

Distribution of Carbonate-Rock Aquifers
in Southern Nevada and the Potential
for their Development

Summary of Findings, 1985-88


PROGRAM FOR THE STUDY AND TESTING OF CARBONATE-ROCK AQUIFERS
IN EASTERN AND SOUTHERN NEVADA

Summary Report No. 1



This report is based on work by the
U.S. GEOLOGICAL SURVEY, DEPARTMENT OF THE INTERIOR
and the
DESERT RESEARCH INSTITUTE, UNIVERSITY OF NEVADA SYSTEM

Prepared in cooperation with the
STATE OF NEVADA
and the
LAS VEGAS VALLEY WATER DISTRICT



COVER PHOTOGRAPH: View to northwest from flank of Sheep Range between Rye Patch Spring and mouth of Picture Canyon, in late afternoon of November 9, 1984. In foreground are northernmost Black Hills; in distance are Desert Range and Pintwater Range. Photograph by Michael D. Dettinger.

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By Michael D. Dettinger, U.S. Geological Survey

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Carson City, Nevada
1989

FOREWORD

The 1985 Nevada Legislature authorized a program for the study and testing of carbonate-rock aquifers of eastern and southern Nevada. The program is a cooperative effort by the State of Nevada and the Federal Government, and the study is being made by an informal coalition of U.S. Department of the Interior agencies (the U.S. Geological Survey and the U.S. Bureau of Reclamation) and the Desert Research Institute, University of Nevada System. Progress and plans for the study are evaluated regularly by a committee of representatives that was created in the authorizing legislation and that represents a wide range of interests throughout the State. The chairman of the evaluation committee has reported findings and recommendations to the Legislature's Interim Finance Committee four times since 1985.

The overall plan for the program is to study the carbonate-rock aquifers of southern, east-central, and northeastern Nevada as separate phases of work, with a summary of findings prepared at the end of each phase. An overall summary would be prepared at the completion of all three phases of study.

This report summarizes findings of the first phase of study, which assessed the resources of the carbonate-rock aquifers of southern Nevada. The summary brings together results from more than 20 technical reports produced during the study to date. It describes the location, magnitude, and resource potential of the carbonate-rock aquifers from a regional perspective and provides information needed to support management and development strategies for meeting southern Nevada's future needs.



Paul R. Fenske, Chairman
Committee to Evaluate Progress
of the Carbonate-Aquifer Study

Agencies represented on the evaluation committee:

Desert Research Institute, University of Nevada System
Nevada Department of Conservation and Natural Resources
Las Vegas Valley Water District
Colorado River Commission
Nevada Association of Counties
Nevada League of Cities
Nevada Water Resources Association
U.S. Geological Survey (non-voting member)
U.S. Bureau of Reclamation (non-voting member)

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CONVERSION FACTORS

"Inch-pound" units of measure used in this report may be converted to metric units by using the following factors:

<i>Multiply</i>	<i>By</i>	<i>To obtain</i>
Acre-feet	1,233	Cubic meters
Acre-feet per month	1,233	Cubic meters per month
Acre-feet per year	0.001233	Cubic hectometers per year
Cubic feet	0.02832	Cubic meters
Feet	0.3048	Meters
Feet squared per day	0.0929	Meters squared per day
Gallons per minute	0.06309	Liters per second
Miles	1.609	Kilometers
Square miles	2.590	Square kilometers

ALTITUDE DATUM

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

DISTRIBUTION OF CARBONATE-ROCK AQUIFERS IN SOUTHERN NEVADA AND THE POTENTIAL FOR THEIR DEVELOPMENT

SUMMARY OF FINDINGS, 1985-88

By Michael D. Dettinger

I. OVERVIEW

Studies of the ground-water resources of carbonate-rock aquifers in southern Nevada by the U.S. Geological Survey, Desert Research Institute, and U.S. Bureau of Reclamation during 1985-88 have helped to answer the following questions:

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

The studies included hydrologic-data collection, geologic mapping, well drilling and testing, geophysical measurements, and geochemistry.

The rocks that compose the carbonate-rock aquifers are layers of limestone and dolomite that were deposited hundreds of millions of years ago in much of the eastern Great Basin. Subsequently, the carbonate rocks were much deformed; as a result, they no longer exist as continuous layers beneath the region. Instead, they have been pulled apart to form a few large areas of thick and relatively continuous carbonate rocks. Separating these areas are noncarbonate rocks, within which are isolated mountain-sized blocks of carbonate rock.

Beneath southern Nevada, the thick carbonate-rock layers are continuous enough to transmit ground water at regional scales only beneath a north-south "corridor" 60-90 miles wide that extends southward from east-central Nevada to and beyond the Spring Mountains area west of Las Vegas. Within this corridor are the two major regional flow systems of southern Nevada: the Ash Meadows-Death Valley system and the White River-Muddy River Springs system. These flow systems link the ground water beneath dozens of valleys and over distances exceeding 200 miles. Flow in these systems probably is concentrated along highly transmissive zones associated with (1) recently active faults and (2) confluences of flow near major warm-water springs. Outside of the corridor, the carbonate rocks are present primarily as isolated blocks that form aquifers of limited extent, recharged mostly by local precipitation.

The sources of ground-water flow in the aquifers of southern Nevada are (1) recharge from precipitation in the mountains and (2) regional inflow from carbonate-rock aquifers farther north. The total contribution from these sources to all the aquifers of southern Nevada--both carbonate and noncarbonate--is about 160,000 acre-feet per year. About 80 percent (130,000 acre-feet per year) passes beneath the central corridor; this includes nearly all flow in the major regional systems. At present, the fraction of the recharge that enters the carbonate-rock aquifers cannot be estimated because the controlling processes are poorly understood and because the available data are insufficient to describe these processes.

Some of the total flow beneath the area discharges through the basin-fill sedimentary aquifers that partly fill valleys, some flows from carbonate-rock aquifers at warm-water springs, and the rest flows out of Nevada into adjacent states (mostly to California) through the carbonate-rock aquifers. Discharge from the springs plus the outflow from Nevada through the carbonate rocks total about 77,000 acre-feet per year. The total rate of flow through the regional carbonate-rock aquifers of southern Nevada is equal to this 77,000 acre-feet per year plus some unknown quantity of ground water that leaks up into basin-fill aquifers.

A much larger quantity of water--on the order of 800 million acre-feet--is stored in the carbonate-rock aquifers. This is because the aquifers underlie about 10,000 square miles and probably are, on the average, about 12,000 feet thick in the central corridor. On the order of 6 million acre-feet of water, the quantity stored in the upper 100 feet of the aquifers, might be economically accessible. However, this volume is equivalent to decades or centuries of recharge; if depleted, it would be replenished very slowly or not at all.

Large-scale development (sustained withdrawals) of water from the carbonate-rock aquifers would result in water-level declines and cause the depletion of large quantities of stored water. Ultimately, these declines would cause reductions in flow of warm-water springs that discharge from the regional aquifers. Storage in other nearby aquifers also might be depleted, and water levels in those other aquifers could decline. In contrast, isolated smaller ground-water developments, or developments that withdraw ground water for only a short time, may result in water-level declines and springflow reductions of manageable or acceptable magnitude.

Confidence in predictions of the effects of development, however, is low; and it will remain low until observations of the initial hydrologic results of development are analyzed. A strategy of staging developments gradually and adequately monitoring the resulting hydrologic conditions would provide information that eventually could be used to improve confidence in the predictions.

II. INTRODUCTION

Rocks that were consolidated from layers of ancient marine sediments underlie many of the basins and mountains of a 50,000-square-mile area of southern and eastern Nevada that is referred to as the carbonate-rock province (fig. 1). These rocks, which are dominated by limestone and dolomite (two common carbonate-rock types), also extend beneath western Utah and into southeastern Idaho and eastern California. Large springs--many with discharges greater than 1,000 gallons per minute--are associated with these carbonate rocks, and several wells drilled into fractured zones in the rocks have been pumped at high rates with little water-level decline. The large area underlain by the rocks, together with their capacity to transmit large volumes of water, suggests that the carbonate-rock province of Nevada contains aquifer systems of regional scale and significance (Hess and Mifflin, 1978, p. viii).

Nevada, the most arid State in the Nation, is facing rapid population growth and increasing demands for water. Historic sources of water--surface water in 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 perennial yields in many parts of the State. The possibility, therefore, that the largely unexplored carbonate-rock aquifers of Nevada are an untapped source of water supply has sparked considerable interest in recent years.

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 to assess the potential for developing these ground-water resources. These 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 toward this end was funded by several agencies (table 1) and done by the U.S. Geological Survey, the Desert Research Institute, and the U.S. Bureau of Reclamation.

