STATE OF NEVADA

DEPARTMENT OF CONSERVATION AND NATURAL RESOURCES

CARSON CITY, NEVADA

WATER RESOURCES BULLETIN NO. 29

GROUND WATER IN LAS VEGAS VALLEY

By

P. A. Domenico, D. A. Stephenson, and G. B. Maxey

Prepared by

Desert Research Institute, University of Nevada

(D.R.I. Technical Report No. 7)

in cooperation with

State of Nevada

Department of Conservation and Natural Resources

April 1964

ERRATA SHEET

Figure 2 West to East is left to right. Black denotes gravel

Heading - STRUCTURE Several faults occur within the valley fill (Fig 1 should read Fig 3)

Page 44 last para should read " pumpage will increase over the 1962 rate by 41,000 feet"

Page 44 Figure 34 Lower half of figure should read R62E not R60E

Figure 37 Water change level adjacent to pumping center 7 should read 25 feet not 15 feet

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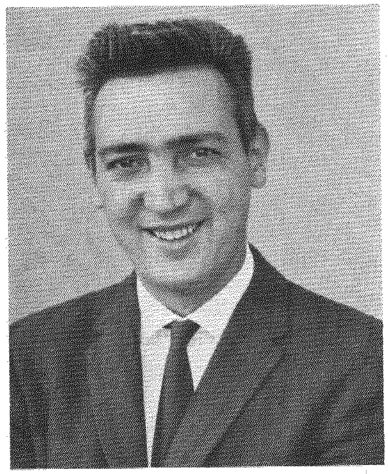
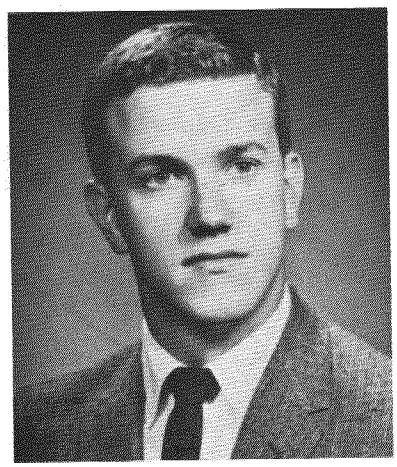


PATRICK A. DOMENICO is a native of Rome, New York. His undergraduate studies were completed at San Diego Junior College, South Dakota School of Mines, and Syracuse University, from which last institution he graduated cum laude in 1959 with a B.S. in geology. This was followed by graduate study at the University of Southern California and Syracuse University. He received an M.S. in engineering geology from Syracuse in 1963.

His experience includes geological and ground-water research in Alberta, Canada, engineering geology and foundation studies of proposed hydraulic structures underflow studies for the Water Resources Department of the State of California, and research work in his present post as Research Associate in Hydrology, Desert Research Institute, University of Nevada, to which he was appointed in 1962, and where he has worked on Project Shoal and Las Vegas Groundwater Studies.

On August 31, 1957, Pat married the former Dolores Ann Walker at Rome, New York. They now have three children, Daniel, born October 10, 1958; Phillip, born May 6, 1960; and Trina, born January 27, 1964. Pat's hobbies include fishing and hunting.



DAVID A. STEPHENSON was born in Moline, Illinois, on July 1, 1936. His undergraduate studies were completed at Colorado School of Mines, 1954 and 1955, and Augustana College, 1956 to 1958 where he received an A.B. in geology. This was followed by graduate work at Washington State University (Pullman) whence he achieved an M.S. in geology in 1961. He continued his studies in graduate work at University of Illinois and University of Nevada.

Since 1961 David Stephenson has specialized in the field of hydrology, and during the period of 1961 to 1963 was a Research Associate at the Desert Research Institute, University of Nevada, working in the field of ground-water geology and hydrology in the Sand Springs Range and in Las Vegas Valley, Nevada.

He was married on August 28, 1958, to the former Maryann Kay Olson, and they have one child, a daughter, Laura.

GEORGE BURKE MAXEY is a native of Bozeman, Montana, and received his elementary education in the Park County public schools. This was followed by 4 years at Montana School of Mines and Montana State University and a B.A. degree in 1939 in geology. He obtained his M.S. at Utah State Agricultural College in 1941 and an A.M. and Ph.D. from Princeton University in 1950 and 1951.

Dr. Maxey has spent a large part of his career in the field of hydrology especially in the Great Basin area and is at the moment particularly interested in the problems of the Las Vegas Valley. He also spent the period of September 1952 to June 1954 as Acting Chief, Natural Resources Division of Point 4 in Libya.

At the date of publication Dr. Maxey is Professor of Hydrology and Geology, Desert Research Institute, University of Nevada, Reno, Nevada, which appointment he accepted on July 1, 1964.

Dr. Maxey is a member of the following organizations:

Member of Geological Society of America (elected fellow, 1952); American Geophysical Union; American Association of Petroleum Geologists; American Association for the Advancement of Science (fellow); Society of Economic Geologists;

Illinois Geological Society; Illinois Academy of Science; Sigma Xi; International Association of Hydrologists; National Water Well Association (Technical Division).

He has also represented the United States in these international assemblies:

U.S. Delegate to:
International Congress of Quaternary Geologists, Rome and Pisa, September 1953.
International Congress on Drainage and Irrigation, Algiers, April 1954.
International Union of Geodesy and Geophysics, 11th General Assembly, Toronto, Canada, September 1957; 12th General Assembly, Helsinki, Finland, July-August 1960; 13th General Assembly, Berkeley, California, August 1963.
International Geologic Congress in Copenhagen, August 1960.
International Association of Scientific Hydrologists Symposium on Ground Water in Arid Zones, Athens, Greece, October 1961.
Chairman, Committee on Ground Water for the American Geophysical Union; May 1956 to September 1960.
Vice President of the Commission on Ground Water of the International Union of Geodesy and Geophysics (International Association of Hydrology), September 1957-August 1960; President, 1960-date.
Chairman, Group on Hydrology of Geological Society of America, September 1959-November 1961.
Member, Committee on Status and Needs in Hydrology, American Geophysical Union, 1963.
Consultant on ground-water problems to Atomic Energy Commission; March 1957-date.
Consultant to State of Nevada on geohydrological problems, 1951–61.
American Editor of the Journal of Hydrology 1962-date.
Appointed Distinguished Lecturer for the American Association of Petroleum Geologists, 1959–60; subject: "Geology of Water and Its Importance to Our Industrial Civilization."
Visiting Geoscientist for American Geological Institute, 1962, 1963.

Burke Maxey married in Butte, Montana on September 11, 1941, the former Jane J. Clow. Their family numbers five, Lee Burke, born March 3, 1943; Nelle Jane, born January 9, 1945; Dan Howell, born August 27, 1949; Ann Dee, born October 13, 1956, and Permilla Jean (commonly known as P. J.), born July 30, 1961.

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ABSTRACT

A rapidly increasing development of ground-water resources in Las Vegas Valley, Nevada, has resulted from the accelerated municipal growth in the Las Vegas metropolitan area. The ground-water reservoirs underlying the valley are currently undergoing depletion at a rate of about 30,000 acre-feet per year and perhaps in excess of 35,000 acre-feet per year. This depletion is reflected by large water level declines, shallow well failures, increased pumping costs, and subsidence of the land surface. Since the depth-to- and potential-of usable water is generally of primary concern to a prospective user, this report attempts to analyze the hydrologic system giving special consideration to the effect on water levels of predicted increases in water withdrawal. The chief hydrologic factors that required definition for this analysis include the external geometry of the aquifer systems and the internal distribution of their transmissive properties. The effect of increased withdrawals is ascertained with an electrical system (analog) embracing these factors and therefore similar in performance to the otherwise less predictable natural system. Several problems are analyzed and the effect of each is shown on a map of Las Vegas Valley.

FOREWORD

The hydrologic and hydrogeologic research program of the Desert Research Institute includes two broad areas:

1. Study of the dynamics of flow systems in arid and semiarid regions.
2. Study of applications of available scientific concepts, methods, and procedures in water resources management in arid and semiarid regions.

The State of Nevada has generously supported studies in both of these categories and previous reports published by the institute give the results of those studies. This report makes public the findings of a detailed investigation of the ground-water conditions in Las Vegas Valley and falls primarily in the second category.

In addition to development of information by conventional methods the work group built an electrical analog which simulates natural conditions in the valley and utilized this unique tool to develop knowledge and understanding of the natural system and to predict the effects of withdrawal of ground water from the system. The predicted data can be and has been used by the State Engineer in the administration and regulation of the water resources in the valley. Since many electrical analogs of ground-water systems have been built in the last decade or so, having built this one is not particularly noteworthy. However, the particular use to which the Las Vegas analog is being put is unique in that it is the only one we know of that is being used on a day-to-day basis in water management. We also call to your attention the exacting methods by which the geological data were analyzed and fed into the analog system. This procedure, while far from perfect, resulted in highly satisfactory recapitulation of the ground-water withdrawals and water-level effects with a minimum of artificial adjustment of the resistance and capacitor networks.

Funds to support this study were furnished by an emergency appropriation of the Legislature of the State of Nevada (Chap. 46, Stats. 1963) and by the Las Vegas Artesian Basin Fund. Also, a part of the cost of development of the analog was supported by funds appropriated by the Nevada State Legislature (Chap. 166, Stats. 1961) for research on ground-water problems. It is our hope that the confidence in the institute as shown by these generous appropriations has been justified and that this work proves useful to the many citizens and organizations in the state who depend upon the water resource for their overall well-being.

Many persons contributed to the success of this report. In the state government we gratefully acknowledge the continued support, assistance, and advice of Mr. Hugh A. Shamberger, Director of the Department of Conservation and Natural Resources, and Mr. Elmo DeRicco, State Engineer. Messrs. George Hardman, George Hennan, Francis Thorne, and Thomas Humphrey also assisted the authors in many ways to increase the effectiveness of the work. The well contractors in Las Vegas Valley and city, county, and federal officials also cooperated wholeheartedly by furnishing information and advice. Field assistants who contributed materially to the study include Lowell A. Reed, Allen E. Eldridge, and Steven D. Shattuck. John Hardaway provided valuable laboratory assistance and helped to build and test the electrical analog.

July 1, 1964

GEORGE B. MAXEY
Research Professor of
Hydrology and Geology
Desert Research Institute
University of Nevada

INTRODUCTION

Scope and Purpose

This report, resulting from the third major investigation of Las Vegas Valley in the last 20 years, describes a study aimed specifically at prediction of regional and local effects of increased ground-water withdrawals upon the ground-water reservoir. The chief determinable factors requiring definition in such an analysis are the physical nature and geometry of the aquifers and the degree to which they influence cause, the withdrawal of water, and effect, the water-level decline. Indeterminate factors include items of information and activity primarily controlled by man, such as amount and time of future withdrawals and location of points of diversion. In general, these factors can only be assumed for any given prediction problem.

Consideration of methods to analyze cause-and-effect problems embracing the above-mentioned factors resulted in selection of an electrical analog model as the most comprehensive and efficient. This report describes the results of the application of the analog to specific problems of ground-water development in Las Vegas Valley.

To analyze quantitatively a hydrologic system in the manner proposed, the physical system, or prototype, is replaced by a model, either mathematical, electrical, or digital. In the electrical model used in this report, an array of resistors and capacitors mounted on a masonite board are analogous to prototype transmissivity (the capacity of the reservoir rocks to transmit water) and storativity (the capacity of the reservoir rocks to release water). The model is a scaled-down version of the prototype. Past pumpage stresses, or causes, in the form of electrical pulses are imposed on the model in a proper time-space sequence. The effect observed on a sensing device, such as an oscillograph, measures the response of the model to these pulses, which are analogous to former changes in water levels in the prototype. If the model faithfully recapitulates the past performance of the prototype, it can then be used to predict future performance with the same degree of accuracy.

The chapters entitled Hydrogeology and Hydrology describe the general geology and hydrology of the aquifers; the physical input data, that is the nature of the rocks and the ground-water system; and the past and present pumpage stresses and their effects. The last chapter attempts to estimate the magnitude of stresses to be imposed on the ground-water system in the future and describes its effect. Thus, this report deals with the system and its response to past, present, and future withdrawals.

In basin and range topography, external boundaries of the flow system undergoing disturbance by man are readily discernible. In Las Vegas Valley, consideration of the geometry of the aquifer boundaries is aided by the presence of mountain ranges underlain by rocks of presumably low permeability. Internal boundaries such as alluvial faults or surface-water bodies in contact with ground-water flow also have definite influence on the response of the system to pumping. Less direct methods are useful in analysis of such phenomena. All of these factors were considered in the input of data to the analog.

In addition to data collected during this study, the results of at least two major ground-water studies in Las Vegas Valley in the past 20 years and several local and reconnaissance studies utilized in developing this report. Both of the major studies were conducted by the U.S. Geological Survey, one in 1944 to 1947 by Maxey and Jameson (1948) and the second in the middle fifties (Malmberg, 1960; 1961). The first report described the geologic environment of the Las Vegas ground-water basin and included a qualitative description of the important aquifer systems, the quality of the water, and reservoir operation (recharge, storage, and discharge). Malmberg contributed further refinement of data on reservoir operation, especially ground-water storage and determination of local transmissivity of the aquifers by pumping tests.

General Geography

Las Vegas Valley, the most populated area in Nevada, is in the arid country of the southwestern part of the State. The cities of Las Vegas, North Las Vegas, Whitney, and Henderson are the chief population centers. The area of intensive study described in this report (Fig. 1) includes about 350 square miles within Las Vegas Valley, the watershed of which involves an area of about 3,000 square miles.

Las Vegas is the county seat of Clark County. Together with a neighboring city, North Las Vegas, it occupies the central part of the valley,

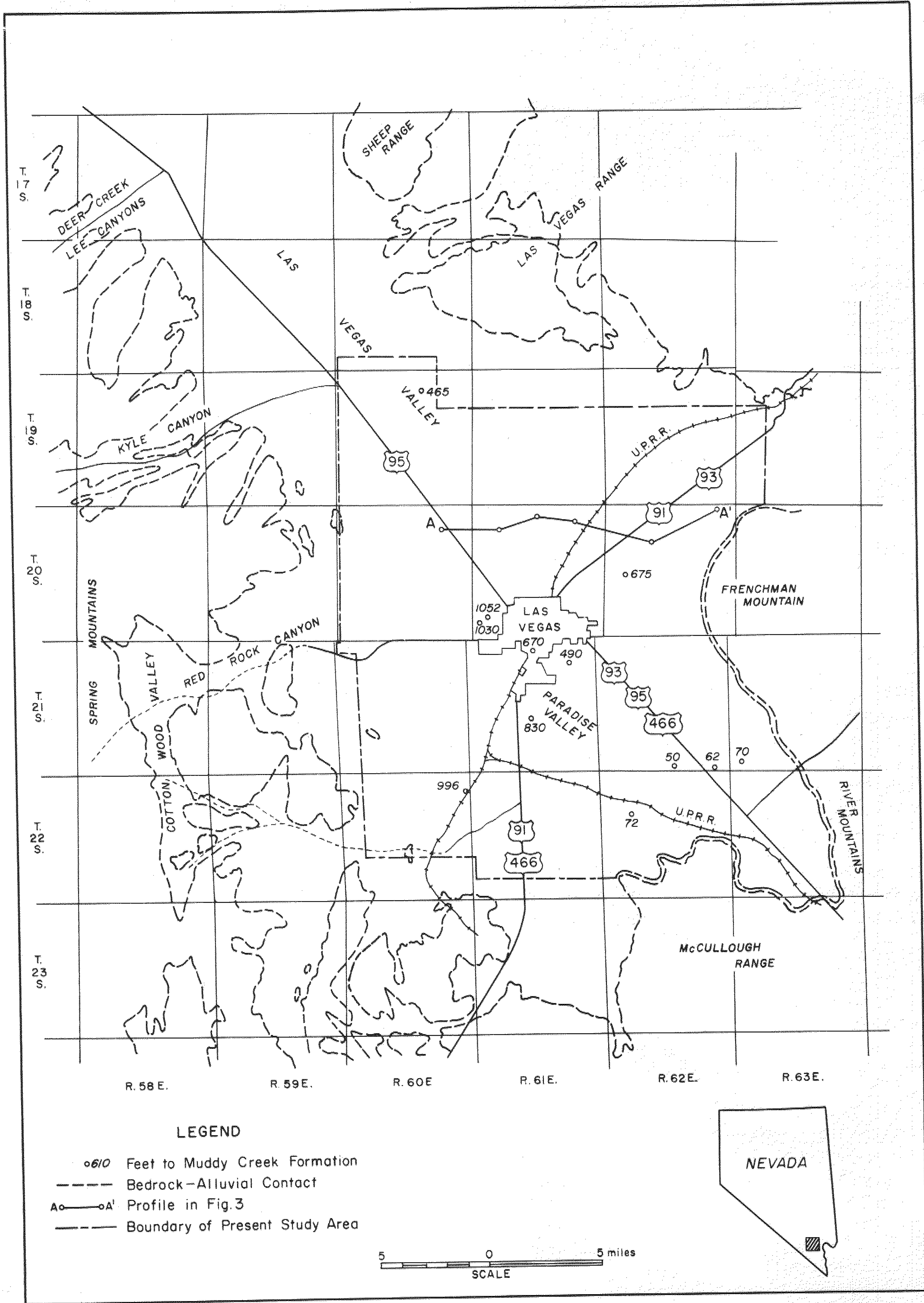

Figure 1. Index Map.

and is the principal center of recreational and industrial activities for Southern Nevada. The relatively smaller community of Whitney (East Las Vegas), and the industrial town of Henderson are southeast of Las Vegas. Two governmental establishments, Nellis Air Force Base and Lake Mead Base, are to the northeast. The southern part of Las Vegas Valley is referred to as Paradise Valley. Tule Springs is northwest, about 9 miles from the City of Las Vegas.

