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Effect of Irrigation Pumping on Desert Pupfish Habitats in Ash Meadows, Nye County, Nevada

GEOLOGICAL SURVEY PROFESSIONAL PAPER 927

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By W.W. DUDLEY, JR., *and* J.D. LARSON

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CONTENTS

ILLUSTRATIONS

TABLES

ENGLISH-METRIC EQUIVALENTS

English unit			Metric equivalent
Length			
inch (in)	=	25.40	millimetres (mm)
inch (in)	=	2.54	centimetres (cm)
foot (ft)	=	30.48	centimetres (cm)
foot (ft)	=	0.3048	metre (m)
mile (mi)	=	1.609	kilometres (km)
Area			
acre	=	4.047×10^{3}	square metres (m^2)
acre	=	4.047×10^{-3}	square kilometre (km^2)
square mile (mi^2)	=	2.590	square kilometres (km^2)
Volume			
gallon (gal)	=	3.785×10^{-3}	cubic metre (m^3)
cubic foot (ft^3)	=	2.832×10^{-2}	cubic metre (m^3)
acre-foot (acre-ft)	=	1.234×10^{3}	cubic metres (m^3)
acre-foot (acre-ft)	=	1.234×10^{-6}	cubic kilometres (km^3)
Discharge			
gallon per minute (gal/min)	=	5.451	cubic metres per day (m^3/d)
acre-foot per day (acre-ft/d)	=	1.234×10^{3}	cubic metres per day (m^3/d)
acre-foot per year (acre-ft/yr)	=	1.234×10^{3}	cubic metres per year (m^3/yr)
Transmissivity			
cubic foot per day per foot width of aquifer (ft^2/d)	=	9.291×10^{-2}	cubic metre per day per metre width of aquifer (m^2/d)
Specific Capacity			
gallon per minute per foot drawdown in well (gal $min^{-1} ft^{-1}$)	=	17.88	cubic metres per day per metre drawdown in well ($m^3 d^{-1} m^{-1}$)
Temperature			
degrees Fahrenheit	=	1.8 × degrees	Celsius (°C)+32°

EFFECT OF IRRIGATION PUMPING ON DESERT PUPFISH HABITATS IN ASH MEADOWS, NYE COUNTY, NEVADA

By W. W. DUDLEY, JR. and J. D. LARSON

ABSTRACT

The Ash Meadows area, at the southern tip of the Amargosa Desert in southern Nevada, discharges ground water collected over several thousand square miles of a regional flow system developed in Paleozoic carbonate rocks. Water moves westward across fault contacts from the bedrock into poorly interconnected gravel, sand, and terrestrial-limestone aquifers in the upper few hundred feet of the basin sediments at Ash Meadows.

A small pool in Devils Hole, which is a collapse depression in Cambrian limestone, and numerous springs in the adjacent desert valley contain rare fish species of the genus *Cyprinodon*, faunal remnants of Pleistocene lakes. The Devils Hole pupfish, *C. diabolis*, is the most endangered of the several surviving species that have evolved since the post-pluvial isolation of their ancestors. This population feeds and reproduces on a slightly submerged rock ledge. Recent irrigation pumping has nearly exposed this ledge.

Correlation of pumping histories with the stage in Devils Hole allows identification of several wells that affect the pool level most severely. Some springs that are habitats for other species of *Cyprinodon* have reduced discharge because of pumping.

Hydraulic testing, long-term water-level monitoring, water quality, and geologic evidence aid in defining the principal flow paths and hydraulic interconnections in the Ash Meadows area.

INTRODUCTION

Devils Hole, a starkly scenic collapse depression in limestone hills in the southeastern part of the Amargosa Desert, Nye County, Nevada (fig. 1), was incorporated by Presidential Proclamation into the Death Valley National Monument in 1952. In a warm pool 50 ft (15 m) below the land surface surrounding this exposed cavern lives a unique species of desert pupfish, *Cyprinodon diabolis*. The Devils Hole pupfish, less than 1 in. (about 2 cm) long, evolved from late Pleistocene ancestors left isolated in this former limestone spring when the level of the pluvial lakes of the Death Valley area receded.

To the west of these hills and their alluvial apron lies Ash Meadows, a linear area of many oases and salt meadows watered by dozens of springs, several of which discharge an even flow of more than 500 gal/min (2,700 m^3/d). Additional species of the genus *Cyprinodon* inhabit these springs and the outlet channels below them. Residents of the valley before the mid-1960's used the natural springflow for irrigation downslope. The springs of Ash Meadows are the principal discharge points for the Ash Meadows ground-water system, shown on figure 1 to integrate the subsurface drainage from a large area of southern Nevada. The westward overflow from the Ash Meadows discharge contributes to water in the adjacent regional system, the Pahute Mesa ground-water system.

In 1967 a ranching corporation, Spring Meadows, Inc.,[1] began acquiring large acreages in Ash Meadows, much of it distant or upslope from the springs. The anticipated development of about 12,000 acres (about 50 km^2) in crops for cattle feed, together with the need for water distant from large springs, spurred intensive development of a well field between 1967 and 1970. Coincident with the expansion of the agricultural enterprise and increasing withdrawal of water from the valley, the water level in Devils Hole began to decline in 1968 (fig. 2). As the pool receded, a slightly submerged rock ledge upon which *C. diabolis* feeds and propagates began slowly to be exposed to the air. A water level of 2.2 ft (0.67 m) below an arbitrary reference point (copper washer) was defined in 1970 by the National Park Service as covering 100 percent of this shelf. The relationship of shelf coverage to water level shown in figure 2 is no longer valid, for removal of debris in 1972 has increased the area covered at a given water level.

Government and private conservationists and biologists, forecasting the extinction of this endangered species, called for action by the Federal Government. In 1969, a Desert Pupfish Task Force was formed within the U.S. Department of the Interior; it was composed of representatives from the National Park Service, the Bureau of Land

[1]A subsidiary of the Farm Land Company; Spring Meadows, Inc., became Cappaert Enterprises in 1972.

Management, the Bureau of Reclamation, the Bureau of Sport Fisheries and Wildlife, and the Geological Survey. After reviewing initial reports by the Geological Survey (Worts, 1963; G.F. Worts, written commun., 1969) and the University of Nevada's Desert Research Institute (G.W. Fiero and G.B.

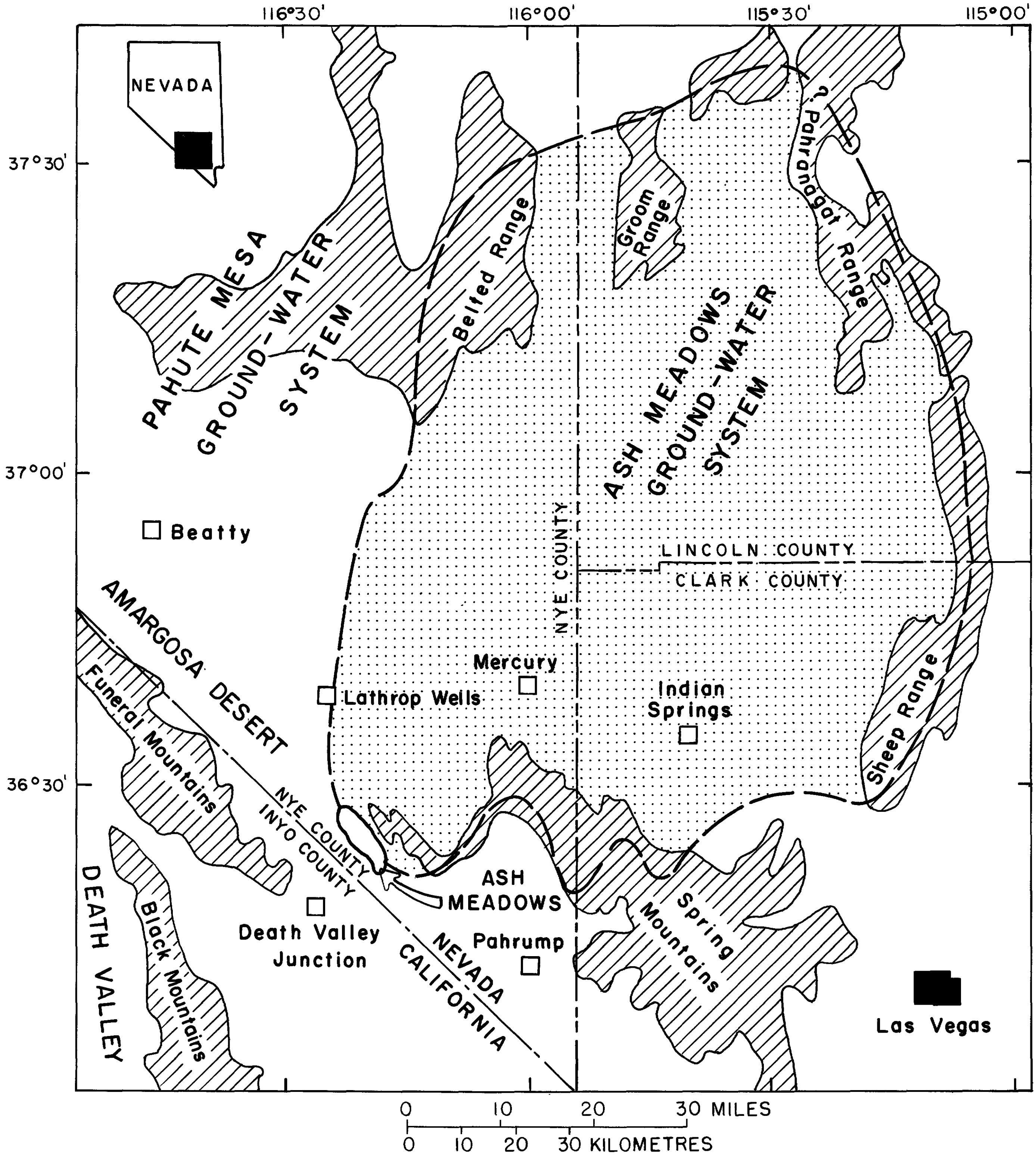


FIGURE 1.—Location of Ash Meadows area.

Maxey, written commun., 1970), the Task Force directed the Geological Survey to begin a study focused on the cause or causes of the decline of the Devils Hole water level and the discharge of the springs in Ash Meadows. The investigation, resulting in this report, was financed jointly by the five member agencies of the Departmental Task Force.

In August 1971 the United States filed a civil suit in the United States District Court, Las Vegas, Nev., seeking to enjoin Spring Meadows, Inc., from pumping certain wells that had known or suspected effects on Devils Hole. An agreement between the parties resulted in terminating pumping from three wells. The suit was reactivated in June 1972, and hearings in July 1972 and in April, May, and June 1973 resulted in a series of orders from the Court. These orders restricted pumping to the degree necessary to maintain the water level in Devils Hole at a stage judged sufficient for the continued survival of *C. diabolis*. On June 5, 1973, the Court appointed a

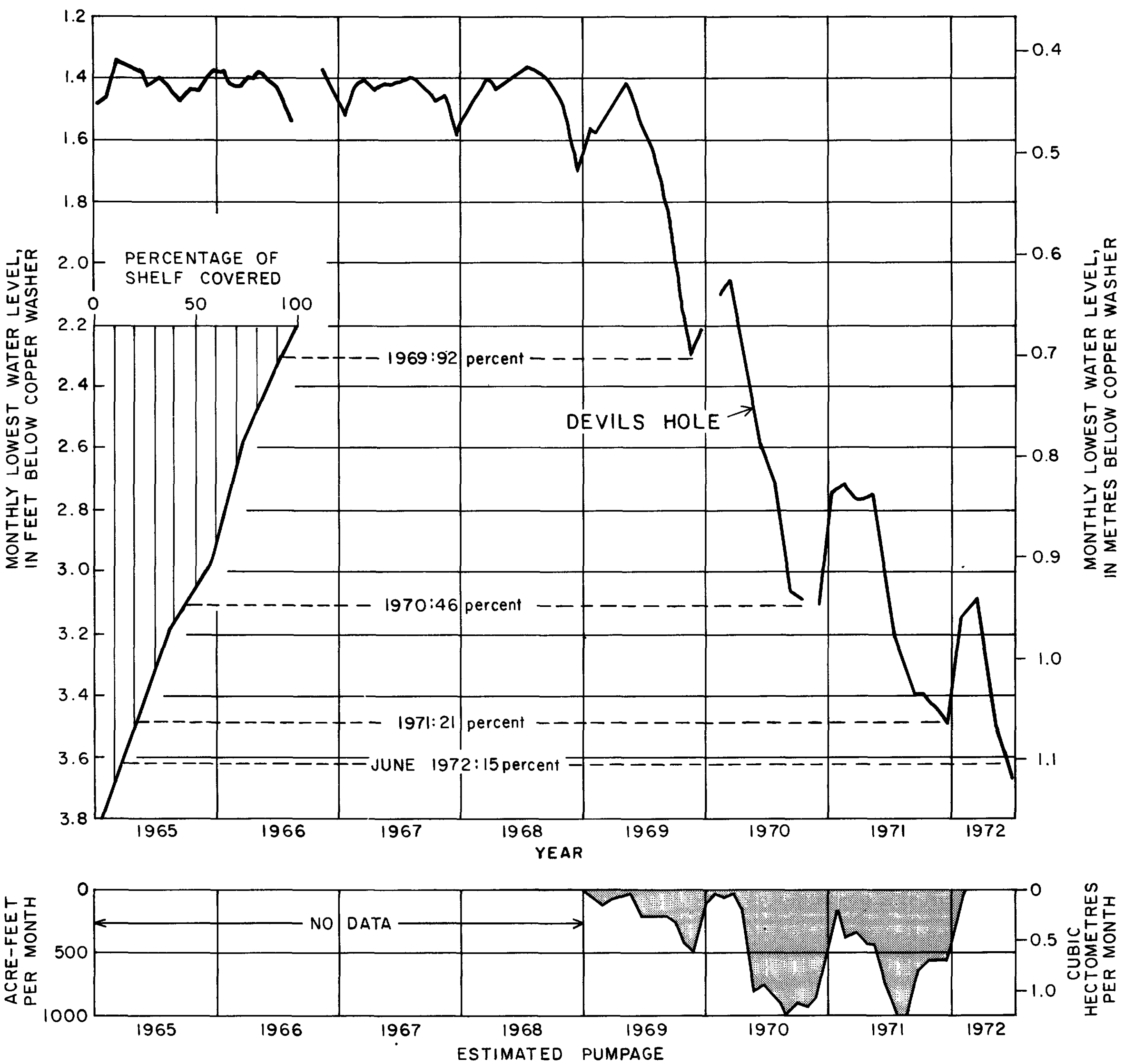


FIGURE 2.—Monthly lowest water levels in Devils Hole, percentage of natural rock ledge submerged, and estimated pumpage from wells in Ash Meadows, 1965 to mid-1972.

Special Master to regulate pumping in Ash Meadows. *Defendants'* appeal of the District Court decision was rejected in 1974 by the United States Court of Appeals for the Ninth Circuit (*San Francisco, California*).

In June 1975 the United States Supreme Court agreed to review during its 1975-76 term the earlier decisions of the District and Ninth Circuit Courts in this case, entitled *United States of America v. Francis Leo Cappaert et al.* Because of the decision's conflict with state-assigned water rights, briefs supporting the ranch's appeal to the Supreme Court were filed by Nevada and jointly by Hawaii, Idaho, Kansas, Montana, New Mexico, and Wyoming.

PURPOSE, SCOPE, AND ORGANIZATION

The primary objective of this investigation is to establish the degree to which controllable causes, such as local pumping, have lowered the pool level in Devils Hole and decreased the flow of springs in the Ash Meadows area. Inherent in this objective is the evaluation of possible alternative causes, such as distant pumping in the past, natural and man-made earthquakes, or climatic changes.

Secondary purposes, required as intermediate steps in reaching the primary objective, are to increase the knowledge of the local hydrogeology and to understand the hydraulics of the relationship among pumping, water levels, and spring discharge. However, the hydrogeologic investigation conducted during the course of this study was limited to the collection of data required to fulfill the primary objective. It is not intended to serve as a complete hydrogeologic description of the Ash Meadows area.

The basic data assembled during this study to meet these objectives are presented in the section "Hydrologic Features of Ash Meadows." Under the heading "Observed Effects of Pumping," these data are correlated and interpreted in terms of the primary objective. Finally, in the section "Movement of Ground Water in Ash Meadows Area," the secondary purposes are fulfilled by an interpretation of local geologic controls on ground-water movement and by consideration of alternative development of water supplies.

A companion study, requested by the Departmental Pupfish Task Force and conducted by the University of Nevada's Center for Water Resources Research, also examines the Ash Meadows area from the standpoint of ground-water management to allow development with a minimum of environmental impact. Bateman, Mindling, Naff, and Joung (1972) have reported results of the initial year of this study.

From September 1970 through October 1971, data on water levels, spring discharges and pumpage were intensively gathered by the Geological Survey. It was necessary to continue a less intensive data-collection program after October 1971 to complete records for the 1971 pumping season. The Geological Survey has continued to monitor selected observation points in order to provide basic data and interpretations for use in the continuing litigation (Larson, 1973 and 1974).

LOCATION SYSTEM

Township, range, and section are used throughout this report for locating features and for indexing wells and springs. Townships south and ranges east, both in increments of approximately 6 mi (9.65 km), are referenced to the Mount Diablo baseline and meridian, respectively. The term *township* is also used to describe an area approximately 6 mi (9.65 km) on each side, which is subdivided into 36 sections, ideally of 1 mi^2 (2.59 km^2) each.

Within a section, points are located according to the quarter-section (160-acre or 0.648 km^2) in which they fall. Where greater precision is needed to distinguish between closely grouped points, locations are given to the nearest 40 or 10 acres (0.162 or 0.040 km^2) by further subdividing quarter-sections. As an example of the notation in standard use, the southeast quarter of the southwest quarter of the northwest quarter of section 10, township 17 south and range 50 east is abbreviated as SE¼SW¼NW¼ Sec. 10, T. 17 S., R. 50 E.

Index numbers lead with the grosser location and progress toward the more precise. The letters a, b, c, and d are applied in counterclockwise manner to the quarters, beginning in the northeast quarter. A feature located in the 10-acre (0.040-km^2) square of the example above, therefore, is indexed as 17S/50E-10bcd. Since only east ranges are referenced to the Mount Diablo meridian, the notation 17S/50-10bcd is an acceptable abbreviation.

ACKNOWLEDGMENTS

Mr. B.L. Barnett, manager of the Spring Meadows Ranch, cooperated graciously in allowing access to ranch properties and by providing flumes and recorders to monitor certain springs.

Unpublished lithologic, hydraulic, and chemical data were provided by Ed L. Reed and Associates, Midland, Texas.

REGIONAL SETTING

PHYSIOGRAPHY

Ash Meadows lies within the Great Basin, a subdivision of the Basin and Range physiographic province, and is typical of this large region of the southwestern United States. Although geologically complex in detail, the Great Basin is characterized by widespread uniformity of its geologically young structural features. Normal faults of large displacement isolate northerly-trending mountain ranges among broad, alluvium-filled valleys. Although low divides commonly occur between valleys, forming closed drainages, Ash Meadows is drained by Carson Slough, a through-flowing tributary of the Amargosa River, which terminates in Death Valley.

The boundaries of Ash Meadows are poorly defined, but the name is generally applied to the gently sloping terrane, watered by numerous springs, within the southeastern part of the Amargosa Desert. The area, depicted in figure 3, lies roughly between altitudes 2,100 ft (640 m) and 2,400 ft (730 m). On the east a segmented group of low hills provides local relief ranging from about 500 ft (150 m) in the north to about 900 ft (270 m) in the central region near Devils Hole. In the southern part and to the east of Jack Rabbit Spring and Big Spring, a prominent range borders the area with relief of about 2,000 ft (600 m).

The western boundary of Ash Meadows corresponds to the western limit of the low salt meadows in the Carson Slough bottomland. Fairbanks Spring defines the northern limit, and Bole Spring is approximately the southern limit. As thus defined, Ash Meadows lies wholly in Nevada and within the townships T. 17 and 18 S., R. 50 E. and T. 18 S., R. 51 E.

The higher slopes bordering the eastern hills are composed of dissected alluvial fans and pediments cut on older Quaternary lakebeds. Dense non-marine limestone beds, including the fossil effluent of now extinct springs, form a resistant westward-sloping planar divide in much of the interchannel area. At some locations, particularly north of Fairbanks Spring, these beds form prominent buttes.

Between altitudes 2,325 ft (709 m) and 2,175 ft (663 m), dozens of springs and small seeps discharge a total of about 11,000 gal/min (60,000 m^3/d), about 3,000 gal/min (16,000 m^3/d) of which is from Crystal Pool (18S/50-3adb) alone. Dense to moderate growths of mesquite occur at the springs and near the outlet channels below. Mixed with the mesquite, and extending farther from the channels, is a cover of saltbush, ranging from healthy to sparse. Saltgrass forms a luxurious growth where the spring channels empty into poorly drained flatlands, particularly along the flood plain of Carson Slough.

CLIMATE

Because the National Weather Service does not maintain weather stations in Ash Meadows, climatic parameters were extrapolated from the published records for Beatty, Lathrop Wells, and Boulder City, Nevada, and from those for Death Valley, California.

The mean annual temperature at Ash Meadows is approximately 18.5°C (65°F), as estimated from the 15.5°C (60°F) mean at Beatty and about 18°C (64°F) at Lathrop Wells. Annual precipitation probably averages between 3 and 4 in. (about 75 to 100 mm) and pan evaporation is probably about 100 in. (2,500 mm) per year.

HYDROGEOLOGY

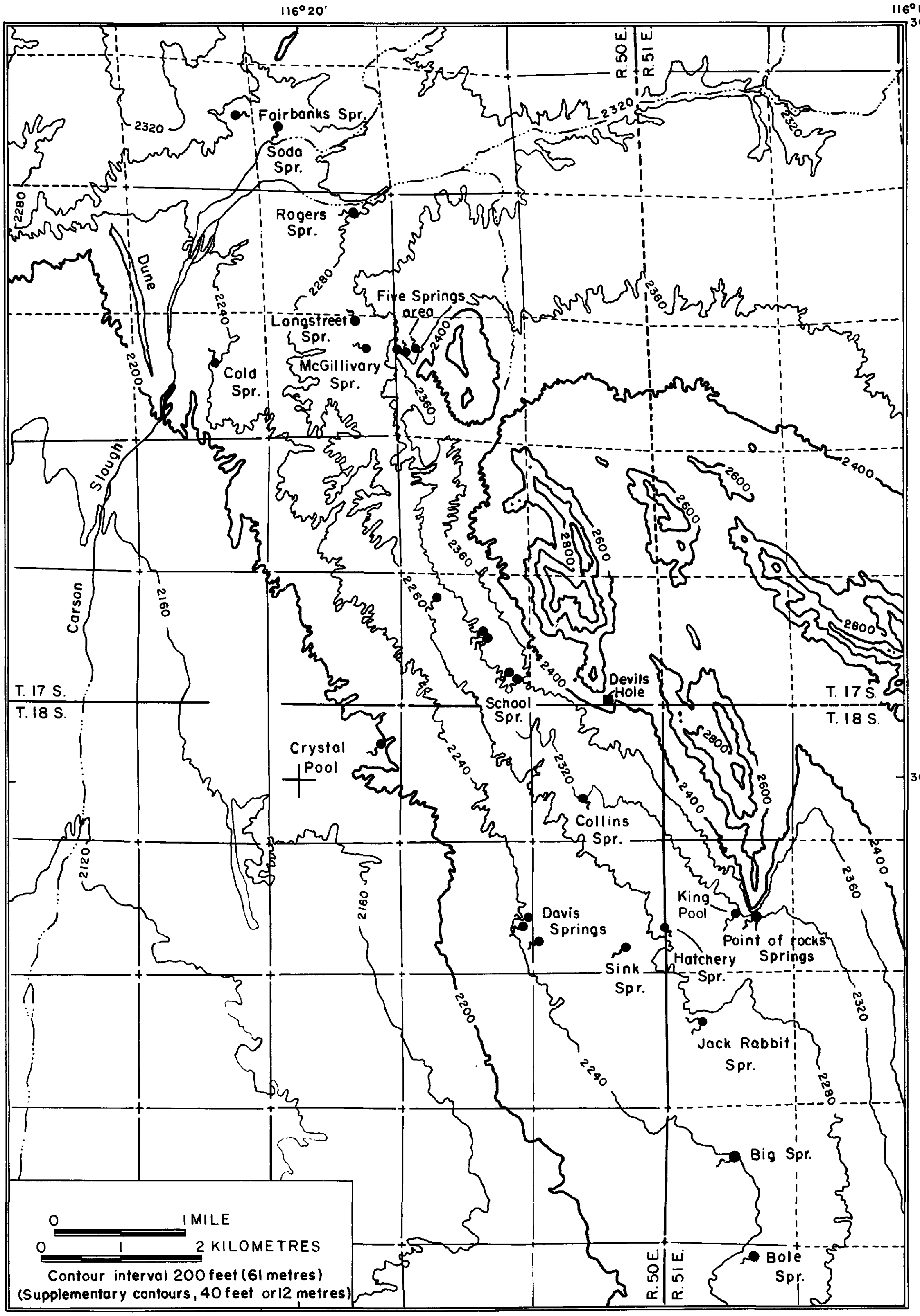
Table 1 shows the wide variety and great thickness of rocks that occur regionally in southeastern Nevada. Upper Precambrian and Paleozoic (Cambrian through Permian) rocks are primarily marine in origin, having been deposited in widespread but shallow seas. The pressure and heat resulting from deep burial and later tectonic forces transformed the sediments into dense limestone, dolomite, argillite, and sandstone.

During several tectonic episodes the Paleozoic and older rocks were folded, fractured, and thrust over each other to form now-extinct mountain ranges. Mesozoic rocks, if ever deposited in this area, were removed by erosion along with thousands of feet of Paleozoic rocks.

The present topography of the Great Basin began its development in the Tertiary Period. Volcanism became widespread, and the region was broken by northerly-trending normal faults that transect older structural patterns. The landscape changed to one of narrow, abruptly rising, isolated mountain ranges and hills that shed their debris into broad basins. Depositional environments became individualized, and the resulting stratigraphy is unique in individual areas. Exposures of Tertiary rocks in the Ash Meadows area, described by Denny and Drewes (1965), are probably Oligocene and younger and are predominantly clastic sediments with lesser amounts of limestone and tuff. At and near the Nevada Test Site, north of Ash Meadows, great thicknesses of volcanic tuff and lava were deposited in Tertiary time. Consequently, the Tertiary and Quaternary Systems are described in table 1 only for the limited area of Ash Meadows.

REGIONAL AQUIFER SYSTEM

Figure 4 shows the distribution of rocks over an area of several thousand square miles. The Paleozoic and older rocks are subdivided into four hydrostratigraphic units, (table 1) as defined by Winograd and Thordarson (1975). The aquifers are composed predominantly of limestone and dolomite which transport water freely through fractures that have been enlarged by dissolution of the carbonate



Base from U.S. Geological Survey, Ash Meadows, 1:62,500

FIGURE 3.—Topography of Ash Meadows and vicinity.

TABLE 1.—*Major stratigraphic units in the vicinity of Ash Meadows, Nye County, Nev.*

[Lithology, thickness, hydraulic characteristics, and distribution of Tertiary and Quaternary described for the limited Ash Meadows area only; adapted in part from Denny and Drewes (1965). Older units described for entire Ash Meadows ground-water basin; adapted from Winograd and Thordarson (1975). *T*, transmissivity, in feet squared per day]

System	Stratigraphic unit	Lithology	Thickness (feet)	Hydraulic characteristics	Distribution	
Quaternary	Valley fill, undifferentiated	Gravel, sand and mudflows; channel and alluvial fan deposits. Local spring deposits (travertine.)	1,000 ±	Discontinuous, linear local aquifers. *T* ranges from less than 100 to 20,000 or more.	Eastern one-third of Ash Meadows, adjacent to carbonate hills.	
		Alluvial and (?) lacustrine silt, clay and limestone; local peat and spring deposits.	2,000 ±	Aquitard; *T* less than 100 where tested.	Throughout western two-thirds of Ash Meadows. Interbedded beneath eastern one-third.	
Tertiary	Undifferentiated	Moderately to well indurated siltstone; lesser tuff, sandstone, conglomerate and limestone. Siliceous where altered by thermal springs.	2,000 ±	Aquitard; untested, but *T* probably less than 100.	Crops out in southwestern Ash Meadows. Beneath Quaternary elsewhere in Ash Meadows.	
Permian(?) and Pennsylvanian	Tippipah Limestone	Limestone.	3,600	Upper carbonate aquifer[1] *T* as much as 10,000.	Limited areas to northeast in Ash Meadows ground-water basin.	Absent in Ash Meadows and adjacent hills
Mississippian and Devonian	Eleana Formation	Argillite with lesser sandstone, quartzite, and conglomerate; minor limestone.	8,000 ±	Upper clastic aquitard[1] *T* less than 70.	West-central part of Ash Meadows ground-water basin. Beneath younger units elsewhere.	
Devonian	Devils Gate Limestone	Limestone and dolomite; minor quartzite and shale.	8,000 ±	Lower carbonate aquifer[1] Fractured aquifer with *T* as much as 100,000. Solution enlargement of fractures near Ash Meadows discharge area and probably where areally restricted upgradient in the Ash Meadows ground-water basin.	Regionally distributed over Ash Meadows ground-water basin. Closest outcrops in Specter Range and Mercury Valley. Possibly beneath Tertiary in northern or western Ash Meadows.	
	Nevada Formation					
Ordovician	Ely Springs Dolomite					
	Eureka Quartzite					
	Pogonip Group					
Cambrian	Nopah Formation	Limestone and dolomite. Dunderberg Shale Member forms lower 200 feet.	2,000 ±		Crops out in hills bordering Ash Meadows on east. Beneath Tertiary in Ash Meadows and beneath younger units throughout Ash Meadows ground-water basin.	
	Bonanza King Formation	Limestone, dolomite, and minor siltstone.	4,500			
	Carrara Formation	Limestone with minor siltstone.	1,000			
		Siltstone and argillite with minor limestone.	1,000	Lower clastic aquitard[1] *T* generally less than 100. Restricts ground-water movement.	Crops out in anticlinal core in hills east of southern Ash Meadows. Forms southern edge of Ash Meadows ground-water basin in Spring Mountains. Locally crops out or present beneath younger units elsewhere.	
	Zabriskie Quartzite	Quartzite, sandstone, siltstone, and minor limestone.	9,000+			
	Wood Canyon Formation					
Precambrian	Stirling Quartzite					
	Johnnie Formation					

[1] As defined by Winograd and Thordarson (1975).

minerals. The aquitards[2] contain only minor thicknesses of soluble rocks and are composed chiefly of clastic rocks that impede the flow of ground water. Because of their geometric distribution (fig. 4), the aquitards function most importantly to restrict lateral ground-water flow, thus determining the boundaries of the Ash Meadows ground-water system.

The lower clastic aquitard includes upper Precambrian and lowermost Cambrian clastic rocks that have generally low permeabilities. Above this unit is the lower carbonate aquifer, composed of about 15,000 ft (4,600 m) of limestone and dolomite, interbedded with minor thicknesses of siltstone, argillite, and shale of Cambrian, Ordovician, and Devonian age. Drill holes penetrating the lower carbonate aquifer show its transmissivity (hydraulic conductivity times thickness) to be highly variable.

[2] An *aquitard* is a body of rock that has low but measurable hydraulic conductivity and, therefore, impedes the flow of ground water. Where an aquitard is in stratigraphic juxtaposition to an aquifer and retards ground-water movement from the aquifer, it functions as a *confining bed*, as defined by Lohman and others (1972). The more specific term, confining bed, is preferred by the Geological Survey where both the hydraulic and stratigraphic conditions warrant its use.

