Geohydrology of Areas Being Considered for Exploratory Drilling and Development of the Carbonate-Rock Aquifers in Southern Nevada--Preliminary Assessment

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
foot (ft)	0.3048	meter
inch (in.)	25.40	millimeter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

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 both the United States and Canada.

GEOHYDROLOGY OF AREAS BEING CONSIDERED FOR EXPLORATORY DRILLING AND DEVELOPMENT OF THE CARBONATE-ROCK AQUIFERS IN SOUTHERN NEVADA--PRELIMINARY ASSESSMENT

By Michael D. Dettinger

ABSTRACT

Water suppliers in Las Vegas Valley face an imminent shortfall for peak demands. As one alternative to meet these and greater long-term demands, the development of ground water from the carbonate-rock aquifers of southern Nevada is being considered. As an early step in an exploratory well-drilling program and hydrologic assessment planned jointly by the U.S. Bureau of Reclamation and U.S. Geological Survey, this report details preliminary effort to identify areas favorable for such development. Twenty-six geographic units in Nevada that are within 100 miles of Las Vegas and are underlain by thick carbonate-rock sequences were considered in this assessment. Simple geohydrologic criteria based on existing data are used in narrowing this group to seven units within 25 to 50 miles of Las Vegas: Coyote Spring Valley, Delamar Valley, Indian Springs Valley, the northern part of Las Vegas Valley, Pahranagat Valley, Three Lakes Valley, and Tikaboo Valley. The criteria used are (1) interbasin ground-water flow conditions, (2) real extent of ground-water flow systems (as an approximate measure of the extent of the carbonate-rock aquifer being tapped), (3) stratigraphic or structural thinning of the carbonate-rock sequences, (4) continuity of the carbonate-rock sequences, (5) distance to discharge areas (springs and pumping centers), (6) depth to the potentiometric surface for water in the carbonate rocks, (7) development of overlying basin-fill aquifers (with some consideration of the degree of hydraulic interconnection of basin-fill and carbonate-rock aquifers), and (8) areas with poor water quality or potential for contamination.

INTRODUCTION

Three major aquifer types underlie southern Nevada: basin-fill sedimentary deposits of Tertiary and Quaternary age; jointed or fractured volcanic rocks of predominantly Tertiary age; and thick sequences of carbonate rocks of Paleozoic age. The carbonate rocks are sedimentary rocks dominated by limestone and dolomite that were deposited in a marine environment. The rocks commonly are intensely fractured and locally include solution openings (openings that result from the dissolving of soluble rocks by water moving through pre-existing interstices or fractures). The capacity of these aquifers to store and transmit water is known to differ from location to location, but aquifer characteristics are largely undetermined throughout most of southern Nevada.

Interest in the carbonate-rock aquifers as a water source grew in the early 1980's as a result of a limited but successful exploratory drilling program completed in 1981 as part of the MX-siting investigations funded by the U.S. Air Force (U.S. Department of the Air Force, 1983). As part of that program, two high-yield wells were completed in middle Paleozoic rocks underlying Coyote Spring Valley, northeast of Las Vegas (fig. 1). Prior to the MX-siting investigations, research on the carbonate-rock aquifers focused on the regional ground-water flow systems that discharge at large springs in the Muddy River Springs area and at Ash Meadows (in the Amargosa Desert) near the Nevada Test Site (Eakin, 1966; Winograd and Thordarson, 1968). But much of the present understanding of carbonate-rock aquifer hydrology in Nevada is a result of research done at and near the Nevada Test Site (Winograd and Thordarson, 1975; Waddell and others, 1984).

Water-supply agencies in Las Vegas Valley face an imminent shortfall in water supplies to meet demands during periods of peak water use. One alternative to meet these demands would be the development of additional water from the carbonate-rock aquifers of southern Nevada (URS Company and Converse Ward Davis Dixon, 1982, p. 185). Siting of wells is one of the most pressing problems in tapping this source, and it has prompted geohydrologic investigations by the Desert Research Institute (Hess and Mifflin, 1978), the U.S. Bureau of Reclamation (1984), and the U.S. Geological Survey (first efforts reported herein). Other issues to be resolved are quantifying the amount of water that might be pumped from these aquifers and what effects might be expected for a given level of pumpage.

The purpose of this report is to present the results of an evaluation of large geographic units in southern Nevada (fig. 1) that are underlain by carbonate-rock aquifers, and to propose areas for subsequent detailed well-siting studies by the U.S. Geological Survey in cooperation with the U.S. Bureau of Reclamation. "Hydrographic areas," as described by Rush (1968a), were used as a basis for defining the geographic units considered in this evaluation. These hydrographic areas do not, in general, define discrete carbonate-rock aquifers or complete ground-water flow systems. The eight criteria used to select the proposed areas are generally hydrogeologic, and do not include detailed engineering considerations at this stage of the investigation. Moreover, the criteria are necessarily limited to areas that have available data and references.

The assessment reported herein was an early step toward exploration of the carbonate-rock aquifers in southern Nevada. The results of this assessment are intended to provide a basis for narrowing the geographic range of geohydrologic studies of the aquifers. The areas considered as part of detailed studies may be narrowed still more on the basis of economic and engineering considerations. Results of such studies and additional data may alter substantially the judgments presented herein, may suggest "preferred" areas beyond those proposed herein, and eventually might narrow the focus of well-siting activities greatly.

AREA ASSESSMENT

Areas Considered

The 26 geographic units considered in this area-assessment process were restricted to basins within Nevada, within the carbonate-rock area (as currently delineated), and within about 100 mi of the City of Las Vegas. The boundaries of these geographic units generally correspond to boundaries of hydrographic areas as defined by Rush (1968a), but in several instances the geographic units considered here incorporate several small hydrographic areas. This definition of the units was chosen to minimize the repetition of effort for closely related basins and to keep the areal extent of all units approximately equal. Figure 1 shows the approximate southern boundary of the carbonate-rock area and the specific units considered in area assessment. The 26 units are:

Amargosa Desert
Black Mountains Area
California Wash
Coyote Spring Valley
Crater Flat

Delamar Valley
Emigrant Valley
Hidden (north) and Garnet Valleys
Indian Springs Valley
Ivanpah, Jean Lake, Hidden (south) Valleys

Jackass Flat and Buckboard Mesa
Kane Spring Valley
Las Vegas Valley (northern part), north of Corn Creek Spring, between the Las Vegas and Desert Ranges

Las Vegas Valley (southern part), the largest part of the Las Vegas hydrographic area
Lower Moapa Valley
Meadow Valley

Mercury and Rock Valleys
Mesquite Valley
Mormon Mesa
Muddy River Springs Area
Pahranagat Valley

Pahrump Valley
Three Lakes Valley
Tikaboo Valley
Tule Desert
Yucca and Frenchman Flats

Criteria for Area Assessment

The criteria applied in assessing areas for detailed well-siting studies were:

1. Interbasin ground-water flow through the unit.
2. Areal extent of associated flow systems (as an approximate measure of the extent of the carbonate-rock aquifer being tapped).
3. Indications of stratigraphic and structural thinning.
4. Continuity of carbonate-rock sequences.
5. Distance to discharge areas and pumping centers.
6. Depth to the potentiometric surface for water in the carbonate rocks.
7. Development of basin-fill aquifers.
8. Potential for poor-quality or contaminated water (proximity to Nevada Test Site or presence of major evaporite deposits).

The significance of these criteria and their application to the units considered in the area assessment are described in the next section.

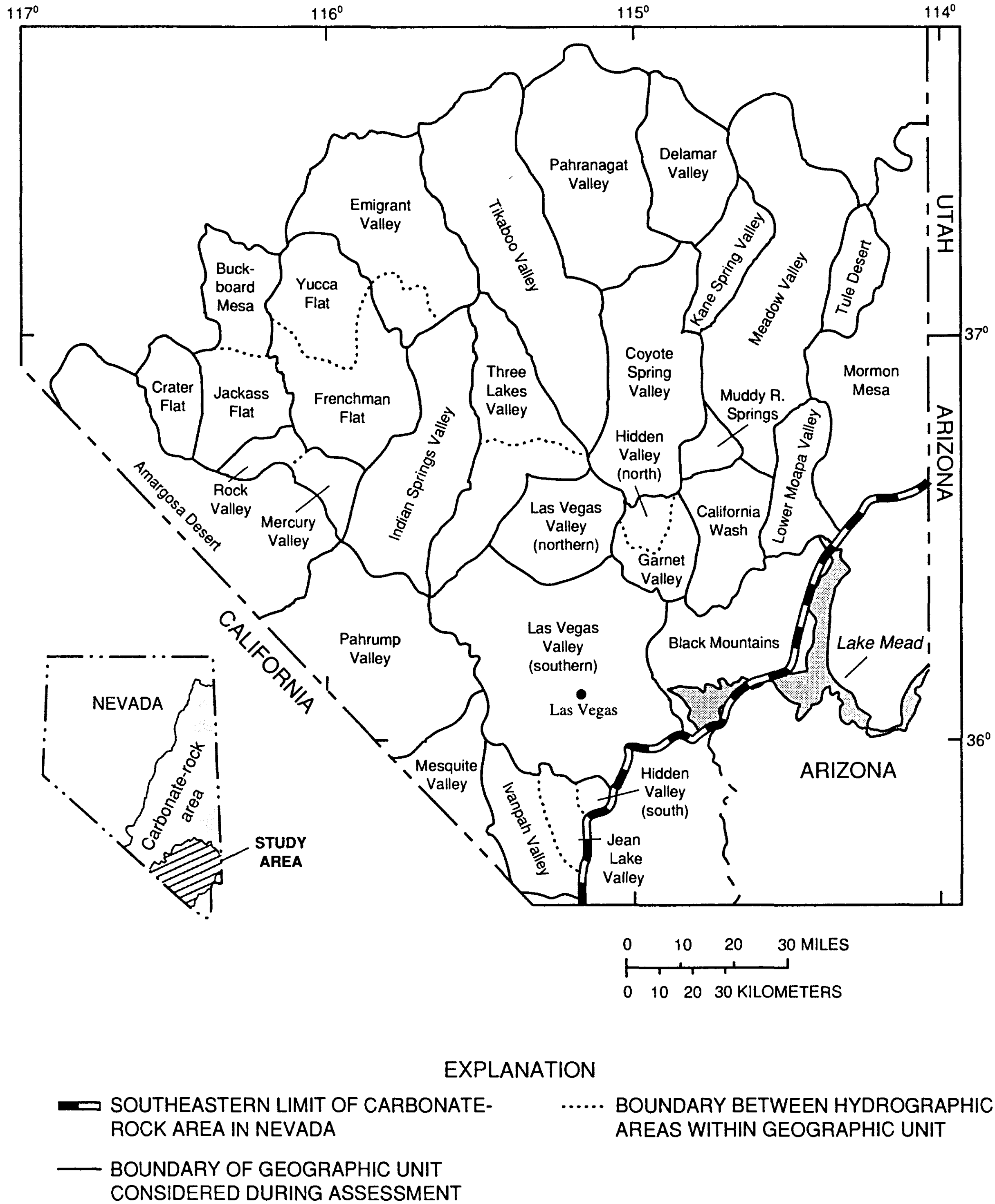


FIGURE 1.--*Geographic units considered in the selection process.*

Additional data were also considered but were found to be inappropriate at this level of assessment. In particular, a review of existing regional-scale aeromagnetic anomalies, Bouguer gravity, and regional lineaments in southern Nevada was made (Zietz and others, 1977; Rowan and Wetlaufer, 1979, fig. 2; National Oceanic and Atmospheric Administration, 1984; Plume, 1989). Aeromagnetic anomalies were found useful in locating possible geologic barriers to ground-water flow and in delineating flow systems (Plume, 1988). In general, though, these methods are logically included in a more detailed investigation than is warranted at this stage of area assessment. Quantitative interpretation of aeromagnetic and gravity data will require two- or three-dimensional numerical modeling, for which the large number of units considered here, was beyond the scope of the current assessment. Mapping lineaments can be informative, but only if the hydrologic impacts of the underlying structures can be determined. At the scale of this assessment, interpretation of this type was not feasible. The review, however, did suggest that these data will be useful in the more localized well-siting investigations. In these investigations, development of geophysical models and detailed hydrologic interpretations of lineaments should generally be useful and feasible.

Another criterion for area assessment that was considered is the thickness of basin fill in each of the units. This criterion would reflect the difficulties and costs of drilling wells and sensing conditions in the carbonate-rock aquifers. The criterion was found to be of limited use at this stage in the screening process because, in virtually every one of the areas concerned, the carbonate rocks crop out in at least one location. Each of the areas also contains places that are underlain by varying thicknesses of younger rocks and sediments that cover the carbonate rocks. Thus, each unit contained a wide range of basin-fill thicknesses and the criterion allows no distinctions among areas. The only exception is Crater Flat where essentially the entire basin is underlain by a caldera (or associated) structure that includes Tertiary-age volcanic rocks over 10,000 ft thick overlying the carbonate rocks (if they are present at all).