Las Vegas Valley may be classified in three physiographic units: the mountains, the alluvial aprons, and the basin lowlands. The valley is bounded on the west by the Spring Mountains; on the northeast by the south parts of the Sheep and Las Vegas Ranges; on the east by Frenchman Mountain and other low lying ranges; and on the south by the River Mountains and McCullough Range. The Spring Mountains are composed of Paleozoic and Mesozoic sedimentary rocks of complex structure (Maxey and Jameson, 1948). The mountains to the north and east are also underlain by sedimentary rocks of Paleozoic and Mesozoic age. An abundance of gypsum occurs in the eastern and southwestern ranges. The southern ranges are of Tertiary volcanics. The valley is topographically closed except for Las Vegas Wash to the southeast which drains into Lake Mead.

The climate is similar to many other areas in the basin and range province ranging from arid in the basin lowlands to semiarid or subhumid in the mountains. The humidity is low, and wide variations in diurnal temperature prevail. Precipitation occurs as snowfall and rainfall in the ranges, and mainly as rainfall in the valley.

The economy of the area is based on recreation, U.S. government defense activities, limited industry, and construction.

Brief History of Ground-water Development

An historical sketch of ground-water development to 1946 was presented by Maxey and Jameson (1948). Significant stages of early development include the first white settlement of Mormons near the large springs in Las Vegas during the period of 1855 to 1865 and the use of spring water for irrigation, and the purchase of the old Stewart Ranch for a townsite in 1903.

The first flowing well of record in the valley was completed in 1907. By 1911 there were 100 deep wells, 75 of which flowed, and 25 shallow wells. During the period of 1910 to 1941, about 22,400 acre-feet of water annually flowed from wells and springs. Flow from individual wells and springs diminished markedly during this period.

By 1930, population in the valley increased as a result of employment for the construction of Hoover Dam. Construction of army camps and training centers supported population growth until World War II, when the industrial complexes at Henderson and Nellis Air Force Base were built. From 1941 until the present, ground-water withdrawals increased by considerable annual increments. Many wells and springs stopped flowing and water levels declined at an accelerating rate.

The early postwar years brought Clark County its first major tourism trade. The construction accompanying resultant population growth coupled with increased governmental activities in conventional and defense operations resulted in a population increase of greater than 250 percent in the 1950 decade. By 1962 the population had increased by over 20 percent of the 1960 census. Ground-water withdrawals in 1963 were at an unprecedented high of 59,436 acre-feet.

HYDROGEOLOGY

Geology and Water-bearing Characteristics of the Rocks

The chief water-yielding rocks in Las Vegas Valley are the alluvial sands and gravels of the upper few hundred feet of valley fill. Minor aquifers occur in the Muddy Creek Formation, a Tertiary valley-fill deposit. The following paragraphs describe the nature, distribution and water-yielding characteristics of these formations and their relationship to other formations in and adjacent to the area described in this report.

A general but essentially adequate description of the geology of Las Vegas Valley and the surrounding bedrock mountains is given in Maxey and Jameson (1948, pp. 34 to 71) and included references. On the basis of these studies, the study area (Fig. 1) is underlain by late Pleistocene (Wisconsinan) lake beds and alluvial sediments at land surface which overlie an unknown thickness of chiefly Pleistocene alluvial fan and playa materials. These valley-fill materials are deposited within a valley eroded into the Muddy Creek Formation, composed of chiefly fine-grained lake and alluvial sediments, which, in turn, partly fills a broader, more extensive basin bounded by the bedrock mountains. The depth of this bedrock basin is not well-known. One well, drilled about one mile east of Whitney is reported to have encountered bedrock after penetrating about 3,000 feet of sediments similar to the Muddy Creek Formation. Another well, about four miles south of the City of Las Vegas, encountered Paleozoic limestone at about 1,200 feet. On the other hand, a well drilled in western Las Vegas Valley penetrated 1,200 feet of alluvial material without encountering sediments characteristic of the Muddy Creek Formation. Thus, little is known or can be inferred as to the type, nature, and distribution of the bedrock beneath the valley fill.

The mountain ranges bounding Las Vegas Valley, especially those to the west and north, are important hydrologically in that they serve as catchment areas for precipitation that ultimately recharges the alluvial aquifers in the basin lowlands. Although ground-water is stored in the bedrock of the mountain ranges, the regionally low transmissivity precludes common use of the indurated rocks as aquifers and these rocks are generally considered to be barriers to the growth of cones of depression that effectively reach them.

Several main canyons in the Spring Mountain Range drain into Las Vegas Valley, including Lee, Deer Creek, Kyle, and Red Rock Canyons, and Cottonwood Valley. Alluvial aprons flank the mountains on all sides and those in the northwestern part of the valley head high up in these canyons. The alluvial fans which form the apron have merged or coalesced at the toes of the ridges between canyons and in the open valley. Most ground-water recharge probably occurs through the alluvial aprons on the west in large part by underflow through the northwest "neck" of the valley in the vicinity of Tule Springs.

The boundaries between the alluvial apron and the basin lowlands are poorly defined. As in most areas in Nevada and elsewhere in the Great Basin, the lowlands are areas of human inhabitance, and the underlying aquifers have been extensively developed. From a practical point of view, the lower part of the basin is the logical location for the development of ground water by wells in that it functions hydrologically as the natural discharge area for ground-water flow.

THE MUDDY CREEK FORMATION

The Muddy Creek Formation is known to underlie the eastern and southern parts of the study area at shallow depths. It has been recognized in drilling samples as far west as the western part of the City of Las Vegas and as far north as Tule Springs. As shown on Figure 1 the top of the formation lies at greater depths to the west and is very shallow to the south. The formation crops out over an area of a square mile or so in Whitney Mesa northwest of Henderson and one to two miles west of Whitney.

In outcrop and in well samples the sediments consist of medium-to-thick bedded siltstones interbedded with thin, sandy, and pebbly strata of fine sand and silt. The beds are fairly well consolidated and some are cemented with caliche. This characteristic lithology seems to be continuous over broad areas both in Las Vegas Valley and in adjacent regions to the east. At no place in Las Vegas Valley are these sediments known to change laterally to coarser grain-size nor to interfinger with strata of coarser clastics. However, west of Las Vegas disappearance of typical Muddy Creek lithology in the known section may indicate that either of these alternatives has occurred. On the other hand adequate properly-collected samples may not be available for accurate identification, or the Muddy Creek Formation is down-faulted below levels that have been sampled, or the formation has been removed by erosion, or it was not deposited west of the presently recognized western limit.

Characteristically, the transmissivity of the Muddy Creek sediments is low and they are not recognized as containing highly productive aquifers satisfactory for municipal or irrigation water supply. The several wells in the valley penetrating Muddy Creek beds are or have been primarily pumped for domestic and stock use except where the water is unsatisfactory because of poor quality. The storage capacity of these sediments may be considerable and the hydraulic gradient is from them into overlying beds. Thus, water moving upward from them may constitute an appreciable source of supply for the overlying aquifers. All or most of the "Deep Zone of Aquifers" (Maxey and Jameson, 1948, p. 82) occur in the Muddy Creek Formation.

PLEISTOCENE AND RECENT VALLEY FILL

The valley fill overlying the Muddy Creek Formation contains aquifers of high transmissivity which are the chief source of water supply for Las Vegas Valley. The fill consists of many sand and gravel layers, lenses, and tongues which are interbedded with strata of finer-grained clastics. Conspicuous among the subsurface materials are

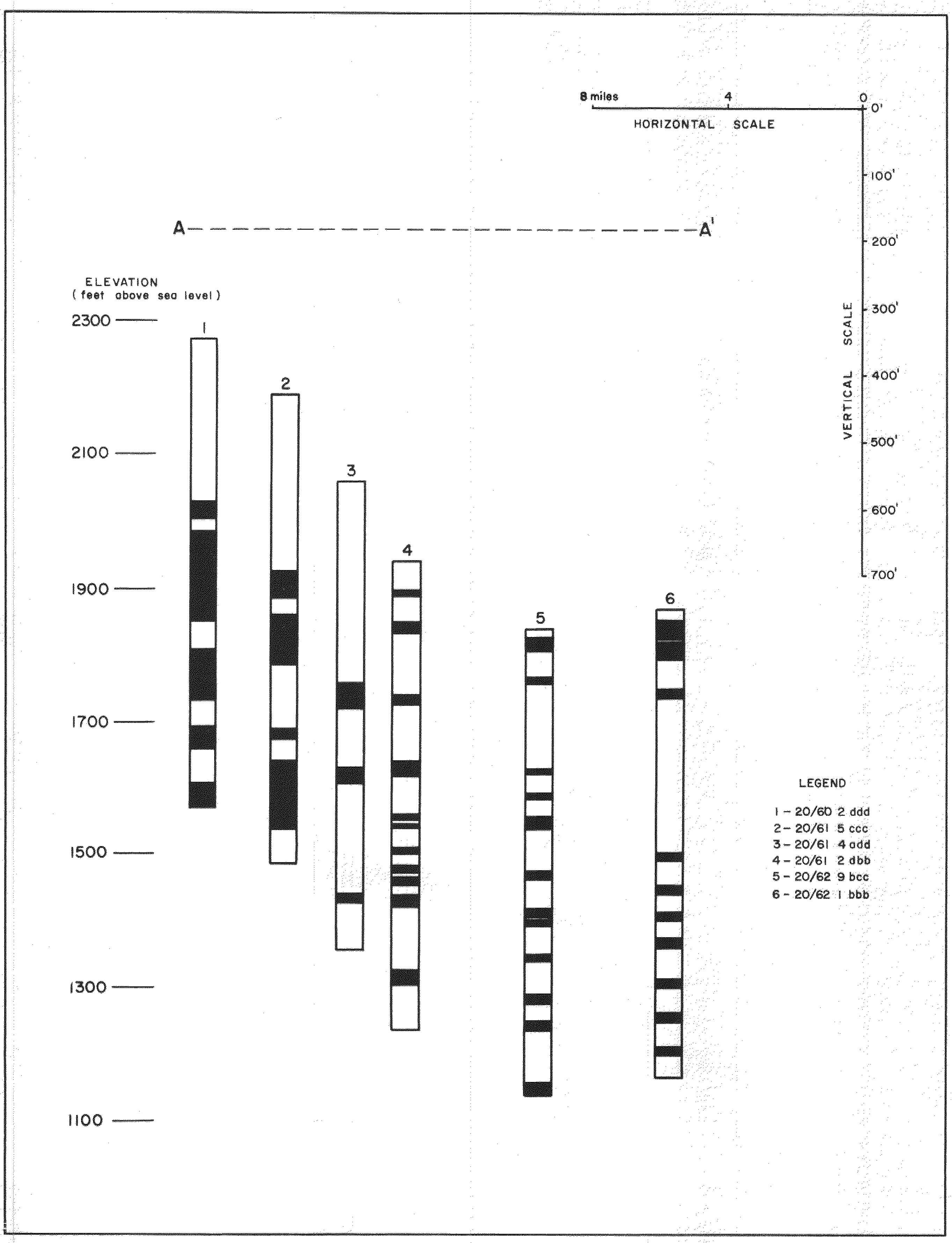

Figure 2. East-West cross-section illustrating typical gravel distribution.

caliche and lime-cemented gravels, products of soil-formation and ground-water action. Figure 2 diagrammatically shows this interbedding and illustrates the distribution of these sediments. Throughout the study area the greatest thickness of coarse clastics is on the west and extends eastward roughly to the latitude of the City of Las Vegas. Farther east to beyond the bottom of the valley coarse clastics are replaced by and interfinger into the finer silts and clays that make up the major part of the valley fill east of Las Vegas.

Interbedded with both the coarse clastics and the silts and clays are several lenses or layers of gray to grayish-blue plastic lacustrine clay. The most persistent of these "blue-clay" layers averages about 1,550 feet in elevation, between 400 and 450 feet below land surface west of Las Vegas and some 150 feet deeper east of the city. The clay thickens from west to east and from south to north and the center of deposition probably was somewhat west of Nellis Air Force Base. The other "blue-clay" lenses which have been recognized seem to be much smaller in extent and probably are the record of deposition in more or less temporary lakes that shifted position with time. The "blue-clay" is the only recognized widespread marker bed in the alluvial-fill sediments.

The origin and conditions of deposition of the valley-fill materials is well understood. In the course of post-Tertiary history, as periods of heavy precipitation alternated with periods of arid climate, the coarser materials were carried farther out into the valleys or were deposited closer to the source areas. Occasionally conditions were such that gravels and coarse-grained sand were transported to the central portion of the valley from the Spring Mountains and other adjacent ranges. As the Spring Mountains received relatively more precipitation than other ranges nearby most of the coarse materials were derived from them.

Contemporaneous with and subsequent to deposition, ground-water action dissolved certain materials and deposited others, thereby helping to make some horizons more water-yielding than others. Soil formation also played a role in development of the present alluvial stratigraphy by formation of caliche horizons.

The end result of deposition of sediments transported from the upland areas, of ground-water action, and of soil formation is the present geologic condition of the subsurface.

A more detailed treatment of the valley-fill deposits is given in the section entitled "Description of the Lithology for Analog Interpretation."

The gravel and sand beds above the persistent "blue-clay" layer constitute the "Shallow Zone of Aquifers" and the interval between the "blue-clay" and about 700 feet is the "Middle Zone of Aquifers" (Maxey and Jameson, 1948, p. 82). The "blue-clay" is an important confining bed or aquitard, probably much more effective in retarding water flow than the usual silt and clay aquitards in the valley fill.

Other aquitards include caliche and lime-cemented gravel beds. Some of these beds are highly fractured and are permeable enough to be used as low-yield aquifers.

Nearly all of the ground water used in Las Vegas Valley prior to 1940 came from the Shallow Zone of Aquifers and presently the Shallow and Middle Zones yield most of the Las Vegas Valley water supply. Areas of highest transmissivity lie on the west coinciding with the thicker sections of sand and gravel. Zones of transmissivity as indicated by specific capacity were plotted by Maxey and Jameson (1948, Plate 8) and illustrate this distribution as do Figures 6 and 8 of this report. Distribution of transmissivity is further discussed in following sections of this report, primarily in the sections on "Hydrology" and "Description of the Lithology for Analog Interpretation."

STRUCTURE

Several faults occur within the valley fill (Fig. 1). The scarps resulting from these faults are conspicuous features as one traverses in an east to west direction from Nellis Air Force Base to west of the City of Las Vegas. Depth of faulting is unknown but deposits are disturbed at least as deep as 500 feet. An argument for lithologic control on these faults is presented by the percentage map to be described in a later section of this report. The lineation of these faults coincides with major changes in lithology from coarse materials on the west to finer-grained materials eastward. Thus, it is believed that they are compaction faults although faulting from deep-seated sources is not entirely ruled out by presently available evidence.

Throw on these faults is as much as 150 to 200 feet with the east side down relative to the west side. This can be seen from the structural contour map, Figure 3, drawn on the surface of the blue clay horizon. Contours on this figure are given in feet of elevation on the clay surface, with a contour interval of 25 feet. It can be seen that faulting has affected this clay, which is

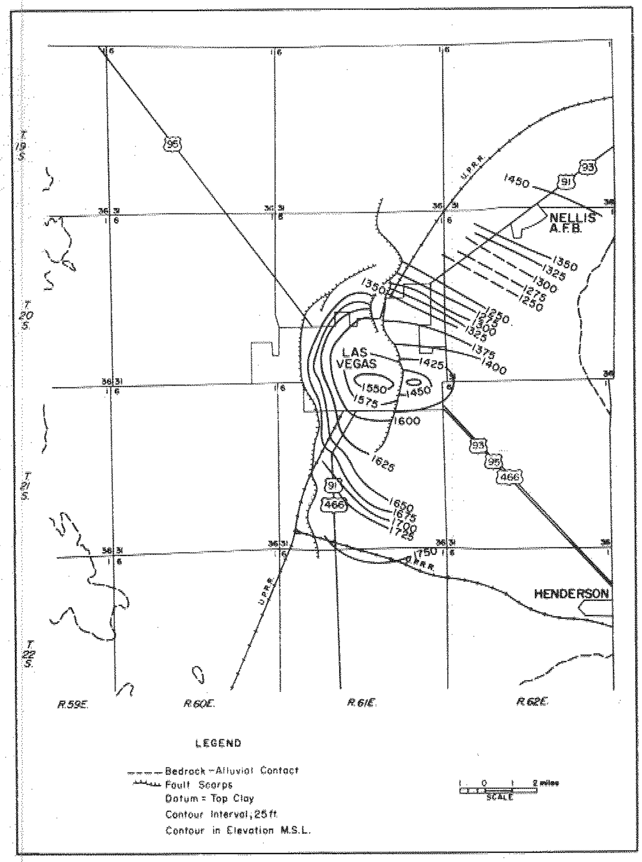

Figure 3. Structure contour map on top of blue clay horizon.

buried an average depth of 450 feet below the surface.

The presence and alignment of alluvial faults influence ground-water flow. The faults act as partial barriers to the flow of ground water because of aquifer displacement and are responsible for the origin and location of former springs in the valley. Since these faults are aligned with major changes in lithology they roughly bound areas of differing transmissivity. Areas of greatest transmissivity are west of the large scarp that cuts through the eastern part of the City of Las Vegas.

Description of Lithology for Analog Interpretation

INTRODUCTION

The ultimate goal of the work described in this section is to develop a quantitative pattern of the regional transmissivity in Las Vegas Valley. The amount and type of information needed to achieve such a goal depends upon the complexities of the system. If the system properties are reasonably uniform, expression of the regional transmissivity may be obtained by a limited number of aquifer performance tests. Where the properties are not uniform, but are the result of complex geologic environments, the location and extent of individual environments, as well as interrelationships between environments, must be known. Without this knowledge, transposition from geologic to hydrologic data is difficult.