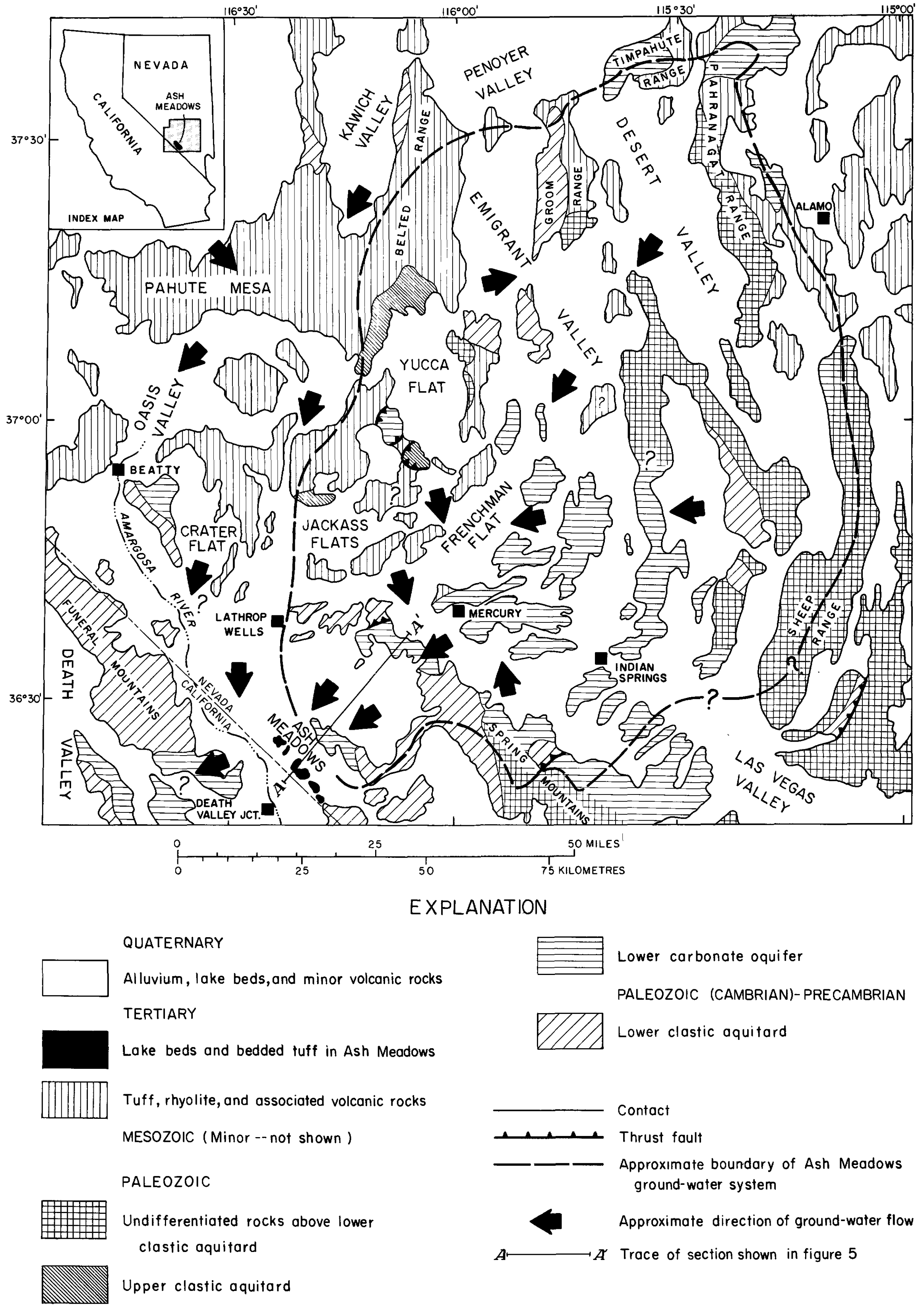


FIGURE 4.—Generalized hydrogeology and boundary of the Ash Meadows ground-water system. Adapted from Carlson and Willden, 1968; Denny and Drewes, 1965; and Winograd and Thordarson, 1975.

Where they are not fractured, these carbonate rocks have low transmissivities, but throughout the region the unit is broken by fractures and faults that often are enlarged by solution. Transmissivities of almost 100,000 ft^2/d (almost 10,000 m^2/d) have been measured in U.S. Geological Survey wells penetrating only about 300 ft (approximately 100 m) of the Bonanza King and Carrara Formations at a site about 8 mi (13 km) northeast of Ash Meadows (Johnston, 1968).

The rocks exposed in most of the hills on the east side of Ash Meadows, and those in which Devils Hole is formed, are of the Bonanza King Formation (Denny and Drewes, 1965).

Above the lower carbonate aquifer there is an 8,000-ft (2,400-m) thickness of Mississippian and Devonian argillite interbedded with coarser clastic rocks and occasional thin limestone of the Eleana Formation. This unit, designated by Winograd and Thordarson (1975) as the upper clastic aquitard, displays transmissivities generally less than 70 ft^2/d (6 m^2/d), even where penetrated for several hundred feet. The Tippipah Limestone (Permian (?) and Pennsylvanian) occurs at scattered localities but has been removed by erosion over most of the area. Where present beneath the water table, however, it is highly transmissive and was defined by Winograd and Thordarson (1975) as the upper carbonate aquifer. Although no Paleozoic rocks above the lower part of the Nopah Formation (table 1) are known in Ash Meadows and the hills on its east border, Denny and Drewes (1965) identified carbonate rocks with minor interbeds of chert and clastics in the southern Funeral Mountains (between Ash Meadows and Death Valley) as probably Silurian and younger. Consequently, the rocks above the Nopah Formation in the lower carbonate aquifer, and younger units, may occur beneath the Tertiary System in Ash Meadows.

The highly transmissive lower carbonate aquifer is widely distributed beneath the ranges and basins lying to the northeast of Ash Meadows. Recharge to the aquifer moves through fractures and fault zones, which form a conduit system so permeable that it acts as a gigantic drain for about 4,500 mi^2 (about 12,000 km^2) (Winograd and Thordarson, 1975). The flow system encompassed by this area (fig. 4) discharges at the numerous springs in Ash Meadows and is therefore known as the Ash Meadows ground-water system. Walker and Eakin (1963) estimated the natural spring discharge of the system to be about 17,000 acre-ft per year (about 21 million m^3 per year).

LOCAL AQUIFER SYSTEM

Scattered exposures of Tertiary sediments occur near the Nevada-California State boundary in western Ash Meadows (fig. 4) (Denny and Drewes, 1965). Except for local occurrences of coarse fanglomerates, the Tertiary rocks are chiefly lacustrine in origin and composed of claystone, siltstone, and fine-grained sandstone (Denny and Drewes, 1965). Similar lithologies are expected to underlie the Quaternary valley-fill sediments beneath most of the Ash Meadows area, but they have not been recognized in drill holes, possibly because of their similarity to lower Quaternary sediments. No productive aquifers are known within the lower Cenozoic section.

During pluvial periods in the Pleistocene Epoch the Death Valley region was occupied by widespread, interconnected lakes. While ancestral forms of present pupfish species spread throughout the region, sediments similar to those of the Tertiary System were deposited in the Ash Meadows basin. The lake levels fluctuated in response to long-term climatic changes, causing now-buried shoreline facies to migrate back and forth laterally. Alluvial deposits above the shoreline consisted of channel gravels and sand, mudflow debris, peat, and travertine from numerous springs. Caliche formed at several times and is commonly encountered in drill holes in the eastern part of Ash Meadows.

The origin of massive beds of continental limestone in the upper Cenozoic section is not well known, but they probably resulted from redeposition of carbonate minerals dissolved from the Paleozoic rocks by ground water. While the travertine and caliche attest to the carbonate load in the ancient spring discharge, a more uniform and widespread environment is required to explain the massive limestones. Possibly the lake occupying the Ash Meadows basin became sufficiently concentrated to precipitate carbonate minerals. More likely, however, large ponds became periodically isolated above the shoreline during periods of lake recession.

The shifting shoreline facies and varied materials deposited above the shoreline resulted in a highly complex local system of aquifers. The most productive aquifers are the channel gravels and travertine beds, but these occur in narrow linear and discontinuous patterns. Moderate production is possible from sand, but the ancient shoreline environment apparently provided only local accumulations of beach and dune sand. Where it is well fractured, the continental limestone yields water freely, but dense, unproductive sections are commonly penetrated.

Figure 5 shows the hydrogeologic framework of the Ash Meadows discharge area. Faults near the eastern edge of Ash Meadows have interrupted the continuity of the lower carbonate aquifer sufficiently to terminate the regional flow system. Ground water

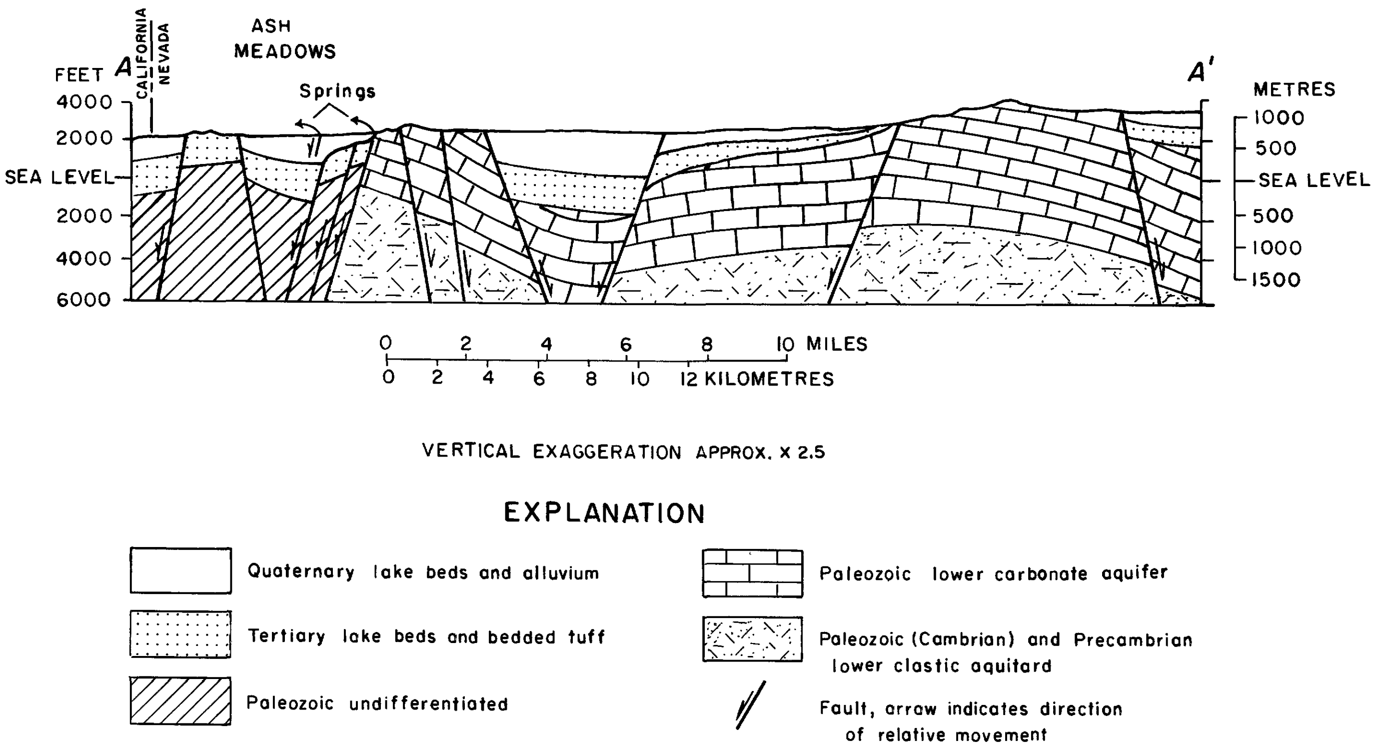


FIGURE 5.—Generalized geologic section along flow path approaching Ash Meadows. Modified from Winograd and Thordarson, 1975.

moves up and westward into the complex local aquifers to discharge at the springs. Later in this report it is convenient to refer to the regional aquifer or regional flow subsystem and the local aquifers or local flow subsystem. The term "subsystem" is used to emphasize that the regional lower carbonate aquifer is the source of virtually all water discharged from the local subsystem in Ash Meadows.

HYDROLOGIC FEATURES OF ASH MEADOWS

DEVILS HOLE

PHYSICAL FEATURES

The present configuration of Devils Hole has resulted from solution enlargement of a fault zone in the Bonanza King Formation and from subsequent collapse of the roof and walls into the cavern. The pool is oriented along the direction of strike of the fault, about N. 40° E. Beneath the water level the cavern system follows the 70° SE dip of the fault and is open to a depth of at least 300 ft (90 m), the present limit of exploration. The width of the tabular cavern opening is as much as 20 ft (6 m). Several "rooms" have been discovered both to the northeast and to the southwest along the strike (Worts, 1963).

Collapse of the roof and walls has left rock rubble that partly obscures the solution opening above the pool surface. A block of limestone about 10 ft (3 m) wide and at least 20 ft (6 m) long is wedged into the opening at the southwest end of the pool, forming the floor of the shelf upon which the Devils Hole pupfish feed and reproduce.

Above the pool the hanging (overhead or southeast) wall of the fault has a discontinuous crust of secondary carbonate minerals where the continued sloughing of rock fragments has not exposed fresh rock. This coating is particularly well preserved at the entrance to Devils Hole, about 30 ft (9 m) above the pool surface. The walls of the cavern opening beneath the water are almost continuously encrusted.

Several formerly sustained pool levels above the present stage are marked by horizontal depositional rings of calcite or dolomite. On the walls of a small room isolated by a "keystone" block at the northeast end of the pool a travertine ledge about a foot wide marks the pre-1969 sustained level of about 1.2 ft (0.37 m) below the copper washer used as the water-level reference.

WATER-LEVEL FLUCTUATIONS

The Geological Survey has recorded the water level in Devils Hole intermittently since 1956, but the record prior to 1962 is discontinuous. A copper washer was placed on the cavern wall in 1962 as a reference for water-level measurements. With respect to this reference, records prior to 1962 may be in error by about 0.3 ft (9 cm). Between 1962 and 1968, however, the water level (fig. 2) was very stable. The seasonal changes of mean daily levels (about 0.2 ft or 6 cm) were small compared with the monthly changes of water level, which ranged from 0.3 to 0.5 ft (9 to 15 cm). Daily fluctuations were frequently as great as the monthly differences.

The stage of the pool in Devils Hole fluctuates in response to several stimuli. Constant variation of the tidal forces exerted on the Earth's crust by the Moon, and to a lesser degree by the Sun, cause elastic deformation of the carbonate aquifer, resulting in continuous changes in its storage volume. Figure 6 shows the cyclic changes in water level that result from the tidal forces. The strongest of the several components of the tidal forces has a periodicity of approximately 1 day and causes the large diurnal change of water level. Superimposed on this is a semi-diurnal change that gradually modifies the shape of the daily hydrograph.

The pattern of reinforcement and interference of various tidal components results in a peak daily amplitude about every 2 weeks, followed by gradually diminishing amplitudes for about 1 week and then increasing during the second week to a new maximum amplitude. The biweekly maxima of daily amplitudes are generally between 0.3 ft (9 cm) and 0.4 ft (12 cm). Daily mean levels tend to be about 0.2 ft (6 cm) to 0.25 ft (7.6 cm) above the daily low.

Changes in barometric pressure affect the water level in Devils Hole to a lesser degree. A barometric high may suppress the stage by as much as 0.1 ft (3 cm), while a low may increase it by a similar amount. Superposition of this irregular stimulus on the cyclic tidal changes causes day-to-day changes in the mean daily level of as much as 0.2 ft (6 cm). This natural variabiltiy has hindered short-term definition of the pool level which, in turn, has prevented precise regulation of the level by modifying pumping schedules.

Short-term fluctuations of the water level result commonly from high winds, which cause local changes of air pressure at the pool surface. The hydrograph trace is frequently "noisy" because of winds.

Seismic events, including natural earthquakes and nuclear explosions at the Nevada Test Site north of Ash Meadows, cause cyclic, short-term fluctuations of the water level in Devils Hole. Figure 6 shows three responses that are typical of most in the record. The Miniata nuclear explosion generated a response having a total amplitude of about 0.1 ft (3 cm). Both of the earthquakes recorded on the hydrograph produced responses that were greater in amplitude and in duration. The water level continued to oscillate for about an hour after the initial reaction to the Chilean earthquake. About 2 hours of oscillation followed the New Ireland earthquake.

Cooper, Bredehoeft, Papadopulos, and Bennett (1965) have explained the relationship between seismically induced changes in the fluid pressure in aquifers and the water-level response in a well. The geometry of Devils Hole is such that its reaction is similar to that of a well. As in response to variations in earth tides, the magnitude of the imposed stresses and the mechanical properties of the aquifer are the first of several parameters affecting the water-level reaction. Because the seismic stresses change rapidly and time is required to move water in and out of the "well", however, the hydraulic properties of the aquifer and the geometry of the "well" also influence hydroseismic response. The interaction of the hydraulic and geometric factors with the frequency of the seismic waves results in varying ratios of change in water level to change in aquifer fluid pressure, according to Cooper, Bredehoeft, Papadopulos, and Bennett (1965). For seismic waves having short periods (high frequency) this amplification factor is less than unity. For very long-period stimuli, such as earth tides, the

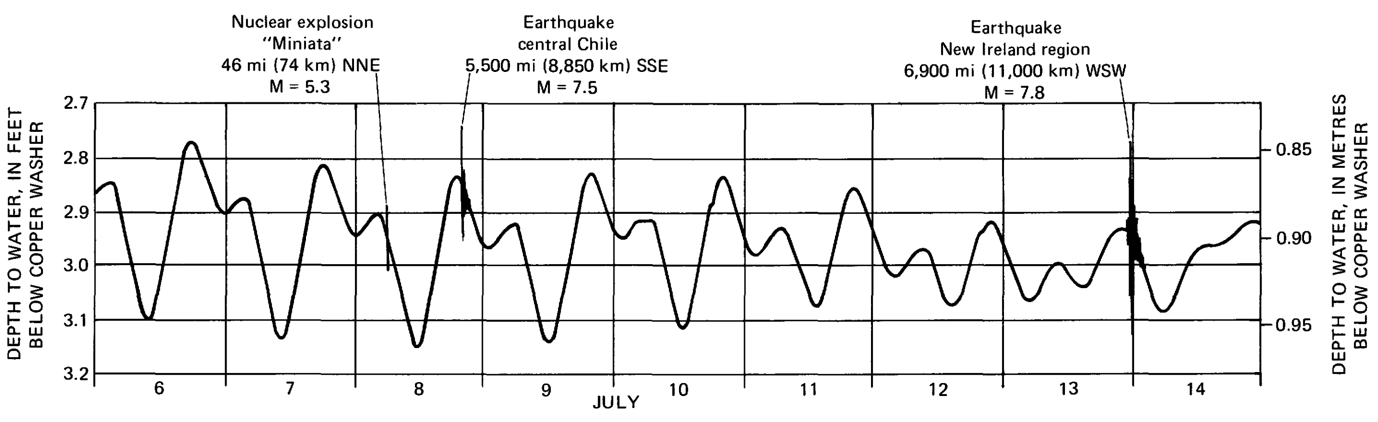


FIGURE 6.—Devils Hole hydrograph for July 6-14, 1971, showing fluctuations caused by earth tides and seismic event. (M is the Richter magnitude of seismic event, as reported by the U.S. Department of Commerce, National Earthquake Information Center.)

water-level change is the same as the pressure change, or the amplification factor is 1. Certain wave periods, however, combine with the hydraulic and geometric parameters to produce resonance, resulting in an amplification factor greater than 1. The test wells 8 mi (13 km) northeast of Devils Hole respond most efficiently to wave periods of about 30 seconds.

The sustained and relatively large reactions of Devils Hole to the distant earthquakes shown on figure 6 suggest that the many factors combined to produce resonance in the system. On several occasions the response of Devils Hole has been sufficiently great to dislodge the float on the U.S. Geological Survey recorder monitoring the water level. The Alaskan earthquake on July 30, 1972, and the Mexican earthquake on January 30, 1973, both dislodged the float, causing gaps in the hydrograph.

Figure 6 illustrates that no permanent change in the Devils Hole water level resulted from the hydroseismic responses. Examination of hundreds of responses on the long-term hydrograph shows the lack of permanent effects.

SPRING DISCHARGE

The large springs of Ash Meadows, in addition to their value as pupfish habitats and an economic resource, have long been of interest to hydrologists. The origin of the discharge and controls upon the locations of the springs have been discussed by Hunt and Robinson (1960), Loeltz (1960), Winograd (1962, 1963, 1971), Walker and Eakin (1963), Hughes (1966), and Winograd and Thordarson (1975). It is the concensus of these authors that the regional lower carbonate aquifer transports most of the spring discharge to Ash Meadows from beyond the boundaries of the topographic drainage basin.

The topographic setting of the major springs in Ash Meadows is shown in figure 3. Their relationship to outcrops of the Paleozoic carbonate rocks is presented in figure 7. With the exception of the Davis Springs and nearby springs in sections 11 and 12 of T. 18 S., R. 50 E., the springs fall into a northern group around the upper Carson Slough drainage, a central group in the vicinity of Devils Hole, and a southern group at and south of the Point of Rocks area (fig. 7).

Table 2, based on data from Walker and Eakin (1963) and supplemented during the present study, lists the springs yielding most of the water discharged in Ash Meadows. The reported measurements show considerable variability; the contrast between early reported flows and those measured by the Geological Survey after 1950 is particularly apparent.

Some of the apparent variability of spring flows may result from slight differences in measurement technique or instruments and in choice of metering locations. The smaller springs, in addition, are quite sensitive to changes in the condition of the orifice by cave-ins, trampling by stock, or cleaning of the orifice.

Examination of table 2 was done, with particular reliance on Geological Survey measurements made during 1953 and 1962, to determine the typical discharge of each spring. Addition of these flows reveals a probable total spring flow of about 10,700 gal/min (58,300 m^3/d) for Ash Meadows before development of ground water by wells. Of this total discharge about 35 percent occurs in the northern group of springs. The central group, dominated by the 2,900 gal/min (15,800 m^3/d) flow of Crystal Pool, accounts for about 28 percent, and about 30 percent is discharged at Point of Rocks and from the springs to the south. The remaining 7 percent represents flow from Davis Springs and the numerous small seeps between Crystal Pool and Point of Rocks area. Some of this scattered minor discharge may represent secondary emergence of the flow from other springs that infiltrated to shallow aquifers in the local subsystem.

The discharges of the major springs are uniform throughout the year under natural conditions. Consequently the average natural spring flow of approximately 10,700 gal/min (58,000 m^3/d) yields about 17,000 acre-ft (21 million m^3) annually, which agrees with the conclusion of Walker and Eakin (1963).

WELLS AND DRILL HOLES

Since 1961 about 40 holes reportedly have been drilled in the Ash Meadows area. Figure 7 shows the locations of the Spring Meadows production wells and certain other wells and drill holes that are of special interest. Drillers' logs filed with the Office of the State Engineer, Carson City, Nev., and an unpublished report by Ed L. Reed and Associates (written commun., 1967) were used to compile table 3.

Although most of the wells are between 200 ft (60m) and 700 ft (215 m) deep, two holes (18S/50-11dd and 18S/50-12db) were drilled to about 1,000 ft (305 m) without encountering productive zones. The "Remarks" column in table 3 reveals that most of the productive wells penetrate travertine or continental limestones of the local aquifer system. Only five drill holes (17S/50-14cac; 17S/50-23bbl; 17S/50-23bb2, also called well 7; 18S/51-7bdb, also called well 13; and 18S/51-7dbl) penetrated Paleozoic rocks. Well 7 is the only one of these that produces significant discharge. Although well 13 is only about 1,000 ft (305 m) west of an outcrop of Paleozoic rocks, these rocks were penetrated at a depth of 815 ft (248 m).

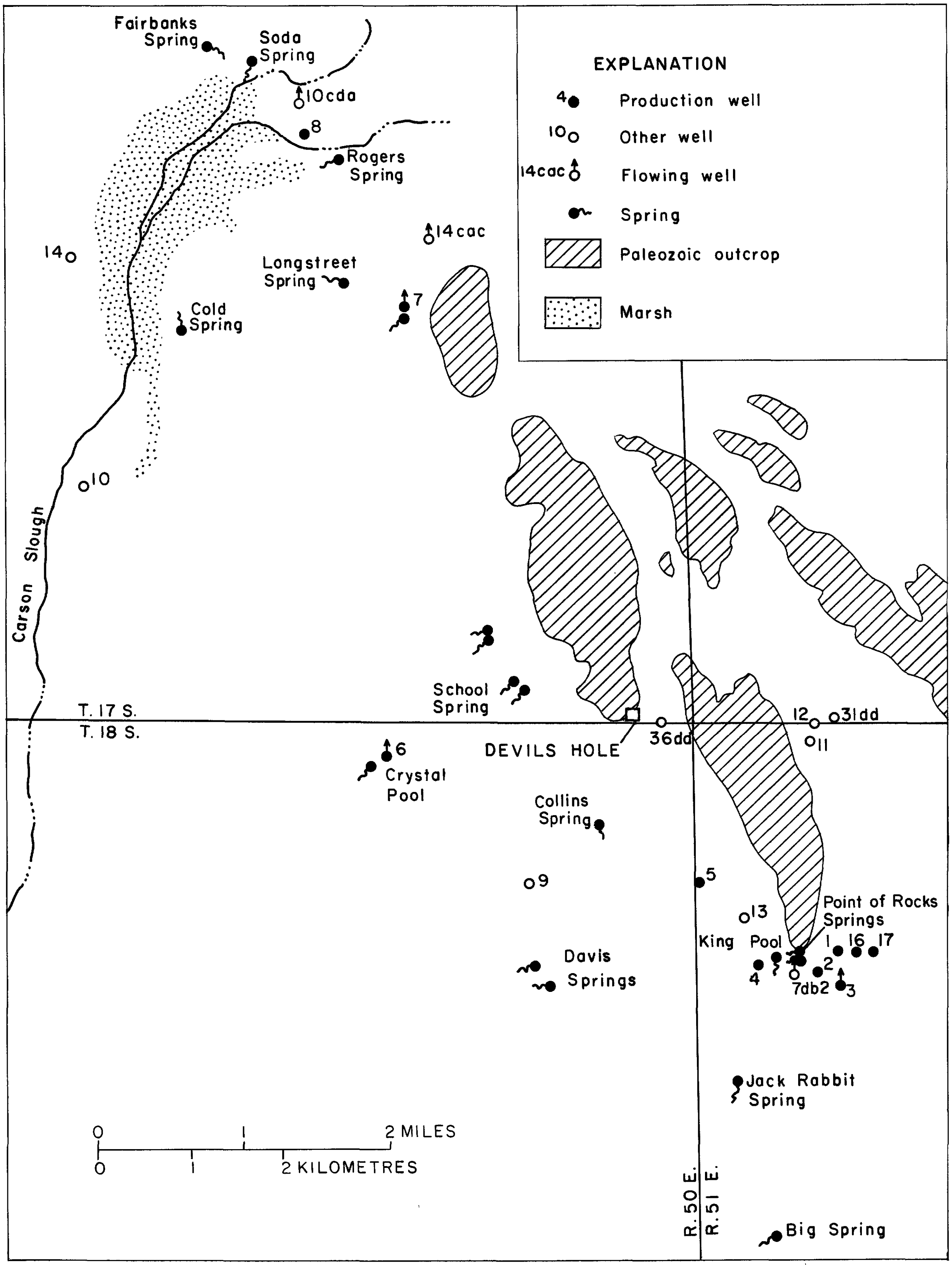


FIGURE 7.—Location of wells and springs in the Ash Meadows area.

TABLE 2.—*Records of springs in Ash Meadows, Nye County, Nev.*

[Data before 1963 from Walker and Eakin (1963). Data below dashed lines collected by the authors. Method and, where indicated, date unknown for data from Ed L. Reed and Associates (written commun., 1967). QTs, quarternary and (or) Tertiary alluvial and lake sediments; aquifers are gravel, sand, travertine, or "fresh-water limestone." QTst, travertine or "fresh-water limestone" outcrops at spring. Pzc, Paleozoic limestone or dolomite; CM, Price current meter in outlet channel; CM/CM, difference of current-meter measurements in channel below and above spring flow entry; PF(6), Standard Parshall Flume with throat size in inches; VW90, 90° V-notch weir; CW18, 18-inch Cipolletti weir; Vol, volumetric measurement with stopwatch; Obs, observed; RW, rectangular weir. m, measured by the U.S. Geological Survey; others reported. Cs, specific conductance in micromhos per centimetre at 25° Celsius]

Location index and name	Water-bearing unit	Method of measurement	Flow (gal/min)	Temp (°C)	Temp (°F)	Date	Remarks[1]
17S/50-9ad Fairbanks	QTst	....	2,360	...	...	1910	
		....	2,040	...	...	7/14/23	
		....	1,760	...	...	8/16/46	
		....	m1,660	28	82	2/1/53	
		....	1,700	...	...	6/?/61	
		....	m1,720	27	81	7/23/62	Cs=650
		PF12	m1,580			(2)	High flow.
				28	82		10/70-12/71
			m1,430			(2)	Low flow.
17S/50-10bcd Soda	QTs	....	m85	22	72	2/1/53	
		....	87	...	...	6/?/61	
		....	m79	23	73	7/31/62	Cs=725
		PF2	m65			5/21/71	High flow.
				22	72		10/70-8/71
			m0	23	73	(3)	Low flow.
17S/50-14cac	Pzc	Obs	50	...	...	9/1/66	Reed (1967).
Flowing well ("Purgatory Spring," USBSFW)		VW90	m23			(2)	High flow.
				34.5	94		2/71-12/71
			m9			(2)	Low flow.
17S/50-15ab Rogers	QTst	....	675	...	...	12/24/23	
		....	m715	29	84	12/1/53	
		....	665	...	...	6/?/61	
		....	m735	28	82	7/29/62	Cs=650
		PF6	m590	28.5	83	2/21/71	Well 8 pumped 2 days.
			m570	28.5	83	2/24/71	
			m590	...	...	3/15/71	
17S/50-21ac Cold	QTs	Obs	80	...	...	9/1/66	Reed (1967).
		PF3	m73	19.5	67	(2)	Stable flow 10/70-4/71.
17S/50-22aba Longstreet	QTst	....	1,260	...	...	3/27/21	
		....	m1,240	26.5	80	2/3/53	
		....	1,270	...	...	6/?/61	
		....	m1,040	28	82	7/29/62	Cs=640
		Reported	1,250	28	82	1965	Reed (1967).
		PF9	m1,040	...	...	10/22/70	
		CM	m1,030	27	81	11/6/70	
			m1,110	...	...	11/23/70	
			m940	...	...	4/2/71	
			m1,040	...	...	4/15/71	
			m1,130	27	81	5/20/71	
		PF9	m1,070	...	...	7/15/71	
			m940	28	82	9/9/71	
			m1,060	...	...	10/8/71	
			m1,130	...	...	10/16/71	
			m995	...	...	11/1/71	
			m980	...	...	11/20/71	
17S/50-22ac McGillivary	QTs	Reported	155	...	...	1965	Reed (1967).
		Obs	m0	...	...	9/30/70	Water level 5 ft below outlet. No flow in 1971.