Application of Criteria

Interbasin Ground-Water Flow

On the basis of existing estimates (principally from Rush and others, 1971), the amount of interbasin flow beneath a given unit was used as a criterion for area assessment. The amount of interbasin flow serves as an approximate indicator of the renewability of water within the carbonate-rock aquifers of the unit. Interbasin-flow estimates are assumed to be a better indicator of the relative volumes of flow through the carbonate-rock aquifers than is total flow beneath an area, because much of local components of total flow may be through shallower basin-fill aquifers. Part of the interbasin flow also may be through basin-fill or volcanic-rock aquifers but, for the most part, is assumed to occur in the underlying carbonate-rock aquifers. The indicator may be in error, however, to the extent that the estimates of interbasin flow are incorrect and to the extent that the flow is in other aquifer media (such as basin fill and volcanic rocks) that are not hydraulically connected to the carbonate rocks.

Table 1 presents estimates, for each unit, of annual rates of ground-water inflow associated with known regional and interbasin flow systems, estimated rates of recharge originating within the unit, and estimated rates of subsurface outflow from the unit to regional systems or adjacent basins. The differences between the inflow-plus-recharge and the outflow corresponds to discharge at land surface within each unit. The figures in table 1 indicate the approximate total estimated rate at which water flows into *all* the aquifers in the part of southern Nevada under consideration: basin-fill as well as volcanic-rock and carbonate-rock aquifers.

TABLE 1.--*Summary of estimates of annual ground-water inflow, recharge, and outflow*

[All values in thousands of acre-feet per year]

Unit[1]	Subsurface inflow	Local recharge	Subsurface outflow	Source of estimates
Amargosa Desert	20	2	20	Walker and Eakin, 1963
Black Mountains	1	0	1	Rush, 1968b; Harrill, 1976
California Wash	1	0	(a)	Rush, 1968b
Coyote Spring	22	6	28	Eakin, 1966; Welch and Thomas, 1984
Crater Flat	2	0	2	Rush, 1970; Rush and others, 1971
Delamar	5	1	6	Eakin, 1963b; Eakin, 1966
Emigrant	0	3	3	Rush, 1970; Rush and others, 1971
Hidden and Garnet	0	1	1	Rush, 1968b
Indian Springs	22	10	32	Rush, 1970; Rush and others, 1971
Ivanpah, Jean Lake, Hidden	0	2	2	Glancy, 1968
Jackass Flat and Buckboard Mesa	6	2	8	Rush, 1970; Rush and others, 1971
Kane Spring	0	1	1	Eakin, 1964
Las Vegas (northern part)	0	5	5	Winograd and Friedman, 1972
Las Vegas (southern part)	2	30	1	Harrill, 1976; Glancy, 1968
Lower Moapa	1	0	1	Rush, 1968b
Meadow	8	1	8	Rush, 1964
Mercury and Rock	33	0	33	Rush, 1970; Rush and others, 1971
Mesquite	0	2	0	Glancy, 1968
Mormon Mesa	2	4	[b]40	Glancy and Van Denburgh, 1969
Muddy River Springs	37	0	(a)	Eakin, 1966
Pahranagat	46	2	23	Eakin, 1966; Welch and Thomas, 1984
Pahrump	0	42	18	Harrill, 1986
Three Lakes	5	8	13	Rush, 1970; Rush and others, 1971
Tikaboo	6	6	12	Rush, 1970; Winograd and Friedman, 1972
Tule Desert	0	2	2	Glancy and Van Denburgh, 1969
Yucca and Frenchman Flats	32	1	33	Rush, 1970; Rush and others, 1971

[1] See Rush and others, 1971.

[a] Indeterminant, but probably small.

[b] This largely indeterminant subsurface outflow is fed by surface-water inflow and leakage from Virgin River.

The subsurface inflows listed in table 1 are defined as annual rates of subsurface flow from outside each unit. The inflows are commonly estimated by regionally matching rough estimates of ground-water recharge from mountainous areas with estimated discharge rates from springs, phreatophyte stands, and playas [for example, Eakin (1966)]. In some cases, geochemical evidence has also been used to develop interbasin flow estimates (Winograd and Freidman, 1972; Welch and Thomas, 1984). Accordingly, the inflow estimates are rough estimates and may not reflect the actual rates of inflow, because unknown modes and areas of ground-water discharge or recharge may occur.

The local-recharge estimate represents the amount of ground-water recharge generated by precipitation within each unit (table 1). All the local-recharge estimates presented in table 1, and most of the interbasin flow estimates, are based (ultimately) on the Maxey-Eakin empirical method of estimating recharge (Maxey and Eakin, 1949, p. 40-41). Recharge is believed to be derived from precipitation within the high-altitude areas shown in figure 2. The Maxey-Eakin method was developed in Nevada for water-resources reconnaissance studies and assumes that from 0 to 25 percent (increasing with precipitation rate) of the precipitation falling within each of five precipitation zones eventually becomes ground-water recharge. The method is simple to apply but may yield uncertain estimates. For the purposes of this report, the primary advantage of this set of recharge estimates is that they are derived in a consistent manner and are available in existing reports.

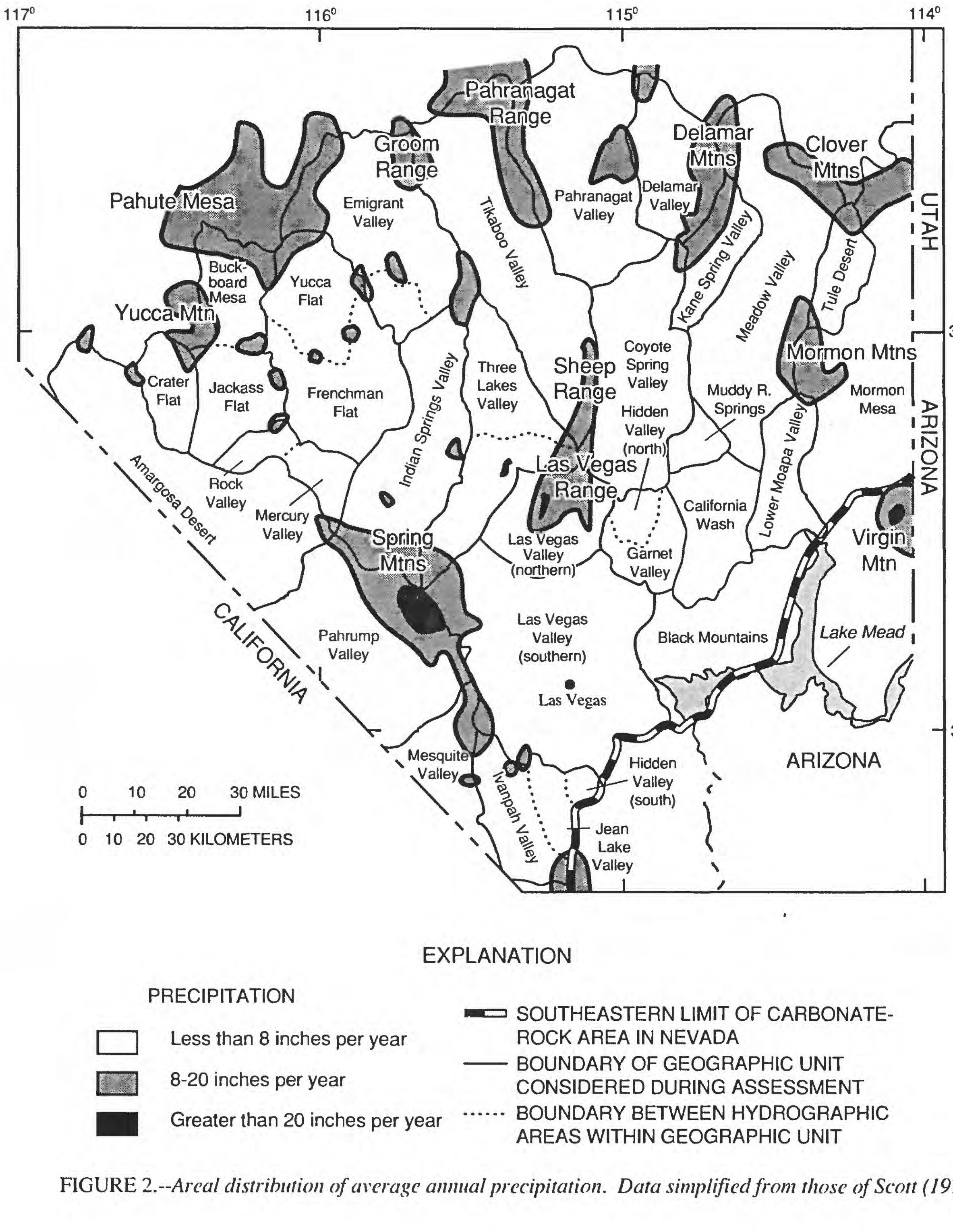


FIGURE 2.--*Areal distribution of average annual precipitation. Data simplified from those of Scott (1971).*

The Spring Mountains contribute most of the 82,000 acre-ft/yr that recharges Las Vegas, Indian Springs, and Pahrump Valleys; the Sheep Range contributes more than 10,000 acre-ft/yr to nearby valleys, such as Tikaboo, Coyote Spring, and northern Las Vegas Valleys. Aside from recharge from these two major mountain ranges, local recharge is limited. The regional ground-water flow systems that contribute subsurface inflow from outside the area being considered are the White River system, the Meadow Valley Wash system, and the Alkali Flat system (fig. 3). These flow systems are supplied mostly by recharge in mountainous areas north of the study area assessed herein.

These estimated volumes of annual ground-water flow, at least some of which is through the regional aquifers, represent measures of the renewability of the ground-water resources within these aquifers. Notable for large volumes of outflow (greater than 10,000 acre-ft annually) are Pahrump, Three Lakes, Indian Springs, Tikaboo, Coyote Spring, Pahranagat, and Mercury and Rock Valleys, as well as the Amargosa Desert, Yucca and Frenchman Flats, and Mormon Mesa (table 1).

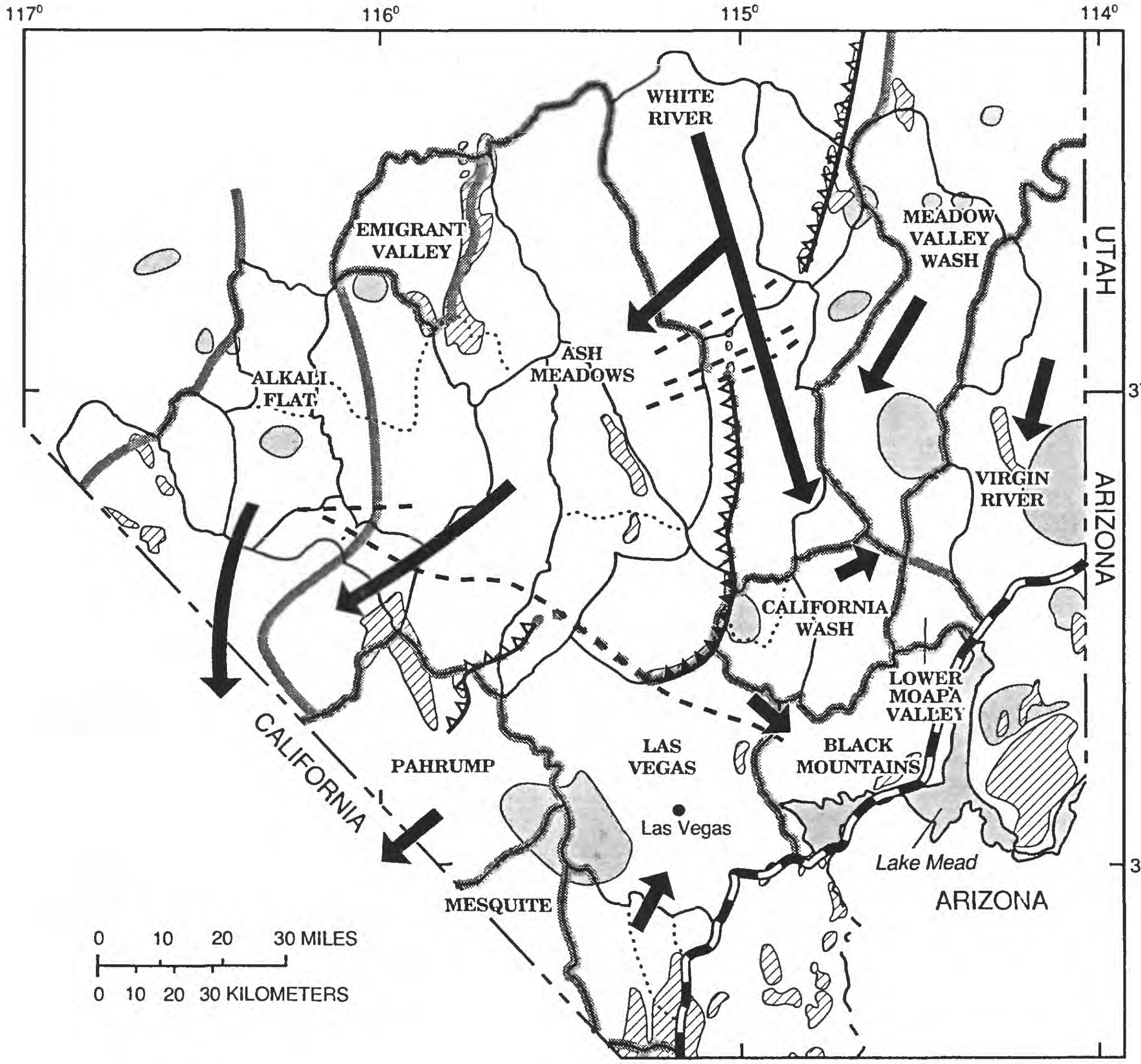
Areal Extent of Carbonate-Rock Aquifers

The areal extent of the carbonate-rock aquifer associated with each unit was estimated on the basis of known geologic barriers and inferred boundaries of the flow systems associated with each (fig. 3). The areal extent was estimated for use as a generalized indicator of carbonate-rock aquifer storage under the assumptions that (1) the influence of aquifer thickness would be assessed elsewhere and (2) spatial variability of the specific storage of a unit volume of the carbonate-rock aquifers cannot be assessed in this study. At present (1984), it is impossible to place physical bounds on the carbonate-rock aquifers. The areal extent of flow systems are used here in hopes that distinctions between flow systems reflect distinctions among aquifers. As such, areal extent is a worst-case indicator of water stored in the rocks, largely equivalent to an assumption that negligible recharge occurs.