TABLE 1.--Agencies participating in the Nevada Carbonate Aquifers Program

Agency	Contributions	Years
State of Nevada	Funding, advisory	1985-88
U.S. Geological Survey	Funding, technical studies	1984-88
U.S. Bureau of Reclamation	Funding, technical studies	1984-87
Desert Research Institute	Funding, technical studies	1985-88
Las Vegas Valley Water District	Funding	1985-88
City of North Las Vegas	Funding	1985

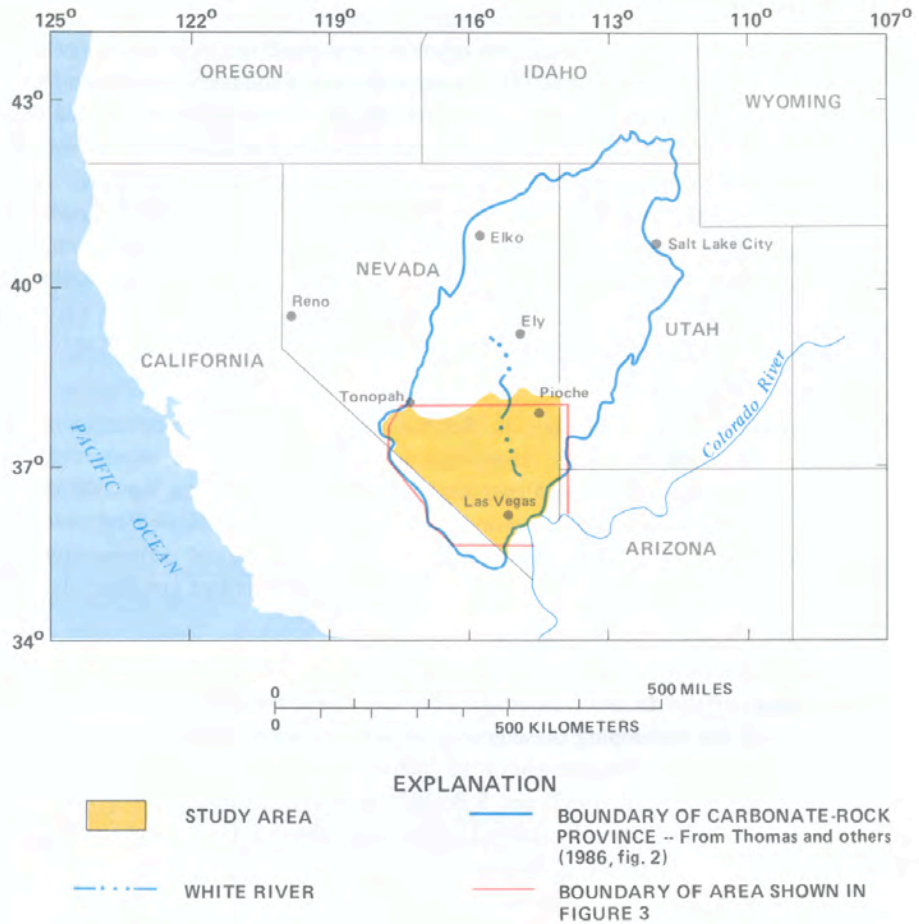


FIGURE 1.--Location of carbonate-rock province, southern Nevada study area, White River, and area shown in figure 3.

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. **Figure 1** shows the southern Nevada study area in relation to the carbonate-rock province as a whole.

The technical studies were intended to address the following basic concerns:

1. Where are appreciable quantities of water potentially available for development in the carbonate-rock aquifers?
2. How much water potentially can be withdrawn from these aquifers for development?
3. What might be the effects of short-term and long-term development of the aquifers?

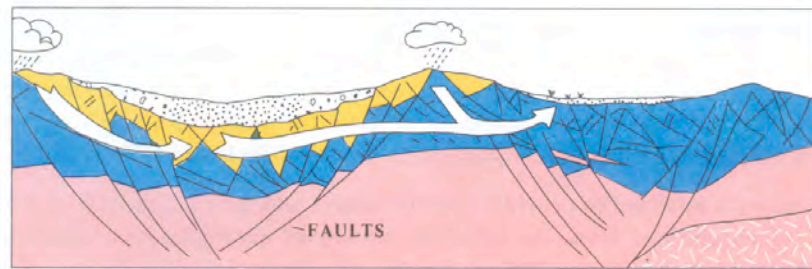
Plans for studies beyond 1988 address the same concerns in east-central Nevada and, by 1992, in northeastern Nevada. During 1985-87, the Bureau of Reclamation pursued an additional objective of evaluating the economic feasibility of specific resource-management alternatives that could be used to supply peak demands for water in the Las Vegas urban area during summer months in the near future (U.S. Bureau of Reclamation, 1988).

This report is intended to provide water managers and policy makers with a brief summary of conclusions from the scientific studies of carbonate-rock aquifers in southern Nevada made during 1985-88 by the U.S. Geological Survey and Desert Research Institute. The report is organized to address the three basic concerns listed above. These conclusions are documented in detailed reports resulting from specific study elements. These additional reports include 20 that are highlighted in the "References Cited" section at the end of this report.

III. WHAT ARE THE CARBONATE-ROCK AQUIFERS?

The carbonate rocks of southern Nevada were deposited as layers of ancient marine sediment that cumulatively were as much as 40,000 feet thick on the continental shelf off the ancestral west coast of North America between about 570 million and 280 million years ago (during that period, the west coast of the continent was in present-day Utah). The carbonate rocks--limestone and dolomite--were deposited on even older, noncarbonate sediments and crystalline basement rocks. Within and between layers of carbonate rock are noncarbonate layers of shale, quartzite, chert, and siltstone, but the overall accumulation is dominated by carbonate rock. In aggregate, these rocks are massive and widely distributed; as a consequence, the aquifers that they comprise provide avenues for ground-water flow beneath much of the area shown in **figure 1**. All the ancient sedimentary rocks, where deformed and fractured, may transmit some ground-water flow, but **the carbonate-rock layers within the rocks--because of their brittleness and tendency to dissolve into flowing water--are believed to be the principal water-bearing (or aquifer) zones.**

Fiero (1986) presents a general background on the geology of these sedimentary sequences, and the various older and younger noncarbonate rocks in southern and eastern Nevada. Plume and Carlton (1988) describe the general water-bearing properties of these rocks and the regional distribution of exposures of the various rock types.



EXPLANATION










- | | |
|---|--|
|  SAND AND GRAVEL -- Basin-fill aquifer |  CLAY AND SILT -- Basin-fill deposits that impede ground-water flow |
|  VOLCANIC ROCKS -- Aquifers as well as layers that impede flow |  CARBONATE ROCKS -- Aquifers |
|  OLDER, NONCARBONATE SEDIMENTARY ROCKS -- Impede flow |  CRYSTALLINE BASEMENT -- Impedes flow |
|  GROUND-WATER FLOW PATH |  PLAYAS, SPRINGS, AND NATIVE VEGETATION |
|  RAIN AND SNOW IN MOUNTAINOUS AREAS | |

FIGURE 2.--Schematic hydrogeologic section across mountain ranges and intervening basins, showing configuration at depth of aquifers and rocks that impede flow. (Modified from Anderson and others, 1983, fig. 10.) Approximate width and depth of schematic section, 30 miles by 8 miles.

The carbonate-rock aquifers have complex shapes and are connected to aquifers of other rock types. Volcanic activity and erosion of rock fragments from ancient and present-day mountain ranges have resulted in the deposition of younger rocks atop the carbonate rocks. Among these younger rocks are sand-and-gravel aquifers that partly fill the basins of Nevada and that are the sources of most of the ground water now used in the State. (These water-bearing sediments are referred to as "basin-fill aquifers.") Although the carbonate rocks were deposited as widespread layers, geologic forces subsequently deformed the rocks into innumerable "blocks" of rock 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 that constitute aquifers is greatly complicated (as are the paths followed by ground-water flow through the rocks).** Figure 2 shows the typical distribution of rocks beneath valleys of southern Nevada. The rocks that compose some of the blocks may be highly productive aquifers, whereas other rocks may transmit only moderate quantities of water, and still others may impede flow altogether. The numerous faults shown in **figure 2** facilitate ground-water flow under some conditions and impede flow under others.

Water in the carbonate-rock aquifers flows away from areas where water has infiltrated the land surface and moves down to the water table (this water is called "ground-water recharge"). Most recharge to the aquifers of southern Nevada (both carbonate-rock and basin-fill) originates in the high mountain ranges, where rainfall and snowfall rates are greatest and where large accumulations of springtime snowmelt release large quantities of water on the land surface over a sustained period of time. Rain that falls directly on the valley floors provides only meager quantities of recharge. Under natural conditions, recharge from the mountains flows within the aquifers toward springs or areas where plants extract and use it or where the water evaporates directly through the overlying soil. The springflow, use by plants, and evaporation are together termed "ground-water discharge." **Along its path from recharge to discharge, water may flow through basin-fill aquifers, carbonate-rock aquifers, or both.** Water flows between aquifers to connect the ground-water systems in some places [for example, in Pahrump Valley (Harrill, 1986, p. 27) and at Ash Meadows (Dudley and Larson, 1976, p. 48)]. As a result, the large flow systems in southern Nevada typically include both basin-fill and carbonate-rock aquifers (Harrill and others, 1988).

