1981) to the thick plate of Paleozoic carbonate rocks at Bare Mountain (fig. 21, section *C-C'*) and the southern Funeral Range (Carr and Monsen, 1988, p. 51 and fig. 1). Interspersed between these carbonate rocks are abundant exposures of noncarbonate sedimentary rocks older than the carbonate rocks, Precambrian crystalline rocks, and plutonic rocks.

Plutonism and hydrothermal alteration associated with the volcanic centers both east and west of the corridor (fig. 20) may accentuate the overall low permeability of these bounding areas. Volcanic centers commonly are underlain by igneous plutons that, at depth, are probably extensive. These plutons displace, disrupt, and—through the action of associated hydrothermal fluids—greatly alter the surrounding sedimentary rocks (Blankennagel and Weir, 1973, p. B17; Byers and others, 1976, fig. 3; Ekren and others, 1977). The alterations commonly tend to reduce permeability in the sedimentary and volcanic rocks. As a result, although the hydrologic characteristics of the rocks within and around the volcanic centers are uncertain (Blankennagel and Weir, 1973), the volcanic centers of southern Nevada probably complicate and possibly impede regional ground-water flow through the carbonate rocks.

East and west of the central corridor are smaller blocks of carbonate rocks (west of Yucca Mountain and beneath the Mormon Mountains) that are thick but largely isolated from aquifers in other areas by noncarbonate, nonaquifer materials (Wernicke and others, 1985, fig. 15; Blank, 1988; Carr, 1988a; Hamilton, 1988; Scott, 1988; Wernicke and Axen, 1988b, fig. 2). The isolated carbonate-rock blocks, as a result, do not receive regional inflow and therefore transmit little water. In the areas outside the corridor, volcanic rocks may form the major (if not very extensive) aquifers where they are permeable enough. Otherwise, and more commonly, ground-water flow is concentrated in several basin-fill aquifers.

Within the central corridor, thicknesses and lateral continuity of carbonate rock are generally greater. Line *C-C'* (fig. 21) shows a nonuniform thickness of carbonate rocks at approximately the latitude of the Clark-Lincoln County boundary. Within the central corridor, two areas are underlain by thick and relatively continuous carbonate rocks connected to a similar thick carbonate-rock section described farther north by Bartley and others (1988, p. 1; Dettinger and Schaefer, in press); these are the Pintwater-Spotted Range area (Guth, 1988) and Coyote Spring Valley area (Guth, 1988; Wernicke and Axen, 1988a, p. 1749). These thick carbonate-rock areas probably contain the principal conduits for regional flow from east-central Nevada into southern Nevada, with the flow ultimately discharging at Ash Meadows and Death Valley and at the Muddy River Springs (Dettinger, 1987; Dettinger and Schaefer, in press).

Farther south, line *D-D'* shows the rocks beneath a short section just north of Las Vegas and shows thick carbonate rocks east of the Sheep Range (Guth, 1980, pl. 2). At moderate to great depths, the carbonate-rock aquifers beneath the Sheep Range are underlain by noncarbonate rock. The uppermost noncarbonate rocks are at high enough altitude along the west side of the range to impede westward flow by water recharging the mountains. These clastic rocks are exposed in the adjacent central and northern Desert Range (fig. 10). This barrier provides a geologic justification for geochemical balances developed during this study that indicate that nearly all the water recharging the Sheep Range flows to the north and east towards Muddy River Springs (Thomas, 1988; Thomas and Welch, in press).

Line *E-E'* shows a single, continuous corridor of thick carbonate rocks surrounded by noncarbonate rocks and a few small and isolated blocks of carbonate rock (as on the western edge of Death Valley). At this latitude the central corridor is centered on the Spring Mountains-Pahrump Valley area (Wright and others, 1981). The carbonate rocks beneath Las Vegas Valley are believed to thin abruptly to the east toward Lake Mead (Smith and others, 1987, p. 38). Water flowing through the corridor at this latitude is derived mostly from recharging snowmelt in the Spring Mountains. Water flows radially away from the high-altitude areas of the Spring Mountains to discharge near Tecopa, at Pahrump, at Indian Springs, and (in the past) at Las Vegas Springs (Hershey and others, 1987).

The sections in figure 21 show that even within the central corridor thicknesses are not always large. Compressional and extensional structures also thickened and thinned the carbonate rocks within the central corridor. Identifying extremely extended areas, where the carbonate rocks are thin, is important to understanding the hydrology of the area. Recent geologic interpretations of structures beneath the central Desert Range (Guth, 1989, p. 34-36) conclude that extension between the northern Sheep Range and northern Three Lakes Valley removed nearly all the carbonate rocks, and erosion has exposed a large area of Precambrian noncarbonate rocks (fig. 21, section *C-C'*). Within this area, which is shown in the center of the corridor in figure 20, ground-water flow probably is restricted primarily to basin-fill aquifers overlying the Precambrian rocks.

Elsewhere, the central corridor is characterized by irregularly thick carbonate rocks relatively uninterrupted by hydrogeologic barriers. Exceptions include a few small igneous plutons, intruding the carbonate rocks at depth (Blank, 1988), which locally might function as barriers to ground-water flow. In some areas, low-permeability noncarbonate sedimentary rocks are near land surface and have only a thin cover of carbonate rocks as inferred near Indian Springs by Winograd and Thordarson (1968). These blocks and layers of upthrown noncarbonate rock may be barriers to near-surface flow, as well as to deep flow in some settings. Finally, some structural zones (especially important shear zones such as the Las Vegas Valley shear zone [Winograd and Thordarson, 1968, p. 44-46; Lyles and Hess, 1988] and the Pahranagat shear zone [Thomas and others, 1986]) may directly influence flow patterns over large distances within the central corridor—impeding flow in some areas and enhancing it in others.

The corridor, as delineated in figure 20, is a region in which the carbonate rocks are thick enough to allow flow of ground water to great depths. Even in areas where vertical movements along faults isolate deeper parts of the aquifer, some shallow avenues for ground-water flow usually remain. Thus, at present (1989), the carbonate rocks are inferred to be laterally continuous within this area, forming regionally extensive aquifers. The central corridor is "where the rocks are" that comprise the regionally important carbonate-rock aquifers.

Distribution of Flow Within the Central Corridor

The central corridor comprises about 10,000 mi^2 in southern Nevada, and within that large of an area determining the "best" places to explore for or develop water supplies from carbonate-rock aquifers is difficult. The overall strategy for such determinations applied in this study involves locating areas where carbonate rocks have been broken by extensional forces, locating recently active fault systems, choosing sites with a reasonable probability of regional throughflow, and identifying sites with known and adequate sources of water to supply eventual production. This strategy is based on the hypothesis that although the carbonate rocks are fractured sufficiently to yield water to wells and to allow some flow nearly everywhere, locally, large flows are concentrated in long established conduits or in more recently established conduits where the rocks have been faulted relatively recently.

Hypotheses Concerning Transmissivity in the Central Corridor

The presence of highly transmissive zones within the central corridor is indicated by (1) large discharges of water from the Muddy River Springs and the Ash Meadow springs supplied by aquifers with nearly horizontal potentiometric surfaces and (2) geologic mapping of exposed remnants of large solution-modified flow tubes and conduits through the carbonate rocks (as old as about 15 million years; Barton and Hsieh, 1989, p. 15-16). Large areas underlain by nearly horizontal potentiometric surfaces are upgradient from the Ash Meadows and Muddy River Springs discharge areas, and the large volumes of water that discharge at these spring systems—together with the low-gradient surfaces immediately upgradient—imply that flow to the springs is at least locally through high-transmissivity zones. The configuration of water levels in the carbonate rocks of much of southern Nevada are poorly delineated and so this approach to delineating zones of high transmissivity is not commonly available. In addition, not all low-gradient areas reflect high transmissivities; some reflect restrictions to flow or low recharge. For instance, the water levels to the south and west of Muddy River Springs remain horizontal for about 30 mi in areas where preliminary exploration suggests low flow rates and a resource potential only of stored water.

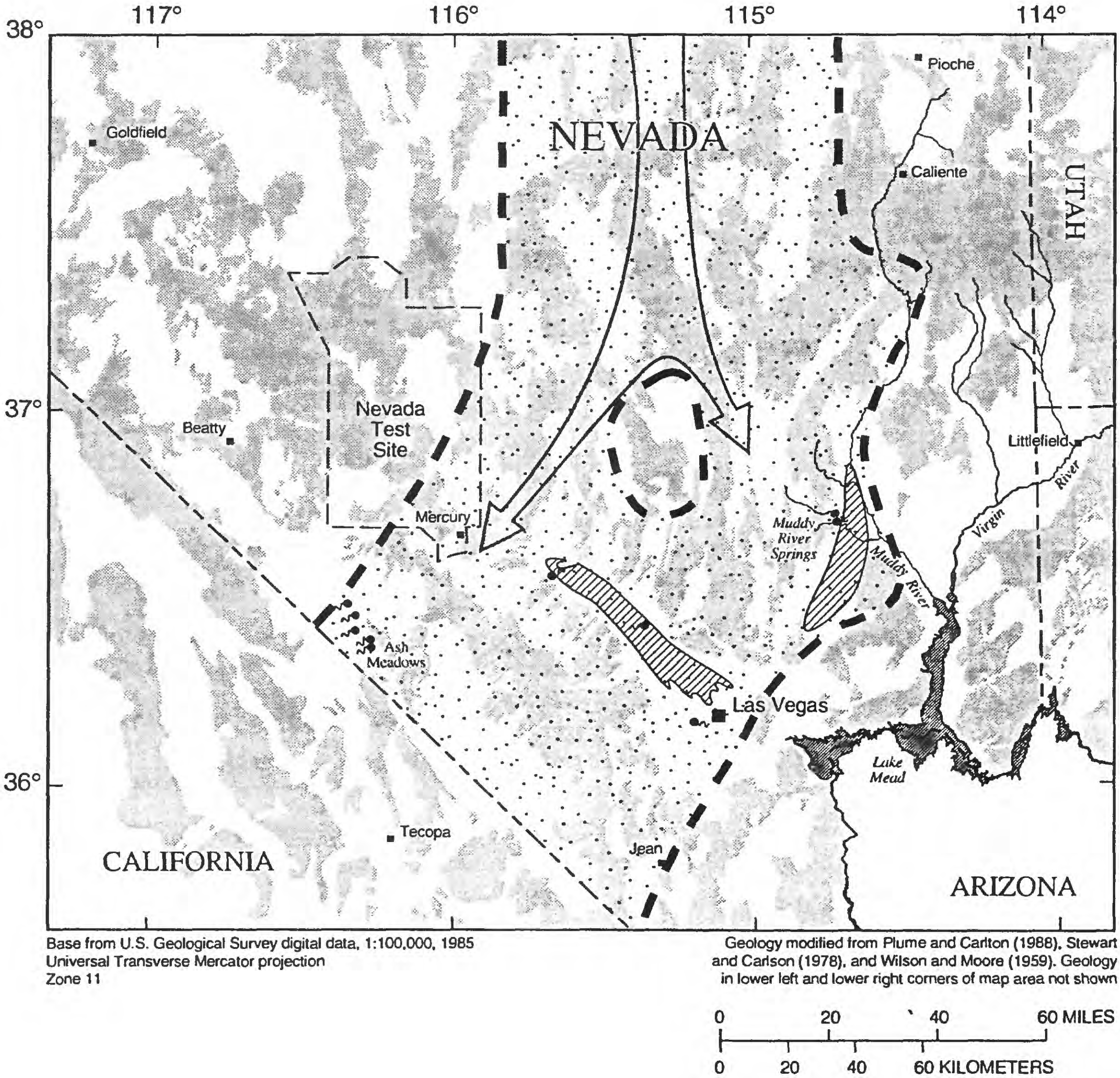
A preliminary hypothesis that emerged from the present studies is that regional flow enhances high transmissivity at the same time as high transmissivity allows regional flow. Clearly, moderate to high transmissivities over long distances promote regional-scale integration of ground-water flow of the type found in southern Nevada. At the same time, speculation (as yet undemonstrated) suggests that faults and fractures through which ground-water flows stay open longer (and better) than isolated openings. This may be the result of slow dissolution or wall-coating on fracture walls that widen or add strength to the openings, or may be due to some as yet undiscovered process of fracture scouring (carrying away gouge and clays) or fracture stabilization. Regardless, this hypothesis seems the simplest explanation for the long-term presence of regional discharge points along specific structural zones identified while mapping ancestral aquifer systems near Muddy River Springs (Dwight L. Schmidt, U.S. Geological Survey, written commun., 1986). Assuming that the hypothesis is true, certain fracture zones along inferred regional flow paths become prime targets in which to seek highly transmissive zones. Analysis of aquifer tests at 39 carbonate wells in Nevada supports this conclusion in that wells located within 10 mi upgradient from regional springs are about 10-20 times more transmissive, on the average, than wells located farther away. Thus, aside from potential effects of developing water from the midst of regional flow paths (more on this later), the pathways appear to be the most likely locations for highly productive wells and also for wells with clearly defined sources of water.

Principal Flow Paths in the Central Corridor

Principal flow paths through the carbonate rocks of southern Nevada are shown in figure 22. Previous and current studies (Eakin, 1966; Winograd and Pearson, 1976; Kirk and Campana, 1988) have suggested that a large volume of ground-water flow north of about 37°30' N. latitude is concentrated in a regional flow system centered beneath the valleys of the White River surface drainage. South of this latitude flow splits to supply discharge at Muddy River Springs and Ash Meadows. South of these discharge areas no regional-scale flow systems have been identified. The large area underlain by noncarbonate sedimentary rocks in the middle of the central corridor may divert southward flow to the southeast and southwest. If so, the flow paths shown in figure 22 are located correctly. Farther south, deep, probably poorly permeable basin-fill deposits along the Las Vegas Valley shear zone and along Meadow Valley Wash and Moapa Valley may divert flow to Ash Meadows and Muddy River Springs. The principal flow paths are tentatively assumed to be zones of highest transmissivity. Areas outside the principal flow paths are expected to have lower transmissivity, ranging mostly from low to moderate. This hypothesized division between zones of high and low transmissivity is still highly speculative.

Local Controls on Transmissivity

At a more local scale, fault structures are of primary importance in the exploration for ground water in the carbonate rocks of southern Nevada. Fractures and other openings are formed along and near faults, and some of these fracture systems can conduct ground water. The number, size, and open spaces in fractures observed in outcrops decreases with distance from larger faults. Large fault zones can function as conduits where much of the flow through the rocks is concentrated. Smaller subsidiary fractures, which are distributed throughout the large volume of rocks between major faults, may function as collectors of ground water. Thus, the prospects for developing highly productive wells are expected to be increased by focusing on fault zones. Young, active faults are preferred for development because the fracture permeability of a fault decreases with age by rock consolidation and cementation (Chapman and others, 1981; de Marsily, 1985). Of the many different types of faults, observations at outcrops indicate that the most open, presumably permeable faults are high-angle normal faults, such as range-front, basin-and-range faults. These faults are responses to extensional forces and so tend to pull apart and form somewhat less gouge (fine rock particles broken from the walls during fault movement that can completely fill and greatly reduce the porosity and permeability of a fracture) than flat-lying normal faults or compressional faults. The range-bounding faults also are commonly the most recently active large structures in the carbonate-rock province of southern Nevada. Other types of faults, such as thrust faults and strike-slip faults, are much less likely to be permeable because they tend (in outcrops) to be filled with gouge.



EXPLANATION

Basin fill

Consolidated rock

Central corridor of carbonate-rock aquifer in Nevada — Area is underlain by thick sequences of carbonate rock; outside corridor, carbonate rock is thin, or present as isolated bodies

Thick basin-fill deposits — May impede or divert regional flow

Major regional flow path — Inferred from Winograd and Thordarson (1975), Eakin (1966), and distribution of thick carbonate-rock sequences. Arrow indicates only general direction of regional flow and does not imply location of specific flow path

Figure 22. Principal paths of regional ground-water flow through carbonate rocks in Nevada part of study area.

Geologic interpretations concerning the nature and geometry of faults and the location and properties of geologic formations (stratigraphic units) are used to delineate potential aquifers in which to site wells and to locate the thickest sections of regional and local flow. Distinction between carbonate and noncarbonate rocks, and between rocks types within the carbonate-rock layers, is important. Hess and Mifflin (1978, p. 32) concluded that carbonate-rock units of certain ages exhibit more indications of high permeability than units of other ages. The present study (in several series of detailed observations of outcrops) has yet to verify this result. In addition, analysis of available aquifer-test data indicate no correlation between permeability and carbonate-rock age.

Although the age of a carbonate-rock unit does not appear to define its permeability, the composition of the rock in a particular unit does. Generally, the shaly or silty carbonate-rock units are less permeable than the cherty or "clean" carbonate rocks in Nevada. Two wells in shaly and silty carbonate rocks in the study area that reflect the tendency for lower productivity from shaly carbonates are the MX well CE-VF-2 in Coyote Spring Valley and CSV-2 well in Upper Moapa Valley. Specific capacities at these wells in shaly carbonates—5.9 and 3.4 (gal/min)/ft, respectively (table 1)—are smaller than at wells drilled in "cleaner" units in the same area, MX wells CE-DT-4, -5, and -6, with specific capacities of 154, 309, and 11.4, respectively (table 1). Outside of Nevada, a similar relation has been found in other carbonate terranes by Sweeting and Sweeting (1969), Dreiss (1974), and Rauch and White (1970, 1977). On the other hand, three of the six most productive wells drilled in the carbonate-rock aquifers (well C at the Nevada Test Site and Tracer wells number 2 and 3 near Ash Meadows) were drilled into the carbonate-rock units nearest the bottom of the Paleozoic-rock sequences. This means that these wells tap thin carbonate-rock aquifers in comparison to most of the other wells that tap carbonates in southern Nevada. Thus, productivity probably is not closely tied to the overall thickness of carbonate rocks underlying a given well. It seems likely that the structures intercepted in a particular well (and the history of those structures) are determining the productivity of a well to a greater extent than either the stratigraphic unit or the thickness of the carbonate-rock section available for ground-water flow.

Water Quality

Water quality (chemistry) is an important consideration in obtaining a water supply. Chemical considerations differ according to the intended uses of the water, but, in general, domestic and municipal uses (especially drinking water) have more stringent chemical requirements than irrigation and other agricultural uses (Nevada Bureau of Consumer Health Protection Services, 1977, p. 8-9). Industrial and commercial uses have requirements that generally range between these two extremes. Because water quality varies from place to place in southern Nevada, ground water in some areas may not be suitable for most uses without expensive treatments to improve the chemistry of the water. Fortunately, regional patterns in water quality can be observed that allow delineation of areas of unacceptable quality.

Geochemical Controls on Quality

Chemistry of ground water in southern Nevada (carbonate rock, volcanic rock, and basin fill) is directly related to the type and amount of minerals present within the flow systems and environmental conditions upon recharge and discharge of the water. As a result, the quality of ground water tends to reflect the conditions along its flow path. Overall, however, the quality of ground water in regional systems in the carbonate-rock province of Nevada is notable for its large-scale homogeneity because of the dominance of carbonate minerals throughout the aquifers (Hess and Mifflin, 1978, p. 38). With a few exceptions, the water quality is also notably good; concentrations of dissolved solids (a general measure of the quality or salinity of water) in water sampled from the carbonate-rock aquifers commonly are less than 500 mg/L, and predominantly contain calcium, magnesium, and bicarbonate ions (Lyles and others, 1986, p. 13).

Within the large-scale homogeneity, local variations in water quality are caused by geologic complexities and localized interaquifer flows between rock types. In some areas, the quality of water discharging from or near carbonate rocks may have been changed by flowing through lake-bed deposits (mostly of late Tertiary age) that commonly contain some dissolvable evaporite minerals. In the area north and west of Las Vegas, some evaporite minerals are found in the basin-fill deposits. The presence of evaporite-bearing deposits will generally be recognized by geologic mapping or by the presence of water with dissolved-solids concentrations unsuitable for public supply and most other uses in basin-fill aquifers. An example of the relation between water quality in these younger basin-fill deposits and in a nearby carbonate-rock aquifer is described by Winograd and Thordarson (1975, p. C106-107). They state that the chemistries of water from the two aquifers are independent of each other and will remain so unless mixing of water from the two aquifers were induced or happened naturally.

Depth and Quality

In much of the carbonate-rock province, the depths from which water can be extracted might not be limited by water-quality constraints. Previous studies have noted that the quality of water in the carbonate-rock aquifers in much of the carbonate-rock province does not increase in dissolved-solids concentration with increasing depth (Winograd and Thordarson, 1975, p. C102-103; Hess and Mifflin, 1978, p. 42). The present study (together with results of the MX Missile Water Resources Program of the early-1980's) found no information to contradict that conclusion. The concentrations of major ions and dissolved solids (as well as some physical properties) of water samples obtained from deeper parts of the carbonate-rock aquifers (between 1,200 and 11,000 ft beneath land surface) are listed in table 6. The locations of these sample sites and the relation between depth below land surface and dissolved-solids concentration are shown in figure 23. As mentioned previously, these data do not indicate a significant increase in dissolved-solids concentration with depth. All the sites in table 6 are located north of the line that delineates the western limit of unsuitable quality water in figure 20, and because the samples selected are from deep in the aquifers, they probably are water that has not contacted young lakebed evaporites. Of the 21 samples, 15 contained less than 500 mg/L (milligrams per liter) dissolved solids; none contained more than 1,000 mg/L, and the median concentration was 366 mg/L. However, saline to briny water frequently has been found in localized pockets and traps penetrated by deep oil-test wells in eastern and southeastern Nevada. These pockets and traps are common in carbonate as well as volcanic and younger rocks (Chamberlain, 1988).

Mesozoic Evaporites and Water Quality

Southeast and east of Las Vegas (southeast of the line that shares the western limit of water with ionic compositions dominated by sulfate and chloride in fig. 20), depths from which water suitable for most uses can be extracted from the carbonate rocks may be severely limited. Water that is unsuitable for most uses is much more commonly found in that area, the dissolved-solids concentration in this water is derived most commonly from rocks that overlie or are in shallow structural juxtaposition with the carbonate-rock aquifers. The water (fig. 24) contains much more sulfate than does most water from farther north, and concentrations of dissolved solids commonly exceed the drinking water standard of 1,000 mg/L (Nevada Bureau of Consumer Health Protection Services, 1977, p. 8-9; Lyles and others, 1986, p. 13). Tertiary lake-bed sediments (such as the Muddy Creek and Horse Spring Formations) and other deposits contain abundant evaporite minerals in this southeastern area (Bohannon, 1984, p. 1-2). In addition to these basin-filling deposits, this southeastern area is underlain by extensive evaporite-rich sedimentary rocks of latest Paleozoic and Mesozoic age (fig. 24); they are older than the lakebed sediments but younger than most of the Paleozoic carbonate rocks. The latest-Paleozoic Kaibab Formation and Mesozoic Moenkoepi Formations are examples of such units, and contain hundreds of feet of soluble gypsum (Longwell and others, 1965, p. 37-39). Dissolution of evaporite minerals from these formations is a widespread source of sulfate in both basin-fill aquifers and carbonate-rock aquifers of southeast Nevada. Rogers Spring (pl. 1, fig. 24), which discharges from carbonate rocks above the Overton Arm of Lake Mead, contains about 1,700 mg/L of sulfate (as compared with a drinking-water standard of 500 mg/L, Nevada Bureau of Consumer Health Protection Services, 1977, p. 8-9) and 3,000 mg/L of dissolved solids (Lyles and others, 1986, p. 51). Even poorer quality water has been penetrated in shallow and deep wells in the carbonate rocks. For example, water in the Callville Limestone (a unit deposited during the middle of the Paleozoic Era) sampled from 17,470 ft in the Virgin River USA 1-A oil-test well (fig. 24) is reported to contain concentrations of dissolved solids of about 80,000 mg/L.

Both the lake-bed deposits and the sedimentary rocks of intermediate (latest Paleozoic and Mesozoic) age most commonly overlie the carbonate-rock aquifers, regardless of the structural deformation of the area, because they are much younger than the rocks

Table 6. Chemistry of water from wells more than 1,000 feet deep in carbonate-rock aquifers

[Dissolved solids.--r, residue on evaporation at 180 degrees Celsius; s, sum of silica and major cations and anions except bicarbonate, plus one-half of bicarbonate (to make result comparable with residual values); and ss, sum of major cations and anions except bicarbonate, plus one-half of bicarbonate (silica not determined); --, no data available]

Site No. (fig. 23)	Site name	Degrees, minutes, seconds: Latitude	Longitude	Sample date	Total well depth (feet)	Temperature (Celsius)	Chemical constituent or property (milligrams per liter): Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO3)	Sulfate (SO4)	Chloride (Cl)	Silica (SiO2)	Dissolved solids	Reference
1	S18/63-34C	36 20 28	114 55 36	9/30/86	1,205	31	128	48	134	12	226	380	190	23	1,000 s	Unpub. USGS analysis
2	TW-4	36 34 54	115 50 08	9/13/62	1,490	26	34	17	13	2.5	197	17	6.1	20	225 r	Schoff and Moore, 1964, p. 68
3	Army 1	36 35 30	116 02 14	3/18/71	1,946	31	44	22	37	5.2	262	51	15	19	301 r	Claassen, 1973, p. 18-19
4	TW-10	36 35 31	115 51 04	2/4/64	1,301	27	37	19	69	0	201	14	5	15	198 s	R.A. Young, USGS, written commun., 1965
5	TW-F	36 45 34	116 06 59	6/17/62	3,400	64	68	30	63	9.6	278	181	11	31	536 r	Schoff and Moore, 1964, p. 69
6	TW-3	36 48 30	115 51 26	5/10/62	1,853	38	51	21	83	7.6	328	84	23	24	444 r	Schoff and Moore, 1964, p. 70
7	UE25P#1	36 49 38	116 25 21	5/12/83	5,922	56	100	39	150	12	710	160	28	41	784 r	Benson and McKinley, 1985, p. 4-5
8	MX CE-VF-2	36 52 27	114 56 51	2/05/86	1,200	34	47	21	81	11	303	90	34	34	470 s	Berger and others, 1988, table 4
9	Well C	36 55 08	116 00 35	3/29/71	1,701	37	72	30	120	14	589	66	33	29	628 r	Claassen, 1973, p. 66-67
10	Well C-1	36 55 07	116 00 34	3/29/71	1,650	38	72	30	120	14	588	66	33	29	621 r	Claassen, 1973, p. 74-75
11	TW-D	37 04 28	116 04 30	1/9/60	1,950	26	17	10	107	14	274	71	20	18	343 r	Thordarson and others, 1962, p. 40
12	TW-1	37 09 29	116 13 23	8/11/62	4,206	31	20	11	35	3.2	150	35	8.7	19	220 r	Schoff and Moore, 1964, p. 72
13	WW-2	37 09 58	116 05 15	3/21/71	3,422	34	31	14	27	6.7	197	21	6	44	228 r	Claassen, 1973, p. 98-99
14	MX DL-DT-3	38 05 31	114 53 42	12/--/80	2,395	27	76	30	18	6.5	404	20	5	24	366 r	Bunch and Harrill, 1984, p. 36
15	MX CV-DT-1	38 07 58	115 20 41	12/--/80	1,837	23	38	18	18	4	221	20	5	35	253 r	Bunch and Harrill, 1984, p. 32
16	N7/55-28CA	38 26 13	115 47 44	10/06/55	1,711	60	12	5	[a]189	--	410	99	16	--	526 ss	Van Denburgh and Rush, 1974, p. 53
17	N7/56-2DAB	38 29 43	115 38 17	11/24/54	10,123	109	7	6	[a]192	--	[b]293	50	68	--	491 ss	do.
18	MX SV-DT-2	38 55 21	114 50 36	1/19/81	2,447	11	66	14	15	4.4	218	57	12	28	305 s	Unpub. USGS analysis
19	Fad shaft	39 30 20	115 59 05	1/21/53	2,465	13	52	26	83	1.4	238	38	10	11	178 s	Harrill, 1968, table 14
20	N23/56-22C	39 50 43	115 39 31	4/22/85	5,800	30	43	19	13	3.4	200	43	8.3	19	350 r	Unpub. USGS analysis

[a] Calculated sodium plus potassium, expressed as sodium.