Table 2 presents the estimated areal extent of ground-water flow systems for each geographic unit under consideration. Notable among these units are Emigrant Valley, Mesquite Valley, and Hidden (north) and Garnet Valleys; these units comprise most of several small flow systems. Near the junction of the White River, Meadow Valley Wash, and Virgin River systems (fig. 3), flow systems are difficult to differentiate. Therefore, areas of carbonate-rock aquifers associated with the Lower Moapa Valley, California Wash, and Black Mountains units could not be estimated in this study.

Stratigraphic and Structural Thinning

Thinning of the stratigraphic column, and in particular the carbonate-rock section, occurs in southern Nevada as a result of differences in the original thickness of the accumulation of carbonate sediments, removal of material by uplift and erosion, and by extensional faulting and denudation. In some areas, thinning is so severe that the entire carbonate-rock section is missing. As noted above, taken together with the areal extent and, as yet unknown, specific storage, the thickness of the carbonate-rock section is an important component in estimating the amount of water in storage in the carbonate-rock aquifers. Markedly thin or missing carbonate-rock sections were considered negative indications in the area assessment.



EXPLANATION

POSSIBLE STRUCTURAL BARRIERS TO DEEP GROUND-WATER FLOW

Clastic sedimentary rocks

Major aeromagnetic anomaly

Fault--Approximately located. Saw-tooth pattern indicates easternmost extent of Mesozoic overthrust. Solid teeth indicate coincident fault, clastic rocks, geographic-unit boundary, and flow-system boundary

SOUTHEASTERN LIMIT OF CARBONATE-ROCK AREA IN NEVADA--Also constitutes flow-system boundary

BOUNDARY OF INFERRED GROUND-WATER FLOW-SYSTEM--Dashed where approximately located. Flow-system names are indicated (serif lettering)

GENERAL DIRECTION OF REGIONAL GROUND-WATER FLOW

BOUNDARY OF GEOGRAPHIC UNIT CONSIDERED DURING ASSESSMENT

BOUNDARY BETWEEN HYDROGRAPHIC AREAS WITHIN GEOGRAPHIC UNIT

FIGURE 3.--*Ground-water flow systems and indications of geologic barriers to flow. Flow systems are in general agreement with those of Winograd and Friedman (1972) and Harrill and others (1983); however, some boundaries have been moved to coincide with geologic controls. Indications of geologic barriers are based on the work of Longwell and others (1965), Winograd and Thordarson (1968), Tschanz and Pampeyan (1970), Cornwall (1972), Zietz and others (1977), Stewart (1980), and Bohannon (1983).*

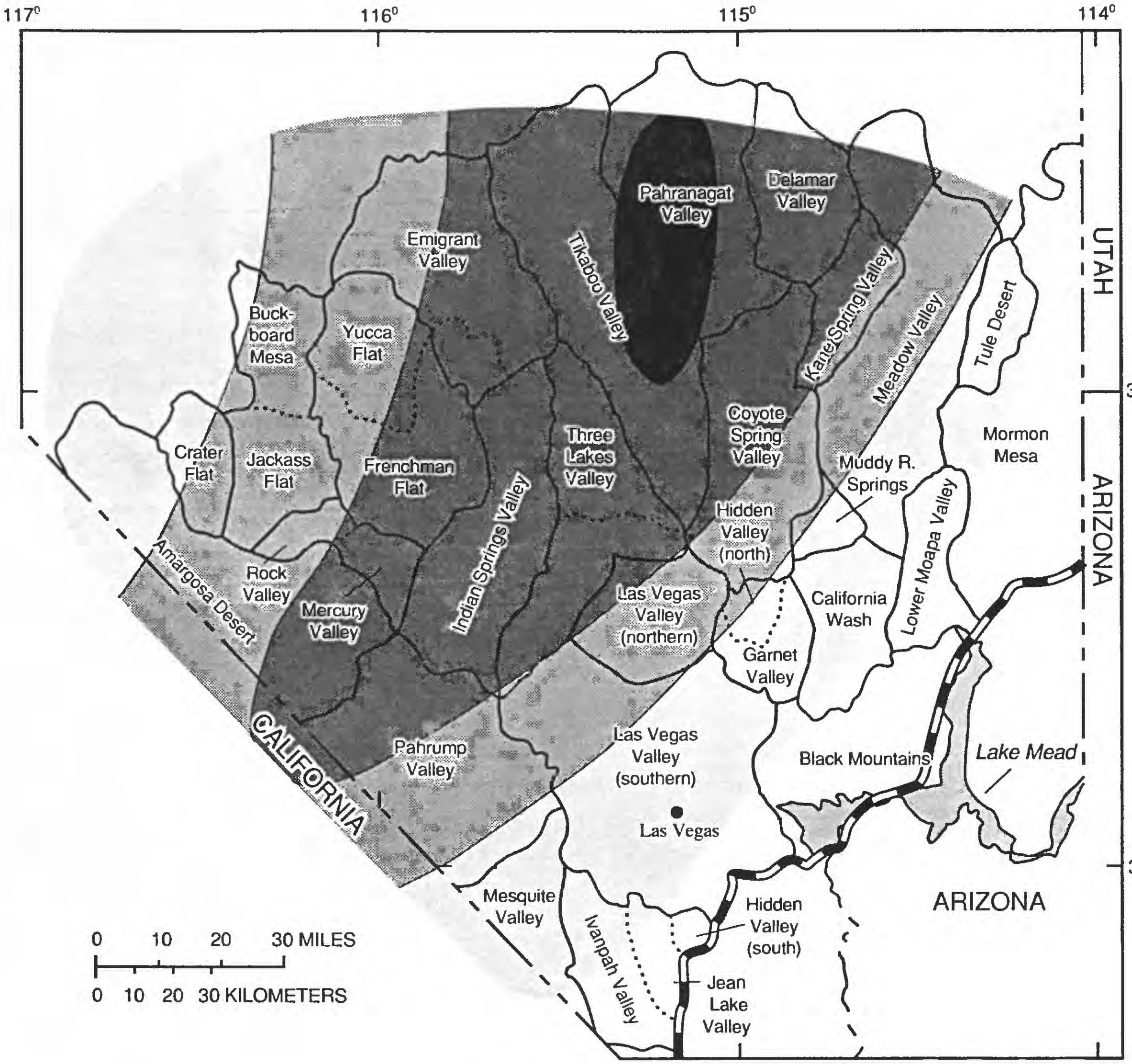
TABLE 2.--*Areal extent of inferred ground-water flow systems*

Unit	Regional flow system	Areal extent of flow system (hundreds of square miles)
Amargosa Desert	Ash Meadows	38
	Alkali Flat	22
Black Mountains	Black Mountains	unknown
California Wash	California Wash	unknown
Coyote Spring	White River	74
Crater Flat	Alkali Flat	22
Delamar	White River	74
Emigrant	Northwest Emigrant Valley	[a]4
Hidden and Garnet	California Wash	6
Indian Springs	Ash Meadows	38
	Indian Springs	[a]6
Ivanpah, Jean Lake, Hidden	Las Vegas	17
Jackass Flat and Buckboard Mesa	Alkali Flat	22
Kane Spring	White River	[b]10
Las Vegas (northern part)	Ash Meadows	38
Las Vegas (southern part)	Las Vegas	17
Lower Moapa	Lower Moapa	unknown
Meadow	Meadow Valley Wash	33
Mercury and Rock	Ash Meadows	38
	Alkali Flat	22
Mesquite	Mesquite	5
Mormon Mesa	Virgin River	17
Muddy River Springs	White River	74
Pahranagat	White River	74
	Ash Meadows	38
Pahrump	Pahrump	15
Three Lakes	Ash Meadows	[b]38
	Las Vegas	[b]17
Tikaboo	Ash Meadows	38 plus some of White River system
Tule Desert	Virgin River	17
Yucca and Frenchman Flats	Ash Meadows	38

[a] Subsystem boundaries inferred from structurally emplaced blocks of aquitard materials discussed in Winograd and Thordarson (1968).

[b] Subsystem boundaries inferred from important thrust faults discussed by Armstrong (1968, p. 436).

Figure 4 shows generalized areal variations in the stratigraphic thickness of the carbonate-rock sequences in southern Nevada. In many areas, however, the rock sequences have been deformed by Mesozoic thrust faults and Tertiary extensional faults. As a result, parts of the section may be structurally thinned or thickened. This complex history of deposition of the carbonate rocks (fig. 5), thickening of the section by compressional forces, and later thinning of the section by extensional processes is not completely understood but is expected to have important hydrologic consequences. The geologic history of the area can be taken only broadly into account in the area assessment.



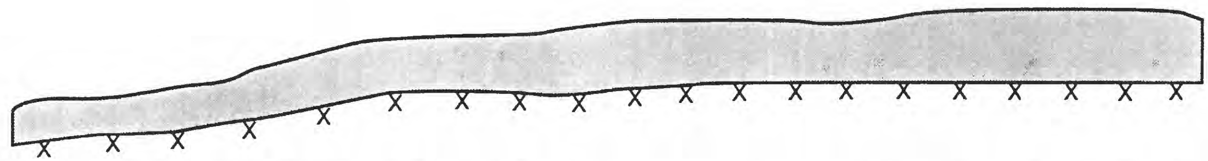
EXPLANATION

STRATIGRAPHIC (OR ORIGINAL) THICKNESS

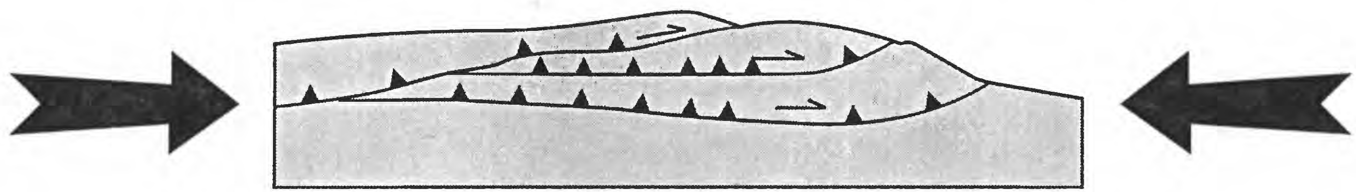
- Less than 10,000 feet
- 10,000 to 15,000 feet
- 15,000 to 20,000 feet
- 20,000 to 25,000 feet
- Greater than 25,000 feet

- SOUTHEASTERN LIMIT OF CARBONATE-ROCK AREA IN NEVADA
- BOUNDARY OF GEOGRAPHIC UNIT CONSIDERED DURING ASSESSMENT
- BOUNDARY BETWEEN HYDROGRAPHIC AREAS WITHIN GEOGRAPHIC UNIT

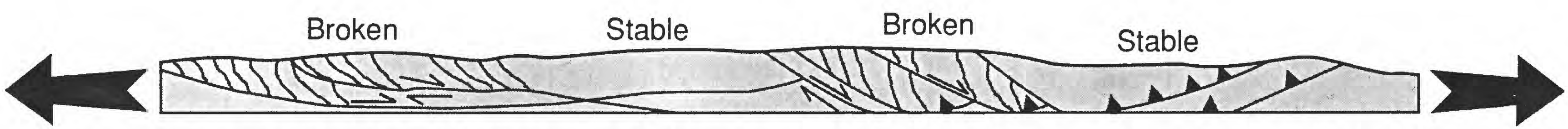
FIGURE 4.--*Generalized stratigraphic thickness of Paleozoic carbonate-rock sequences. Compiled by graphical addition of thicknesses given by Stewart (1980, figures 13, 15, 17, 19, 23, 26, and 29). The thicknesses shown specifically do not include units listed by Stewart as "carbonate-terrigenous detrital deposits" or "limestone-and-shale province deposits."*



During Paleozoic time (570-245 million years before the present), carbonate rocks were deposited in varying thickness on crystalline basement (x) of the ancient continental shelf of western North America.