IV. HOW ARE THE CARBONATE-ROCK AQUIFERS BEING STUDIED?

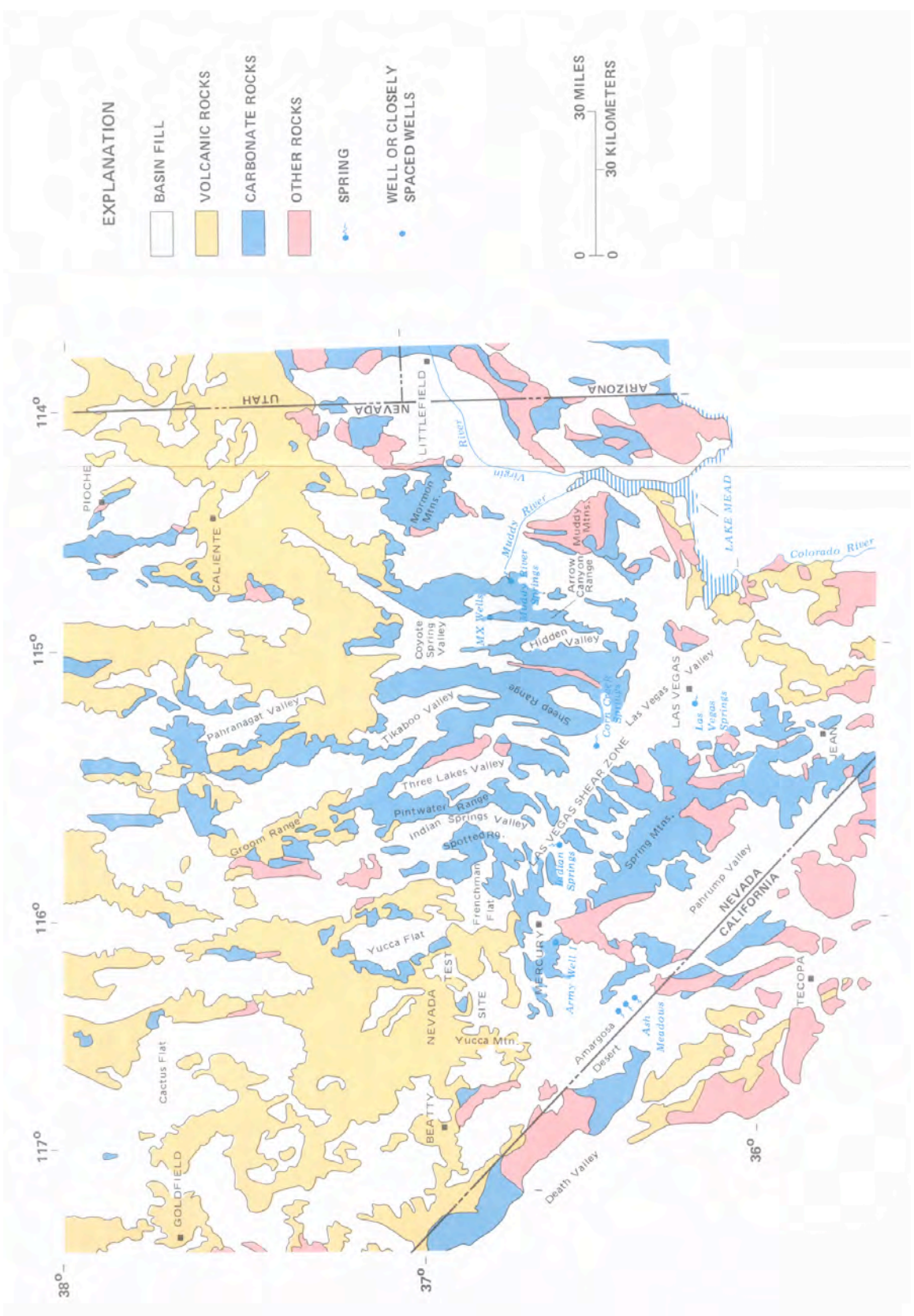
Accurate definition of the potential for developing carbonate-rock aquifers requires an understanding of the configuration and physical properties of the carbonate and intervening noncarbonate rocks, coupled with estimates of the volume of water contained in and moving through them. To develop the required understanding, the following activities were undertaken in 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 at 2 sites used to estimate evaporation rates and water consumption by native plants.

Continuous measurements (data in Pupacko and others, 1988, p. 48, 50, 61; and Pupacko and others, 1989, p. 45-47, 57) 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-feet per year) reported by Eakin (1964, p. 17) and that the discharge from Corn Creek Springs also is nearly uniform at about the rate measured during 1947-55--about 200 acre-feet per year (Malmberg, 1965, p. 60). (The location of these springs and all other sites and features specifically mentioned in this section is shown in **figure 3**.) The continuing long-term and short-term uniformity of these discharges indicate that the springs have not been affected measurably by the pumping of nearby wells. 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. Water levels in some wells, for example, fluctuate about 0.2 foot seasonally.

Geology was mapped for an area of about 1,800 square miles 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 (Guth, 1986; Guth and others, 1988), interpretation of geophysical measurements (Blank, 1988), and correlation of observations with aerial photography and satellite imagery (McBeth, 1986).

Results of the mapping indicate that small openings through which small volumes of water can flow probably are common throughout the region. These openings resulted from region-wide geologic forces that fractured the rocks. Along certain recently active, steeply dipping faults (such as those that form the steep margins of mountain ranges), rocks were fractured and fragmented under conditions that allowed them to develop and maintain larger openings through which large volumes of water can flow. These fault zones may constitute the principal paths through which most ground water flows in the carbonate rocks. In contrast, rocks that were fractured and fragmented along older, flat-dipping fault zones subsequently resolidified into rock masses that now can impede ground-water flow (Dwight L. Schmidt, U.S. Geological Survey, written communication, 1987).



EXPLANATION

- BASIN FILL
- VOLCANIC ROCKS
- CARBONATE ROCKS
- OTHER ROCKS
- SPRING
- WELL OR CLOSELY SPACED WELLS



Land-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. This effort included collection of about 200 gravity measurements, 7 seismic-refraction profiles, and more than 65 geoelectrical measurements of the resistivity of rock far below the land surface using direct-current, audiomagnetotelluric, and magnetotelluric methods (Pierce and Hoover, 1986).

Interpretation of these measurements shows that thicknesses of basin fill overlying carbonate rocks range from less than 500 feet in Hidden Valley to about 1,000 feet in Coyote Spring Valley, about 2,000-3,000 feet in northwestern Las Vegas Valley, and more than 6,000 feet beneath southern Tikaboo Valley (Donald H. Schaefer, U.S. Geological Survey, written communication, 1988). Estimates of thickness are critical in siting exploration wells in these valleys. The geoelectrical measurements also showed that the highly productive wells drilled in Coyote Spring Valley during the Air Force's MX Missile-Siting program during 1980-81 (referred to as MX wells hereafter) 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 (Pierce and Hoover, 1986, fig. 2).

Water samples were collected and analyzed to characterize ground water and 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 budgets 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 (Emme, 1986; Hershey and others, 1987; Kirk and Campana, 1988; Lyles and Hess, 1988; Noack, 1988; Thomas, 1988). 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 (Thomas, 1988). Also, flow in the basin-fill aquifers of the Las Vegas shear zone--a complicated geologic feature extending from the northeastern part of Las Vegas Valley nearly to Mercury, Nev., beneath the valley floors--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). The studies of Emme (1986), Schroth (1987), Kirk and Campana (1988), and Thomas (1988) generally verify the overall water budgets developed by previous investigators (Rush, 1964; Eakin, 1966; Winograd and Friedman, 1972) for regional flow beneath the White River drainage in east-central Nevada (fig. 1). 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 inadequate quality for many uses (Lyles and others, 1986; Schroth, 1987, p. iii).