[b] Also detected, 43 milligrams per liter of carbonate (CO_3); included in dissolved-solids sum.

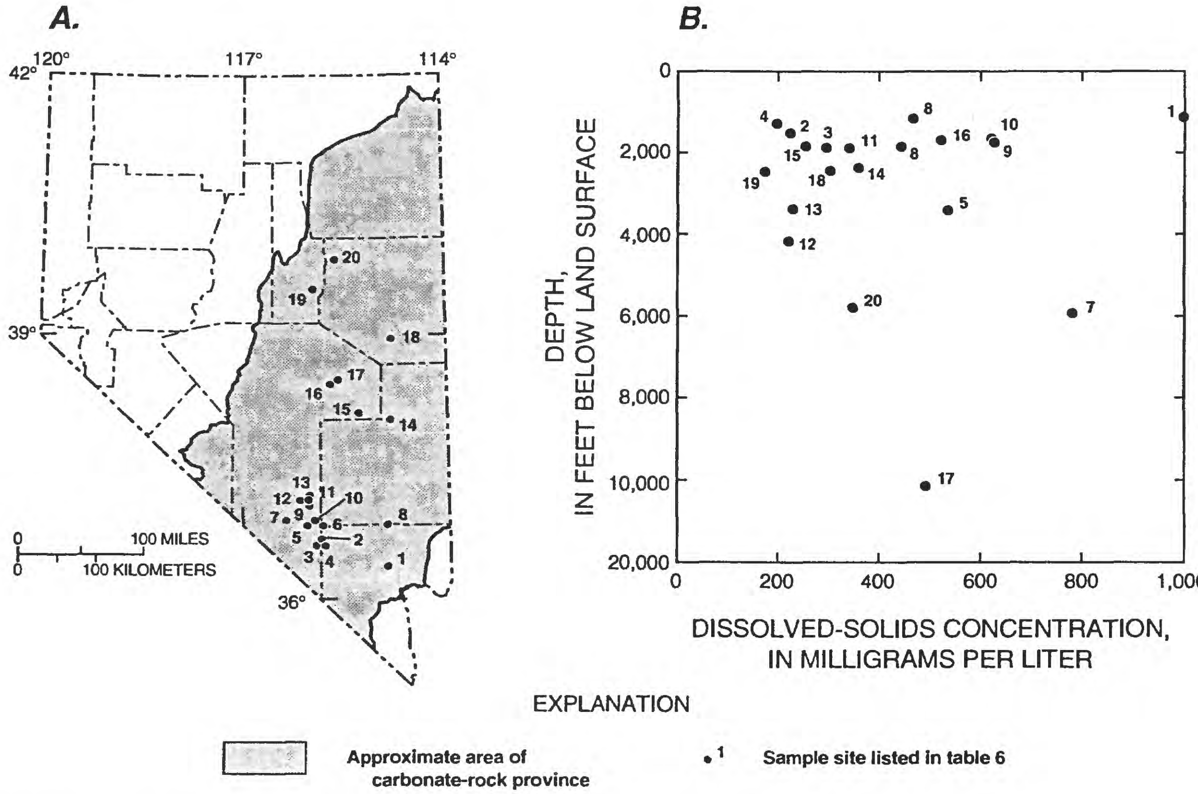


Figure 23. Relation between dissolved-solids concentration and depth below land surface.

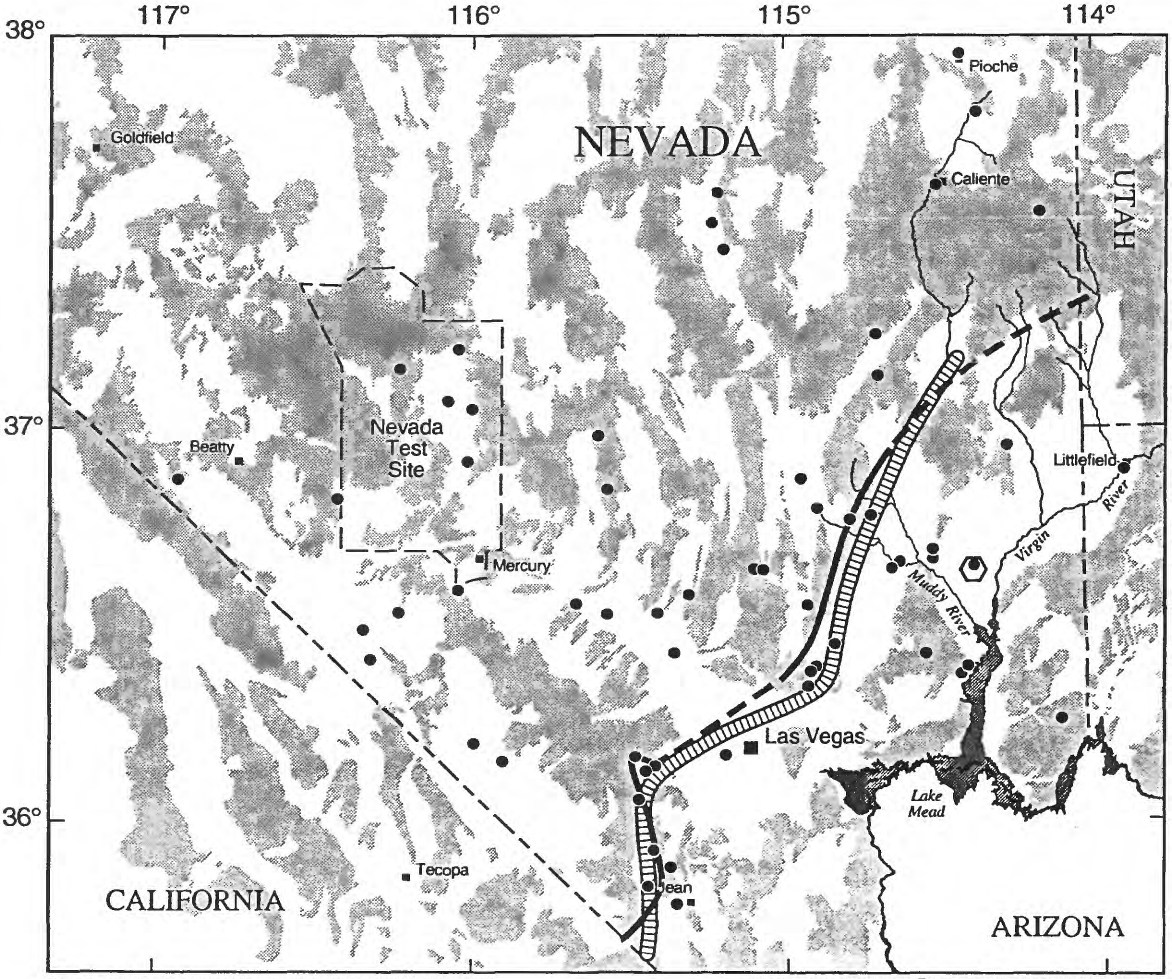
comprising the aquifers. Thus, at great enough depths in the carbonate rocks, freshwater might underlie the zones of water contaminated by the younger evaporite minerals. However, the complex geology of southern Nevada includes many places where the stratigraphic relations are reversed (just upgradient from Rogers Spring, for example). This complexity, together with flow paths that may traverse several rock types as water moves from recharge areas to discharge areas, can greatly extend the chemical influence of the contaminating deposits under even natural conditions. Once the carbonate-rock aquifers are developed, it is difficult to estimate how long pumping can proceed before capturing water of unacceptable quality.

At a regional scale, areas south and east of the lines shown on figure 24 have a relatively low potential for successful aquifer development because of the presence of water with dissolved-solids concentration commonly in excess of 1,000 mg/L. Therefore, assessments of the resources of this area were not emphasized in this study. This area is only a small fraction of the total area under consideration.

HOW MUCH WATER POTENTIALLY CAN BE WITHDRAWN FROM THE CARBONATE-ROCK AQUIFERS?

The water resource of carbonate-rock aquifers is the sum of sustained yield of the aquifers and a one-time reserve of water stored in the thick rocks. The magnitude of each of these components is estimated as described in the following paragraphs.

The sustained yield of the aquifers is the quantity of water that could be withdrawn annually for an indefinite period of time without depleting the ground-water reservoir (Scott and others, 1971, p. 13). In order to use the concept of sustained yield in this area of sparse data, the aquifers are assumed to be in a state of dynamic equilibrium—the long-term average recharge equals the average discharge and the quantity of water in storage remains constant except for minor seasonal and short-term climatic fluctuations. In arid areas such as southern Nevada, pumping from carbonate-rock aquifers is unlikely to induce additional recharge, except by inducing leakage from overlying basin-fill aquifers. Thus, the sustained yield of the



Base from U.S. Geological Survey digital data, 1:100,000, 1985
Universal Transverse Mercator projection
Zone 11

Geology modified from Plume and Carlton (1988), Stewart and Carlson (1978), and Wilson and Moore (1959). Geology in lower left and lower right corners of map area not shown

0 20 40 60 MILES
0 20 40 60 KILOMETERS

EXPLANATION

Basin fill

Consolidated rock

Northwestern limit of area known to contain thick or abundant evaporite beds — Evaporites are in rock of late Paleozoic and Mesozoic age

Boundary between areas where ionic composition of water in carbonate-rock aquifer is dominated by sulfate and chloride (to southeast) and by bicarbonate (to northwest) — Modified from Lyles and others (1986, fig. 13), using data from Winograd and Thordarson (1975, pl. 3), Glancy and Van Denburgh (1969, table 17), Trudeau and others (1983, table 1), and compiled for present study. Dashed where uncertain

Sample site — Used to delineate between bicarbonate-type and sulfate-chloride-type water

Petroleum-exploration well referenced in text

Figure 24. Location of transition between areas where ionic composition of water in carbonate-rock aquifer is dominated by sulfate and chloride (to southeast) and by bicarbonate (to northwest) in Nevada part of study area.

carbonate-rock aquifers is limited mostly to the fraction of natural discharge that can ultimately be captured by pumping. Because most of the discharge from the carbonate-rock aquifers is springflow, which has been appropriated for use, development of large parts of the sustained yield by pumping eventually will affect existing water rights. Protection of prior appropriations will place limits on pumping from the carbonate-rock aquifers. However, given conditions of high water demand, pumping water directly from the aquifers may use the resource more efficiently in the sense that pumpage can be turned off or varied to meet fluctuating demands, whereas spring discharge is relatively uniform and may not be readily used or stored during periods of low demand.

Ground water is stored in the water-saturated sections of carbonate rocks. Thicknesses of these sections range from less than 3,000 to about 20,000 ft. Because of the great thickness and vast areal extent of the rocks, volumes are measured in tens of thousands of cubic miles. Even though only a small percentage of the total volume of the aquifers is open for storage of water (fractures and interstitial spaces), the volume of water stored must greatly exceed the annual recharge or discharge rate. The water discharged in a given year has been in transit through the aquifers for thousands of years on average (for example, Thomas and Welch, in press). This large volume of water in slow transit through the carbonate rocks is a reservoir that potentially could be developed for use. Once this stored volume of water is tapped and a significant part is removed, however, the large disparity between the volume in storage and annual recharge means that very long periods without further pumping would be required for the storage reserve to refill.

The quantity of water that can be removed from storage without effects that would be unacceptable to the State is unknown. Minimum-effect strategies to develop stored water probably could be based on observations that recharge areas are separated from discharge areas (springs) by more than 100 mi in some flow systems, that relatively fresh water has been found at depths of 10,000 ft (implying that active ground-water flow occurs deep within the carbonate rocks), and that certain rock types and geologic structures form local barriers to prevent flow within regional ground-water flow systems. These observations imply that the aquifers to be developed, and the distances between developments, may be chosen to be large enough to minimize effects in key areas. Also, development might be strategically located behind geologic barriers that prevent or reduce the effect from extending in critical directions. The possibility of pumping stored water from some parts of the carbonate-rock aquifers appears to offer the most potential for additional development and is the component of the resource being most closely evaluated by this study.

Sustained Yield

The sustained yield of the carbonate-rock aquifers is equal to that fraction of the total discharge that can be captured by pumping without causing unacceptable effects. This will be less than or equal to the total discharge, and will be less than or at most equal to the total rate of natural recharge and inflow to an area.

Precipitation in the mountains is the ultimate source of virtually all recharge to the carbonate-rock aquifers. Of the precipitation that remains after sublimation, evaporation, and transpiration in the mountains, some or all percolates down into the rocks as recharge to the ground-water flow system and the rest supplies runoff and recharge to the adjacent basin-fill ground-water reservoirs. How much total recharge and runoff is generated by precipitation on the mountains is uncertain; how much of the recharge enters the carbonate-rock aquifers as opposed to the basin-fill aquifers is even less certain.

The quantity of water recharging the carbonate rocks is uncertain because once water enters the rocks it can follow one of several flow paths, and at each point will follow the one defined by least resistance. Flow paths may involve lateral movement through the carbonate-rock aquifers into adjacent basin-fill aquifers. The water that follows these paths leaves the carbonate-rock aquifers and becomes part of the resource of the basin-fill aquifers where it may be extracted as pumpage, discharged by evapotranspiration in areas of shallow ground water, or returned to an adjacent carbonate-rock aquifer. Some basin-fill aquifers receive recharge from adjacent carbonate-rock aquifers, some basin-fill reservoirs provide recharge to adjacent carbonate-rock aquifers, and others both receive and provide recharge. Because these interactions are deep within the subsurface, they are difficult to identify and quantify. Consequently, it also is difficult to estimate the quantity of water recharging the carbonate-rock aquifers. At present (1989), attempts at quantification are only adequate (1) to derive an estimate of the upper to the estimated recharge to all aquifers in the area, and (2) to estimate a lower limit based on discharge from the carbonate-rock aquifers at regional springs and by flow from the State through carbonate-rock aquifers. This latter estimate is a lower limit because it neglects the water that is moving from the carbonate-rock aquifers, through basin-fill aquifers, to discharge areas that have not been recognized as discharging water from the carbonate-rock aquifers. This unrecognized discharge from the carbonate-rock aquifers is not an additional water supply because it already has been included in the water budgets of the basin-fill aquifers.

Water Budget for All Southern Nevada Aquifers

The total of natural recharge to mountains and subsurface inflow for the study area is estimated to be about 160,000 acre-ft/yr. This estimate is based on the empirical method used to calculate recharge resulting from precipitation in mountains for water budgets in all basins of Nevada (Scott and others, 1971, p. 40) and on numerical models of ground-water flow in basin-fill aquifers around the Spring Mountains (Harrill, 1976, p. 50; Harrill, 1986, p. 46). The major mountain ranges of southern Nevada are shown in figure 25, and estimates of the recharge contributed by each are listed in table 7.

Some recharge enters the carbonate-rock aquifers and some enters the basin-fill reservoirs. Of the part that enters the carbonate-rock aquifers (directly or indirectly though basin fill), about 77,000 acre-ft/yr discharges from the carbonate rocks at major discharge areas for regional flow and identifiable regionally fed springs (fig. 25 and table 8). This discharge rate is believed, on the basis of the present studies, to include about 21,000 acre-ft/yr that enters the area from recharge sources in the high mountains of east-central Nevada along the northern part of the White River flow system (table 7; Kirk and Campana, 1988, scenario 1; Thomas, 1988; Thomas and Welch, in press). This table does not include springs believed to be supplied by local recharge (for example, Indian Springs). Local flow through the carbonate rocks represents a local resource that is little different from and probably intimately connected with the local basin-fill flow systems. Consequently, the local springs are included in estimates of discharge from the basin-fill aquifers that follow. Estimates of the quantity of water locally recharged to and discharged from carbonate rocks may have to be modified according to the extent that presumptions about the local recharge are modified by findings of future studies.

Assuming that the discharge information in table 8 accounts for most of the regionally derived discharge from the carbonate rocks in southern Nevada, all the recharge (listed in table 7) other than that supplying these discharge areas is believed to be discharged from the basin-fill aquifers. This is illustrated by a ground-water budget encompassing flows in both basin-fill and carbonate-rock aquifers (table 9). Discharge information in table 8 was supplemented by summing published estimates (see table 7 for references) of ground-water evapotranspiration—excluding areas where evapotranspiration was supported by discharge from regional springs—the Virgin River, and the Colorado River. Table 9 shows the total estimated inflow for all aquifers is about 161,000 acre-ft/yr and the total estimated discharge is about 165,000 acre-ft/yr. The difference, about 4,000 acre-ft/yr, may be attributed to estimation errors or unresolved hydrologic factors. This budget accounts for virtually all the replenishable water supply in southern Nevada.

Water Budget for the Central Corridor

The basin-fill and carbonate-rock water budgets are so intimately intertwined that an estimate is difficult to develop for the total flow through the carbonate-rock aquifers that does not also include the total flow through basin-fill aquifers. Either the total of flow in both aquifers can be estimated or that part of the flow that discharges directly from the carbonate-rock aquifers (neglecting that part of flow through carbonate-rock aquifers that discharges from the basin-fill aquifers) can be estimated, but not just the total flow through the carbonate rocks. As noted earlier (fig. 20), the central corridor contains the principal carbonate-rock aquifers of southern Nevada; it also contains 21 basins with basin-fill aquifers. Table 10 shows the estimated ground-water budget for the central corridor. The component of flow moving through the rocks of the central corridor that ultimately supplies regional discharge areas totals about 77,000 acre-ft/yr, 73 percent of which is derived from recharge areas in the corridor and 27 percent of which flows into the area from ground-water systems farther north.Water in a system having a dynamic equilibrium between recharge and discharge (which the authors assume is an adequate description of the carbonate-rock aquifers of southern Nevada) will not flow unless flow is ultimately toward

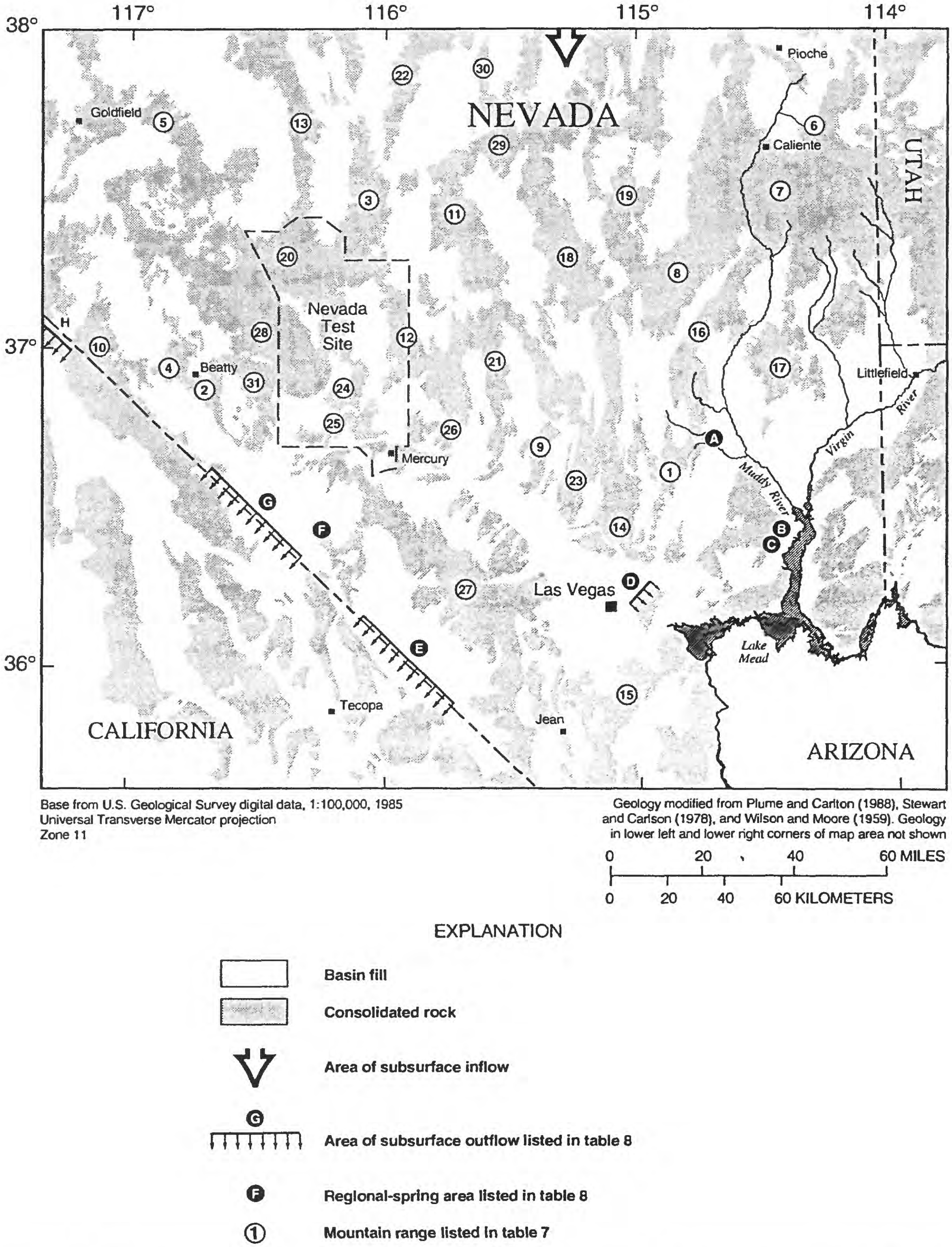


Figure 25. Mountain ranges where ground water is recharged and areas where regional ground-water flow is discharged in Nevada part of study area.

Table 7. Estimated recharge from the 31 most significant mountain ranges

[Abbreviations: N., North; S., South; V., Valley; W., West]

Map No. (fig. 25)	Mountain range	Total recharge[1] (acre-feet per year)	Adjacent hydrographic areas and referenced reports[2]
1	Arrow Canyon Range	400 *	Garnet V., Hidden V., California Wash (R50)
2	Bare Mountain	800	Crater Flat, Amargosa Desert, Oasis V. (R14, R54)
3	Belted Range	4,400	Buckboard Mesa, Groom Lake V., Kawich V., Yucca Flat, Penoyer V. (R54, R60)
4	Bullfrog Hills	700	W. Amargosa Desert, Oasis V. (R14, R54)
5	Cactus Range	700	Gold Flat, Ralston V., S. Stone Cabin V. (R12, R54)
6	Cedar Range	400	Meadow V. Wash (R27)
7	Clover Mountains	5,500	Meadow V. Wash, Tule Desert, Virgin River V. (R27, R51)
8	Delamar Mountains	1,500 *	Delamar V., Coyote Spring V., Meadow V. Wash (R16, R25)
9	Desert Range	5,200 *	Groom Lake V., Las Vegas V., N. Three Lakes V., S. Three Lakes V., N. Tikapoo V., S. Tikapoo V. (R54, B44)
10	Grapevine Mountains	1,100	W. Amargosa Desert, Sarcobatus Flat (R14, R10)
11	Groom Range	2,100 *	Groom Lake V., N. Tikapoo V., Penoyer V. (R54, R60)
12	Halfpint Range	200 *	Frenchman Flat, Yucca Flat (R54)
13	Kawich Range	3,400	Kawich V., Gold Flat, S. Stone Cabin V. (R12, R54)
14	Las Vegas Range	3,100 *	Coyote Spring V., Las Vegas V., Hidden V., Garnet V. (R25, R50, B44)
15	McCullough Range	1,000	Las Vegas V., El Dorado V., Ivanpah V. (B44, R46, B44)
16	Meadow Valley Mountains	1,400 *	Coyote Spring V., Meadow V. Wash (R25, R27)
17	Mormon Mountains	2,100	Meadow V. Wash, Tule Desert, Lower Virgin River V. (R27, R51)
18	Pahranagat Range	2,700 *	N. Tikapoo V., S. Tikapoo V., Pahranagat V. (R21, R54)
19	Pahroc Range	1,300 *	Delamar V., Pahranagat V. (R21, R16)
20	Pahute Mesa	4,000	Buckboard Mesa, Gold Flat, Kawich V., Oasis V. (R54, R10)
21	Pintwater Range	3,300 *	Groom Lake V., Indian Springs V., N. Three Lakes V., S. Three Lakes V. (R54)
22	Quinn Canyon Range	1,300 *	Penoyer V. (R60)
23	Sheep Range	11,000 *	Las Vegas V., Coyote Spring V., S. Tikapoo V. (B44, R54, R25)
24	Shoshone Mountains	800	Buckboard Mesa, Jackass Flat, Yucca Flat (R54)
25	Skull Mountains	200	Jackass Flat, Yucca Flat (R54)
26	Spotted Range	1,100 *	Frenchman Flat, Indian Springs V. (R54)
27	Spring Mountains	72,000 *	Amargosa Desert, Las Vegas V., Pahrump V., Mesquite V., Ivanpah V., S. Three Lakes V., Indian Springs V. (R14, R54, R46, B44, W2279)
28	Timber Mountain	400	Buckboard Mesa, Oasis V. (R54, R10)
29	Timpahute Range	1,200 *	N. Tikapoo V., Penoyer V. (R54, R60)
30	Worthington Mountains	900 *	Penoyer V., Garden V. (R18, R60)
31	Yucca Mountain	400	Crater Flat, Jackass Flat, Oasis V. (R10, R54)
	TOTAL (rounded)	[3]140,000	

[1] Asterisk indicates recharge estimate for mountain range within central corridor. Estimate based on published estimates of recharge in adjacent hydrographic areas, prorated for appropriate mountain ranges.