During Mesozoic time (245-66 million years before the present), the carbonate-rock section was shortened laterally and thickened by compression forces and resulting thrusts. Arrow indicates direction of thrust; sawteeth point to thrusted plate.



During Tertiary time (66-1.7 million years before the present), the carbonate-rock section was thinned by stretching of the Earth's crust and resulting extensional structures. Extension produced alternating broken and stable terranes (see text).

FIGURE 5.--*Schematic history of major geologic events that modified the carbonate-rock section. The schematic cross-sections are oriented east-west.*

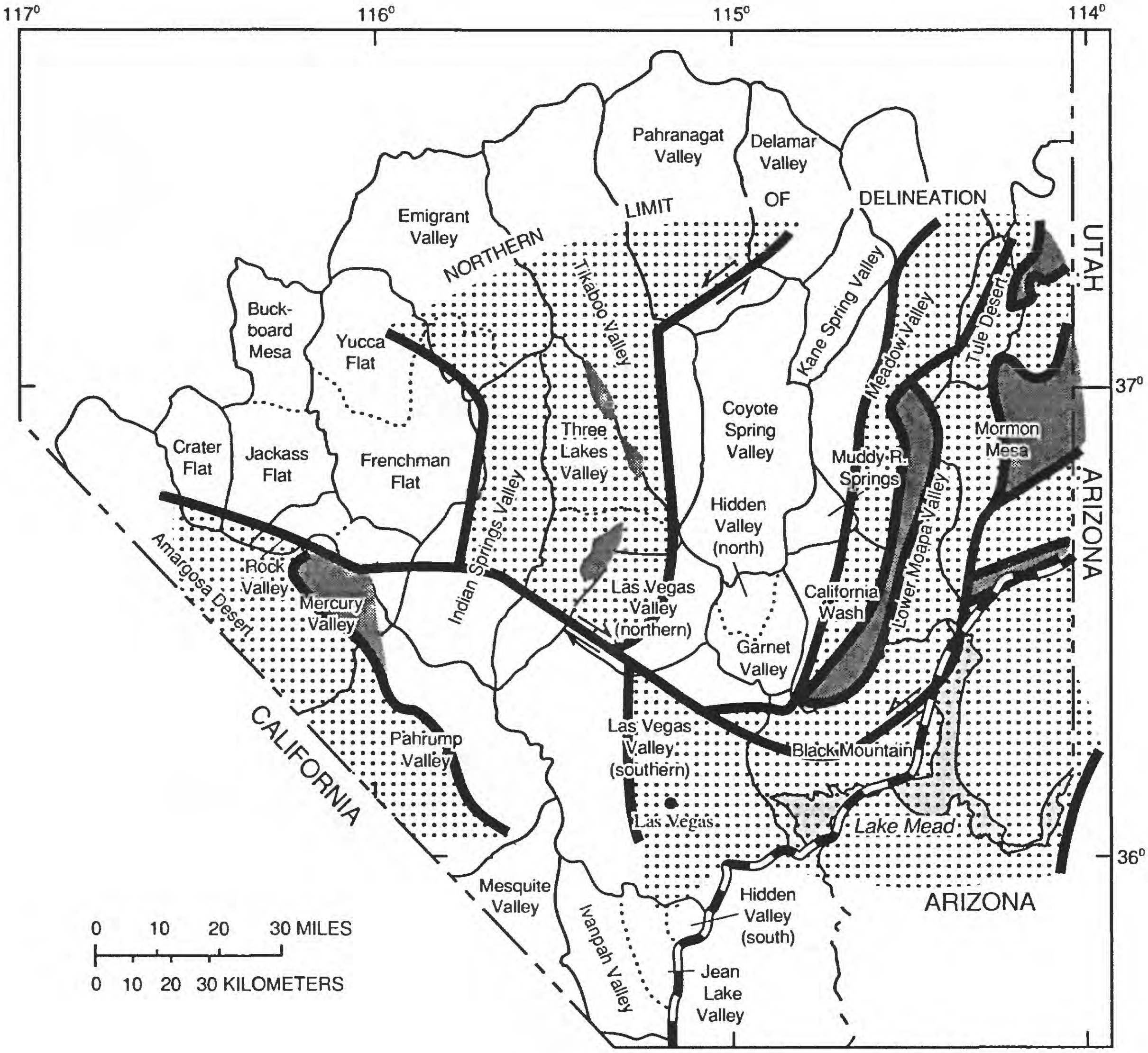
During Mesozoic time, the carbonate rocks of southern Nevada were compressed to such an extent that vast slabs of the rock in the west slid up and over the rocks of similar age to the east (Armstrong, 1968). One result of repeated occurrences of this thrusting was the development of areas beneath which the carbonate-rock section might occur not once but twice or several times (fig. 5). Where such thrusts developed (west of the line delineating the easternmost extent of Mesozoic thrusts on fig. 4), the carbonate-rock section may be thick, although the total thickness remaining today is commonly unknown. The only safe conclusion at present (1984) is that areas to the east of the Mesozoic thrusts probably are underlain by less than the depositional thickness of carbonate rocks. Thrusting did not thicken the section in these areas and subsequent extension of the area (discussed next) probably thinned the section (Wernicke and others, 1984, p. 473). Thus, Lower Moapa Valley, Mormon Mesa, Black Mountains, Ivanpah Valley, Jean Lake Valley, Hidden Valley, and parts of southern Las Vegas Valley are probably underlain by relatively thin carbonate-rock sections.

Later, during Tertiary time, the rocks of southern Nevada were stretched and extended along numerous fault systems (fig. 5). These extensional processes resulted in large-scale thinning of the crust including the carbonate-rock section (Wernicke and others, 1984, p. 473). The response of the shallow crust differed from area to area. Broken terranes developed that are "characterized by imbricate faulting, rotated blocks, gravity slides, and other manifestations of extreme extension" (Wernicke and others, 1984, p. 483). Elsewhere, stable terranes developed that are "coherent, intact" rock masses. At the surface, broken terranes exhibit much more thinning of the Paleozoic rock section than do the nearby stable terranes. In some areas, thinning was so extreme that denuded stable terranes developed. These are areas in which the entire extended rock mass has been pulled or eroded away to expose underlying rocks, many of Precambrian age and noncarbonate lithology. The geographic distribution of these terranes today is shown in figure 6, primarily as mapped by Wernicke and others.

The significance of figure 6 in the context of structural thinning is that all the areas under consideration have experienced some extension and thinning. But thinning of the carbonate-rock aquifers may be most severe in the areas indicated as denuded terranes and, to a lesser extent, the areas indicated as broken terranes.

Many areas listed as denuded terranes are recognized by exposures of Lower Cambrian and Precambrian rocks. These rocks may form barriers to deep ground-water flow at the base of the carbonate-rock section where this base is sufficiently close to the surface that flow can interact with them. Thus, the carbonate-rock aquifers of these areas have experienced considerable thinning near the surface. In some areas, these denuded terranes may be underlain by still deeper carbonate-rock reservoirs as a result of Mesozoic overthrusts. Determining the extent, thickness, and hydrologic connection of these deeper carbonate rocks would be difficult. Detailed geophysical investigations might be useful in addressing some of these uncertainties. Three Lakes Valley, Indian Springs Valley, Amargosa Desert, California Wash, Meadow Valley, Tule Desert, and Mormon Mesa seem to have significant exposures of denuded terrane and possibly very thin Paleozoic sections (Wernicke and others, 1984, fig. 10; Wernicke and others, 1989, figs. 2-2 and 4-2).

The areas described as broken terranes have undergone extreme extension and thus, may have undergone considerable thinning. Beneath the imbricate faulting and rotated blocks characterizing these terranes, extension may be small, and thus, these areas are uncertain indicators of stratigraphic thinning. However, direct evidence of extreme extension is available in some units. Indian Springs Valley, Black Mountains, Lower Moapa area, and Mormon Mesa contain areas of extreme extension and potential stratigraphic thinning (Wernicke and others, 1989, p. 484-491). Other broken terranes are buried beneath thick sections of more-recent basin-fill materials. As a consequence, stratigraphic thinning is unknown in such units as Pahrump, South Las Vegas, and Tikaboo Valleys.



EXPLANATION

EXTENSIONAL FEATURES

Broken terrain

Stable terrain

Denuded stable terrain

Shear zone. Arrows show relative horizontal movement

SOUTHEASTERN LIMIT OF CARBONATE-ROCK AREA IN NEVADA

BOUNDARY OF GEOGRAPHIC UNIT CONSIDERED DURING ASSESSMENT

BOUNDARY BETWEEN HYDROGRAPHIC AREAS WITHIN GEOGRAPHIC UNIT

FIGURE 6.--*Delineation of Tertiary extensional modes. Modified from Wernicke and others (1984, figure 10; 1989, figure 4-2). Broken and stable terrain are defined in text.*

Continuity of Carbonate-Rock Sequences

In developing a plan for exploratory drilling in the carbonate-rock aquifers of southern Nevada, consideration must be given to the continuity and complexity of the carbonate-rock sequences in a given area. First, if the carbonate sequences are structurally complex and discontinuous, ensuring that a particular unit or structure would be penetrated by drilling, and that a sufficiently thick sequence of carbonate rocks would be encountered during drilling, will be difficult. Second, recharge and interbasin flow in southern Nevada probably occur in small enough amounts that are spread over large enough areas so that aquifers with large areal extent for catchment and throughflow of water will be required to ensure that sufficient water is available for sustained pumping at production wells without prohibitively large drawdown. This areal requirement is partially described by the measures of areal extent of flow systems presented in table 2; the issue of how continuous carbonate rocks are within these areas must also be considered. One may view the issue as one of how much of the area in a given flow system is divided by geologic barriers to ground-water flow.

In certain parts of southern Nevada, portions of the carbonate-rock sequences are so badly broken and tilted that flow paths may be randomly but repeatedly diverted and retarded by up-tilted blocks of low-permeability rock and breccia zones. Such breakage might improve the degree of secondary porosity in a localized area but could reduce the distance over which unimpeded lateral flow could bring water to a well. Thus, the long-term yield of a well could be reduced by block tilting and brecciation along normal faults. This argument is speculative because in some instances faults could produce exceptional secondary porosity and high permeability.

The immediate purpose of the area assessment is to locate areas in which exploratory drilling might produce useful hydrologic data. Areas with well-defined geologic structure and stratigraphy are preferable. This choice could certainly be weighed in reappraisals of the initial drilling results.

As an approximate measure of the continuity of the carbonate-rock sequences, the percentages of carbonate rocks in bedrock exposures within each unit were determined (table 3). Post-Paleozoic noncarbonate-rock outcrops, such as flat-lying ash flows, may contribute to the complexity of the outcrop pattern and lower the percent of carbonate-rock outcrops without substantially disrupting the continuity of the underlying carbonate-rock sequences. Post-Paleozoic rocks include those of Mesozoic and Tertiary ages. Because the continuity of Paleozoic rocks underlying these deposits could not be reasonably quantified for units in which most of the outcrops are post-Paleozoic, the percentages reported for these units yield little information.

An overall subjective assessment of the complexity of exposures is also listed in table 3. The division of units in terms of geologic complexity was extremely subjective and based on relations apparent from geologic maps at 1:250,000 scale and on the Tertiary extensional processes at work in each unit. The broken terranes shown in figure 6 are interpreted for this assessment as potentially containing extremely complicated structural zones and probably tend toward discontinuity of the carbonate-rock sequences and aquifers. Not all the complexity of the structures in southern Nevada is associated with Tertiary extension, and several units in the stable terranes rank as "complex" in the terms used in table 3.