TABLE 2.—*Records of springs in Ash Meadows, Nye County, Nev.*—Continued

Location index and name	Water-bearing unit	Method of measurement	Flow (gal/min)	Temp (C°)	Temp (F°)	Date	Remarks[1]
17S/50-23b1	QTs	....	m115	34.5	94	2/3/53	
		....	m195	34.5	94	7/23/62	Cs=650 Same as 23bb1 and (or) 23bb2 below?
17S/50-23bb1 Unnamed (at Five Springs area)	QTs	PF3	m75			(3)	High of record.
				34.5	94		10/70-9/71
			m0			(3)	Low of record. Well 7 on.
17S/50-23bb2 Unnamed (at Five Springs area)	QTs	Vol	m60	32	90	2/17/71	
			m0	...	...	2/17/71	Well 7 on.
17S/50-23b Unnamed (8 seeps at Five Springs)	QTs	Vol	m35	...	...	2/16/71	Combined flow.
17S/50-35a1 Scruggs?	QTs	....	m90	33	91	2/3/53	Two springs combined?
		....	m140	33.5	92	7/24/62	Cs=640
17S/50-35acc Scruggs	QTs	PF3	m60	33	91	(2)	Northern of two orifices. Steady flow recorded 11/70-2/71
17S/50-35b1 Unnamed	QTs	....	m17	28.5	83	7/23/62	Cs=620
17S/50-35d1 School	QTs	....	m25	32	90	1/31/53	
		....	m6	34.5	94	7/24/62	Cs=620
18S/50-3adb Crystal Pool	QTst	....	3,070	...	...	4/1/59	
		....	m2,820	31.5	89	1/31/53	
		....	2,980	...	...	6/?/61	
		....	m2,820	33	91	7/29/62	Cs=650
		RW	3,290	...	...	3/3/67	Reed (1967).
		PF24	2,940	...	...	2/22/71	High of record.
			(3)	32	90		10/70-11/71
			1,670	...	...	9/1/71	Low of record.
18S/50-1ca Collins	QTs	VW90	m10	...	...	(2)	High of record.
			(2)	25.5	78		2/71-12/71
			m5	...	...	(2)	Low of record. (Sept. 1971).
18S/50-11d1 Davis	QTs	....	m720	23.5	74	2/2/53	
		....	m395	25	77	7/25/62	Cs=750
18S/50-11d2 Davis	QTs	....	m175	23.5	74	2/2/53	
		....	m5	...	...	7/25/62	
18S/50-11d3 Davis	QTs	....	m38	21	70	2/2/53	
		....	m30	22	72	7/25/62	
18S/50-12c1	QTs	....	m52	23	73	2/2/53	
		....	m11	26.5	80	7/25/62	Cs=725

TABLE 2.—*Records of spring in Ash Meadows, Nye County, Nev.*—Continued

Location index and name	Water-bearing unit	Method of measurement	Flow (gal/min)	Temp (C°)	Temp (F°)	Date	Remarks[1]
18S/50-12dc Sink	QTs	Obs	25	...	...	9/1/66	Reed (1967).
		Obs	m0	...	...	3/2/71	Water level 3 ft below outlet. No flow in 1971.
18S/ 51-7dbb King Pool	QTst	....	2,130	...	...	7/17/43	
		....	m1,250	31.5	89	1/31/53	
		....	685	...	...	6/?/61	
		....	m1,080	32	90	7/25/62	Cs=675
		Reported	1,500	...	...	(?)	Reed (1967).
		CM/CM	....	32	90	10/2/70	Temp. at orifice.
			m1,250	...	...	11/6/70	
			m1,230	...	...	11/23/70	
			m1,360	...	...	12/8/70	
			m1,160	...	...	12/29/70	
			m1,230	...	...	1/12/71	
18S/51-7d2 Indian Rock	QTst	....	135	...	...	3/31/50	
		....	m69	32	90	1/31/53	
		....	120	...	...	6/?/61	
		....	m22	33.5	92	7/25/62	Cs=640
18S/51-7d3	QTs	....	m345	32	90	1/31/53	
		....	300	...	...	6/?/61	
		....	m380	33	91	7/26/62	Cs=645
18S/51-7d4	QTs	....	m19	34	93	7/26/62	Cs=650
18S/51-7d5	QTs	....	m2	34	93	7/26/62	Cs=650
18S/51-7dba Point of Rocks, Indian Rock, Indian Seeps	QTs, Pzc, and QTst	....	m420	32 34	90 93	7/27/62	Total of 7d2, 7d3, 7d4, and 7d5.
		PF6 + PF6	m385			5/17/71	High of record. 10/70-9/71
			(3)	32 34	90 93		
			m290			8/10/71	Low of record. Total of 2 flumes.
18S/51-18bc Jack Rabbit	QTst	....	m500	28	82	2/1/53	
		....	640	...	...	6/?/61	
		....	m585	...	...	7/27/62	Cs=675
		Reported	600	...	...	(?)	Reed (1967).
		PF6	m425			5/11/71	High of record. 10/70-12/71
			(3) m0	26	79	(3)	Low of record.
18S/51-19ac Big; (Deep; Ash Meadows)	QTst	....	1,120	...	...	1916	
		....	m1,060	28.5	83	2/2/53	
		....	1,080	...	...	6/?/61	
		....	m1,040	...	...	7/19/62	
		....	m1,040	...	...	7/26/62	
		....	....	28.5	83	8/27/62	Cs=700
		CW18	m1.040			(2)	High of record. 1/71-10/71
			m920	28.5	83	(2)	Low of record.
18S/51-29b1 Unnamed	QTs	....	m1	22	72	7/28/62	Cs=790
18S/51-30ab Bole	QTs	....	m12	22	72	7/27/62	
18S/51-30d1 Last Chance	QTs	....	m1	20	68	7/28/62	Cs=575

[1]Highs and lows of record determined from continuous records over period indicated.
[2]Discharge steady or changes gradually; high or low flow occurs for sustained periods.
[3]Discharge variable and responsive to pumping or other causes; high or low occurs commonly during period of record.

RESULTS OF AQUIFER TESTS

Aquifer tests of the production wells, some adequately controlled and some made during normal ranch operations, were conducted during February, March, and April 1971. Several of the wells were examined during more than one cycle of drawdown and recovery, particularly in southern Ash Meadows, where interference from other wells nearby (fig. 8) required constant surveillance from the field party in order to reconstruct usable data.

Additional tests conducted during 1967 by E.L. Reed, a consultant to the ranch, were analyzed by Reed (written commun., 1967) and by R.H. Johnston of the Geological Survey (written commun., 1967).

Drawdown measurements (the difference between depths to water before and during pumping) in the 1971 tests were hampered in many of the pumped wells by water cascading down the casing from shallow aquifers intersected above the pumping levels. The use of float switches and shields on electrical probes aided in measuring pumping levels but the aeration and mixture with oil from pump columns resulted in a foamy mixture of water, air, and oil in several wells. Calculations of specific capacities (well yield, in gallons per minute, per foot of drawdown) were affected, for drawdowns in these shallow aquifers should not be computed from the pumping levels in the wells, but rather from the depths at which the cascading water enters the wells. Because the relative contributions of these zones are not known, all hydraulic parameters computed from drawdowns in wells that had cascading inflow are inaccurate to some degree.

Type curves compiled by Lohman (1972) from several sources were used to relate the time-drawdown data to transmissivities and storage coefficients. The data were matched most successfully to curves prepared by Lohman from Boulton's (1963) equation which describes ground-water flow when the yield from storage in the aquifer is delayed. Figure 9 shows time-drawdown data from three wells observed during testing of well 1 and the matches of these data to delayed-yield type curves. Although the matches are satisfactory, the wide range of calculated transmissivities suggests that analyses based on radial-flow equations are not widely applicable to wells in Ash Meadows. Rather, they reflect the inhomogeneity and complexity of the local aquifers.

Table 4 summarizes the observations during the pumping tests and hydraulic parameters calculated from the drawdown data. Note that wells 1, 2, 3, 6, 7, and 8 were observed to lessen the discharge of one or more springs. The rapid effect of well 2 on Jack Rabbit

TABLE 3.—*Records of selected wells and drill holes in Ash Meadows, Nye County, Nev.*

[Includes wells or holes drilled before June 1971, and selected, significant data after June 1971. Sources, in addition to this study, are drillers' logs filed with the State Engineer, Carson City, Nevada, by September 1970, and Ed L. Reed and Associates (written commun., 1967). e, estimated from topographic map and (or) field inspection, generally accurate to +5 feet. Leaders (........) indicate no information available or not applicable. m, measured by the Geological Survey; f, flows (discharge in gallons per minute, if known); p, well not pumping at time of measurement, but is or might be affected by earlier pumping or pumping of other wells; w, "first water," as reported on driller's log and may not be static level. C, commercial, excluding agricultural irrigation; Obs, the Geological Survey maintained water-level recorder on well in 1971 and (or) 1972; S, stock watering; U, use abandoned or suspended in 1971 or before. Lithologies in quotes are from driller's log; others are from sample studies by Ed L. Reed and Associates (written commun., 1967)]

					Casing			Water level[4]		Production[5]					
Well number and location	Owner and owner's number[1]	Date completed (Mo-Yr)	Land-surface altitude (feet)[2]	Depth (feet)[3]	Diameter (inches)	Depth range (feet)	Perforated zone (feet)	Below land surface (feet)	Date (Mo-Yr)	Yield (gal/min)	Draw-down (feet)	Temperature (°C/°F)	Date (Mo-Yr)	Status or use	Remarks, lithology and aquifer identification (depth ranges in feet[2])
17S/49 3dd	G. Swink	1966	e2190	703	14-1/2	0-460	38-436	3	07-66	....	....	....	....	U	"Limestone" [travertine?], 0-14. Mainly "clay with limestone" and "clayey sand and gravel."
17S/50 6cd	G.C. Hanks	12-63	e2260	400	12-3/4	0-400	200-390	w85	12-63	....	....	....	....	Ir,D	"Sand" and "gravel," 85-95, water-bearing during drilling. Production from "limestone," 287-290, 327-340, 374-392.
17S/50 9dd	Nye County Land Co. (Reed 11)	01-67	e2265	278	14 12	0-144 134-278	12-278	w3	01-67	....	....	....	....	Ir,U	Aquifers are "crevice" in limestone (92 feet) and "gravel and sand," 225-255.
17S/50 10cda	Spring Meadows, Inc.	06-68	e2270	157	6-5/8	0-157	7-157	f(15) m6 mf(10)	06-68 02-71 10-71	....	....	22/72	06-68	Ir,Obs	"Sand and gravel," 0-20. Production from "hard, porous lime," 112-157. Well deepened to unknown depth in 1971.
17S/50 10cdd	Spring Meadows, Inc., 8	1968	e2260	....	....	....	....	.... m3 m1	.... 02-71 04-71	.... m900	.... >140	.... 21/70	.... 02-71	Ir	Aquifers not identified. Water cascades from 56 feet when pumping. Chemical sample, table 6. Pumping test, table 4.
17S/50 14cac	Spring Meadows, Inc.	06-68	e2360	92	6-5/8	0-92	0-92	f(70 f(m20 to m8)p	06-68 1970-1972	....	....	.... 34/93	 1970-1972	Ir,U	Aquifer is "fractured dolomite" (Paleozoic), 25-92. Drilled on travertine spring mound. Developed as pupfish refuge and named "Purgatory Spring" in 1972.
17S/50 15aca	Nye County Land Co. (Reed 2)	03-62	e2310	497	16	0-186 175-480	0-480	f(25) f(<.5)	03-6? 1971	150	....	.... 19.5/67	03-62 1971	Ir,U	Aquifers are "limestone," 0-40; 100 feet "sand and gravel," 125-405.
17S/50 16aa	G. Swink (Reed 4)	04-66	e2250	700	14	0-641	46-640	12 15	03-67 08-66	 150	.... > 138 (10 hrs)	....	 08-66	U	Aquifers not identified. Possibly "gravel and sand," 50-65; "hard lime," 172-184; "sand and lime," 309-347.
17S/50 16dd	G. Swink (Reed 5)	06-66	e2255	602	14 10	0-502 492-602	60-497	12 15	06-66 03-67	 137	.... >164	.... 18/64	 03-67	Ir,U	Aquifers not identified.
17S/50 17dd	Nye County Land Co. (Reed 12)	02-67	e2210	558	14 12	0-280 270-558	28-558	w7 11	01-67 03-67	 110	.... 209 (1 hr)	.... 19.5/67	 03-67	U	No productive aquifers. Chemical sample, table 6. Pumping test, table 4.
17S/50 19aa	D.G. Trenary	03-64	e2185	100	14	0-100	15-100	15	03-64	....	....	"cool"	03-64	Ir,D	Aquifer is "fine sand to coarse gravel," 84-95.
17S/50 21aa1	Spring Meadows, Inc.	04-70	e2240	500	16	0-500	99-500	22	04-70	500	143	"cold"	04-70	U	
17S/50 21aa2	Spring Meadows, Inc.	05-71	e2240	500	16	0-300	0-300	m17	05-71	< 300	>200	19.5/67	05-71	U	Water cascaded from 180 feet during test. Water carried sand.
17S/50 21ac?	Spring Meadows, Inc.	06-68	e2240?	202	6-5/8	0-202	0-202	8	06-68	....	....	....	....	?	Probably 17S/50-21ca, providing small domestic supply of poor quality.

See footnotes at end of table.

TABLE 3.—*Records of selected wells and drill holes in Ash Meadows, Nye County, Nevada*

Well number and location	Owner and owner's number[1]	Date completed (Mo-Yr)	Land-surface altitude (feet)[2]	Depth (feet)[3]	Casing: Diameter (inches)	Casing: Depth range (feet)	Casing: Perforated zone (feet)	Water level[4]: Below land surface (feet)	Water level[4]: Date (Mo-Yr)	Production[5]: Yield (gal/min)	Production[5]: Drawdown (feet)	Production[5]: Temperature (°C/°F)	Production[5]: Date (Mo-Yr)	Status or use	Remarks, lithology and aquifer identification (depth ranges in feet[2])
17S/50 21bb	Spring Meadows, Inc.	06-68	e2210	202	6-5/8	0-202	7-202	5	06-68	....	....	24.5/76	06-68	U	Log shows "hard porous lime," 0-55, 85-202.
17S/50 23bb1	Spring Meadows,	06-68	e2345	90	6-5/8	0-90	0-90	1 1	06-68 02-71	....	....	....	....	Ir,D, U	Aquifer is "fractured dolomite" (Paleozoic), 50-90. "Hard, porous lime," 0-12, is probably travertine.
17S/50 23bb2	Spring Meadows, Inc., 7	07-70	e2345	140	14	0-100	0-100	f(30) f(20)	07-70 02-71	500 m530	90 m40	.... 34.5/94	07-70 02-71	Ir	10 feet west of 23bb1. Penetrates Paleozoic "black limestone," 48-140. Chemical sample, table 6. Pumping test, table 4.
17S/50 28ca	Spring Meadows, Inc.	06-68	e2180	200	none	....	....	....	....	....	....	....		U	Test hole only "hard lime," 24-28; rest is "peat," 20-24, and clay.
17S/50 29ad	Nye County (Reed 1) Spring Meadows, Inc., 10	01-62	2171	530 m471	16	0-514	150-500	9 w22 mf(5) 12	01-62 11-61 06-62 03-67	2,000 1,375	91 .... 136 (10 hrs)	... . 19.5/67 19.5/67	01-62 .... 06-62 03-67	Ir	"First water in fractured lime at 22 feet." Aquifers are "sand" or "sand and gravel," 245-250, 280-320, 338-342, 415-490; "fractured lime," 140-200. Chemical sample, table 6. Pumping test, table 4.
17S/50 36dd	Nye County Land Co.	10-66	2405	248	16	0-248	48-248	48 mp51 m50	03-67 '09-71 02-72	900	39	33.5/92	03-57	Ir,U	900 feet east of Devils Hole. Aquifer is gravel. 100-248; possibly also "lime," 6-100, [travertine?]. Chemical sample, table 6. Pumping test, table 4.
17S/51 31dd	Spring Meadows, Inc.		2418	....	12	0-	....	.... m63 mp65	.... 02-72 06-72	.... m47	....	.... 25.5/78	.... 03-71	Ir,U Obs	No log on record 9/70. Obs in 1972. Affected by pumping 1½ miles to the south. Chemical sample, table 6.
18S/50 2aa	U.S. Bureau of Land Management	09-70	e2320	>252	....	....	....	51	09-70	40 60	103 (2hr) >198 (1-1/2 hr)	....	09-70 09-70	See remarks	No log on record 9/70. Pumped to supplement flow of pupfish sanctuary at School Spring (17S/50-35d1).
18S/50 3aa	Nye County Land Co. (Reed 3) Spring Meadows, Inc.	03-66	e2205	516	14	0-516	0-516	f(37)	03-66	1,000 m900 m1370	130 (3 hr) >220 120 hr)	31.5/89 31.5/89	03-66 04-71 08-71	Ir,U	"White lime" and "sticky lime" for entire depth. Tools dropped several times during drilling. Owner said mud appeared in Crystal Pool. Water cascades from about 50 feet. Chemical sample, table 6. Pumping test, table 4.
18S/50 5aa	Nye County Land Co. (Reed 7)	08-66	2140	670	14	0.570	60-530	f(5) f(5)	08-66 03-67	 200	 225	.... 23.5/74	 03-67	U	Welded cap. Chemical sample, table 6. Pumping test, table 4.
18S/50 11aa	Spring Meadows, Inc., 9		e2240	....	....	....	....	.... mp21	 02-71	....	....	....	....	S	No log on record, 9/70. Pumps intermittently to pressure tank.
18S/50 11dd	Nye County Land Co. (Reed 8)	10-66	e2240	960	14	0-852	210-840	.... f(15)	 02-67	 190	.... >433 (1 1/2 hr)	.... 30.5/87	 02-57	U	Clay and marl in upper 300 feet; clayey and cemented sand and gravel, 300-700. Chemical sample, table 6. Pumping test, table 4.
18S/50 12db	Spring Meadows, Inc.	1971	e2270	1,000 ±	16	0-	....	f m12	02-71 03-71	....	....	....	....	U	Abandoned in 1971.
18S/50 25ab	Ash Meadows Lodge	06-65	2200	267	12 8-5/8 6-5/8	0-50 0-120 0-267	80-267	6	06-65	24	>85	....	06-65	C	8-5/8 casing cemented to 50 feet.

TABLE 3.—*Records of selected wells and drill holes in Ash Meadows, Nye County, Nevada*—Continued

Well number and location	Owner and owner's number[1]	Date completed (Mo-Yr)	Land-surface altitude (feet)[2]	Depth (feet)[3]	Casing: Diameter (inches)	Casing: Depth range (feet)	Casing: Perforated zone (feet)	Water level[4]: Below land surface (feet)	Water level[4]: Date (Mo-Yr)	Production[5]: Yield (gal/min)	Production[5]: Drawdown (feet)	Production[5]: Temperature (°C/°F)	Production[5]: Date (Mo-Yr)	Status or use	Remarks, lithology and aquifer identification (depth ranges in feet[2])
18S/51 6aa1	Spring Meadows Inc., 12	1970	e2435		12	0-	0-	.... 76 mp81 m76	.... 05-70 03-71 05-71	.... m60	....	.... 25.5/78	.... 01-71	Ir,U	No log on record 9/70. Pump removed in 1971.
18S/51 6aa2	Spring Meadows, Inc. 11	1970	e2450		12	0-	0-	95 mp97 m95	05-70 03-71 05-71	m57	....	25.5/78	01-71	Ir,U	Do.
18S/51 7bbb	Spring Meadows, Inc., 5	02-70	2320	500	16	0-500	139-500	24 m25	20-70 03-71	1,500 > 1,600	75 110 ±	.... 30.5/87	02-70 03-71	Ir,U	Water cascades. Aquifer not identified, but log shows "limestone," 155-210, 235-290; "gravel," 405-460; rest is clay. Chemical sample, table 6. Pumping test, table 4.
18S/51 7bdb	Nye County Land Co. (Reed 9) Spring Meadows, Inc., 13	1966	e2340	818	14	0-468	132-467	f(20) 43 98 112 m27	1966 05-70 07-70 09-70 03-71	.... 285 .... e200	.... 253 (3 hr)	.... 31.5/89 .... 31.5/89	.... 03-67 .... 03-71	Ir	Collapsed below casing. Paleozoic limestone at 815 feet. Water in "white lime" at 35 feet during drilling. Chemical sample, table 6. Pumping test, table 4.
18S/51 7ca	Spring Meadows, Inc., 4	08-69	e2295	500	16	0-500	100-500	6 m11	08-69 03-71	1,200 m900	 180	.... 30.5/87	08-69 03-71	Ir,U	No aquifer identified. Water cascades from 100 feet. Log shows "limestone" 92-230, 268-290, 320-370; "gravel," 370-385; "sandstone," 385-470. Chemical sample, table 6. Pumping test, table 4.
18S/51 7daa	Spring Meadows, Inc., 1	07-69	e2320	395	16	0-395	155-395	15 mp10	07-69 03-71	.... m1,600	.... m50	.... 28/82	 03-71	Ir	Probable aquifers are "brown limestone," 170-178; "broken brown lime," 225-350. Chemical sample, table 6. Pumping test, table 4.
18S/51 7dac	Spring Meadows, Inc.,2	05-69	e2315	300	16	0-300	60-300	16 m8	05-69 03-71	.... m1,200	.... 70 ±	.... 26.5/80	 04-71	Ir	Probably aquifers are "caliche," 54-63 (cascading water); "loose caliche," 203-209, 216-224 (tools fell free). Chemical sample, table 6. Pumping test table 4.
18S/51 7dad	Spring Meadows, Inc., 3	12-69	e2315	780	16 12	0-490 475-780	10-780	f(75) pf(t) f	12-69 04-71 02-72	1,200 1,200	141 150 ±	.... 29.5/85	12-69 03-71	Ir	Aquifers probably are "white lime," 242-255; "brown limestone," 635-690; or "red sandstone," 690-715. Minor cascading water from 12 feet. Chemical sample, table 6. Pumping test, table 4.
18S/51 7db1	Nye County Land Co. (Reed 9A)	12-66	e2320	72	....	....	....	....	....	....	....	....	....	....	Limestone gravel, 55-60; dark dense, siliceous [Paleozoid] limestone, 65-72. No production test.
18S/51 7db2	Spring Meadows, Inc.	04-69	e2315	282	14-3/4 10-1/4	0-242 240-282	40-282	10	04-69	300	180	....	04-69	Obs	Driller noted water from "limestone," 15-30; "brown clay," 65-70; "limestone," 145-160; and "loose caliche," 160-183.
18S/51 8cb1	Spring Meadows, Inc., 16	02-72	e2320	495	16	....	....	12	02-72	....	....	....	....	Ir	Low yield well. (Also called Well No. 1A).
18S/51 8cb2	Spring Meadows, Inc., 17	03-72 (?)	e2320	?-500	16	0-?	....	13	03-72	....	....	....	....	Ir	High-yield well, possibly about 3,000 gal/min.

[1] Spring Meadows, Inc., (1968-71; Cappaert Enterprises in 1972) purchased holdings of Guerdon Industries, Nye County Land Co., and George Swink, Spring Meadows, Inc., well numbers are those labeled on pumps during summer 1971. Where "Reed" numbers are given, his data (written commun., 1967) are used to supplement drillers' logs and production records.

[2] Altitude referenced to mean sea level, to nearest foot.

[3] Reported by driller except where noted.

[4] Static level except where noted.

[5] Production data before 1971 from driller's log or Reed (written commun., 1967). Drawdown is in feet below static level and, where known, is followed by the duration of pumping before measurement.

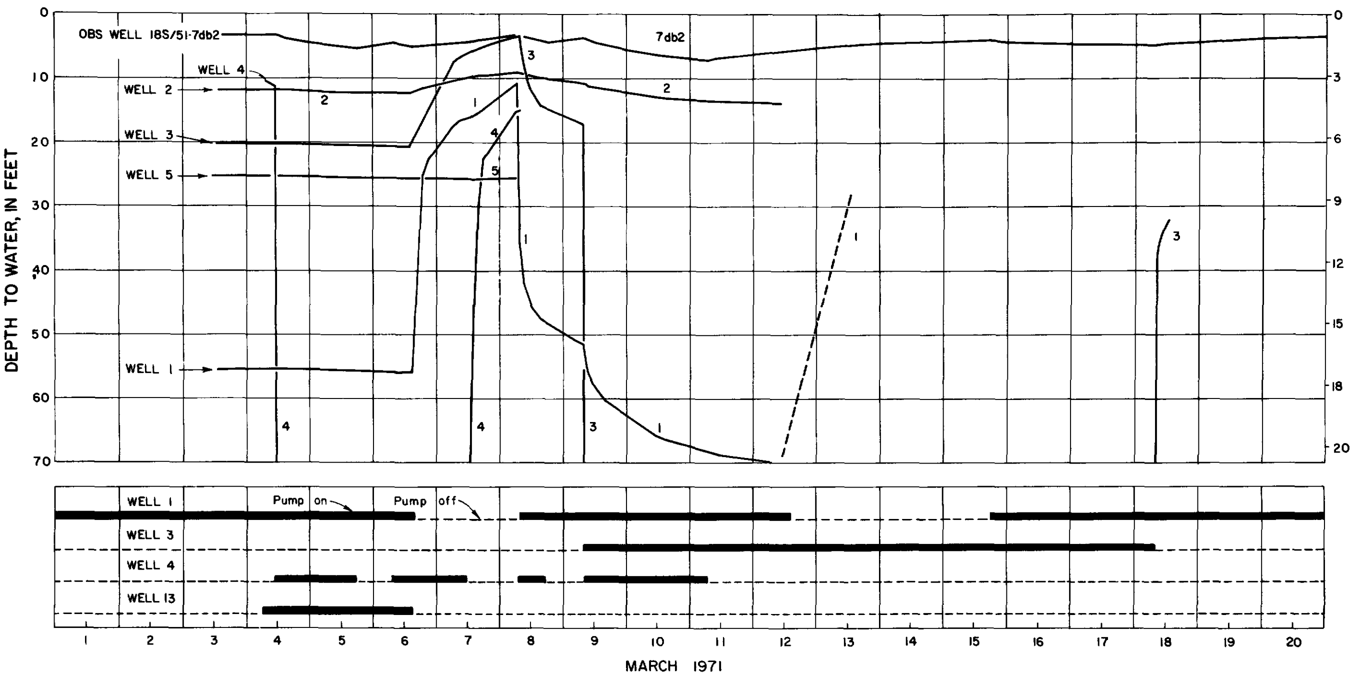


FIGURE 8.—Water levels and pumping histories of wells in southern Ash Meadows during March 1971.

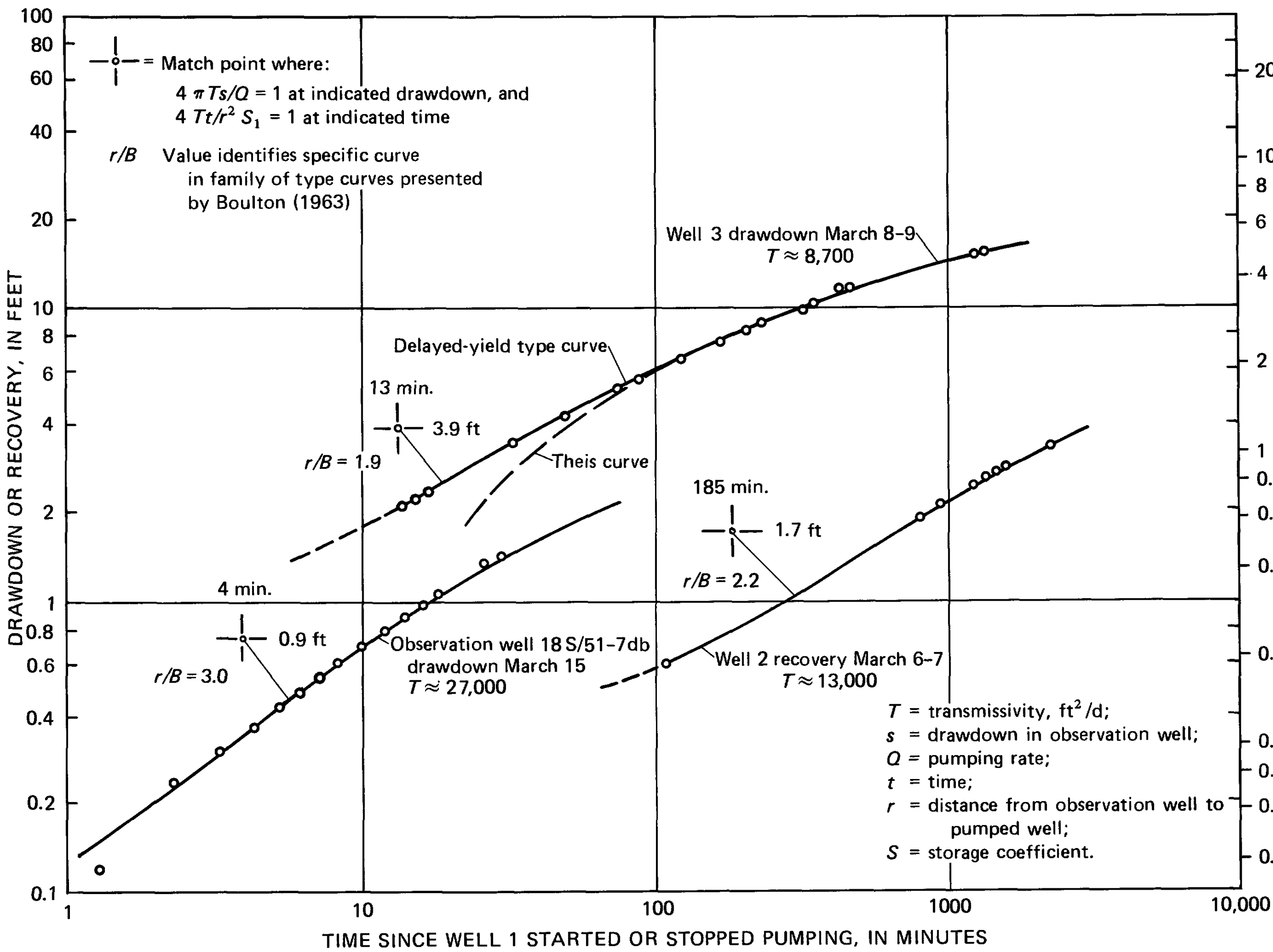


FIGURE 9.—Type-curve analyses of drawdown and recovery measurements during tests of well 1, March 1971.

TABLE 4.—*Aquifer-test data for selected wells in Ash Meadows, Nye County, Nev.*

[f, flows; discharge in gallons per minute in parentheses were reported or measured. d, pumping level still declining at end of test. e, estimated from insufficient data or from specific capacity; includes effect of well-entry losses, which reduces apparent value. r, recovery-phase solution; others calculated from drawdown data]

Well tested	Elapsed time (hours)	Discharge (gal/min)	Depth to water[1] Static (feet)	Depth to water[1] Pumping (feet)	Specific capacity[2] (gal min^{-1} ft^{-1})	Well observed	Transmissivity[3] (ft^2/d)	Storage coefficient	Date of test and remarks
17S/50-10cdd (well 8)	0.3 4 27 48	.... 1,280 980 ≅ 900	3	≅ 140 150	$<$ 6	same	e350	....	Feb. 23-25, 1971. Large part of discharge cascaded from 60 feet.
						17S/50-10cda	4,800	$6x10^{-3}$	1,200 feet from pumped well.
Other effects.—Rogers Spring (17S/50-15ab) flow decreased from 590 to 555 gal/min. Soda Spring (17S/50-10bcd) flow decreased from 40 to 4 gal/min. Pumping has no measureable effect on Fairbanks Spring (17S/50-9ac) or well 17S/50-14ca.									
17S/50-17dd	1	110	8	d220	0.4	same	r30	....	March 1, 1967. Data from E.L. Reed[4]. Negative boundary at 8 minutes during recovery[5].
17S/50-29ad	4	1,400	f(6)	d148	10	same	610	....	March 6, 1967. Data from E.L. Reed[4].
17S/50-23bb2 (well 7)	22.5	537	f(20)	38	14	same	e3,700	....	Feb. 17-18, 1971. Paleozoic carbonate aquifer.
						17S/50-23bb1	4,300 3,500	....	3-30 minute interval. 90-400 minute interval.
Other effects.—Flow of numerous springs within 500 feet of pumped well stopped or decreased during test. Well 17S/50-14ca decreased in flow from 24 to 21 gal/min. Total loss of natural discharge during test was about 170 gal/min. Pumping had no measurable effect on Longstreet Spring (17S/50-22aba).									
17S/50-36dd	2.7	900	48	87	23	same	r27,000	....	March 10, 1967. Data from E.L. Reed[4]. Positive boundary after 60 minutes of recovery.
18S/50-3aa (well 6)	1 120 170	1,300 900 860	f	.... $>$ 220 $>$ 220	$<$ 4	same	....	....	April 8-16, 1971. Large part of discharge cascaded from about 50 feet.
Other effects.—Crystal Pool (18S/50-3adb) flow decreased from 2,930 to 2,480 gal/min after 170 hours of pumping.									
18S/50-5aa	1.5	200	f(5)	d $>$ 225	$<$ 0.8	same	....	....	March 18, 1967. Data from E.L. Reed[4].
18S/50-11dd	1.5	190	f(15)	d433	$<$ 0.4	same	r24	....	Feb. 28, 1967. Data from E.L. Reed[4]. Negative boundary at 10 minutes during recovery; positive boundary at 60 minutes.
18S/51-7bbb (well 5)	9	1,800	25	78	20	same	6,000 r6,000	....	March 22, 1971. Part of discharge cascaded from about 42 feet. Measured in annulus outside slotted casing. Negative boundary at 20 minutes.
						18S/51-7bdb (well 13)	18,000	$2x10^{-3}$	Solutions show delayed yield, partial penetration, or other evidence of poor hydraulic connection.
						18S/51-7ca (well 4)	19,000 ±	$3x10^{-2}$	
Other effects.—Pumping had no measurable effect on wells 18S/51-7daa (well 1), 18S/51-7dac (well 2), 18S/51-7dad (well 3), 18S/51-7db2, or 18S/51-12db; no measurable effects on spring flows.									
18S/51-7bdb (well 13)	3	285	f(20)	254	1.1	same	r82	....	March 3, 1967. Data from E.L. Reed, 1967[4]. Recovery data showed negative boundary at 10 minutes.
18S/51-7ca (well 4)	1 4 31 45	1,400 1,280 1,000 890	11	$>$ 120	$<$ 7	same	r800	...	March 4-5 and 6-8, 1971. Obstruction prevented measurement below 120 feet. Negative boundary at 60 minutes during recovery.
Other effects.—Wells 18S/51-7bbb (well 5). 18S/51-7daa (well1), 18S/51-7dac (well 2), 18S/51-7dad (well 3), and 18S/51-7db2 were observed. Solutions for all showed delayed yield, partial penetration or other evidences of poor hydraulic connection.									