The methods applied are both geologic and hydrologic. The geologic approach utilizes subsurface mapping techniques to portray the significant environmental factors in space. Investigations of a hydrologic nature are conventional aquifer performance tests. Basic data for construction of geologic maps was gathered from drillers' reports submitted to the State Engineer's office and from geophysical information, all of which were supplemented by detailed descriptions by experienced hydrogeologists of control-well samples. These maps, when used in conjunction with the results of the aquifer testing program, provide an effective means for ascertaining the regional transmissivity of the alluvial basin.

SOURCE AND INTERPRETATION OF DATA

Quantitative mapping techniques applied to unconsolidated or semiconsolidated alluvial-fill deposits have been utilized to represent the complex subsurface characteristics in Las Vegas Valley. Conventional stratigraphic approaches, such as cross sections and lithofacies maps, are inadequate when working with these highly irregular valley-fill deposits. Lithofacies maps were selected to illustrate variations in positions of strata, vertical variability and percentage. Map types were defined based on information from drillers' logs, geophysical logs, and samples of drill cuttings from water wells.

The State Engineer's office has several thousand drillers' logs from Las Vegas Valley. These drillers' reports are the main source of subsurface geologic data. Electric logs from a limited number of wells have been made available by the City of North Las Vegas. These logs record vertical changes in resistivity and conductivity in the rock interval from which lithologic changes, porosity and permeability can be interpreted.

Representative samples of the subsurface materials were collected from as many deep wells as possible using a sample interval of every 5 or 10 feet or every change of lithology. The information gained from examination of these samples aided in the interpretation of many drillers' logs and served as control points in the subsurface geologic mapping program.

Description of the collected samples included examination with a binocular microscope and comparison with known particle sizes to determine the clastic sediment textures. A geologic interpretation was determined for drillers' reports utilizing the drill-cutting samples as control. These standard interpretations are described in Table 1.

TABLE 1

Geologic Interpretation of Driller Terminology

Driller Terminology	Interpretation
Sand and Gravel	Interbedded units of sand and gravel. 100 percent permeable materials.
Cemented Gravel	All gravel, pebble-sized grains predominate. 100 percent permeable materials.
Gravel and Clay	Pebbles and larger clastic material in a matrix of clay, fine sand, silt; interbedded with some beds of gravel (probably mudflow deposits interbedded with some stream sediments). 25 percent permeable materials.
Sand	All sand, predominantly medium-grained or larger. 100 percent permeable materials.
Sandy Clay	Similar to gravel and clay. 25 percent permeable materials.
Silty Clay	No sand or gravel. Negligible permeability.
Clay and Caliche	No sand or gravel. Negligible permeability.
Clay	No sand or gravel. Negligible permeability.

For purposes of this study, cemented gravel was considered permeable, even though some or all portions of it could range widely in permeability. Caliche was considered to have negligible permeability and classed with clays, even though some of the caliches yield water. No practical method is presently available to decipher what percentages of cemented gravel and caliche are permeable or to what degree this permeability exists.

MAP TYPES AND PREPARATION PROCEDURES

Procedure

The mapping unit chosen was the interval between 200 and 700 feet below land surface. From previous geologic work in the area (Maxey and Jameson, 1948), it was recognized that the major water-yielding sands and gravels in the artesian basin lie below 200 feet and above 700 feet. Although a few wells penetrate as deeply as 1,000 feet or more in the valley, detailed data is primarily available for the selected 500-foot interval from which most of the water is now pumped. It is assumed that this hydrologic unit is as representative as could be selected considering the limitations of available data.

Vertical variability and lithologic percentage maps of permeable material are graphical methods of illustrating selected stratigraphic variables in a three-dimensional aspect. The selected variables in this case are the sands and gravels considered to be permeable within the mapping unit. Degree of permeability was determined after comparing all lithologic logs to the same set of standards, as defined in Table 1. The control used for these maps included some 200 logs, of which samples or electric logs were available for 25. The remainder of the control was drillers' logs, selected from the many hundreds available.

Vertical variability maps are a special class of facies maps that define a stratigraphic unit in terms of the position and arrangement of rock types as well as the composition of the unit. These vertical variability maps are divided into two categories: (1) Maps designed to show the degree of differentiation of a section into discrete units of different lithologic parts; and (2) maps that show relative position of one lithologic type within a given section. The latter category was chosen for this study. Within this category are center-of-gravity and standard deviation maps. Variations in gross lithology can be described by mapping the relative center-of-gravity and the relative standard deviation around the center.

The relative center-of-gravity expresses the average position of selected units within a larger unit either as a distance in feet from a predetermined datum plane or as a percentage of the total thickness of the section, also measured from the datum plane. A map depicting this parameter is given in Figure 4.

The relative standard deviation indicates distribution or spread of a selected unit around the center-of-gravity, expressed as a percentage of the total thickness of a section. By adding and subtracting the value of this spread to the center-of-gravity, a range is provided which is occupied by approximately two-thirds or more of the total number of the selected units in a section (Krumbein and Libby, 1957; Meyboom, 1960). A standard deviation map is given in Figure 5. A significant feature of the west boundary between the shaded and non-shaded area in Figure 5 is the transition zone where relatively thick aquifers to the west grade into thinner sand and gravel units eastward, with ever increasing percentages of silt and clay occurring to the east.

The two maps described above can be combined

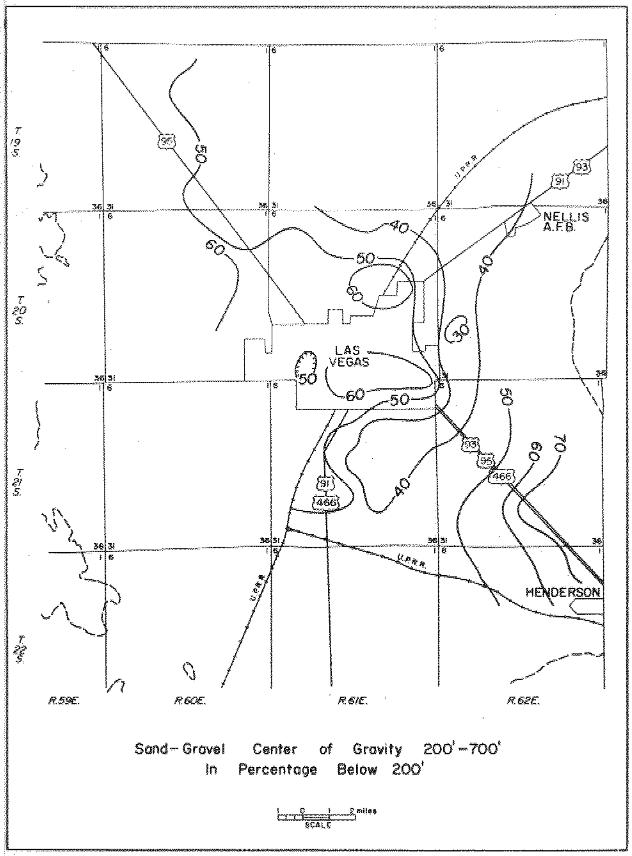

Figure 4. Center-of-gravity map of sands and gravels.

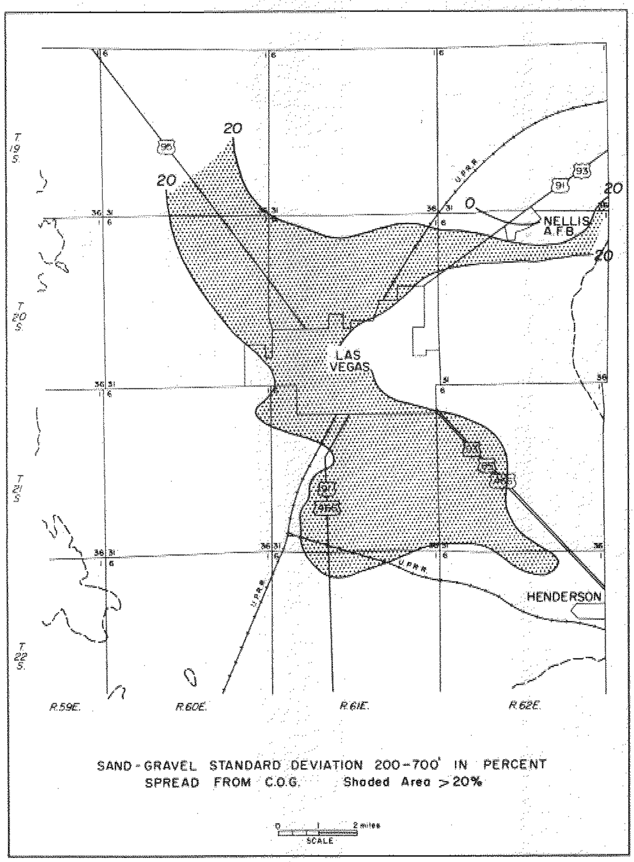

Figure 5. Standard deviation map on sand and gravels.

by means of superposition to give a vertical variability pattern map, Figure 6. Appropriate subdivisions of the center-of-gravity and standard deviation are selected resulting in a series of classes that are patterned on a map.

The method for computing the center-of-gravity and standard deviation is illustrated in Figure 7 (modified from Krumbein and Libby, 1957, p. 201). Each of approximately 200 lithologic logs from the sources previously mentioned is analyzed for the position (h) and thickness (t) of each permeable horizon. The parameter "h" is computed in feet below a predetermined datum (200 feet below ground surface) to the center of each permeable interval. Those intervals that are not all sand or gravel and for which a predetermined scale is used to compute percentages are treated as a partial percentage of overall thickness of the interval. The parameter "t" is computed in feet and tenths of a foot. The reader is referred to Krumbein and Libby (1957) for a detailed explanation of computation methods.

As is evident from the sample in Figure 7 the computations for this process are long and tedious by long-hand methods. By programming all computations for an IBM 1620, or equivalent computer, the time involved is greatly reduced and this system is made practical. There remains only the initial sorting of all logs for the number, position below datum, and thickness of each permeable horizon. This data is then punched on IBM cards and fed into the digital computer.

Based on the values of relative center-of-gravity and of relative standard deviation, contour maps can be constructed for these parameters (see Figs. 4 and 5). In this instance a 10 percent contour interval is chosen for the center of gravity map and a 20 percent contour interval is chosen for the standard deviation map. In Figure 5 the greater than 20 percent area is shaded.

After superposing the two map types described above a resulting vertical variability pattern map can be constructed (Fig. 6). This method is chosen for this report as it best illustrates the data in a simplified manner.

In order to describe the nature of the lithology at any given point, as well as the position of selected units, it is necessary to incorporate a sand-shale ratio or a lithologic percentage map as a supplement to the vertical variability pattern

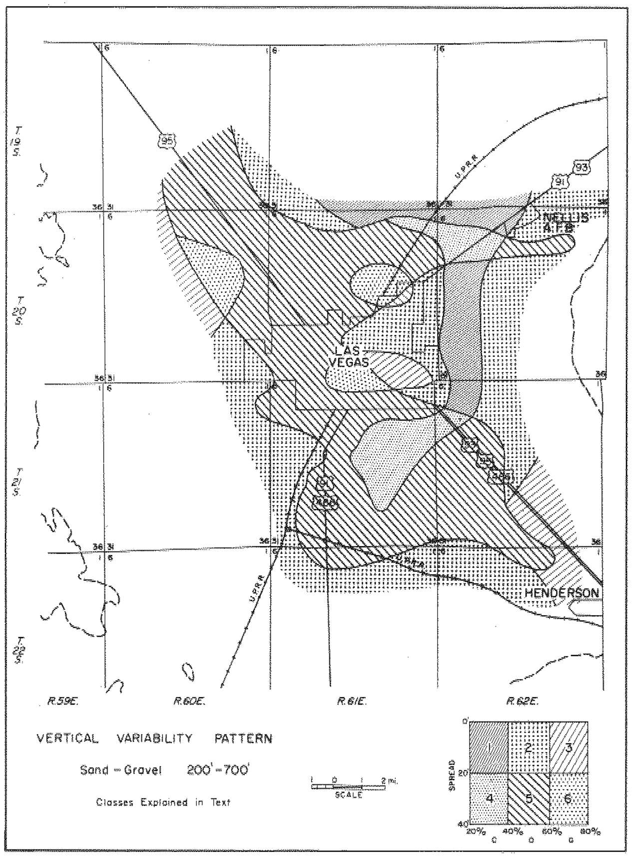

Figure 6. Vertical variability pattern map of sands and gravels.

(Forgotson, 1960; Meyboom, 1960). In this study a percentage map is constructed to show the relative percentages of permeable materials in the 500-foot slice, see Figure 8. The criterion used in selecting permeable materials is given in Table 1. The need of this supplement is obvious when one considers that a thick sand or gravel unit lying in the middle of a section will have the same relative center of gravity (50 percent) and the same spread (0 percent) as a thin sand or gravel unit lying in the middle of the section.

In general the percent of sand and gravel decreases eastward with a marked change occurring at the large fault scarp that lies in the west part of the City of Las Vegas. Within a 2-mile interval in the vicinity of this north-south trending scarp the percent of permeable materials decreases eastward from values over 70 percent to values of 30 percent or less, thus illustrating that the fault is localized along a major lithologic change.

Interpretation of the Data

Utilizing the vertical variability pattern map and the lithologic percentage map (Figs. 6 and 8) various classes can be described for the varying lithologies within the mapping unit. These classes are based on arbitrarily selected parameters that best fit the data. Each class has distinct characteristics of vertical and horizontal position of permeable materials including possible combination of high, middle, or low center-of-gravity with either small or large spreads. Each class is further characterized by an average value of the percentage of permeable material as interpreted from the lithologic percentage map. Because of the addition of percentage lithofacies data a class number on one side of the valley may have entirely different characteristics from that same number of class on the other side of the valley. Six such classes are described for Las Vegas Valley. The class descriptions are given in Table 2.

TABLE 2

Description of Classes

Class 1. Characteristics:
Relative center of gravity high = 20 percent to 40 percent.
Relative standard deviation (spread) small = 0 percent to 20 percent.
Average percentage of permeable materials (lithologic percentage) = 10 percent (which represents a low sand-shale ratio).

Description:
The main sand and gravel development occurs in the upper portion of the section and generally consists of one or a few thin lenses interbedded with the materials of negligible permeability. In reference to the ground surface the center-of-gravity is between 300 to 400 feet in depth with at least two-thirds of the permeable materials lying between 0 to 100 feet either side of the center-of-gravity.

Class 2. Characteristics:
Relative center-of-gravity medium = 40 percent to 60 percent.
Relative standard deviation small = 0 percent to 20 percent.
Average percentage of permeable materials: in the north and east portions of the basin = 15 percent; in the south and west portions of the basin = 50 percent.

Description:
North and east: the main sand and gravel development occurs in the middle portion of the section and consists of thin lenses spread from 0 to 100 feet either side of the center-of-gravity. In reference to the ground surface, the center-of-gravity is between 400 to 500 feet in depth.
South and west: the center-of-gravity and spread are similar to the north and east portions; however, as the percentage averages 50 the permeable materials occur as relatively thick lenses with equal lenses of silt and clay interbedded.

Class 3. Characteristics:
Relative center-of-gravity low = 60 percent to 80 percent.
Relative standard deviation small = 0 percent to 20 percent.
Average percentage of permeable materials: in the east portion = 20 percent; in the west portion = greater than 50 percent.

Description:
East portion: the main development of permeable

materials is in the lower portion of the interval and consists of thin lenses spread from 0 to 100 feet either side of the center-of-gravity, which lies 500 to 600 feet below the ground surface.
West portion: the main development of permeable materials is in the lower portion of the interval with a few relatively thick lenses occuring from 0 to 100 feet either side of the center-of-gravity.

Class 4. Characteristics:
Relative center-of-gravity high = 20 percent to 40 percent.
Relative standard deviation large = 20 percent to 40 percent.
Average percentage of permeable materials = 20 percent.

Description:
The main development of permeable materials occurs in the upper portions of the interval with a spread of 100 to 200 feet either side of the center-of-gravity. The low percentage of permeable materials coupled with a large spread indicates that there are many thin lenses of sand and gravel with large quantities of material of negligible permeability interspersed.

Class 5. Characteristics:
Relative center-of-gravity medium = 40 percent to 60 percent.
Relative standard deviation large = 20 percent to 40 percent.
Average percentage of permeable materials = 40 percent.

Description:
The large spread combined with a relatively high percentage of permeable materials indicates a general alternating sequence of sand-gravel and silt-clay throughout the total section with the main development near the middle of the section. The spread is from 100 to 200 feet either side of the center-of-gravity, which lies between 400 to 500 feet below the ground surface. As the percentage of permeable materials generally decreases from west to east, the distribution of sand and gravel probably grades from a few relatively thick lenses of the west to the many interfingering lenses to the east.

Class 6. Characteristics:
Relative center-of-gravity low = 60 percent to 80 percent.
Relative standard deviation large = 20 percent to 40 percent.
Average percentage of permeable materials: west portion = 60 percent; east portion = 20 percent.

Description:
West: the high sand and gravel percentage coupled with a large spread indicates relatively thick sequences in an upper and lower position with the main development to the bottom. The spread is 100 to 200 feet either side of the center-of-gravity which lies between 500 to 600 feet below the ground surface.
East: the low sand and gravel percentage coupled with a large spread indicates relatively thin lenses interspersed with large quantities of silt and clay. The spread is 100 to 200 feet either side of the center-of-gravity which is 500 to 600 feet below the ground surface.