[2] Adjacent hydrographic area numbers in ( ) refer to references cited: B44, Harrill (1976); R10, Malmberg and Eakin (1962); R12, Eakin (1962); R14, Walker and Eakin (1963); R16, Eakin (1963a); R18, Eakin (1963b); R21, Eakin (1963c); R25, Eakin (1964); R27, Rush (1964); R36, Rush and Huxel (1966); R46, Glancy (1968); R50, Rush (1968); R51, Glancy and VanDenburgh (1969); R54, Rush (1971); R60, Van Denburgh and Rush (1974); W2279, Harrill (1986).

[3] Carbonate-rock aquifers of southern Nevada also receive about 21,000 acre-feet per year of subsurface inflow from northern parts of White River flow system, in east-central Nevada. Thus, total recharge plus subsurface inflow is about 160,000 acre-feet per year.

Table 8. Regional springs and areas of subsurface outflow through carbonate-rock aquifers

Map No. (fig. 25)	Name or area	Type of discharge	Total discharge (acre-feet per year)	Discharge derived from east-central Nevada (acre-feet per year)
A	Muddy River Springs	Springflow	36,000	14,000
B	Blue Point Spring	Springflow	240	0
C	Rogers Spring	Springflow	920	0
D	Frenchman Mountain	Underflow toward Colorado River	2,100	0
E	Pahrump Valley	Underflow to California	18,000	0
F	Ash Meadows	Springflow and evapotranspiration	17,000	6,800
G	Amargosa Desert	Underflow to Death Valley	[a]3,000	0
H	Grapevine Canyon	Underflow to Death Valley	400	0
TOTAL (rounded)			[b]77,000	21,000

[a] Does not include underflow (amount unknown).

[b] Total does not include flow from Hiko, Crystal, and Ash Springs in Pahranagat Valley, which discharge about 26,000 acre-feet per year (as measured during this study) near north edge of southern Nevada study area (fig. 1). This discharge is just inside study-area boundary but virtually all springflow derived from outside study area (Eakin, 1966, p. 265; Kirk and Campana, 1988, p. 32-34).

a discharge area (however indirect the path). Stated another way, the quantity of water in storage in a given area does not significantly change with time in a system in dynamic equilibrium. Therefore, unless the carbonate-rock aquifers of southern Nevada are not in dynamic equilibrium, the quantity of discharge from the carbonate rocks (observed at springs or inferred as underflow) must equal to annual net inflow and recharge to the aquifers. There can be no more water entering the study area unless some other mechanism of discharge has been overlooked, and unless the carbonate and basin-fill budgets are to be managed as a single system, the sustained yield of the carbonate-rock aquifers can be no greater than this discharge directly from them. Development of flow through the carbonate-rock aquifers on a sustained basis, however, ultimately would deprive some springs of some of their natural discharge. Thus, the sustained yield may be much smaller than the quantity of water directly discharging from the carbonate-rock aquifers, depending on how effects and development are managed and how "sustained yield" is ultimately defined.

Table 9. Estimated ground-water budget for entire study area

[All rates in acre-feet per year]

Inflow	
Locally generated recharge (table 7)	140,000
Subsurface inflow from the north (table 7)	21,000
Total	161,000
Outflow	
Discharge at regional springs and areas of subsurface outflow (table 8)	77,000
Evapotranspiration from basin fill, excluding that supplied by regional springs, Virgin River, or Colorado River (from published estimates for individual basins)[1]	88,000
Total	165,000

[1] Estimates were published in Nevada Division of Water Resources reports in the Reconnaissance and Bulletin series, and summarized by Scott and others (1971, table 3).

Development and Sustained Yield

If the basin-fill and carbonate-rock aquifers are managed together (locally or regionally), then the overall sustained yield of the area would be closer to the total recharge from mountains in the area plus regional inflow. This total is estimated to be about 160,000 acre-ft/yr. Joint management of the basin-fill and carbonate-rock aquifers would mean deciding where effects would be allowed to develop (in the carbonate rocks, in the basin fill, or both), where water would be extracted (again, in the carbonate rocks, in the basin fill, or both), and what degree of interaction between aquifers would be accepted. An understanding that precipitation in or near the

Table 10. Estimated ground-water budget for the central corridor

[All rates in acre-feet per year]

Recharge source	Rate	Discharge mechanism	Rate
Mountains of southern Nevada	110,000	Regional springs	54,000
Subsurface inflow from east-central Nevada	21,000	Subsurface outflow	about 23,000
		Discharge from basin fill under natural conditions	about 50,000
Sum of estimated rates	131,000		127,000
TOTAL RECHARGE (rounded)	130,000	TOTAL DISCHARGE (rounded)	130,000

mountains of southern and eastern Nevada (and vicinity) is the one source of all natural recharge to both the basin-fill and carbonate-rock aquifers of southern Nevada is needed to manage the resources for optimum effects. Confusion can arise when water from that common source is found in several different places as it moves through the different aquifers. For example, the water that recharged a given area may be present as infiltration of snowmelt, ground water flowing through a carbonate mountain block, ground water in a basin-fill aquifer, ground water in deeply buried carbonate-rock aquifers, and as springflow or evapotranspiration. Double-accounting or double-allocating of the water would be very easy given the complex and unseen interactions between aquifers. However, this would lead to eventual overallocation of the joint resource. Sustained development of the natural resource ultimately will be limited by the quantity of water supplied from their shared source of recharge—precipitation in the mountains of the carbonate-rock province.

Uncertainties in the Water Budgets

The ground-water balances developed in the preceding section contain several sources of uncertainty: empirical estimates of recharge, uncertain rates of ET, and relatively small errors in measuring springflow. The largest sources of uncertainty, however, are probably in the estimates of subsurface outflow to other States, the potential for subsurface inflows besides that from east-central Nevada, and the rough estimates of recharge to mountain ranges of the area. The potential for errors in estimates of recharge in mountains of the area and for subsurface inflow to southern Nevada near the Littlefield Springs in Arizona will be discussed in this section. Subsurface outflows are the most difficult budget components to identify and quantify. Four such outflows are listed in table 8: flow toward the Colorado River, flow toward Death Valley at Ash Meadows, flow toward the southern Death Valley area from Pahrump Valley, and flow towards northern Death Valley. This section also will summarize evidence for the occurrence and approximate magnitude of these outflows.

Potential for Additional Recharge in Mountains

Current estimates of recharge to the mountains of southern Nevada are based on relatively simple empirical methods developed during reconnaissance studies of basins throughout Nevada. These methods do not take geology and micro- or local meteorology into account, but rather are based on estimates of average annual precipitation or land-surface altitude. Despite these limitations, the estimates have proved useful and surprisingly robust in the face of regional studies subsequent to the original estimates (Harrill and others, 1988; Dettinger, 1989b).

The largest source of recharge in southern Nevada is the Spring Mountains (table 7), which receive about 72,000 acre-ft of recharge per year. The Sheep Range is a distant second, receiving about 11,000 acre-ft/yr. As a result, a 10-percent error in the estimate for the Spring Mountains would dwarf any other individual error in other ranges. Fortunately, because the range is near two highly developed basins, recharge has been studied in some detail. Models of ground-water flow in basin-fill aquifers of Las Vegas Valley (east of the Spring Mountains) and Pahrump Valley (west of the range) have been developed in previous studies, and provide additional estimates of recharge from the range (Harrill, 1976, 1986; Morgan and Dettinger, 1994).

Calibration of the model of flow in Las Vegas Valley required about 10,000 acre-ft/yr more recharge from the Kyle Canyon area of the Spring Mountains than estimated by the empirical methods (Harrill, 1976,

p. 50; Dettinger, 1989b). Recharge to the valley was much less than expected from the Sheep Range, north of Las Vegas. The higher than expected recharge to the valley from the Spring Mountains is attributed to the high altitude areas of the mountains where significant winter snowpacks accumulate and where underlying permeable carbonate rock facilitates copious and rapid percolation of ground water. Thus, the Spring Mountains may indeed receive much more recharge than would be expected from mountains of similar altitude in other parts of the State. The meager recharge from the Sheep Range is probably caused by local geologic barriers that direct flow north and east through carbonate-rock aquifers toward the Muddy River Springs rather than south toward Las Vegas Valley, and is in agreement with water budgets for the Muddy River Springs developed in this study (Kirk and Campana, 1988; Thomas and Welch, in press). A subsequent three-dimensional flow model of the valley (Morgan and Dettinger, 1994) required virtually the same conditions for adequate calibration.

The model of Pahrump Valley required recharge rates from the Spring Mountains that are about 10,000 acre-ft/yr higher than previously had been estimated (Harrill, 1986, p. 46).

Together these models indicate about 40 percent more recharge to the Spring Mountains than would be estimated using empirical methods. This additional recharge is included in tables 7, 9, and 10, and is detected by calibrations that attempt to adjust the models to match observed discharge rates and observed water levels, simultaneously. A similar error in all other estimates is unlikely since the additional recharge is probably related to large snowpacks that develop on the Spring Mountains and nowhere else in southern Nevada. However, if the empirical estimates were generally 40 percent low in southern Nevada, then an additional 27,000 acre-ft/yr of recharge would be circulating through the different aquifers of southern Nevada. Perhaps 15,000 acre-ft/yr of that additional water would be recharged in the mountains of the central corridor where they might enter the large-scale carbonate-rock aquifers. Nearly all of that water, if it existed, would be discharging from the basin-fill aquifers or to the Death Valley area. The alternative—discharging from the carbonate-rock aquifers in areas other than the Death Valley area—is mostly precluded because other avenues of discharge from the carbonate-rock aquifers are not observed (no large quantity of springflow is being missed and ET is from basin-fill aquifers, not carbonate-rock aquifers, in southern Nevada) or are precluded by geologic barriers to outflow (which will be discussed below). Even if as much as 15,000 acre-ft/yr additional recharge is circulating to eventually discharge from the basin-fill aquifers (perhaps after flowing through carbonate-rock aquifers for a time), the water is probably already accounted for in water budgets of those basins.

Potential for Additional Subsurface Inflow

Regional inflow of ground water into southern Nevada through carbonate-rock aquifers from east-central Nevada has been studied and quantified repeatedly since the 1960's (Eakin, 1966; Winograd and Friedman, 1972; Welch and Thomas, 1984; Kirk and Campana, 1988; Thomas, 1988). Recent studies (Welch and Thomas, 1984; Kirk and Campana, 1988; Thomas, 1988) have tended to generally corroborate each others' budgets. The reader is referred to the previous studies for discussions of the uncertainties involved in the present estimates of inflow from east-central Nevada (especially, Kirk and Campana, 1988). This section will present evidence that other sources of inflow through the carbonate-rock aquifers from less intensely studied areas are unlikely.

Subsurface inflows can be ruled out along most of the boundaries of the present study area because water levels in the study area are higher than those of Death Valley and vicinity and the Colorado River (pl. 2). The one other area where large quantities of ground water might flow into the carbonate-rock aquifers of southern Nevada is along the eastern edge of the Great Basin region near the town of Littlefield, Ariz. The following review of hydrology and geology indicates that such inflow is unlikely.

At Littlefield, Ariz. (fig. 26), about 10 mi east of the Nevada border on Interstate 15, springs and seeps are estimated to discharge about 50,000 acre-ft/yr of water to the Virgin River (Glancy and Van Denburgh, 1969, p. 37). This flow is believed to be supplied from the Upper Virgin River in southeastern Utah, and from the Beaver Dam Mountains north of Littlefield (Glancy and Van Denburgh, 1969, p. 36; Trudeau and others, 1983), and reaches the springs by flowing through carbonate-rock aquifers of the Colorado Plateau. The Colorado Plateau is the geologic province east of the Basin and Range Province of the Great Basin. The Plateau is east of the Beaver Dam and Virgin Mountains,

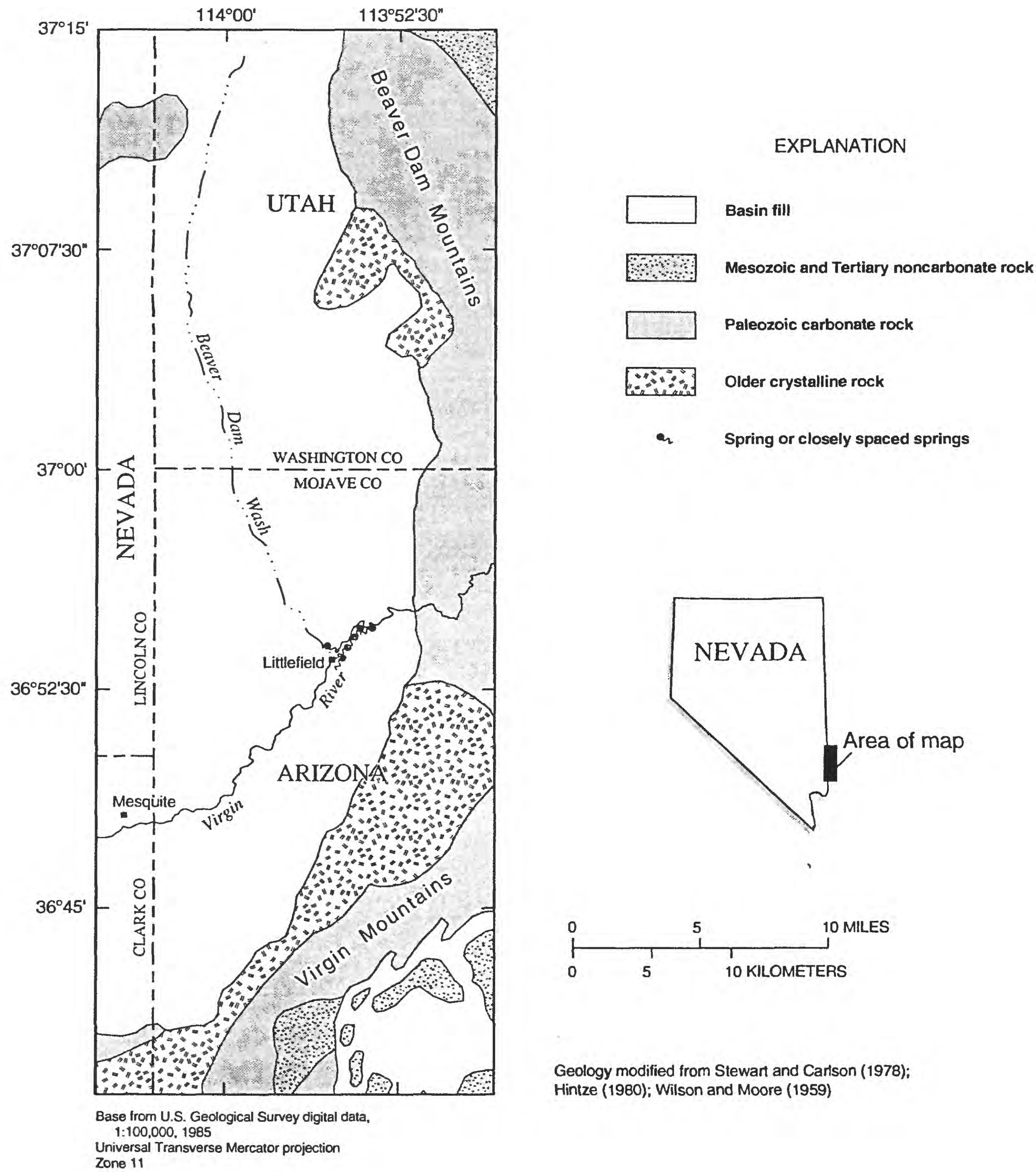


Figure 26. Area of regional ground-water flow near Littlefield, Arizona. Modified from Glancy and Van Denburgh (1969, pl. 1).

and in this area is underlain by sedimentary rocks similar to those in southern Nevada but that are much less deformed than those of the Great Basin.

Subsurface inflow beyond the springs, however, is unlikely unless it is supplied by downward leakage from the thick basin fill in the Lower Virgin River Valley, which in turn is supplied by downward leakage from the river and springs. The springs near Littlefield probably are located in that particular area because the carbonate rocks pinch out against crystalline basement rock that crop out to the north and south and against the very thick, probably low-permeability basin fill of the Lower Virgin River Valley (fig. 21, section *C-C'*). Both east and west of the Beaver Dam Mountains, the carbonate rocks thicken to 10,000 ft or more, but along much of the western edge of the range, carbonate rocks have been removed by erosion and structural events (Smith and others, 1987, p. 389). The area where the carbonate rocks were removed extends north of Littlefield for about 20 mi and to the south about 40 mi (along the Virgin Mountains; Wilson and Moore, 1959; Stewart and Carlson, 1978; Hintze, 1980). Directly east of Littlefield (fig. 26), no crystalline basement rocks are exposed; the exposed carbonate rocks might explain why the springs are located there. Even though carbonate rocks are exposed between the Virgin and Beaver Dam Mountains, the Littlefield area itself is underlain by basin fill and basement rock; therefore, no carbonate-rock aquifers are present through which ground water could flow.

Potential for Subsurface Outflow to the Colorado River

The principal evidence for ground-water discharge to the Colorado River through the subsurface are water-level gradients and numerical-model results for basin-fill aquifers in the northeast part of Las Vegas Valley. Water levels observed in basin-fill wells just east of Nellis Air Force Base (location shown in fig. 27) infer that flow is toward the base of Frenchman Mountain (Loeltz, 1963, p. Q5). A numerical modeling study of principal basin-fill aquifers of Las Vegas Valley by Harrill (1976, p. 50) inferred subsurface outflow from that same area of 1,200 acre-ft/yr. A subsequent modeling study that simulated more aquifers in the basin required a similar outflow (Morgan and Dettinger, 1994). This outflow is listed in table 8 based on the assumption that it is underflow toward the Colorado River. Another, more regional model (Prudic and others, 1993) showed as much as 10,000 acre-ft/yr flowing toward the Virgin River and Overton Arm of Lake Mead. This model result is as yet unverified in the field. Supporting the regional model results is the regional slope of water levels in carbonate-rock aquifers toward the Colorado River (Thomas and others, 1986).

Locally, however, several lines of evidence imply that little water reaches the river through carbonate-rock aquifers. First, geologic (Longwell, 1936) and topographic mapping of the floor of the present-day Lake Mead basin (including the Overton Arm of Lake Mead) located no large springs or spring deposits (except near Hualapai Wash, Ariz. [fig. 27], where subsurface flow to the lake is from the southeast [Longwell, 1936, p. 1431; Laney, 1977, p. 47; Remick, 1981]). Geologic mapping on the floor of the lake as well as of those parts of Nevada that border it (south and west of the Overton Arm of Lake Mead) shows that the carbonate-rock aquifers do not extend to or under Lake Mead except possibly in isolated areas (Longwell, 1936; Bohannon, 1983, pl. 1). Lake Mead is in that part of southern Nevada (and adjacent States) underlain by Tertiary deposits laid directly on crystalline basement rocks. Geologic and seismic studies have shown that the Overton Arm of Lake Mead is physically and hydraulically isolated from underlying rocks (including carbonate rocks) by a thick and impermeable salt body (fig. 27 in this report; Anderson and Laney, 1975). Finally, historical water balances of Lake Mead rule out large ground-water inflows—that is, inflows greater than about 50,000 acre-ft/yr (Harbeck and others, 1958, p. 11; Smith and others, 1960, p. 103). Thus, it is unlikely that the Colorado River is a sink for large flows through the carbonate-rock aquifers. Undiscovered flows to the Colorado River are likely to be few (if any) and to be of a magnitude comparable to the underflow from Las Vegas Valley at Frenchman Mountain: about 1,000 acre-ft annually.

Basin-fill aquifers along the Muddy River (which is supplied by the Muddy River Springs) and Virgin River conduct some flow toward and into Lake Mead, but outflow to the lake from bedrock aquifers is less likely. Nearly all the flow that is, at regional scales, directed toward the Colorado River is actually discharged from the carbonate-rock aquifers about 25 mi upgradient at Muddy River Springs before reaching the river. The Muddy River Springs, the authors believe, drain all the water flowing in the carbonate-rock aquifer because the carbonate rocks pinch out against geologic barriers to the east and south. One barrier to

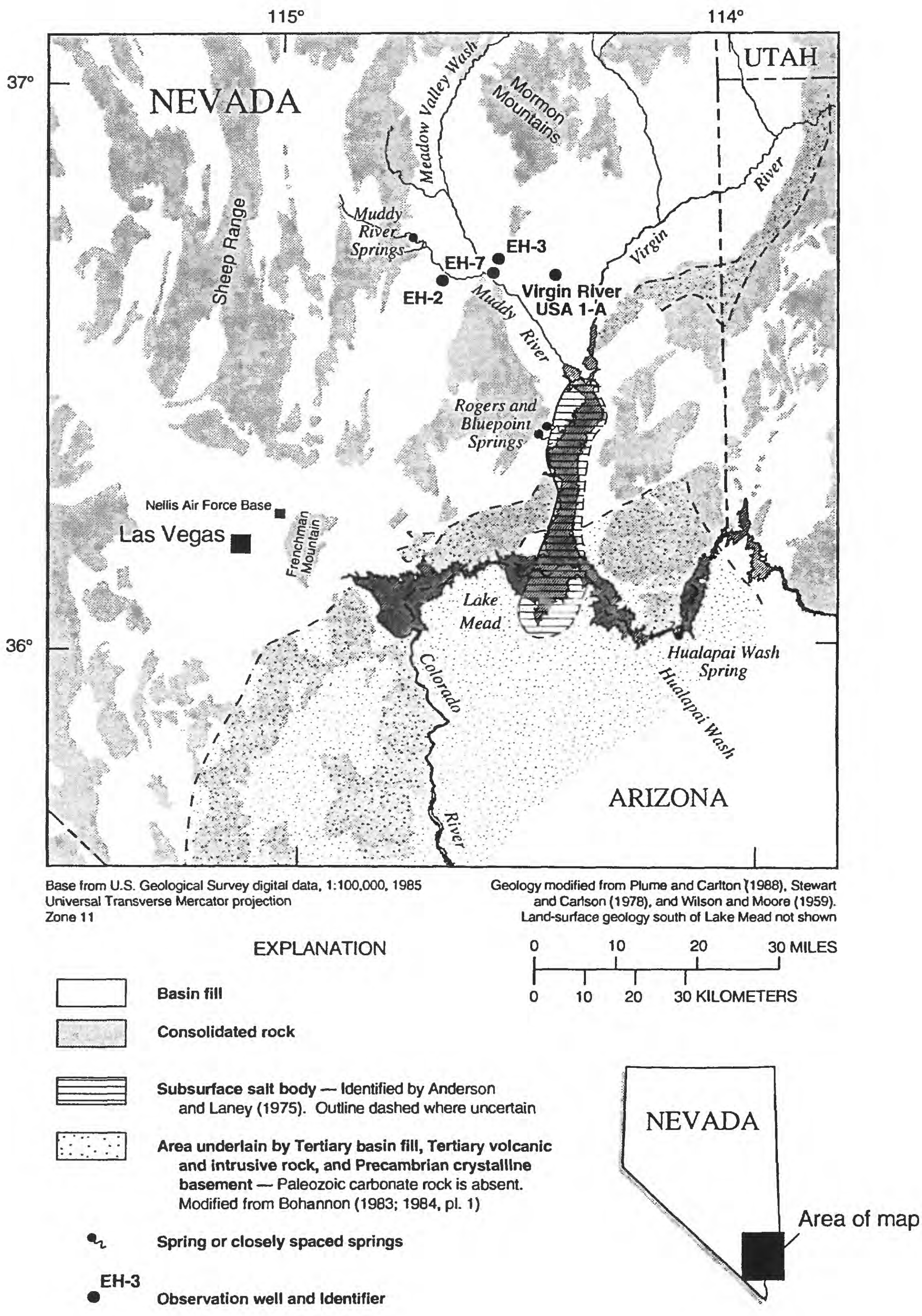


Figure 27. Region of outflow from carbonate-rock aquifers to Lake Mead and Colorado River in southeastern part of study area.

eastward flow is crystalline basement, which shallows to the east from great depth below the springs area and is exposed at the surface along the western base of the Mormon Mountains (fig. 21, section *C-C'*, this report; Wernicke and others, 1985, fig. 15). Another probable barrier is the deep basin that lies just east of the springs. A well was drilled in this basin to a depth of 4,000 ft without penetrating carbonate-rock aquifers (well EH-2 at the Nevada Power Company Reid-Gardner facility near Moapa, fig. 27). The basin-fill sediments and rocks penetrated consisted of lake-bed clay and silt all of which were of low permeability. This deep basin probably extends northward many miles along the Meadow Valley drainage as interpreted from the area's low gravity anomaly (Kane and others, 1979), and in some places probably directly overlies impermeable crystalline-basement rock. Farther east beneath Mormon Mesa, the basin-filling deposits are as much as 7,000 ft thick as measured in the Virgin River USA 1-A oil-test well (fig. 27). Finally, the isotopic composition (deuterium composition, -93 permil SMOW) and temperature (24°C) of water from the carbonate-rock wells EH-3 and EH-7 (fig. 27) are sufficiently different from those of water at Muddy River Springs (deuterium, -98 permil; temperature, 32°C) that the regional flow system that supplies the springs cannot be the source of water in the carbonate rocks east of Meadow Valley Wash (Schroth, 1987, p. 65, 82, 86). Thus, regional flow does not continue past the Muddy River Springs in an easterly direction.