TABLE 4.—*Aquifer-test data for selected wells in Ash Meadows, Nye County, Nev.*—Continued

Well tested	Elapsed time (hours)	Discharge (gal/min)	Depth to water[1] Static (feet)	Depth to water[1] Pumping (feet)	Specific capacity[2] (gal min^{-1} ft^{-1})	Well observed	Transmissivity[3] (ft^2/d)	Storage coefficient	Date of test and remarks
18S/51-7daa (well 1)	500	1,650	3	56	31	same	e8,300	....	February, 1971.
	24	1,650	10	56	....	same	14,000 (see remarks)	....	March 8-9, 1971, after 2-day shutdown. Negative boundary after 20 minutes. Apparent transmissivity for rest of 24-hour test was 8,800 ft^2/d
						18S/51-7dac (well 2)	13,900	$4x10^{-2}$	March 8-9, 1971. All solutions show delayed yield, partial penetration or other evidence of poor hydraulic connection.
						18S/51-7dad (well 3)	8,700	$1x10^{-3}$	
						18S/51-7db2	27,000	$6x10^{-4}$	

Other effects.—Pumping had no measurable effect on wells 18S/51-7daa (well 1), 18S/51-7dac (well 2), 18S/51-7dad (well 3), 18S/51-7db2, or 18S/51-12db; no measurable effects on spring flows.

Well tested	Elapsed time (hours)	Discharge (gal/min)	Depth to water[1] Static (feet)	Depth to water[1] Pumping (feet)	Specific capacity[2] (gal min^{-1} ft^{-1})	Well observed	Transmissivity[3] (ft^2/d)	Storage coefficient	Date of test and remarks
18S/51-7dac (well 2)	20 220	1,200 1,000	8	70	<71	same	....	....	April 5-6, 1971. Large part of discharge cascaded from about 60 feet.
						18S/51-7daa (well 1)	4,500	$3x10^{-3}$	Solutions show delayed yield or partial penetration.
						18S/51-7db2	12,700	$3x10^{-2}$	

Other effects.—Discharge of Jack Rabbit Spring (18S/51-18bc) began to decline within minutes after pumping started; declined from 410 gal/min to 310 gal/min after 1 day and to 180 gal/min after 9 days of pumping. Well 3 (18S/51-7dad) also affected, but cascading water and oil prevented accurate measurement. No effect on well 5 (18S/51-7bbb).

Well tested	Elapsed time (hours)	Discharge (gal/min)	Depth to water[1] Static (feet)	Depth to water[1] Pumping (feet)	Specific capacity[2] (gal min^{-1} ft^{-1})	Well observed	Transmissivity[3] (ft^2/d)	Storage coefficient	Date of test and remarks
18S/51-7dad (well 3)	2 54 190	1,200 1,150 1,000	20 (see remarks)	$\cong 170$	$\cong 6$	same	e1,600 r5,900	....	March 9-18, 1971. Minor part of discharge cascades from 12 feet. Static level affected by nearby pumping during test. Well has natural flow.
						18S/51-7daa (well 1)	18,300	$3x10^{-4}$	Drawdown-phase solution, March 9, 1971. Well 1 also pumping, but near steady state.
						18S/51-7db2	21,000	$5x10^{-4}$	Recovery-phase solution, March 18, 1971.

Other effects.—Well 2 (18S/51-7dac) drawdown about 1 foot in 480 minutes. Discharge of Point of Rocks springs (18S/51-7dba) declined slightly. No effect on Jack Rabbit Spring (18S/51-18bc) or well 5 (18S/7bbb).

[1] Static depth to water at start of pumping.

[2] Gallons per minute discharge per foot of drawdown (pumping level minus stat level) in the well; effects of well-entry loses are included.

[3] Cubic feet per day per foot width of aquifer under unit hydraulic gradient.

[4] Unpublished consultant's report to Spring Meadows, Inc., dated June 1967 by Ed L. Reed and Associates, Midland, Texas.

[5] Negative boundary indicates area of lower transmissivity within area of influence of pumped well. Positive boundary may indicate area of higher transmissivity within area of influence.

Spring is particularly interesting because of the distance between them, about 1 mi (1.6 km).

Complete discussion of the transmissivities and storage coefficients reported in table 4 will be deferred to a later section of the report. It should be re-emphasized here, however, that the inhomogeneity of the aquifer system and the errors inherent in measuring drawdown in wells with cascading water together make these data meaningless for quantitative applications.

PUMPING RECORDS

With the exception of minor use in watering shrubbery at Ash Meadows Lodge, all irrigation withdrawals of underground water in Ash Meadows are made by the Spring Meadows Ranch. Water from eight major wells, supplemented by three small-capacity wells and, where feasible, the flow of several springs, is used to irrigate more than 3,000 acres (12 km^2) of crops. This pumping rate reached a peak of about 1,000 acre-ft (1.2 million m^3) per month in both 1970 and 1971. Detailed records of the pumpage were not maintained after 1971.

Those wells with field numbers 1 through 8, and 13, were active during 1971 until September, when wells 4, 5, and 6 were turned off by agreement with the Federal Government. Late in 1971 well 10 and unnumbered well 17S/50-10cda were pumped intermittently. Wells 16 and 17 were drilled and began production in 1972. Wells 9, 11, 12, and 17S/51-31dd have produced only minor quantities. The other wells shown in figure 7 were not pumped during this study, but injection of water from King Pool into well 17S/50-36dd began on June 30, 1973, in an effort to support the water level in Devils Hole while litigation is continuing.

For 1969 and 1970 there are no accurate discharge records. Records were to have been obtained by the use of accumulating discharge meters during the 1971 irrigation season. However, coarse detritus carried in the discharge stream eventually fouled these meters. During the spring of 1971, through frequent repair and exchange of meters, the field party was able to use the meters to obtain typical pumping rates for the main wells in the field. These were supplemented by current-meter measurements in irrigation ditches and by trajectory measurements of the discharge from open pipes.

Electrical-power-consumption meters were read at least monthly from September 1970 through December 1971. The frequency of readings was weekly during the summer of 1971; during February to June 1971, most meters were read several times each week. Rates of power consumption were correlated with measured pumping rates and used to reconstruct the pumping history of each well in the field. During 1971, when discharges were well documented, the average error in the reported withdrawals probably is no greater than 10 percent. Because of varying lift, pump condition, and well efficiency, the withdrawals estimated for previous years may be in error by as much as 20 percent.

Table 5 gives the estimated monthly withdrawals from individual wells that produced more than 200 gal/min (1,100 m^3/d) during 1969, 1970, and 1971. These data show that the preponderance of pumping has been in the vicinity of Point of Rocks, or sec. 7, T. 18 S., R. 51 E.

TABLE 5.—*Estimated withdrawals in acre-feet from electrically pumped wells operated by Spring Meadows Inc., in Ash Meadows, Nye County, Nev., January 1969-January 1972*

[Based on correlation of 1971 discharge rates with electrical power consumption. Estimated accuracy ± 20 percent in 1969, 1970; ± 10 percent in 1971]

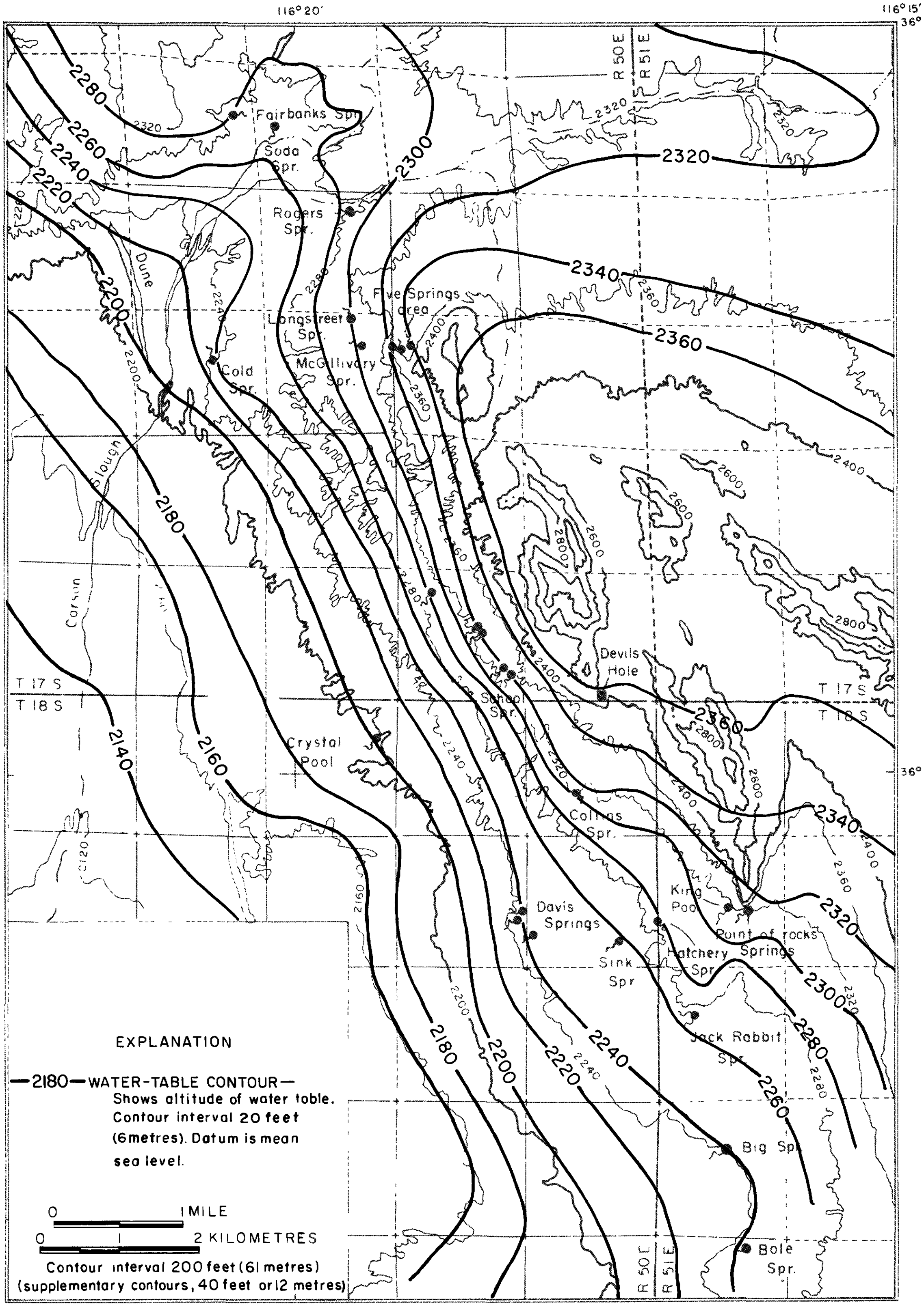
Well no.	1	2	3	4	5	6	7	8	13	Field
Location	18S/51 7daa	18S/51 7dac	18S/51 7dad	18S/51 7ca	18S/51 7bb	18S/50 3aa	17S/50 23bb	17S/50 10cdd	17S/50 10bdb	...
1969										
January	0	0	0	0	0	0	0	0.7	0	0.7
February	0	0	0	0	0	0	0	110	0	110
March	0	0	0	0	0	0	0	0	0	0
April	0	0	0	0	0	0	0	0	0	0
May	0	0	0	0	0	0	0	0	0	0
June	160	0	0	0	0	0	0	0	40	200
July	150	0	0	0	0	0	0	0	41	190
August	91	0	0	0	0	40	0	.1	55	190
September	33	91	0	6	0	0	0	82	53	260
October	140	66	0	140	0	20	0	0	55	420
November	130	90	0	110	0	14	0	97	53	490
December	17	32	0	9	0	15	0	.7	34	110
Total	720	280	0	260	0	90	0	290	330	2,000
1970										
January	0	4	0	0	0	0	0	0	0	4
February	0	.8	0	37	0	0	0	0	0	38
March	0	.1	0	13	0	0	0	0	0	14
April	8	56	54	76	0	0	0	0	0	190
May	200	74	120	62	340	0	0	0	0	800
June	190	80	110	120	330	25	0	0	0	750
July	180	83	76	120	240	27	0	120	0	850
August	210	120	160	120	300	26	0	69	0	1,000
September	190	110	160	110	270	26	25	15	0	910
October	200	130	110	80	290	4	2	140	0	960
November	190	100	45	120	270	0	14	140	0	870
December	81	120	12	70	120	0	0	60	0	460
Total	1,500	880	850	930	2,100	110	40	540	0	6,900
1971										
January	0	0	32	15	73	0	0	0	0	120
February	190	0	0	34	130	0	7	9	0	370
March	150	0	49	39	44	0	56	0	test	340
April	120	65	74	43	49	30	39	0	0	420
May	150	29	0	39	120	60	32	20	0	440
June	240	87	81	120	95	9	44	89	10	770
July	210	110	160	100	120	140	74	89	18	1,000
August	210	130	160	77	120	180	64	85	20	1,000
September	200	130	150	[1]20	[1]35	[1]41	13	20	20	630
October	200	130	160	0	0	0	43	31	1	570
November	180	120	160	0	0	0	59	48	0	560
December	200	65	140	0	0	0	54	90	0	560
Total	2,000	870	1,200	490	790	450	480	480	71	6,900
1972										
January	100	0	0	0	0	0	0	[2]90	0	[2]190

[1] Pumping stopped on September 9, 1971.
[2] Well 8 assumed pumping, January 25-31, 1972.

WATER-TABLE CONFIGURATION

Water flowing southwestward to Ash Meadows in the regional lower carbonate aquifer is confined by the less permeable Cenozoic sediments that overlie the carbonate rocks. The potentiometric head in the lower carbonate aquifer and in the confined aquifers of the local subsystem increases with depth. Consequently, the water level in deep wells rises above that in shallow wells, and commonly the deeper wells flow without pumping. This is the condition expected in discharge areas, where flow has an upward component or at least the potential for upward flow exists.

The water table is thus somewhat lower than water levels in the wells would indicate, but it is generally higher than the altitudes of discharging springs. Using the altitudes of the springs as lower limits and of the static water level in wells as upper limits for the water-table altitude, together with topography and a few precise data points such as Devils Hole, it is possible to construct an approximate contour map of the configuration of the water table. Figure 10 shows this configuration for the Ash Meadows region.



Base from U S Geological Survey, Ash Meadows, 1:62,500

FIGURE 10.—Generalized contours of water-table altitude in the Ash Meadows area.

Except in the northeast quarter of the area these contours show a continuation of the southwestward horizontal component of flow existing in the regional aquifer. Within the group of limestone hills bordering Ash Meadows on the east, however, there is mounding of the water table and consequent flow to the north and northeast also. Faults and joints that rupture the lower carbonate aquifer have apparently provided paths for upward flow. Except beneath these hills and the steep alluvial slopes that border them, the water table conforms to the land surface quite well. In most of the area along Carson Slough south of Fairbanks Spring, encompassing the western one-third of the area in figure 10, the water table is at the land surface.

WATER QUALITY

TEMPERATURE

Tables 2 and 3 give the temperatures of water from the springs and wells in the Ash Meadows area. The water in Devils Hole remains quite constant at about 33.5°C (92°F to 93°F). Well 7, drill hole 17S/50-14cac, and one spring at Point of Rocks discharge water from the lower carbonate aquifer at a temperature of 34.5°C (94°F). This is 15.5°C (28°F) higher than the mean annual air temperature, which ground water tends to approach, and indicates that the water emerging from the regional aquifer has circulated deeply before being forced up along fault zones.

Springs close to the regional source (fig. 7) are commonly a few degrees cooler but still much warmer than the mean annual temperature. Springs located 0.5 mi (0.8 km) or more from the outcrops of Paleozoic rocks generally have temperatures below 28.5°C (83°F), but Crystal Pool discharges water at 32°C (90°F), indicating a rapid rate of flow from the regional aquifer to the spring. The small discharge of Cold Spring (19.5°C or 67°F) apparently spends enough time in transit to approximate the mean annual temperature.

Water from the wells is generally somewhat cooler and less predictable than that from the natural discharge points, that is, the springs. Well 8, although it is comparable in discharge to the major springs around it, discharges water at 21°C (70°F), about 6°C (10°F) cooler than the spring flow. In the Point of Rocks area wells 1, 2, 3, and the flowing observation well 18S/51-7db2, respectively, have temperatures of 28°, 26.5°, 29.5°, and 30.5°C (82°, 80°, 85°, and 87°F), which again underscores the complexity of the local flow subsystem. The variability in temperatures of water pumped from different wells indicates that the wells, even where close to one another, produce from different aquifers that vary in their degree of adjustment to the mean annual temperature.

CHEMISTRY

The locations and general chemical character of water samples collected during this and previous studies are shown in figure 11. An arbitrary number has been assigned each location and date of sampling to minimize space requirements. Table 6 gives the identification and complete analyses of the samples, as recorded in the files of the Geological Survey and, where noted, by Ed L. Reed and Associates (written commun., 1967).

Winograd and Thordarson (1975) have discussed the chemistry of water in southern Nevada in detail. To reiterate their work here would not further the stated objectives, but selected samples show the general chemical framework of the Ash Meadows area.

On the left map of figure 11, sample 6, from Army well 1 along U.S. Highway 95 near the Nevada Test Site, shows a clear dominance of calcium plus magnesium over sodium. This chemical character and the position of Army well 1 within the Ash Meadows flow system suggest that its water is typical of relatively recent recharge from the Spring Mountains. Comparison of the analysis of this sample with that of Devils Hole water (sample 42 in table 6) shows that additions of all major constitutents, and particularly of sodium, are made to the water before its arrival at the discharge area. Water pumped from two wells penetrating carbonate rocks northeast of Devils Hole (sample 3 from the Geological Survey tracer site and sample 54 from a private well) are more similar chemically to Devils Hole water.

GENERAL CHARACTER

With the exception of Big Spring all major springs in Ash Meadows, those discharging about 500 gal/min (2,700 m^3/d) or more, and Devils Hole show great uniformity in chemical character. Sodium is typically 41 plus or minus 3 percent of the total cations, and calcium dominates magnesium only slightly. Potassium, strontium, and lithium are minor constituents of all samples.

Among these natural discharge points the bicarbonate ion is about 70 percent of total anions, followed by sulfate (about 20 percent), chloride (about 8 percent), and fluoride (less than 2 percent).

Samples from well J-12 (sample 0) and Ash Tree Spring (sample 9) are shown in figure 11 and in table 6 to illustrate the character of water from the volcanic terrane of the Pahute Mesa ground-water system, which is contiguous to the western boundary of the Ash Meadows system (Rush, 1970; and Winograd and Thordarson, 1975). As shown on the left side of figure 11, the samples differ from those in the Ash Meadows system by lower dissolved solids, dominance of sodium over other cations, and greater concentrations of silica and nitrate. The ratio of calcium to magnesium is about 2:1 in the Pahute Mesa system, whereas it is between 3:2 and 1:1 in the Ash Meadows system.

This uniform chemical picture of the Ash Meadows flow system changes when the wells and smaller springs are considered. The longer period of residence in local aquifers results in enrichment of sodium to dominance among the cations, as shown on the right side of figure 11. Sulfate, and chloride to a lesser degree, become relatively more important among the anions. Water from wells 1 and 3 (samples 78 and 84 respectively) have anion compositions of about 30 percent bicarbonate, 50 percent sulfate, and 20 percent chloride. The enrichment of both sulfate and chloride is greatest among all the samples in the water from well 2 (sample 81) and in the 1970 sample (96a) from Jack Rabbit Spring. In these samples bicarbonate is only about 10 percent while sulfate and chloride are increased to about 60 percent and almost 30 percent respectively. Jack Rabbit Spring is particularly interesting because sample 96, taken in 1966 before development of the well field, was virtually identical in character to water from the other major natural discharge points. A decrease of 2°C (3.5°F) in temperature accompanied the change in

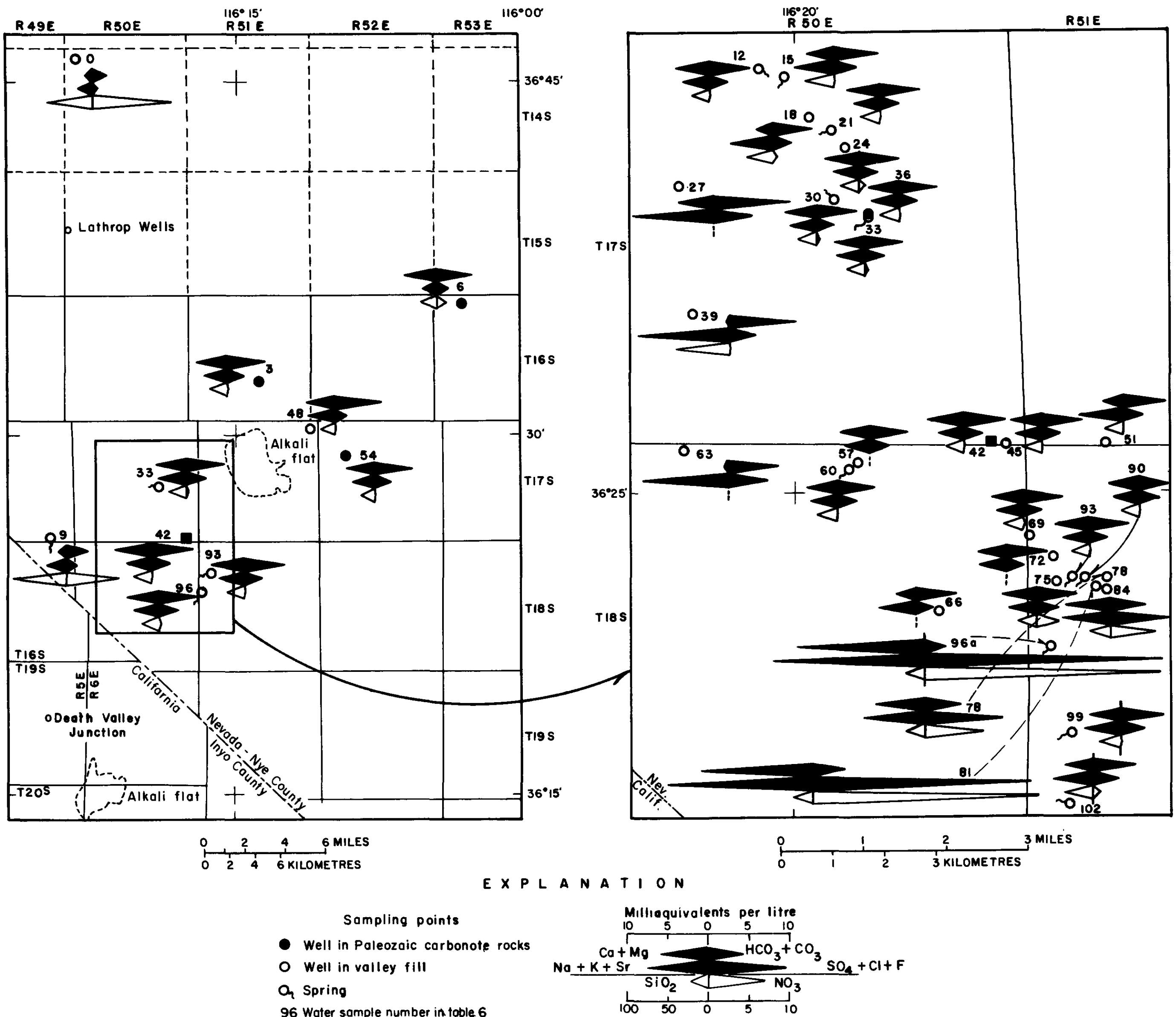


FIGURE 11.—Locations of sampling points and distribution of dominant and selected minor constituents of water samples from the Ash Meadows region.

TABLE 6.—*Chemical analyses of water samples from Ash Meadows and vicinity, Nye County, Nev.*

[Analyses by the U.S. Geological Survey except as noted in first column; R, reported by Ed L. Reed and Associates (written commun., 1967); e, estimated from partial data; ..., not reported]

Water sample no.	Location - S/E-Sec. and index	Source	Date Mo.-Yr.	Temp (°C/°F)	Dis. sol.[1]	Milligrams per litre: Total hardness as $CaCO_3$	SiO_2	Li	B	NO_3	Milliequivalents per litre / Percent of total cations or anions[2]: Cations: Ca	Mg	Na	K	Total	Anions: HCO_3[4]	SO_4	Cl	F	Total	SAR[3]
0	14S/50-06(J12)	Well J-12	04-69	26.5/80	205	46	56	0.04	0.13	9.7	0.70 25	0.21 7.5	1.74 62	0.14 5.0	2.80 99.6	1.92 68	0.46 16	0.18 6.4	0.11 3.9	2.83 94.3	2.6
3	16S/51-27baa2	Tracer well 2	02-68	30.5/87	400	188	22	.08	.27	< .1	2.25 34	1.48 22	2.70 41	.20 3.0	6.66 99.5	4.65 70	1.33 20	.59 8.8	.11 1.6	6.68 100	2.0
6	16S/53-05b1	Army well 1	04-69	30.5/87	308	202	20	.04	.20	1.1	2.20 38	1.81 31	1.57 27	.15 2.6	5.76 99.5	4.23 74	1.06 18	.37 6.4	.06 1.0	5.74 99.7	1.1
9	17S/49-35dd	Ash Tree Spring	07-70	22/72	282	56	76	.07	.28	6.7	.75 20	.35 9.4	2.39 64	.23 6.1	3.74 99.5	2.56 69	.73 20	.19 5.1	.14 3.8	3.73 97.1	3.2
12	17S/50-09adc	Fairbanks Spring	11-66	27/81	424	199	22	.09	.51	< .1	2.40 33	1.56 22	3.00 42	.20 2.8	7.19 99.6	4.92 70	1.56 22	.48 6.8	.09 1.3	7.05 100.0	2.1
15	17S/50-10bcd	Soda Spring	11-66	23/73	488	161	35	.10	.99	< .1	1.80 22	1.40 17	4.61 57	.26 3.2	8.10 99.6	5.41 66	1.94 24	.76 9.2	.11 1.3	8.22 100.0	3.6
18	17S/50-10cdd	Well 8	10-70	21/70	430	100	31	.14	...	.5	1.10 15	.90 12	4.78 66	.38 5.3	7.21 99.3	4.85 68	1.54 22	.62 8.7	.11 1.5	7.13 99.9	4.7
21	17S/50-15ab	Rogers Spring	11-66	28/82	412	205	23	.09	.31	< .1	2.35 32	1.73 24	3.00 41	.20 2.7	7.31 99.6	4.95 68	1.62 22	.59 8.1	.08 1.1	7.24 100.0	2.1
24	17S/50-15ad	Well	08-62	19.5/67	447	209	23	.10	.28	.9	2.50 34	1.65 23	2.91 40	.24 3.3	7.30 100.3	5.00 68	1.64 22	.65 8.8	.06 .82	7.36 99.6	2.0
R27	17S/50-17dd	Well 14	03-67	19.5/67	838	248	...	...	...	...	... ...	... ...	9.31 e65	... ...	e14.35 ...	9.51 e66	3.16 e22	1.58 e11	e.1 e1	e14.35 ...	5.9
30	17S/50-22aba	Long-street Spring	11-66	28/82	419	199	22	.09	.26	.4	2.40 33	1.56 22	3.00 42	.20 2.8	7.19 99.6	4.92 70	1.56 22	.48 6.8	.09 1.3	7.06 99.9	2.1
33	17S/50-23bbc	Spring	10-70	33.5/92	376	190	22	.08	...	.3	2.25 32	1.56 22	3.13 44	.21 2.9	7.18 99.6	4.41 65	1.71 25	.56 8.3	.09 1.3	6.77 100.0	2.3
36	17S/50-23bb2	Well 7	10-70	34.5/94	393	190	22	.08	...	.1	2.25 31	1.56 22	3.13 44	.21 2.9	7.18 99.6	4.61 67	1.67 24	.56 8.1	.09 1.3	6.93 100.0	2.3
39	17S/50-29add	Well 10	08-62	19.5/67	733	28	67	.14	1.4	< .1	.14 1.2	.24 2.0	10.87 92	.38 3.2	11.81 98.4	8.10 72	2.19 20	.73 6.5	.17 1.5	11.19 100.0	27.6
42	17S/50-36dc	Devils Hole	12-66	33.5/92	423	225	22	.09	.32	.2	2.50 33	1.97 26	2.83 38	.19 2.5	7.52 99.6	5.08 70	1.58 22	.56 7.7	.08 1.1	7.30 100.0	1.9
45	17S/50-36dd	Well	03-67	33.5/92	432	199	24	.08	.29	< .1	2.30 32	1.65 23	3.00 42	.22 3.1	7.20 99.6	4.93 69	1.60 22	.56 7.8	.09 1.3	7.18 100.0	2.1
48	17S/51-01a1	Well	01-61	23/73	372	180	18	...	...	< .1	1.95 28	1.65 24	3.00 44	.26 3.8	6.86 99.8	5.74 82	1.10 16	.17 2.4	.03 .2	7.04 100.6	2.4
51	17S/51-31ddd	Well	03-71	25.5/78	435	130	22	.12	...	< .1	1.50 19	.99 13	5.22 66	.16 2.0	7.91 100.0	5.13 68	1.87 25	.54 7.1	.08 1.0	7.62 101.1	4.7
54	17S/52 08c1	Well	04-58	28/82	342	176	18	...	...	< .1	1.70 27	1.81 29	2.65 42	.18 2.8	6.34 100.8	4.49 70	1.31 20	.59 9.1	.06 .93	6.45 100.0	2.1
R57	18S/50-03aa	Well 6	03-67	31/88	416	190	...	...	...	...	... ...	... ...	3.05 e44	... ...	e6.93 ...	4.65 e67	1.60 e23	.59 e8.5	e0.1 e1.4	e6.93 ...	2.2
60	18S/50-03adb	Crystal Pool	11-66	33/91	432	184	25	.09	.31	< .1	2.00 28	1.65 23	.313 45	.22 3.1	7.03 99.6	4.56 66	1.69 24	.62 8.9	.09 1.3	6.96 100.0	2.3
R63	18S/50-05aa	Well	04-67	23.5/74	792	22	22	...	...	...	... ...	... ...	10.35 e95	... ...	e10.89 ...	1.74 e16	3.54 e33	1.18 e11	e0.1 e1.0	[4]e10.89 ...	22.0
R66	18S/50-11d	Well	02-67	30.5/87	412	126	...	...	...	...	... ...	... ...	4.39 e63	... ...	e7.00 ...	4.98 e71	1.33 e19	.59 e8.4	e.1 e1.4	e7.00 ...	3.9
69	18S/51-07bbb	Well 5	10-70	31.5/89	335	190	23	.08	...	.3	2.20 31	1.56 22	3.04 43	.21 3.0	7.04 99.6	3.51 61 69	1.64 28 23	.56 9.7 7.8	.08 1.4 1.1	7.14 ... adj.[5]	1.9
R72	18S/51-07bdb	Well 13	03-67	30.5/87	410	192	...	...	...	...	... ...	... ...	3.09 e44	... ...	e7.02 ...	4.98 e71	1.35 e19	.59 e8.4	e.10 e1.4	e7.02 ...	2.22
75	18S/51-07caa	Well 4	10-70	30.5/87	428	210	23	.09	...	2.6	2.54 32	1.73 22	3.39 43	.21 2.7	7.90 99.6	4.80 65 68	1.73 23 22	.71 9.6 9.0	.09 1.2 1.1	7.37 ... adj.[5]	2.3
78	18S/51-07daa	Well 1	10-70	28/82	883	300	23	.12	...	7.1	2.99 22	2.96 22	7.40 54	.28 2.0	13.68 99.6	4.31 31	6.87 49	2.68 19	.08 .57	14.05 99.2	4.3
81	18S/51-07dac	Well 2	10-70	26.5/80	2160	690	23	.19	...	27	6.99 22	6.75 21	17.40 55	.49 1.5	31.75 99.6	3.97 12	19.5 61	8.46 26	.07 .22	32.09 99.7	6.6
84	18S/51-07dad	Well 3	10-70	29.5/85	617	270	24	.12	...	5.6	2.94 26	2.47 22	5.66 50	.23 2.0	11.35 99.6	3.00 30	4.79 47	2.14 21	.09 .89	10.11 99.1	3.4