Wells were drilled, logged, and tested in the basin-fill and carbonate-rock aquifers to provide direct observations of aquifer characteristics (Lyles, 1987; Berger and others, 1988; Morin and others, 1988). 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 MX wells. The aquifers were tested at three of the new wells and at three of the MX wells during 1985-88 to determine transmissivity (the capacity of the aquifers to transmit water). Results from reports of specialized tests in 13 oil-test wells (McKay and Kepper, 1988, p. 21, 39) 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 (about 200,000 feet squared per day) and productivity also is high [3,400 gallons per minute pumped with only 12 feet of water-level decline (Ertec Western, Inc., 1981, p. 51)], 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, where 455 gallons per minute can be pumped for long periods of time with 85 feet of water-level decline (drawdown) in the well. The transmissivity at Army Well 1 is estimated to be between 5,000 and 11,000 feet squared per day (Winograd and Thordarson, 1975, table 3, well 67-68).

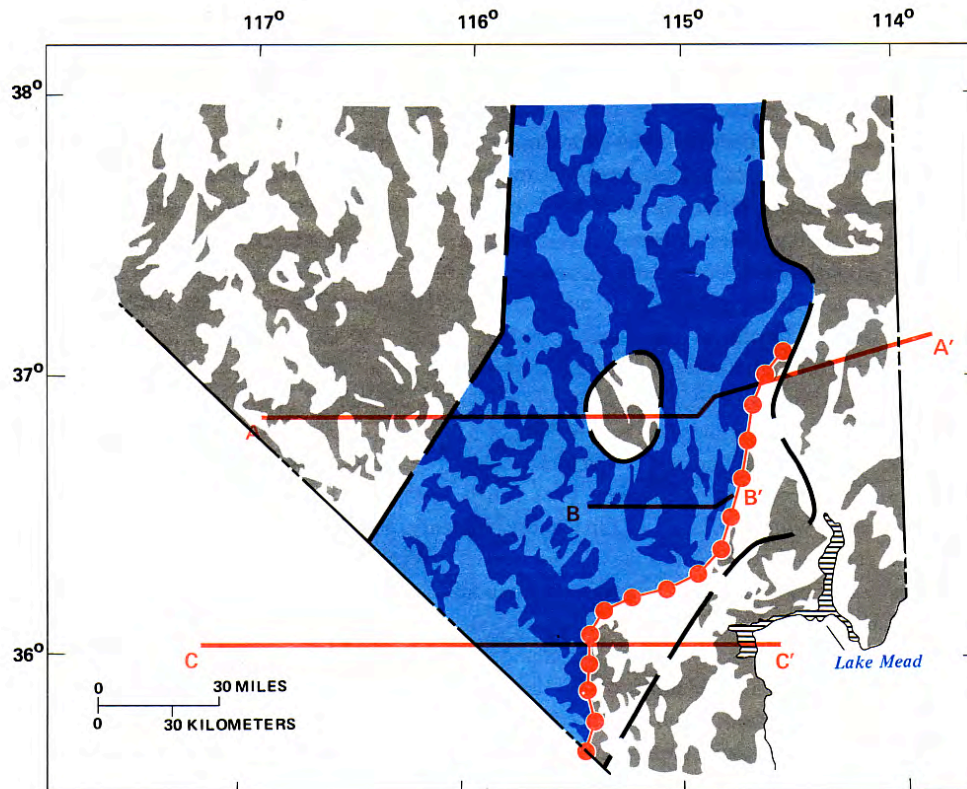
Geophysical logging in the wells measured rock properties that are dependent on primary porosity (open spaces between grains in the rocks) and secondary porosity (fracture and dissolution cavities). These porosities are important in determining the quantity of water contained in a given volume of aquifer material. The total porosities--primary plus secondary--estimated from the geophysical logging were similar to those reported from laboratory measurements of rocks collected at the Nevada Test Site (Winograd and Thordarson, 1975, p. C17), which averaged 5.5 percent. Secondary porosity, as estimated from the logs in zones where many fractures are present, locally may constitute almost half of that total (David L. Berger, U.S. Geological Survey, written communication, 1988).

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, an additional effort synthesized the results from all of these activities, together with results from many other hydrogeologic and geologic investigations. The following sections report on the results of that synthesis in terms of the three basic concerns listed earlier: the location of water in the aquifers, the quantity of water, and the potential effects of development.

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

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 are widespread and originally were very thick (up to 40,000 feet 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 feet. **Figure 4** shows the location of the central corridor of thick carbonate rocks and **figure 5** shows cutaway views of subsurface geology along several lines across southern Nevada. **Line A-A'** coincides approximately with the Clark-Lincoln County boundary, and shows a very nonuniform thickness of carbonate rocks (the blue shaded zones). Within the central corridor, two areas are underlain by thick and relatively continuous carbonate rocks--the Pintwater-Spotted Range area (Guth, 1988) and Coyote Spring Valley area (Guth, 1988; Wernicke and Axen, 1988a, p. 1749). These two areas are connected to a similarly thick carbonate-rock mass described 60 miles farther north by Bartley and others (1988, p. 1). 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 (Dettinger, 1987). Thus, **these thick and continuous carbonate-rock masses largely constitute the regional carbonate-rock aquifers.** East and west of the central corridor are blocks of carbonate rock (west of Yucca Mountain and beneath the Mormon Mountains) that are thick but largely isolated from carbonate-rock aquifers in other areas by noncarbonate materials of low transmissivity (Wernicke and others, 1985, fig. 15; Blank, 1988; Carr, 1988; Hamilton, 1988, p. 57, 61, 79; Scott, 1988; Wernicke and Axen, 1988b, fig. 2). The blocks are much thinner both north and south of the section shown, and, as a result, do not receive regional inflow. These carbonate rocks therefore transmit little water.

Farther south, **line B-B'** shows the rocks beneath a short line of section just north of Las Vegas and indicates the presence of thick carbonate rocks east of the Sheep Range (Guth, 1980, plate 2). At moderate 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 of water that recharges the range. This barrier provides geologic support for geochemical balances developed during this study which suggest that nearly all the water recharging the Sheep Range flows to the north and east toward Muddy River Springs (Thomas, 1988)



EXPLANATION






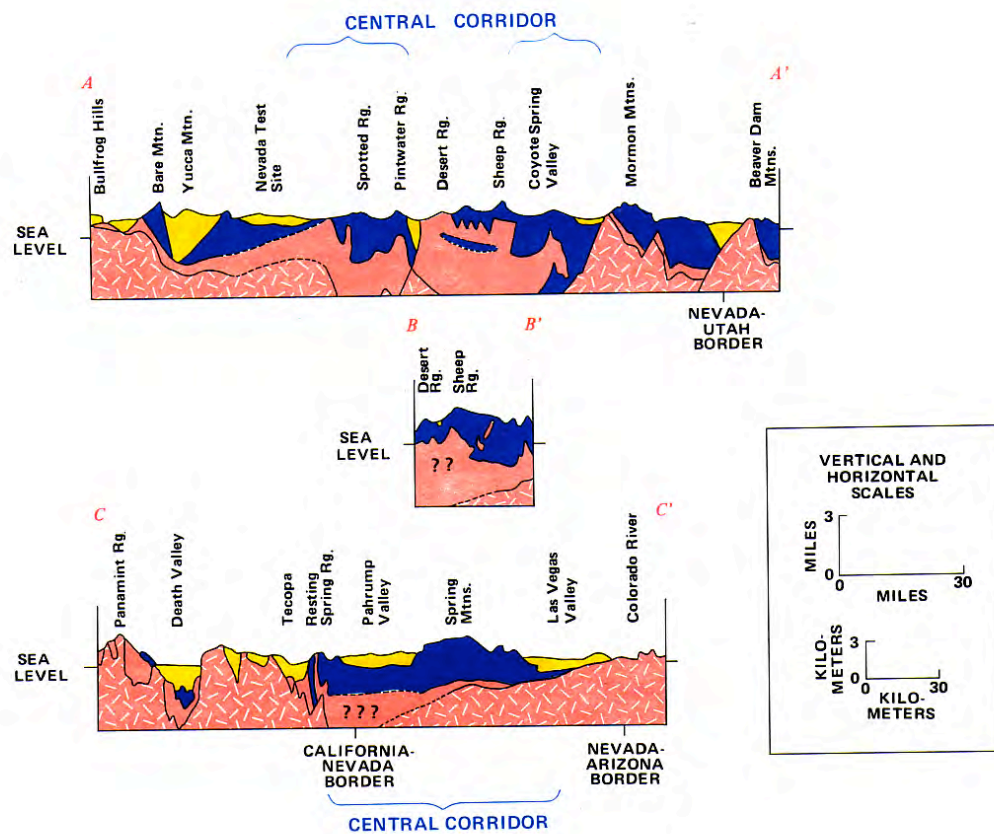
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| <p> AREA UNDERLAIN BY THICK SEQUENCES OF CARBONATE ROCKS THAT ARE EXPECTED TO CONTAIN WATER OF GENERALLY GOOD QUALITY -- Dark blue areas, bedrock outcrops; light blue areas, basin fill</p> <p> BOUNDARY OF CENTRAL CORRIDOR</p> <p> LOCATION OF HYDROGEOLOGIC SECTION IN FIGURE 5</p> | <p> AREAS UNDERLAIN BY THIN OR ISOLATED CARBONATE ROCKS, OR CARBONATE ROCKS THAT MAY CONTAIN POOR-QUALITY WATER -- Gray areas, bedrock outcrops; white areas, basin fill</p> <p> WESTERN LIMIT OF ROCK SEQUENCES CONTAINING SALT-BEARING MINERALS AND OVERLYING CARBONATE ROCKS -- Ground water east of line is of generally poor quality</p> |
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FIGURE 4.--Central corridor of thick carbonate rocks that contain water of generally good quality (that is, water suitable for most uses). Delineation of bedrock and basin fill from Stewart and Carlson, 1978.