Description of Hydrologic Properties for Analog Input

The significant hydrologic properties of an aquifer may be expressed mathematically by the coefficient of transmissibility (T) and storage (S). Data to calculate values for these properties are usually obtained by pumping one well at a constant rate measuring in adjacent wells the change in water levels caused by the pumping. A graphical solution is used to solve equations which express the relationship between numerous measured variables (discharge of the well, distance to the point of observation, lowering of water levels at the observation point, and time) and the coefficients of transmissibility and storage. The formula most commonly used is the nonequilibrium formula (Theis, 1935) or derivations thereof.

The coefficient of transmissibility indicates the capacity of an aquifer to transmit water, and is equal to the product of the field coefficient of permeability and the aquifer thickness. It is one of the limits of the radius of a cone of depression and its depth, the radius for any given time increasing with increasing transmissivity and the depth being inversely proportional to transmissivity. The difficulties in obtaining accurate transmissivity data from pumping-test results in complex geologic environments are recognized by most hydrologists (Ferris, et al., 1962; Skibitzke and da Costa, 1962) and will not be discussed here.

The coefficient of storage of an aquifer is defined as the volume of water released from or taken into storage per unit of plan area of the aquifer per unit change in the component of head normal to that surface. Because of its relation with time, the coefficient of storage is a limit on the rate of lateral growth of a cone of depression, this rate being inversely proportional to its value. Because of partial confinement of an aquifer and other factors, a calculated coefficient of storage invariably increases with time (Guyton, 1941; Jacob, 1941). Later work by Poland (1961) suggests that the calculated value may be meaningless in an area of appreciable compaction.

The results of aquifer performance tests are sometimes used in predicting the consequences of large-scale depletion taking place in many arid areas as well as the ultimate depletion-time history of a water resource. Skibitzke and Brown (1961) have pointed out that little is known about hydrologic events in arid regions until at least 50 years of record become available. Hence, the dependability of the results of aquifer performance tests in predictions of longterm water-level behavior not only at the pumped wells, but at various distances from them and at various times, is

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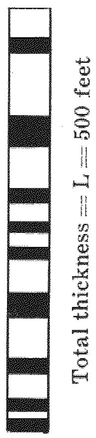
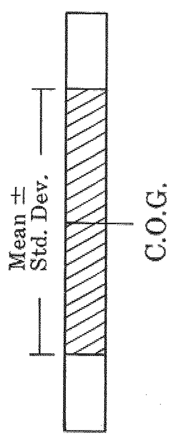


Sand number	Distance from top h	Thickness in feet t	ht	h^2t
1	35	15	525	18,375
2	140	25	3,500	490,000
3	215	4	860	184,900
4	240	8	1,920	460,800
5	275	5	1,375	378,125
6	325	8	2,600	845,000
7	334	6	2,004	669,336
8	401	17	6,817	2,773,617
9	470	3	1,410	662,700
10	495	3	1,485	735,075
Sums:		94	22,496	7,217,928
		(A)	(B)	(C)



Center of gravity: $B/A = 239.3$

Relative center of gravity $= \dfrac{\text{c.o.g.}}{L} \times 100 = 48\%$

Approximate variance $= \dfrac{C-(B^2/A)}{A} = \dfrac{1{,}834{,}205}{94} = 19{,}513$

Approximate standard deviation = a.v. = 140

Relative standard deviation $= \dfrac{\text{ap.st}}{L} \times 100 = 28\%$

* (Modified from Krumbein and Libby, 1957, p. 201.) An actual log from Las Vegas Valley has been used.

Figure 7. Method of computing center-of-gravity and standard deviation (modified from Krumbein and Libby).

questionable. However, most authorities agree that an accurately interpreted test result describes the approximate nature of the aquifer in the vicinity of the pumped well. Each accurately interpreted test result adds to the overall knowledge of the hydrologic sytsem.

The geologic parameters considered important to this study are expressed as summation products of vertical position, thickness of permeable material, and areal variations in the lithologic units. The large variations that occur are known from the results of subsurface mapping. If geologic patterns can be correlated with transmissivity data obtained from aquifer tests, extrapolations of these correlations on the basis of geologic mapping will provide the regional distribution of transmissivity which is sought. The relationship between geologic environments and aquifer characteristics serves as a basis for modeling untested aquifers within the area of geologic control.

The coefficient of transmissibility in Las Vegas Valley as determined from 23 aquifer performance tests ranges from 1,000 to 280,000 gallons a day per foot. Distribution of the transmissivity corresponds closely to the lithological trends shown in Figures 6 and 8.

East of the 30 percent contour on Figure 8, the coefficient of transmissibility ranges from 1,000 to 6,500 gallons a day per foot (Table 3), hardly a large range in view of the known full range of variations in transmissivity in the valley. The relatively uniform geologic conditions in this part of the basin (Fig. 8) suggests that a sufficient number of local tests are available to supply a reasonably accurate transmissivity pattern in the eastern part of the study area.

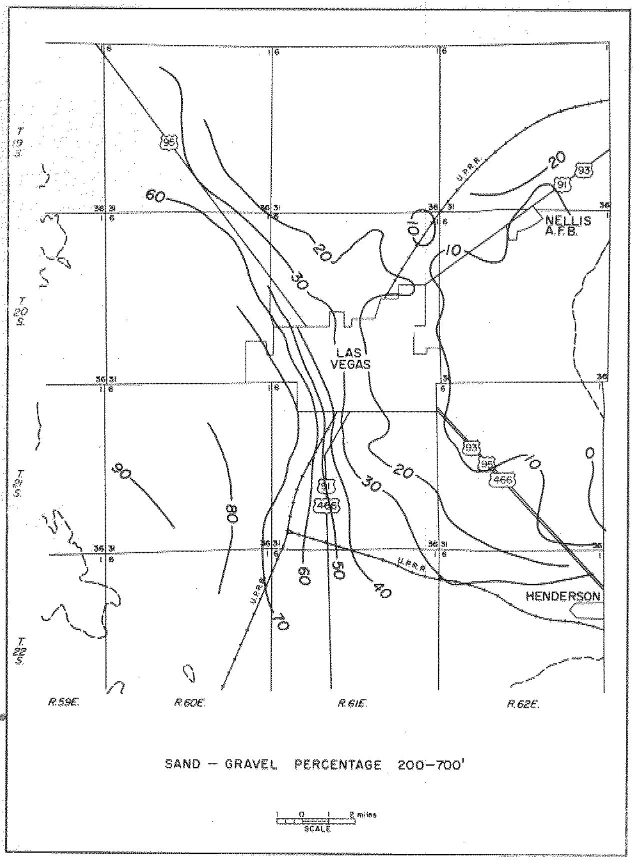


Figure 8. Sand and gravel percentage map.

West of the 30 percent contour, the coefficients of transmissibility are known from eight aquifer performance tests and range from 4,000 to 280,000 gallons a day per foot (Table 4), a range too great to determine distribution of transmissivity by a reasonable test program. The classes of importance in the western, southwestern, and central parts of the valley are the sand and gravel aquifers in the mid-portion of the section (class 2) that grade into thinner sand and gravel units eastward (class 5) with no significant shift in the vertical position of the beds. The western margin of class 5 marks the beginning of the transition (Fig. 6). The pattern depicted on the vertical variability map (Fig. 6) augmented by the sand and gravel map (Fig. 8) suggests the presence of partial boundary conditions within the transition margin and provides information with which the response of the aquifer to pumping along this margin may be better understood. West of the transition (class 2, Table 4) and east of the transition (class 5, Table 4) the range in transmissivity values correlates with gravel thickness. Extrapolation of these data aided by a knowledge of the position in space of an important partial boundary condition has provided an estimate of the regional transmissivity pattern in western Las Vegas Valley.

TABLE 3

Transmissivity Data in Eastern Las Vegas Valley

		Coefficient of Transmissibility (gpd/sq. ft.)	
Class	No. of tests	Range	Average
1	1	....	4800
2	4	1600–6500	4100
3	1	....	1300
4	3	1000–4000	2930
5	5	1600–4600	3925
6	1	....	3200

TABLE 4

Transmissibility Data in Western Las Vegas Valley

		Coefficient of Transmissibility (gpd/sq. ft.)	
Class	No. of tests	Range	Average
2	3	240,000–280,000	253,333
5	4	4,000– 18,100	9,775
6	1	....	100,000

HYDROLOGY

Introduction

The shallow ground-water flow system for Las Vegas Valley and environs is comparable to the idealized system described by Hubbert (1940) and further discussed by Tôth (1962; 1963). The essential components of the system, shown diagrammatically in Figure 9, consist of a recharge area in the mountains and a discharge area in the lowlands separated by a region of varying width of lateral flow. The boundaries of the system include the ground-water divides in the highlands, which commonly conform to topographic divides; the water table, the upper surface of the system; and a zone of highly impermeable rocks or some other boundary which impedes flow along the lower part of the system.

The mountain ranges bounding Las Vegas Valley, especially the Spring Mountains and the Sheep Range, rise to high altitudes and receive considerable amounts of precipitation, in some years in excess of 25 inches. This precipitation is the chief source of the water in the ground system. A considerable part of it, that which is not lost by local evapotranspiration, percolates downward to the water table and thus develops a continuous source of potential to drive the water downward and laterally to the discharge area. Since this downward

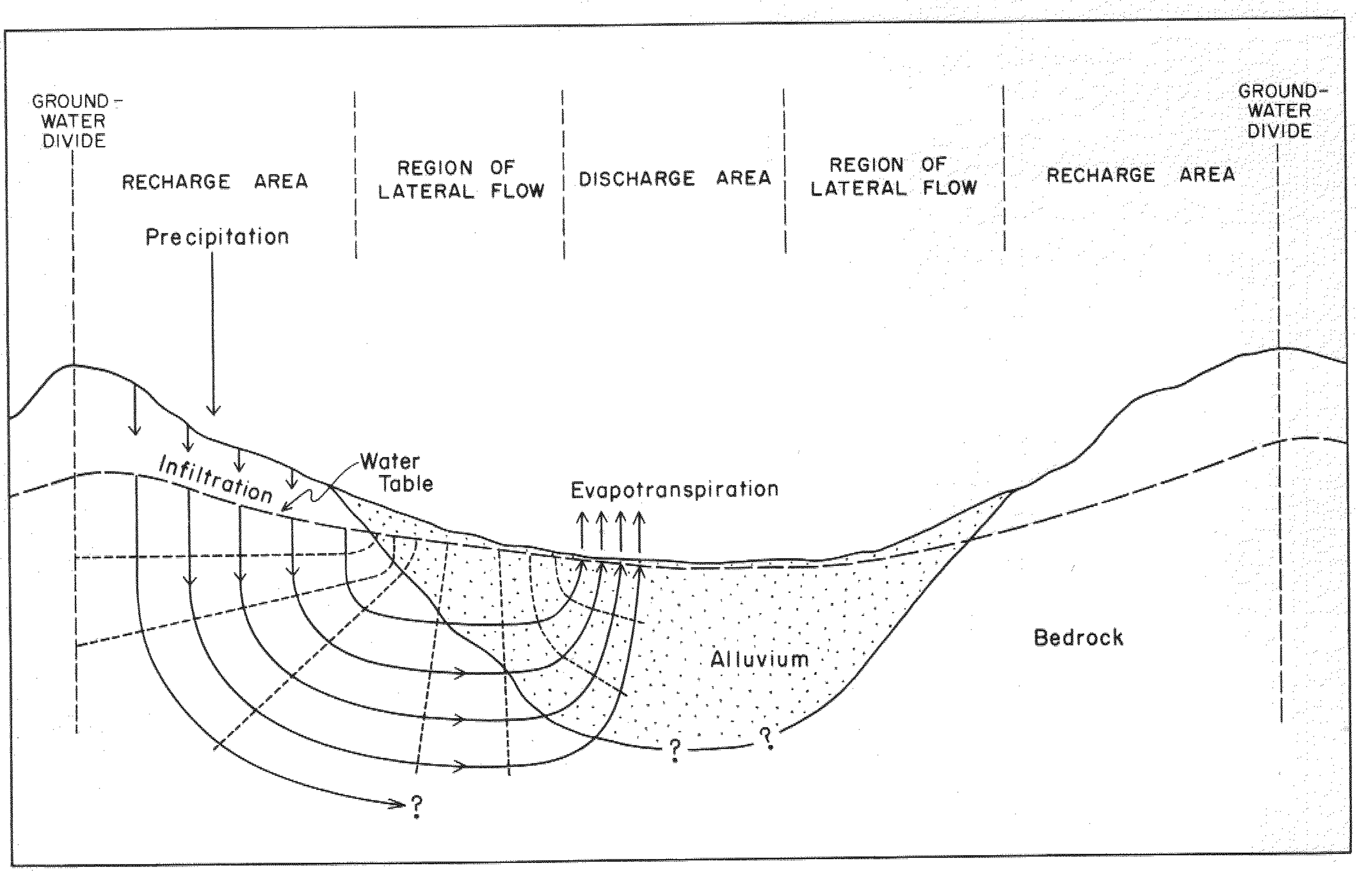


Figure 9. Idealized flow system, Las Vegas Valley.

and lateral movement beneath the water table requires energy, the potential in the recharge area decreases with depth as is shown in Figure 9. Estimates of the amount of water available annually from the watershed of Las Vegas Valley range from 25,000 to 35,000 acre-feet (Maxey and Jameson, 1948; Malmberg, 1961).

In some parts of the region flow lines, directed more or less vertically in the recharge area, swing into nearly horizontal position and remain horizontal for considerable distances. In this part of the system, potential lines are essentially vertical and, therefore, the potential is essentially the same regardless of depth.

In the discharge area flow lines again become directed upward and approach vertical positions. Potential lines are then diagonal or horizontal and the potential in the discharge area increases with increasing depth. This feature is clearly demonstrated in Las Vegas Valley where the potential always increases with depth, at least to depths of several hundred feet, when wells are drilled in unexploited areas.

As in many other bolsons in the Great Basin, the discharge area in Las Vegas Valley is an area with a shallow water table which releases water to phreatophytic plants and to the land surface through springs where it is discharged by transpiration and evaporation to the atmosphere. If there is no underflow from the bolson, as seems to be the case in Las Vegas Valley, this natural discharge is a fair measure of the amount of recharge available to the ground-water system. Estimates of the annual natural discharge previous to well development made by Malmberg check closely with his values for perennial recharge to the valley (Malmberg, 1961).

The foregoing discussion describes conditions in the upper thousand or so feet in Las Vegas Valley. This shallow system may be a part of a deeper system which extends regionally far beyond the confines of Las Vegas Valley and its bounding ranges. The possibility for this is indicated by studies of Winograd (1963) just north of Las Vegas Valley and Eakin (personal communication) in other parts of Nevada. Such a system could materially contribute to the water resources of Las Vegas Valley. However, at this time no binding evidence is available that this occurs—indeed we have too little information to define even the lower boundary of the shallow system. Therefore, it seems proper to consider only the shallow system until such evidence is available.

Ground-water Motion and Losses Under Natural Conditions

In the western part of the study area it seems reasonable to assume that lateral flow occurs in the ground-water reservoir (Fig. 9). Precipitation is too scanty to afford recharge to the reservoir at the lower elevations between the bottom of the valley and about 6,000 feet (Maxey and Jameson, 1948, pp. 107–108). Also, discharge does not occur west of the main spring areas just west of the City of Las Vegas and Tule Springs. Eastward from these spring areas considerable upward flow occurs—indeed all discharge in the valley under natural conditions was fed by such movement.

As has been shown previously, several zones or intervals of sediments of high transmissivity are interspersed with intervals of low transmissivity in the middle part of the valley. The thickness of the beds of low transmissivity increases rapidly to the east from the west boundary of the area of spring discharge.

Thus, two conditions have opposing effects upon the hydraulic gradient from west to east: (1) that of continuous loss of water eastward across the spring area; (2) that of decreasing transmissivity eastward. The first results in a decrease of gradient and the second results in an increase of gradient eastward.

The potentiometric map in Figure 10 illustrates the hydraulic gradient in 1912 prior to heavy ground-water development in the study area. The map consists of equipotential lines, that is, lines drawn between points of equal potentials in wells determined by measurements or estimates based on measurements of the potential in wells at a given time. It reflects the conditions described above as well as a third condition of significance, that is, it is a composite surface because wells of varying depth were used as control points. Inaccuracies in the map, then, must occur because of head differences resulting from upward movement of ground water and from differences in conditions of local confinement of the water. For the purposes of this report it is believed that these differences are negligible or introduce only minor errors.

Figure 10 depicts the position of equipotential lines at a time when pumping or flow from wells had not materially disturbed the natural condition. Thus, the position of the lines was controlled chiefly by the transmissivity of the sediments and the quantity of flow from point to point. As has previously been indicated, variations in homogeneity of the reservoir materials and loss from the reservoir as the water moves eastward result in irregular spacing of the lines.

Using the data in Figure 10 and the range of transmissivity as it is known from pumping tests or is estimated from geological information, a quantitative estimate of distribution of natural losses may be made. This distribution of losses is of primary importance in the distribution of pumpage in Las Vegas Valley. For example, if the amount of water pumped does not exceed that prevented from leaving the system naturally, the cones of pumping depression will stabilize and full development of the water resource will not be accomplished. Full development can occur only when all natural losses are eliminated.