TABLE 3.--*Abundance of carbonate-rock outcrops and complexity of structural relations*

[Complexity of structural relations: Simple, noncarbonate-rock exposures limited to one part of area, or juxtaposition of carbonate and noncarbonate rocks controlled by one or two major faults; intermediate, wide distribution of small exposures of noncarbonate rocks, or moderately complex juxtaposition of carbonate and noncarbonate rocks by faults; complex, very complicated juxtapositions of carbonate and noncarbonate rocks by many faults throughout unit]

Area	Abundance of carbonate-rock outcrops (percent of total outcrops)	Predominant age of noncarbonate rocks in outcrops	Complexity of structural relations between carbonate and noncarbonate rocks
Amargosa Desert	72	Precambrian and Tertiary	Intermediate
Black Mountains	47	Mesozoic	Complex
California Wash	85	Mesozoic	Simple
Coyote Spring	78	Tertiary	Simple
Crater Flat	16	Precambrian and Tertiary	Intermediate
Delamar	6	Tertiary	Complex
Emigrant	5	Precambrian, Mississippian, and Tertiary	Complex
Hidden and Garnet	100	none	Simple
Indian Springs	71	Tertiary	Complex
Ivanpah, Jean Lake, Hidden	54	Precambrain	Simple
Jackass Flat and Buckboard Mesa	0	Tertiary	Simple
Kane Spring	14	Tertiary	Simple
Las Vegas (northern part)	92	Precambrian/Cambrian	Intermediate
Las Vegas (southern part)	58	Precambrian to Tertiary	Intermediate
Lower Moapa	61	Mesozoic	Simple
Meadow	43	Mesozoic and Tertiary	Intermediate
Mercury and Rock	49	Precambrian and Tertiary	Intermediate
Mesquite	86	Precambrain	Simple
Mormon Mesa	26	Precambrian and Mesozoic	Complex
Muddy River Springs	100	none	Simple
Pahranagat	18	Tertiary	Intermediate
Pahrump	63	Cambrian and Permian	Intermediate
Three Lakes	76	Precambrian and Tertiary	Intermediate
Tikaboo	42	Tertiary	Intermediate
Tule Desert	51	Tertiary	Intermediate
Yucca and Frenchman Flats	22	Devonian and Tertiary	Intermediate

Distances to Discharge Areas and Pumping Centers

Distance to the principal discharge areas associated with the flow system beneath each geographic unit is a useful criterion in the area-assessment process. Impacts of pumping water from carbonate-rock aquifers on natural discharge at springs, playas, and stands of phreatophytes, as well as at well fields tapping basin-fill aquifers that might be hydraulically connected to the carbonate-rock aquifers, are likely to be more immediate and more severe when a well tapping carbonate rocks is close to an existing discharge area than when it is far away. Figure 7 shows the location of ground-water discharge areas in southern Nevada. The potential for adverse impacts on major discharge areas is a key concern in formulating plans for carbonate-rock aquifer development. Thus, proximity to major discharge areas was considered to be a negative factor at this stage of the analysis.

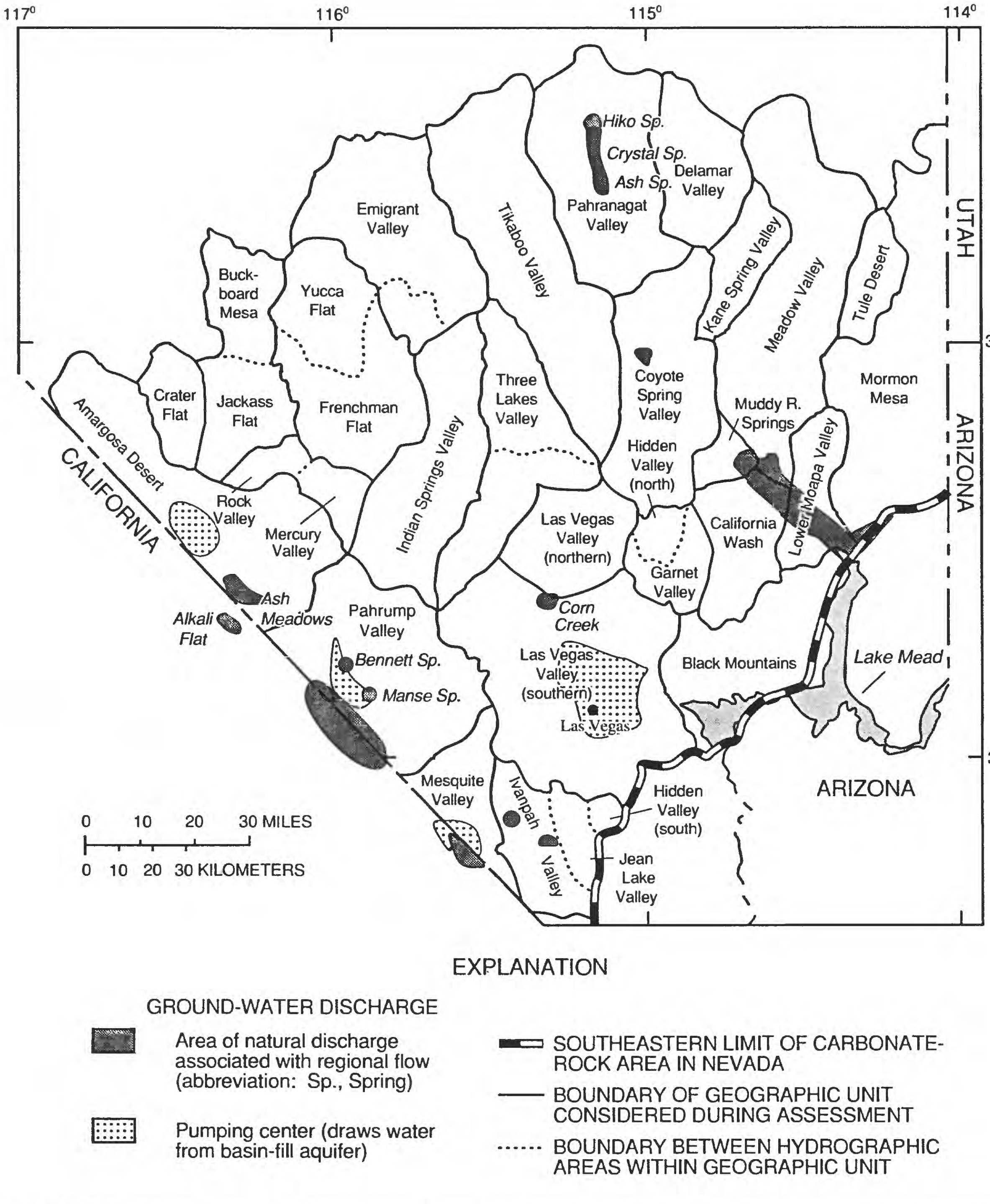


FIGURE 7.--*Ground-water discharge areas. Includes springs, gaining reaches of streams, evapotranspiration areas, and major pumping centers. Although Corn Creek, Coyote, and Manse Springs discharge from carbonate rocks, they may not be parts of regional flow systems.*

The potential for impacts at minor springs, such as Indian Spring and Corn Creek Spring, and smaller pumping centers, such as Glendale, Indian Springs, and near Mercury (fig. 7), would have to be considered in siting of carbonate-rock production wells. Impacts on small water uses would probably be more easily mitigated in terms of engineering and cost considerations than impacts at larger springs or pumping centers.

Table 4 presents a summary of representative ranges of distances to major ground-water discharge areas from points in each unit. The Upper Muddy Springs, Pahranagat, and southeastern Amargosa Desert units include major carbonate-rock aquifer discharge areas; impacts of pumping in these units could be immediate and severe. Las Vegas, Mesquite, Pahrump Valleys, and the Amargosa Desert are (or were) the sites of major ground-water discharge (pumpage, evapotranspiration, and springflow) from basin-fill aquifers that may be hydraulically connected to deeper carbonate-rock aquifers. At the other extreme are units such as Tikaboo, Three Lakes, and Kane Spring Valleys that are from 30 to 90 mi from the springs at which most of the underlying ground-water flow is believed to discharge.

TABLE 4.--*Distances to major discharge areas*

[Abbreviation: approx., approximately]

Unit	Associated discharge areas	Range of distances to discharge areas (miles)
Amargosa Desert	Local pumping from basin fill Alkali Flat	local 0-45
Black Mountains	Lake Mead	0-10
California Wash	Muddy River	0-30
Coyote Spring	Muddy Springs	10-30
Crater Flat	Wells in Amargosa Desert Alkali Flat	15-30 approx. 40
Delamar	Muddy Springs	45-70
Emigrant	Ash Meadows	55-75
Hidden and Garnet	Muddy River	approx. 20
Indian Springs	Indian Springs Ash Meadows	0-30 25-60
Ivanpah, Jean Lake, Hidden	Las Vegas pumping center	20-40
Jackass Flat and Buckboard Mesa	Wells in Amargosa Desert Alkali Flat	10-60 30-65
Kane Spring	Muddy Springs	25-50
Las Vegas (northern part)	Las Vegas pumping center Ash Meadows Corn Creek Spring	20-45 60-70 local
Las Vegas (southern part)	Pumping from basin fill Interbasin flow	local unknown
Lower Moapa	Muddy River/Lake Mead	unknown
Meadow	Muddy River/Lake Mead Deep-carbonate discharge	0-50 unknown
Mercury and Rock	Ash Meadows	20-40
Mesquite	Discharge from local basin fill	local
Mormon Mesa	Lake Mead	0-50
Muddy River Springs	Muddy Springs	local
Pahranagat	Hiko, Crystal, and Ash Springs Muddy Springs	local 50
Pahrump	Pumping centers and Manse Spring Amargosa River	local 10-35
Three Lakes	Indian Springs Ash Meadows	5-40 45-80
Tikaboo	Ash Meadows	70-90
Tule Desert	Lake Mead	40-60
Yucca and Frenchman Flats	Ash Meadows	35-50

Depth to Water

Depth to water in wells tapping the carbonate-rock aquifers is an important criterion for area assessment for several reasons. In terms of the detailed studies that will follow this scoping report, the deeper the water is beneath land surface the more expensive will be the studies required to determine conditions within the aquifers. Test drilling will involve greater depths, geophysical methods will have to differentiate conditions deeper in the rocks, and outcrop studies will be less directly tied to conditions in the deeper rocks where the ground-water is flowing. In terms of eventual development, drilling of exploratory, monitoring, and production wells will be more expensive and pumpage costs will be greater where depths to water are large.

The minimum depths to the potentiometric surface in carbonate rocks in each unit are shown in table 5. Depths are generally less than 1,000 ft and, in many of the units, rise to near or above land surface in at least some areas. Also indicated in table 5 is how representative of the unit the reported depths are; that is, is the minimum depth to water different from the depths to water elsewhere in the basin? It is common in the basins for depths to ground water to increase as one travels up the alluvial fans surrounding the valley floor (the land-surface altitude rises with a smaller underlying change in water-table altitude). In those units where the mountain ranges do not receive large amounts of recharge, depths to water beneath the ranges are likely to be large also. Thus, depths to water *do* vary within each of the areas and, as a criterion, must be understood to be a general indicator of conditions.

The depths to water are likely to be small in Las Vegas Valley (southern part), Mesquite Valley, Muddy River Springs area, Lower Moapa Valley, Meadow Valley, and Amargosa Desert. Depths to water are probably large beneath most or all Kane Spring Valley, Delamar Valley, Yucca and Frenchman Flats, Mercury and Rock Valleys, Jackass Flat, Crater Flat, and Tule Desert area.

Ground-Water Development in Basin Fill

Several basins or parts of basins in the study area have been "designated" in terms of ground-water appropriations by the State Engineer. This means that the ground-water resources of the basin are believed to be depleted and increases the State Engineer's powers to manage water-resource development in the basin (Rice, 1974, p. 21-22). Figure 8 delineates those areas in southern Nevada that have been so designated, which include Mesquite, Amargosa Desert, Mormon Mesa, Lower Moapa, and Meadow Valleys. Parts of Three Lakes and Indian Springs Valleys have also been designated. Aquifer overdraft conditions in Las Vegas Valley, Pahrump Valley, and the Lower Meadow Valley Wash area have raised sufficient concern to warrant special designation by the State Engineer whereby all new applications for water for irrigation are denied. In most other areas of southern Nevada, existing ground-water uses are minimal.

The degree of ground-water development in the valley fill of the designated basins suggest that special care would have to be taken in managing the ground-water resources of the adjacent and underlying carbonate rock. Proper management of the resources of these areas would require evaluation and control of the extent to which pumping from carbonate-rock aquifers adjacent to or underlying such basins would aggravate overdraft conditions and affect existing ground-water rights in basin-fill aquifers.

TABLE 5.--*Estimated minimum depths to potentiometric surfaces within carbonate rocks*

[Extent of occurrence: E, extremely small depth to water is characteristic of only a small part of unit (nearly all depths to water are much larger elsewhere in unit); C, depths to water this small are common over a moderate proportion of unit; R, depths to water this small are common enough over a large enough part of the unit to make this value representative for entire unit. Altitudes of potentiometric surface estimated from Thomas and others, 1986; associated land-surface altitudes estimated from 1:250,000-scale topographic maps.]