The possibility that regional flow continues south beyond the Muddy River Springs is difficult to eliminate. As indicated earlier, the Overton Arm of Lake Mead appears isolated from underlying aquifers by a large salt body within the basin fill. The volcanic rocks of the Black Mountains area directly north of Lake Mead are underlain by Precambrian crystalline rocks. Finally, the water level in carbonate rocks beneath a 750-mi^2 area around, south, and west of the Muddy River Springs is extremely uniform between about 1,800 and 1,830 ft above sea level. The water levels surrounding this area, in contrast, have much steeper gradients (pl. 2), and thus, give the impression of a dead end in the White River system. One interpretation of this observation is that the area south of the springs offers no outlet for regional flow that trickles past the springs area. If the aquifers of the central corridor are isolated from the Colorado River (as discussed above) then flow that passes the Muddy River Springs area moving south might be virtually ponded at the same water level as the springs with little through flow except to supply leakage to basin-fill aquifers along the Muddy River. This interpretation may be supported by the general uniformity of chemistries and, in particular, isotopic compositions in most of the same area. The chemistry is uniform because the water is scarcely moving through the area and because it is at equilibrium with the aquifer materials. In contrast, upgradient from the Springs, water chemistry and isotopic compositions evolve in readily detectable patterns along flow distances no longer than those in the uniform area south of the Springs (Thomas and Welch, in press).

Another possibility that cannot be discounted, however, is that the flat water levels and uniform chemistries reflect high transmissivities in the area. If transmissivities are very high, water-level gradients would be flat regardless of flow rates, but then a vertical low-permeability barrier would be required to explain the steep gradients outside the uniform area. If the flow rates are large, this alternative requires significant discharge areas somewhere to the south that are at present (1989) unrecognized. The most likely discharge for water flowing southward past the Muddy River Springs are Rogers and Bluepoint Springs, which are warm-water springs that together discharge about 1,100 acre-ft annually from carbonate rocks above the Overton Arm of Lake Mead. Chemistry of water discharging from these springs indicates dissolution of large amounts of gypsum which tends to mask possible similarities to water in rocks further north. Isotopic composition of the ground water (-92 permil deuterium), however, implies that the water is not derived entirely from the White River flow system (as represented by water from the Muddy River Springs at -98 permil deuterium) but at most could contain about 20 percent of that water. To generate water of the isotopic composition of Rogers Spring, that small component of White River water would have to be mixed with 80 percent water derived from recharge in the relatively low mountains of southeastern Nevada. Chemical effects such as gypsum dissolution would not alter the isotopic composition of the water. Discharge at Rogers Spring is best attributed to recharge in either nearby Sheep Range or Mormon Mountains.

Thus, for practical purposes, springflow from the Muddy River Springs, along with upward leakage into overlying basin-fill aquifers in the area, constitutes virtually all the subsurface outflow from the White River flow system into southeastern Nevada. No other large discharge areas have been identified and geologic constraints prevent large-scale flow past the region. This implies that the White River flow system is contained within Nevada, and does not discharge directly into the Colorado River.

Potential for Subsurface Outflow to Death Valley

Ground water may flow toward Death Valley through the carbonate rocks of Nevada from three general areas (pl. 1 and fig. 28): (1) the Grapevine Mountains, (2) Ash Meadows, and (3) south from beneath Pahrump Valley. Geologic barriers limit how far these flows can extend because Death Valley (at least in the south and possibly as far north as the Furnace Creek area) is sparsely underlain by carbonate rocks. Large uncertainties in estimates of the rate of ground-water discharge from the basin fill in Death Valley make it difficult, however, to argue where regional flow in the Ash Meadows flow system ends or how much underflow passes beneath Ash Meadows.

Ground water from beneath Sarcobatus Flat, Lida Valley, and possibly Stonewall Flat flows toward northern Death Valley through consolidated rocks in the Grapevine Mountains (locations shown on pl. 1). Grapevine and Staininger Springs in central Death Valley discharge about 400 acre-ft/yr (Rush, 1968, p. 32), which probably represents the total outflow through consolidated rocks in that area. Few carbonate rocks crop out in the area that is well outside the central corridor (Stewart and Carlson, 1978). Thus, the outflow is probably through isolated blocks of carbonate rock, through some of the noncarbonate rocks, or through thin basin-fill connections between Sarcobatus Flat and Death Valley.

In the Ash Meadows-Furnace Creek area, regionally fed ground water discharges from two lines of springs—at Ash Meadows and from the Furnace Creek area on the eastern flank of Death Valley (fig. 28). Between the two lines of springs, water levels seem to vary smoothly rather than in discontinuous steps (Thomas and others, 1986). The chemistry and isotopic compositions of the water at both sets of springs are similar enough for the water to have originated from the same source (Winograd and Friedman, 1972, p. 3704). Finally, the subsurface geology and aquifer geometries between the two lines of springs are poorly understood and provides considerable latitude for postulating flow paths.

Several authors have postulated that discharge from springs in the Furnace Creek area is fed by water that flows past the springs at Ash Meadows (Winograd and Friedman, 1972, p. 3704; Czarnecki, 1987). This underflow then discharges at Death Valley at several springs and as ET. Czarnecki (1987) hypothesized that the Ash Meadows-Furnace Creek connection is in a carbonate-rock aquifer overlain by flow mostly in basin fill toward Franklin Lake (also known as Alkali Flat; Czarnecki, fig. 3-8). Others, however, have stated that the springs in the Furnace Creek area might be supplied by flow from the north in Amargosa Valley and Pahute Mesa (Waddell and others, 1984, p. 37). Considerable uncertainty with respect to the hydrology and geology controlling underflow precludes any strong conclusions about any of these hypotheses.

In addition to uncertainties about the general occurrence of underflow from Ash Meadows, the rate of underflow from beneath Ash Meadows is uncertain. Springflow is about 3,000 acre-ft/yr from the springs near Furnace Creek (Miller, 1977, p. 27), but many phreatophyte stands and an enormous area of salt pan may account for much more discharge by ET (Miller, 1977, p. 55). The origins of this water may include surface-water inflows (during floods), recharge from surrounding ranges, and regional inflow; all may be present in some unknown proportions. The discharge rates of the regional component could be significantly greater than those estimated in table 8.

Despite uncertainties about the existence and rate of underflow from Ash Meadows to Death Valley, flow and discharge of water from Nevada in areas beyond Death Valley are unlikely. Any underflow must discharge in Death Valley because the valley is a regional topographic and hydrologic low point. Also, the mountain ranges farther north, south, and west are composed of impermeable rocks.

Ground water flows toward the southern Death Valley area from beneath Pahrump Valley. Malmberg (1967, p. 32) estimated that between 5,000 and 15,000 acre-ft/yr of ground water flows southwest from beneath Pahrump Valley in carbonate-rock aquifers. A numerical model of ground-water flow beneath Pahrump Valley suggests that the total outflow is about 18,000 acre-ft (Harrill, 1986, p. 46). This flow is assumed to pass mostly through the carbonate rocks

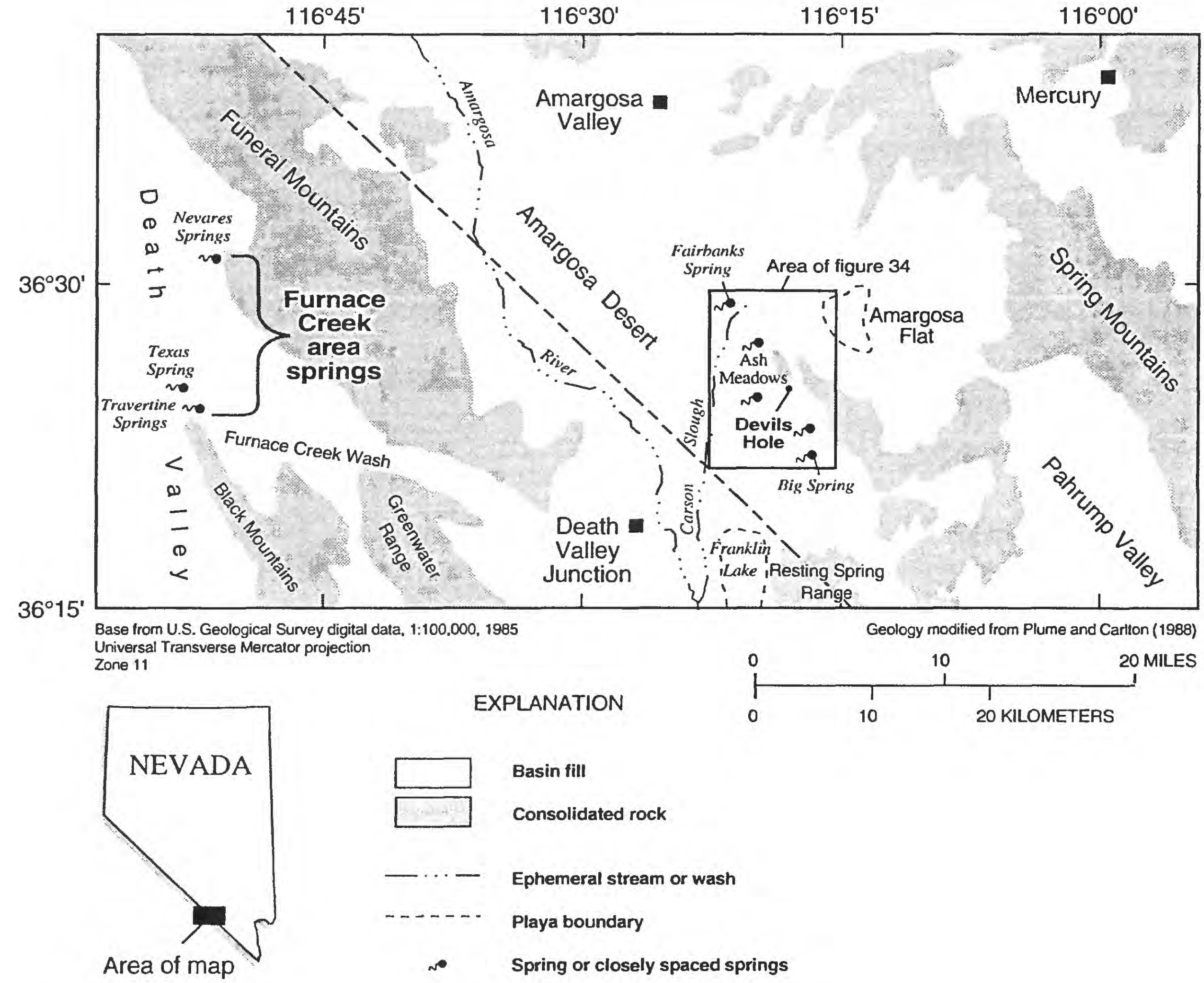


Figure 28. Region of possible ground-water throughflow from Ash Meadows area, Nevada, to Furnace Creek area, California. Modified from Winograd and Szabo (1986, fig. 1) and Plume and Carlton (1988).

of the Nopah and Resting Spring Ranges prior to discharging at warm water springs and phreatophyte stands near Tecopa and Shoshone, Calif., and into the lower reaches of the Amargosa River, also in California (Harrill, 1986, p. 15; locations shown in fig. 29). These estimates are based on interpretations and simulations of ground-water conditions in the basin-fill aquifers of Pahrump Valley.

Flow beyond the Amargosa River area almost certainly is impeded by the structural removal of the carbonate-rock aquifers. West of the Nopah Range, Wright and others (1981) and Wright and Troxel (1973, p. 404 and 406) show that in Resting Spring Range only small fragments of carbonate rock overlie predominantly older noncarbonate rocks and that mountain ranges even farther west consist of low-permeability granites and crystalline basement (fig. 21, section *E-E'*). Together these rocks constitute a formidable barrier to westward or southward flow beyond the Amargosa River.

Summary of Budget Uncertainties

Overall, this discussion of subsurface inflows and outflows to the carbonate-rock aquifers of southern Nevada implies that considerable uncertainty exists in the estimates in table 10. In each area, however, with the exception of the possible Ash Meadows-Furnace Creek connection, uncertainties are not large enough to allow for major regional flow paths to have been missed in previous analyses. Each of the other major discharge areas discussed (Muddy River Springs, the Tecopa-Shoshone area, and the Littlefield Springs) appear to comprise nearly all of the regional flow into

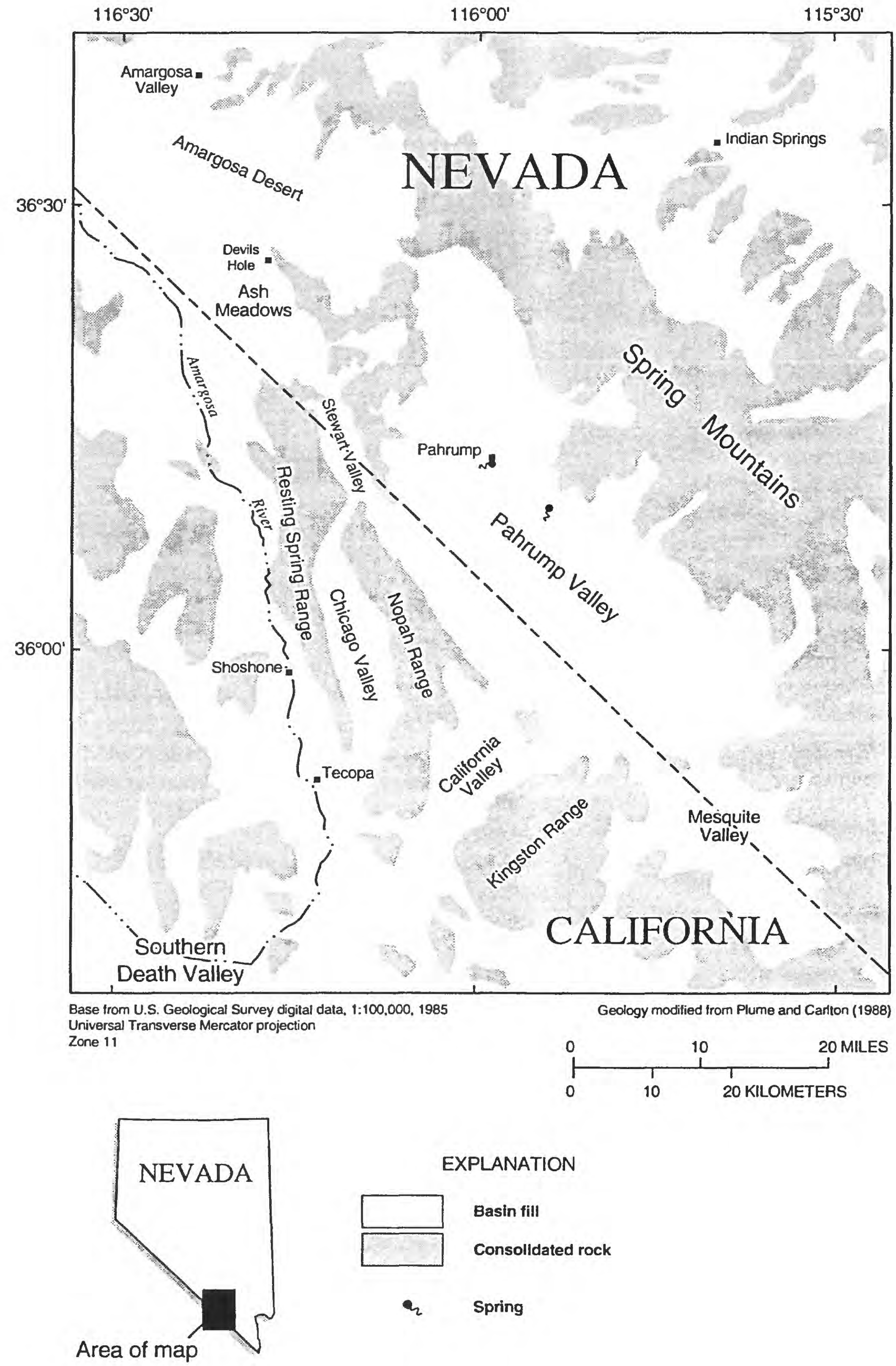


Figure 29. Area of underflow from Pahrump Valley, Nevada, to southern Amargosa River area, California. Modified from Harrill (1986, fig. 1).

each area. In each setting, geologic conditions have dictated that little water passes beneath the major springs and discharge areas to be consumed elsewhere. Thus, the same conditions that result in major spring discharges also account for virtually all flux through the regional flow systems.

Storage of Water in the Carbonate Rocks

Estimates of the total quantity of water stored as a one-time reserve in the carbonate-rock aquifers are based on current (1989) understanding of the present-day geometry of the rock sequences and of how much water is actually stored per cubic foot of rock.

The geometry of the layers and blocks of carbonate rock defines the maximum volume in which water may be stored. In order to calculate this volume, the thickness of carbonate-rock sequences must be estimated. Thickness is dependent on the geologic history of the area: the original depositional thicknesses, the amount of compressional thickening during Mesozoic time, the amount of extensional thinning during late-Tertiary time, and the amount of erosional thinning of the section during geologic time. Surficial geology, regional and local models of geologic structures at depth, and interpretations of geophysical data are all used to estimate present-day thicknesses in selected areas. Once the thickness is determined or estimated, it can be multiplied by an area for which that thickness is representative to estimate the total volume of rock.

The volume of water stored in the rocks is a small fraction of the total volume of rock. Water is stored in fractures, other secondary openings in the rock mass, and in tiny interstitial or intercrystalline (primary) openings in the unfractured rock. Secondary openings can comprise about 0.1 percent of total rock mass, whereas primary openings probably comprise about 1-10 percent. The volume associated with these two types of openings constitute the quantity of water available if all extractable water were drained from a given volume of carbonate-rock aquifer.

The ratio of the volume of water to the volume of saturated rock is commonly called the specific yield of the carbonate-rock medium. The total quantity of water stored in the aquifer is equal to the volume of the aquifer multiplied by its specific yield. If the spatial variability of the yield can be quantified, then stored water equals the integral of this product over the entire aquifer volume.

Pumping all the water stored in aquifers as thick as the carbonate-rock aquifers is neither economical or practical. The quantity of water that could be extracted from one-time storage in the carbonate-rock aquifers is limited by the depth of rock that can be dewatered before technical, economic, or environmental problems are experienced. Thus, the carbonate-rock province probably contains much more water than could ever be extracted. To estimate the fraction of the total stored water that could be realistically extracted for use, the fraction of the rock volume that could be dewatered has to be estimated. This fraction of rock volume would then be multiplied by the total volume of stored water to estimate practical limits of the stored-water resource. In this report, the fraction of rock volume that could be dewatered will be estimated in terms of the fraction of rock thickness that might under extreme conditions be dewatered.

Volume of Water Stored in a Unit Volume of Rock

In a confined aquifer, the measure of the volume of water stored in a unit volume (cubic foot) of water-saturated rock is the storage coefficient. In an unconfined aquifer, the measure is the specific yield of the aquifer. These numbers are generally quite different and are the result of differing storage processes. As a consequence, the volume of stored water that must be extracted to dewater a given thickness of an aquifer depends on, among other things, whether the aquifer is under unconfined ("water table") or confined ("artesian") conditions. Heath (1983, p. 6) describes unconfined aquifers as aquifers where water only partly fills the transmissive rocks so that the upper surface of water in the openings in the rocks can rise and decline in response to pumping. In contrast, a confined aquifer is one where water fills the entire thickness of transmissive rocks up to a layer or cap that restricts vertical flow. In confined aquifers, water pressure—not water level—rises and declines in response to pumping. Water added to storage is accommodated by compressing both the rock matrix and water into smaller volumes. Accomplishing this compression requires high pressures in the aquifer that force water to rise in a well to levels above the low-permeable cap and in some places to flow freely from a well that penetrates the aquifer. In contrast, water added to storage under unconfined conditions raises the water table by filling previously dry (or unsaturated) pores with water increasing the volume of the aquifer. The level of water in wells rises as high as the water table (top of the aquifer) under these conditions.

On the basis of a standard equation for estimating the storage coefficient of a confined aquifer from Bear (1979, p. 107) and assuming physically reasonable values for physical and mechanical properties of the carbonate-rock aquifers, the estimated storage coefficient of a confined part of the carbonate-rock aquifers is about 0.0001. In making this estimate, total porosity is assumed to be about 10 percent, the reciprocal of the modulus of elasticity of the rock itself is assumed to be about 10^{-10} ft^2/lb, the reciprocal of the modulus of elasticity of the water is assumed to be 2.3×10^{-8} ft^2/lb, and the aquifer thickness is assumed to be about 3,000 ft. A storage coefficient of 0.0001 indicates that if an acre-foot of stored water were extracted from a 1-acre block of carbonate rock that was responding as an isolated and confined aquifer, fluid pressure in the block would decline by the equivalent of the weight of a column of water 10,000 ft high. Consequently, in an area where the carbonate-rock aquifer is confined, relatively little water needs to be extracted to cause large reductions in the water pressure in the aquifer and the consequent water level in wells.

Under unconfined conditions, water to supply a pumped well is derived principally from drainage of water from previously saturated openings (matrix and secondary) in the aquifer (following a short initial period before drainage becomes fast enough to supply the demand). The specific yield is equal to that fraction of the porosity near the water table that is drained as the water table declines in the aquifer. Some pores are left undrained—pores that are poorly connected or unconnected to the permeable parts of the medium. As a result, the specific yield is always less than or equal to the total porosity of the aquifer and generally is equal to an "effective" porosity of the aquifer (Bear, 1979, fig. 5-4).

Estimating effective porosity of the carbonate-rock aquifers is difficult. Effective porosity is directly dependent on the fraction of total porosity that yields water to pumped wells. Field observations and laboratory measurements indicate that the large-scale average fracture porosity of carbonate rocks ranges from less than 0.01 percent to about 0.5 percent with a median that is probably on the order of 0.1 percent (Winograd and Thordarson, 1975, p. C17; Alan M. Preissler, U.S. Geological Survey, written commun., 1987). Laboratory measurements and geophysical logs, in contrast, indicate that the matrix porosity is commonly between 0 and about 20 percent with a median around 5 percent (Winograd and Thordarson, 1975, p. C17; Berger and others, 1988). Of this total matrix porosity, Winograd and Thordarson (1975, p. C17) determined that 20 percent is "effective" in rock samples from the Nevada Test Site area.

Water-level responses to constant pumping stress provides important clues as to the volume of storage that might be yielded by long-term pumping of carbonate-rock aquifers. Measured drawdowns in pumped wells completed in carbonate rocks in Nevada have two or more distinct breaks in slope when plotted against the logarithm of time since pumping began. As examples specific to this study, figure 30 shows drawdown curves for two of the wells tested as part of the present study. Distinct breaks in slope are evident in the upper curve (for MX well CE-DT-6) and a similar break is indicated in the lower curve (for well CSV-2). Similar responses also have been noted in aquifer tests in carbonate rocks of the Nevada Test Site area (several wells: Winograd and Thordarson, 1975, p. C20; well UE16d: Dinwiddie and Weir, 1979; well UE25p#1: Craig and Robison, 1984, p. 26). This response is characteristic of fractured porous media where flow to the well is through high-permeability, low-storage fractures but where most water is from the low-permeability, high-storage pores of the unfractured rock (Streltsova, 1988, p. 368). Media of this sort are called "double-porosity" media (Streltsova, 1988, p. 370), and would be expected to yield water from both the fractures and matrix over the long term—initially water is drawn from the fractures and later water is extracted from pores in the unfractured rock. Thus, the overall volume of stored water that might be yielded by long-term pumping of the carbonate-rock aquifers is most likely to approximate that contained in the effective part of the primary porosity (and is not limited to the fracture porosity).

Two alternative explanations for the breaks in the drawdown curves are: initial depletion of borehole storage or a transition from confined storage to gravity drainage as drawdowns develop. In large-diameter wells, the first storage depleted by the pumped well is the water in the borehole itself, and this can lead to breaks similar to those shown in figure 30. However, other characteristics of such initial depletion include a unit-slope when the drawdowns are plotted against time on a log-log graph. This slope is not found in the wells completed in the carbonate rocks being discussed

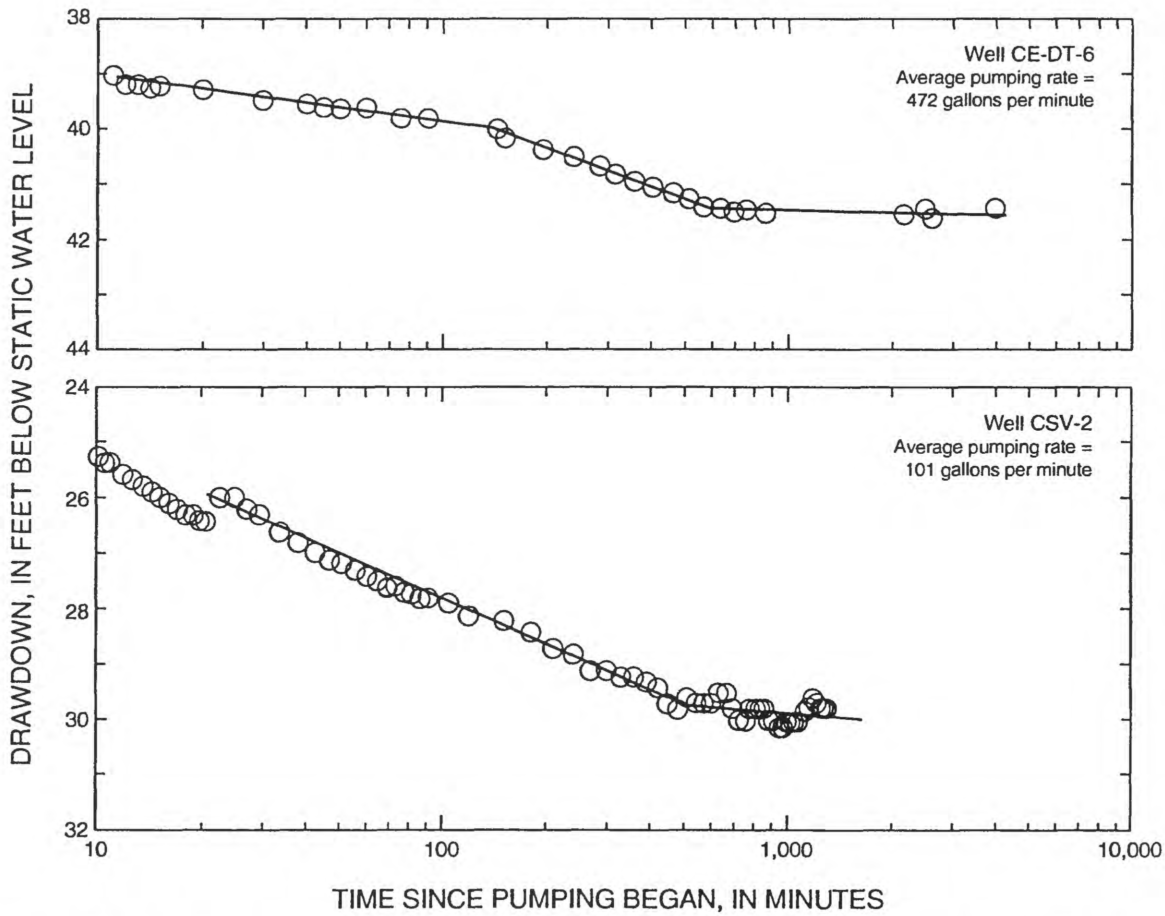


Figure 30. Water-level drawdown during aquifer tests at two carbonate-rock wells in Upper Muddy River Springs area. Solid lines indicate generalized straight-line slopes of drawdown curves.

and so is considered an unlikely explanation for the breaks. After moderate-to-long periods of pumping, water flowing to a pumped well in an unconfined aquifer is from gravity drainage of pores (and fractures) at the water table. Initially, however, water is derived from release of pressure (as in a confined aquifer) because gravity drainage is not instantaneous. This change in the storage mechanism that is being depleted by a well results in a set of changes in slope of drawdowns similar to that discussed above—although usually not as abrupt. This explanation for the breaks is inappropriate in several of the wells because they are clearly open to confined aquifers. Aquifer tests for wells 88-66 (Winograd and Thordarson, 1975, p. C30) and UE-25p#1 (Craig and Robison, 1984, p. 25-26) provide clear examples of the breaks in the drawdown curves and yet are confined by confining units that are hundreds or thousands of feet thick. Breaks in the slope of drawdown curves for other wells may result from a combination of dual-porosity response and delay of gravity drainage.