A nondimensional analysis of the distribution of losses is given in the following steps:

1. Total ground-water flow crossing the 2250 equipotential line diminished by almost 40 percent in the region between this potential value

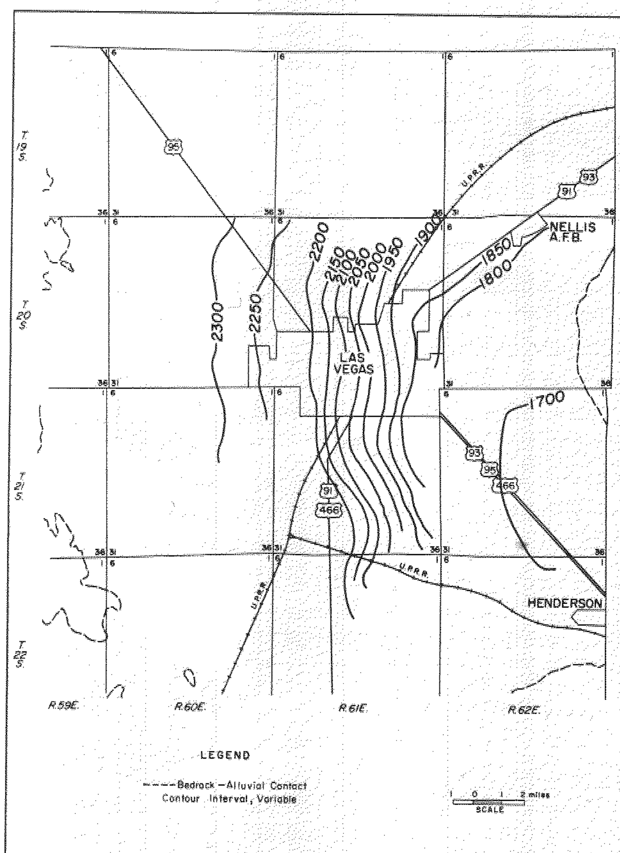


Figure 10. Approximate elevation of potentiometric surface, 1912.

and the fault in the alluvium coincident with the 2200 equipotential line. A large part of this water was discharged as spring flow along the fault line. This large loss is reflected in the wide spacing between the 2250 and 2200 equipotential lines.

2. In the central part of the valley, from the above-mentioned fault west of Las Vegas to the fault west of North Las Vegas (on the 1900 equipotential line), 80 percent of the remaining flow in the system was discharged naturally. Thus, cumulative losses amounted to about 88 percent of the original flow. Spring discharge along the eastern fault was a large contributor to this loss. The function of these faults as partial barriers to ground-water flow is shown by the steep hydraulic gradient necessary to move water across them.

3. From the 1900 equipotential line to the 1850 equipotential line, 40 percent of the remaining flow was discharged naturally and cumulative losses amounted to about 94 percent of the total flow. The remaining 6 percent was discharged naturally east of the 1850-foot equipotential line.

The percentages mentioned above can be given dimensional values by assuming that slightly more than 80 percent of the average estimate for recharge by the U.S. Geological Survey (30,000 acre-feet per year) might have been available to enter this area as underflow. Thus, of the 24,000 acre-feet assumed to enter this area annually, 9,600 acre-feet were discharged naturally in the area described in (1), and only 14,400 acre-feet of flow remained in the system. In the area described in (2), 11,520 acre-feet of water were discharged naturally, and the ground-water flow crossing the alluvial fault west of North Las Vegas amounted to only 2,880 acre-feet per year. In the area described in (3), 1,150 acre-feet were discharged and the remainder (approximately 1,400 acre-feet) was discharged farther east.

Although the above estimates are as accurate as available data will allow, they are, at best, approximations. The approximations in reconstructing a potentiometric map, the limitations of the quantitative methods used to describe subsurface conditions and to measure aquifer properties, and the many uncertain factors in construction of flow systems as a whole precludes an exact analysis.

Under natural conditions previous to development of water by wells, such as those assumed in Figure 10, the ground-water reservoir was in approximate equilibrium, that is, recharge to the system approximated discharge from it. When pumping commences and the perennial recharge is considered to be a measure of the "safe yield" of the basin, it is assumed that diversion of the recharge to pumping wells will eliminate natural discharge. In a theoretical sense and with no consideration for time, this assumption is correct; in a practical sense elimination of all natural discharge probably cannot be achieved.

When a well in Las Vegas Valley is initially pumped, the water is obtained from local storage and diverted natural discharge, from regional storage, and from diverted regional natural discharge. Removal of stored water is often referred to as "mining," and must be expected regardless of the amount of recharge and the well location. Contributions from diverted discharge often increase with time. Ultimately, if pumpage does not exceed the amount of water derived from natural discharge, there will be no further removal from storage and the cones of pumping depression will stabilize. If total pumpage exceeds the amount of water that can be diverted effectively from natural discharge, stabilization of the cones may never occur.

The amounts and distribution of natural discharge mentioned above are indicative of the amount of water that might be available from this source. However, areas of natural discharge are widely spaced in the valley whereas the centers of major withdrawal from wells are concentrated locally. In order to divert natural discharge to wells, the latter must be properly spaced with regard to where natural discharge occurs. The pattern of ground-water development in the valley has not adhered exactly to such conditions. Rather it has been dictated by factors involving immediate economic concern such as points of use, head, and transmissivity of aquifers. In order to divert natural recharge efficiently, pumping centers must be placed in such remote areas as Tule Springs and Paradise Valley.

Reservoir Operation to 1962

Kazmann (1958) has described a functional reservoir as one that will admit water, store water, and permit water to be withdrawn economically. The factors to be ascertained in order to identify the functional operation of a ground-water reservoir are those of recharge, storage, and discharge. These factors have been determined in previous studies (Maxey and Jameson, 1948; Malmberg, 1960, 1961), and summarized to some extent earlier in this report.

Since the first flowing well was drilled in 1907, total discharge from the main aquifers has exceeded total replenishment. The first quantitative estimate of total draft was made by Maxey and Jameson (1948) and further described by Malmberg (1961). In Malmberg's estimate for the entire valley during the year 1955, total draft on the main zone of aquifers was 48,000 acre-feet of water, comprised of 3,200 acre-feet for spring flow, 6,000 acre-feet from upward movement into the near-surface system, and 39,000 acre-feet pumped from wells. Based on this estimate and assuming Malmberg's recharge rate of 25,000 acre-feet per year, over 15,000 acre-feet of water formerly being discharged naturally was diverted into wells in 1955, and approximately 24,000 acre-feet of water was derived from storage.

By 1962, spring flow in the valley had essentially ceased. Although no estimates are made of upward movement, an accelerated pumping rate and subsequent water-level declines throughout the valley since 1955 has assuredly reduced the amount of such movement from the 1955 figure. By assuming that upward movement has decreased by about 50 percent and considering the 54,800 acre-feet of water withdrawn by wells in 1962, total draft on the main zone of aquifers in 1962 is estimated to be about 58,000 acre-feet. On the basis of the estimated range in recharge quantities, this suggests that about 23,000 to 33,000 acre-feet of water was derived from storage in 1962.

Upward or downward movement into the sand and gravel aquifers supplying the basin may take place from three sources: (1) the near-surface reservoir in the sediments above the artesian zone of aquifers; (2) the Muddy Creek Formation below the main reservoir rocks; and (3) the fine-grained sediments within the main reservoir rocks.

Under natural conditions, the amount of water stored in the near-surface sediments was dependent solely upon upward movement from the underlying sands and gravels and evapotranspiration processes. Although this source of supply has apparently been practically eliminated in the area of principal use, recycling of water has prevented material changes in storage in the near-surface system. Malmberg (1961) estimated that almost three-fourths of the recharge to the near-surface system in 1955 was water that was used at least once, not including about 5,000 acre-feet of water from operations in Henderson (Leeds, Hill, and Jewett, 1961). Thus, a sizeable reservoir is available from which downward movement may take place during periods of heavy withdrawals.

In central Las Vegas Valley, as in all natural discharge areas, ground-water potential increases with depth. Thus, movement of water from as much as a few thousand feet of saturated Muddy Creek sediments may take place upward and ultimately contribute to the reservoir supplying most of the water.

The compaction of the fine-grained sediments due to effective stress increases brought about by fluid withdrawals contributes stored water with no subsequent reflection in aquifer heads. This is truly a "mined" commodity, as it is available only once (Poland, 1961).

Pumpage and its Effect on Ground-water Levels

The major effect of ground-water withdrawal commonly understood by all water users is a change in water levels. This effect is most often evaluated in terms of pumping lifts or in terms of ultimate depletion of the resources by dewatering. As all parts of a ground-water reservoir do not respond uniformly to development, the physical nature of the rocks is the factor relating cause and effect, that is, pumpage and water-level change.

PUMPAGE AND PUMPAGE DISTRIBUTION

Many of the water wells and well fields in Las Vegas Valley are ideally located to divert ground-water formerly being discharged naturally. As a result of this development, nearly all of the springs have ceased to flow. The present areas of natural discharge are those parts of the valley where artesian levels are still high or where recycled water recharges the "near-surface" water. These include Paradise Valley, the southeastern part of the valley along U.S. Highway 95, and parts of the area extending eastward from the City of Las Vegas to just south of North Las Vegas.

The pumpage in Las Vegas Valley increased from an estimated 15.3 million gallons per day in 1924 to 49.3 million gallons per day in 1962, as shown in Figure 11. Pumpage has been increasing at a considerable rate only since 1941.

Maxey and Jameson (1948) estimated the areal distribution of pumpage during the early periods of ground-water development (Table 5).

TABLE 5

Estimated Distribution of Pumpage by Area, in Acre-feet Annually, for the Years 1912, 1924, 1941, 1944. (After Maxey and Jameson.)

Location	1912	1924	1941	1944
Vicinity of Las Vegas	9,700	17,800	17,400	20,100
Paradise Valley	10,000	3,500	3,900	4,000
Tule Springs	300	700	500	3,100
Other	500	400	300	1,100
	20,500	22,400	22,100	28,300

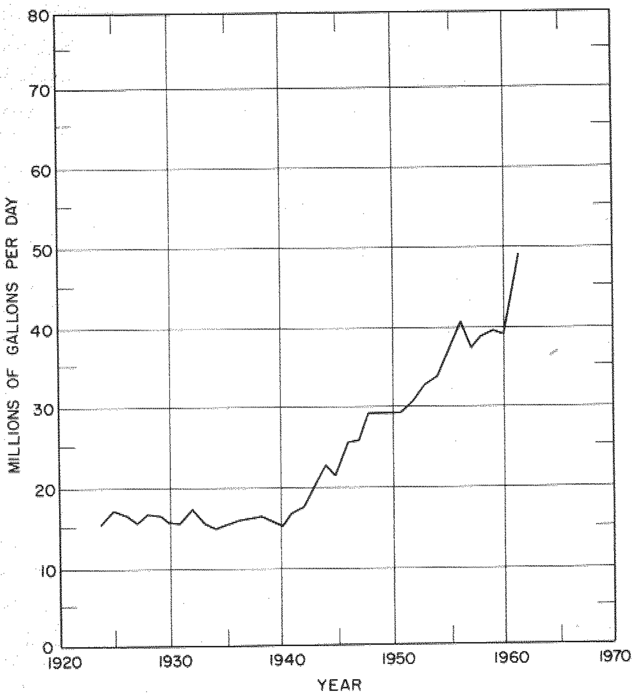


Figure 11. Estimated pumpage in Las Vegas Valley, 1924 to 1962.

Figures 12 and 13 show the distribution of pumpage from the major pumping centers in 1956 and 1962. Increases during the period 1956 to 1962 were greatest in the well fields supplying the cities of Las Vegas and North Las Vegas. Thus, the largest increment in pumpage since 1944 (Table 5) has taken place within the vicinity of Las Vegas.

The spacial relationships between major pumping centers has not been materially altered since the beginning of ground-water development. The Las Vegas Valley Water District well field, which has consistently produced one-half or more of the water pumped in the valley, has occupied only one-half of a square mile since pumping began. Practically all of the water developed by North Las Vegas prior to 1963 was pumped from within or near the city's original limits, an area of less than 7 square miles. Nellis Air Force Base has developed a water supply from the aquifers underlying the base and from a smaller area about 6 miles west on Craig Road known as the Off-Base well field. Withdrawals for the hotels, resorts, and golf courses are within a narrow strip aligned in a north-south direction southwest of Las Vegas. A few wells in the northwestern part of the valley supply irrigation water in the vicinity of Tule Springs. Most of the additional appropriated ground water developed since the early 1950's, other than by the municipal water producers mentioned, is withdrawn from wells within the area of influence of the Las Vegas Valley Water District and North Las Vegas well fields. Only within the area of the City of Las Vegas and in Paradise Valley prior to 1924 has pumpage diminished since early development. Thus, with minor exceptions, increased development of ground-water supplies since 1941 has taken place by an expansion or addition of multiple well facilities wholly within previously developed pumping centers.

Practically all of the water pumped within the area of principal ground-water withdrawal is from wells classified as municipal or quasimunicipal. The largest consumers are those served by the Las Vegas Valley Water District and the City of North Las Vegas water utilities, the resort hotels and golf courses in the Strip area, and Nellis Air Force Base. Ground water used for crop irrigation is more or less restricted to northwestern Las Vegas Valley (Tule Springs and Gilcrease Ranches), to a few ranches in Paradise Valley and the Winterwood Ranch a few miles southeast of North Las Vegas.

To illustrate seasonal use of water, monthly

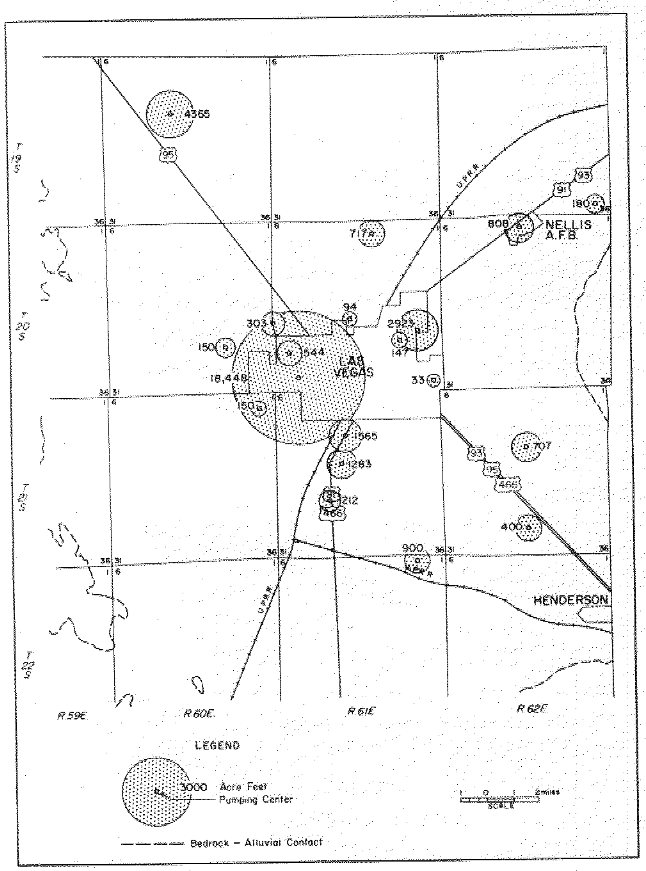


Figure 12. Distribution of estimated pumpage, 1956.

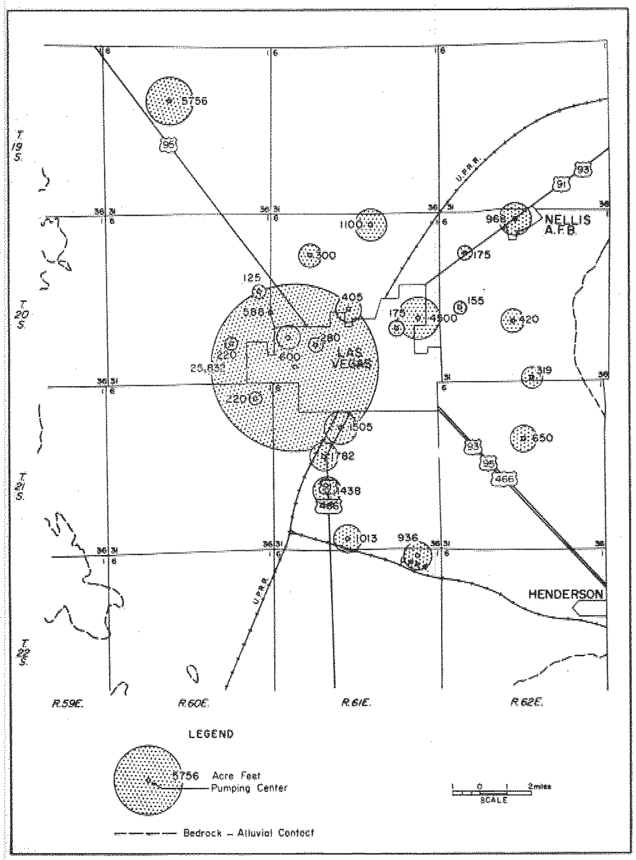


Figure 13. Distribution of estimated pumpage, 1962.

pumpage records furnished by the Las Vegas Valley Water District for the periods 1958 to 1961, have been averaged and their graphical presentation clearly shows the changes in the typical monthly demand, Figure 14. From this figure, November through February are relatively low production months, with minimum monthly production occurring in February. Two periods of intermediate water production (March through May, and September through October) are separated by the period of high water production, June through August, the maximum month occurring in July. The average of each of these intermediate periods approximates the average monthly demand, as shown on the figure.

WATER LEVELS IN WELLS

In 1912, the artesian pressure in aquifers underlying Las Vegas Valley was sufficient to cause wells to flow in many parts of the valley (Carpenter, 1915). The first complete outline of the area of artesian flow was ascertained in 1946 (Maxey and Jameson, 1948). According to this work, the area of artesian flow extended over approximately 75 square miles in the central part of the valley, and approximately 8 square miles in the Tule Springs area. By 1955, the area within which wells flowed was reduced by about 24 square miles in central Las Vegas Valley, and flow had essentially ceased in the Tule Springs area (Malmberg, 1960).