EXPLANATION

- BASIN FILL OR VOLCANIC ROCKS, OR BOTH**

OLDER, NONCARBONATE SEDIMENTARY ROCKS -- Edges dashed where thickness is particularly uncertain
- CARBONATE ROCKS -- Includes layers of noncarbonate sedimentary rocks. Edges dashed where thickness is particularly uncertain**

OLDER METAMORPHIC AND IGNEOUS ROCKS (CRYSTALLINE BASEMENT) -- Locally includes younger igneous rocks

FIGURE 5.--Hydrogeologic sections across southern Nevada. Section A-A' is based on work of Scott and Whitney (1987), Guth (1988), P.L. Guth (U.S. Naval Academy, written communication, 1988), and G.L. Axen (Harvard University, written communication, 1988). Section B-B' is based on work of Guth (1980) and D.L. Schmidt (U.S. Geological Survey, written communication, 1986). Section C-C' is based on work of Wright and others (1981) and Smith and others (1987).

Line C-C' shows a single, continuous corridor of thick carbonate rocks that is 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 underlies 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. 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 (Hershey and others, 1987).

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 highly transmissive zones may act 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. This hypothesis is supported by field observations of a few flow tubes--resembling very long, narrow caves--that evidently formed during transmission of large volumes of water prior to being lifted up to the present-day land surface by geologic forces (Dwight L. Schmidt and Alan M. Preissler, U.S. Geological Survey, written communications, 1986). The few tubes observed are located along major fault zones around the Muddy River Springs area and are surrounded by large volumes of rock containing myriad small, sealed fractures that evidently never developed into important flow conduits after they were opened long ago.

In addition to suggesting a relation between highly transmissive zones and regional springs, the present study has hypothesized that **such zones may stay highly transmissive only if large volumes of water continue to flow through them**. Otherwise, openings in the rocks gradually fill with minerals and the rocks resolidify. Many of the 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, the flow tubes along major fault zones exhibit numerous characteristics of wall dissolution by flowing ground water. This dissolution widened the openings and enhanced what probably were already fairly high transmissivities. Results from tests of carbonate-rock aquifers throughout eastern and southern Nevada indicate that within 10 miles of regional springs, aquifers are an average of 25 times more transmissive than they are farther away. These are areas where flow is converging and flow rates are locally high. The high transmissivities near regional springs could reflect the presence of structures that were more recently active than elsewhere (although that is not demonstrated by the present study), or they may be a further indication that the large volumes of flow concentrated upgradient from the springs are enhancing or maintaining the high transmissivities.

If these hypotheses prove true, then wells that tap conduits of concentrated regional flow probably will be most productive. Certain faults--especially recently active range-bounding faults--are most likely to create openings in the rocks through which concentrations of flow can be transmitted, as noted previously. 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 commonly intermingle with other rocks containing thick or numerous layers of salts (evaporite minerals such as gypsum and halite), and (2) areas elsewhere in southern Nevada where these other rocks are nearly absent (fig. 4). The evaporite-bearing rocks east of the transition are younger than most of the carbonate rocks and older than the volcanic rocks and basin-fill aquifers (Longwell and others, 1965, p. 38; Tschanz and Pampayan, 1970, p. 60-63). The complex geologic history of the area has placed these younger rocks in complicated and unpredictable juxtaposition with the carbonate rocks. **The present investigation minimized study efforts in southeasternmost Nevada because development of the carbonate-rock aquifers there risks the encounter of ground water that is unsuitable for many uses (Lyles and others, 1986).**

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

The water resource of the carbonate-rock aquifers is the sum of the perennial yield of the aquifers and the reserve of water stored in them. The perennial yield is the quantity of water that can be extracted for use each year over an indefinite period of time without depleting the ground-water reservoir (Scott and others, 1971, p. 13). The perennial yield can be no greater than the total rate of flow through the aquifers, and it probably is less. For the estimates presented herein, the quantity of water that goes into the aquifers (as recharge and inflow from other areas) is assumed, on average, to equal the quantity that discharges. Under this assumption, the rate of flow within the aquifer is equal to the total income (recharge) and the total output (discharge) of the aquifers. At present (1989), the total rate of flow through the carbonate-rock aquifers cannot be estimated directly, but rather must be 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 the aquifers of southern Nevada, both carbonate and noncarbonate. Because the fraction recharging the carbonate-rock aquifers alone cannot be estimated, the total recharge will be estimated to provide an upper limit on estimates of total flow. 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

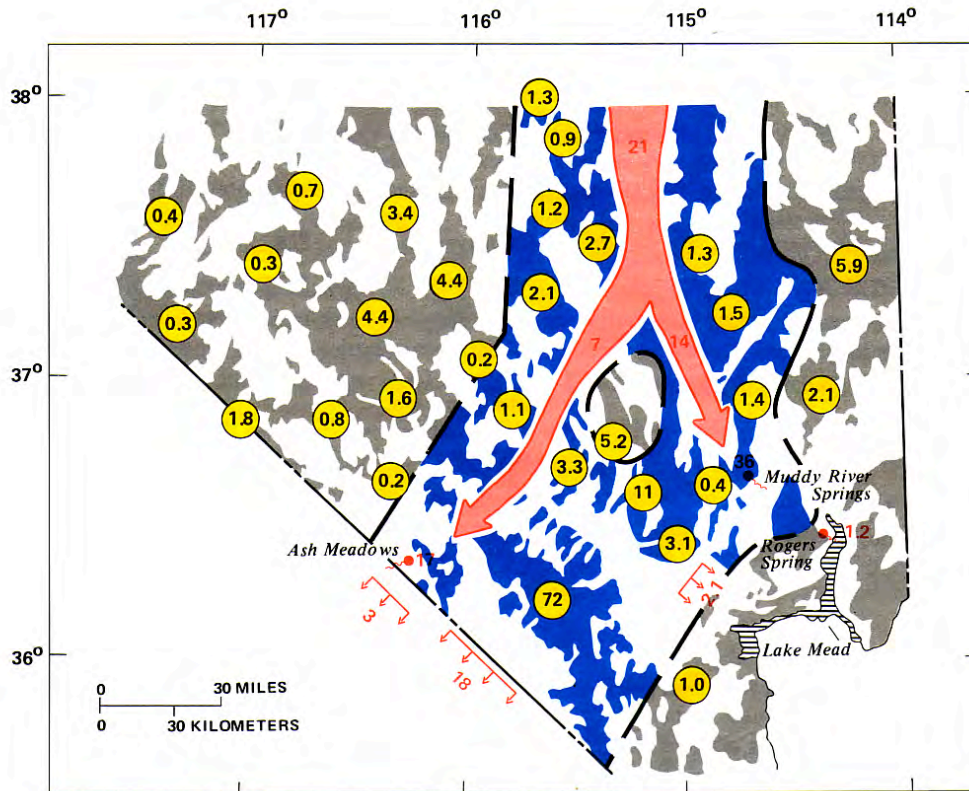
discharge from the carbonate-rock aquifers is by unseen subsurface leakage of water into adjacent basin-fill aquifers. The rate of land-surface discharge from the carbonate-rock aquifers therefore provides a lower limit on estimates of total flow. Thus, the total flow rate is bracketed between a regional 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-feet annually, of which about 110,000 acre-feet is generated within the central corridor of thick carbonate-rock aquifers (**fig. 6**). The estimates are based mostly on previous studies that range from reconnaissance investigations to numerical models of ground-water flow (Harrill, 1976, p. 50; Harrill, 1986, p. 46; Harrill and others, 1988, sheet 2). The principal insights from the present study define where recharge may be entering regionally extensive aquifers.

In addition to ground-water recharge in southern Nevada, geochemical balances computed in the present study show that **another 21,000 acre-feet per year is supplied to southern Nevada by inflow through carbonate-rock aquifers from east-central Nevada** (Kirk and Campana, 1988; Thomas, 1988). Together recharge plus inflow totals about 160,000 acre-feet per year.