Unit	Altitude of potentiometric surface (feet above sea level)	Depth to potentiometric surface (feet below land surface)	Extent of occur-rence	Part of unit where minimum occurs
Amargosa Desert	2,200	0	C	Southeast
Black Mountains	[a]1,600	0	E	East (Rogers Spring)
California Wash	[a]1,600	0	E	Northeast
Coyote Spring	1,800	350	C	Southeast
Crater Flat	2,400	400	E	South
Delamar	[b]3,400	900	R	South
Emigrant	4,200	100	C	West
Hidden and Garnet	[a]1,800	100	E	East
Indian Springs	3,200	0	E	South (Indian Springs)
Ivanpah, Jean Lake, Hidden	3,700	50	E	Goodsprings
Jackass Flat and Buckboard Mesa	2,400	300	E	South
Kane Spring	[b]2,000	800	E	South
Las Vegas (northern part)	2,900	0	E	South (Corn Creek Springs)
Las Vegas (southern part)	2,000	0	C	Central (oil-test well, T.21S, R.61E., sec. 24)
Lower Moapa	[a]1,700	0	R	South
Meadow	[a]1,600	0	C	South
Mercury and Rock	2,300-2,400	600	C	West
Mesquite	[a]2,550	<50	C	South
Mormon Mesa	[b]1,600	<100	E	South
Muddy River Springs	1,800	0	R	Central
Pahranagat	3,600	0	R	Central (Alamo)
Pahrump	2,770	0	E	East (Pahrump and Manse Springs)
Three Lakes	[b]2,700	<100	E	South
Tikaboo	[b]3,000	200	C	Southwest
Tule Desert	[a]2,700	400	R	Central
Yucca and Frenchman Flats	2,350	800	R	South (Frenchman Flat)

[a] Level inferred from pontentiometric surface in basin-fill aquifers.

[b] Level inferred with no control points on the basis of levels in other parts of the flow system.

The vulnerability of these prior water uses to impacts from development of carbonate-rock aquifers depends on the degree of hydraulic interconnection between the basin-fill and carbonate-rock aquifers. The current knowledge concerning hydraulic connection between basin-fill and consolidated-rock aquifers in Nevada is limited; therefore, the impact of pumping from carbonate-rock aquifers generally cannot be predicted. Studies in the southeastern part of the Amargosa Desert (Ash Meadows) and Pahrump Valley have demonstrated that development of the overlying basin-fill aquifers resulted in water-level changes in the underlying carbonate-rock aquifers (Hughes, 1966, p. 69; Bateman and others, 1974, p. 1; Dudley and Larson, 1976; Harrill, 1986, p. 32-39). On the other hand, an early study in the Muddy River Springs area suggested that adverse impacts resulting from such development are unlikely in that area (Maxey and others, 1966, p. 7). Outside these basins, such impacts, or lack thereof, have not been reported.

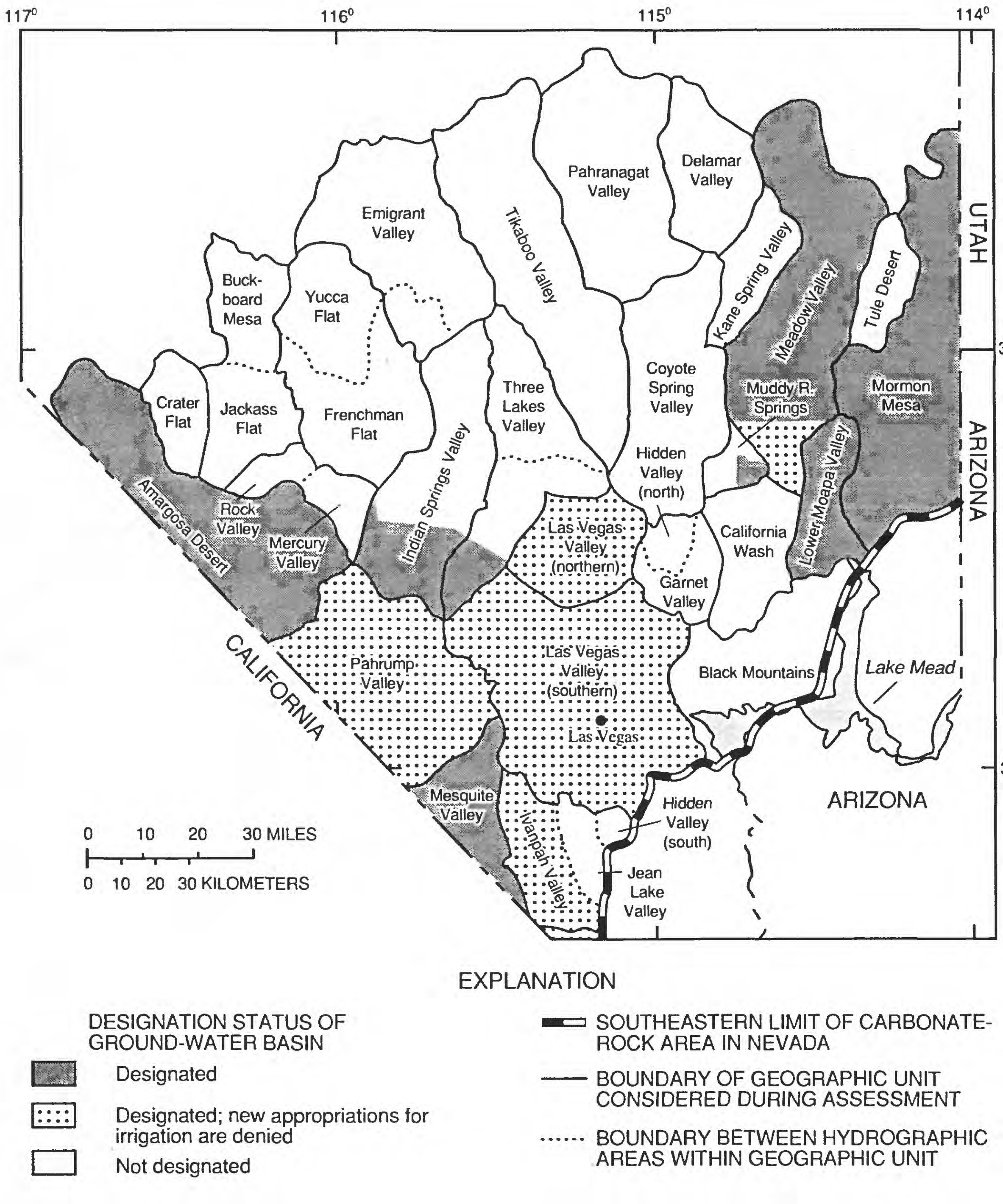


FIGURE 8.--*Ground-water basins "designated" by the Nevada State Engineer as of January 1984. The designation signifies that the ground-water resource in the basin already is being depleted.*

The transferability of these results to other basins is not simple. The studies show that both (1) conditions that favor and (2) conditions that restrict hydraulic connection between aquifers can be found in the carbonate-rock area of southern Nevada. Pumping from carbonate-rock aquifers may, or may not, impact natural discharge or affect water levels in wells in adjacent basin-fill aquifers; impacts would depend on the local geologic and hydrologic conditions.

Indirect evidence of the potential for hydraulic connection between consolidated-rock aquifers is provided by the drained basins of southern Nevada. Recharge to drained basins, such as Delamar, Ivanpah, Garnet, Three Lakes, Tikaboo, Tule Desert, and Mercury Valley, apparently drains into underlying or adjacent consolidated-rock aquifers. Such subsurface discharge is indicated by large depths to water throughout the basins and by the absence of discharge by springs or evapotranspiration within the basins. This discharge demonstrates that, within these basins and under natural conditions, basin-fill and carbonate-rock aquifers are connected. A few of the basins, namely Yucca Flat, western Jackass Flat, and Mercury Valley, are completely drained; that is, the basin-fill sediments are either wholly unsaturated or only locally saturated (Winograd and Thordarson, 1975, p. 37). Within these basins there can be no impact of development on basin-fill ground-water levels or discharge because the basin fill is unsaturated.

Water Quality

Two types of water-quality considerations were included in the area assessment. Figure 9 shows the boundary of the Nevada Test Site and figure 10 shows those units that lie near and immediately downgradient from the Nevada Test Site. They were considered to be of dubious merit as potential water-supply sources because of the possibility of contamination by radionuclides generated during testing of nuclear weapons or from the proposed high-level nuclear-waste repository at Yucca Mountain (fig. 2). Moreover, permission for an exploratory drilling program for public-water supplies beneath the Nevada Test Site is doubtful, which in itself rules out these areas. The results of geologic and hydrologic investigations being done by the U.S. Geological Survey and other agencies at and near the Nevada Test Site will, however, be used to the extent possible in the course of the assessment and subsequent studies.

The second water-quality consideration involves the possibility that the water in the carbonate rocks is contaminated by saline water derived from evaporite deposits. Carbonate rocks in some areas in southern Nevada contain, or are interbedded with, evaporites. Wells open to these rocks would encounter slightly to very saline water [these salinity levels, as defined by Hem (1985, p. 157) and range from 1,000 to 35,000 mg/L of dissolved solids] as a result of solution of evaporite minerals. Data regarding the presence of saline waters are sparse or nonexistent in most areas. Certain stratigraphic units, however, are known to include evaporites, which would be dissolved by water flowing through or in contact with these units and, thus, would result in saline ground water. Other units stratigraphically or structurally near these contributing sequences could also yield saline water.

The Permian Kaibab Limestone, for example, is stratigraphically above the carbonate-rock section and contains numerous beds of gypsum and other evaporites that can substantially degrade the quality of water that contacts them (Longwell and others, 1965, p. 37). Special notice was paid to the presence of thick sequences that include these minerals in the area-assessment process, because their presence might have an important bearing on the minimum well depths required to reach good-quality water, or whether water of acceptable quality would be present at any depth.

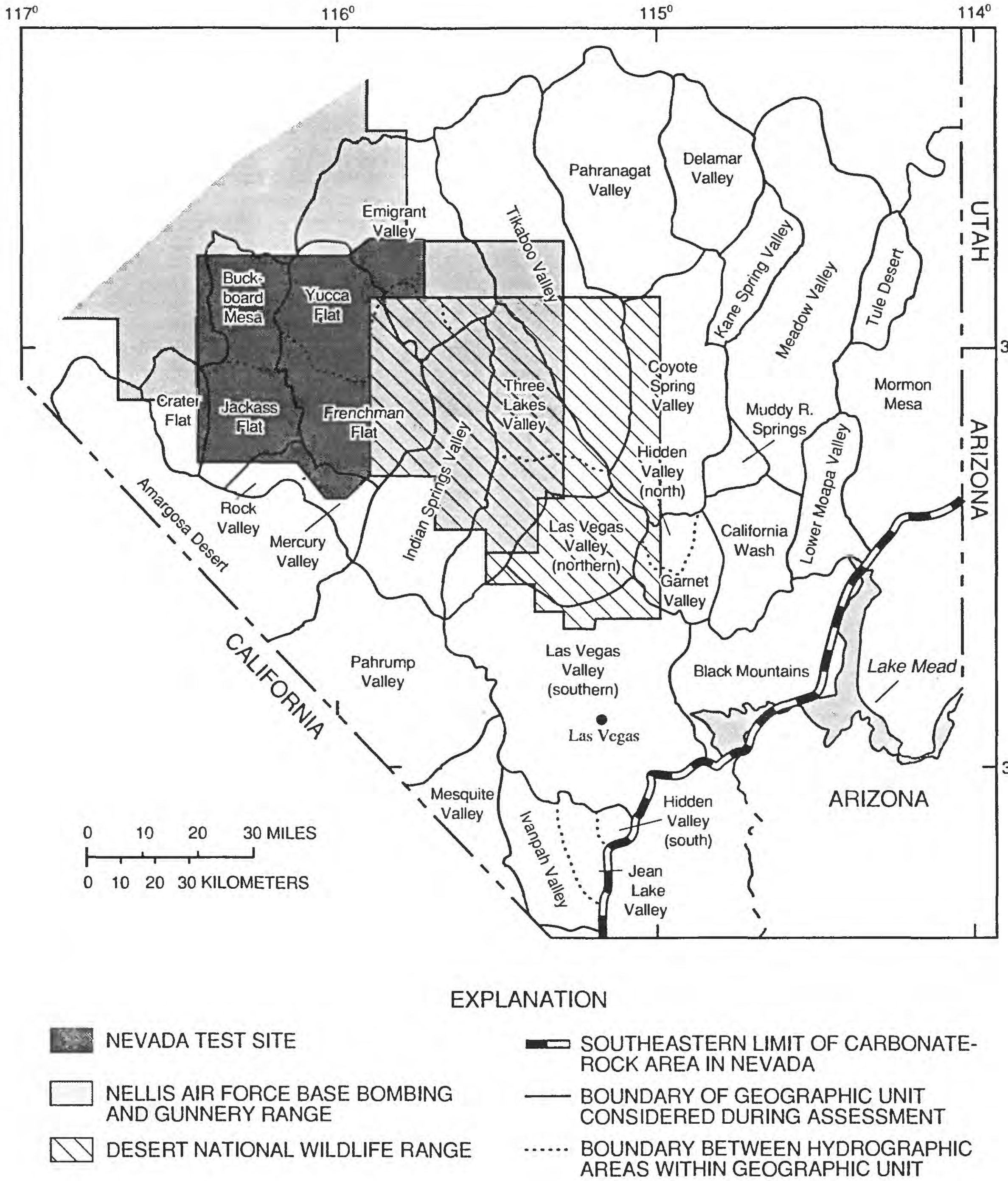
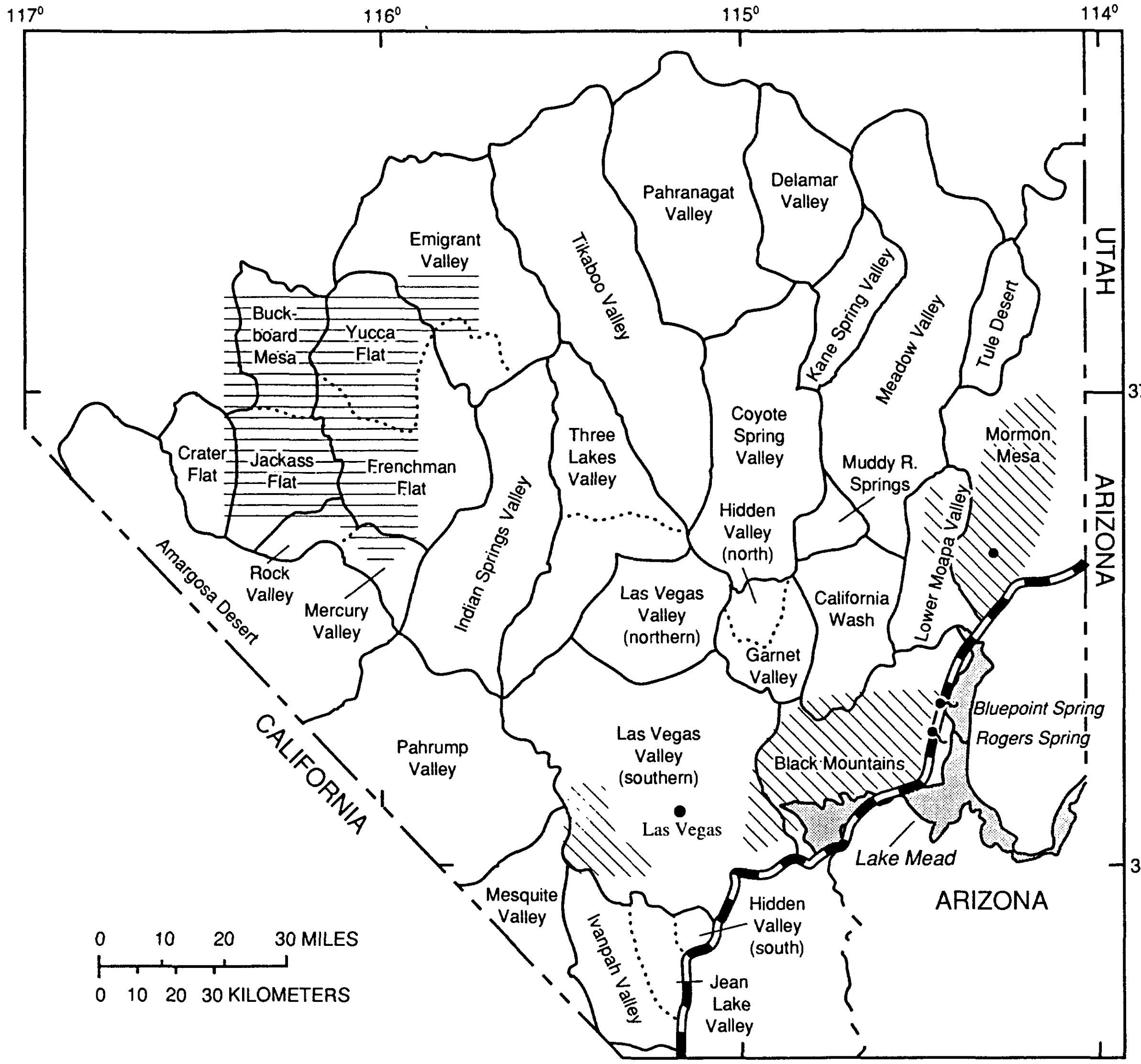