As a result of increased pumpage, the nonpumping water levels have continued to decline everywhere in the valley with only minor exception. The main area of artesian flow has changed from the area of major ground-water extraction to Paradise Valley. The boundary of the area is irregular because of topographic changes, well depth, and well use. The northern boundary is in the vicinity of McCarran Field and the western boundary is 1½ miles east of U.S. Highway 91. This area is separated, in part, by Whitney Mesa from another area of flowing wells along Boulder Highway. A few wells in the City of Las Vegas east of the district well field still flow. The above-mentioned features are diagrammatically shown in Figure 15. The boundary fluctuates with time, it encloses a larger area during the period of low draft of water and a smaller area during periods of large withdrawals. For example, water wells in and adjacent

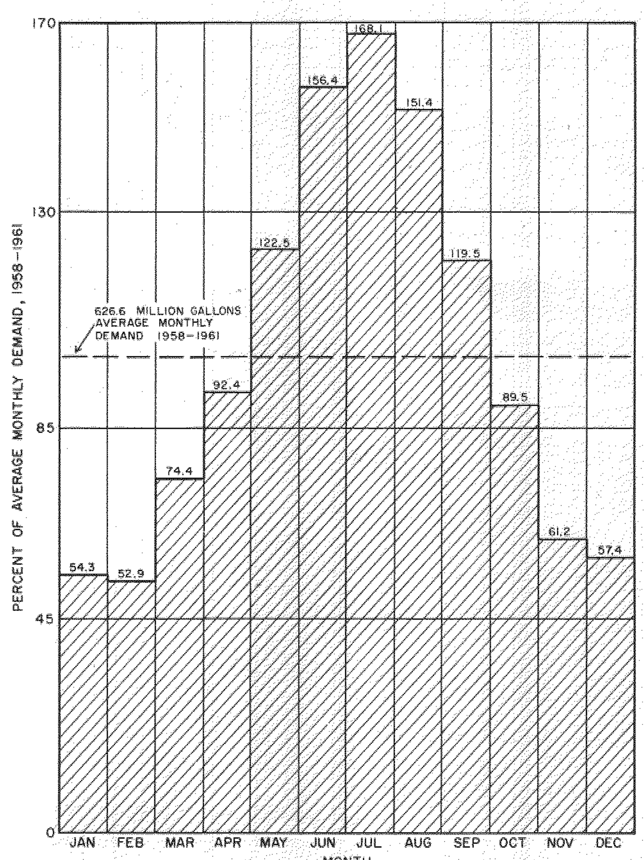


Figure 14. Typical monthly water demand, 1958 to 1961, Las Vegas Valley Water District.

to the district well field are known to flow when pumps are stopped in the field.

Rate of Water Level Decline

Maxey and Jameson (1948) published hydrographs showing water-level fluctuations in 11 wells in Las Vegas Valley for the period prior to 1946. Hydrographs from over 30 wells measured quarterly by the U.S. Geological Survey show water-level changes during various periods of development since that time. The most characteristic of these for all regions of the valley are shown in Figures 16 through 20.

The hydrographs show a steady decline of water levels as a result of increased withdrawal of water. Superimposed upon the long-term downward trend are seasonal fluctuations caused mainly by changes in pumping rates in nearby wells. Water levels in deep wells generally decline during the spring, summer, and early fall months when pumpage is at its peak. Water levels start to recover in late fall when pumpage is reduced. Lowest annual water levels are usually recorded during July and August and highest water levels are recorded in

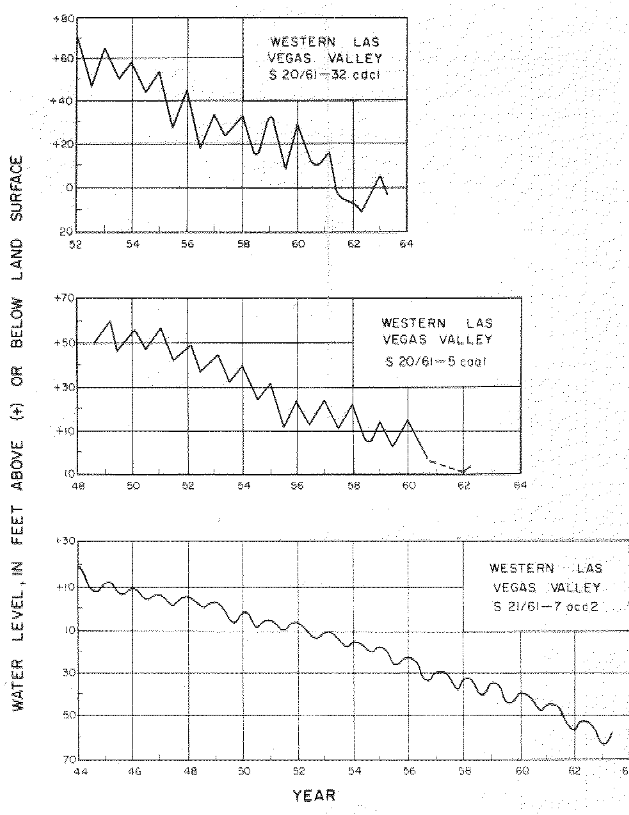


Figure 16. Water levels in wells in western Las Vegas Valley.

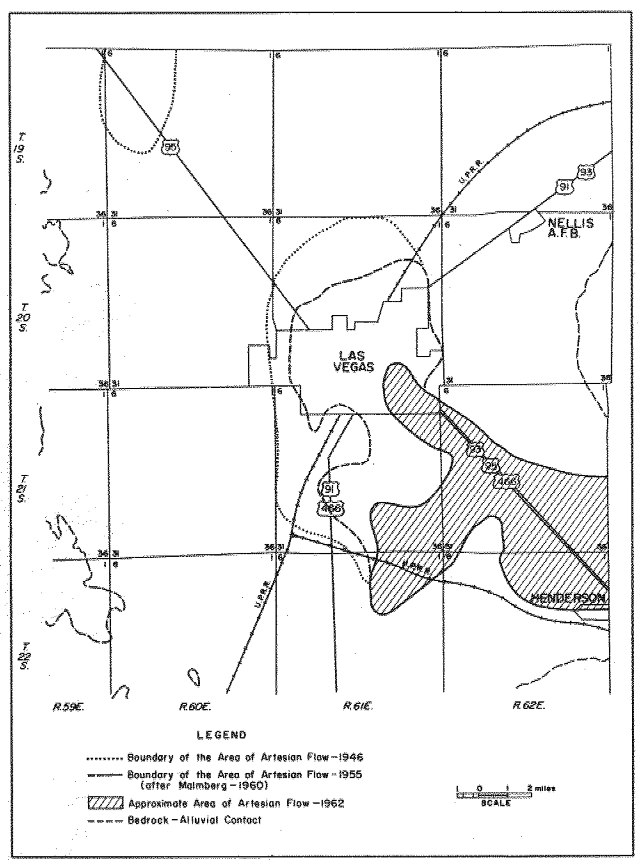


Figure 15. Areas of artesian flow, 1946 to 1963 (in part after Maxey and Jameson; Malmberg).

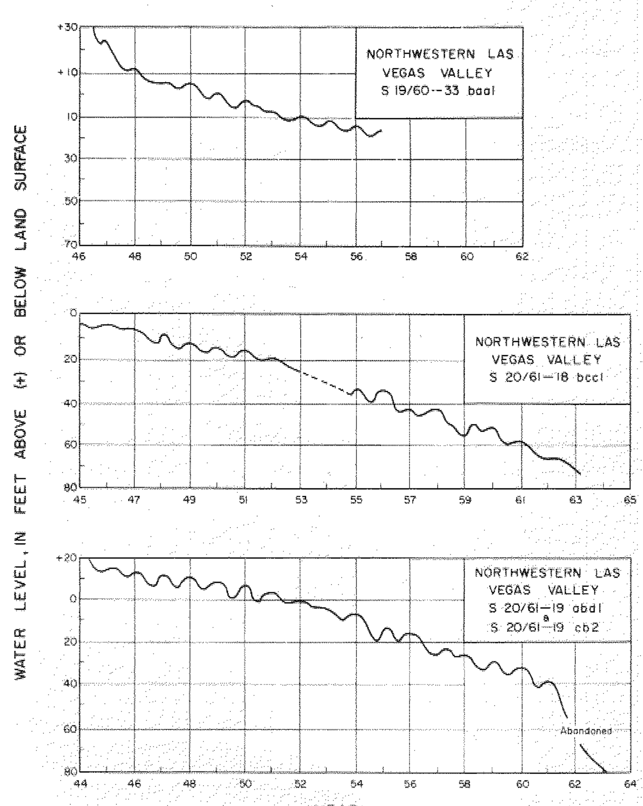


Figure 17. Water levels in wells in northwestern Las Vegas Valley.

January and February. Short-term fluctuations reflect intermittent pumping, day-to-day variations in pumping, and changes in atmospheric pressure. In general, water levels in wells reflect the seasonal use of municipal and quasimunicipal water (Fig. 15).

Comparison of potentiometric maps for the period 1912 to 1944 shows that water-level declines in western and central Las Vegas Valley approximated 1 foot annually. Elsewhere in the valley, the rate of decline was considerably less. The average annual rate of water-level decline for the period 1944 through 1963 is given in Table 6.

TABLE 6

Rate of Decline in Nonpumping Water Levels, 1944–63

Pumping Area	Avg. annual decline, ft. 1944–56	Avg. annual decline, ft. 1956–63
Western Las Vegas Valley	3.5	5.5
Northwestern Las Vegas Valley	2.5	3.5
Central Las Vegas Valley	2.0	4.0
Eastern Las Vegas Valley	1.0	5.0
The Strip	3.0	4.0
Paradise Valley and Northern Boulder Highway	1.5	1.5

From 1944 to 1956, water levels in wells in western Las Vegas declined about 3.5 feet per year. Total decline in this area over this period was over 40 feet. The high rate of decline is attributed to increased pumping from the Las Vegas Valley Water District well field. At the end of this period, most of the wells in this area were still flowing. During the period, 1956 to 1962, the rate of decline increased to 5.5 feet per year. The increased rate of decline is attributed to increased pumpage in the District well field plus the effects of previous pumpage.

In northwestern Las Vegas Valley, the rate of decline of water levels for the period 1944 to 1956 was about 2.5 feet per year. During the period 1956 to 1962, the rate increased to about 3.5 feet per year. The increased rate is attributed mainly to the new development of ground water in this area plus the increased withdrawals in the District well field and the increase in pumpage at Tule Springs.

In central Las Vegas Valley, the annual rate of water-level decline increased from 2 to 4 feet. Most of the wells underlying the City of Las Vegas are characterized by water levels rising to a few feet from ground surface. The increased rate of decline is attributed to increased pumpage in this area, to pumpage increases in the District well field, North Las Vegas, and the Nellis Off-Base well field on Craig Road. The annual rate of decline

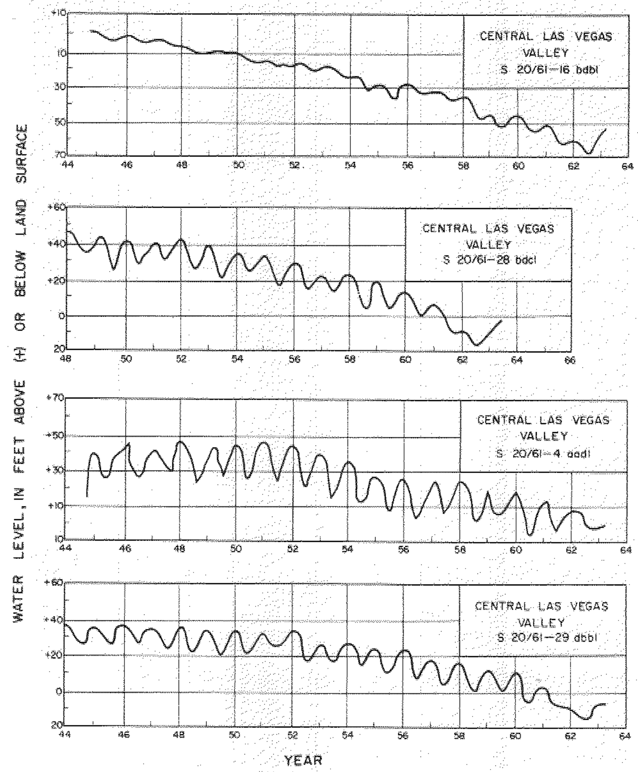


Figure 18. Water levels in wells in central Las Vegas Valley.

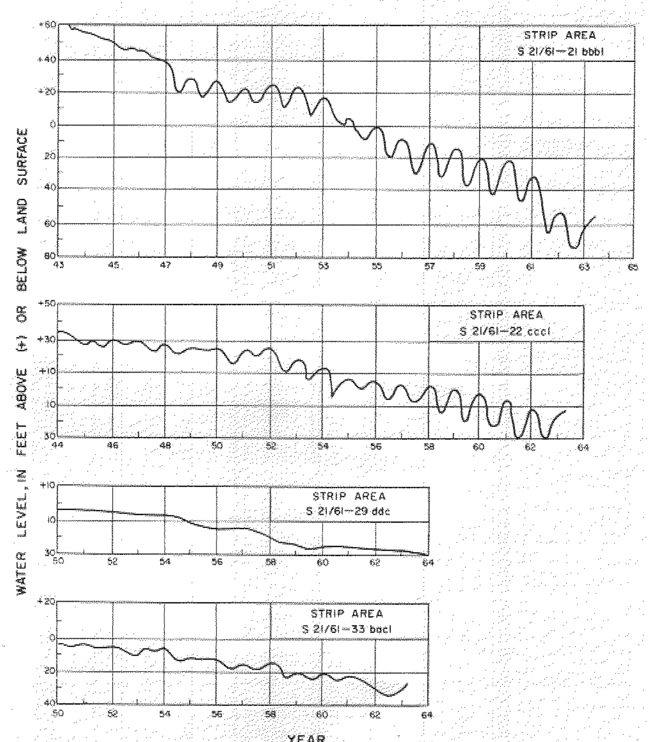


Figure 19. Water levels in wells in the Strip area.

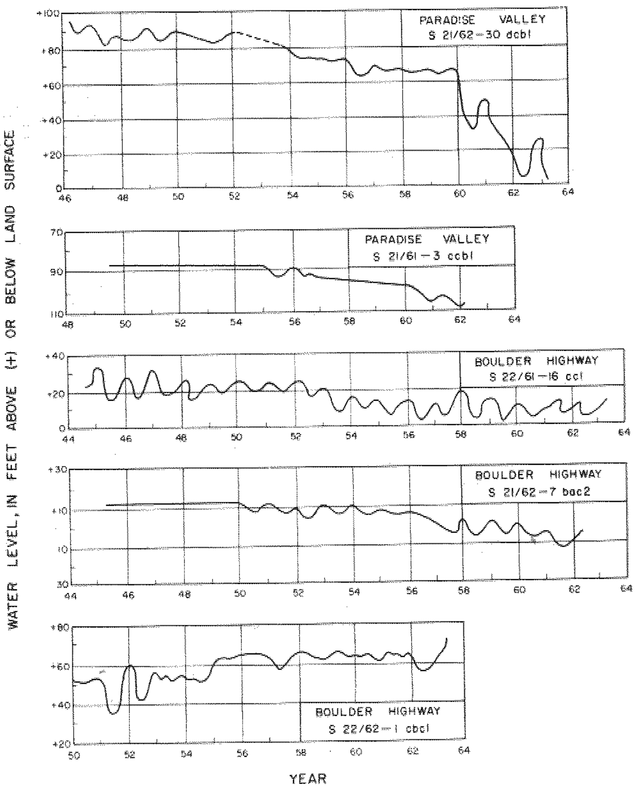


Figure 20. Water levels in wells in southern and southeastern Las Vegas Valley.

in the vicinity of the Off-Base well field increased from 3 to over 5 feet.

Although representative hydrographs for the period of record are not available for eastern Las Vegas, the rates of water-level decline are known from occasional water-level measurements. During the period 1944 to 1956 water levels declined about 1 foot per year, except for the Nellis Air Force Base area, where the rate of decline was about 2.5 feet per year. The large increase over the period 1956 to 1962 is due mainly to the development of additional ground water by North Las Vegas, especially in the last 3 years. In the vicinity of the North Las Vegas wells water levels have declined over 60 feet since 1956.

In the Strip area, the rate of decline increased from 3 feet per year between 1944 and 1956 to 4 feet per year, largely due to pumpage increases at the resort hotels and golf courses, and in the District well field.

In the Paradise Valley and northern Boulder Highway area, the water levels declined about 1.5 feet per year during the period 1944 to 1956. The rate of decline has remained about the same over the period 1956 to 1962. As the total pumpage from this area has not increased materially over the past 20 years, the effects of pre-1956 pumpage in the area are probably very small and the steady rate of decline must be attributed to effects of increased pumpage elsewhere in the Valley. Water levels in the near-surface sediments rose along southern Boulder Highway between 1944 and the present as a result of infiltration of waste water from Henderson.

Potentiometric Surface Maps

The potentiometric map illustrates the level to which water will rise in wells. It is, in essence, a projection of the three dimensional flow field upon an arbitrary horizontal plane. Quantitative deductions are often made from this graphical presentation and are valid only if the confining beds are horizontal (or nearly so) and impermeable. Under these conditions flow is everywhere tangential to the impermeable boundaries, and is two dimensional as assumed.

The inherent assumption in this concept are hardly valid in Las Vegas Valley. Vertical direction is one of the principal components of ground-water movement. Further, the potentiometric surface, being one single imaginary surface related to one aquifer, is not mappable as such in Las Vegas Valley; potentiometric measurements as observed in wells of varying depths reflect the composite of varying potentials with depth. Nevertheless, the potentiometric surface qualitatively indicates the lateral direction of ground-water movement and provides a base of reference to which longterm records of changes in composite water levels may be referred.

The estimated potentiometric surface in its natural state prior to development by man is shown in Figure 10. Early development of the water supply led to subsequent changes in ground-water levels, and distortion of the ground-water flow field. For purposes of this report, the period of early ground-water development is considered to be the period of record in which total annual ground-water withdrawals were approximately uniform, that is, from 1924 to 1941 (Fig. 11).