Part of the total ground-water income (recharge plus inflow) flows 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-feet directly from carbonate-rock aquifers of the central corridor**, as summarized in **figure 6** (Harrill, 1976, p. 50; Hess and Mifflin, 1978, appendix II; Harrill, 1986, p. 46; Harrill and others, 1988, sheet 2; and springflow measurements made during this study). 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-feet per year (Scott and others, 1971, table 3); natural discharge from the basin fill is primarily by evaporation or use by native plants excluding those supplied by regional springs.

The various inflows to and outflows from all aquifers of the central corridor are summarized in **table 2**, which shows that about 130,000 acre-feet may be entering the aquifers each year. Under natural conditions, an equal quantity was discharged from springs, streams, and playas in southern Nevada and nearby parts of California each year.



EXPLANATION

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|--|--|--|---|
| | BASIN FILL | | BEDROCK WITHIN CENTRAL CORRIDOR |
| | BEDROCK OUTSIDE CENTRAL CORRIDOR | | BOUNDARY OF CENTRAL CORRIDOR |
| | GROUND-WATER RECHARGE, BY MOUNTAIN RANGE -- Number is thousands of acre-feet per year (modified from Scott and others, 1971; Harrill 1976, 1986) | | GENERAL DIRECTION OF REGIONAL GROUND-WATER INFLOW -- Number is thousands of acre-feet per year (from Thomas, 1988) |
| | REGIONAL SPRINGS -- Number is discharge, in thousands of acre-feet per year (from Hess and Mifflin, 1978; and measurements made during this study) | | REGIONAL GROUND-WATER OUTFLOW -- Number is thousands of acre-feet per year (from Scott and others, 1971; Harrill, 1976, 1986) |

FIGURE 6.--Components of regional ground-water budget.

TABLE 2.--Water budget for the central corridor of carbonate-rock aquifers
 [All rates are in thousands of acre-feet per year]

Recharge source	Rate	Discharge mechanism	Rate
Mountains of southern Nevada	110	Regional springs	54
Regional ground-water inflow	21	Regional ground-water outflow	about 23
		Discharge from basin-fill under natural conditions	about 50
TOTAL RECHARGE (ROUNDED)	130	TOTAL DISCHARGE (ROUNDED)	130

As a result of this equilibrium between income and output, 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. This equality between observed rates of discharge and inferred rates of recharge can be wrong only if the present-day system is not in a natural equilibrium or if some component of discharge has been overlooked. A review of aquifer conditions within and along the boundaries of the central corridor suggests 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 be overlooked in this study.** In particular, no large, currently unidentified quantities of water are likely to be flowing out of southern Nevada to the Colorado River or Arizona.

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: **For practical purposes, 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-feet per year).**

The actual rate at which water can be withdrawn without continual depletion of the ground-water reservoir may depend on how the resource is developed. This is because practical strategies to capture spring flow and outflow may entail inefficiencies that allow part of the flow to avoid capture. These inefficiencies will depend on where and how the water is withdrawn. For example, Harrill (1986, p. 43) used a computer model to show that ground water flowing toward regional springs near Tecopa, Calif. (fig. 3), would be difficult to capture at pumping sites upgradient in Pahrump Valley. Thus, **if wells some distance from regional springs are pumped in an effort to capture the spring flows at logistically convenient locations, the sustainable rates of withdrawal may be considerably less than the present flow rates from the regional springs and discharge areas.**

If the basin-fill and carbonate-rock aquifers were managed together, then 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. **Ground-water flow beneath southern Nevada totals about 160,000 acre-feet per year--**about 110,000 recharges mountains in the central corridor, about 30,000 recharges mountains outside the central corridor, and about 21,000 originates in east-central Nevada. **This ground water flows through the carbonate rocks or basin fill, or (along many flow paths) both. Managing the aquifers separately will not increase the total resource.**

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 square miles; fig. 4) and great thickness of the carbonate rocks in the central corridor (between 3,000 and 19,000 feet and averaging about 12,000 feet), the total volume of rock is enormous. Carbonate rocks that might store and transmit water south of the latitude of Pioche and Tonopah are estimated to total about 20,000 cubic miles. Borehole geophysical measurements made during 1985-88 suggest that the total amount of open space within these rocks may be on the order of 1 to 10 percent, and previous studies at the Nevada Test Site (Winograd and Thordarson, 1975, table 2) suggest that about one-fifth of that space is connected and will allow ground water to move through it. Therefore, if the water stored in selected parts of the carbonate-rock aquifers were extracted, the volume obtained might be 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 on the order of 800 million acre-feet. For practical purposes, not all this water can be extracted. However, **if all the water stored in the upper 100 feet of the aquifer's thickness could be extracted, the central corridor could yield on the order of 6 million acre-feet of stored water.**

Stored water is by far the largest part of the water resource of the carbonate-rock aquifers; that is, the total volume of water stored in the carbonate-rock aquifers of southern Nevada greatly exceeds the annual rate of flow through the aquifers. For example, the current rate of spring discharge and subsurface outflow from the carbonate-rock aquifers (about 77,000 acre-feet per year) is only about one ten-thousandth of the estimated total volume of storage and one one-hundredth of the water stored in the upper 100 feet of aquifer. The water stored in the upper 100 feet, if depleted regionally, would be replenished only by the equivalent of decades or centuries of recharge. In contrast, if stored water were depleted only locally, adverse effects might be manageable, especially if well fields were sited to take advantage of geologic barriers that could partly or wholly prevent the large-scale spread of effects. Regional and local depletions of stored water can be expected to decrease discharge from the aquifers eventually, but the magnitude and timing of even these decreases may be manageable by advantageous choices of well sites.

The volumes of water moving through and stored in the carbonate-rock aquifers can be compared in magnitude to other water resources in southern Nevada:

- The recharge rate to all aquifers in the central corridor south of Pioche and Tonopah (about 110,000 acre-feet per year) is equal to about one-third of Nevada's allocation for consumptive use of Colorado River water (300,000 acre-feet per year, according to URS Company and Converse Ward Davis Dixon, 1982, p. 74).
- The rate of discharge directly from the carbonate-rock aquifers (77,000 acre-feet per year) is 2.6 times the estimated natural recharge rate to the basin-fill aquifers of Las Vegas Valley as given by Harrill (1976, p. 50).
- The volume of water stored in the upper 100 feet of the carbonate-rock aquifers of the central corridor (on the order of 6 million acre-feet) is equivalent to about one-quarter of the usable storage volume of water in Lake Mead, about 8 months of average flow in the Colorado River (as given by Pupacko and others, 1988, p. 78-80), and about 23 years of Nevada's allocation for consumptive use of Colorado River water.
- Finally, the volume of water stored in the upper 100 feet of carbonate-rock aquifers is about one-sixth of the quantity stored in the upper 100 feet of basin-fill aquifers overlying the central corridor (the latter as compiled from Scott and others, 1971, table 1).

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

VII. WHAT EFFECTS MIGHT RESULT FROM DEVELOPMENT OF THE CARBONATE-ROCK AQUIFERS?

Possible effects of developing the carbonate-rock aquifers include declining water levels, decreasing spring-flow rates, drying up of some streams, playas, and meadows, and changing 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.

Sustained effects within the carbonate-rock aquifers resulting from development of those aquifers have not been observed to date, but this reflects more the lack of aquifer development than a lack of potential for effects if such development were undertaken. The magnitude and extent of water-level changes and, eventually, changes in spring-flow rates caused by development would depend on the geometry of the aquifers and their capacity to transmit and store water. Such effects can be predicted roughly by using either engineering-style hydraulic calculations or more complex computer models of ground-water flow. The hydraulic equations--such as those of Theis (1935)--ignore much of the complex structure of the carbonate-rock aquifers but still can provide useful insight into the probable extent of water-level declines on the basis of the observed capacity of the aquifer to transmit and store water.

Hydraulic calculations such as those made by using the Theis equation involve many restrictive assumptions that are only loosely applicable to southern Nevada, but they nonetheless indicate that **water-level declines associated with a pumped well in a carbonate-rock aquifer may be moderate to small in most locations where the aquifer is unconfined, but would be much larger where the aquifer is confined.**¹ Water-level declines in extensive, unconfined carbonate-rock aquifers commonly would be between about 1 and 70 feet within 1 mile of a production well after 10 years of pumping at 1,000 gallons per minute. This predicted range is calculated by assuming that the range of transmissivities includes the middle two-thirds of those calculated on the basis of measurements at 39 carbonate-rock wells in Nevada; the particular values assumed were between 700 and 114,000 feet squared per day. Also assumed is a storage coefficient of 1 percent under unconfined conditions. Applying these assumptions further, calculated water-level declines 10 miles from the pumped well in an unconfined part of the aquifers would be between a fraction of a foot and several feet. If, instead, the developed aquifer is confined

¹ Heath (1983, p. 6) describes unconfined aquifers as those in which water only partly fills the transmissive rocks, so that the upper surface of water in the openings in the rock can rise and decline in response to pumping. In contrast, confined aquifers are those in which water completely fills the entire thickness of transmissive rock up to an overlying layer that restricts vertical flow of ground water. In confined aquifers, water pressure, not water level, rises and declines in response to pumping.