The preceding discussion is based on indirect inferences. Direct measurements of specific yields of the carbonate-rock aquifers in Nevada would be useful and would add reliability to storage calculations that follow. However, direct measurements of long-term storage properties of aquifers are difficult and expensive. Direct measurement of specific yield requires a aquifer test with observations of water levels in both a pumped well and an observation well. In general, the few production wells that draw water from Nevada's carbonate-rock aquifers are not accompanied by observation wells. Only three "direct" measurements of specific yield in the carbonate rocks of Nevada are available. A 30-day aquifer test at well CE-DT-5 (as observed from well CE-DT-4 that is 300 ft away) yielded an estimated storage coefficient of about 0.15

(based on data reported in Ertec Western, Inc., 1981; and Berger and others, 1988, table 9). A 30-day aquifer test made with several observation wells at the Fad Shaft near Eureka in east-central Nevada yielded storage coefficients between 0.00064 and 0.0014 (Stuart, 1955, table II). Finally, analyses of tidal and barometric fluctuations of water levels in well UE25-p#1 near Yucca Mountain indicated that the aquifer is confined (probably by the 5,000 ft of volcanic rocks overlying the carbonate rocks) and that the storage coefficient for the aquifer is 0.0003 (Galloway, 1986). Galloway also estimated the total porosity of the aquifer as 9 percent. In the future, improved estimates of the volume of water stored in the carbonate-rock aquifer will depend largely on collection of more data describing specific yields.

Despite the limited data available, and solely on the purposes of deriving estimates of the overall quantity of water stored in the carbonate-rock aquifers of southern Nevada, the specific yield or storage coefficient is assumed to be 0.01. This estimate actually is in the center of the probable range, and specific yield could be an order of magnitude smaller or larger in any given area. This assumed specific yield is about 100 times greater than the confined-aquifer storage coefficient values, and will be used in these storage calculations for two reasons:

1. In an isolated block, the quantity of water available from dewatering the top 100 ft of the aquifers under unconfined conditions would be equal to that required to lower water pressure under confined conditions by 10,000 ft (which would be enough to convert aquifers from confined to unconfined conditions almost everywhere). Thus, the quantity of water that would be available from dewatering a confined block of rock is so much smaller than the quantity available from an unconfined block that most water available by dewatering is likely to be from unconfined conditions.

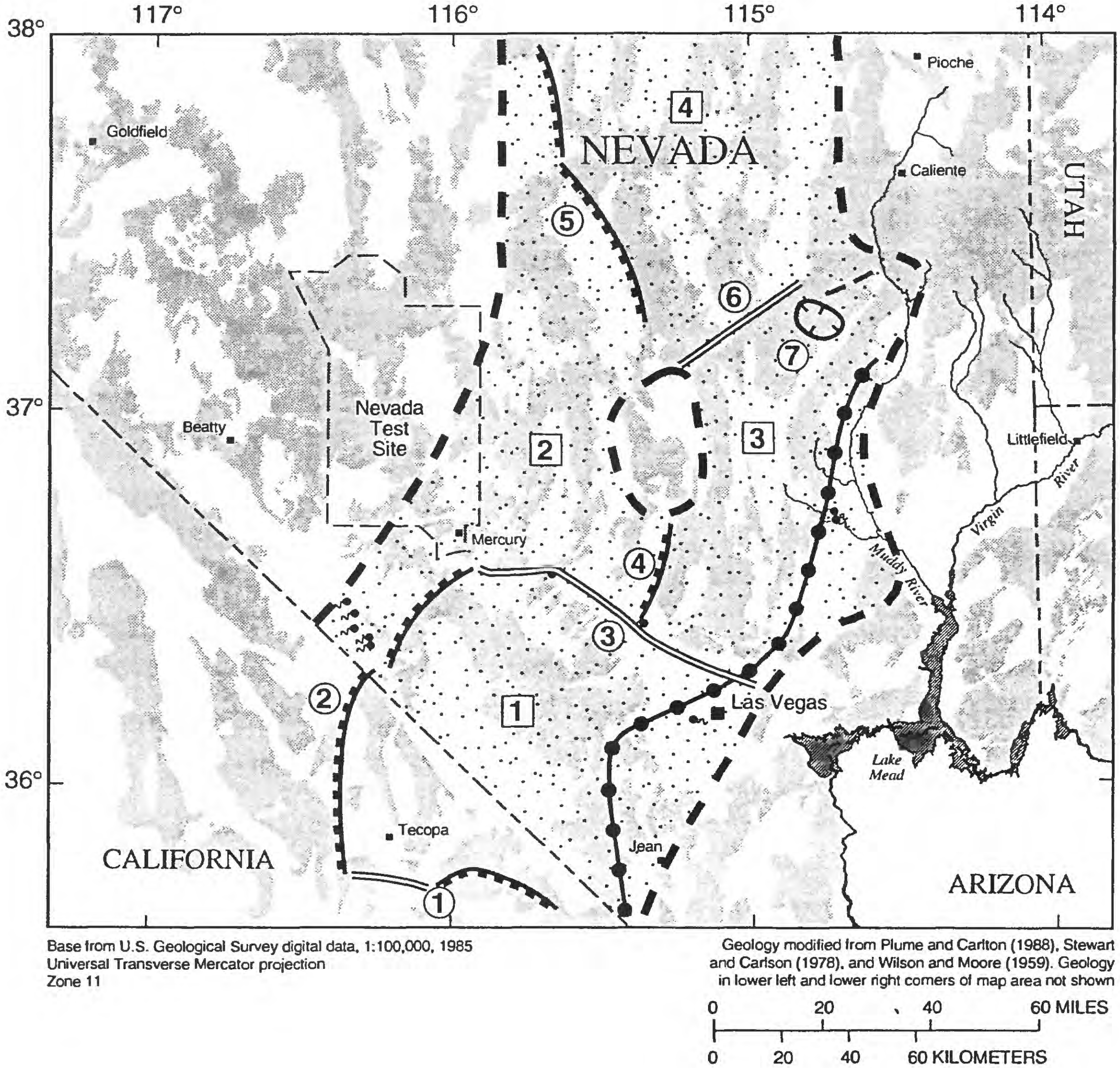
2. At the regional scales to be considered here and when the issue being considered is the one-time storage of water, the carbonate-rock aquifers probably will respond as if unconfined. This hypothesis is based on the regional-scale geologic heterogeneity of the Basin and Range Province. In this block-faulted province, it is unlikely that any one confining unit is laterally continuous enough to maintain regional-scale confinement of the aquifers. The ubiquity of high-angle faults that function as vertical flow paths through confining units reduces the chance for large-scale confinement even where layers are present that otherwise could confine the aquifers.

Thickness of Aquifers

Most water stored in the carbonate rocks of southern Nevada is localized within the central corridor. The thickness of carbonate-rock aquifers within the central corridor of southern Nevada is estimated in this section. Blocks of carbonate rock outside the corridor are apt to be small and isolated and many are relatively thin. Some estimates of thickness of rocks in these blocks are presented in this section but the total volume of carbonate rocks (or water stored) in these isolated blocks and in areas assumed to contain poor-quality water is not estimated.

Thickness of the carbonate rocks within the central corridor ranges from several thousand feet to possibly greater than 19,000 ft. Variations of thickness are smooth in some areas and abrupt across structures in others. No one structural style or structural feature is predominate in the entire corridor, and at a regional scale, spatial variations of thickness depend on the particular structural features in a given area. The central corridor with some major structures used to delineate broad areas having distinct structural styles or boundaries is shown in figure 31; the structures are described in table 11. These areas are the framework used below for making estimates of representative thicknesses of carbonate rocks.

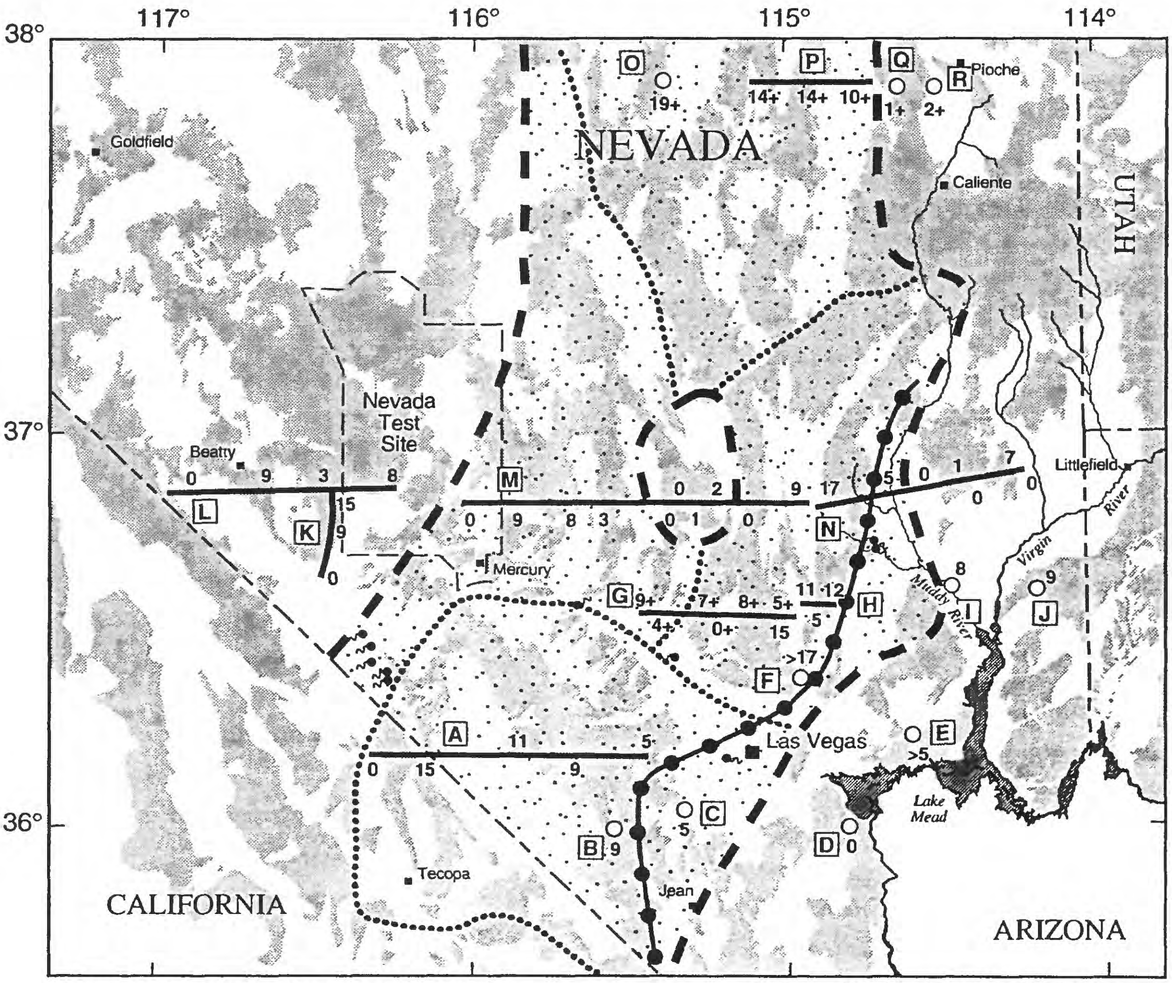
The few locations and estimates of the total thickness of Paleozoic rocks available in southern Nevada are shown in figure 32 and table 12. The numbered areas on figure 31 are each influenced by an overall structural style (for example, unextended contrasting to highly extended) or a controlling structure (for example, extension along a particular fault system). The thickness in one area is not structurally related to the thickness in any other area. Because of this relative independence among areas, and because thickness estimates are available only in a few locations, estimates of thicknesses of carbonate rock within the central corridor can usefully be combined into generalized estimates of thickness for each area. These generalized estimates (quantitative and qualitative) indicate that the carbonate rocks within the White River flow system (areas 3 and 4, fig. 31) are thickest, and those in areas



EXPLANATION

- Basin fill
- Consolidated rock
- Central corridor of carbonate-rock aquifer in Nevada — Area is underlain by thick sequences of carbonate rock; outside corridor, carbonate rock is thin, or present as isolated bodies
- Western limit of ground water generally too mineralized for most uses
- Shear zone or high-angle fault
- High- to low-angle normal fault
- Outer margin of volcanic complex
- (1) Geologic structure listed in table 11
- [4] Storage-estimate area listed in table 13
- Spring or closely spaced springs

Figure 31. Storage-estimate areas and geologic structural boundaries within central corridor of carbonate rock in study area.



Base from U.S. Geological Survey digital data, 1:100,000, 1985
Universal Transverse Mercator projection
Zone 11

Geology modified from Plume and Carlton (1988), Stewart and Carlson (1978), and Wilson and Moore (1959). Geology in lower left and lower right corners of map area not shown

0 20 40 60 MILES

0 20 40 60 KILOMETERS

EXPLANATION

Basin fill

Consolidated rock

Central corridor of carbonate-rock aquifer in Nevada — Area is underlain by thick sequences of carbonate rock; outside corridor, carbonate rock is thin, or present as isolated bodies

Western limit of ground water generally too mineralized for most uses

Boundary of storage-estimate area shown in figure 31

G 7+ 8+ 0+ **Thickness estimates from alignment of geologic sections** — Number is saturated thickness, in thousands of feet. Letter refers to table 12

O R 2+ **Site of thickness measurement or estimate** — Number is saturated thickness, in thousands of feet. Letter refers to table 12

Spring or closely spaced springs

Figure 32. Estimated present-day saturated thickness of Paleozoic rock in study area.

Table 11. Description of structures used to define boundaries of storage-estimate areas

Structure number (fig. 31)	Name	Description	Reference
1	Sheephead fault zone and Kingston Range detachment	Shear zone separating denuded areas to south from thick Paleozoic sections in Nopah Range and Pahrump Valley	Stewart, 1983, figs. 1, 2; Jennings and others, 1962; Jennings, 1961
2	Detachment at Resting Spring Range	Zone of extreme surficial extension and thinning (separating thick Paleozoic sections to east from thinned and missing Paleozoic sections to west)	Stewart, 1983, p. 154; Wright and others, 1981
3	Las Vegas Valley shear zone	Shear zone separating areas of extreme extension to north from much-less extended Spring Mountains to south	Guth, 1981, p. 769
4	Sheep Range detachments	Major faults within and along west side of Sheep Range that juxtapose noncarbonate rocks within the range against carbonate rocks to west	Guth and others, 1988; Guth, Petmar Trilobite Breeding Ranch, written commun., 1988
5	Detachment(s) beneath Tikaboo and Penoyer Valleys	Boundary between extensional thinning beneath Tikaboo and Penoyer Valleys and less extended terrains farther east beneath Pahranagat and Garden Valleys	Jayko, 1988; Martin and Bartley, 1989
6	Pahranagat shear zone	Shear zone separating areas that experienced major extension at different times	Axen and others, 1987; Wernicke and others, 1984, p. 48
7	Kane Springs volcanic center	Volcanic center that interferes with present-day ground-water flow in much the same way as a small caldera complex	Ekren and others, 1977

Table 12. Estimated total and saturated thickness of Paleozoic rocks

[Letters A through R refer to locations indicated in figure 32. Symbol: ±, more approximate than most; <, less than; >, greater than. All numbers are estimates. Numbers followed by + are thicknesses or depths to bottom of uppermost thrust sheet; underlying thrust sheets may exist and contain additional Paleozoic carbonate rocks at much greater depths]

Area (and reference)	Thickness of Paleozoic section (feet)	Depth to top of carbonate rocks (feet)	Depth to water (feet)	Approximate saturated thickness of Paleozoic rocks (feet, rounded)
A. Resting Spring - Blue Diamond alignment (Wright and others, 1981; Harrill, 1986, p. 17)				
Resting Spring Range	0	--	--	0
Nopah Range	16,000	0	>1,000	15,000
Pahrump Valley	11,000	4,000	<1,000	11,000
Spring Mountains	11,000	0	500-3,000	9,000
Blue Diamond	5,000	0	200	5,000
B. Spring Mountains aeromagnetic anomaly (Blank, 1988)	10,000	0	500-2,000	9,000
C. Karmarden oil well (Garside and others, 1977, p. 6)	5,000	0	500	5,000
D. River Range (Smith and others, 1987, p. 2)	0	--	--	0
E. Bowl of Fire oil well (Schilling and Garside, 1968, p. 8)	>5,000	1,000	800	>5,000
F. Arrow Canyon oil well (unpublished records from Nevada Bureau of Mines and Geology)	>17,000	1,000-2,000 ±	700±	>17,000
G. Desert - Las Vegas alignment (Guth, 1980, pl. 2)				
Desert Range	10,000 +	0	1,100	9,000 +
Black Hills	5,000 +	0	1,500	4,000 +
Hoodoo Hills	11,000 +	0	4,000	7,000 +
East of Hoodoo Hills	3,000 +	0	4,000	0 +
Sheep Range	12,000 +	0	>4,000	8,000 +
North of Yucca Forest	8,500 +	0	3,500	5,000 +
Las Vegas Range	16,000	0	0-2,000	15,000

Table 12. Estimated total and saturated thickness of Paleozoic rocks—Continued

Area (and reference)	Thickness of Paleozoic section (feet)	Depth to top of carbonate rocks (feet)	Depth to water (feet)	Approximate saturated thickness of Paleozoic rocks (feet, rounded)
H. Las Vegas - Meadow Valley alignment (Dwight Schmidt, written commun., 1985)				
East Las Vegas Range	12,000	0	1,400	11,000
Arrow Canyon Range	7,000	0	2,300	5,000
South Meadow Valley Range	>13,000	0	800	12,000
I. Virgin River USA No. 1-A oil well (unpublished records from Nevada Bureau of Mines and Geology)	8,000	11,000	11,000	8,000
J. Basement outcrops in Virgin Mountains (Longwell and others, 1965, pl. 1)	0	--	--	0
K. Yucca - Lathrop Wells alignment (Robinson, 1985, fig. 9)				
Yucca Mountain	15,000.±	7,000	2,500	15,000 ±
Fortymile Wash	9,000.±	3,000	400	9,000 ±
Lathrop Wells	0	--	?	0
L. Bull Frog - Calico alignment (Scott and Whitney, 1987; R.B. Scott, U.S. Geological Survey, written commun., 1988)				
Bull Frog Hills	0	--	--	0
Bare Mountain	11,000	0	1,800	9,000
Crater Flat	3,000	11,000	1,000 ±	3,000
Calico Hills	10,000	0	1,600	8,000
M. Frenchman - Las Vegas alignment (Guth, 1989, fig. 4-2)				
Frenchman Flat	0	--	--	0
Spotted Range	12,000	0	2,600	9,000
Indian Springs Valley	8,000	2,000±	<2,000	8,000
Pintwater Range	5,000	0	2,000	3,000
Three Lakes Valley	0	--	--	0
North Desert Range	0	--	--	0
East Desert Range	4,00	0	2,500	1,500
Mule Deer Range	4,00	0	2,000	2,000
North Sheep Range	3,000	0	3,500	0
North Las Vegas Range	9,000	800	600	9,000
N. Meadow Valley - Mormon alignment (Axen and Wernicke, 1989, fig. 2-2)				
Meadow Valley Mountains	8,000 ±	0	1,000	17,000
Lower Meadow Valley	5,00	>2,000	200	5,000
Western Edge, Mormon Mountains	0	0	--	0
Western Mormon Mountains	4,000	0	3,000	1,000
Central Mormon Mountains	1,000	0	>1,000	0
Eastern Mormon Mountains	8,000	0	1,500 ±	7,000
East Mormon Mountains	0	0	--	0
O. Golden Gate Range (Tschanz and Pampeyan, 1970, p. 38-39, 95; Bartley and others, 1987)	20,000 +	0	1,250	19,000 +
P. Seaman - Drylake alignment (G.J. Axen, Harvard University, oral commun., 1988; Tschanz and Pampeyan, 1970, p. 38-39, 95)				
Seaman Range	15,000 +	0	1,400	14,000 +
North Pahroc Range	15,000 +	0	>1,000	14,000 +
Dry Lake Valley	10,000 +	5,000-10,000	<1,000	10,000 +
Q. Ely Springs Range (G.J. Axen, Harvard University, oral commun., 1988)	1,000 +	0-2,000	0-50	1,000 +
R. Meadow Valley (G.J. Axen, Harvard University, oral commun., 1988)	2,000 +	0-2,000	0-300	2,000 +

west of the Sheep and Pahranagat Ranges (area 2, fig. 31) are thinnest. The carbonate rocks beneath the Spring Mountains and Pahrump Valley (area 1, fig. 31) are of intermediate thickness.

Regardless of the structural differences between the areas designated in figure 31within the central corridor, the areas probably are not distinct hydrologic units; that is, flow and water levels in aquifers in one area cannot be assumed to be independent from conditions in adjoining areas. The major extensional structures in the corridor can only locally be shown to restrict flow (Dettinger, 1987, 1988). These barriers commonly can only be shown to restrict shallow flow (less than about 5,000 ft). Deeper flow, in principle, could pass beneath these barriers at greater depths. The Las Vegas Valley and Pahranagat Valley shear zones (fig. 31, table 11)—to the extent that they are barriers to flow—may extend deep enough to restrict both deep and shallow flows (Gary Axen, Harvard University, oral commun., 1987). Most of the structures that form the outer edges of the corridor (for example, the Sheephead fault and Kingston Range detachment) also are assumed to be barriers to both deep and shallow flow.

Outside the corridor, saturated thicknesses are generally less than within the corridor but are variable. For example, along the line through the Mormon Mountains water-saturated thickness estimates vary—5,000; 0; 1,000; 0; 7,000; and 0 ft—along a west-to-east distance of 20 mi.

The storage calculations that follow assume the entire thickness of carbonate rock beneath the central corridor constitutes carbonate-rock aquifers. Oil wells provide evidence that these rocks include permeable zones and function as aquifers to depths of at least 10,000 ft (Hess and Mifflin, 1978, p. 19). In southern Nevada, drill-stem tests in the Colorock Quarry No. 1 (T. 18 S., R. 65 E., section 22dcd) and Virgin River USA No. 1 (T. 15 S., R. 68 E., section 09cd) oil test wells are notable for having recovered thousands of feet of fluid during drill-stem tests at depths 10,000 ft and greater. These kinds of test results, together with freshwater recoveries in some deep oil-test wells, indicate that where carbonate rocks are 10,000 ft or more thick, they can constitute aquifers throughout any part or all of that thickness.

Total Volume of Aquifers and Stored Water

The total area of the central corridor of carbonate rocks south of 38°N. latitude is about 10,000 mi^2. The corridor is divided into four areas in figure 31, and estimates of their areas and representative thicknesses are listed in table 13. Together these estimates imply the volume of carbonate-rock aquifers in southern Nevada may be more than 70 billion acre-ft (as much as 23,000 mi^3 of rock).

If this estimate of the volume of the aquifers is correct, and if the quantity of storage in a given volume is equal to the specific yield or about 0.01, then about 800 million acre-ft of water are stored in the carbonate-rock sequences of southern Nevada. The largest volume of stored water is in the storage-estimate area centered on Pahranagat Valley (area 4, fig. 31; table 13).

Practical Limits on Stored-Water Resources

Not all of this large volume of water is extractable for use under any practical development strategy. Practical issues that might limit development of the stored water in the carbonate-rock aquifers include pumping lifts, water quality, economic constraints, and adverse effects.

Constraints resulting from well and pump performance are probably not the limiting aspect of developing the stored-water resource in the carbonate-rock aquifers. Pumps can be designed to lift water from depths of greater than 1,000 ft (Driscoll, 1986, p. 602). The principal constraints on achieving such pumping lifts and rates are well construction and aquifer properties. For instance, well diameter must be large enough to accept the pump. For example, a 16-in. casing diameter is required to contain a pump that can efficiently pump 2,000 gal/min from such depths (Driscoll, 1986, table 13.1). The aquifer also must be sufficiently permeable and thick to allow a given pump rate to be sustained (for both short and long times) without having water levels in the well drop below the intakes on the pump.

Other than in the zone of poor-quality water shown in figure 24, water quality also should not limit the resource severely. Most water recharging the aquifers rapidly becomes chemically saturated with respect to calcite and dolomite in the carbonate rocks of the recharge areas. Whole-rock chemical analyses of the carbonate rocks show that they contain only trace amounts of minerals other than calcite and dolomite (Thomas and Welch, in press). As a result, once equilibria with respect to those dominant minerals are attained, constituent concentrations do not significantly increase as water circulates through the aquifers.