TABLE 6.—*Chemical analysis of water samples from Ash Meadows and vicinity, Nye County, Nev.*—Continued

						Milligrams per litre					Milliequivalents per litre / Percent of total cations or anions[2]										
											Cations					Anions					
Water sample no.	Location S/E-Sec. and index	Source	Date Mo.-Yr.	Temp (°C/°F)	Dis. sol[1]	Total hardness as $CaCO_3$	SiO_2	Li	B	NO_3	Ca	Mg	Na	K	Total	HCO_3[4]	SO_4	Cl	F	Total	SAR[3]
87	18S/51-07dba1	Ind. Rk. Spring	11-70	33.5/92	412	203	22	.09	.35	.2	2.30 32	1.73 24	2.96 41	.19 2.6	7.22 99.4	4.98 69	1.62 22	.59 8.1	.08 1.1	7.27 100.0	2.1
90	18S/51-07dba	Many springs	10-70	31/88	340	200	22	.08	...	.2	2.25 31	1.65 23	3.04 42	.21 2.9	7.18 99.6	3.65 62 69	1.54 26 21	.59 10 8.2	.08 1.4 1.1	5.86 ... adj.[5]	2.2
93	18S/51-07dbb	King Pool	11-66	32/90	408	208	22	.09	.30	.2	2.40 33	1.73 24	2.91 40	.18 2.5	7.25 99.6	4.98 69	1.58 22	.59 8.1	.11 1.5	7.26 100.0	2.0
93a	do	do	10-70	32/90	371	190	22	.08	...	.3	2.25 32	1.56 22	3.04 43	.20 2.8	7.08 99.6	4.56 67 68	1.64 24 23	.56 8.2 7.9	.08 1.2 1.1	6.84 ... adj.[5]	2.2
96	18S/51-18dbd	Jack Rab. Spring	11-66	28/82	412	200	22	.08	.38	.1	2.23 32	1.75 24	2.96 41	.20 2.8	7.17 99.6	4.92 69.	1.62 23	.56 7.8	.08 1.1	7.18 100.0	2.1
96a	do	do	10-70	25.5/78	2140	800	24	.21	...	29	7.98 23	7.81 22	18.27 53	.54 1.6	34.73 99.6	2.75 8.5	20.40 63	8.75 27	.09 .27	32.46 98.6	6.5
99	18S/51-19acb	Big Spring	11-66	28.5/83	480	190	28	.12	.44	.2	2.20 27	1.56 19	4.22 51	.22 2.7	8.25 99.4	5.21 64	2.19 27	.71 8.7	.07 .9	8.18 100.0	3.1
102	18S/51-30a	Bole Spring	07-62	22/72	500	173	...	...	...	1.0	1.90 23	1.56 19	4.61 55	.24 2.9	8.32 99.9	5.01 61	2.35 29	.76 9.3	.05 .61	8.17 99.9	3.5

[1] Dissolved-solids residue on evaporation at 180°C.
[2] Missing percentage of cations is mainly Sr; minor Li.
Missing percentage of anions is mainly NO_3; minor PO_4.
[3] Sodium-adsorption ratio.
[4] 4.33 meq/l CO_3 (40 percent) in sample 63; no CO_3 in other samples.
[5] Anions adjusted to same meq/l as cations, assuming precipitation of $CaCO_3$ from anion sample before analysis.

chemistry. The 1970 samples from Jack Rabbit Spring and well 2 have almost five times the dissolved-solids concentration of the water from the lower carbonate aquifer. These results confirm the close hydraulic relationship shown between well 2 and Jack Rabbit Spring during the pumping tests of 1971.

LITHIUM

The lithium concentration in water from the lower carbonate quifer ranges between 0.08 and 0.10 mg/l, but well 2 and Jack Rabbit Spring have about 0.2 mg/l. Wells 1 (sample 78), 3 (sample 84), 8 (sample 18), 10 (sample 39), and well 17S/51-32dd (sample 51) have lithium concentrations ranging from 0.12 to 0.14 mg/l. Big Spring (sample 99) also has 0.12 mg/l and Bole Spring (sample 102) has 0.17 mg/l lithium. All samples have lithium concentrations greater than 0.10 mg/l also contained more than 50 percent sodium in their total cation concentration. Well J-12 (sample 0) and Ash Tree Spring (sample 9) have only about 0.04 mg/l and 0.07 mg/l, respectively.

BORON

Boron analyses were made for only a few of the samples. Water in the regional aquifer, as indicated by Devils Hole and most of the major springs, has boron concentrations ranging between 0.26 and 0.38 mg/l. Big Spring (sample 99) is slightly enriched in boron, having 0.44 mg/l. The highest boron concentration observed (1.4 mg/l) is in sample 39 from well 10. Boron is the only constituent detected for which Fairbanks Spring (sample 12, 0.51 mg/l) differs from the water in the regional aquifer. Nearby Soda Spring (sample 15) has about 1 mg/l boron.

SILICA

Silica is generally present with concentrations less than 25 mg/l. Samples from the Pahute Mesa groundwater system (samples 0 and 9) show 2 to 3 times this concentration, as does well 10 (sample 39).

NITRATE

Nitrate is a minor constituent of most samples, being generally less than 0.5 mg/l. The highest concentrations are in water from the 1970 sample (96a) of Jack Rabbit Spring (29 mg/l) and from well 2 (27 mg/l, sample 81). Wells 1, 3, and 4 (samples 78, 84, and 75) have moderate concentrations (2.6 to 7.1 mg/l), as do the samples (0 and 9) from the Pahute Mesa flow system.

CHEMICAL STABILITY OF DEVILS HOLE AND KING POOL

The change noted above in the quality of water from Jack Rabbit Spring raises the question of whether the chemistry of Devils Hole has also changed. In addition, water from King Pool was compared to that of Devils Hole before injection into well 17S/50-36dd was begun. Samples taken in June 1973 were analyzed by Southwestern Laboratories, Midland, Texas, and reported to the authors by Ed L. Reed and Associates (written commun., July 1973). In table 7 these analyses are compared to each other as well as to earlier analyses of each source by the Geological Survey.

Table 7 shows that the samples are all very similar chemically. The exceptions are a tenfold increase in nitrate in water from both sources and a possible slight increase in chloride. It is highly probable that differences in analytical technique, which are particularly critical in anion analysis, account for these apparent increases. The nitrate content could also result from reactions on organic materials in the unfiltered samples taken in 1973.

TABLE 7.—*Comparative analyses of samples taken at different times from Devils Hole and King Pool*

[Southwestern Laboratory (SWL) data from Ed L. Reed and Associates, written commun., July 1973]

	Devils Hole			King Pool		
Date sampled	1-22-53	12-9-66	6-15-63	11-21-66	10-4-70	6-14-73
Laboratory	USGS	USGS	SWL	USGS	USGS	SWL
Diss. solids (mg/l)[1]	425	423	398	408	371	389
Major cations [mg/l]						
Ca	51	50	48	48	45	47
Mg	21	24	24	21	19	25
Na	66	65	69	67	70	65
Major anions [mg/l]						
HCO_3	311	310	304	304	[2]278	300
SO_4	79	76	80	76	79	77
Cl	22	20	25	21	20	25
F	1.6	1.6	1.4	2	1.5	1.4
NO_3	.5	.2	2.9	.2	.3	2.7
Minor ions [mg/l]						
B	.38	.32	.08	.30	--	.08
Fe (total)	.04	.00	< .05	.00	.09	< .05
Se	--	--	.005	--	--	< .005
As	--	--	.01	--	--	< .01
Mn	--	< .01	< .05	.03	< .01	< .05

[1]Dissolved solids by Geological Survey determined as residue upon evaporation at 180°C; Southwestern Laboratory values are calculated.

[2]Imbalance in total cations and anions indicates precipitation of HCO_3 ion before analysis of anion sample.

QUALITY FOR IRRIGATION

The suitability of water for irrigation decreases as either the conductivity or the sodium-adsorption ratio (SAR) increases. The U.S. Department of Agriculture classification of irrigation waters is shown in figure 12; descriptions of the use of these classes given below are from Bateman, Mindling, Naff, and Joung (1972, p. 42-43):

The classification of irrigation waters with respect to SAR is based primarily on the effect of exchangeable sodium on the physical condtion of the soil. Sodium-sensitive plants may, however, suffer injury as a result of sodium accumulation in plant tissues when exchangeable sodium values are lower than those effective in causing deterioration of the physical condition of the soil.

Low-Sodium Water [*S1*] can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium. However, sodium-sensitive crops such as stone-fruit trees and avocados may accumulate injurious concentrations of sodium.

Medium-Sodium Water [*S2*] will present an appreciable sodium hazard in fine-textured soils having high cation-exchange-capacity, expecially under low-leaching conditions, unless gypsum is present in the soil. This water may be used on coarse-textured or organic soils with good permeability.

High-Sodium Water [*S3*] may produce harmful levels of exchangeable sodium in most soils and will require special soil management—good drainage, high leaching, and organic matter additions. Gypsiferous soils may not develop harmful levels of exchangeable sodium from such waters. Chemical amendments may be required for replacement of exchangeable sodium, except that amendments may not be feasible with waters of very high salinity.

Very High-Sodium Water [*S4*] is generally unsatisfactory for irrigation purposes except at low and perhaps medium salinity, where the solution of calcium from the soil or use of gypsum or other amendments may make the use of these waters feasible.

Sometimes the irrigation water may dissolve sufficient calcium from calcareous soils to decrease the sodium hazard appreciably, and this should be taken into account in the use of C1-S3 and C1-S4 waters. For calcareous soils with high pH values or for non-calcareous soils, the sodium status of waters in classes C1-S3, C1-S4, and C2-S4 may be improved by the addition of gypsum to the water. Similarly, it may be beneficial to add gypsum to the soil periodically when C2-S3 and C3-S2 waters are used.

Low-Salinity Water [*C1*] can be used for irrigation with most crops on most soils with little likelihood that soil salinity will develop. Some leaching is required, but this occurs under normal irrigation practices except in soils of extremely low permeability.

Medium-Salinity Water [*C2*] can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control.

High-Salinity Water [*C3*] cannot be used on soils with restricted drainage. Even with adequate drainage, special management for salinity control may be required and plants with good salt tolerance should be selected.

Very High Salinity Water [*C4*] is not suitable for irrigation under ordinary conditions, but may be used occasionally under very special circumstances. The soils must be permeable, drainage must be adequate, irrigation water must be applied in excess to provide considerable leaching, and very salt-tolerant crops should be selected.

Boron, although required in small amounts for proper plant nutrition, is toxic to some plants in larger quantities (Walker and Eakin, 1963). The boron hazard presented by Ash Meadows waters cannot be evaluated completely because of the limited number of analyses made. Well 10, however, with 1.4 mg/l boron, presents a high hazard to sensitive crops and a low hazard only to very tolerant crops (Scofield, 1936). Water from Big Spring and Fairbanks Spring may be moderately harmful to sensitive crops.

The conductivities and sodium-adsorption ratios for sources of irrigation water in Ash Meadows are plotted in figure 12. Well 10 (sample 39), rated C3-S4, has little value for crop production, and contemplated use should also consider the boron hazard noted above. With some precautions the water from well 2 (sample 81) or Jack Rabbit Spring (sample 96a), rated C4-S2, can be used to a limited degree. The Spring Meadows Ranch mixes well 2 water with that from wells 1 and 17 and applies it mainly to fields that are heavily treated with gypsum. Class C3-S1 water from wells 1 and 3 and from Big Spring and Bole Spring is used successfully to irrigate bermuda grass, which is relatively tolerant of salt (Bateman, Mindling, Naff, and Joung, 1972). Alfalfa is irrigated by wells 1, 3, and 17, but, wherever possible, it is mixed with King Pool water (class C2-S1) to reduce the salinity hazard. No analysis of water from well 17 is available, but hydraulic considerations suggest that it is similar to water from wells 1 and 3.

The remaining irrigation sources fall within class

C2-S1. Except for application on the poorly drained land along Carson Slough, this water is of moderately good quality.

QUALITY FOR DOMESTIC USE

With few exceptions the water sources in Ash Meadows do not exceed concentrations recommended by the U.S. Public Health Service (1962) for any chemical constituent other than fluoride. All samples reported from Ash Meadows exceed the recommended limit for fluoride (0.8 mg/l under the existing temperature) by a factor of 2 or more. Dental fluorosis and discoloration may occur in the teeth of children raised here. Recommended maximum concentrations of sulfate and chloride are exceeded in wells 1 and 2 and in the 1970 sampling of Jack Rabbit Spring.

OBSERVED EFFECTS OF PUMPING

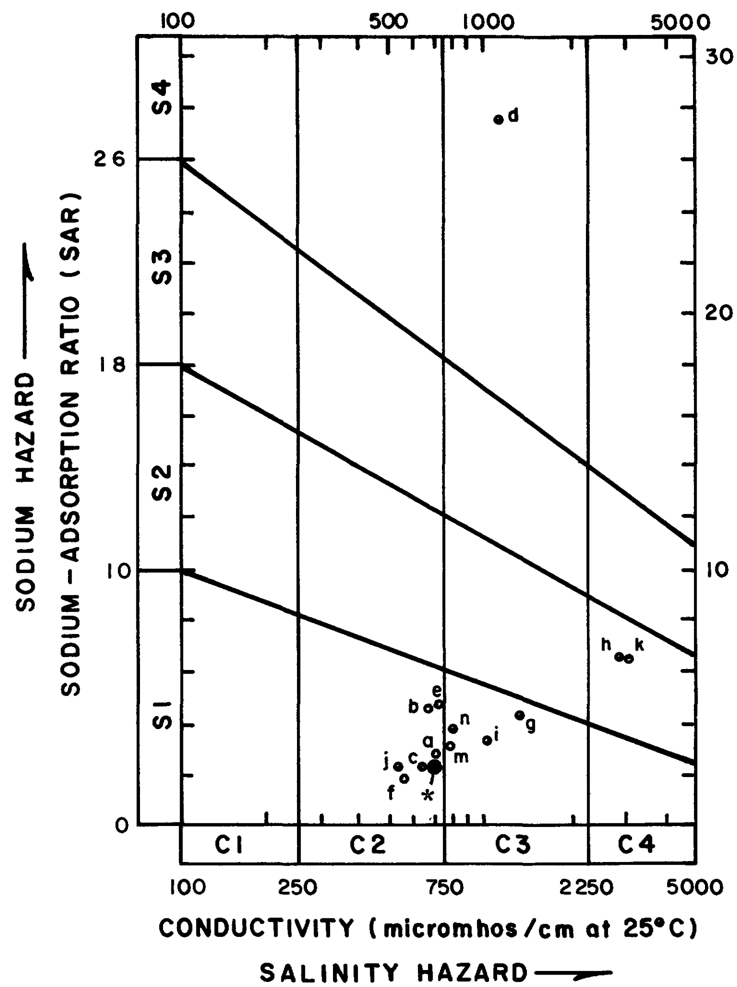
The effects of pumping were monitored during 1971 and 1972 by water-level recorders in Devils Hole, in several observation wells, and in flumes and weirs installed in most of the major springs. (See table 2.) Moderately detailed records of pumpage from the production wells in 1971 were reconstructed from electrical-meter readings, discharge measurements, and frequent observations of whether or not they were pumping.

Because gaps in the hydrograph of Devils Hole had occurred before, well 17S/50-36dd was instrumented in January 1971 as a precaution against lost record. An excellent correlation was established between the depths to water in this well and in Devils Hole, which is about 900 ft (275 m) west of the well.

EFFECT ON DEVILS HOLE WATER LEVEL

During the aquifer tests of the individual production wells, no effects on the water level in Devils Hole were discernable. Daily fluctuations of the pool (as much as 0.5 ft or 15 cm) would easily have masked any changes due to pumping.

The correlation between gross pumpage from the well field and the water level in Devils Hole, however,



SAMPLE IDENTIFICATION

Class C2-S1

a Soda Spring
b Well 8
c Well 7
e Observation well 17S/51-31dd
f Well 5
j Point of Rocks spring group
* Fairbanks Spring
* Rogers Spring
* Longstreet Spring
* Devils Hole
* Observation well 17S/50-36dd
* Well 6
* Crystal Pool
* Well 13
* Well 4
* King Pool
* Jack Rabbit Spring (1966)

Class C3-S1

g Well 1
i Well 3
m Big Spring
n Bole Spring

Class C3-S4

d Well 10

Class C4-S2

h Well 2
k Jack Rabbit Spring (1970)

FIGURE 12.—Classification of irrigation water from Ash Meadows sources by conductivity and sodium-adsorption ratio. Classification diagram from U.S. Salinity Laboratory Staff (1954).

is evident in figure 2. The pumpage records in table 5 indicate that the decline of water level in June and July 1969 must have resulted from well 1 or well 13 unless other wells were pumped without electrical power, in which case no record of this pumping is available. The significantly greater decline from August through November 1969 correlates with additional pumping from wells 2 and 4 and lesser withdrawals from wells 6 and 8.

The 1970 pumping season provides even less insight into the effects of individual wells. Pumping began near the end of April, with wells 1, 2, 3, 4, and 5 operating at or near their capacities, and the water level in Devils Hole began a relatively uniform decline until pumping was curtailed in December 1970. Moderate reductions in the use of wells 3 and 5 may be responsible for the decreased rate of drop in July. Reduced production from wells 4 and 6 may account for the leveling of the hydrograph in October.

In 1971, however, the pumping history was more varied, and individual wells could be evaluated more easily. Figure 13 shows the mean daily water levels computed from the hydrographs of Devils Hole and well 17S/50-36dd and the pumping history reconstructed from the detailed field observations. The observation well shows greater response than does Devils Hole to the pumping of some wells and thus allows subtle deviations of the Devils Hole hydrograph to be detected.

Although the early February 1971 decline in the well and Devils Hole might be attributed to either well 1 or well 4, their recovery, beginning about February 10, correlates only with the shutdown of well 4. The effects of well 5 can be detected from the period mid-March to mid-April, from the 0.1 ft (3 cm) recovery of the observation well in late May, and from the smaller recovery in late June. Limited use of well 6 continued to prevent identification of its effects.

The pumping histories of wells 7, 8, and 13 varied sufficiently that their effects, if significant, should have been detectable; the hydrographs show no apparent reaction to these wells. Considering their

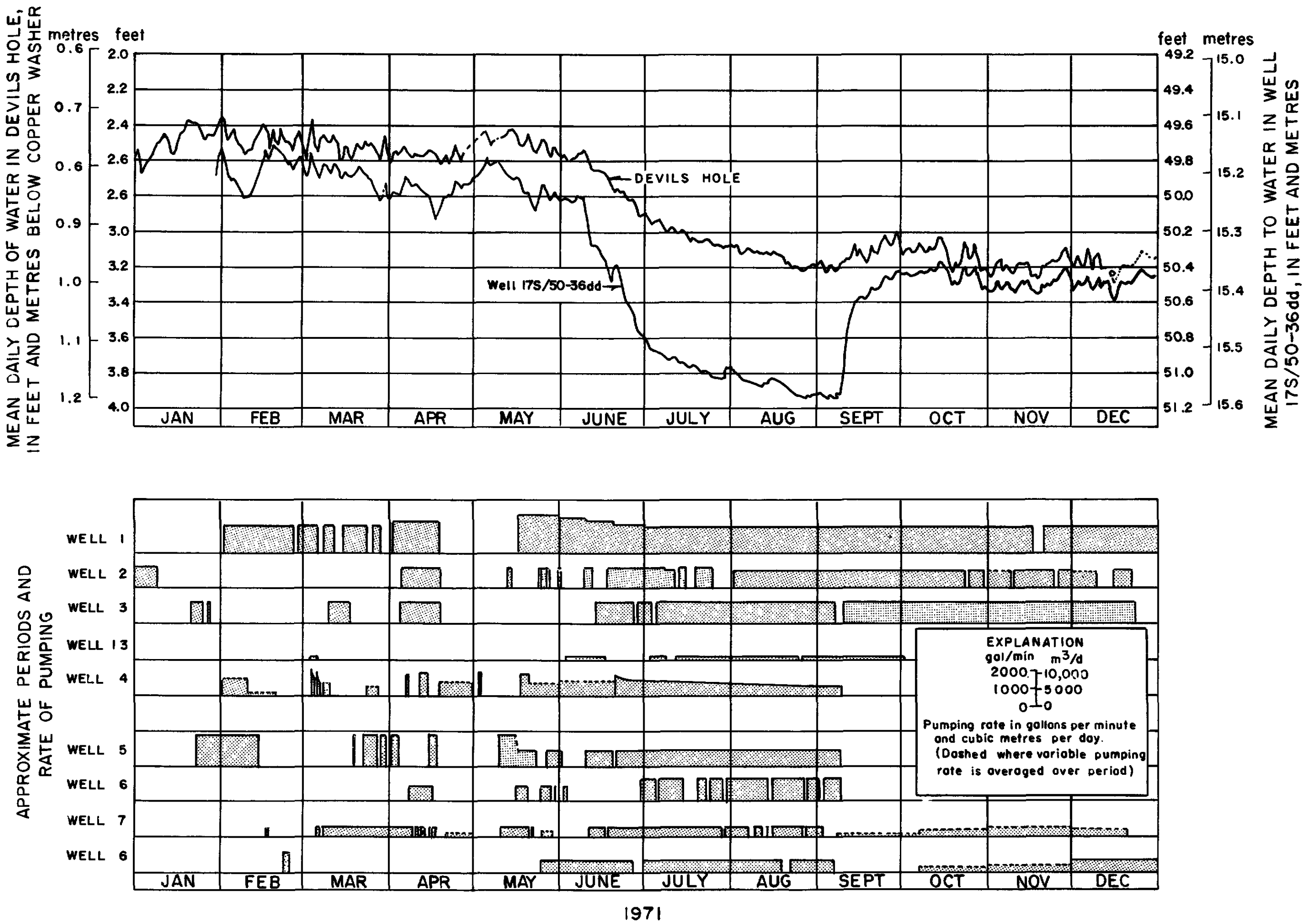


FIGURE 13.—Mean daily water levels in Devils Hole and observation well 17S/50-36dd and estimated pumping from wells in Ash Meadows during 1971. Dashed segments in upper hydrograph denote extrapolation through periods of no data.

distances from Devils Hole (except for well 13), their small to moderate discharges, and the chemistry of the water from well 8, this observation was to be expected.

On August 4, 1971, the senior author submitted to the U.S. District Court, Las Vegas, Nev., an affidavit stating his opinion that, among all wells of the field, wells 4, 5, and 6 had the most direct effects on the water level in Devils Hole. This conclusion was based on their yields and closeness to Devils Hole, the similarity in chemistry and temperature of their waters to that of Devils Hole, and the correlations of pumping history with the hydrograph discussed above. In late August, the Federal Government and the ranch reached an agreement to shut down wells 4, 5, and 6, and the immediate recovery beginning on September 9, 1971, is apparent on figure 13. The observation well recovered 0.5 ft (15 cm) within 1 week and 0.7 ft (21 cm) by the end of September. The change in Devils Hole was equally encouraging, recovering almost 0.2 ft (about 5 cm) by the end of the month. This rate compared favorably with the rapid drawdown of 0.3 ft (9 cm) in a 20-day period during heavy pumping of the field in June and July 1971. The variability in the mean daily hydrograph levels, which had diminished during the summer drawdown, returned in late September.

In October 1971 the hydrographs of Devils Hole and well 17S/50-36dd resumed slow and parallel declines. It became evident that the cessation of pumping for wells 4, 5, and 6 had produced only about 0.2 ft (6 cm) of recovery in Devils Hole and that continued pumping of wells 1, 2, or 3 was lowering the water level.

The recorder in Devils Hole malfunctioned in mid-December 1971, but the recorder in well 17S/50-36dd continued to operate. On December 20, wells 2 and 3 were shut down, and a slow recovery of the water level began in the observation well. In January 1972, well 1 stopped pumping, and the recovery in well 17S/50-36dd increased in rate.

Analysis of the data collected through January 1972 showed that wells 7, 8, and 13 had no detectable effect on the water level in Devils Hole; wells 1, 4, and 5 had significant effects; and either well 2 or well 3, or both, had a measurable effect.

No direct hydraulic data pertinent to the effect of well 6 had been obtained before it was abandoned. However, reduction of the discharge records of Crystal Pool during the late summer of 1971 show that about 90 percent of the well 6 discharge was compensated by reduction of the flow of Crystal Pool.

Because observation well 17S/50-36dd did not respond as clearly to pumping in the Point of Rocks area as it did to use of wells 4 and 5, an alternative

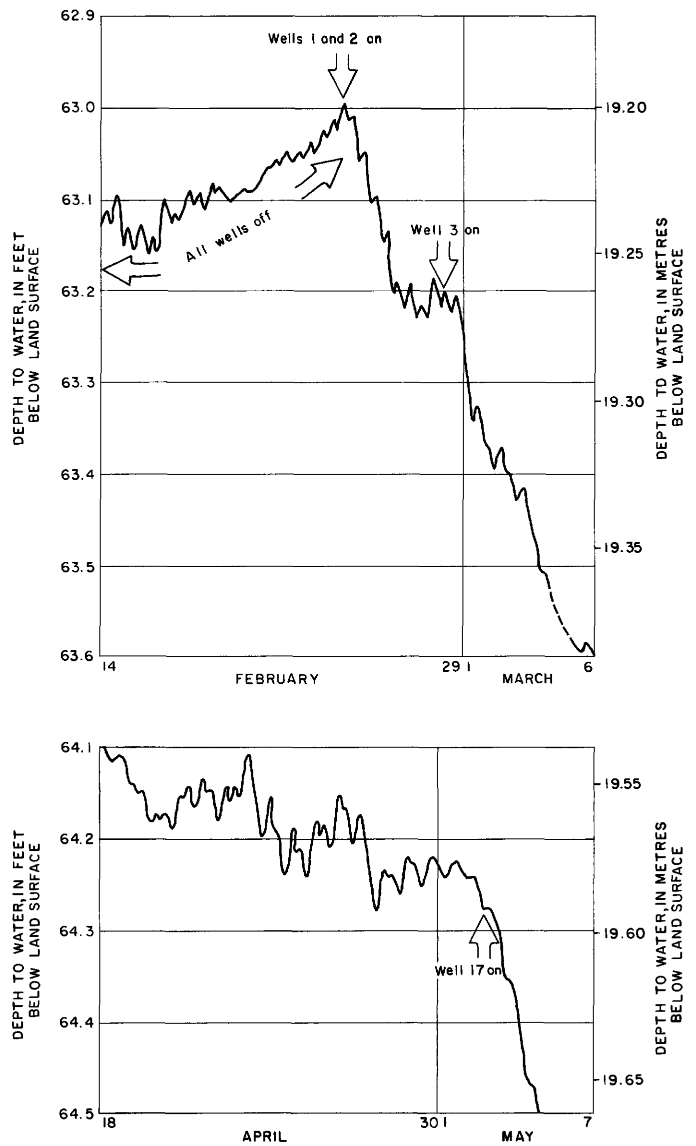


FIGURE 14.—Segments of the 1972 hydrograph of observation well 17S/51-31dd, showing effects of wells 1, 2, 3, and 17. Dashed segments in upper hydrograph denote extrapolation through periods of no data.

path of influence was sought. Well 17S/51-31dd (fig. 7) was equipped with a water-level recorder in January 1972, and subsequently provided an expressive hydrograph. Figure 14 shows the drawdown produced by wells 1, 2, and 3 in February and March 1972.

Two new wells (16 and 17 on fig. 7) were completed about 2 mi (3.5 km) southeast of Devils Hole in the spring of 1972. Well 16 proved to be of low yield, but well 17 produced about 2,500 gal/min (about 14,000 m^3/d). Well 17 began production in early May 1972. Its effect on the new observation well 17S/51-31dd was immediate and significant (fig. 14). By the end of June 1972, the water level in well 17S/51-31dd had dropped about 1 ft (30 cm) to 65.5 ft (20 m) below the

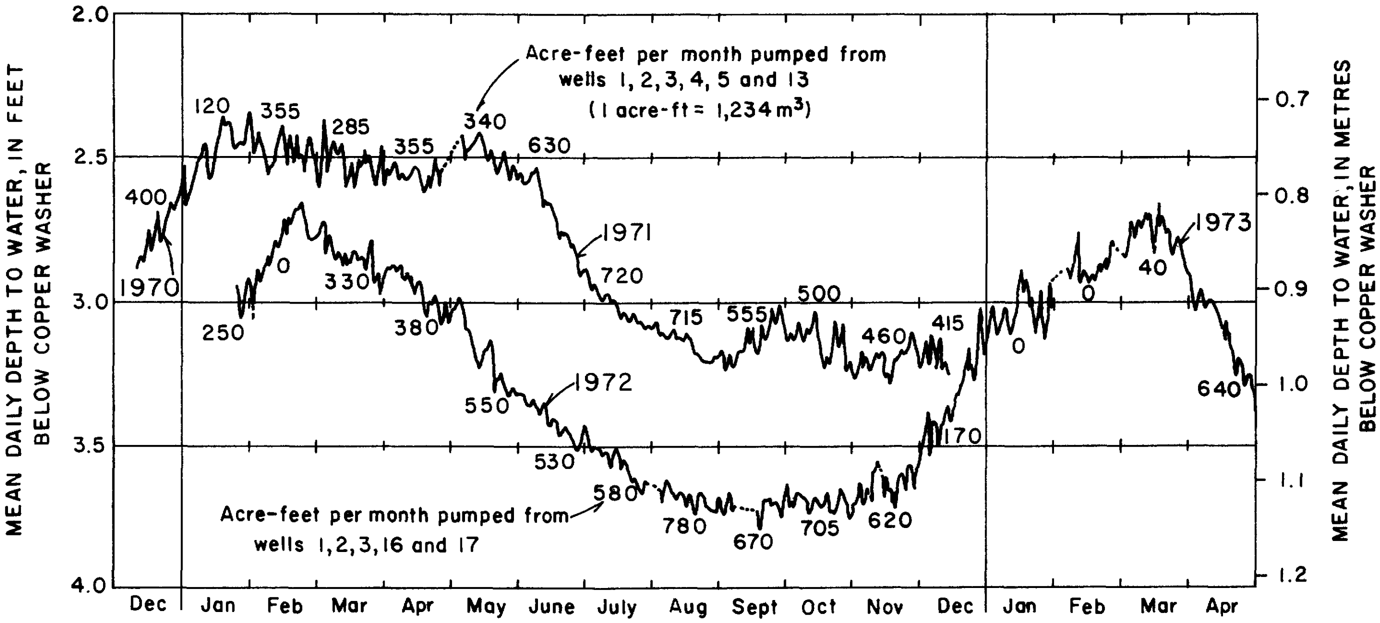


FIGURE 15.—Mean daily water levels in Devils Hole and approximate monthly pumpage from wells in southern Ash Meadows, late 1970 through early 1973. Dashed segments denote extrapolation through periods of no data.

land surface. As with pumping from wells other than 4 and 5 in the Point of Rocks area, the effect of well 17 at Devils Hole is sluggish and not readily apparent. Figure 15 shows the mean daily levels in Devils Hole and the approximate monthly pumpage from the Point of Rocks area from late 1970 through mid-May 1973. The effect of well 17 in early May 1972 is visible.