FIGURE 9.--*Location of Nevada Test Site, Nellis Air Force Base Bombing and Gunnery Range, and Desert National Wildlife Range.*



EXPLANATION

WATER-QUALITY ISSUES

Nevada Test Site

Area associated with thick sequences of evaporite-rich rocks, where ground water could contain large concentrations of dissolved solids

Oil-test well where thick sequence of evaporite-rich deposits or saline water has been reported

Regional spring yielding saline water

SOUTHEASTERN LIMIT OF CARBONATE-ROCK AREA IN NEVADA

BOUNDARY OF GEOGRAPHIC UNIT CONSIDERED DURING ASSESSMENT

BOUNDARY BETWEEN HYDROGRAPHIC AREAS WITHIN GEOGRAPHIC UNIT

FIGURE 10.--*Areas where potential for poor-quality ground water exists.*

Figure 10 shows the units known to be underlain by thick sequences of sedimentary rocks containing thick sequences of evaporite beds, as well as the locations of two oil-test holes and two regional springs that yield saline water from carbonate rocks (which suggest that saline water could be encountered in carbonate-rock aquifers). The salinity of water from the holes and springs imply that the upper carbonate-rock aquifers in the Mormon Mesa and Black Mountains units contain saline water. The southwest corner of the Las Vegas Valley (southern part) unit is underlain by stratigraphic units of similar age to those underlying the Black Mountains area. The shallowest of these rocks yield water with high sulfate concentrations while the deeper, older rocks may contain fresh ground water.

In many ground-water systems, water quality is poorer at greater distance from the recharge area, and thus, distance of an area from the recharge source could have been considered in the assessment. This factor is, however, of small consequence because in the carbonate-rock aquifers, water is generally of good quality and is at or near chemical equilibrium with the aquifer matrix (except in the presence of evaporites). For example, two wells drilled into carbonate-rock aquifers in Coyote Spring Valley (near the lower end of the White River system) during the MX studies yielded water that was of good quality (400 and 490 mg/L of dissolved solids; Berger and others, 1988, p. 8); the only constraint on its use would be imposed by its high fluoride levels (water from both contained 1.9 mg/L).

DESCRIPTIONS OF SEVEN PREFERRED AREAS FOR FUTURE INVESTIGATIONS

Table 6 summarizes how each of the 26 geographic units considered was evaluated with respect to the criteria discussed. The overall rating, unless otherwise indicated, was derived by simply noting which ratings were more prevalent for a specific area: '+' ratings or '-' ratings. No criteria were given more or less weight than others. This approach is believed to have worked well because, at a subjective level, no misjudgments or undue weighting of one criterion or another is evident.

Among the 26 units, the following 7 are proposed for further evaluation and specific drilling-site selection:

Coyote Spring Valley
Delamar Valley
Indian Springs Valley
Las Vegas Valley (northern part)
Pahranagat Valley
Three Lakes Valley
Tikaboo Valley

Investigating these particular units is expected to prove most fruitful, on the basis of the criteria discussed above. The units together form a broad area directly north of Las Vegas that is about 100 mi from north to south and 60 mi from east to west (fig. 1). Presumably, investigations within this area can be detailed enough to allow reference to and discussion of the many issues associated with development of the carbonate aquifers, as well as detailed considerations of where test, exploration, and production wells might be sited.

Among the issues beyond well siting that must eventually be addressed are: what are the sources of water, would the water developed be replenishable, how much water is stored in the rocks, how much hydraulic interconnection is there between carbonate-rock and other aquifers, how deep must wells be drilled to be representative of the carbonate-rock aquifer conditions, how deep must wells be drilled to tap important production zones, what are the likely impacts of aquifer development, and can these impacts be managed within Nevada's water law? Within the considerable uncertainty associated with this area assessment, no preference is assigned to any of the seven units; their order in the preceding list is alphabetical, and not in order of preference. A brief description of each of these units follows.

TABLE 6.--*Rating of unit by area-assessment criteria*

Criteria: 1, Interbasin ground-water flow conditions; 2, areal extent of flow system; 3, stratigraphic thinning; 4, continuity of carbonate rocks; 5, distance to discharge areas and pumping centers; 6, depth to water; 7, level of ground-water development in overlying basin fill; 8, water-quality considerations; see text for clarification

Rating: +, notable positive indications for potential aquifer development; 0, neither positive nor negative; -, notable negative indications; =, very strong negative indications; ?, not enough information to make a rating (when listed with a rating, available information makes this rating very uncertain)

Unit	Criteria								Overall rating
	1	2	3	4	5	6	7	8	
Amargosa Desert	+	+	−?	+?	−	+	=	0	0
Black Mountains	−	?	−	−	−	0	+	=	=
California Wash	−	?	+	+	−	+	0	−?	0
Coyote Spring	+	+	0	+	−?	0	+	+	+
Crater Flat	−	+	?	−	−?	−	+	=	[a] −
Delamar	+?	+	?	−?	+	−	+	+	+
Emigrant	−	=	−	−	+	−	+	+	[a] −
Hidden and Garnet	=	−	+	+	0	0	+	?	0
Indian Springs	+	+	−	−?	+?	0	−	+?	+?
Ivanpah, Jean Lake, Hidden	=	?	−?	+	−	−	−?	?	=
Jackass Flat and Buckboard Mesa	+	+	?	−	−?	−	0	=	[a] −
Kane Spring	−	−	0	?	+?	−	+	?	−?
Las Vegas (northern)	0	+	?	+	+	+	−?	+	+
Las Vegas (southern)	?	0	+	0	−	+	=	−?	−
Lower Moapa	−	?	?	+	−?	+	−?	−?	−
Meadow	?	+	0	0	0	+	−	−?	0
Mercury and Rock	+	+	0	0?	0	−	0	=	[a] −
Mesquite	−	=	?	+	−	+	−	?	−
Mormon Mesa	?	0	−	−	?	+	?	=	−
Muddy River Springs	−	+	0	+	=	+	=	+	−
Pahranagat	+	+	+	+?	=	+	=	+	+?
Pahrump	+	0	+	−	−	+	=	+	0
Three Lakes	+	+	?	0	+?	0	+	+?	=
Tikaboo	+	+	+	+?	+	+	+	?	+
Tule Desert	−	−	0	+	+	−	+	−?	−?
Yucca and Frenchman Flats	+	+	+?	−?	+	−	0	=	[a] −

[a] Unit lies within Nevada Test Site or other restricted area (Emigrant Valley), and thus is logistically an unlikely site for aquifer development.

Coyote Spring Valley

The Coyote Spring Valley unit (hydrographic area 210, Rush and others, 1971) comprises 650 mi ^{2} north-northeast of Las Vegas Valley. The area is underlain by a relatively coherent Paleozoic section (Wernicke and others, 1984, fig. 10) and lies near the lower end of the White River flow system (Eakin, 1966, fig. 2). Immediately to the southeast is the Muddy River Springs area where underflow from Coyote Spring Valley and Meadow Valley Wash discharges in large, warm springs (Alan H. Welch, U.S. Geological Survey, written commun., 1984). The area includes potential drilling sites anywhere from 40 to 70 mi from Las Vegas. Basin-floor altitudes range from about 2,500 to 3,000 ft above sea level. The static depth to water in a well tapping the carbonate-rock aquifers is known to be less than 400 ft in southeastern Coyote Spring Valley and is probably about 600 ft to the north (Thomas and others, 1986). Local recharge appears to be derived from the Las Vegas and Sheep Ranges although the path followed by recharge from the Sheep Range to Coyote Spring Valley is uncertain (Welch and Thomas, 1984). These local recharge sources contribute about 6,000 acre-ft/yr to the valley. In addition, approximately 17,000 to 22,000 acre-ft/yr (Welch and Thomas, 1984) flows beneath Coyote Spring Valley toward the Muddy River Springs from basins farther north in the White River flow system (fig. 3). A small spring (and seep) and well near the north end of the area serves a small ranch; the next nearest water users are in the Upper Muddy Springs area.

Technical studies in support of carbonate-rock aquifer development in the Coyote Spring Valley unit could address potential hydrologic impacts on the Muddy River Springs area and ground-water movement from the Sheep Range to Coyote Spring Valley. The western third of the valley lies in the Desert National Wildlife Range (fig. 9) and may require detailed environmental assessment of impacts on that nearly wilderness area.

Delamar Valley

The Delamar Valley unit (hydrographic area 182, Rush and others, 1971) is a relatively high-altitude area, about 4,500 ft above sea level, that is 80 to 100 mi from Las Vegas. The valley includes about 380 mi ^{2} directly east of the regional springs in Pahranagat Valley. Delamar Valley is a drained basin (see section "Ground-Water Development in Basin Fill") and depths to water in the basin fill are 600 ft or more. Depths to water in wells tapping the carbonate-rock aquifers would probably be between 1,000 and 2,000 ft throughout much of the valley (Thomas and others, 1986). The basin drains into the White River flow system either in southern Pahranagat Valley or Coyote Spring Valley. The Delamar Mountains (fig. 2) may contribute about 1,000 acre-ft/yr of recharge. The northern part of the area may receive 5,000 acre-ft/yr of underflow from the valley immediately north of it (Eakin, 1963b). A large percentage of the exposures of consolidated rocks in the area are Tertiary volcanic rocks that overlie the Paleozoic section of carbonate rocks. As such, the structural continuity of the underlying carbonate rocks is unknown. A major thrust fault along the east side of the basin presumably has raised a barrier (of uncertain continuity) of Precambrian confining units between this basin and basins to the east and south (Armstrong, 1968).