Table 13. Estimated areas and representative thicknesses of saturated carbonate rocks in central corridor, and calculated total volume of stored ground water

[Symbols: +, thickness or depth is estimated to bottom of uppermost thrust sheet; underlying thrust sheets may exist and contain additional Paleozoic carbonate rocks at much greater depths; >, greater than; --, not applicable]

Area No. (fig. 31)	Area (thousands of acres)	Range of reported thickness (thousands of feet)	Assumed representative thickness (thousands of feet)	Estimated specific yield (dimensionless)	Calculated volume of water stored (millions of acre-feet)
1	1,700	5 - 15	10	0.01	170
2	1,800	3 - 9+	8	.01	140
3	1,200	5 - >17	15	.01	180
4	1,800	10+ - 19+	15	.01	270
AVERAGE	--	--	12	0.01	--
TOTAL	6,500	3 - 19+	--	--	760

Perhaps the principal water-quality constraint on how deep water can be taken from and used is the increase in temperature of water in rocks with increasing depth. Temperature of the water in the southern carbonate-rock province increases by about 10°F for every 1,000 ft of depth (Kron and Heiken, 1980). This means that water from rocks 10,000 ft below land surface would be about 150°F (assuming that water near land surface is about 50°F), which could limit some uses of the water.

Removing water from storage lowers water pressure or water levels within aquifers. The possible effects of developing the carbonate-rock aquifers will be discussed later in this report, but to estimate the practical limits of how much water might be withdrawn from storage in the carbonate-rock aquifers, it is instructive to consider water-level declines that have been induced by regional development in other large aquifers. Declines in selected aquifers are summarized in table 14. Average declines greater than 50 ft are not common in the larger aquifers. However, even 50-ft declines generally are viewed as excessive when prevalent over large areas. In order to develop such extensive declines, large drawdowns are induced in the vicinity of the pumping centers. In Nevada, some of the most severe declines are in the basin-fill aquifers of Las Vegas, Diamond Valley (in east-central Nevada), and Paradise Valley (in west-central Nevada) where local declines as large as 50 to 240 ft have been observed together with broader scale declines of as much as 30 ft over tens to hundreds of square miles.

A More Practical Estimate of Stored-Water Resources

From a regional and historical perspective, therefore, water-level declines greater than 100 ft over large areas are unlikely to be tolerated. Table 15 presents the estimated volumes of water stored in the upper 100 ft of carbonate-rock aquifer for the four areas shown in figure 31. As noted above, water-level declines in and near well fields developed to withdraw this volume of water from the aquifers would be many times greater than 100 ft. Dewatering on this scale would alter ground-water flow paths to deplete springflow and subsurface outflow from Nevada. Dewatering also would change flow directions and rates between the carbonate-rock aquifers and adjacent aquifers of other rock types.

The estimated total volume of water of quality acceptable for most uses present in the top 100 ft of carbonate-rock aquifers in the central corridor south of 38°N latitude is about 6 million acre-ft (table 15). This volume of water is about one-quarter of the average volume of water stored in Lake Mead. If this volume of water were withdrawn suddenly from the carbonate-rock aquifers, about 100 years would be required to refill the aquifers to present levels (assuming the recharge rate discussed in a previous section).

Comparison of Carbonate-Rock and Basin-Fill Storage

The estimated 6 million acre-ft of water stored in the top 100 ft of carbonate-rock aquifers in the central corridor south of 38°N latitude is about one-sixth of the volume of water stored in the upper 100 ft of the over-

Table 14. Water-level declines in areas of major municipal and agricultural development

Aquifer name and location	Aquifer type	Reported large-scale average decline (feet)	Estimated area of decline (square miles)	Maximum decline (feet)	Sources of data
Central Valley Alluvial Aquifer System (Central Valley, California)	Alluvial sediments	10	12,000-15,000	400	Williamson and others, 1985
Northern Midwest Regional Aquifer System (Chicago, Illinois area)	Sandstone	100	7,000	800	Young and others, 1986
Floridian Regional Aquifer System (Southeast Georgia and northeast Florida, Fort Walton Beach and Tampa, Florida areas)	Carbonate rock	10	15,000	30	Bush and Johnston, 1986
Ogallala Formation (Texas, Kansas, Nebraska, Colorado, Oklahoma, and New Mexico)	Alluvial sediments	10	50,000	200	Weeks, 1986
Southwest Basin and Range Alluvial Aquifers (Area between Phoenix and Tucson, Arizona)	Basin-fill sediments	50	8,000	400	Anderson, 1986
Chicot and Evageline Aquifers (Houston, Texas area)	Alluvial sediments	50	5,000	400	Meyer and Carr, 1979
Las Vegas Valley (Las Vegas, Nevada)	Basin-fill sediments	20	300	240	Harrill, 1976
Diamond Valley (Diamond Valley, Nevada)	Basin-fill sediments	30	50	50	James R. Harrill, oral commun., 1988
Paradise Valley (Paradise Valley, Nevada)	Basin-fill sediments	10	40	80	Prudic and Herman, in press

lying saturated basin-fill aquifers (about 39 million acre-ft [Scott and others, 1971, table 1]). This large quantity of water stored in basin-fill aquifers (relative to the carbonate-rock aquifers) relates directly to the large specific yield of unconsolidated sand and gravel (10 times that of fractured carbonate rocks). The disparity between the volumes of water stored in basin-fill aquifers and carbonate-rock aquifers can be viewed as a final practical limit on development of the stored water in the carbonate-rock aquifers. The basin-fill aquifers are much more accessible and familiar as water supplies and developing a one-time resource from an unfamiliar type of aquifer may seem impractical. However, withdrawing water stored in the carbonate-rock aquifers has some possible advantages over

Table 15. Estimated volume of water stored in upper 100 feet of saturated carbonate rocks in central corridor

Area No. (fig. 31)	Area (thousands of acres)	Estimated specific yield (dimensionless)	Calculated volume of water stored (millions of acre-feet)
1	1,700	0.01	1.7
2	1,800	.01	1.8
3	1,200	.01	1.2
4	1,800	.01	1.8
TOTAL	6,500		6.5

that stored in basin-fill aquifers, including: (1) Water is stored beneath large areas in which flow is well integrated. As a consequence, effects of the withdrawals would be dispersed over larger areas. Dispersal of effects is a disadvantage if the effects remain large everywhere but is an advantage if the effect at any given location is small. (2) Some areas in the carbonate-rock aquifers may prove to be sufficiently isolated from other aquifers so that effects of storage depletion could be contained far from other water wells, springs, or aquifers. Basin-fill aquifers have been more widely developed and storage depletions from basin-fill aquifers accessible for development are more likely to be near and to affect other water wells or springs. (3) The water stored in the carbonate-rock aquifers is water that generally has not been accounted for in previous budgets (unlike basin fill). (4) Extracting water from the carbonate rocks in certain areas might actually allow water from inaccessible basin-fill reservoirs (such as beneath lands withdrawn from public use) to be extracted. Under these conditions, in addition to producing water from storage, the carbonate-rock aquifers would function as a collector of basin-fill water and a conduit conducting flow from inaccessible areas to the carbonate-well fields.

WHAT EFFECTS MIGHT FOLLOW DEVELOPMENT OF THE CARBONATE-ROCK AQUIFERS?

Two broad areas of concern regarding the potential for effects from developing the carbonate-rock aquifers are adverse effects within the carbonate-rock aquifers and adverse effects on adjacent basin-fill aquifers presently used for water supply. Effects resulting from withdrawing water from the carbonate-rock aquifers might include reduction of springflow from carbonate-rock and basin-fill aquifers; water-level declines in wells in all types of aquifers; drying up of some streams, playas, and meadows; and changes in water chemistry. These effects are direct or indirect responses to water-level changes associated with aquifer development, and are related to disturbances of the natural equilibrium between aquifer recharge and discharge. These changes in turn can affect the water rights of current users, affect wildlife habitat, and cause increased pumping lifts. The extent and severity of effects are dependent on the local and regional hydrogeologic setting.

Many of the potential effects from development of the carbonate-rock aquifers can be simulated providing sufficient hydrogeologic data are available. These data include transmissivities, storage coefficients, vertical hydraulic conductivities and thicknesses of various aquifers, distances between points of interest, and times involved. On the basis of the above information one can calculate the spread of water-level declines induced in different aquifers by pumped wells. The data taken together can be used to calculate the extent and magnitude of declines surrounding an area of development, using simple mathematical equations, using complex numerical models of ground-water flow, or by analogy to historical experiences with other aquifer developments in the area. These calculations can be used to assess the acceptability of effects over the time period of interest.

Of particular concern when evaluating effects associated with development of the carbonate-rock aquifers (in contrast to basin-fill aquifers), is the probability that effects may be asymmetrical around pumped wells. Conditions within the carbonate-rock aquifers may favor flow in "preferred" directions along such localized pathways as fracture zones. For example, distributions of water-level declines may be elongated in a direction parallel to major fracture traces (Jenkins and Prentice, 1982, p. 15). The extent of declines depends on local hydrogeologic conditions but would be spread greatly along paths of high transmissivity.

In this section, the potential for simulating effects within the carbonate-rock aquifers will be addressed through hydraulic calculations and by a review of existing numerical models of flow in the study area. The potential for effects in adjacent basin-fill aquifers will be addressed through a review of the lessons derived from historical experiences of development. Considerable uncertainties are inherent in resulting calculations and conclusions; thus, a strategy for safeguarding against severe effects is described also.

Potential for Effects Within the Carbonate-Rock Aquifers

The primary effects anticipated from development of the carbonate-rock aquifers are water-level declines within the aquifers. These declines, in turn, may induce decreases in springflow and other natural discharge when they become significant in areas of natural discharge. Sustained effects within the carbonate-rock aquifers resulting from development of wells in the same aquifers have not been observed to date, but this reflects lack of development of the aquifers rather than a lack of potential for effects if development were undertaken. The hydraulic properties together with the geometry of a carbonate-rock aquifer will determine the distribution of water-level declines around pumped wells.

Influence and Range of Aquifer Properties

Under idealized conditions, water-level declines around a pumped well would be distributed as a "cone of depression," with a shape (depth and areal extent) determined by the capacity of the aquifer to transmit and store water (properties described by the transmissivity and specific yield, respectively). The cones of depression around production wells in parts of the aquifers with high transmissivities will be broader in extent but generally shallower than cones around production wells in aquifers with moderate transmissivities. Water-level declines or drawdowns around production wells in aquifers with low transmissivities will be large near the well but the large drawdowns will be restricted to areas close to the well. The extent to which an aquifer is confined or unconfined also will effect the drawdown around a production well. Confined parts of aquifers will be drawn down more and the drawdown will occur more quickly than parts of the aquifer that are unconfined.

Water-bearing properties of the carbonate-rock aquifers are uncertain and vary from place to place. In order to calculate the general range of drawdowns that might be induced around a well (or well field) that is developed in the carbonate-rock aquifers, a 'general' range of variability must be hypothesized or assumed. The best available estimate of this variability is from actual observations, and table 1 shows the available estimates of pertinent aquifer properties from tests in water wells in carbonate-rock aquifers (39 estimates of hydraulic conductivity and 4 estimates of storage coefficients). The estimates of hydraulic conductivity (fig. 5) are lognormally distributed (at a 99-percent confidence level using a Shapiro-Wilk test [Ryan and others, 1982, p. 48-49]), with a median value of 4.3 ft/d and a coefficient of variation (the standard deviation divided by the mean) of 2.6. (By definition [Benjamin and Cornell, 1970, p. 262-264], the logarithm of a lognormally distributed variable is statistically distributed according to a normal distribution—the familiar bell curve.) The relative frequency with which hydraulic conductivities of different values have been measured in the carbonate-rock aquifers (listed in table 1) are hypothesized to approximate the likelihood that a well in an untested location will penetrate aquifers with similar hydraulic conductivities. This hypothesis implies likelihoods of inducing a particular levels of drawdown by pumping at an untested location. For example, the odds of drilling a new well with a specific capacity of at least 5 (gal/min)/ft of drawdown are about 5 out of 10, whereas the odds of drilling a new well with a specific capacity of at least 25 (gal/min)/ft of drawdown are about 2 out of 10.

Only four hydraulic determinations of storage coefficient are available. As discussed in an earlier section, the storage coefficient or specific yield of the carbonate rock aquifers is estimated to range from about 0.01 to 0.10. Storage coefficient of the confine parts of the aquifers is probably on the order of 0.0001 or 0.01 (for example, at well UE25p#1 on the Nevada Test Site, storage coefficient is 0.03). The specific yield of unconfined parts of the aquifers is probably, at least, on the order of 0.1 (for example, at well CE-DT-5, storage coefficient is 0.14). Current (1989) understanding of the distribution of confined as opposed to unconfined parts of the aquifers or the change from confined to unconfined conditions as a result of pumping is limited. Thus, a statistical description of storage coefficient is not presented.

Predictions of Potential for Drawdowns on the Basis of Measured Aquifer Properties

Where aquifer properties are known, water-level drawdowns caused by pumping can be projected roughly using hydraulic analyses of Theis (1935). This method assumes temporal and spatial invariance of aquifer properties, strictly horizontal flow, and no lateral barriers (an infinitely extensive aquifer; Bear, 1979, p. 318-319). These assumptions at best are only approximately applicable to the carbonate-rock aquifers, and thus the assumptions represent limitations of varying severity on the projections presented herein.

The assumption of spatial invariance (homogeneity and, in simplest form, isotropy) is probably poorly met in the carbonate-rock aquifers. Transmissivity of these aquifers is predominantly associated with flow through fractures that are neither uniformly distributed nor uniformly oriented. Thus transmissivity (or hydraulic conductivity, to be more precise) varies from point to point and also varies depending on the direction of flow. Point-to-point variations in transmissivity are assumed small when averaged over relatively large areas. The validity of this assumption is difficult to assess with available information, but the assumption itself has precedent (for example, Harrill and others, 1983, p. 26). Possible effects of fracture orientations on transmissivity and drawdowns probably cannot be so easily neglected. Simple drawdown projections based on the Theis equation include the assumption that drawdowns will be identically distributed in all directions around the pumped well. If flow is preferentially conducted over long distances through a set of fractures of a single orientation, then the calculations will underestimate the drawdown at points along those fracture sets and will overestimate the drawdown at points along lines from the well not parallel to the fractures (Boehmer and Boonstra, 1987, fig. 3). This limitation is potentially severe and should be considered before applying results of simple calculations based on the Theis equation to a real-world situation.

The analyses by Theis were derived for confined-aquifer conditions so that time-invariant transmissivities and storage coefficients could be assumed. In some parts of southern Nevada, the carbonate-rock aquifers are confined under natural conditions (for example, at Well UE25p#1 on the Nevada Test Site). Other areas are not confined (for example, at MX well CE-DT-5), and some confined aquifers could become unconfined if development and drawdowns were extensive. The Theis analysis can however be applied under unconfined conditions provided the projections are (1) for times sufficiently long after pumping began so that water is all derived from drainage of open spaces, (2) for parts of the aquifer far enough from the pumped well so that flow is virtually horizontal, and (3) for aquifers with saturated thicknesses that are large compared to the amount of drawdown projected (Freeze and Cherry, 1979, p. 324-327).

Finally, Theis analyses assume that aquifer boundaries are far enough from the pumped well so that water-level declines at the boundaries never become significant during the period over which calculations are being made. Figure 33 compares these idealized aquifer geometries to those of block-faulted aquifers in the carbonate-rock province. The idealized aquifers of Theis analyses (fig. 33*A*) are assumed to be separated by an impermeable layer (if the separating layer is not completely impermeable, analytical methods developed by Hantush, 1956, can be substituted). The idealized aquifer also is infinite in lateral extent. Block-faulted aquifers, however, may be sufficiently deformed so that parts of the carbonate rocks and basin fill may be laterally isolated by juxtapositions of permeable and impermeable material along fault zones. These faults (which formed the Basin and Range topography) create partially isolated blocks within regional flow systems. These blocks commonly may be smaller than the calculated area of influence of the pumped well. Thus, the assumption of an infinite aquifer may not be satisfied in many areas of the carbonate-rock province. Because this condition is not satisfied, the Theis solution may over- or underestimate drawdowns. If the faults or offsets form barriers to flow, over long periods of time the Theis equation will underestimate drawdowns within the pumped block and overestimate drawdowns at larger distances. If the faults act as conduits for flow, water levels in other blocks somewhat removed from the developed block may be drawn down because of their connection to the conduits, and drawdowns will be less localized. Wells either within the pumped block or in adjacent and connected fault-conduits will experience concentrated drawdowns by pumping. Because the fault-conduits can extend for many miles and might conduct flow that supports springs, this potential for error is a major shortcoming of analyses made using the Theis equation. As with assumptions of spatial invariability of aquifer properties, site specific evaluations of this potential error are needed.

Regardless of the limitations outlined in the preceding paragraphs, the Theis equation can be used to develop generalized information about the magnitudes of drawdowns that might be expected around a production well in the carbonate-rock aquifers. Calculating drawdowns using Theis's equation requires that the time since pumping began and distance from the pumped well be specified and that a transmissivity and storage coefficient be estimated for the aquifer. For purposes of developing an example calculation of drawdowns resulting from small, long-term developments of the regional aquifers, drawdowns around a production well in a large, continuous and hydraulically uniform part of the carbonate-rock aquifers will be projected. The aquifer tapped is assumed to have a hydraulic conductivity of 0.35, 4.5, and 57 ft/d. These values represent the hydraulic conductivity that is less than all but one-sixth of the tests in carbonate-rock aquifers in table 1, the median hydraulic conductivity, and the conductivity greater than all but one-sixth of the tests. The perforated interval of the well and thickness of the aquifer penetrated both are assumed to be 2,000 ft. Storage coefficient is assumed to be 0.0001 for confined conditions and 0.01 for unconfined conditions. Table 16 shows the drawdowns projected at 1 and 10 mi from the pumped well after 1 and 10 years of pumping 1,000 gal/min (1,614 acre-ft/yr). All projections are based on the Theis equation for drawdown described in Bear (1979, p. 318-319).

These simple calculations show that water-level declines associated with a pumped well in the carbonate-rock aquifers may be moderate to small in most locations where the aquifer is unconfined (water table as opposed to confined or artesian) and would be much larger where the aquifer is confined. The projected water-level declines in extensive, unconfined carbonate-rock aquifers would commonly be between about 1 and 22 ft at a distance of 1 mi from a production well after 1 year of pumping. The drawdown at that distance in a part of the aquifer with the median hydraulic conductivity would be about 6 ft after 1 year. Those drawdowns would increase to range between 1 and 70 ft after 10 years. At a distance of 10 mi from the pumped well, drawdowns after 10 years are calculated to range between a fraction and several feet. If, instead, the

Table 16. Calculated drawdowns after 1 and 10 years of pumping at 1,000 gallons per minute from a fully penetrating well in a 2,000-foot-thick aquifer for selected hydraulic conductivities and storativities

Distance from pumped well (miles)	Drawdown after 1 year, in feet, for the following hydraulic conductivities, in feet per day			Drawdown after 10 years, in feet, for the following hydraulic conductivities, in feet per day		
	0.35	4.5	57	0.35	4.5	57
CONFINED (STORAGE COEFFICIENT=0.0001)						
1	120	13	1.4	170	17	1.7
5	48	7.9	1.0	97	12	1.3
10	21	5.6	.8	67	9.5	1.1
UNCONFINED (STORAGE COEFFICIENT=0.01)						
1	21	5.6	0.8	67	9.5	1.1
5	.0	.9	.4	8.5	4.1	.7
10	.0	.1	.2	.4	2	.5

developed aquifer is confined, then calculated water-level declines after 10 years range between 1 ft and about 170 ft at 1 mi from the pumped well and between 1 and 70 ft at 10 mi. The small area projected as experiencing 10 ft or more of drawdown in unconfined parts of the aquifers—less than a 1-mi radius for aquifers with the median conductivity and less than a 5-mi radius for aquifers for the less-permeable aquifers—implies that in many settings the effects of development of the carbonate-rock aquifers might be manageable. In confined parts of the aquifers, the projected drawdowns are substantially larger and might cause unacceptable effects.

Influence of Aquifer Geometry

Water-level declines or drawdowns resulting from development of a part of the carbonate-rock aquifers will be influenced by the geometry of the aquifer and by hydraulic properties. The present study has shown that the carbonate-rock aquifers are not a single massive, continuous layer beneath southern Nevada but rather have been broken into corridors and isolated blocks. The generalized hydrogeologic sections shown in figure 21 illustrate the irregular external boundaries of the carbonate aquifers. Development in a block or part of the corridor isolated from other carbonate-rock aquifers by impermeable barriers will not induce drawdowns in those other aquifers (or if the isolation is only partial, may induce much smaller effects). Within the developed block, however, drawdowns may be much greater than those expected if the barriers were not present. The influence of aquifer geometries is expected to be large, site-specific, and most important over large distances and long times. Bear (1979, section 8-10) describes techniques that can be used to simulate the effects of barriers when using simple analytical models such as the Theis equation. Use of these techniques where the geology is understood well enough to delineate barriers would significantly improve projections of drawdown.

Modeling Flow in Complex Geometries

Accurate prediction of drawdown in the carbonate-rock aquifers will require techniques that take full account of variations in hydraulic properties of the aquifers, aquifer geometry, and vertical components of flow. Numerical models are the tools most capable of taking of these factors into account. However, a great deal of detailed factual information is required to calibrate these models and, currently (1989), this type of information is lacking over most of eastern and southern Nevada. Until additional detailed hydrogeologic information is obtained, results of model simulations are probably only slightly better than results based on careful evaluation of the simple analytical calculations described in the previous paragraphs. However, some models developed for other uses are available and can provide insights into the complexities of projecting effects within the carbonate-rock aquifers. The following paragraphs briefly describe two such models.

Bedinger and others (1989) simulated flow paths and travel times along several profiles beneath the Death Valley region of Nevada and California. The profiles included flow through basin-fill, volcanic-rock, and carbonate-rock aquifers, and addressed the influence of probable geologic deformations on aquifer geometry. Flow paths were affected by changes in hydraulic conductivity between aquifer types and hydraulic barriers formed by impermeable rocks and geologic structures. Results indicate that ground water will preferentially flow in the upper parts (about the upper 3,000 to 4,000 ft) of the aquifers and that flow paths become convoluted in areas containing major structures or abrupt changes in rock type. No simulations of the effects of development in the carbonate-rock aquifers were undertaken with these profile models.

Prudic and others (1993) constructed a regional-scale model of the carbonate-rock aquifers within virtually the entire carbonate-rock province of the Great Basin shown in figure 1. The model includes both basin-fill and carbonate-rock aquifers, and simulates flow in two layers that are intended to represent shallow and deep ground-water flow systems, respectively. Simulated flow patterns in the upper layer can be divided into 17 largely independent flow systems that closely match flow systems delineated in previous basin studies. Flow was more integrated at depth. Flow in the bottom layer can be divided into five deep flow systems that drain toward major regional sinks. Flow boundaries in the deeper layer did not coincide with boundaries in the upper layer, which imply that flow-system boundaries are not always vertical. Thus, development in one flow system (as delineated in the shallow aquifers) could have influences on much larger flow systems that are only poorly understood at present (1989). In addition, the success of the regional model in reproducing observed regional conditions imply that its explicit assumption of hydraulic continuity among all aquifers throughout the region is a viable (and conceivably, a necessary) assumption. This, in turn, implies that effects of development are not precluded from spreading over very large distances and between the carbonate-rock aquifers and adjacent basin-fill ground-water reservoirs.

These two modeling studies imply that flow in the aquifers is complex at regional scales. The geologic complexity of southern Nevada is a constraint on development of more detailed models and on accurate predictions of effects of development. Numerous fault-zone orientations, changing aquifer thicknesses, and difficult-to-delineate masses of noncarbonate rock that function as barriers to flow make detailed aquifer descriptions a necessary input to site-specific (or even regional) predictions of development effects. An adequate incorporation of those detailed descriptions into predictions will probably involve use of new, specially constructed models of flow in the study area.

Potential for Effects in Basin-fill Aquifers

Effects in adjacent basin-fill aquifers resulting from development of the carbonate-rock aquifers are another concern. As water levels are drawn down in the carbonate-rock aquifers by withdrawals from those aquifers, leakage may be induced into those aquifers from adjacent aquifers or naturally occurring leakage into the adjacent aquifers from the carbonate-rock aquifers could be reduced. These diversions of water from the adjacent aquifers could result in water-level declines, depletions of springflow and evapotranspiration from those aquifers, and changes in distributions of water quality.

As with effects within the carbonate-rock aquifers, water-level declines in the basin-fill aquifers will be determined by aquifer properties of the two aquifer systems—carbonate-rock and basin-fill aquifers—and by the geometry and properties of any intervening units that restrict hydraulic contact between the aquifers. In the ideal aquifer system shown in figure 33, these factors are described by the aquifer properties of the upper and lower aquifers and the vertical hydraulic conductivity and thickness of the intervening layer of low-permeability material. Methods for hydraulic calculation of effects in an aquifer that overlies a second, stressed aquifer (Hantush, 1956)—similar in style and simplicity to the Theis (1935) equations and based on the ideal aquifer system shown in figure 33—are probably not applicable to the complex geologic setting in southern Nevada at the scales being considered here. However, historical experience with such conditions is available at two areas in southern Nevada that have experienced ground-water development from basin-fill aquifers adjacent to carbonate-rock aquifers: Ash Meadows and Muddy River Springs. Observations in these areas provide information concerning the potential for interaction of aquifers under developed conditions. However, the historical conditions are the reverse of the development being assessed herein (the basin-fill aquifer were developed instead of the carbonate-rock aquifers). One can presume that reversing the pumping conditions (withdrawing water from the carbonate rocks instead of the basin fill) might lead to effects that would be related to—although not a mirror image of—the general distribution and magnitude of the observed effects. Thus, a look at these two areas with different hydrogeologic settings gives some insight into what to expect under similar hydrogeologic conditions elsewhere.