Although the 1972 pumping history was less varied than that in 1971, the total amounts pumped were almost the same: 5,500 acre-ft (6.8 million m^3) in 1971 and 5,600 acre-ft (6.9 million m^3) in 1972. Figure 15 illustrates that, on the average, the declines for the 2 years are nearly parallel, the hydrograph for 1972 being about 0.5 ft (15 cm) below that for 1971. In late March 1973, wells 1, 2, 3, and 17 were turned on, and the resulting decline in April (fig. 15) is the steepest of record.

IMPACT OF INDIVIDUAL WELLS

Evaluation of the effects of individual wells is a subjective process. Although wells 4 and 5 produce sharp responses in well 17S/50-36dd and discernible responses in Devils Hole, the longer-term records suggest that they have less effect than wells 1 and 17. The authors assign the following probable effects to individual wells.

Wells 1 and 17.—These wells produce the greatest drawdown in Devils Hole during sustained pumping. Their high yields contribute substantially to their effects.

Wells 3, 4, and 5.—These wells produce significant drawdowns in Devils Hole. The effects of wells 4 and 5 arrive more sharply at Devils Hole than do those of other wells, but the September 1971 recovery suggests that the magnitude may be somewhat less than that produced by the higher yields of wells 1 and 17.

Wells 2, 6, 13, and 16.—These wells have only small effects on the water level of Devils Hole. The discharges of wells 2 and 6 are largely compensated by reduced spring flow; wells 13 and 16, although near wells having greater impact, produce only minor yields.

Wells 7 and 8.—These wells have no presently detectable effects on Devils Hole.

Well 9.—Because of its location, just more than 1 mi (2 km) southwest of Devils Hole, well 9 is a potential threat to the Devils Hole water level. Through mid-1973, however, it has been used only intermittently to water stock. Table 3 (location 18S/50-11aa) shows that no production test was reported, so the potential impact of well 9 cannot be evaluated.

Wells 10, 11, 12, and 14.—There are not sufficient hydraulic observations to evaluate these wells, but their remoteness, small yield, and chemical character suggest little or no effect on Devils Hole.

EFFECT ON SPRING DISCHARGE

Documenting the reduction of spring discharge, and the consequent threat to pupfish habitats other than Devils Hole, was an important objective of this investigation. Moreover, that part of the total pumpage that is diverted from natural discharge by springs to artificial discharge by nearby wells generally affects only details of the local flow subsystem but has little effect on the regional system, including Devils Hole.

Reductions of spring discharges were noted during aquifer tests of some of the wells (table 4). Additional data were gained by detailed observation during the 1971 pumping season. Figure 16 shows the 1971 springflow data for four springs in the southern half of Ash Meadows.

BIG SPRING

The hydrograph of Big Spring during 1971 (fig. 16) shows that the discharge declined slowly from 1,040 gal/min (5,700 m^3/d) in January to 920 gal/min (4,900 m^3/d) by mid-October. Although past measurements (table 2) are not significantly different from the January 1971 flow, the decline began in June, which was the beginning of heavy and sustained pumping. In December 1972, the discharge of Big Spring again reached a low of 900 gal/min (4,800 m^3/d), indicating that during 1972 there possibly was a slight accumulated effect of pumping on the discharge of Big Spring.

JACK RABBIT SPRING

The documented effect of well 2 on the flow of Jack Rabbit Spring, and the consistency of the water-quality data with the hydraulic observations, has been discussed earlier in this report. When compared with the 1971 pumping history of well 2 in figure 13, the hydrograph in figure 16 demonstrates this relationship clearly. At several times, such as in mid-April, the hydrograph provided a more detailed record of the pumping periods than did electric-meter readings and field observations.

The greatest discharge of Jack Rabbit Spring in 1971 occurred on May 11 and was 425 gal/min (2,320 m^3/d), but the hydrograph suggests that continued recovery would have increased this to at least 450 gal/min (2,450 m^3/d). This discharge is about 100 gal/min (545 m^3/d) less than previous (1953 and 1962) Geological Survey measurements (table 2) and indicates an effect accumulated during several years of pumping.

The expressiveness of the hydrograph in March 1971 shows that well 1 also affects Jack Rabbit Spring,

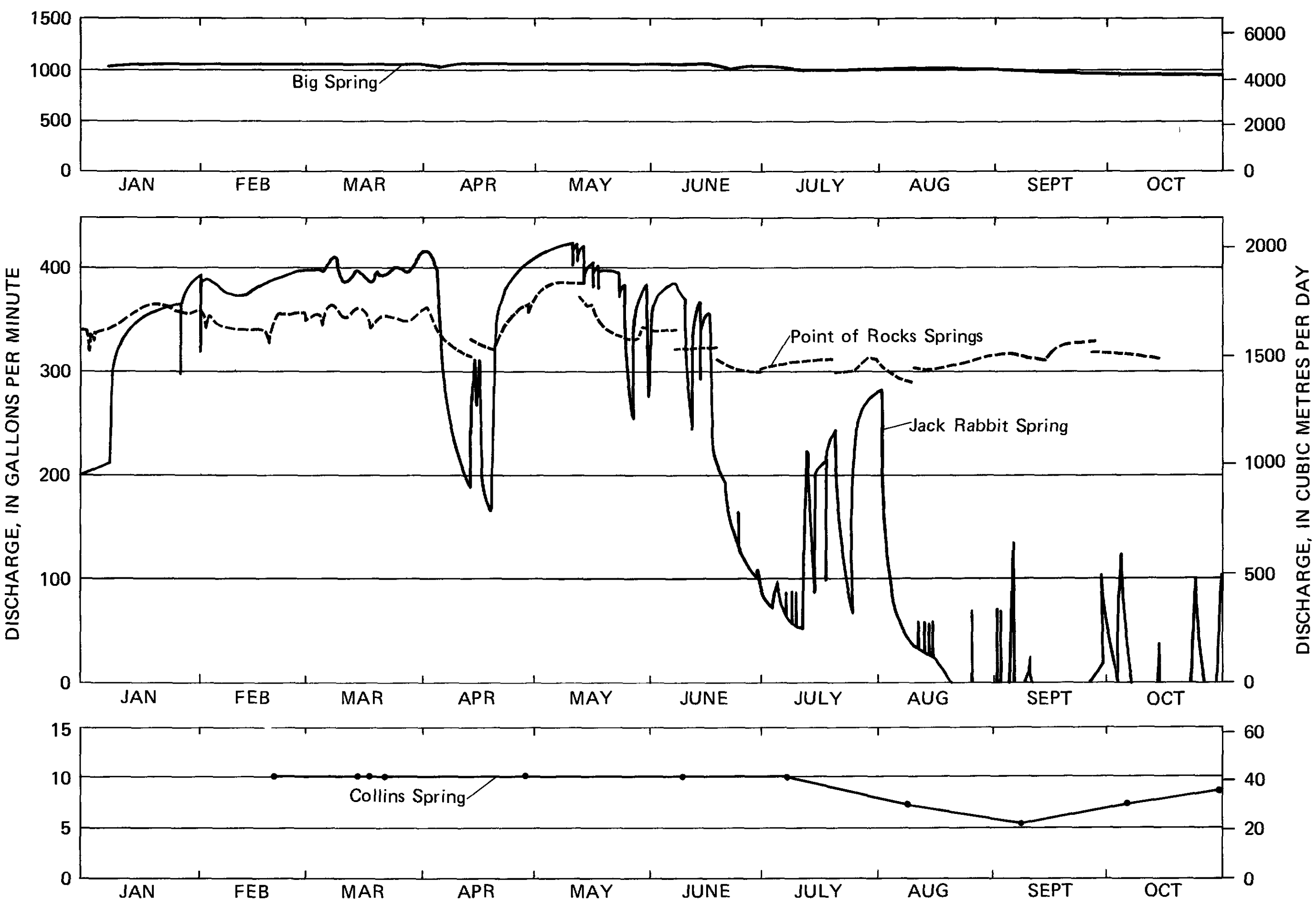


FIGURE 16.— Discharge of selected springs in Ash Meadows, January-October 1971.

although to a much smaller degree than does well 2. In early July a 2-day period of recovery is not as rapid as those typically caused by well 2 and apparently correlates with the temporary shutdown of well 3, shown in figure 13. Using the degree to which the chemistry of the discharges of wells 1 and 3 approach the unique chemistry of water from well 2 and Jack Rabbit Spring as an indication of relative effect, the capture of springflow by well 1 is probably about 50 gal/min (270 m^3/d), and that by well 3 may be about 25 gal/min (135 m^3/d). Well 2 intercepts the remaining 350 gal/min (1,900 m^3d) under the pumping conditions of 1971, but it probably is capable of capturing the entire discharge if pumped for sustained periods without interference from other wells.

POINT OF ROCKS SPRINGS

The group of small springs at Point of Rocks, designated collectively as 18S/51-7dba on table 2, was gaged by 6-inch Parshall flumes on each of two alternate diversion paths carrying their total discharge. In figure 16 the recorded flow is superimposed on the hydrograph of the responsive Jack Rabbit Spring.

The record in figure 16 shows a pattern similar to that of Jack Rabbit Spring, although the variations are less distinct. The fluctuations during March on both hydrographs correlate with a period of intermittent pumping of well 1. In late April irrigation was severely curtailed and did not resume until mid-May. The recovery of the Point of Rocks group is evident, and the flow also reached the 1971 high during this shutdown. This maximum discharge was 385 gal/min (2,100 m^3/d), about 35 gal/min (190 m^3/d) lower than the reported 1962 flow (table 2). Because of the difficulty of measuring the combined discharge of this group of springs, however, the 8-percent difference may not be significant.

After September 9, 1971, when pumping from wells 4, 5, and 6 ended in accordance with the agreement between the ranch and the Federal Government, there was no distinguishable recovery of these springs. Water leaking from a rubber irrigation line distributing water from well 1 made the Point of Rocks record unreliable after mid-October and may be responsible for the apparent increase of flow beginning on September 15; a change in the diversion path also occurred on this date.

Difficult channel conditions and the presence of a pump in King Pool, also commonly called Point of Rocks Spring in the literature, prevented continuous measurement of its discharge. Current-meter measurements were made upstream and downstream from its entry into a nearby irrigation ditch. Because the flow of the Point of Rocks spring group usually was channelled into King Pool, further correction was required. The probability for significant measurement errors was high, but the flows shown in table 2 indicate that this spring was not affected by pumping in 1970 nor by the following recovery.

COLLINS SPRING

The small flow of Collins Spring, located 0.75 mi (1.2 km) south of Devils Hole in SE¼, sec. 1, T. 18 S., R. 50 E., declined about 5 gal/min (27 m^3/d) in 1971 (fig. 16). Although the quantity of loss was small, it did represent a 50-percent reduction of flow. The decline began in July and was recovered after wells 4, 5, and 6 stopped pumping in September, 1971. The pumping history of well 6 (fig. 13), 1.6 mi (2.6 km) west of Collins Spring, provides an apparent correlation with this reduction.

CRYSTAL POOL

In April 1971, Crystal Pool declined 450 gal/min (2,450 m^3/d) in flow after well 6 had pumped at a rate of 900 gal/min (4,900 m^3/d) for 1 week. The well apparently developed itself by caving in May, and the discharge rate was increased to 1,370 gal/min (7,470 m^3/d). After 2 months of sustained pumping of well 6, the flow of Crystal Pool declined to 1,670 gal/min (9,100 m^3/d), a loss of 1,270 gal/min (6,920 m^3/d). The total volume of lost springflow could not be compared with the total pumpage because the discharge of Crystal Pool was diverted around the flume before recovery was completed. The interception of Crystal Pool flow is estimated at 90 percent of the pumpage of well 6 for seasons of combined intermittent and sustained pumping.

FIVE SPRINGS AREA

East of Longstreet Spring, in NW¼, sec. 23, T. 17 S., R. 50 E., a total of 170 gal/min (925 m^3/d) is discharged from a number of small springs and seeps (table 2). The springs are within 500 ft (150 m) of exposures of Paleozoic limestone, and well 7 (table 3), which is in the middle of the spring group, penetrated the limestone at a depth of 48 ft (14.6 m). The 34.5°C (94°F) temperature of well 7 water is the same as that of the largest spring, which discharges 75 gal/min (408 m^3/d).

Pumping of well 7 at 530 gal/min (2,900 m^3/d) stops most of the spring flow within 1 hour, and sustained pumping captures the entire 170 gal/min (925 m^3/d).

PURGATORY SPRING

During sustained pumping of well 7, a loss of 12 gal/min (65 m^3/d) was measured in the discharge of flowing well 17S/50-14cac. Drilled into a travertine spring mound about 0.75 mi (1.2 km) north of well 7, this flowing well normally discharges 20 gal/min (110

m^3/d) from the Paleozoic limestone penetrated from 25 ft (7.6 m) to 92 ft (28 m). In 1972 it was developed as a refuge for *Cyprinodon diabolis* and named "Purgatory Spring."

LONGSTREET SPRING

The location of well 7, about 0.5 mi (0.8 km) east of Longstreet Spring (fig. 7), suggests that it might reduce spring flow significantly. However, only about 360 gal/min (1,960 m^3/d) of the well 7 discharge is not compensated by reduced flow of other springs. Measured discharges of Longstreet Spring (17S/50-22 aba in table 2) show a variability of about ± 10 percent, but comparison with the pumping history of well 7, shown on figure 13, reveals no correlation. The spring discharge is 7°C (13°F) cooler than that of well 7, indicating that the effect of the well, if any, would be manifested subtly over a long period of time, rather than arriving sharply in a short period. There is, of course, a possibility that the November 1971 measurements of Longstreet Spring show some impact of well 7, but subsequent curtailment of the observation program prevented further documentation.

ROGERS SPRING

The 1971 measurements of Rogers Spring (17S/50-15ab in table 2) show about a 20-percent reduction from earlier Geological Survey measurements. Whether the orifice has been changed physically during reworking of the outlet channel system or by traffic on the road immediately adjacent to the spring, or whether this decrease is due to pumping, cannot be stated with certainty. During the aquifer test of well 8 in February 1971, however, Rogers Spring decreased in flow from 590 gal/min (3, 215 m^3/d) to 555 gal/min (3, 025 m^3/d). The loss was fully recovered within a few days after the aquifer test was completed.

SODA SPRING

Soda Spring (17S/50-10bcd in table 2) has also apparently lost about 20 percent of its earlier reported discharge, on the basis of highest flow measured in 1971. This 65-gal/min (355-m^3/d) flow was completely captured during periods of sustained pumping of well 8 in 1971.

FAIRBANKS SPRING

The measurements reported in table 2 for Fairbanks Spring (17S/50-9ad) suggest a lesser reduction of flow (an average of about 10 percent) than is apparent for Rogers Spring and Soda Spring. Although the discharge of Fairbanks Spring decreased from a maximum of 1,580 gal/min (8,600 m^3/d) to a minimum of 1,430 gal/min (7,800 m^3/d) during 1971, the decline was gradual and could not be correlated with pumping histories. Moreover, during the pumping test of well 8, no reduction of flow was evident on the continuous record of discharge through the Parshall flume.

OTHER SPRINGS

Several other springs reported in table 2 and located on figure 3 were observed but not examined in detail. Ed L. Reed and Associates (written commun., 1967) reported that McGillivary Spring (17S/50-22ac) flowed 155 gal/min (845 m^3/d), but it was not flowing when visited in September 1970. The condition of the outlet channel, however, indicated that it had flowed in the past, and the reported discharge was compatible with the size of the channel.

Cold Spring (17S/50-21ac) had a stable flow during the observed period of October 1970 through April 1971, when pumped diversion for a domestic supply ended the record. The flow was about the same as reported earlier by Ed L. Reed and Associates (written commun., 1967).

Three small springs west of Devils Hole in sec. 35, T. 17 S., R. 50 E. continued to flow during 1970 and 1971. The lack of earlier data prevents identification of pumping effects, if any. One of these, School Spring (17S/50-35d1), is developed as a pupfish sanctuary, and its flow has been supplemented by well 18S/50-2aa. The minor flow of School Spring, however, was within the range reported earlier (table 2) and is so small that it is highly sensitive to changes in the orifice.

Several springs in the vicinity of the former Davis Ranch (18S/50-11d and 12c) could not be measured because of irrigation-ditch patterns, but their combined flow appears smaller than those reported for 1962 in table 2. The 1962 flows were also smaller than those reported for 1953.

Two conical former spring orifices occur in sec. 12, T. 18 S., R. 50 E. east of the Davis Ranch (fig. 3). Sink Spring has a channel indicating former discharge and was reported by Ed L. Reed and Associates (written commun., 1967) to have flowed 25 gal/min (135 m^3/d). Hatchery Spring has no earlier record and the outlet has been destroyed by agricultural leveling. During 1971 the orifice was a pond with a level about 4 ft (1.2 m) below the surrounding land. The pond declined slightly (about 0.1 ft or 3 cm) during aquifer tests of well 5, about 0.6 mi (1 km) to the north, and it has sufficient permeability to accept minor irrigation tailwater.

It is difficult to state with certainty whether pumping has reduced the flow of these springs in secs. 11 and 12, T. 18 S., R. 50 E. The records for 1953 and 1962 suggest that natural phenomena, such as gradually evolving diversion of flow to other springs or deterioration of orifice condition, might be responsible for the declines. However, it is evident that the water table has declined at Sink Spring and Hatchery Spring. An alternative explanation is that the discharge of King Pool formerly infiltrated sufficiently to raise the water table and to allow secondary springs to erupt. Diversion of King Pool water for irrigation would have caused the decline of this recharge mound and subsequent decay of the secondary spring flow.

It is estimated that the total loss of spring discharge in 1971 not identified as caused by a specific well was between 250 gal/min (1,360 m^3/d) and 400 gal/min (2,180 m^3/d). The average of 325 gal/min (1,770 m^3/d) is considered by the authors to be the best estimate.

OTHER SOURCES OF WATER CAPTURE

The effects of agricultural pumping on the local hydrologic subsystem and adjacent regional system may be reduced by three factors in addition to the diversion of spring discharge. These factors are:

1. infiltration of pumped water to the ground-water reservoir;
2. reduction of evapotranspiration by lowering the water table locally around the wells; and
3. reduction of evapotranspiration by clearing fields.

For these factors to be effective in making the net well-field discharge less than the gross pumpage, however, they must act at positions in the system that retard a general and sustained lowering of the water table in the well field.

EFFECT OF WATER-TABLE DEPTH

Ash Meadows can be divided (fig. 17) into eastern and western sections having significantly different hydrologic characteristics. From the highlands of the Paleozoic outcrops, where the water table is generally from a few tens to many tens of feet beneath the land surface, the land slopes westward more steeply on the average than does the water table. The springs that occur close to the hills in eastern Ash Meadows are generally warm, 32°C (90°F) or higher, and relatively small. The exceptions are King Pool, which discharges about 1,200 gal/min (6,500 m^3/d), and Longstreet Spring, with a similar discharge but the significantly lower temperature of 27°C (81°F). Around the spring orifices and along the outlet channels phreatophytes and evaporation consume the total discharge of all the springs except Longstreet Spring and King Pool.

The westward slopes of the land surface and the water table in eastern Ash Meadows intersect generally along a line connecting the other major springs (fig. 17). West of this spring line the water table is at or within a few feet of the land surface, and recharge water applied to the land by irrigation or by spring flow from eastern Ash Meadows is generally rejected by the shallow ground-water reservoir. Instead, it evaporates, is consumed by the dense phreatophyte growths, or runs off to Carson Slough.

The spring line, if defined only on the basis of rejected recharge, should be carried eastward to King Pool between Crystal Pool and Jack Rabbit Spring, as shown in figure 17. The former discharge of the Davis Springs, however, favors the westward position of the line for stratigraphic reasons. Exploratory drilling indicates that the valley-fill sediments are much less permeable in western Ash Meadows than are those east of the spring line. With the exception of well 10, which produces a moderate discharge of very poor quality, productive wells are confined to eastern Ash Meadows. Evidence presented later suggests that faults define the spring line, but this conclusion is not necessary to support the observation that none of the factors compensating well discharge can be effective in western Ash Meadows. Because of the proximity of the water table to the land surface, no reduction of consumptive water use nor application of additional water can raise the water table significantly west of the spring line. The spring line, therefore, is effectively a hinge about which the water table in eastern Ash Meadows may rotate, but along the line and to the west the water table may not build up.

In addition to reduced spring flow, the infiltration of pumped water and salvage of evapotranspiration in eastern Ash Meadows may be deducted from gross pumpage to determine the net withdrawal of ground water in excess of natural discharge.

DEFINITION OF PUMPING UNITS

Figure 17 shows further divisions of eastern Ash Meadows into five pumping units. Unit A, which extends northward into the wide valley east of Devils Hole, contains production wells (1, 2, 3, 16, and 17) that are variable in chemical quality and, where not compensated by reduced spring flow, produce a slow but persistent drawdown in Devils Hole. Unit B has two major wells (4 and 5) producing water of quality very similar to that of Devils Hole. Drawdown from pumping these wells arrives distinctly at Devils Hole.

The separation of unit C from unit B may arise only from the lack of data from unit C. The discharge of well 6 is compensated by reduced flow from Crystal Pool, and no other wells exist in the unit. Water temperature and quality in this unit, however, suggest a close hydraulic relationship with the lower carbonate aquifer. Consequently, future wells would probably lower the water level in Devils Hole.

Unit D has only one well (well 7) and minor spring discharge (about 170 gal/min or 925 m^3/d). This

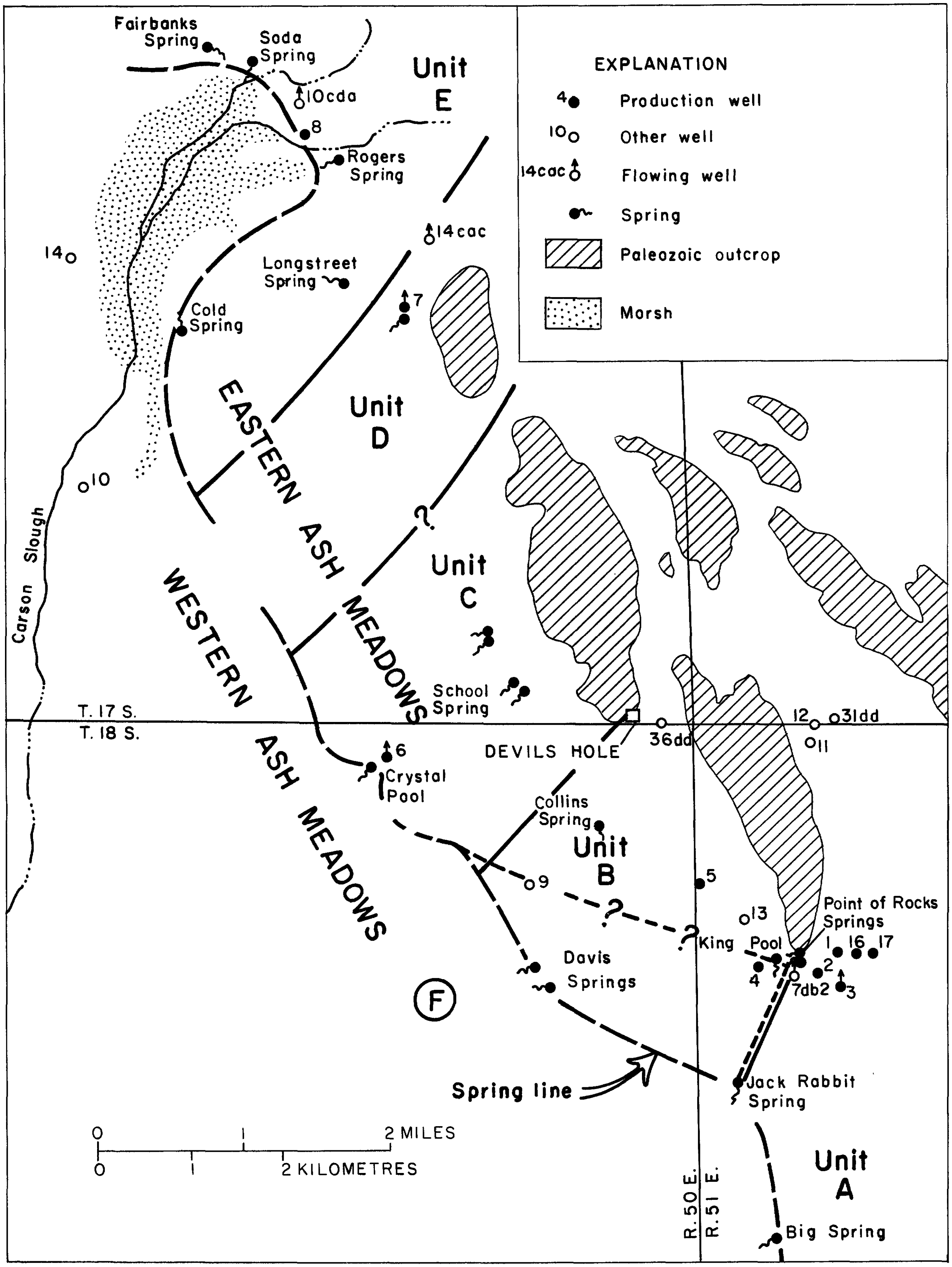


FIGURE 17.—Location of the spring line and pumping units in Ash Meadows.

discharge is similar in temperature and chemistry to Devils Hole water.

The temperature of discharge from both wells and springs in pumping unit E suggests that the probability of significant effects on Devils Hole is remote. However, the close chemical similarity of the spring discharge to Devils Hole water points clearly to the lower carbonate aquifer as the regional source, and it would be imprudent to rule out completely an eventual effect of increased pumpage from this unit.

CAPTURE OF EVAPOTRANSPIRATION

Reduction in the use of water by phreatophytes within the cone of depression around the wells is difficult to establish because of the complexity of the hydraulics in this area. Field examination indicates that it is small compared to the other sources of water capture, for phreatophytes are only sparsely distributed near most of the wells. Eradication of phreatophytes to clear fields east of the spring line, however, is potentially a significant factor affecting the net withdrawal from the Ash Meadows discharge area at the 1971 stage of ground-water development.

Wells 1, 2, and 3, as a group or singly, dry up 20-30 acres (80,000-120,000 m^2) of seepage that evaporates and supports dense mesquite and saltgrass growth below the spring group at Point of Rocks. Not more than 150 acre-ft (190,000 m^3) was captured in pumping unit A in 1971. The actual amount is probably less, as the drawdown over this area at the peak of the pumping season was not more than a few feet, and water was still within reach of the mesquite.

In unit B, wells 5 and 13 are situated on relatively high ground that is only sparsely covered with vegetation and are assigned no capture of evapotranspiration. The effect of well 4 is less certain, although none can be demonstrated. The clearing of phreatophytes from nearby fields probably has made this a moot point.

About 10 acres (40,000 m^2) of dense mesquite and grasses between well 6 and Crystal Pool, and thus not watered by the emergent flow of Crystal Pool, may be affected by pumping. Together with seepage at the ground surface on about 2 acres (8,000 m^2), a potential gain of about 60 acre-ft (74,000 m^3) per year exists here. Under the pumping conditions of 1971, the net withdrawal from unit C was probably compensated entirely by salvage from spring discharge and evapotranspiration.

The dense growth of mesquite, saltgrass, saltbush, and other phreatophytes in pumping unit D below the springs in the vicinity of well 7 probably are watered entirely by recycling of the spring water. Consequently the salvage is taken into account under spring-flow reduction.

Well 8 has minor acreages of saltgrass and meadow grass within its possible zone of influence in unit E. Most of this, however, merely intercepts surface water in channels on its way to the low meadows west of the spring line.

The clearing of fields causes a substantial reduction of evapotranspirative withdrawal east of the spring boundary. The coverage of phreatophytes on this land was estimated by comparison with nearby undeveloped land. Water-use rates were estimated with the assumption that only transpiration was stopped; evaporation from the soil should have remained the same or increased beyond the cones of depression of the wells.

The fields east and southeast of wells 1 and 3 that have been cleared and are partly planted with Bermuda grass were, in the natural state, covered with sparse saltgrass, mesquite, and healthy sagebrush. Based on rates of use estimated by F.E. Rush (written commun., 1970) for southern Clark County, Nev., the average rate of use for dense coverage of such vegetation would be on the order of 5 ft (1.5 m) per year (an abbreviated form of acre-feet per acre per year). A generous estimate of the natural cover density is 20 percent, and the height of growth was probably less than optimum. Consequently the salvaged evapotranspiration does not exceed 1 ft (0.3 m) per year over the approximately 600 acres (2.4 million m^2) of cleared land. The maximum annual salvage of 600 acre-ft (740,000 m^3) is assigned to pumping in unit A, which in 1971 provided all well water applied to these fields.

An additional 48 acres (194,000 m^2) at wells 1, 2, and 3 was probably more densely covered with mesquite, sagebrush, and saltgrass. An estimated use rate of 3 ft (0.9 m) of water over this area suggests a saving of about 150 acre-ft (185,000 m^3) each year. Combined with the fields to the east, about 750 acre-ft (925,000 m^3) per year can be deducted from pumpage in Unit A that is applied there.

Between Point of Rocks and the Davis Springs in pumping unit B, about 220 acres (890,000 m^2) formerly supported luxurious growths of mesquite and willows along the discharge channel of King Pool and moderately dense mesquite, sagebrush, saltbush, and saltgrass away from the channel. This area probably has been dried by diversion of King Pool water, but, to avoid underestimating salvage, a ground-water consumption rate of 2 ft (0.6 m) is applied to the 200 acres (810,000 m^2) having moderate coverage, and a saving of 400 acre-ft (494,000 m^3) might have been achieved by clearing of these fields. Although the discharge of wells 4, 5, and 13, combined with the flow of King Pool is more than adequate to irrigate this acreage, pumpage from Unit A was used to supplement King Pool after wells 4 and 5 were shut down in September, 1971. The addition of wells 16 and 17 in 1972 created a surplus of water in unit A (at the 5 acre-ft per acre or 1.52 m^3/m^2 per year alloted by the State Engineer for southern Nevada), and diversion to unit B continued.

All fields that have been cleared of phreatophyte growth and watered from pumping unit C (well 6) are in western Ash Meadows. Therefore, no salvage is allotted from clearing fields in unit C.

About 60 acres (240,000 m^2) between Longstreet Spring and well 7 in unit D were formerly covered with a moderate growth of mesquite, sagebrush, and saltgrass. This is believed to have been watered by spring flow emerging near well 7 and completely captured by pumping of that well. Even if this is in error, not more than 300 acre-ft (370,000 m^3) is saved annually.

Fields cleared east of the spring line in unit E are restricted to about 100 acres (405,000 m^2) of sandy uplands west and northwest of Longstreet Spring. The pre-agriculture coverage of these fields is not known, but phreatophytic use of water away from the outlet channels of Longstreet Spring and the former McGillivary Spring is believed to have been minor.

RECHARGE BY INFILTRATION

Early in 1971 about 200 acre-ft (250,000 m^3) pumped from well 1 into a leaky reservoir northeast of Point of Rocks infiltrated with little evaporative loss. An estimated 30 percent of the 130 acre-ft (160,000 m^3) pumped from well 8 into a reservoir on Carson Slough east of Rogers Spring also re-entered the ground-water reservoir. This recycled water is not considered in the following estimate of infiltration through irrigated fields.