The potentiometric surface of the ground-water system in 1944, after a few years of increased development, is shown in Figure 21. In addition to a general lowering of water levels throughout the valley, the initial formation of extended cones of depression are shown in western and central Las Vegas Valley.

From 1944 to 1963, water levels declined appreciably in Las Vegas Valley as a result of increased ground-water withdrawals. Figure 22 shows the

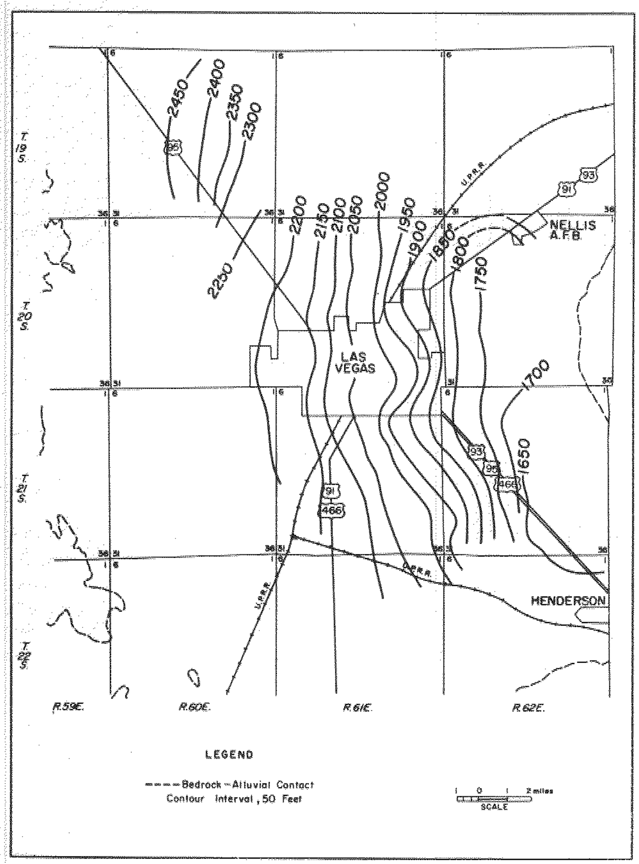


Figure 21. Approximate elevation of the potentiometric surface, Spring 1944 (after Maxey and Jameson).

piezometric surface in 1955 well into the period of increased ground-water development. The deepest cone of depression is in the Las Vegas Valley Water District well field. The steeply inclined eastern slope of the cone, as opposed to the gently inclined western slope, is the result of the unequal transmissivity of the sediments. Other pronounced cones are centered in major pumping centers, but are not as obvious because of map scale.

The most recent potentiometric surface to be considered in this report is for early 1963, Figure 23. Most noteworthy is the continued growth since 1944 of the cone of depression in the Las Vegas Valley Water District well field, and the more recent (post-1956) cone of depression developed in North Las Vegas. The asymmetric nature of the cone of depression in western Las Vegas Valley again appears.

The potentiometric surfaces for 1955 and 1963, and to a lesser degree, 1944, are not truly representative of non-pumping water levels because pumpage in the valley did not stop completely during any measured period. They do, however, show the water-level configuration in non-pumping wells during the annual period of minimum ground-water withdrawals.

Change in Water Levels

Comparison of the potentiometric surface map for the year 1912 with the potentiometric surface map for 1944, and computation of water-level changes shows the approximate change in water levels that occurred from the selected pre-development period to a few years following the beginning of increased ground-water development, Figure 24. The greatest decline of water levels over this 23-year period occurred within the present area of principal development, indicating that major pumping centers did not shift to a great degree since 1912. Although no great accuracy is presumed in the construction of Figure 24, the order of magnitude of water-level decline is representative and is worthwhile presenting in order to compare the effects of various periods of ground-water development.

The second period of interest in relating pumpage to water-level decline is the period of increased ground-water extractions. Figure 25 shows the

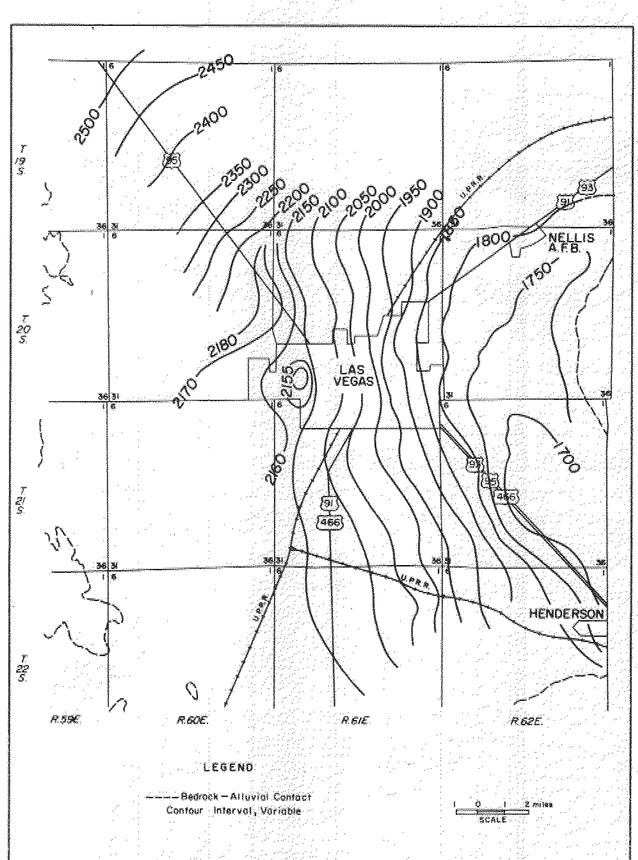


Figure 22. Approximate elevation of the potentiometric surface, February 1955 (after Malmberg).

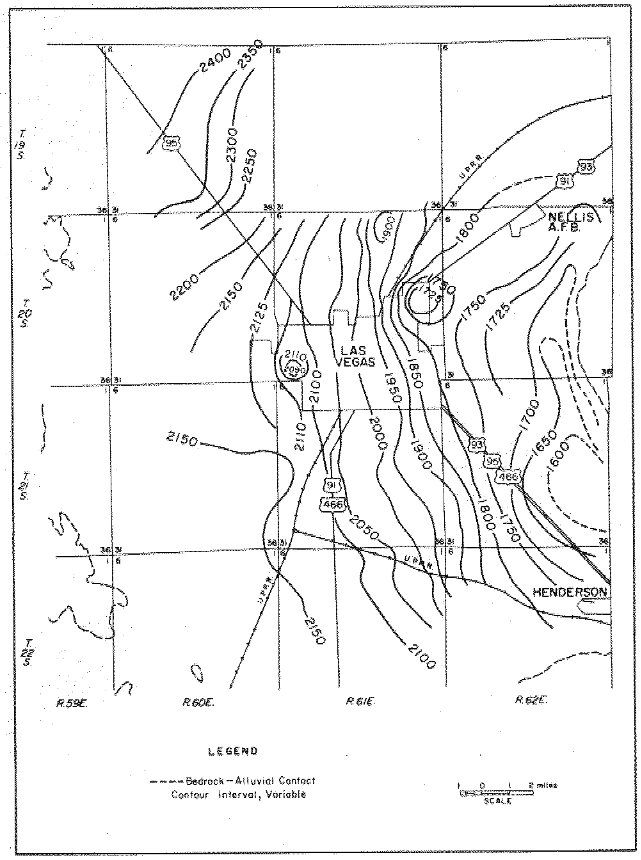


Figure 23. Approximate elevation of the potentiometric surface, January-February 1963.

approximate change in water levels that occurred from 1944 to 1963, which includes most of the period of increased ground-water withdrawals. The effects of long-term development in the western and south central parts of the basin as well as the effects of more recent ground-water extractions in the eastern part of the basin are clearly shown.

A recent period of water-level change within the period 1944 to 1963 is shown on Figure 26. The figure shows the change in water levels over the period 1956 to 1963, and demonstrates clearly the effect of increased ground-water development in the North Las Vegas area.

OTHER EFFECTS OF GROUND-WATER WITHDRAWAL

The withdrawal of ground water from aquifers can result in detrimental effects other than decline in water levels. These include chiefly reduction of well yield due to excessive interference and land-surface subsidence brought about by the effects of fluid withdrawal. In Las Vegas Valley, ample evidence suggests that both of these effects have occurred in various degrees.

Decrease in Well Yields

The yields of individual wells within the area of influence of most of the cones of depression shown on Figure 23 are known to decrease with time. In a few instances, pumping levels in some of the wells have been lowered below the top of the bowl setting, and production has been stopped. This well interference causes increased pumping lifts and decreases available drawdowns and is present to some degree in all major cones.

In the original North Las Vegas well field, individual cones of depression caused by 15 producing wells have coalesced, resulting in one large cone with enclosed low points at the centers of the main pumping wells. To demonstrate the effect of mutual interference between wells, average pumpage figures have been processed for nine representative municipal wells within this area covering the peaking period (May through August) for the period 1959 to 1962. Selection of the peaking period only for comparison is based on the fact that total output of the well field during peaking periods has been consistently inadequate to meet water demand making it necessary to purchase

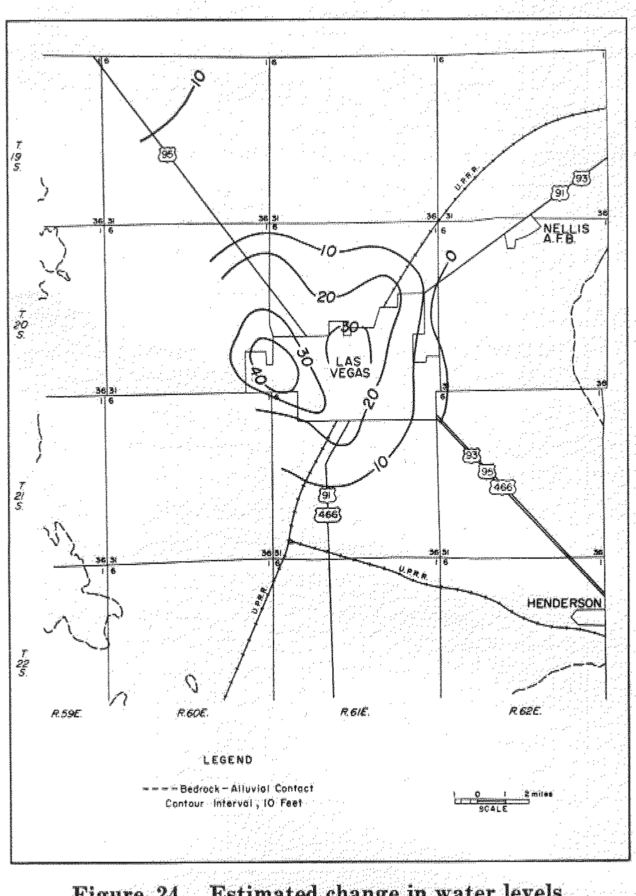


Figure 24. Estimated change in water levels, 1912 to Spring 1944.

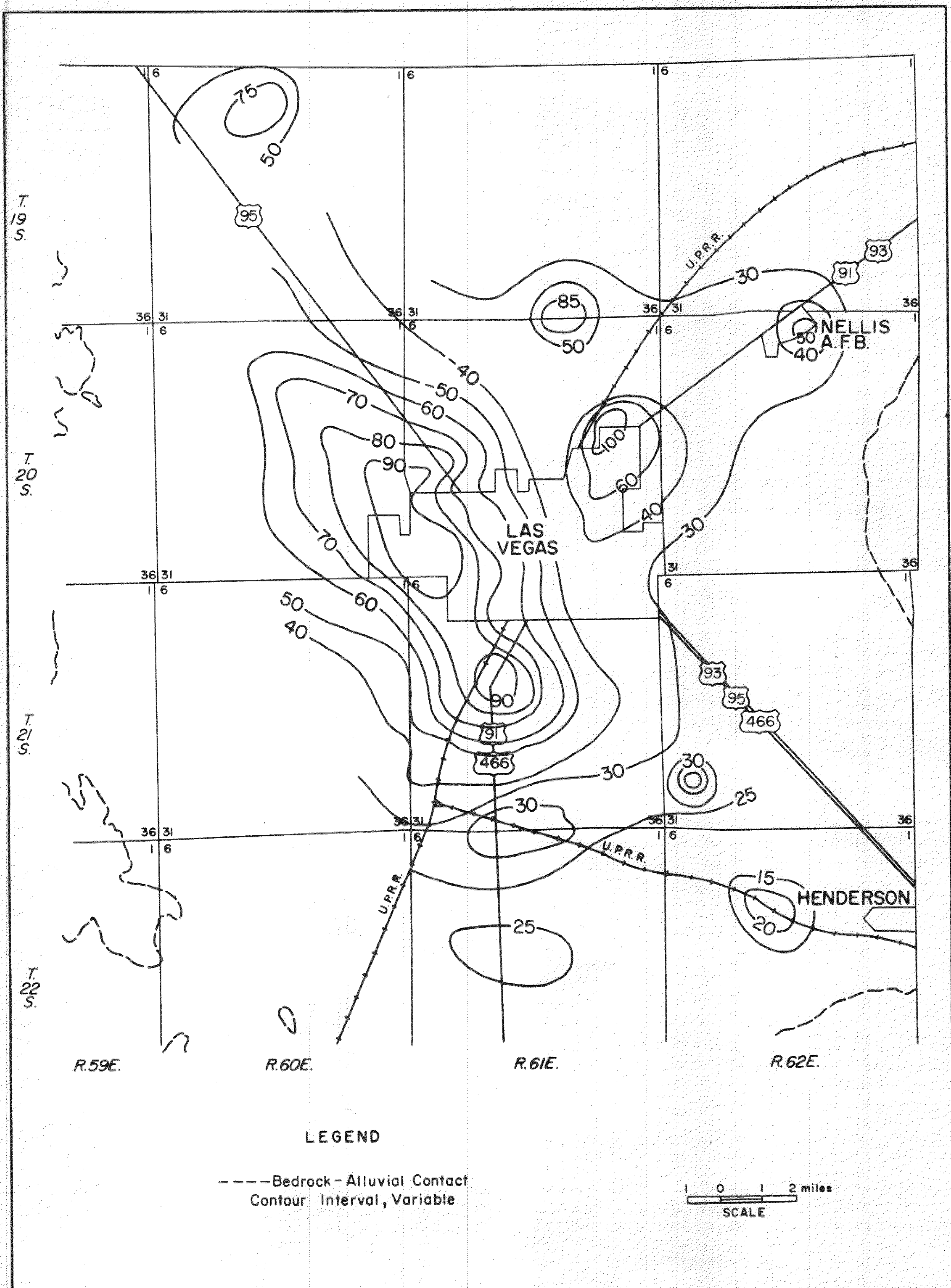


Figure 25. Estimated change in water levels, Spring 1944 to January-February 1963.

additional water. It is certain that the wells were not intermittently pumped, but continually produced at their maximum output during the peaking period. Six of the 15 wells were purposely omitted from the comparison because of inconsistent production due to abandonment, deepening, or temporary renovations at some time during the period 1959 to 1962.

The figures in Table 7 indicate that the cumulative yield during the peaking period decreased by about 8 percent per year. Inasmuch as the specific capacity of the wells was not materially altered over that period, the decrease in yield is attributed mainly to increased pumping lifts without commensurate increase in motor horsepower and to decreases in available drawdown, both of which limit well yield in that area. Table 7 also shows that in all but one instance the individual May and June production exceeded production during the peak month of July. Thus, both cumulative and individual monthly production shows a decrease in yield with time.

TABLE 7

Pumpage in Millions of Gallons, From Nine Municipal Wells in the North Las Vegas Well Field During the Peaking Periods of the Years 1959 to 1962.

	May	June	July	August	Total
1959	69.55	70.50	66.41	64.49	270.95
1960	64.97	60.73	61.89	58.86	246.45
1961	60.94	56.38	50.53	53.27	221.12
1962	54.51	53.37	51.04	51.10	210.02

Although pumpage figures for the other major water producers in the Valley are not as readily analyzed, it is known that similar effects have occurred at both well fields operated by Nellis Air Force Base, and at the municipal Las Vegas Valley Water District well field.

Solutions to this problem by manipulating horsepower requirements and bowl settings, or increasing well depths, are only temporary. For this reason, major water developers have only recently expanded their facilities outside areas of major extraction. The effect of concentrating too many production wells in an area was the prime motivator for this expansion which will result in a more suitable pattern of development in the future.

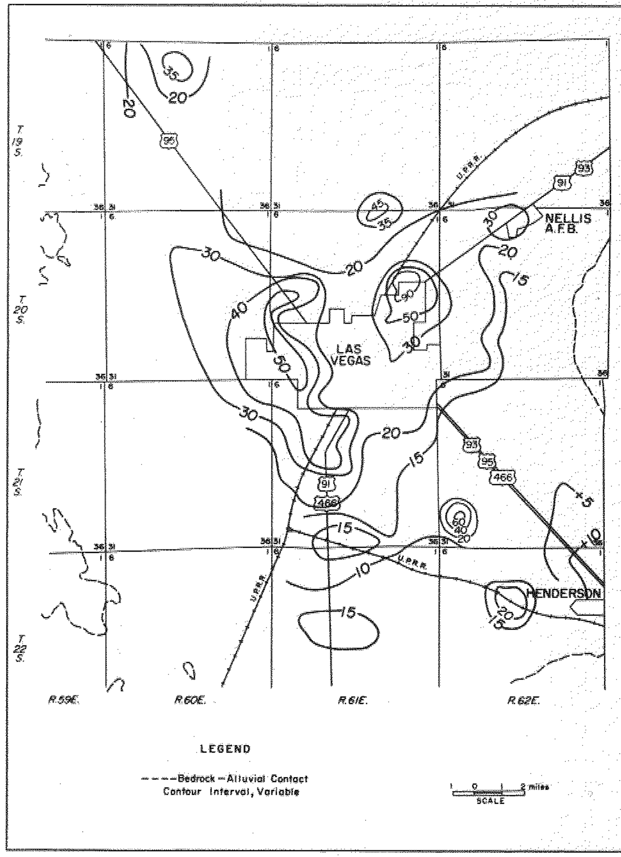


Figure 26. Estimated change in water levels, January 1956 to January-February 1963.