Ash Meadows

The Ash Meadows discharge area (fig. 34) is located in the southeastern and east-central Amargosa Desert. It represents the terminus of the Ash Meadows regional ground-water flow system that encompasses approximately 4,500 mi^2. Water discharges at about

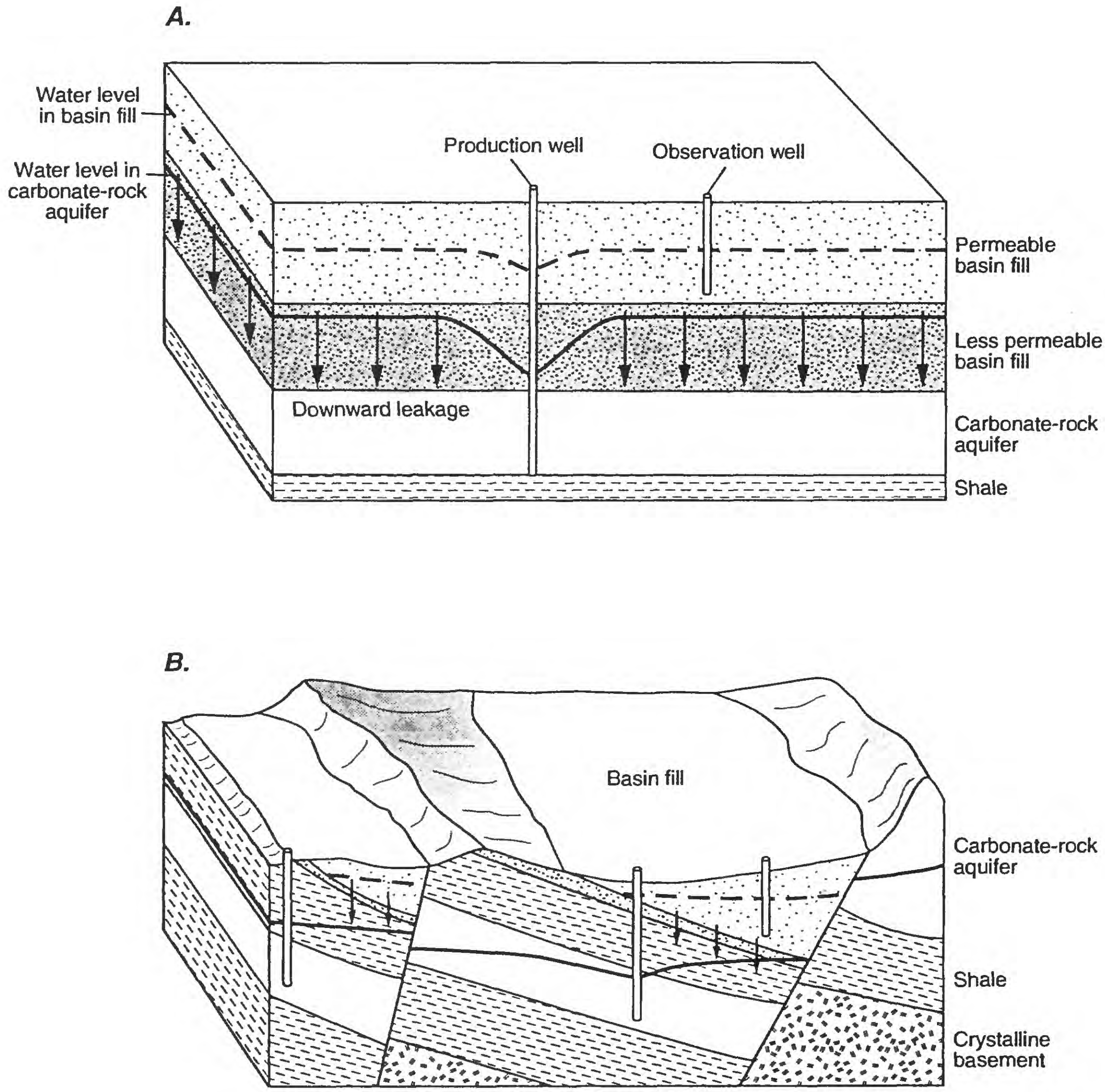


Figure 33. Examples of (A) ideal, laterally infinite aquifers (as assumed by Theis, 1935; Hantush, 1956) and confining units, and (B) block-faulted aquifers and confining units of carbonate rock province.

30 carbonate springs along a generally northwest-southeast line that is about 10 mi long. Discharge totals about 17,000 acre-ft/yr (Winograd and Pearson, 1976). All the major springs emerge from circular pools, are relatively warm, and discharged at a nearly constant rate from 1953 (and possibly from 1910) until agricultural development in the area beginning in 1969. Devils Hole, a collapse depression in the bordering carbonate rock (Carr, 1988b, p. 10), also contains a pool of water. The springs and Devils Hole support several species of *Cyprinodon*, commonly known as desert pupfish, which are unique to the area.

Irrigation using water from the basin-fill aquifers in the area around Devils Hole began in 1969. The subsequent progress of pumping is shown in figure 34. During 1969, approximately 2,100 acre-ft of groundwater were pumped. Pumping increased to in excess of 6,000 acre-ft during 1970. These high pumping levels were maintained during 1971 and declined starting in 1972 (Bateman and others, 1974). In August 1971, a Federal law suit stopped pumping in wells most directly affecting water levels in Devils Hole. A subsequent court order restricted pumping to maintain the water level in Devils Hole at a fixed level.

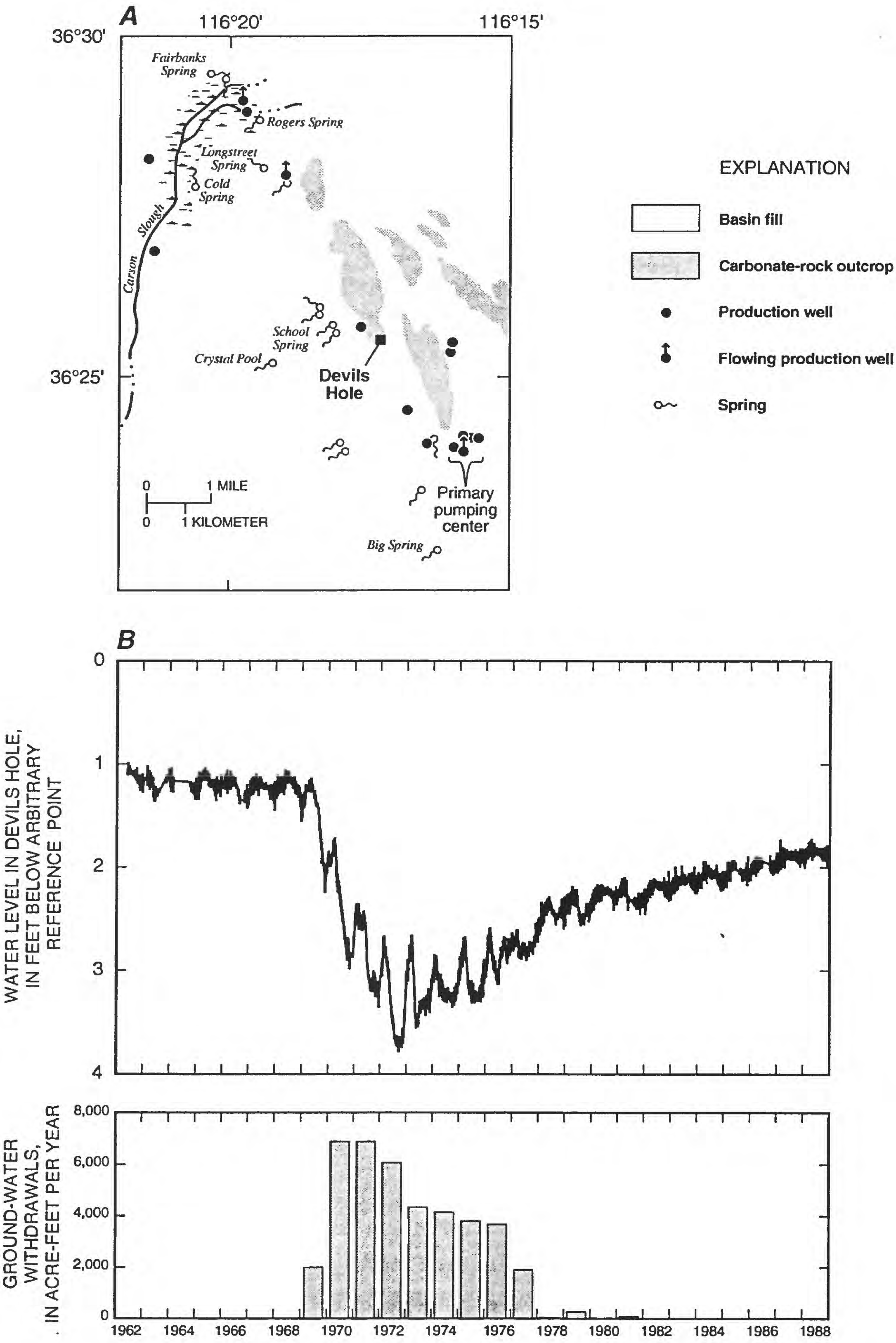


Figure 34. Interaction of basin-fill and carbonate-rock aquifers in Devils Hole (Ash Meadows) area. *(A)* Location of springs, production wells, and Devils Hole (from Larson, 1974a); *(B)* water-level history at Devils Hole, 1963-87, and available estimates of annual pumpage, 1969-75. Pumpage reported by Bateman and others (1974); Dudley and Larson (1976); Larson (1974a, 1974b, 1975); Hanes (1976); Carson (1980); and Westenburg (1993).

The effect of this pumping on hydrologic conditions in the area was extensive and was manifested primarily by water-level declines observed in Devils Hole (fig. 34), the decrease or temporary cessation of flow of several major carbonate springs in the area during pumping, and the gradual recovery of water levels and springflow after some pumping stopped.

In addition, the effect of pumping on individual springs differed indicating that a variable degree of hydraulic connection exists between the basin-fill ground-water reservoir and the carbonate-rock aquifer. The complex network of fractures that connected pumped wells to Devils Hole are distributed such that withdrawals from some wells caused greater declines than similar withdrawals from other wells closer to the Hole. This illustrates potential difficulties in attempting to simulate precise changes in localized areas of the carbonate-rock aquifers. Two modeling efforts have simulated the effects of nearby pumping on the water level in Devils Hole (Bateman and others, 1972; Bateman and others, 1974; and more recently, Rojstaczer, 1987). In general, however, special models of flow through specific faults or other corridors may be required before accurate predictions of small changes in localized areas are feasible. Application of such models requires much detailed and site-specific hydrogeologic data.

Muddy River Springs Area

The Muddy River Springs area is northwest of Glendale, Nev., and is an area of extensive surface- and ground-water development for irrigation, public water supply, and cooling water for power generation. Water has been developed directly from the Muddy River, from the regionally fed Muddy River Springs, and from wells completed in the basin-fill aquifer. Ground water has been withdrawn at varying rates during the last 20 years (Eakin, 1964, p. 24). Monitoring wells are completed in the basin fill and in the underlying and surrounding carbonate-rock aquifers to address concerns that increased ground-water development in the basin fill (as well as new development from nearby carbonate-rock aquifers) will reduce discharge rates from the Muddy River Springs. Locations of these features are shown later in figure 36.

Carbonate-rock aquifers are the main aquifers in the area. In the valleys, carbonate-rock aquifers are overlain by basin-fill deposits consisting of sands and gravels above thick sections of older less-permeable lake-bed deposits in the late Tertiary Muddy Creek and Horse Spring formations. The older basin-fill formations generally are not productive aquifers and probably act as semipermeable layers separating the aquifers of the uppermost basin fill from underlying carbonate-rock aquifers. The younger, productive basin-fill aquifers are localized along the valley floor of the White River drainage. In contrast, the carbonate-rock aquifers extend over large areas and have continuity with several upgradient areas. The basin-fill aquifers are recharged by springflow and seepage from the carbonate-rock aquifers and by secondary recharge from irrigated lands. The general direction of flow is down valley (to the southeast). The depth to water in the valley generally is less than 10 ft. In many parts of Upper Moapa Valley, wells drilled through the basin fill into the underlying carbonate-rock aquifers would flow naturally. Natural discharge occurs as surface outflow to the Overton Arm of Lake Mead and as evapotranspiration. During summer months, flow at the Muddy River gage (located on the river between Muddy River Springs and the town of Moapa) is reduced by evapotranspiration. Measured flow rates are below the winter flow rates by about 1,500 acre-ft/yr (Eakin and Moore, 1964). .

Short-term water-level fluctuations in two adjacent wells—Lewis North and EH-5—completed in the basin fill and carbonate rocks, respectively, were analyzed to help determine whether or not the aquifers are hydraulically connected (Pohlmann and others, 1988). Generally, water levels in the carbonate-rock well (EH-5B) rose (depth to water decrease) as atmospheric pressure or earth-tide dilation increase, with no discernable delay. This response is characteristic of confined or semiconfined conditions, which was indicated also by lithologies encountered during the drilling of the well. This interpretation implies the carbonate-rock aquifer in this locale functions as a confined aquifer in response to short-term pressure fluctuations, and, locally, may not be hydraulically connected to other aquifers. Meanwhile, the response in the basin-fill well (Lewis North) was similar in magnitude, but with a phase shift. This may imply unconfined conditions in the basin-fill aquifer, but alternatively could be related to other factors (Pohlmann and others, 1988). The uniformity and periodicity of these diurnal fluctuations and their correlation to changes in atmospheric pressure and earth tides imply that these short-term water-level changes do not reflect pumping in the area.

At longer time scales, however, fluctuations may reflect seasonal ground-water use in the Muddy River Springs area, which is characterized by pronounced seasonal fluctuations. Pumpage peaks in the summer due to irrigation demands and increased demands for water by the Nevada Power Company power plant nearby. A small (less than 0.5 ft) decline of water levels was measured during the summer of 1987 in two monitoring wells completed in the carbonate-rock aquifers on the edges of the valley floor (Pohlmann and others, 1988). This decline was most likely in response to increased pumping and drawdowns in the basin-fill aquifers during the summer months. Mifflin & Associates (M.D. Mifflin, written commun., 1987) mapped a drawdown distribution for the 1987 pumping-season in the basin fill around the Nevada Power Company Lewis Wells (fig. 36) with a maximum drawdown of greater than 15 ft. The seasonal water-level declines measured in carbonate-rock wells are small in comparison and difficult to attribute to water-level changes in the basin-fill aquifer (fig. 35). Other factors that could cause the seasonal water-level fluctuations in the carbonate-rock aquifers include pumping from elsewhere in the carbonate-rock aquifers (such as at MX well CE-DT-6 about 6 mi away, fig. 36) and natural seasonal variations in ground-water flux in the carbonate-rock aquifers. No corresponding decline in spring discharge has been observed during more than 3 years of continuous monitoring at these springs for the present study

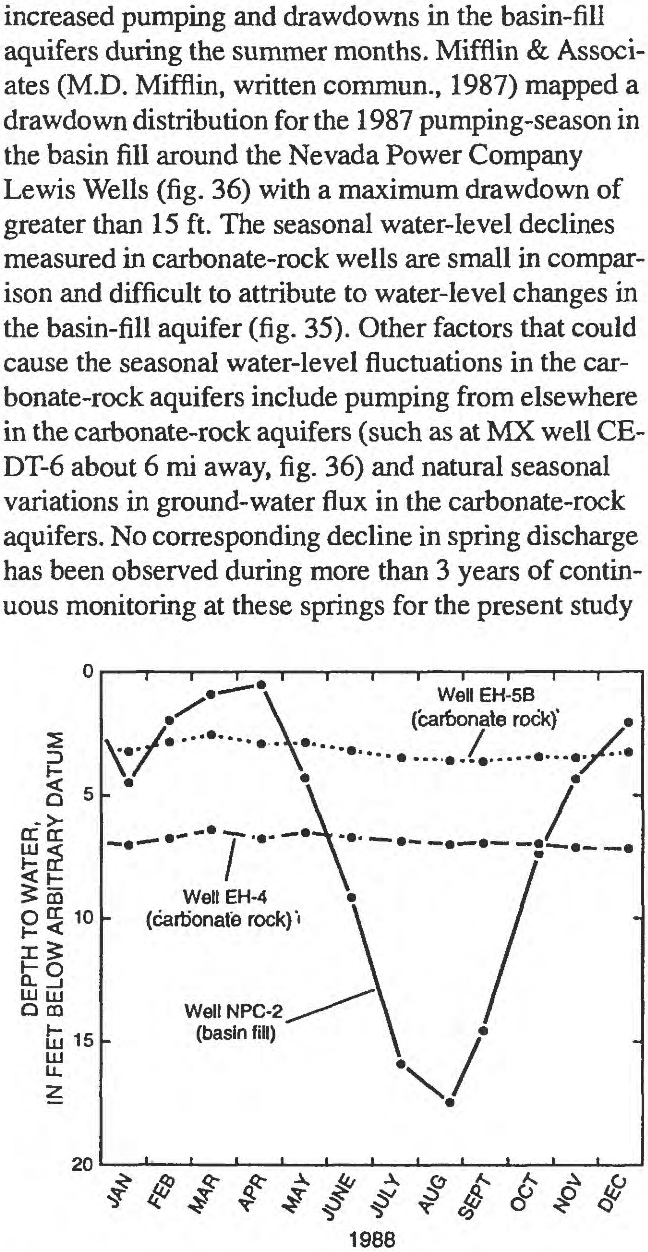


Figure 35. Water levels in wells completed in basin-fill and carbonate-rock aquifers in the Upper Muddy River Springs area, 1988.

(fig. 7). Continued monitoring in the Muddy River Springs area will help to better evaluate the relation between the carbonate-rock aquifers and local basin-fill aquifers.

Comparison of Historical Experiences

Experience from Ash Meadows and Upper Muddy River Springs area indicates the site specific nature of the magnitude and extent of ground-water development effects. In both cases, observations were of the effect of development of the basin-fill aquifers on the carbonate-rock aquifers. It is presumed that opposite types of effects (but not magnitudes of effects) might be observed if the situations were reversed, that is to have the pumping occur in the carbonate-rock aquifers. In Ash Meadows, an immediate and measurable water-level decline in the carbonate-rock aquifers and springflow decline resulted from development of ground water from the basin-fill aquifer. This indicates a direct hydraulic connection between the carbonate and basin-fill aquifer systems.

In the Upper Muddy River Springs area, only small changes in water levels in the carbonate-rock aquifers were measured. The carbonate-rock aquifers are confined in at least some areas, which implies that the carbonate-rock aquifer is isolated hydraulically (little exchange of pressure or water) from the overlying basin-fill aquifers. Causes of the small seasonal water-level changes remain uncertain and no decline in springflow has been measured. Thus, the hydraulic connection between the two aquifers is less than at Ash Meadows.

These two available case studies of development suggest that future development will need to be assessed on a site-by-site basis. In general, each hydrogeologic setting will respond differently to pumping stresses, ranging from immediate responses that directly reflect greater drawdowns in adjacent aquifers to slowly developing responses that only gradually reflect pumping in nearby aquifers.

Simulation of Interaquifer Effects in Pahrump Valley

Although based on a hypothetical development scenario rather than historical experience with aquifer development, numerical simulations of ground-water flow beneath Pahrump Valley by Harrill (1986) provide another insight into controls on interaquifer effects.

The simulations indicate that about half of the ground-water budget of Pahrump Valley discharges from the area as subsurface outflow through carbonate-rock aquifers (Harrill, 1986). Simulations of responses to hypothetical, long-term basin overdraft conditions showed almost no capture of this subsurface outflow despite widespread declines in water levels and spring-flows in the basin-fill aquifers (Harrill, 1986, p. 43). This response implies that developing basin-fill aquifers can result in severe effects within the basin-fill aquifer with little or no effect on the underlying carbonate-rock aquifers, in some places. In part, this response was simulated in Pahrump Valley because water levels in the basin-fill and carbonate-rock aquifers could not be drawn down (by any reasonable rate of pumping) to a level that would reverse or even flatten the steep gradients driving flow toward the southern end of Death Valley. Thus, the relation between the drawdowns associated with a pumped well and the natural gradients driving water toward regional discharge areas may determine what the mix of storage depletion, capture of discharge close to the well, and capture of regional discharge will be. If drawdowns are small compared to the head differences associated with the regional gradient then regional flow will continue unimpeded and the source of water to the pumped well will be depletion of storage or capture of discharge from nearby areas at altitudes close to that of the bottom of the drawdown cone. If the head differences associated with a regional gradient are smaller than or about equal to those induced by pumping, the drawdown cone will more readily capture the regional flow.

Monitoring and Prevention of Effects

Large uncertainties exist in prediction of the general effects of developing the carbonate-rock aquifers and even larger uncertainties where site-specific issues are considered. Given these uncertainties and the wide range of possible effects, observation and interpretation of the actual response to development remains the best approach to developing site-specific predictions and more general models capable of predicting a real response to pumping stress. In light of these uncertainties, how can development proceed with assurances that effects will not overshadow the benefits of the expanded water supplies? At present (1989), the best answer seems to be staging ground-water developments with adequate monitoring of related effects.

All ground-water development causes declines in water level and some depletion of stored water. If development is gradually undertaken (rather than undertaken in one sudden step), then water-level declines can be observed and judged in terms of the attendant benefits and costs at each step. Most effects are reversible, as the water-level changes at Devils Hole demonstrate (fig. 34). Once decisions to develop have been made, the prevention of adverse effects is best accomplished through active monitoring to provide early warning of undesirable changes.

Monitoring needs include more than just repetitive measurements at convenient locations. The information obtained needs to be indicative of changes in the aquifers, specific enough to indicate probable cause-and-effect relations, and reliable enough to support the start of corrective actions as needed.

Given these requirements, the initial monitoring need is to develop a basic understanding of the hydrologic conditions in the area of concern. This includes recognition of the major aquifers present, general directions of ground-water flow, general magnitudes of recharge and discharge, areas and magnitudes of pumpage, water levels in wells, and knowing if a trend in water-level changes exists.

This information can then be used to formulate a monitoring strategy. This generally involves determining the resources that need to be protected and the pumping stresses or other factors that might affect those resources. The monitoring network should provide specific information consistent with the general monitoring strategy. In addition to water-level measurements in wells, the network might have to include discharge measurements of springs and streams, determinations of pumpage, water-quality analyses, and other hydrologic characteristics. In most cases, the network is designed to use existing structures as much as possible for economic reasons. Measurement frequencies are based on long and short-term needs and historical data. Regular reporting and analysis of results is also a desirable part of operation of the monitoring network. Annual changes in monitored parameters should be supplemented by evaluations of long-term trends where data permit. The adequacy of the data needs to be periodically reviewed and the network modified as hydrologic and other needs change.

A Case History: Monitoring Around the Muddy River Springs

The Coyote Spring-Moapa area (fig. 36) is an example of how monitoring can help to identify (and provide information that could be used to prevent) undesirable changes in hydrologic conditions that could result from development. Water resources are supplied primarily by the discharge of about 36,000 acre-ft/yr from the Muddy River Springs. These springs are the regional discharge area for the lower White River flow system and are supplied by carbonate-rock aquifers that transmit water from mountain ranges far upgradient. Some water derived from the north travels more than 100 mi through carbonate-rock aquifers before discharging from the springs (Eakin, 1964, p. 1).

Water has been developed directly from the Muddy River, from the regionally fed Muddy River Springs, and from wells completed in the basin-fill aquifer. Discharge from the Muddy River Springs has been used for irrigation since the area was settled. Water is pumped from the basin-fill aquifer for irrigation, power plant cooling, and domestic water (pumpage in 1985 was about 7,000 acre-ft [Pohlman and others, 1988, p. 12; E. James Crompton, U.S. Geological Survey, written commun., 1989]). In 1986, the Moapa Valley Water District began pumping a well in the adjacent carbonate-rock aquifer (well CE-DT-6). This well is about 4 mi northwest of the springs and the pumped water is transported by pipe to the valley. Pumpage from the well in 1987 was about 200 acre-ft. Another well, CE-DT-5 drilled in the carbonate-rock aquifers of southern Coyote Springs Valley about 10 mi northwest of the springs, is slated for industrial development. This well could be pumped to provide as much as 5,000 acre-ft of water per year.

Despite these long-term developments of water, no significant long-term trend in water levels or spring discharge has been noted as of 1988. Short-term and seasonal fluctuations of water levels in both the basin-fill and carbonate-rock aquifers have been observed.

The water rights for the springs and for the river are longstanding and are protected under Nevada water law. In addition, desert fish live in the ponds and discharge channels of some of the springs and are protected by law. Several of the springs are included in the Moapa National Wildlife Refuge.

The general monitoring strategy discussed in this report includes continuous flow measurements at some springs and on the river as it flows from the area to determine the extent of any induced changes. Frequent measurements of other springs are desirable also. At the same time, the general monitoring strategy recognizes that causal relations between pumping and springflow declines will be difficult to verify without monitoring of ground-water levels. Monitoring of water levels also can provide early warning of impending springflow declines. Where possible and economically feasible, pumping rates at production wells and water-level changes in a network of observation wells would be monitored to determine the magnitude and areal extent on water-level declines associated with pumping. In the event that spring discharges decline, a critical question will be whether the changes were being caused by pumping in one specific area or whether combined effects from several areas were causing the changes. Detailed records of the actual times and rates that individual wells were pumped would be a useful addition to the monitoring data, and could be compared with the spring-discharge records to show correlations between specific pumping practices and springflow declines. Identifying cause-and-effect relations also would require that water levels in all aquifers be monitored, at pumped wells, near pumped wells, and between the wells and the springs. Finally, observations of short-term and naturally occurring seasonal fluctuations would be useful data for sorting out the relations under stressed conditions.