Recharge from precipitation at elevations below 4,000 ft (1,220 m) in the arid basins of southern Nevada is negligible, according to Maxey (1968). Walker and Eakin (1963) estimated the annual recharge to the Amargosa Desert from precipitation falling within the topographic drainage basin to be about 1,500 acre-ft (1.85 million m^3), all of this occurring in zones having 8 in (200 mm) or more of precipitation per year. Soil saturation by the more intense application of irrigation water, however, may destroy capillary forces in the formerly unsaturated zone, thus allowing infiltration to occur in zones having less than 8 in (200 mm) of applied moisture.

No direct observations are available for use in selecting the percentage of water applied that might infiltrate in fields east of the spring line. Visual estimates of tailwater runoff and the probable use by crops and evaporation from the soil suggest that not more than 30 percent of the pumped water re-enters the local ground-water system. This is thought by the writers to be an upper limit and probably unrealistically high.

The total pumpage from unit A that was applied to fields east of the spring line in 1971 was 3,870 acre-ft (4.8 million m^3). If a rate of one-fourth of the pumpage is used, almost 1,000 acre-ft (1.2 million m^3) would have infiltrated. About 40 percent of the pumpage from unit B was transported west of the spring line, resulting in a net useful infiltration of 18 percent of gross pumpage, or about 240 acre-ft (300,000 m^3). All withdrawals from units C (well 6) and E (well 8) are applied west of the spring line. About 150 acre-ft (180,000 m^3) of the discharge of well 7 is recovered in unit D.

OVERDRAFT OF LOCAL SUBSYSTEM IN 1971

The possible sources of salvage of pumped water are summarized by well and by pumping unit in table 8. Subtracting these savings, including the long-term declines in Big Spring and the springs in unit B, from gross pumpage gives the 1971 overdraft (excess of total discharge over natural discharge) for each pumping unit. The estimated overdrafts for units A and B are minimum values, for all salvages were estimated at their upper limits.

The net pumpage shown for unit E may be high, for the long-term reduction of the flows of the springs has not been subtracted. If the apparent long-term decreases in Fairbanks, Soda, Rogers, Longstreet, and McGillivary Springs, as shown in table 2, are

TABLE 8.—*Estimated capture of water pumped from wells and overdraft from pumping units in 1971*

Pumping unit	Well no.	Gross pumpage (acre-ft)[1]	Percent captured from			Net pumpage (acre-ft)[1]
			Springs	Drawdown[2]	Infiltration[3]	
A	1	1,800	6.7	3.9	30	1,070
A	2	870	45	3.4	30	190
A	3	1,200	4.6	4.2	30	740
Transpiration captured by clearing fields						-750
Long-term spring flow decline						-100
Overdraft from unit A						1,150
B	4	490	...	...	18	400
B	5	790	...	...	18	650
B	13	70	...	...	18	60
Transpiration captured by clearing fields						-400
Long-term spring flow decline						-280
Overdraft from unit B						430
C	6	450	90	10	...	0
D	7	480	33	...	30	180
E	8	440	20	...	...	350
Capture of transpiration and long-term spring flow						-0
Overdraft from units C, D, and E						530

[1]Rounded to nearest 10 acre-ft. Infiltration beneath reservoirs deducted from pumpage of wells 1 and 8.

[2]Evapotranspiration captured by drawdown zone around well.

[3]30 percent of water applied east of spring line assumed to infiltrate.

accurate, they total about 570 gal/min (3,100 m^3/d) or 920 acre-ft/yr (1.1 million m^3/yr). This is more than twice the average annual pumpage from well 8 and significantly greater than combined pumpage from wells 7 and 8 that is not otherwise compensated by observed reductions of spring discharge. Obviously pumping from wells operated by the Spring Meadows Ranch has not salvaged the entire long-term reduction, and it is unlikely that it has salvaged a significant part.

The overdraft during 1971 from units A and B was at least 1,580 acre-ft (1.9 million m^3) or a 9-percent additional load on the total discharge from the Ash Meadows ground-water system. Because of the liberal estimates of salvage, the overdraft might have been twice that amount.

SOURCE OF OVERDRAFT

Lohman (1972, p. 63), in summarizing C.V. Theis' (1940) discussion of the source of water derived from wells, stated:

> Prior to development by wells, aquifers are in a state of dynamic equilibrium, in that over long periods of time recharge and discharge virtually balance. Discharge from wells upsets this balance by producing a loss from storage, and a new state of dynamic equilibrium cannot be reached until there is no further loss from storage. This can only be accomplished by:
> 1. Increase in recharge (natural or artificial).
> 2. Decrease in natural discharge.
> 3. A combination of 1 and 2.

As of 1972, based on annual low water levels in Devils Hole, the upset of this balance produced by pumping in Ash Meadows was still producing a loss in storage, and equilibrium had not been re-established. The easily salvaged flow of Jack Rabbit Spring and the reduction of phreatophytic use of water, the two most significant sources of salvaging pumping from units A and B, have been realized fully or almost fully. The decline of the water table, and of potentiometric head in the confined aquifers at depth, must continue until additional natural discharge is captured, or until the 4,500-mi^2 (about 12,000-km^2) Ash Meadows ground-water system expands its boundaries to capture 10 to 20-percent more recharge. In either case water levels throughout the local subsystem and in the adjacent lower carbonate aquifer, including Devils Hole, must continue to fall.

Figure 18 illustrates that not all reduction of spring discharge is effective in reducing the threat to the Devils Hole pupfish. Wells that affect springs easily (fig. 18*A*) may indeed salvage the spring flow. In the complex geologic setting of Ash Meadows, however, more remote pumping may find that its easiest path of communication with the spring (fig. 18*B*) is along a longer but more permeable path through the regional lower carbonate aquifer. In this case the reduction of spring flow may help prevent an overdraft in the overall regional system but, nevertheless, it produces drawdown in Devils Hole.

Although figure 18 is schematic and generalized, it is closely similar to conditions presently believed to exist in Ash Meadows. The spring shown is similar to Crystal Pool, and the well in figure 18*A* represents well 6, which probably did not affect the water level in Devils Hole. In figure 18*B* the remote diversion of water is similar to the effects of the wells in unit A (1, 2, 3, 16, and 17). The late 1971 and later effects of pumping these wells strongly suggest that their recent apparent influence (E.L. Reed, oral commun., 1973) on the flow of Crystal Pool has been transmitted northward into the regional aquifer east of Devils Hole and then west to Crystal Pool. To reduce the flow of Crystal Pool, which lies on the spring line, or the "hinge" for the eastern Ash Meadows water table, it must first lower the water table in the lower carbonate aquifer, thereby causing drawdown in Devils Hole.

SAFE YIELD

As pointed out by Lohman (1972), the term "safe yield", or its close equivalent "perennial yield", has as many definitions as definers. He credits Meinzer with probably having first defined safe yield as "the rate at which the ground water can be withdrawn year after year, for generations to come, without depleting the supply * * *" (Meinzer, 1920, p 330). Since 1920 the term has been redefined innumerable times and with such a wide variety of meanings that it no longer has meaning. All of these ultimately reduce to the "grass roots" definition of Lohman (1972, p. 62), who has stated that safe yield is "the amount of ground water one can withdraw without getting into trouble."

According to this definition, even a planned period of mining ground water from storage to develop the economic base for importing water later, as proposed by Maxey (1968), would be compatible with the safe-yield concept provided that all parties affected by the overdraft had previously agreed. However, as small ground-water systems attempt to establish a new equilibrium under heavy pumping stresses, they may expand their boundaries so as to injure water rights existing in adjacent systems. When only the availability of water for domestic, industrial or agricultural use is considered, still the decision for a planned overdraft may not be a local one.

In an era of environmental concern, where the supply for immediate human use is increasingly subordinated to sustained use for generations to come, Meinzer's (1920) original definition of safe yield seems to be becoming increasingly appropriate again.

Walker and Eakin (1963, p. 28) defined perennial yield as "the maximum amount of water that can be withdrawn from the ground-water system for an indefinite period of time without causing a permanent depletion of the stored water or causing a deterioration in the quality of the water." They further estimate that the perennial yield of the Amargosa Desert, of which Ash Meadows is a part, as tentatively about 24,000 acre-ft (30 million m^3) per year. Of this "about 17,000 acre-ft [21 million m^3] can be obtained by full development of the springs at Ash Meadows. The remaining amount would be available for development by wells largely in the area northwest and northeast of the springs." (Walker and Eakin, 1963, p. 29.) Note that the total discharge of the Ash Meadows area, as defined in this report, is limited essentially to the spring discharge.

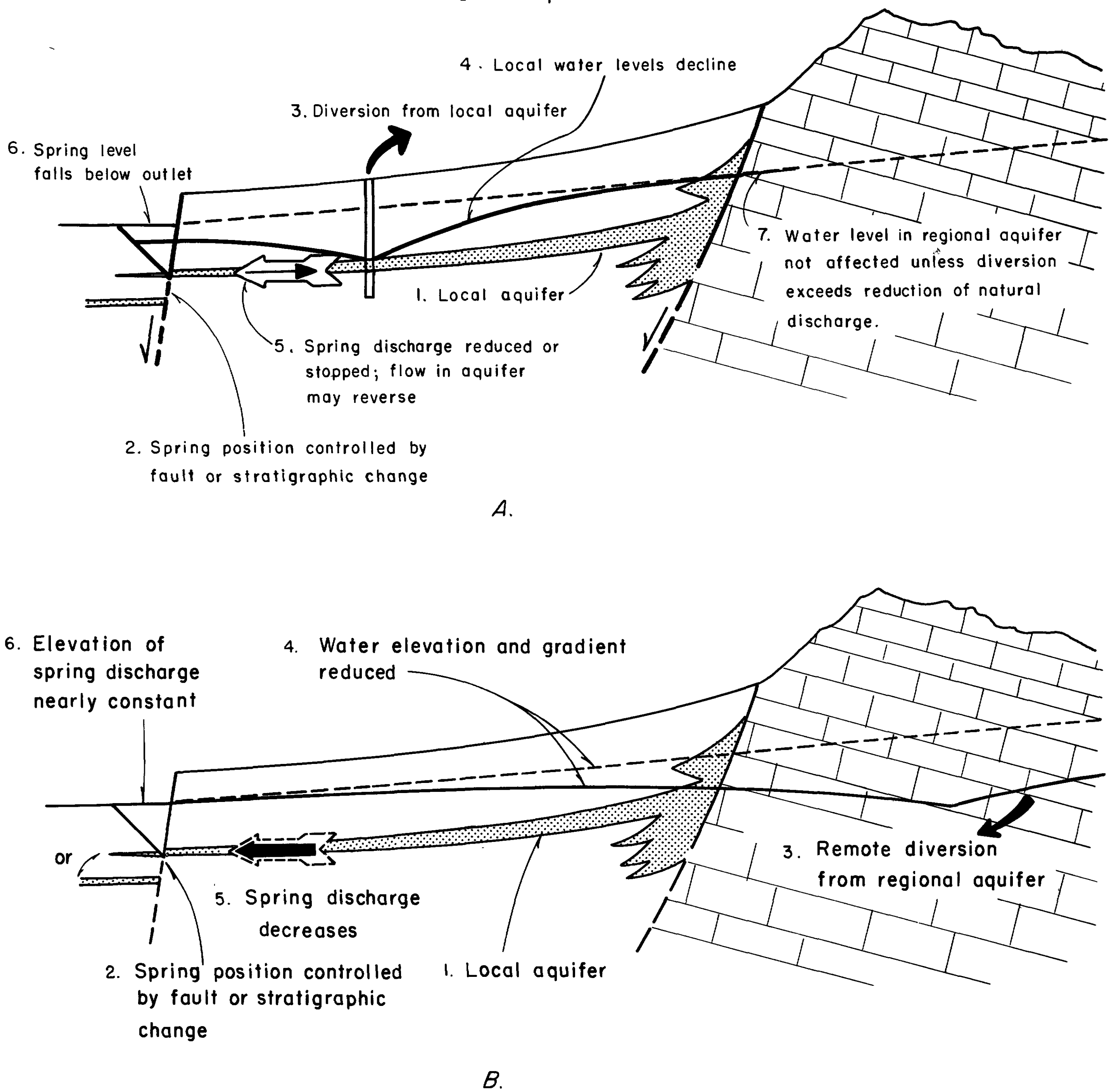


FIGURE 18.—Comparison of the effects on spring discharge and the water level in the regional aquifer when pumping is (A) close to and (B) remote from the spring.

EXAMINATION OF ALTERNATIVE CAUSES

The possibility that other causes have produced the drawdown in Devils Hole is very remote, but it should be examined briefly.

Pumping from the Ash Meadows ground-water system at the Nevada Test Site totalled about 20,000 acre-ft (25 million m^3) from 1951 through 1971 (Claassen, 1973), an average of about 1,000 acre-ft (1.25 million m^3) annually. Most of this has been produced from wells in the lower carbonate aquifer or in overlying Cenozoic units that are sources of recharge to the regional flow system. Production records and periodic water-level measurements presented by Claassen (1973), however, show that the peak production was in the early to mid-1960's and that there is not yet a measurable effect on water levels in the regional aquifer beneath the Nevada Test Site. The water levels in Geological Survey experimental wells located between the Nevada Test Site and Ash Meadows (sampling point 3 on fig. 11) remained stable from 1966, when measurements began, through 1969. By September 1973, however, the levels had declined about 1 ft (30 cm), suggesting that the drawdown at Ash Meadows had spread at least 8 mi (13 km) to the northeast. These wells are developed in the Bonanza King Formation, the limestone in which Devils Hole is formed.

The stability of water levels in the lower carbonate aquifer cited above also discounts long-term reductions of recharge as a possible cause. In addition, according to the U.S. Fish and Wildlife Service Desert Game Range (Refuge Manager, oral commun., 1971), the Spring Mountains, during the winter of 1968-69, received their heaviest precipitation in 40 years. Figure 2 shows no effect of this on the Devils Hole hydrograph.

Elastic changes of the aquifer storage volume by earthquakes and nuclear explosions have been recorded by the hundreds as short-term, oscillating water-level changes in Devils Hole, but permanent offsets of the stage record have not been observed.

Most effective in precluding these other factors as causes for the decline in Devils Hole and the reduction of spring discharge, except for those springs in pumping unit E, is the positive correlation of the Devils Hole hydrograph and recorded spring flows with the detailed pumping record obtained in 1971 and generalized pumping schedules since 1967.

The reduced flow of the large springs in northern Ash Meadows (pumping unit E) indicates the possibility that pumping in the Amargosa Farms area northwest of Ash Meadows has diverted some water from the Ash meadows ground-water system into the Pahute Mesa system (fig. 4). If this is in fact true, it illustrates that the dynamic equilibrium in ground-water flow is not confined to a single flow system. In its effort to re-establish equilibrium by capturing enough additional recharge to satisfy overdrafts, a ground-water system will expand its boundaries, thereby passing the overdraft on to its neighbors. Measurements of the springs in northern Ash Meadows have not been frequent enough to define the variations in discharge. Estimates of pumping in the Amargosa Farms area, abstracted by the Office of the Nevada State Engineer (written commun., 1970), show that pumping reached its maximum in the mid-1960's and has declined to a minor amount since then. The effect on the Ash Meadows ground-water system may indeed be recovering now, but only additional years of measurements can verify this.

MOVEMENT OF GROUND WATER IN ASH MEADOWS AREA

NATURE OF THE REGIONAL FLOW SYSTEM

Local details of the flow system and actual rates of movement are difficult to establish in carbonate aquifers. Although the hydrogeology approaches a level of homogeneity when considered on a gross scale, it appears quite capricious as the area of observation is decreased.

The irregular development of secondary permeability by chemical solution is responsible for this unpredictability. Three factors are dominant in controlling the geometry of solution-channel growth. The first is the areal pattern of recharge. Second is the position and orientation of structural discontinuities (faults and joints), which initially provide a secondary permeability that is commonly several orders of magnitude greater than that in the primary interstices. The third is the position of the discharge area, for the drain system which develops must eventually deliver the water where it can be expelled from the system.

The existing paths of fracture permeability receive seepage from the far reaches of the basin and focus it upon the discharge area. This geometric requirement provides a corollary that the flow must become larger and more concentrated along the paths from the recharge areas to the discharge points. Consequently, the paths tend to combine into fewer but more open conduits as they approach the discharge area. Because the ability of fractures to transmit water increases approximately as the square of their width, the more open fractures grow into conduits much more rapidly than the smaller ones. The result is that flow is concentrated into a few master conduits at the discharge areas (fig. 19) and in places within the basin

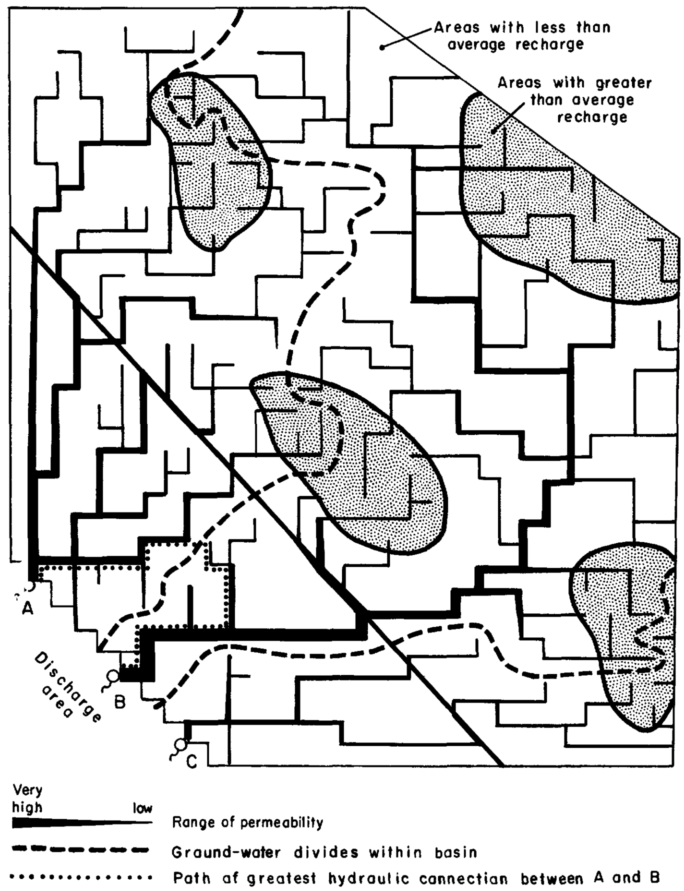


FIGURE 19.—Concentration of flow in a carbonate aquifer from many paths of low permeability into a few highly permeable conduits.

where flow is constricted to narrow zones by geologic conditions.

In this sense, even artesian flow systems in carbonate rocks resemble surface river systems particularly those in which rock-fracture systems affect the geometry, although ground-water systems are three-dimensional. One distinct and very important difference, however, is that surface drainages are discrete entities, in which tributary branches contribute to the flow of only one trunk. In a ground-water flow system the master conduits may share secondary trunks, which in turn share lesser tributaries. Because the smaller tributaries are not discrete to a single subsystem, hydraulic interference between subsystems is to be expected. Interference effects are usually difficult, if not impossible, to predict in detail; however, they may require transmission upgradient in the first subsystem to the point where there is good hydraulic connection with an adjacent subsystem.

Figure 19 shows schematically, in two dimensions only, how the easiest path of communication between conduits leading to different discharge points may be much longer on the map than the mere distance between the points. Because numerous paths of varying hydraulic conductivity are available, the effect of pumping at point A will be dispersed and will arrive at point B in a complex manner.

Although schematic in intent, this illustration is similar in important ways to the hydraulic geometry in the vicinity of the Ash Meadows springs and the flow path approach from the east. The upward movement of warm water at Ash Meadows from deep within the regional system, however, adds the three-dimensional aspect that further complicates the natural system.

FLOW IN THE LOCAL SUBSYSTEM

The development of the Spring Meadows well field, and the observed effects of pumping, provided an opportunity that was not available for earlier workers to examine some of the details of flow in the local subsystem. The complexity of the local aquifers has been mentioned several times previously in this report. In this section the water-quality data, the hydraulic-test data, and the observed effects of pumping will be combined with geologic observations to explain the pattern of flow from the regional aquifer to the points of discharge by springs.

EVIDENCE FROM WATER CHEMISTRY AND TEMPERATURE

Percentages of the major chemical constituents of the water samples are shown in table 6 and on the quadrilateral plot in figure 20. Starting with the sample (6) from Army well 1 near the Nevada Test Site, most of the analyses show a progressive enrichment in sodium over the sum of calcium and magnesium and a lesser enrichment of other anions (mainly sulfate) over bicarbonate plus carbonate. Sample 6 is thought to represent the chemical quality of water shortly after entering the flow system from the Spring Mountains. By the time it is released to the local subsystem, however, the composition has evolved to that of Devils Hole (sample 42) and the 17 samples represented by the bold circle in figure 20.

Where the water is forced to travel considerable distances to points of discharge after release from the regional aquifer, its composition follows essentially the same progression through sample 60 (Crystal Pool) and sample 99 (Big Spring) to sample 102 (Bole Spring). It is significant, however, that the 1966 sample (96) from Jack Rabbit Spring and the samples from all springs except Soda Spring (sample 15) in pumping unit E of northern Ash Meadows fall in the bold circle although they are distant from outcrops of the lower carbonate aquifer.

It is instructive to examine the samples represented by the bold circle. They fall into five groups, identified by general location and temperature.

Two of the samples are from wells developed in the lower carbonate aquifer at depths of about 600 ft (180 m) several miles northeast and east of Ash Meadows:

Sample 3, Geological Survey tracer well 2, 30.5°C (87°F);

Sample 54, well 17S/50-08c1, 28°C (82°F).

Four of the samples are from three large springs and one slightly flowing well in northern Ash Meadows:

Sample 12, Fairbanks Spring, 27°C (81°F);

Sample 21, Rogers Spring, 28°C (82°F);

Sample 24, well 17S/50-15ad, 19.5°C (67°F);

Sample 30, Longstreet Spring, 28°C (82°F).

Nine samples are from springs and wells in or very close to the outcrops of Paleozoic carbonate rocks:

Sample 33, spring 17S/50-23bbc, 33.5°C (92°F);

Sample 36, well 7, 34.5°C (94°F);

Sample 45, well 17S/50-36dd, 33.5°C (92°F);

Sample 69, well 5, 31.5°C (89°F);

Sample 72, well 13, 30.5°C (87°F);

Sample 75, well 4, 30.5°C (87°F);

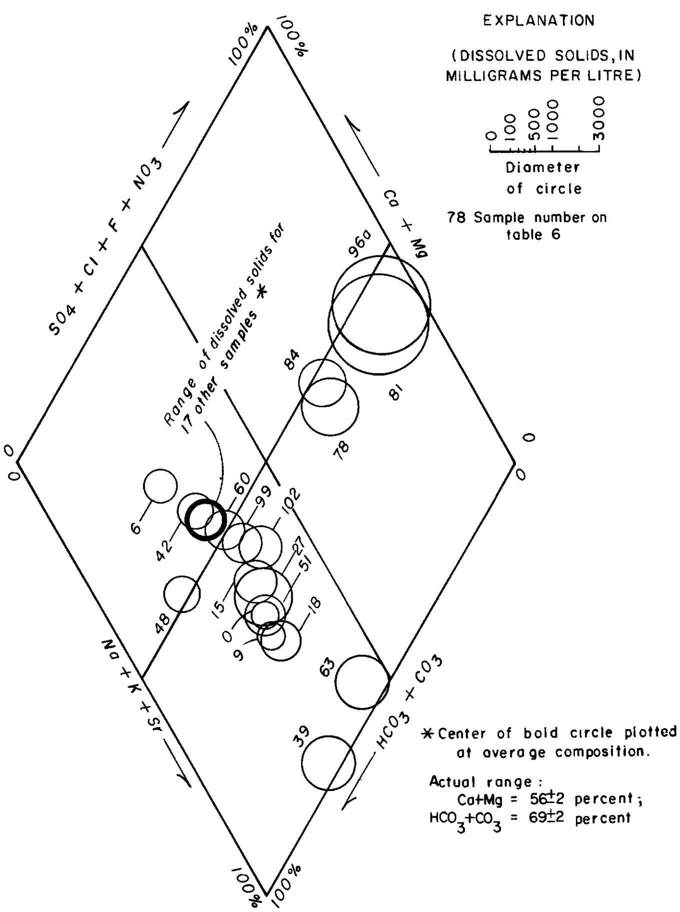


FIGURE 20.—Percentage reacting values of dominant ions in water samples from wells and springs in Ash Meadows and vicinity.

Sample 87, Indian Rock Spring, 33.5°C (92°F);

Sample 90, Point of Rocks spring group, 31°C (88°F);

Sample 93, King Pool, 32°C (90°F).

The last two samples in the grouping are:

Sample 57, well 6, 31°C (88°F);

Sample 96, Jack Rabbit Spring (1966), 28°C (82°F).

The first group appears to represent water which has adjusted to a state of equilibrium with the carbonate aquifer and which follows shallow flow paths toward northern Ash Meadows. By the time it arrives at Ash Meadows the water is at a temperature of 28°C (82°F). Where it can escape at high rates through a short and permeable path, such as at Longstreet and Rogers Springs, it emerges at the surface essentially unchanged in temperature or chemistry. The larger discharge of Fairbanks Spring probably has a much longer path through Cenozoic deposits, for it cools slightly and adds a slight amount of boron not present in the other samples.

The largest group of water samples, taken from and near the Paleozoic rocks, display an equally stable composition, but their greater temperatures indicate approach to Ash Meadows through the deeper part of the regional flow system. Where it is discharged at high velocities through a path of even more than a mile (about 2 km) in length, such as at Crystal Pool and well 6, it changes little in character. If the discharge velocity is somewhat less or if the local aquifer is shallower, the water cools but still retains its basic chemical composition, as did the discharge of Jack Rabbit Spring before development of the well field.

Figure 20 also illustrates that the three samples (27, 39, and 63) taken from west of the spring line (fig. 17) are enriched in sodium, but not in sulfate, with respect to the composition of water in the carbonate rocks. This tends strongly to support the reliance placed by the authors on the function of this line in the earlier discussions of water salvage and pumping overdraft from Ash Meadows.

Sample 15 from Soda Spring, sample 18 from well 8, and sample 27 from the unused well 14 group closely with the samples from the Pahute Mesa ground-water system, although the latter are lower in total dissolved solids. The silica contents of Soda Spring, well 8, and well 10 (sample 39) further indicate that, west of the spring line and along the spring line in pumping unit E, water typical of the Pahute Mesa system may be mixed during discharge with that typical of the Ash Meadows system. Waters of the different compositions may in fact come from discrete aquifers at different depths. If this is the case, the subsurface flow paths may indeed resemble a multi-level freeway interchange.

There remain five samples that require discussion. With their temperatures these are:

Sample 51, well 17S/51-31dd, 25.5°C (78°F);

Sample 78, well 1, 28°C (82°F);

Sample 81, well 2, 26.5°C (80°F);

Sample 84, well 3, 29.5°C (85°F); and

Sample 96a, Jack Rabbit Spring (1970), 25.5°C (78°F).

Water from the low-yield well 17S/51-31dd is very similar in composition to the samples from the Pahute Mesa system (fig. 20). Its chemistry is apparently determined primarily by the silicate minerals in the lower clastic aquitard, which crops out in the unnamed range east of the well.

The close similarity between the samples from well 2 and Jack Rabbit Spring in recent years has been discussed earlier. Examining the nature of the change in Jack Rabbit Spring, however, may provide some insight into the reason for the change. Dividing the total ion concentration (in milliequivalents per litre) of the 1970 sample with that of the 1966 sample reveals that the total ion concentration increased by a factor of 4.8. The enrichment factor for individual ions can similarly be determined and then divided by 4.8 to give the relative enrichment factors following:

Ca	0.73	Na	1.3	HCO_3	0.21	F	0.24
Mg	.93	K	.56	SO_4	2.6	NO_3	60 ±
Sr	.94	Li	.48	Cl	3.2		

It is evident that among the cations sodium has been enriched by the greatest factor and that this has been essentially at the expense of calcium. The contents of potassium and lithium are too small to have contributed significantly. Among the anions, nitrate, chloride, and then sulfate have become relatively more abundant, with a large loss of bicarbonate.

The samples of typical water in Ash Meadows are nearly saturated with respect to the bicarbonate ion, as indicated in table 6 by the common loss of bicarbonate from unacidized anion samples. Analyses for calcium in these anion samples showed an attendant loss of calcium. Bicarbonate could not have been enriched as the character of Jack Rabbit Spring water changed, and the 1970 analysis shows that it is still saturated. There are at least two possible sources of this contamination that are consistent with the agricultural activities. The first is connection, by the drilling of well 2, of an aquifer containing brackish water with the aquifer connecting well 2 with Jack Rabbit Spring. The brackish-water aquifer would have to be of higher potentiometric head to cause flow up the well bore and displace the normal water in the Jack Rabbit aquifer. Secondly, the addition of gypsum and fertilizers by infiltrating irrigation water could explain the increase of sulfate and nitrate and the small decrease of calcium relative to that of bicarbonate. This would not, however, explain the enrichment of sodium and chloride. It is entirely possible that both mechanisms have acted simultaneously.

The compositions (fig. 20) and temperatures of water from wells 1 and 3 suggest mixing of normal carbonate waters with that from the now-contaminated Jack Rabbit aquifer.

EVIDENCE FROM HYDRAULIC TESTING

Although the transmissivities and storage coefficients determined from type-curve solutions of drawdown and recovery data were given in table 4, there was little discussion other than to caution against using them quantitatively. For evaluating the aquifers quantitatively, they appear to have little use in this area. Although the deeper aquifers in the local subsystem are artesian and probably well confined by thick, relatively impermeable lakebeds, the shallow zones were obviously being partly dewatered whenever cascading occurred in the wells.

For wells of these depths (300-800 ft, or 100-250 m) and lithology, storage coefficients greater than 10^{-4} would be uncommon if the aquifers were indeed confined and not dewatered. On the other hand, if 10 percent of the discharge came from unconfined or dewatered aquifers having a porosity of 20 percent, an effective storage coefficient, $S_{eff} = (0.9)(10^{-4}) + (0.1)(0.20 - S_r)$, might be determined, where S_r is the specific retention, or the porosity resisting gravity drainage within the period of observation. Because S_r rarely exceeds a few hundredths except in clays, it is evident that storage coefficients will generally be dominated by the unconfined portion.

An alternate explanation is required if we assume that the transmissivity is concentrated primarily in confined aquifers with intercalated clay and silt beds. The quality of the data matches with the delayed-yield type curves (or with those for partial penetration which give almost identical results) suggests that this assumption may be justified. Although well 1 drew down as much as 70 ft (21 m) during the March 1971 tests, the casing is not perforated above a depth of 155 ft (47 m). It is highly unlikely, therefore, that dewatering occurred except in the immediate vicinity of well 3, which had minor cascading from a zone 12 ft (3.7 m) beneath the surface during testing of well 1. The large storage coefficient of 4×10^{-2} determined from observations in well 2 apparently reflects a lack of good hydraulic connection between the two wells. The effect of pumping arrived later than it would have in a homogeneous, extensive aquifer. Because the cone of depression grows preferentially along paths of the greatest hydraulic conductivity, the drawdown at poorly connected observation wells is correspondingly low, resulting in transmissivities that are too high. This, in turn, adds to the error in the storage coefficient.

Transmissivities calculated from pumping-well data, or estimated from specific capacities, do not exceed 8,800 ft^2/d (820 m^2/d). This suggests that falsely high transmissivity values, resulting from the lack of hydraulic isotropy, were calculated from observation-well data. Transmissivities determined from measurements in pumped wells are affected by well losses and are usually considered inferior to those calculated from measurements in observation wells. However, this generalization is true only where aquifers are continuous and uniform between the pumped well and observation wells. Because of the complexity of the local aquifer system in Ash Meadows, pumped-well data probably provide the more realistic estimates of transmissivity.