(assuming a storage coefficient of 0.01 percent with all other assumptions unchanged), then the predicted water-level declines after 10 years would range between about 1 foot and about 200 feet at 1 mile from the pumped well, and between about 1 and 70 feet at 10 miles.

These calculated drawdowns range over hundreds of feet, reflecting broad uncertainties. The calculations, however, demonstrate the important difference between developing unconfined parts of the aquifers rather than confined parts. Until more experience is gained with stressed carbonate-rock aquifers, site-specific predictions of the degree of confinement exhibited by a selected part of the carbonate-rock aquifers will be accurate only where based on direct observation of water-level fluctuations and analysis of short-term effects of development. Still, a preliminary review of hydrogeologic conditions leads to the hypothesis that water levels in the aquifers will respond to development over tens of years and at long distances from pumping as if the aquifers were unconfined. Continuous, low-permeability layers that might confine the aquifers over large distances are expected to be uncommon because the carbonate-rock aquifers have been deformed along steep faults in so many places. If so, adverse effects may be restricted to relatively small areas around a development.

Neither set of calculations (for unconfined and confined conditions) accounts for the large directional influence on declines that would be expected if the well were drawing water from narrow, highly transmissive zones such as those hypothesized in an earlier section. As a consequence, the calculated declines around wells drawing water from these zones may be underestimated along the zones and overestimated away from the zones. The calculated declines therefore are only general indications of the magnitude of effects that might be expected, and are subject to large revisions when nonuniform properties of the aquifers can properly be taken into account.

The carbonate rocks do not form a single, thick layer beneath southern Nevada, but rather are distributed as corridors and blocks. The preceding calculations of drawdown around aquifer developments assume that the aquifer extends far beyond the area affected by pumping. Currently (1989), data that accurately account for the influence of aquifer geometry are not available to support detailed predictions of potential effects of development. The study discussed herein did not attempt to model development effects at any specific localities, but several previous studies have included computer models that provide insight into the problems of prediction. A review of those models suggests 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 (Bateman and others, 1974; Rojstaczer, 1987) or whether the flow toward Death Valley is being simulated at a regional scale (Bedinger and others, in press), **the geologic complexity of southern Nevada is hydrologically important and must be considered in predicting development effects.** The numerous fault-zone orientations, differing 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 predictions can be made, and probably (2) that those predictions be based on effective use of sophisticated computer models. An alternative that may be adequate in some areas of relatively simple aquifer geometry is the application of hydraulic equations using boundary representations, of the sort described by Bear (1979, section 8-10).

The potential for adverse effects in adjacent aquifers resulting from development of the carbonate-rock aquifers is another concern. Available methods for hydraulic calculation of effects in an aquifer that overlies a second, stressed aquifer--similar in style and simplicity to the Theis equations of 1935--probably are not applicable to the complex geologic setting in southern Nevada. However, historical experience with such conditions is available at two areas in southern Nevada that have undergone 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 near pumped wells. However, the historical conditions at Ash Meadows and Muddy River Springs, where the basin-fill aquifers were developed instead of underlying carbonate-rock aquifers, are the reverse of the type of development being assessed herein. **At Ash Meadows, direct connections between pumping from basin-fill aquifers and water-level declines in the carbonate rocks were demonstrated (fig. 3).** Withdrawals from irrigation wells near Devils Hole drew down water levels by more than a foot in the carbonate-rock aquifers between 1969-72 (fig. 7; Bateman and others, 1974; Dudley and Larson, 1976). The water levels recovered slowly but steadily over a period of about 15 years after pumping ceased (fig. 7). Pumping water from some of the wells also resulted in rapid declines of flow from nearby springs that discharge from the carbonate-rock aquifers. **Around the Muddy River Springs (fig. 3), in contrast, varying levels of development of ground water from basin-fill aquifers over the last 20 years have resulted in minimal changes in water levels of the carbonate-rock aquifers** (Martin D. Mifflin, Mifflin and Associates, Inc., written communication, 1987; Pohlmann and others, 1988, p. 14). These small changes are difficult to quantify or to attribute to specific development activities. No long-term changes in spring flow have been measured or recognized during this study. The difference between historical responses at these two areas probably could not have been predicted before the aquifers were pumped and early effects observed. Thus, experience with aquifer development at the Ash Meadows and Muddy River Springs areas indicates that the potential for adverse effects on both basin-fill and carbonate-rock aquifers can be assessed only on a site-by-site basis. **Different hydrogeologic settings in southern Nevada can be expected to respond differently to aquifer development.**

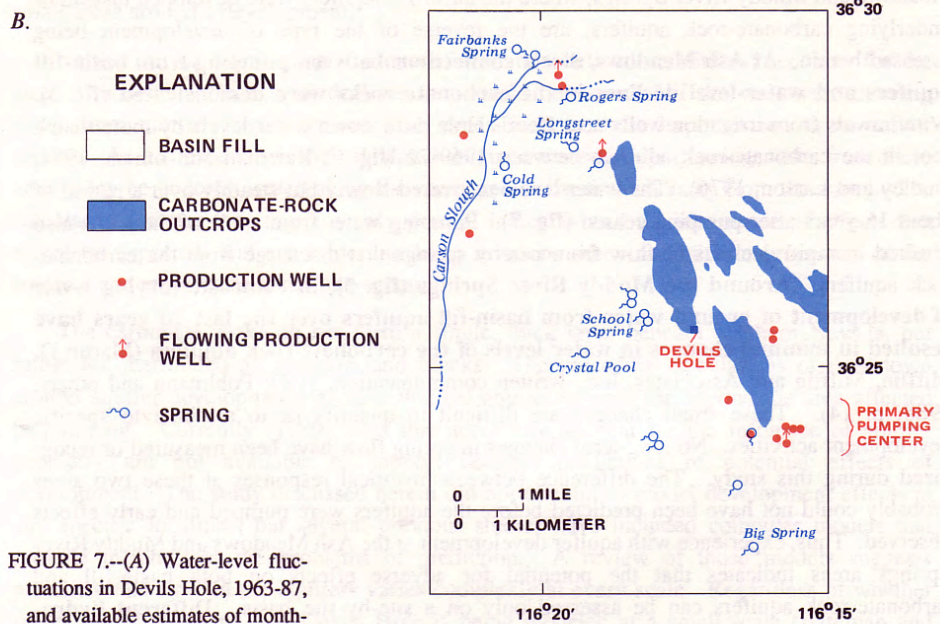
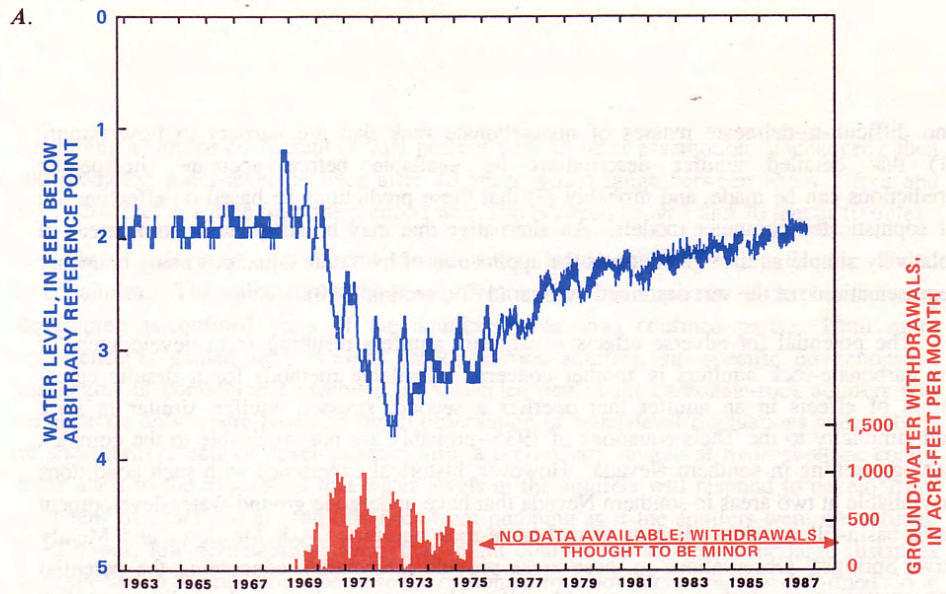


FIGURE 7.--(A) Water-level fluctuations in Devils Hole, 1963-87, and available estimates of monthly ground-water withdrawals for irrigation in Ash Meadows area.