The foundation of an adequate monitoring network is already in place as a result of several separate efforts in the past 10 years. The success of nearby MX drilling programs in 1981 not only demonstrated the potential for high yield from some carbonate-rock aquifers but also provided valuable background information on hydrologic conditions prior to development in areas upgradient from the springs. Test wells drilled as part of an exploration program by Nevada Power Company provided similar information in areas generally downgradient from the springs (Desert Research Institute, 1986, p. 1). Two monitoring wells also were drilled into the carbonate-rock aquifers adjacent to major springs as part of this program. These wells can monitor small water-level changes in the immediate vicinity of the springs that might provide early indications of changes in spring discharge. Three wells were drilled as part of the present study to provide information in areas where data are lacking. Discharge from several springs also has been monitored with continuous recorders as part of the present study. In addition to continuous monitoring of several springs, nearly all other springs are measured semi-annually. This mix of occasional discharge measurements at most springs

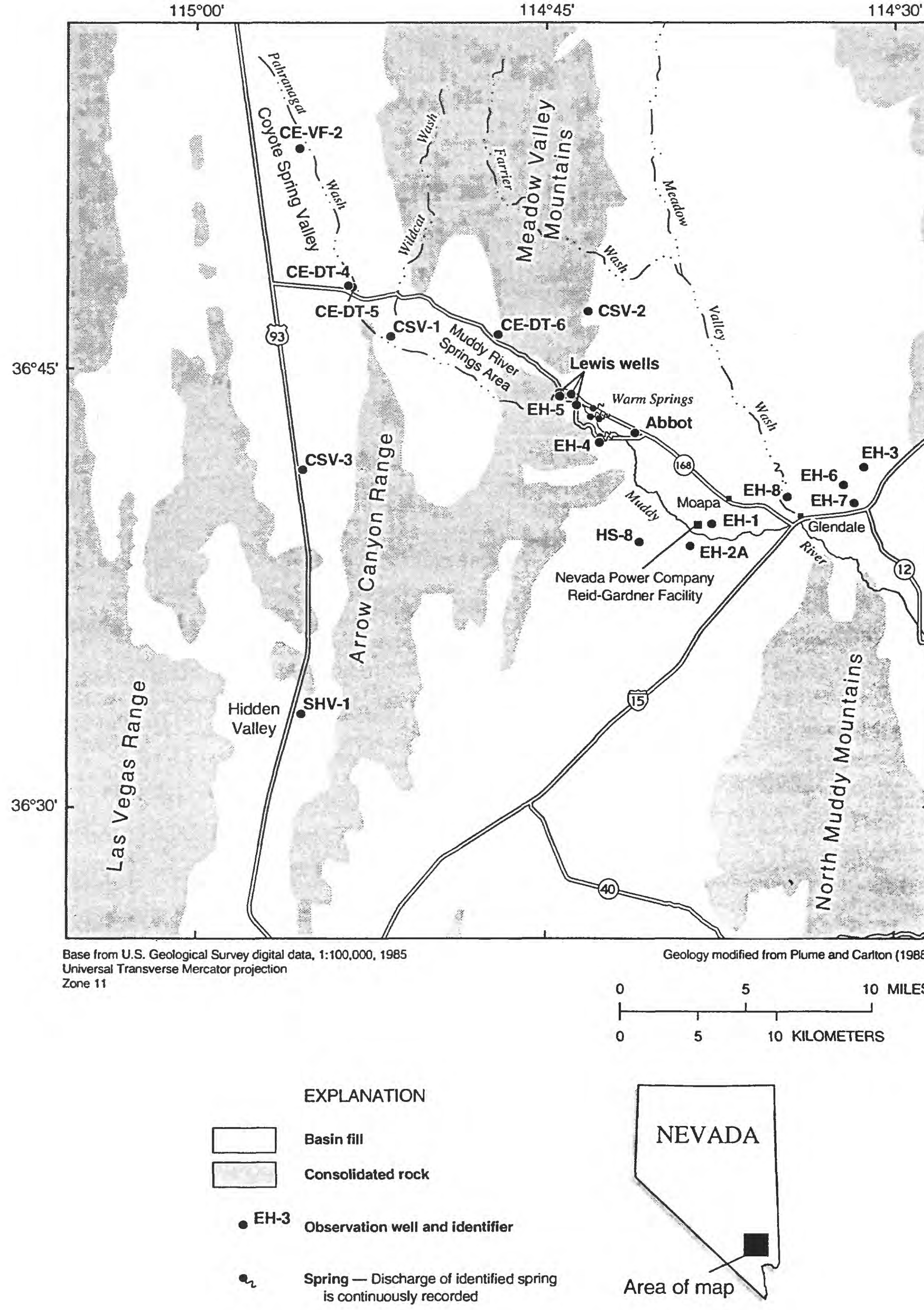


Figure 36. Observation wells and selected springs in and near Upper Muddy River Springs area.

and continuous discharge measurements at a few springs is designed to allow widespread identification of effects in an economical manner. The continuous measurements should detect changes in flow rates and the occasional measurements could be correlated to those continuous records to estimate the areal scope of the changes.

The existing network of well and spring discharge measurements coupled with a detailed inventory of pumpage will provide most of the information required for a comprehensive monitoring network. One or two additional monitoring wells might be needed upgradient from the springs to improve definition of possible effects of upgradient pumping from the carbonate-rock aquifers. Regular reporting of the results will provide managers and local officials with early warnings of detrimental changes and provide data to support decisions and actions that they might subsequently take. As such, the monitoring program that has developed will provide data to use in protecting against effects at this, likely the first area of significant development of the carbonate-rock aquifers in southern Nevada. It also can serve as a model for the kinds of considerations and detail required at other potential development sites.

A General Development and Monitoring Strategy

The monitoring network in the Muddy River Springs area has been developed during more than 10 years of investigations in the area. As a result, this real-world network has many features specific to data availability and history of development there. A broader range of monitoring wells penetrating the carbonate-rock aquifers is available than would be expected around some new developments. The proximity of MX well-siting investigations is propitious but not likely to be the norm near other developments.

Considering the network that evolved around Muddy River Springs and the prospects for development of carbonate-rock aquifers in other settings, however, leads to a more general strategy for managing effects around future aquifer developments. Many uncertainties that will plague predictions of effects have been discussed in this section, and a basic lesson of these discussions is that initially, assurances that effects from development will not overshadow benefits cannot be made with a high degree of confidence. However, if staged development was undertaken together with adequate monitoring, effects of continued or increased development could be estimated with progressively higher degrees of confidence. Staging development means not developing the resources in one large step but rather starting with small developments that are increased gradually as conditions and confidence warrant. This approach allows effects to be observed and analyzed as they develop so that the effects and benefits of development can be judged and, if necessary, reversed if the development proves too costly (in economic and environmental terms). Adequate monitoring means monitoring that provides data for a timely and sound judgement of effects and benefits. Monitoring of all aquifers that may be effected, and all hydrologic conditions that may reflect these effects, would be required for a sound basis. Regular monitoring, that recognizes early signs of effects and that allows natural fluctuations to be distinguished from development-induced variations, would be required for timely judgments.

SUMMARY

Rocks that were consolidated from layers of ancient marine sediments underlie the basins and mountains of a 50,000-mi^2 area of southern and eastern Nevada that is referred to as the carbonate-rock province. These rocks, which are predominantly limestone and dolomite, also extend beneath western Utah and into southeastern Idaho and eastern California. The large area underlain by the rocks, together with their capacity to transmit large volumes of water, indicate that the carbonate-rock province of Nevada contains aquifer systems of regional scale and significance.

In 1985, the State of Nevada entered into a cooperative effort with the U.S. Department of the Interior to study and test the carbonate-rock aquifers, in an effort to assess the potential for developing these ground-water resources. The studies were proposed in a report by the U.S. Department of the Interior (1985) and funded through Nevada State Senate bills S.B. 277 (in 1985) and S.B. 209 (in 1987). Technical work was funded by several agencies and done by the U.S. Geological Survey, the Desert Research Institute, and the Bureau of Reclamation.

During 1985-88, the technical studies were focused on southern Nevada, mostly north of Las Vegas and south of Pioche and Tonopah, although some activities—notably basic-data collection and geochemical analyses—extended farther to the north in Nevada and into adjacent states. The technical studies were intended to address the following basic concerns:

1. Where is water potentially available in the aquifers?
2. How much water potentially can be withdrawn from the aquifers?
3. What effects might result from development of the aquifers?

The carbonate rocks and subordinate noncarbonate rocks of southern Nevada were deposited as layers of ancient marine sediment that cumulatively were as much as 40,000 ft thick on the continental shelf off the ancestral west coast of North America between about 570 million and 250 million years ago (during that period, the west coast of the continent was in present-day Utah). In aggregate, the carbonate rocks are massive and widely distributed, and as a consequence, the aquifers they contain provide avenues for ground-water flow beneath much of the province. All the ancient sedimentary rocks, where deformed and fractured, can transmit some ground-water flow, but the carbonate-rock layers—because of their brittleness and tendency to dissolve into flowing water—are believed to contain the principal water-bearing (or aquifer) zones.

The carbonate-rock aquifers have complex shapes and are connected to aquifers in other rock types. Volcanic activity and erosion of the mountain ranges have resulted in the deposition of younger rocks atop the carbonate rocks. Among these younger rocks are basin-fill aquifers that are the sources of most of the ground water now used in the State. Although the carbonate rocks were deposited as widespread layers, geologic forces subsequently deformed the rocks into innumerable "blocks" that are bounded by faults, and folded rock masses of all sizes. Because of this deformation, rocks of widely differing geologic age are intermingled, and the distribution of rocks constituting aquifers is greatly complicated (as are the paths followed by ground-water flow through the rocks).

Accurate definition of the potential for developing carbonate-rock aquifers requires an understanding of the configuration and physical properties of the carbonate and intervening noncarbonate rocks, coupled with estimates of the volume of water contained in and moving through them. To develop the required understanding, the following activities were undertaken during 1985-88.

Several types of basic hydrologic data were collected in eastern and southern Nevada, including semiannual measurements of cumulative rain and snowfall at 15 high-altitude sites; continuous measurements of discharge at 8 representative springs; regularly scheduled measurements of discharge at 59 other springs; continuous measurements of water levels in 4 wells open to the carbonate-rock aquifers; regularly scheduled measurements of water levels at 11 other wells; and measurements of meteorological conditions used to estimate evaporation rates and water consumption by native plants at 2 sites. Continuous measurements made as part of previous studies indicate that the discharge from two of the larger of the Muddy River Springs remains nearly uniform at the rates (totaling about 8,000 acre-ft/yr) and that the discharge from Corn Creek Springs also is nearly uniform at about the rate measured during 1947-55—about 200 acre-ft/yr. Small, short-term fluctuations in spring discharge and water levels in carbonate wells, however, are observed; they represent responses to atmospheric pressure change, tides, local precipitation, and other natural stresses.

Geology was mapped in an area of about 1,800 mi^2 north of Las Vegas and centered on the Sheep Range. The mapping emphasized carbonate rocks and younger sediments, and was based on detailed field observations, interpretation of geophysical measurements, and correlation of observations with aerial photography and satellite imagery. Results of the mapping indicate that small openings (primary porosity) through which small volumes of water can flow probably are ubiquitous in the carbonate rocks throughout the region. Along many high-angle normal faults, fractured and fragmented carbonate rocks develop and maintain larger openings through which large volumes of water can flow. These fault zones may constitute the principal paths through which most water flows in the carbonate rocks.

Surface geophysical measurements were made to estimate thicknesses of basin-fill aquifers overlying the carbonate-rock aquifers and to locate faults deep beneath land surface. Measurements detected spatial variations in the density, strength, and electrical properties of rocks in the subsurface. Interpretation of these measurements indicate that thicknesses of basin fill overlying carbonate rocks range from less than 500 ft in Hidden Valley to more than 6,000 ft beneath South Tikaboo Valley. Estimates of thickness are critical in siting exploration wells in these valleys. The geoelectrical measurements also indicated that highly productive wells in Coyote Spring Valley penetrate a fault zone along the east edge of the Arrow Canyon Range, rather than the more visible fault zone on the steep west side of the range.

Water samples were collected and analyzed to characterize the quality of ground water and to delineate flow paths in terms of physical and chemical properties of the water. Samples were collected from 209 springs, streams, and wells during 1985-88. Hundreds of analyses from previous studies also were compiled. Geochemical balances and models were used to update water balances and to identify flow and mixing rates in six parts of southern Nevada, including the Spring Mountains, Las Vegas Valley, Ash Meadows area, and Muddy River Springs area. The results alter previous concepts of regional flow beneath southern Nevada by indicating that most recharge from the Sheep Range flows toward the Muddy River Springs rather than radially toward other adjacent valleys including Las Vegas Valley. Also, flow in the basin-fill aquifers of the Las Vegas Valley shear zone was shown to be impeded in some areas and enhanced in others, presumably by the influence of deeply buried geologic structures. Elsewhere, the studies generally verify the overall water budgets developed by previous investigators for regional flow beneath the White River drainage in east-central Nevada. A broad reconnaissance of water quality in southern Nevada demonstrated that aquifers beneath and east of Las Vegas Valley and elsewhere in southeasternmost Nevada are likely to contain water of quality not suitable for many uses.

Wells were drilled, logged, and tested in the basin-fill and carbonate-rock aquifers to provide direct observations of aquifer characteristics. Nine wells were drilled (a total of about 4,500 ft in basin fill and 5,500 ft in carbonate rocks) and two abandoned wells in key locations were rehabilitated. Borehole-geophysical logs were made from selected depth intervals in all these wells and in four more wells. The aquifers were tested at three of the new wells and at three of the wells during 1985-88 to determine transmissivity. Results from reports of specialized tests in 13 petroleum-exploration wells and aquifer tests at 33 other wells in the carbonate-rock aquifers of Nevada were compiled. The capacity of the carbonate-rock aquifers to transmit water ranges from low to very high, depending on location. Whereas the transmissivity of aquifers at the MX wells in Coyote Spring Valley is extremely high (greater than 200,000 ft^2/d) and productivity also is high, most other wells drilled in carbonate rocks are much less productive. In fact, the aquifer at the MX wells is somewhat more transmissive than at any other site for which test results are available. The average aquifer properties, as reported in compiled tests at water wells, are similar to those at Army Well 1 near Mercury (about 5,200 to 11,500 ft^2/d).

All these activities provided useful information about the movement of water in aquifers near and immediately north of Las Vegas. To address the regional distribution of the carbonate-rock aquifers throughout southern Nevada and their potential for development, however, synthesis of the results from all these activities, together with results from many other hydrogeologic and geologic investigations was made.

Understanding where water potentially could be developed from the carbonate-rock aquifers requires an understanding of where the carbonate rocks are present, and where they are continuous enough to form local and regional aquifers. Although the carbonate rocks and subordinate noncarbonate rocks are widespread and originally were thick (as much as 40,000 ft thick in some places), subsequent geologic forces disrupted and partly or completely removed these sedimentary rocks from large parts of southern Nevada. As a result of the action of those forces, much of present-day southern Nevada is underlain by areas where the carbonate rocks remain only as isolated blocks having dimensions that range up to miles on a side. In contrast, the central third of southern Nevada is underlain by a north-south corridor of thick, laterally continuous carbonate rocks. Even within the central corridor, the thickness of carbonate rocks was reduced to between about 3,000 and 19,000 ft. North of Las Vegas, within the central corridor, two areas are underlain by thick and relatively continuous carbonate rocks—the Pintwater Range-Spotted Range area and the Coyote Spring Valley area. These two areas are connected to a similarly thick carbonate-rock mass farther north. The thick carbonate rocks probably contain the principal conduits for regional flow from east-central Nevada into southern Nevada, where the flow is ultimately discharged at Ash Meadows and Death Valley, and at the Muddy River Springs. East and west of the central corridor are blocks of carbonate rock that are thick but largely isolated by noncarbonate materials of low transmissivity from the carbonate-rock aquifers of the central corridor. These carbonate blocks transmit little water.

Farther south, the central corridor underlies the Spring Mountains-Pahrump Valley area. Water flowing through the corridor at this latitude is derived mostly from recharging snowmelt in the Spring Mountains. This recharge moves radially away from the high-altitude areas of the Spring Mountains to discharge near Tecopa, in Pahrump Valley, at Indian Springs, and (in the past) at Las Vegas Springs. The carbonate rocks beneath Las Vegas Valley are believed to thin abruptly to the east toward Lake Mead.

Some zones within the central corridor are highly transmissive, as indicated by large spring discharges that are fed by parts of the aquifers having imperceptibly sloping water tables, and by geologic mapping of ancestral flow paths. The present study developed the hypothesis that highly transmissive zones may function as large-scale drains, collecting water from adjacent, less transmissive rock that underlies most of the study area. The drains would ultimately conduct much of the flow that discharges at large regional springs. The present study also hypothesizes that such zones might stay highly transmissive only if large volumes of water continue to flow through them. Otherwise, openings in the rock gradually fill with fault breccia and the rock reconsolidates. Small, filled fractures observed in outcrops of the carbonate rocks throughout the area appear to have been sealed while still below the water table, and they generally show no evidence of prior mineral dissolution from the fracture walls. In contrast, some flow tubes observed along major fault zones exhibit some characteristics of wall-rock dissolution by flowing ground water. This dissolution widened the openings and enhanced already high transmissivities. If this hypothesis proves true, then wells that tap conduits of concentrated regional flow probably will be most productive. Maps of recently active faults and delineations of regional flow confluences might be used to systematically locate the most productive structure beneath areas being considered for development.

A natural transition exists between (1) areas in southeasternmost Nevada where the carbonate rocks either are intermingled with—or depositionally juxtaposed against—other rocks containing abundant salts (evaporite minerals such as gypsum and halite), and (2) areas elsewhere in southern Nevada where these other rocks are nearly absent. The present investigation minimized study efforts in the former areas because development of the carbonate-rock aquifers risks the encounter of ground water that is unsuitable for most uses.

The water resource of the carbonate-rock aquifers is the sum of the perennial yield of the aquifers and reserve of water stored in them. The perennial yield can be no greater than the total rate of flow through the aquifers, and it probably is less. At present (1989), the total rate of flow through the carbonate-rock aquifers cannot be estimated directly, but rather is bracketed by other rates that can be estimated. The total flow is assumed equal to the recharge to the carbonate-rock aquifers alone, which is less than the total rate of recharge to all aquifers of southern Nevada, both carbonate and noncarbonate. In contrast, the total rate of flow through the carbonate-rock aquifers is greater than the rate of land-surface discharge directly from the carbonate-rock aquifers, because some discharge from the carbonate-rock aquifers is by unseen subsurface leakage of water into adjacent basin-fill aquifers. Thus, the total flow rate is bracketed between a regional total-recharge rate and a land-surface discharge rate.

Natural recharge in the mountains of southern Nevada has been estimated to total about 140,000 acre-ft annually, of which about 110,000 acre-ft is from within the central corridor of thick carbonate-rock aquifers. In addition to ground-water recharge in southern Nevada, geochemical balances computed in the present study indicate that another 21,000 acre-ft/yr is supplied to southern Nevada by inflow through carbonate-rock aquifers from east-central Nevada. Together, recharge plus inflow totals about 160,000 acre-ft/yr.

Part of the total ground-water inflow (recharge plus inflow) moves directly or indirectly into the carbonate-rock aquifers and discharges (1) at regional springs, (2) by flowing out of the study area through carbonate rocks that extend into California, or (3) by leaking into basin-fill aquifers. The first two mechanisms discharge about 77,000 acre-ft from carbonate-rock aquifers of the central corridor. The remaining water either leaks upward into the basin fill or directly recharges the basin fill, and ultimately discharges at local springs, playas, meadows, and streams. Previous studies have estimated natural discharge from basin-fill aquifers in the central corridor to be about 50,000 acre-ft/yr.

The different inflows to and outflows from all aquifers of the central corridor total about 130,000 acre-ft/yr. Under natural conditions, an equal quantity was discharged from springs, playas, meadows, and streams, in southern Nevada and nearby parts of California each year. As a result of this equilibrium between inflow and outflow, future wells that continuously extract any part of the annual recharge eventually can be expected to decrease the discharge from one or more of the aquifers. A review of other possible avenues of regional inflow and outflow along the boundaries of the central corridor of southern Nevada identified no sources of regional inflow, other than the White River system. The review also indicates that only along the California border are the carbonate-rock aquifers continuous enough to transmit large quantities of water to areas where its discharge at land surface could have been overlooked in this study. In particular, no large currently (1989) unidentified quantities of water are likely to be flowing out of southern Nevada to the Colorado River or Arizona. No sources of regional inflow, other than the White River system, were identified.

The perennial yield of the carbonate-rock aquifers cannot exceed the total flow through them. However, part of this flow discharges by leaking into adjacent basin-fill aquifers. This component of flow probably is accounted for already in the water budgets (and estimated perennial yields) of those basins and cannot be included properly in estimates of the perennial yield of the carbonate-rock aquifers unless it is first subtracted from the basin-fill budgets. The perennial yield of the carbonate-rock aquifers of southern Nevada, therefore, should be defined in terms of the remainder of the total flow. Thus, the perennial yield is no more than the combined rates of discharge at regional springs in southern Nevada and at discharge areas in the Death Valley region (total, about 77,000 acre-ft/yr).

The actual rate at which water can be withdrawn without continual depletion of the ground-water reservoir might depend on how the resource is developed. This is because practical strategies to capture springflow and outflow can entail inefficiencies that allow part of the flow to avoid capture. As a result, for practical purposes, if wells some distance from regional springs are pumped in an effort to capture the springflows at logistically convenient locations, the sustainable rates of withdrawal might be considerably less than the present flow rates from the regional springs and discharge areas. Alternatively, if the basin-fill and carbonate-rock aquifers were managed together, the overall perennial yield still could not be more than the total recharge to the area. Management of both aquifer types together would not lessen overall effects on natural discharge, but rather it would permit tradeoffs as to what effects would be allowed, and where.

The other component of the carbonate-rock water resources is the large volume of water stored in the rocks. Because of the areal extent (10,000 mi^2) and great thickness of the carbonate rocks in the central corridor (between 3,000 and 19,000 ft and averaging about 12,000 ft), the total volume of rock is enormous. Carbonate rocks that might store and transmit water south of Pioche and Tonopah are estimated to have a total volume of about 20,000 mi^3. Borehole geophysical logs made during 1985-88 indicate that the total amount of open space within these rocks might be on the order of 1 to 10 percent, and previous studies at the Nevada Test Site indicate that about one-fifth of that space is interconnected and will allow ground water to move through it. Therefore, if selected parts of the carbonate-rock aquifers were dewatered, they might yield a water volume on the order of 1 percent of the aquifer volume. Assuming the same percentage of recoverable water in each cubic foot of aquifer, the total quantity of water stored in the rocks south of Pioche and Tonopah would be about 800 million acre-ft. For practical purposes, not all this water can be extracted. However, if an average of 100 ft of the aquifer's thickness could be dewatered, the central corridor could yield a volume of stored water of about 6 million acre-ft. However, the water stored in the upper 100 ft, if depleted regionally, would be replenished only by the equivalent of decades or centuries of recharge.

Ultimately, long-term development of the carbonate-rock aquifers would result in depletion of stored water, or capture of water that otherwise would discharge from the aquifers of southern Nevada and vicinity, or both. In many places, development might extract water from both carbonate rock and basin-fill aquifers. Reasonable tradeoffs among these alternative sources might be possible given (1) improved local understanding of the aquifers and the effects of development, and (2) careful planning of the developments.

Possible effects of developing the carbonate-rock aquifers include declining water levels, decreasing springflow rates, drying up of some streams, playas, and meadows, and changing water quality. These effects are direct or indirect responses to water-level changes associated with aquifer development, and are related to disturbances of the natural equilibrium between aquifer recharge and discharge.

Sustained effects within the carbonate-rock aquifers resulting from development of those aquifers have not been observed to date (1989). The magnitude and extent of water-level changes and, eventually, changes in springflow rates caused by development would depend on the geometry of the aquifers and their capacity to transmit and store water. Such effects can be calculated roughly by using either complex hydraulic calculations or computer models of ground-water flow. Hydraulic calculations indicate that water-level declines in extensive, **unconfined** carbonate-rock aquifers commonly would be between about 1 and 70 ft at a distance of 1 mi of a production well after 10 years of pumping at 1,000 gal/min. Projected water-level declines as far as 10 mi from the pumped well in a **confined** part of the aquifer would be of similar magnitude.

Neither set of calculations (for unconfined and confined conditions) accounts for the large directional influence of narrow, highly transmissive zones in the aquifers. Calculated declines around wells drawing water from these zones could be underestimated along the zones and overestimated away from the zones. The calculated drawdowns are based also on an assumption that the aquifer extends far beyond the area affected by pumping. Currently (1989), data that allow a more realistic representation of the real-world influence of aquifer boundaries are not available; however, several previous studies have included computer models that provide insight into the limitations of estimates. A review of those models indicates primarily that flow in the aquifers varies complexly at every scale. Regardless of whether the effect of pumping near Devils Hole is being modeled at a small scale or whether the flow toward Death Valley is being simulated at a regional scale, the geologic complexity of southern Nevada is hydrologically important. The numerous fault-zone orientations, differences in aquifer thicknesses, and difficult-to-delineate masses of noncarbonate rock that are barriers to flow require (1) that detailed aquifer descriptions be available before accurate site-specific estimates can be made, and probably (2) that those estimates be based on effective use of sophisticated computer models.

The potential for adverse effects in adjacent aquifers resulting from development of the carbonate-rock aquifers is another concern. Historical experience with such conditions is available at two areas in southern Nevada that have undergone development of basin-fill aquifers adjacent to carbonate-rock aquifers: Ash Meadows and Muddy River Springs. At Ash Meadows, direct connections between pumping from basin-fill aquifers and water-level declines in the carbonate rocks were demonstrated. Around the Muddy River Springs, in contrast, differing levels of development of water from basin-fill aquifers have resulted in minimal changes in water levels of the carbonate-rock aquifers. The difference between historical responses at these areas probably could not have been estimated before the aquifers were pumped and early effects observed.

Simple projections of water-level declines in the carbonate-rock aquifers, together with a review of historical experiences with the effects of drawing water from basin-fill aquifers adjacent to carbonate-rock aquifers, indicate that the carbonate-rock aquifers might be developed in some areas without introducing unacceptable effects. In other areas—for example, where a stressed aquifer is fully confined or where adjacent aquifers are closely connected—effects could be more severe. The effects of depletion of stored water and capture of water that otherwise would discharge from the aquifers would depend on site-specific conditions around areas where water is withdrawn from the aquifers. Confidence in the projection of effects that might result from the carbonate-rock aquifers will remain limited until observations are available that document changes as the aquifers respond locally to long-term pumping stresses.

Initially, assurances that the adverse effects of development will not overshadow benefits cannot be made with a high degree of confidence. However, if staged development were undertaken together with adequate monitoring, effects of continued or increased development could be estimated with progressively higher degrees of confidence. Staging means not developing the resources in one large step but rather starting with small projects that are augmented gradually as conditions and confidence warrant. This approach allows the effects of development to be observed and analyzed continually, so that the adverse effects and the benefits of development can be judged and the effects reversed or mitigated if they prove to be too costly (in economic and environmental terms). Adequate monitoring means monitoring that provides data for a timely and sound judgment of adverse effects and benefits. Monitoring of all aquifers that may be affected, and all hydrologic conditions that may reflect these effects, should provide a basis for sound judgments. Regular or continuous monitoring that permits the recognition of early effects of development and that allows these effects to be distinguished from natural fluctuations, would provide information for timely judgments.

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