Because of the varied pumping histories of wells in southern Ash Meadows in 1971, it was possible at certain times to use nonpumping production wells as observation wells during pumping tests of other production wells. Also, observation well 17S/50-7db2 (fig. 7) provided data during tests of production wells 1, 2, 3, and 4. Figure 21 presents a graphical method for testing the consistency of the aquifer-test data in table 4 and for recognizing degrees of hydraulic connection or isolation. Transmissivities determined from pumped wells are plotted on the right side of the graph; no estimates of storage coefficients were made from pumped-well data. The remaining data points represent transmissivities and storage coefficients resulting from observations in nonpumping wells (lower numbers) during pumping of wells 1 through 5 (upper numbers). Where pairs of wells were observed, first with one pumping and then with the other pumping, the data points are connected. No implication of a relationship between transmissivity and storage coefficient is intended in this illustration.

As an example of the use of figure 21, consider the data gained from wells 1, 2, and 3. The transmissivity calculated from well 3 data during pumping of well 1 was about the same as that determined from measurements in the pumped well. Apparently this means that the major transmissivity in well 1 is in the same aquifer as that in well 3. When well 3 was pumped, however, a significant part of discharge came

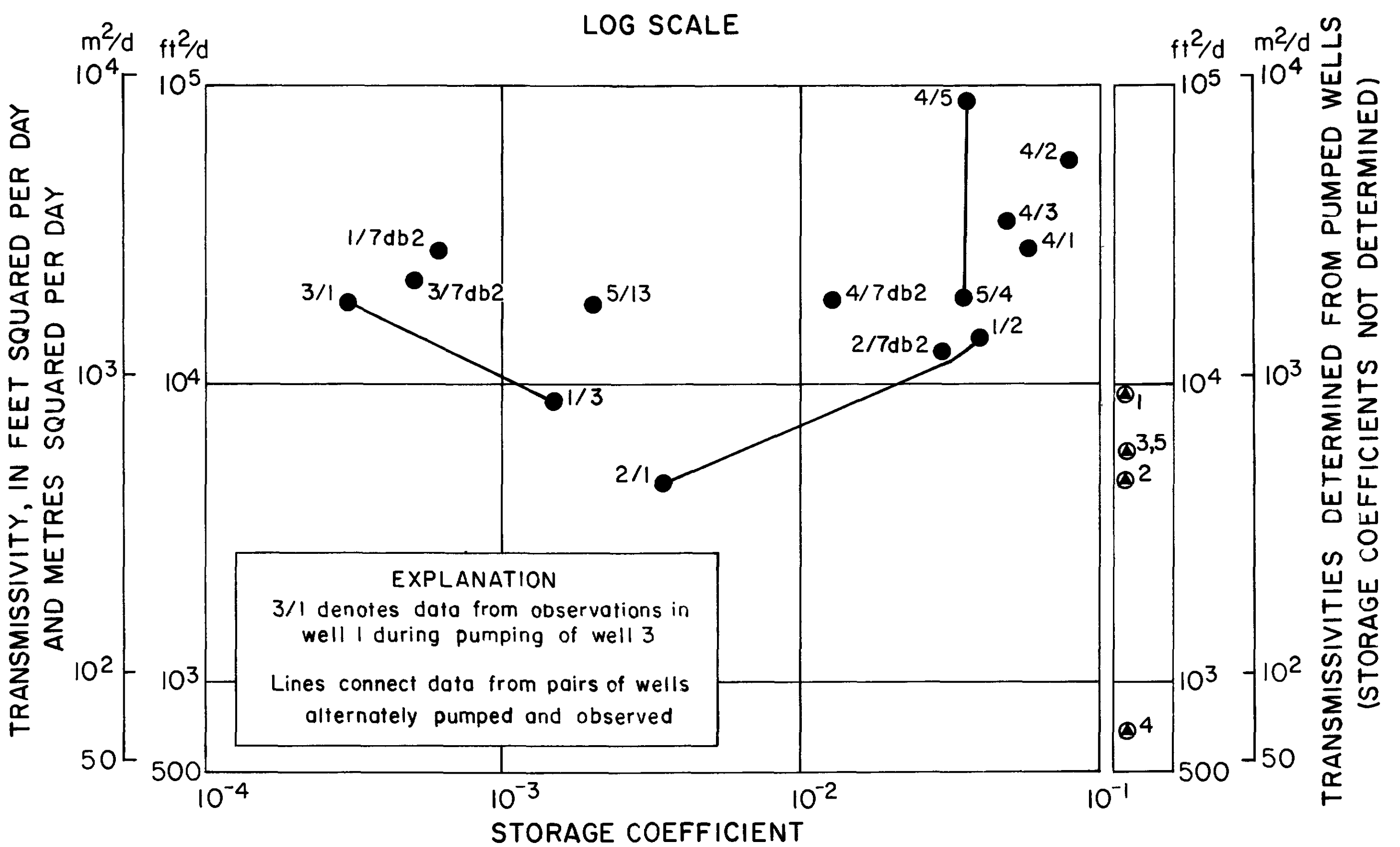


FIGURE 21.—Transmissivities plotted against storage coefficients calculated from aquifer tests in southern Ash Meadows.

from a zone not penetrated by well 1, and the drawdown in well 1 was less than it would have been if the entire discharge came from the aquifer that wells 1 and 3 mutually draw upon. This resulted in a falsely high calculated transmissivity. The value determined from well 3 alone when it was pumped may be closer to the true value. The range of transmissivities in this interplay is from 5,900 ft^2/d (550 m^2/d) to 18,000 ft^2/d (1,700 m^2/d), or within a factor of about 3. The storage coefficients are reasonable if some dewatering is considered. Consequently, the degree of hydraulic connection, considered in the context of this complex aquifer system, is classed "good."

Similar analyses of other data in figure 21, combined with the observed long-term effects of pumping in 1971 and 1972 as described earlier in this paper, lead to a general and largely intuitive classification of the degree of hydraulic communication among various wells and Devils Hole (fig. 22). The degree of isolation of well 2 within a triangular array of wells having good connections is consistent with its unique tie to Jack Rabbit Spring.

The implications as to the usefulness of mathematical models of this complex system are obvious. Through a long process of trail and error and the introduction of many poorly justified assumptions, it would be possible to reproduce effects that have been observed. Predicting the effects of changing the magnitude or, more importantly, the points of applications of pumping stresses must usually meet with failure.

GEOLOGICAL EVIDENCE

ROLE OF TRAVERTINE BEDS

It has been stated or implied at several places earlier in this report that travertine beds, and some of the more massive continental limestones for the purposes of this discussion, are the dominant local aquifers. There are three lines of evidence supporting this belief.

First, among the productive wells and test holes, only three (well 5, well 10, and observation well 17S/50-36dd) have production from gravel, according to the drillers' logs (table 3). The aquifers in well 5 were not identified, but the log shows more "limestone" than gravel. Moreover, frequent dismantling of the discharge meter on well 5 during 1971 showed the mechanism to be immobilized by flakes of a calcareous, light brown, crystalline mineral about the size of coarse sand and believed to be travertine. All other productive wells and test holes in Ash Meadows have a dominant lithology variously described as "limestone," "lime," "caliche," and "travertine."

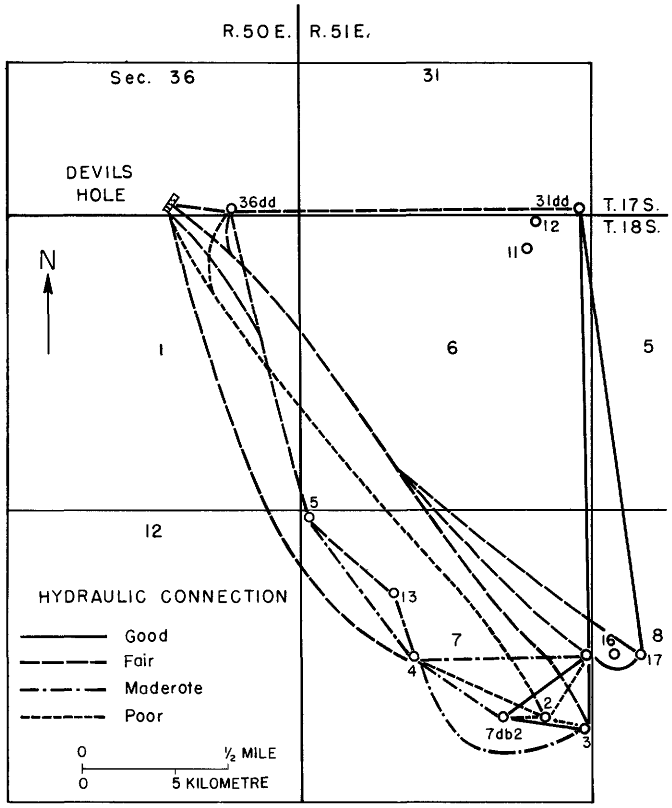


FIGURE 22.—Generalized degrees of hydraulic connection among Devils Hole, production wells, and observation wells in southern Ash Meadows.

Secondly, drilling records show that dropping of the drilling tools in these beds is not uncommon, attesting to the conduit permeability of the travertines. Among the wells in which the tools dropped were well 2 and well 6, both of which when pumped produce immediate effects on springs.

Most convincing, however, is examination of the lithology occurring at the major springs, loci of almost all of the natural discharge. Without exception among the springs discharging 400 gal/min (2,200m^3/d) or greater, these carbonate beds crop out in or on the sides of the spring pools. At many of the springs (King Pool, Crystal Pool, and Fairbanks Spring are the clearest examples) the water can be seen to issue from the travertine.

STRUCTURAL CONTROL

An additional feature of the travertine beds is that they rarely occur west of the springs except in southernmost Ash Meadows. At several of the major springs they are terminated abruptly at the eastern walls of the conical spring pools. Big Spring, Crystal Pool, and Rogers Spring demonstrate this particularly well. Fairbanks Spring is an exception in that the travertine is terminated at the north side of the spring pool. These observations leave little room for doubt that the springs are fault controlled.

Gravity data presented by Healey and Miller (1971) show that the valley-fill deposits are thickest in two localities. The first is centered about 1 mi (1.6 km) southeast of Big Spring. Big Spring lies within the gravity low, while the northern limit is approximately at Jack Rabbit Spring. Crystal Pool is at the southeastern limit of the second gravity low, which extends in an elliptical pattern to the northwest, its northeastern side corresponding with the spring line. With the observed truncation of the travertine at Crystal Pool and the linearity of the 2,200-ft (670-m) contour to the northwest, the gravity data indicate that a persistent, high-angle fault controls the spring line. It may be tectonic, bounding down-faulted blocks beneath Ash Meadows. Greater compaction of the thick lake beds in the gravity lows could also provide the strain necessary for non-tectonic compaction faults.

The topography of Ash Meadows and the hills to the east display numerous lineations that suggest an extensive network of faults, some of them displacing the youngest deposits. Figure 23 shows this pattern, perhaps carried to the extreme but useful in explaining certain peculiarities of the hydrologic system.

The fault defining the Devils Hole cavern, which strikes N. 40° E., can be extended with little stretch of the imagination to explain the offset of the segmented hills east of Devils Hole. The southwestward extension is less certain, for the offset of the 2,200-ft (670-m) contour between Davis Springs and Crystal Pool is of the opposite sense of movement (right-lateral rather than left-lateral). A fault that is subparallel to this might explain the southward twist of the topography on the east side of Point of Rocks and the apparent isolation of King Pool from the wells in unit A. A fault having the same general orientation southeast of Longstreet Spring provides explanation for the apparent (on the basis of temperature) hydraulic isolation of pumping unit E from areas to the south. The sharp contrast between water in the "Five Springs" area, including well 7, and water from Longstreet Spring supports the hypothesis of a major fault.

The gravity data presented by Healey and Miller (1971) show that the topographic high represented by the hills extends northwestward in the shallow subsurface.

The northwest-trending fault shown west of Cold Spring, in the northwest corner of the map, is inferred on the basis of a narrow, linear dune that is held by phreatophytes (largely salt cedar), presumably watered by the greater permeability of the fault.

PATHS OF SPRING DISCHARGE

Two widely separated points along the discharge path of Jack Rabbit Spring are known. These are the spring itself and travertine beds penetrated by well 2, probably those at a depth of about 60 ft (18 m). Jack Rabbit Spring, then, discharges through a shallow, linear conduit system in travertine that is terminated at the spring by a fault.

The setting of Crystal Pool is almost as clear, although well 6 is much closer to the spring. It is possible that the travertine beds at Crystal Pool were draped over the land surface by an ancestral spring issuing from Devils Hole, thus providing a permeable path for discharge when the water level declined.

On the basis of their temperatures and chemistry, Big Spring, Bole Spring, and Fairbanks Spring are thought to discharge through long paths in local aquifers, probably at relatively shallow depth.

Rogers and Longstreet Springs, because of their proximity to the gravity high, may discharge along faults vertically from the carbonate rocks, as proposed most recently by Winograd (1971). The chemical and temperature data neither confirm nor dispute this interpretation.

SYNTHESIS OF FLOW NEAR DEVILS HOLE

The water-table map (fig. 10) presented earlier implies that the deep southwestward flow in the lower carbonate aquifer is forced upward along faults that segment the hills east of Ash Meadows. This produces a mound of unconfined water which discharges laterally into the shallower local aquifers. Water confined in the deep local aquifers is given a high potentiometric head by communication with the faults defining the southwestern boundary of the hills.

The most active flow paths of the local subsystem are those in the shallow aquifers feeding the springs of southern Ash Meadows. Figure 24*A* shows conceptually the horizontal component of this rising, confined flow in the regional aquifer and its subsequent discharge to warm springs close to the hills or alternate discharge to local aquifers supplying the outlying springs.

Under the stresses of pumping (fig. 24*B*) the system changes little in pattern. Pumping of wells 4 and 5 produces a significant change along the range front between Devils Hole and Point of Rocks. The reality of this flow path, which may in fact be along the boundary faults close to the hills, is borne out by the distinct response of observation well 17S/50-36dd (900 ft or 275 m east of Devils Hole) to pumping of wells 4

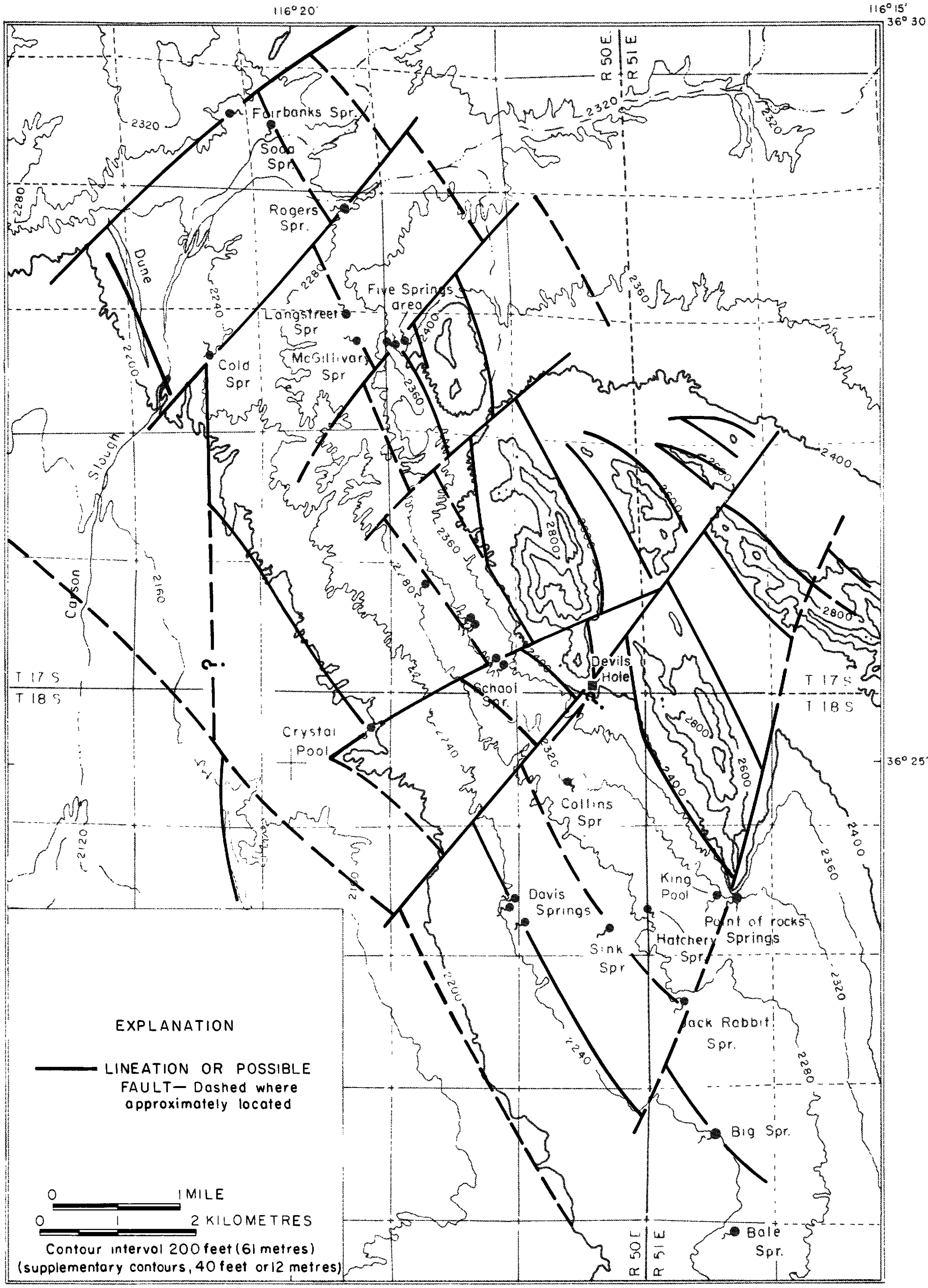


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FIGURE 23.—Lineations and possible faults in Ash Meadows and vicinity.

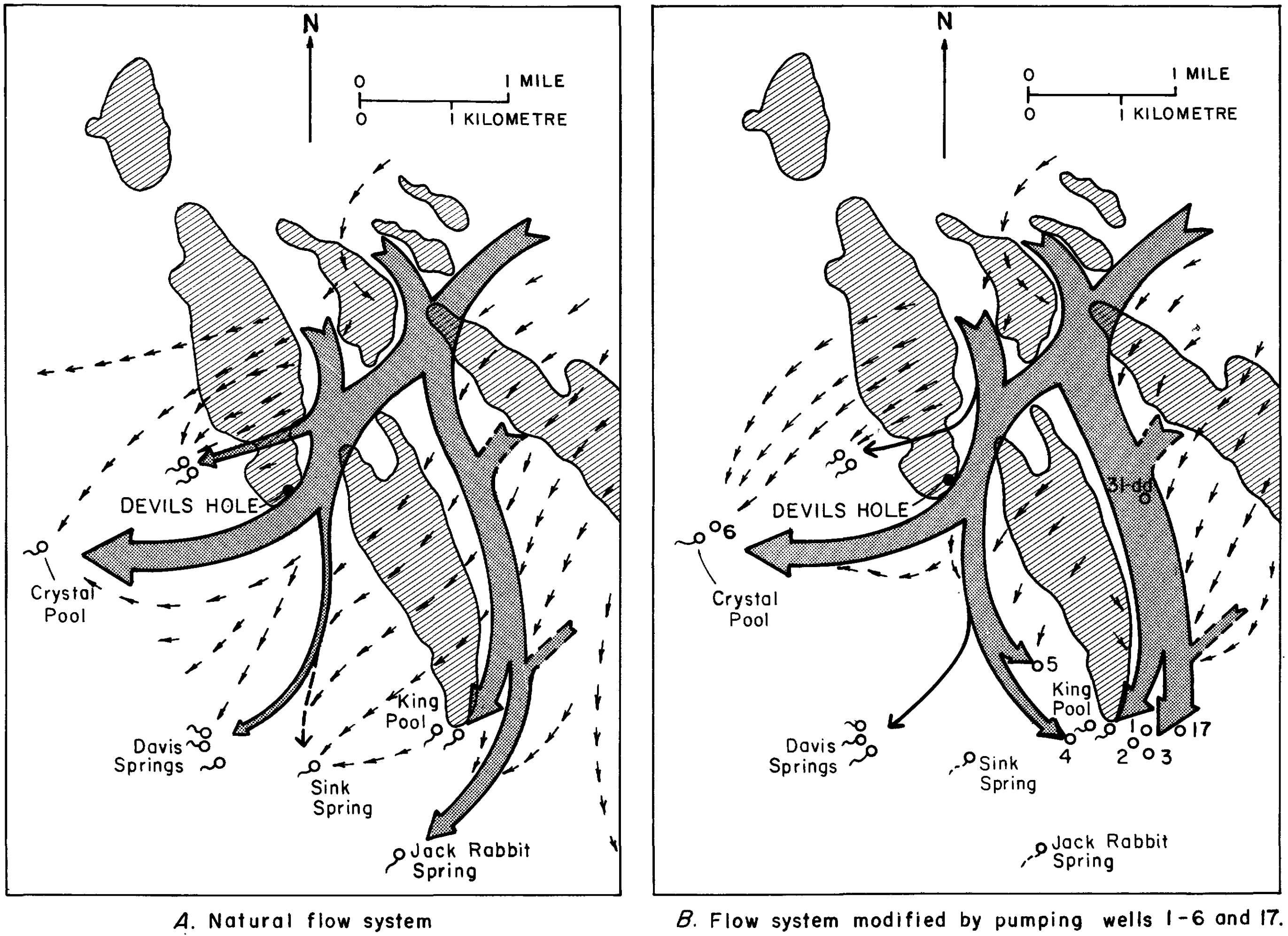

FIGURE 24.—Conceptual models of dominant and diffused flow in the vicinity of Devils Hole.

and 5. The small arrows on figure 24 represent diffused flow through fractures and joints that are not enlarged significantly by solution.

The greatly increased diversion to pumping unit A, however, captures water that otherwise would rise near Devils Hole and thus allows a relaxation or lowering of the pool in Devils Hole. Whether this flow path remains in the lower carbonate aquifer beneath the valley north of the well field, or rises in the northern part of the valley to flow south through local aquifers, is unimportant. The response of observation well 17S/51-31dd to pumping in unit A and the diffused but significant effect on Devils Hole adequately confirm this general flow path. Diffused flow through minor faults and joints supplies some of the smaller springs, but it is evident that two or three master conduits expel most of the water to discharge points in southern Ash Meadows.

DEVELOPMENT WITH MINIMUM IMPACT

The discussion above makes it clear that pumping from units A and B has a very high probability of affecting Devils Hole significantly. New wells in unit C, unless compensated by further reducing the flow of Crystal Pool, also carry a high risk. It is difficult to evaluate the impact on Devils Hole of developing additional supplies from unit D. Moreover, no productive aquifers other than the lower carbonate aquifer have been found in unit D, and the lack of major springs suggests that none occur at relatively shallow depth.

Development west of the spring line would have less effect on Devils Hole, but the low productivity of the sediments and poor quality of the water preclude western Ash Meadows as a significant and useable source of irrigation water.

This process of elimination leaves only pumping unit E, the northern part of the ranch property and of the Ash Meadows discharge area. The temperature of the significant discharge from Longstreet, Rogers, and Fairbanks Springs suggests a long and shallow approach path from the northeast and east. Whether one, two or three master conduits in the lower carbonate aquifer feed these springs is not important. There is no evidence presently (August 1974) available which would indicate that such conduits are in close communication with those in the deeper aquifer supplying areas to the south.

Exploratory drilling in unit E has been quite extensive and almost completely without success. Moreover, if the master conduit(s) is eventually discovered and found to be very shallow, sufficient drawdown may not be available to increase significantly the gradient toward the discharge area. Compensation of well discharge by decreased spring flow would be the result.

If a few tens of feet of drawdown could be induced without dewatering the conduit or conduits, the total discharge of unit E might be increased greatly. Because the better farmland is in the south, export of most of this water would be necessary.

Note, however, that overdraft pumping is inherent in this, and the ground-water basin, again thrown into nonequilibrium, would attempt to readjust. Whether the new balance would be achieved by northwestward growth of the Ash Meadows ground-water system to capture a part of the Pahute Mesa system, or whether it would be achieved by reducing flow to and water levels in the southern part of the Ash Meadows discharge area, cannot be predicted. If the former occurs, water rights within the Pahute Mesa system may be injured, thus initiating another water-rights dispute.

In a classic paper describing types of carbonate aquifers, the frustrations of investigating them were stated by W. B. White (1969, p 15): "Carbonate aquifers have long posed a headache for hydrologists because of the localized characters of the ground-water flow and the lack of response to standard techniques for aquifer evaluation." The evidence presented in this study indicates that the aquifers in the local subsystem at Ash Meadows are no less capricious than the paths of flow in the carbonate aquifer that supplies them.

CONCLUSIONS

The Ash Meadows discharge area is geologically and hydraulically very complex in detail. It can, however, be divided into two gross units by a line defining the western limit of significant spring discharge which, over much of its path, coincides with a persistent high-angle fault cutting the youngest strata beneath the valley floor.

There is no evidence at the present time that withdrawals of ground water to the west of the spring line would produce drawdown in the Paleozoic carbonate rocks nor diminish the flow of major springs. However, production from this area does not appear feasible because of the low productivity of the aquifers and poor quality of the water.

The quality and quantity of water produced east of the spring line are generally suitable for irrigation. Used together with pumping-test and temperature data within the framework of observed and inferred geologic features, chemical data confirm that the regional lower carbonate aquifer is the source of the discharge at Ash Meadows and allows delineation of flow paths in the local discharge area. Most if not all of the larger springs remote from outcrops of the regional aquifer are supplied by shallow and linear travertine aquifers.

Pumping from the shallow aquifers in eastern Ash Meadows south of Crystal Pool (units A and B on fig. 17) caused the 2.5-ft (0.75-m) decline observed between 1968 and 1972 in the pool level in Devils Hole. All wells in secs. 7 and 8, T. 18 S., R. 51 E., draw water from the lower carbonate aquifer by lowering the water table and potentiometric surface in the local aquifers, thus inducing more flow from the east. Of all the wells in units A and B, only well 2, which totally captured the flow of Jack Rabbit Spring, was significantly compensated by reduced spring flow.

Liberal estimates of additional salvage of water from springs, by infiltration of irrigation water, and by clearing of phreatophytes, still resulted in an estimated overdraft in 1971 from units A and B of more than 1,500 acre-ft (1.85 million m^3), or an increase of almost 10 percent in the total discharge from the Ash Meadows ground-water basin.

Well 6 in pumping unit C captured most of its discharge from nearby Crystal Pool and had little effect on water levels elsewhere. In unit D well 7, the only well producing directly from the lower carbonate aquifer, also was largely compensated by reduced spring flow. Additional wells in units C and D would have a greater probability of affecting Devils Hole.

Fairbanks, Rogers, and Longstreet Springs responded little or not at all to pumping of well 8 in unit E, although the well captured the total flow of Soda Spring. Spring discharge in unit E has declined on a sustained basis in comparison to pre-1963 records. Pumping from the Amargosa Farms area to the northwest may have been responsible for these declines.

The only area for developing additional water in Ash Meadows with possibly only a slight impact on Devils Hole is in pumping unit E. Adjustment of the regional flow system to new pumping stresses in this area may occur as expansion of the boundary of the Ash Meadows ground-water system into the adjacent Pahute Mesa system.

REFERENCES

Bateman, R. L., Mindling, A. L., Naff, R. L., and Joung, H. M., 1972, Development and management of ground water and related environmental factors in arid alluvial and carbonate basins in southern Nevada: Proj. Rept. No. 18, Univ. of Nevada, Desert Research Inst., Center for Water Resources Research, 43 p.

Boulton, N. S., 1963, Analysis of data from non-equilibrium pumping tests allowing for delayed yield from storage: Inst. Civil Engineers Proc. [London], v. 26, p. 469-482.

Carlson, J. E., and Willden, Ronald, 1968, Transcontinental geophysical survey (35°-39°N) geologic map from 112°W longitude to the coast of California: U.S. Geol. Survey Misc. Geol. Inv. Map I-532-C.

Claassen, H. C., 1973, Water quality and physical characteristics of Nevada Test Site water-supply wells: U.S. Geol. Survey rept. USGS-474-158, 145 p.; available *only* from U.S. Dept. Commerce, Natl. Tech. Inf. Service, Springfield, Va. 22151.

Cooper, H. H., Jr., Bredehoeft, J. D., Papadopulos, I. S., and Bennett, R. R., 1965, The response of well-aquifer systems to seismic waves: Jour. Geophys. Research, v. 70, no. 16, p. 3915-3926.

Denny, C. S., and Drewes, Harald, 1965, Geology of the Ash Meadows Quadrangle, Nevada-California: U.S. Geol. Survey Bull. 1181-L, p. L1-L56.

Healey, D. L., and Miller, C. H., 1971, Gravity survey of the Amargosa Desert area of Nevada and California: U.S. Geol. Survey rept. USGS-474-136, 29 p.; available *only* from U.S. Dept. Commerce, Natl. Tech. Inf. Service, Springfield, Va. 22151.

Hughes, J. L., 1966, Some aspects of the hydrogeology of the Spring Mountains and Pahrump Valley, Nevada, and environs, as determined by spring evaluation: Masters thesis, Univ. of Nevada, Reno.

Hunt, C. B., and Robinson, T. W., 1960, Possible interbasin circulation of ground water in the southern part of the Great Basin: U.S. Geol. Survey Prof. Paper 400-B, p. B273-B274.

Johnston, R. H., 1968, U.S. Geological Survey tracer study Amargosa Desert, Nye County, Nevada, Part I: Exploratory drilling, tracer well construction and testing, and preliminary findings: U.S. Geol. Survey open-file rept., 64 p.

Larson, J. D., 1973, Water-resources data collected in the Devils Hole area, Nevada, 1972 – 73: U.S. Geol. Survey Water-Resources Inv. 61 – 73, 30 p. [1974[.

______1974, Water-resources data collected in the Devils Hole area, Nevada, 1973 – 74: U.S. Geol. Survey Open-File Rept. 74 – 330, 19 p.

Loeltz, O. J., 1960, Source of water issuing from springs in Ash Meadows valley, Nye County, Nevada [abs.]: Geol. Soc. America Bull., v. 71, no. 12, Part 2, p. 1917-1918.

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

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

Maxey, G. B., 1968, Hydrogeology of desert basins: Ground Water, v. 6, no. 5, p. 10-22.

Meinzer, O. E., 1920, Quantitative methods of estimating groundwater supplies: Geol. Soc. America Bull., v. 31, p. 329-338.

Rush, F. E., 1970, Regional ground-water systems in the Nevada Test Site area, Nye, Lincoln, and Clark Counties, Nevada: Nevada Dept. Conserv. and Nat. Resources, Water Resources Reconn. Ser. Rept. 54, 25 p.

Scofield, C. S., 1936, The salinity of irrigation water: Smithsonian Inst. Ann. Rept., 1935, p. 275-287.

Theis, C. V., 1940, The source of water derived from wells: Civil Eng., v. 10, no. 5, p. 277-280.

Walker, G. E., and Eakin, T. E., 1963, Geology and ground water at Amargosa Desert, Nevada-California: Nevada Dept. Conserv. and Nat. Resources, Water Resources Reconn. Ser. Rept. 14, 45 p.

White, W. B., 1969, Conceptual models for carbonate aquifers: Ground Water, v. 7, no. 3, p. 15-21.

Winograd, I. J., 1962, Interbasin movement of ground water at the Nevada Test Site: U.S. Geol. Survey Prof. Paper 450-C, p. C108-C111.

______1963, A summary of the ground water hydrology of the area between the Las Vegas Valley and the Amargosa Desert, Nevada, with special reference to the effects of possible new withdrawals of ground water: U.S. Geol. Survey openfile rept. TEI-840, 79 p.

______1971, Origin of major springs in the Amargosa Desert of Nevada and Death Valley, California: Ph.D. dissertation, Univ. of Arizona, Tucson.

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

[U.S.] Public Health Service, 1962, Drinking water standards: U.S. Dept. Health, Education and Welfare, Public Health Service Pub. 956, 61 p.

[U.S.] Salinity Laboratory Staff, 1954, Diagnosis and improvement of saline and alkali soils: U.S. Dept. Agriculture handbook 60, 160 p.

Worts, G. F., 1963, Effect of ground-water development on the pool level in Devils Hole, Death Valley National Monument, Nye County, Nevada: U.S. Geol. Survey open-file rept., 27 p.

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