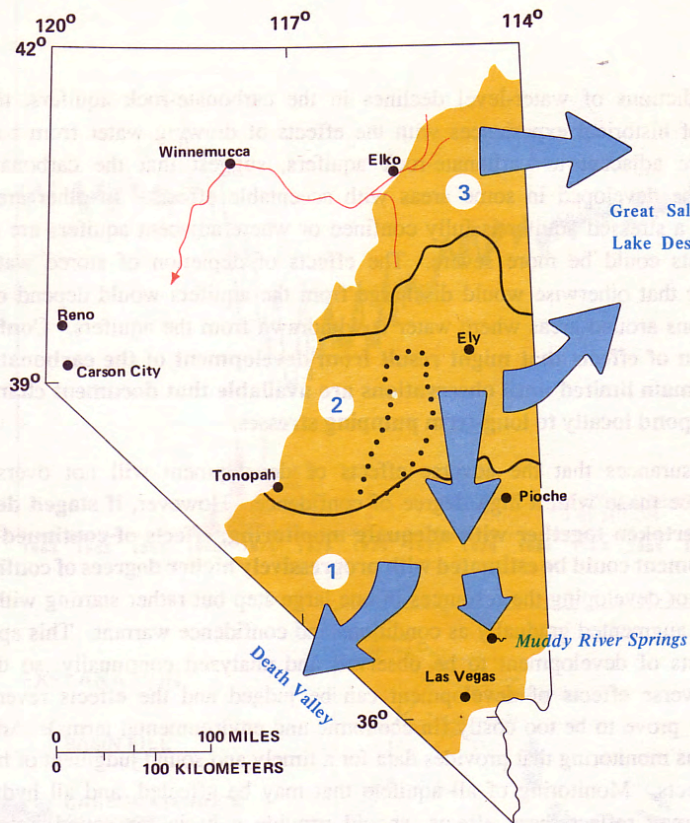
Water-level data from U.S. Geological Survey files; pumpage estimates from Bateman and others (1974), Larson (1974a, 1974b, and 1975), and Dudley and Larson (1976). (B) Location of Devils Hole, production wells, and springs in Ash Meadows area (see fig. 3). Modified from Larson (1974b, fig. 2).

Simple predictions 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 that are adjacent to carbonate-rock aquifers, suggest that the carbonate-rock aquifers might be developed in some areas with acceptable 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 prediction of effects that might result from development of 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 benefits and adverse effects 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 benefits and adverse effects. 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 signs of effects of development and that allows these effects to be distinguished from natural fluctuations, would provide information for timely judgments.

VIII. WHAT ISSUES REMAIN TO BE RESOLVED?

In southern Nevada (fig. 8), studies during 1985-88 have advanced the understanding of ground-water flow in the carbonate-rock aquifers, but the foundations of this new understanding still are of a qualitative and regional nature. Uncertainties remain concerning some regional flow components and most site-specific issues. Despite these limitations, the studies provide a groundwork for future resource evaluations of local areas and for site-specific studies intended to locate and design production well fields.



EXPLANATION

- CARBONATE-ROCK PROVINCE OF NEVADA
- GENERAL DIRECTION OF REGIONAL GROUND-WATER FLOW
- EXISTING OR PROPOSED STUDY-AREA BOUNDARY WITHIN CARBONATE-ROCK PROVINCE
- HUMBOLDT RIVER
- BOUNDARY OF RAILROAD VALLEY
- 1 STUDY AREA -- 1, southern Nevada; 2, east-central Nevada; 3, northeastern Nevada

FIGURE 8.--Location of existing southern Nevada study area (1985-88) and proposed east-central and northeastern study areas, in relation to directions of regional ground-water flow and other features.

Future studies could productively include drilling and testing beyond that done for the studies described herein (for instance, to locally identify flow systems that would be penetrated by production wells, to determine engineering-design requirements for such wells, and to address other site-specific issues such as whether the aquifer is confined or unconfined). In contrast, additional regional-scale investigations in this part of the State reasonably could be postponed until after some of these localized investigations. Consequently, **work in southern Nevada in the near future could focus productively on localized drilling and testing programs, whereas regional-scale studies and resource evaluations could focus productively on the central and northeastern parts of the State.**

Higher altitudes and more northern location make east-central Nevada (fig. 8) much wetter than southern Nevada. As a result of this greater wetness, some components of the water budgets of the carbonate-rock aquifers may be as yet undetected or underestimated. In fact, **if water unaccounted for in present water-budget estimates is to be found anywhere in the carbonate-rock aquifers, it most likely is in east-central Nevada.** This area is the source of most regional ground-water flow throughout the carbonate-rock province. Regional flow systems originating in east-central Nevada discharge both to the south into southern Nevada and to the northeast into Utah (fig. 8; Harrill and others, 1988). In addition, a smaller interbasin flow system discharges tens of thousands of acre-feet per year in Railroad Valley (fig. 8; Van Denburgh and Rush, 1974, tables 8 and 9).

Studies in east-central Nevada could focus on defining the areas that contribute recharge to regional flow systems and on further quantifying the regional outflow. These studies also could determine which areas contribute recharge to the more localized flow systems. This focus would help improve estimates of regional flow rates into southern Nevada and western Utah. Most of the same methods discussed in this report could be applied also to studies of regional ground-water flow in east-central Nevada. One complicating factor, however, is the widespread presence of volcanic rocks that form thick sub-regional aquifers (Fiero, 1968; Winograd, 1971, fig. 1; Stewart and Carlson, 1976). Thus, ground water in east-central Nevada would have to be considered in three aquifer types--basin fill, volcanic rocks, and carbonate rocks.

Studies in northeastern Nevada (fig. 8) could focus on locating and delineating supplies for regional water-management plans--for example, the combined water resources of the Humboldt River, the adjacent basin-fill aquifers, and the carbonate-rock aquifers. Other studies could be designed to address the potential for developing water supplies from the carbonate-rock aquifers for uses such as mining, power plants, and small municipalities. Regional-scale flow in northeastern Nevada is believed to be generally eastward toward the Great Salt Lake Desert in Utah. This regional flow, combined with outflow to Utah from east-central Nevada, has been estimated to total about 50,000 acre-feet per year (Harrill and others, 1988). Studies could address which part of this water might be developed with little or no adverse effect in Nevada or western Utah.

IX. CONCLUSIONS

The carbonate-rock aquifers of Nevada are widely distributed, fractured and solution-modified rocks that transmit water beneath mountains and basins. In southern Nevada, the aquifers are thick enough and continuous enough to collect and transmit regional groundwater flow only within a north-south corridor centered under Pahrangat Valley, the Sheep Range and Spotted Range areas, and Spring Mountains. Outside of this corridor, carbonate rocks are present mostly as isolated mountain-sized blocks that do not form regional aquifers.

About 130,000 acre-feet of water recharges to and discharges from aquifers of all types (carbonate and non-carbonate) in the central corridor each year. Of that total, about 77,000 acre-feet discharges each year directly from the carbonate-rock aquifers; nearly all this discharge occurs in Ash Meadows and at Muddy River Springs in Nevada and in Death Valley and vicinity in California. Because regional aquifers are limited to the central corridor, little additional, currently unidentified outflow from the carbonate-rock aquifers of southern Nevada is likely; in particular, the Colorado River does not receive large quantities of outflow from the carbonate-rock aquifers.

Because of the great thickness and extent of the carbonate-rock aquifers and the long distances between the high-altitude recharge areas and the lower-altitude discharge areas, water that discharges today has spent thousands of years flowing through the aquifers. Thus, the quantity of water present in the aquifers at any particular moment is far greater than the quantity entering or leaving the aquifer in a single year. The quantity of water in transit through the aquifers at present may be on the order of 800 million acre-feet, and the quantity stored in just the top 100 feet of the aquifers may be on the order of 6 million acre-feet.

Sustained withdrawal of water from the carbonate-rock aquifers would entail (1) depleting some of the large store of water in transit through the aquifers and (2) capturing some water that would otherwise discharge from the Ash Meadows, Muddy River Springs, and Death Valley areas. These depletions can be expected to result in (1) water-level declines in the carbonate-rock aquifers and, under some circumstances, in the basin-fill aquifers, and, ultimately, (2) spring-flow reductions. The magnitude and geographic range of these effects, however, is largely unpredictable at present. Confidence in predicting effects of specific plans for developing the aquifers is likely to be increased only through a gradual (staged) approach to aquifer development, together with adequate monitoring and interpretation of short-term effects.

In southern Nevada, a regional-scale framework has been developed during the present study that can be used as a basis for site-specific studies in support of actual aquifer developments. Consequently, in the immediate future, regional-scale studies might be focused most productively in wetter areas farther north in the carbonate-rock province.

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