Technical studies to determine the potential of carbonate-rock aquifer development in the Delamar Valley unit could address potential hydrologic impacts on the regional springs in Pahranagat Valley and in the Muddy Springs area.

Indian Springs Valley

The Indian Springs Valley unit (hydrographic area 161, Rush and others, 1971) comprises about 655 mi^2 among the Pintwater Range, Spotted Range, and northern Spring Mountains. The Paleozoic rocks in the area are extended and broken to varying degrees in various parts of the valley. At least two east-west trending geologic barriers to ground-water flow have been documented in the vicinity of Indian Springs (Winograd and Thordarson, 1968, p. 44-47). Potential drilling sites would be about 35 to 60 mi from Las Vegas and at altitudes around 3,200 ft above sea level. The static depth to water in a well tapping the carbonate-rock aquifers would probably be small near Indian Springs and would increase to more than 1,000 ft to the north (Waddell and others, 1984). The Indian Springs Valley unit is part of the Ash Meadows flow system, and locally some of the ground water discharges at springs and at wells near the Indian Springs Air Force Base. The northern Spring Mountains provide about 10,000 acre-ft/yr recharge to the area, whereas about 22,000 acre-ft/yr is believed to enter the area as subsurface underflow from Three Lakes Valley and Emigrant Valley.

Technical studies in support of carbonate-rock aquifer development in the Indian Springs Valley unit could address potential impacts on the water supplies at Indian Springs and hydrologic impacts on Ash Meadows. The northern two-thirds of the Indian Springs Valley unit is on land jointly managed by the Desert National Wildlife Range and Nellis Air Force Base (fig. 9), which could add considerably to the environmental and security issues that would have to be addressed in even a short-term exploratory drilling program.

Las Vegas Valley (Northern Part)

The northern part of Las Vegas Valley (part of hydrographic area 212, Rush and others, 1971) comprises about 275 mi^2 of rugged terrane between the Las Vegas Range and Desert Range. The geographic unit is underlain by a structurally extended and broken Paleozoic section that is probably at least partially bounded laterally by Precambrian confining units in both the Las Vegas and Desert Ranges, on the east and west, respectively. To the south, the unit area may be bounded hydrologically by the Las Vegas shear zone. The shear zone has been demonstrated to be a hydrologic barrier to the west near Indian Springs (Winograd and Thordarson, 1968, p. 44-47). The unit includes potential drilling sites that are about 25 mi from the original well field for Las Vegas Valley Water District in west central Las Vegas. Basin-floor altitudes range from 2,800 to almost 6,000 ft above sea level. The static depth to water in a well tapping the carbonate-rock aquifers probably would be less than 100 ft below land surface near Corn Creek Springs (location shown in fig. 7), but would increase to the north to more than 1,500 ft (Waddell and others, 1984, pl. 3). The unit lies at the inferred boundary of the Ash Meadows regional flow system and as far as is known receives no throughflow from other basins (Winograd and Thordarson, 1975, pl. 1). Local recharge is believed to be derived primarily from precipitation in the Sheep Range, and is estimated to be about 5,000 acre-ft/yr (Rush and others, 1971). There are no major water users in the unit, although Corn Creek Springs, which contain an endangered species of pupfish, is near its southernmost point and could be impacted by carbonate-rock aquifer development.

Technical studies to assess hydrologic impacts of potential development in this unit could address the issue of location of the ground-water divide between Ash Meadows and Las Vegas Valley flow systems and the nature of the divide. If the divide is caused by a geologic barrier to flow, such as the Wheeler Pass-Gass Peak thrust, then development of carbonate-rock aquifers on the north side of the barrier might not impact the hydrology of Las Vegas Valley. If the divide is not an impermeable boundary, then development north of the divide could reduce total recharge to Las Vegas Valley and thus, impact existing water supplies.

Pahranagat Valley

The Pahranagat Valley unit (hydrographic area 209, Rush and others, 1971) is located along the axis of the White River drainage with a valley floor that is about 3,200 to 4,000 ft above sea level. The unit is about 75 to 115 mi north of Las Vegas. The valley includes about 770 mi^2 north of Coyote Spring Valley and west of Delamar Valley. The valley is notable for three regional springs--Hiko, Crystal, and Ash Springs--that discharge a total of about 25,000 acre-ft/yr along the east side of the valley (Eakin, 1963a). Water from these springs is used primarily for agriculture and to supply a series of wetlands and lakes that form a wildlife refuge at the southern end of the valley. The valley may receive 46,000 to 58,000 acre-ft/yr of inflow from valleys to the north (Eakin, 1966; Welch and Thomas, 1984). The water flowing beneath this valley that does not discharge at the springs may continue on to the south (1) beneath Coyote Spring Valley and toward Muddy River Springs (17,000 to 35,000 acre-ft/yr; Eakin, 1966; Welch and Thomas, 1984) and (2) by some unknown path toward Ash Meadows in the Amargosa Desert (6,000 acre-ft/yr; Winograd and Friedman, 1972). Thick sequences of Tertiary volcanic rocks that overlie the carbonate-rock sequences are common in this area and mask much of the structure of the carbonate-rock aquifers.

Technical studies to determine the potential of carbonate-rock aquifer development in the Pahranagat Valley unit could address potential hydrologic impacts on the regional springs and lakes in that valley, the possibility of drawing from the flows to the south without impacts in the valley, and the impact that drawing from the flows to the south could have on discharges at regional springs at Ash Meadows and Muddy River Springs.

Three Lakes Valley

The Three Lakes Valley unit comprises about 600 mi^2 in two hydrographic areas, North Three Lakes Valley and South Three Lakes Valley (hydrographic areas 168 and 211, respectively, Rush and others, 1971). The unit is underlain by a highly extended, complexly fractured and tilted Paleozoic section (Wernicke and others, 1984, fig. 10). The section is probably at least partially bounded on the east by Precambrian quartzites in the Desert Range. Potential drilling sites could be about 30 to 60 mi from Las Vegas. Basin-floor altitudes are about 3,000 to 4,000 ft above sea level. The static depth to water in a well tapping the carbonate-rock aquifers would probably range from less than 500 ft at the foot of the Spring Mountains to over 1,000 ft at the north end of the valley (Waddell and others, 1984, pl. 3). Both hydrographic areas are part of the Ash Meadows flow system and receive about 8,000 acre-ft/yr recharge from the Spring Mountains and Sheep Range (table 1 and fig. 3). Another 5,000 acre-ft/yr probably flows under the unit from southern Tikaboo and Las Vegas (northern part) Valleys (Rush and others, 1971). The nearest major water users are at Indian Springs about 15 mi away.

Technical studies prior to extensive carbonate-rock aquifer development in the Three Lakes unit could address potential impacts on the water supplies near Indian Springs, hydrologic impacts on the Ash Meadows area, and nature of the divide between Ash Meadows and Las Vegas Valley flow systems. The northern two-thirds of the Three Lakes unit is on land jointly managed by the Desert National Wildlife Range and Nellis Air Force Base (fig. 9), which could add considerably to the environmental and security issues that would have to be addressed in even a short-term exploratory drilling program.

Tikaboo Valley

The Tikaboo Valley unit (hydrographic areas 169A and 169B, Rush and others, 1971) is a large basin at the boundary between the Ash Meadows flow system (which it apparently is part of) and the White River system to the east (Winograd and Thordarson, 1975, pl. 1). The unit comprises about 1,000 mi^2 and lies at an altitude of about 3,000 to 4,400 ft above sea level. The Paleozoic section is structurally extended but is not known to be bounded on any side by geologic barriers to flow. The unit is about 45 to 100 mi from Las Vegas. The unit has the advantage of being some 80 mi from the discharge area for water flowing beneath it (at the springs at Ash Meadows). The Paharanagat Range, Sheep Range, and Groom Mountain (fig. 2) provide about 6,000 acre-ft of recharge to the unit, which is believed to receive an approximately equal amount from leakage of the White River flow system at Paharanagat Valley (Winograd and Friedman, 1972; Welch and Thomas, 1984). There are no ground-water discharge areas in Tikaboo Valley because the static depth to water in both basin-fill and carbonate-rock aquifers is probably more than 1,000 ft (Waddell and others, 1984, pl. 3).

Technical studies to determine feasibility of carbonate-rock aquifer development in the Tikaboo Valley unit could address potential hydrologic impacts on Ash Meadows and the connection of the White River and Ash Meadows systems at Tikaboo Valley. The southern half of Tikaboo Valley contains land jointly managed by the Desert National Wildlife Range and Nellis Air Force Base (fig. 9), which could add considerably to the environmental and security issues that would have to be addressed in even a short-term exploratory drilling program.

SUMMARY

As an early step in hydrologic-assessment programs planned jointly by the U.S. Bureau of Reclamation and U.S. Geological Survey, 26 geographic units in the carbonate-rock area of southern Nevada were assessed and rated as candidates for more detailed studies related to the potential for development of carbonate-rock aquifers in southern Nevada. The objective was to select a manageable number of units that seem, on the basis of existing data, to show good potential for development of water from the carbonate-rock aquifers. Seven units were designated as the most promising for detailed studies: Coyote Spring Valley, Delamar Valley, Indian Springs Valley, Las Vegas Valley (northern part), Pahranagat Valley, Three Lakes Valley, and Tikaboo Valley. The parts of these units closest to Las Vegas range from 25 to 50 mi away. Together, the units constitute a broad area north of Las Vegas.

The criteria used in this assessment were as follows:

(1) Interbasin ground-water flow conditions--The amount of subsurface inflow and outflow associated with regional flow systems is an indication of how readily the water resources of carbonate-rock aquifers in an area could be evaluated. Units such as Indian Springs, Pahranagat, Coyote Spring, and Tikaboo Valleys, where regional flow is a large part of the water budget, rated well in this category.

(2) Areal extent of flow systems associated with a unit--This measure was used along with other criteria as an indication of the size and storage of carbonate-rock aquifers associated with a given unit. To the extent possible in this preliminary assessment, geologic barriers and boundaries to ground-water flow were considered. Units in the White River and Ash Meadows regional flow systems, such as Las Vegas (northern part), Three Lakes, Indian Springs, Tikaboo, Pahranagat, Delamar, and Coyote Springs Valleys, rate well under this criterion.

(3) Stratigraphic or structural thinning--This factor was considered to be a negative indicator where known to be severe. Thinning has occurred in parts of southern Nevada as a result of erosion, extensional faulting and deformation, and differences in stratigraphic thickness. In some areas, the entire thickness of carbonate rocks has been removed. Units south, east, and far west of Las Vegas tend to be most suspect with respect to potentially severe thinning. Knowledge of thinning is not detailed enough to determine which areas rate best in this criterion.

(4) Continuity of the carbonate-rock sequences--Continuity of the sequence was considered a positive indication. Continuity of the rocks will be helpful in designing exploratory and observation wells. Continuity also may result in larger areas in which lateral flow is connected and larger areas over which recharge may be collected. The Coyote Spring Valley and Las Vegas Valley (northern part) units rated particularly well with respect to this criterion.

(5) Distances between a candidate unit and its ground-water discharge area--Large distances were considered a positive indication, because of reduced potential for impacts on existing water uses (which most commonly are at or near the natural discharge area). Units such as Delamar, Tikaboo, and Emigrant Valleys, Frenchman and Yucca Flats, and Tule Desert rated best in this regard.

(6) Potentiometric surface for water in the carbonate rocks--A shallow potentiometric surface was considered a positive indicator because this condition would require smaller pumping lifts if the aquifers are developed and could result in reduced drilling costs for testing, exploration, monitoring, and production. Las Vegas (southern part), Mesquite, Meadow, Pahranagat, and Lower Moapa Valleys, as well as the Amargosa Desert and Muddy River Springs units, rated well under this criterion.

(7) Basin-fill aquifer development--The present amount of development was considered in area assessment. The degree of hydraulic interconnection between carbonate-rock and basin-fill aquifers under varying development conditions is largely undetermined. The intensely developed basin-fill aquifers of units such as Pahrump, Amargosa Desert, and Las Vegas (southern part) were considered uncertain but dubious risks in this regard. Remote, undeveloped areas such as Tikaboo Valley and Tule Desert rated best under this criterion.

(8) Potential for water-quality problems--Potential for water-quality problems was considered in terms of (a) the possibility of radionuclide transport to deep wells and (b) thick sequences of post-Paleozoic rocks that include extensive evaporite beds. This criterion is inherently a negative measure because present knowledge will not allow delineation of areas with the best water quality. The Black Mountains, Frenchman and Yucca Flats, Mercury and Rock Valleys, and Mormon Mesa units were disqualified under this criterion.

The units proposed in this preliminary assessment can be further restricted on the basis of economic and engineering criteria to provide a small number of areas or sites for studies in much greater detail to choose optimal exploratory-well drilling sites in southern Nevada. Studies of broader scope could answer three important questions: Where is the ground water, how much is there, and what would be the impacts of developing that resource?

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