Land-surface Subsidence

Land-surface subsidence in heavily pumped artesian basins is relatively common and is often related to changes in the distribution of stresses brought about by fluid withdrawals. Noteworthy cases of appreciable land-surface subsidence attributed to this cause have been reported in California (Poland and Davis, 1956; Poland, 1960) and parts of Texas (Winslow and Wood, 1959). The geologic requisites and qualifying conditions for the occurrence of subsidence are so well adapted to most alluvial basins in the arid western United States that it is likely far more occurrences of this phenomenon have taken place than have been reported. The chief reason for this is the lack of close control of benchmarks necessary to detect small changes in land-surface altitude.

Since the establishment of an extensive benchmark network in 1935 by the U.S. Coast and Geodetic Survey, a broad belt of regional subsidence over an area of about 8,000 square miles has been revealed in Southern Nevada and parts of adjoining states. Although various possible causes have been considered, at least some of the settlement and conspicuous pattern of subsidence has been attributed to the load of Lake Mead (U.S. Geological Survey Prof. Paper, 295, 1960). Since the benchmark network was not established prior to the filling of Lake Mead, it is not possible to determine how much of the regional tilting of the land surface had occurred prior to the water and sediment load.

According to studies by the U.S. Geological Survey, the regional tilt of the land surface during the period 1935 to 1941 was to the southeast. A larger area was affected during the period 1941 to 1950 and the regional tilt shifted to the southwest. Superimposed upon the regionally affected area, a localized bowl of subsidence in Las Vegas Valley has expanded at a greater rate than that of the accompanying regional subsidence. In 1950, the benchmark showing maximum subsidence in Las Vegas Valley showed a change in land-surface altitude almost twice the magnitude of any recorded change within the region. This is so despite the fact that Las Vegas Valley is along the western margin and at least 33 miles from the focal point of the regionally affected area.

Observational data available to study land-surface subsidence in Las Vegas Valley include all first-order leveling results by the U.S. Coast and Geodetic Survey. First-order leveling was initiated in 1915. A second survey was run in 1935. The benchmarks set in 1935 were releveled in 1940 to 1941, and again in 1949 to 1950. Additionally, a second-order survey was conducted in 1957 on a limited number of benchmarks. The regional network of benchmarks was releveled in the spring and summer of 1963. Comparison of the results of leveling in the vicinity of the City of Las Vegas in 1915 and 1935 (pre-Lake Mead) first revealed the changes in land-surface altitude (Maxey and Jameson, 1948). The settlement as determined at four benchmarks in the city ranged between 2 (51 mm) and 3 inches (76 mm). Northwest of the city the settlement was less than 1 inch (25 mm). Benchmarks farther from the valley axis showed little or no settlement.

A comparison of the results of later surveys shows an accelerated rate of subsidence in the affected area. Maximum subsidence recorded during the period 1935 to 1950 was 349.9 mm (approximately 13.5 inches). During the period 1950 to 1957, maximum subsidence was 231 mm (approximately 9 inches) and was recorded at a benchmark other than the one registering maximum subsidence during the earlier period of record. Maximum subsidence during the period 1957 to 1963 was 879 mm (approximately 34.5 inches).

In the late 1950's and especially in 1961, spectacular failures in the earth's crust have occurred near the axis of the valley. New fissures have been opened parallel to the scarp west of North Las Vegas, both near North Las Vegas and the Nellis Air Force Base Off-Base well field, and near the scarp in the Las Vegas Valley Water District well field near well number 5. According to Water District observations, the land surface in the vicinity of well number 5 subsided 2¼ inches from September 1961 to June 1962. The fissure in the vicinity of North Las Vegas is over one-quarter of a mile in length. The reported fissures are characterized not only by their close proximity to fault scarps, but by their location within areas of large ground-water withdrawals.

The accelerated rate of subsidence, the slight shift noted in its focal point, and its association with subsurface conditions favorable to compaction in areas subjected to relatively recent ground-water extractions and water-level declines, constitutes a plausable cause-and-effect relationship. Whether this relationship will hold under closer investigation; whether the process of subsidence materially contributes water to the underground reservoir and in what manner; and when, or whether the effects of land-surface subsidence will be economically intolerable are some of the objectives of a current investigation by the Desert Research Institute. This research, supported by National Science Foundation funds, will be completed in 1966.

ANALOG ANALYSIS OF PUMPING EFFECTS

Introduction

Karplus (1958) said, "To solve a problem of analysis is to determine the response due to a given excitation acting upon a known or fully specified system." In this study, we are concerned with the analysis of a hydrologic system, whose response to a disturbance or excitation, in this instance the pumping of wells, causes a change in water levels to which we relate an economic evaluation of the future of the hydrologic system as a source of useable water. The change in water levels is used as the common denominator between the system and its economic evaluation since the depth to and potential of useable water is generally of primary concern to the prospective user.

In many hydrologic systems the aquifers are relatively nonhomogeneous throughout the region of interest. Often their shapes and boundaries are far from regular, and streams, reservoirs and barriers to flow create intricate configurations of the force or potential field of the fluid flow. It is not possible to obtain and express quantitative geologic and hydrologic parameters to use competently in the solution for the effect of pumping on potentiometric head by means of mathematical models. Instead, experiments have shown that it is possible to find a one-to-one correspondence in equations describing hydrologic, thermal and electrical phenomena, such as the Laplace Equation, the Diffusion Equation, the Wave Equation or other mathematical relationships. Thus the vagaries of some natural phenomena may be isolated and their effects measured through the use of systems of similar performance to the less predictable natural systems. Two such systems are said to be analogous if there exists this one-to-one correspondence between each element as well as between the excitation and response functions of the elements and of the system as a whole. The term analog is sufficiently descriptive by definition to include the model of the hydrologic system and the principles behind the design of the model. The analogy of the descriptive differential equations for fluid flow and electrical "flow" as pertains to this report is the result of the similarity of these two systems.

In flow through constricted channels, viscous forces resulting from the friction of the fluid against the pore walls outweigh the inertial forces to such an extent that the latter may be neglected (as in the derivation of Darcy's law from the Navier-Stokes Equations of motion). Then, provided the fluid is compressible, the Diffusion Equation governs the hydrologic system. This results in a system of energy-dissipative elements and energy-storage elements, analogous to resistors and capacitors or inductors in an electrical network, respectively. The analogy's advantage over conductive liquid models lies in the fact that abrupt variations in field properties may be readily simulated as opposed to their more difficult representation in liquid analogies.

The electrical analogy of the flow of water in underground porous media owes its existence and development to many individuals. Skibitzke and members of the U.S. Geological Survey were instrumental in the design of workable aquifer-simulating models. In particular, B. J. Bermes (1960) has developed many specifications of accurate electric analogs of ground-water systems. W. J. Karplus (1958) and W. W. Soroka (1954) developed much of the theory of analog simulation. W. C. Walton and T. A. Prickett (1963) have applied the analog theory to case histories of ground-water development. The Kansas State Division of Water Resources under the direction of C. E. Nuzman has applied the analog theory to the recharge of aquifers by precipitation.

The electrical analog of the hydrologic system for Las Vegas Valley applies the time-varient or transient flow of ground water as simulated by the time-varying flow of current in electricity. In the model, the electrical resistance is inversely proportional to the coefficient of transmissibility of the aquifer and the electrical capacitance is directly proportional to the coefficient of storage of the aquifer. The resistance of the model changes the potential of the flow as the aquifer permeability reduces the potential of the moving fluid. The capacitor causes the associated voltage to rise linearly across its plates or dielectric as a function of time, analogous to the release of water from storage as the potentiometric head changes with time. The lack of inductors with suitable magnitudes and sufficiently small internal resistances economically prevents the utilization of a resistance-inductance network although such an analogy is identically suited, mathematically, for simulation of ground-water flow (Karplus, 1958).

The characteristics of the Las Vegas hydrologic system have been described previously in this report. Most of this data, in one form or another, has been incorporated in the construction and operation of the electric model. Figures 27 and 28 show the front and back of the Las Vegas Valley analog.

Procedure

In the application of electric analog models to hydrologic problems two periods of pumpage are of interest: (1) a predetermined interval extending from some point in past time when water levels in the reservoir were essentially stable to the present; (2) an arbitrarily selected interval extending from the present to some time of interest in the future. As the magnitude of ground-water development changes with time over the total interval of interest, numerous approximating functions such as step-type, sine-wave, or pulse waveform are required to simulate pumpage during each of the two main periods. Because the effect resulting from several pumping stresses acting simultaneously is equal to the sum of the effects which would be caused by different pumping stresses acting separately, the method of

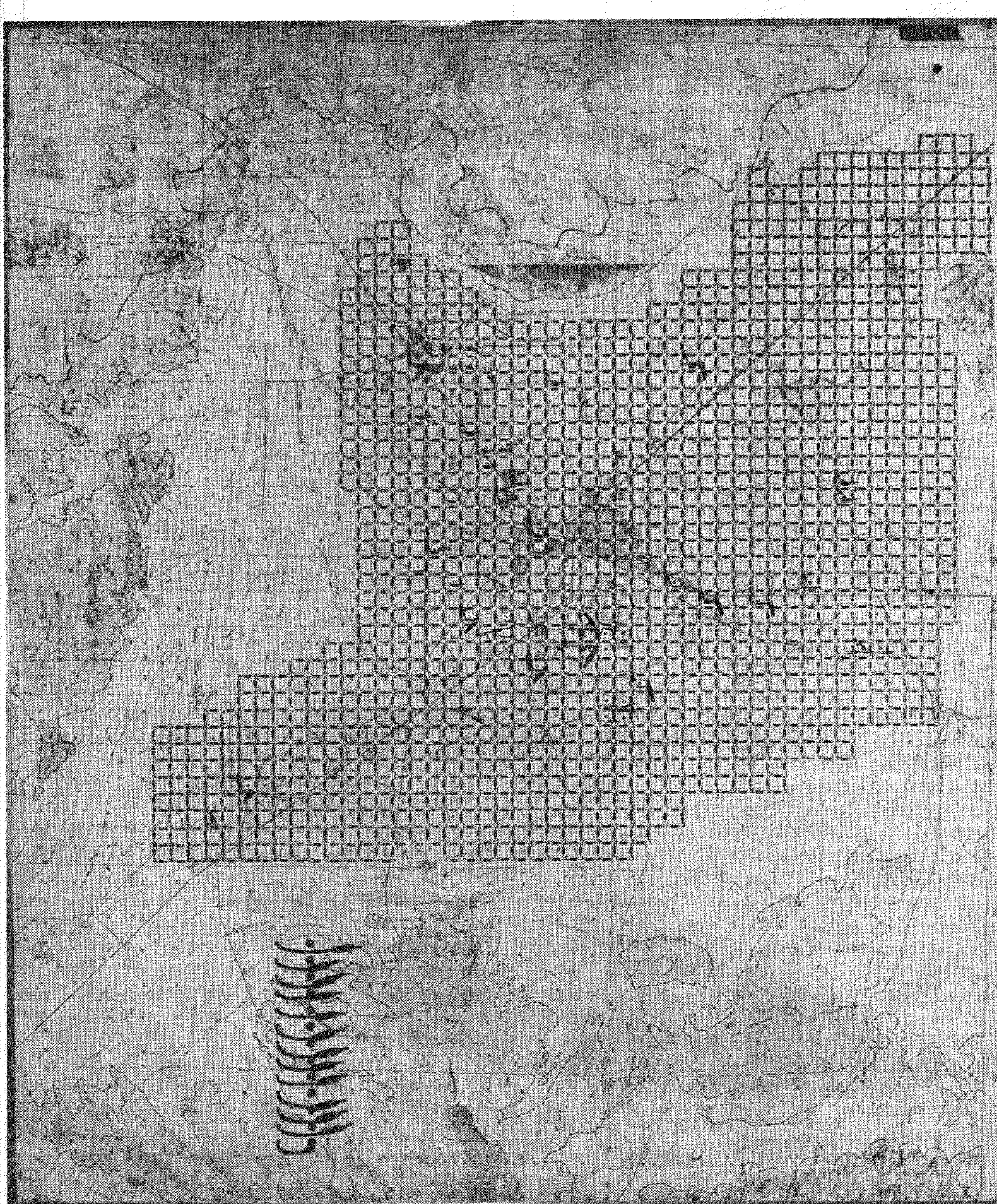


Figure 27. Front view of electric analog of Las Vegas Valley.

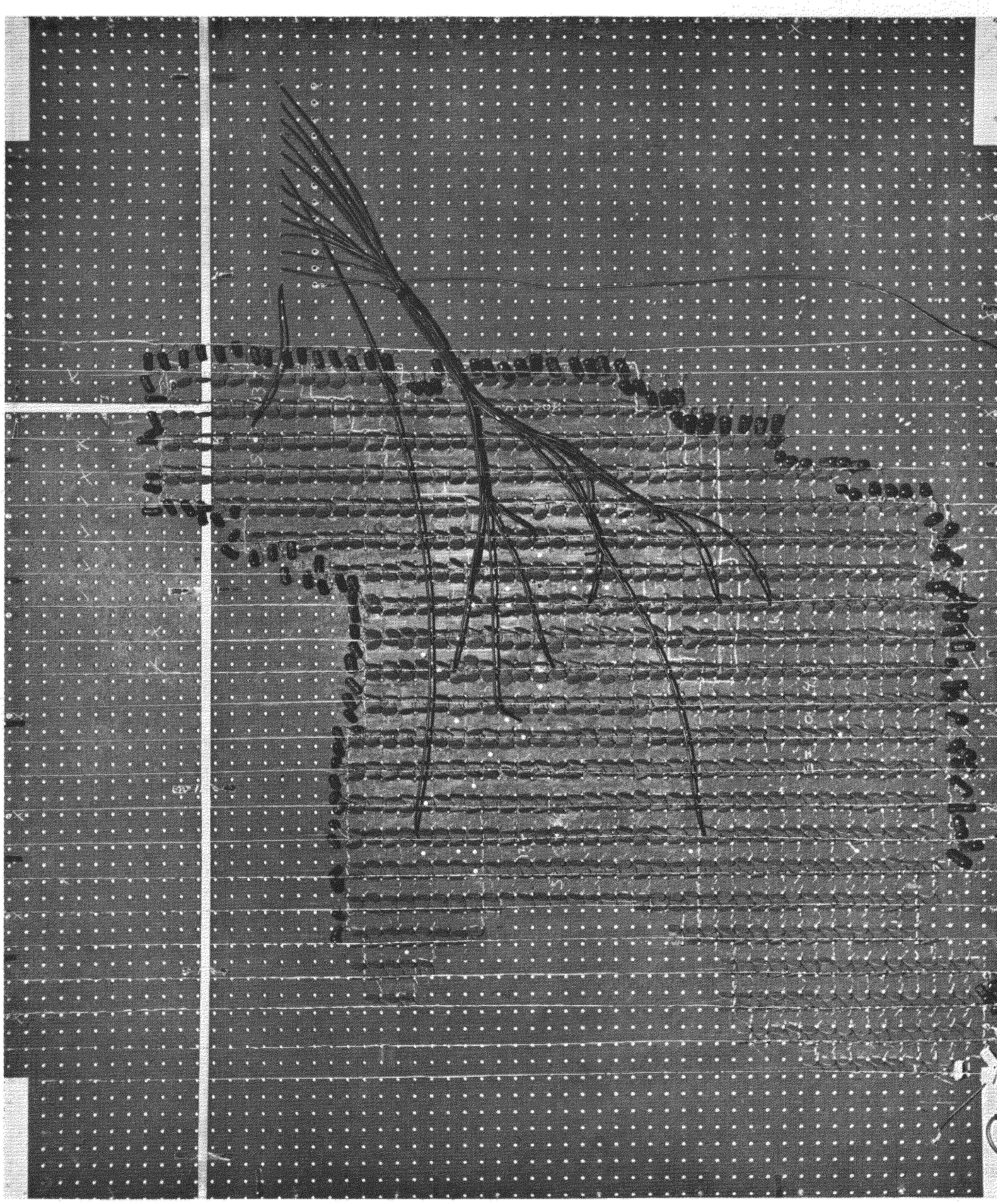


Figure 28. Rear view of electric analog of Las Vegas Valley.

superposition is the easiest method of calculating total energy-level changes.

Ground-water levels have not been in a state of equilibrium in Las Vegas Valley since the first artesian well was drilled in 1907. However, in view of the pumpage history, certain idealization may be justified to permit less rigorous simulation of past pumpage. This is diagrammatically illustrated in Figure 29 where the quantities of water pumped and to be pumped are approximated by a step-curve divided into segments along the time axis. The figure shows that prior to 1941, the rate of ground-water extraction was relatively uniform, as shown by segment A. It is reasonable to assume that most of the regional water-level response to early pumping was registered on pre-1941 potentiometric levels. Therefore, in this analysis, a condition of near-equilibrium is assumed to have existed previous to the increase in pumpage in the 1940's, and pre-1941 pumping effect on post-1941 water levels is considered to be negligible. Thus, the extension of pre-1941 pumpage represented by segment A′ (Fig. 29) is considered not to affect water levels. Changes in potentiometric levels over the period 1941 to 1963 are assumed to result from the increment in pumpage, shown in Figure 29 as segment B. The assumptions recognized in this section are not without error, especially locally where wells were added or abandoned late in the period of early development, but appear to be satisfactory for a regional analysis.

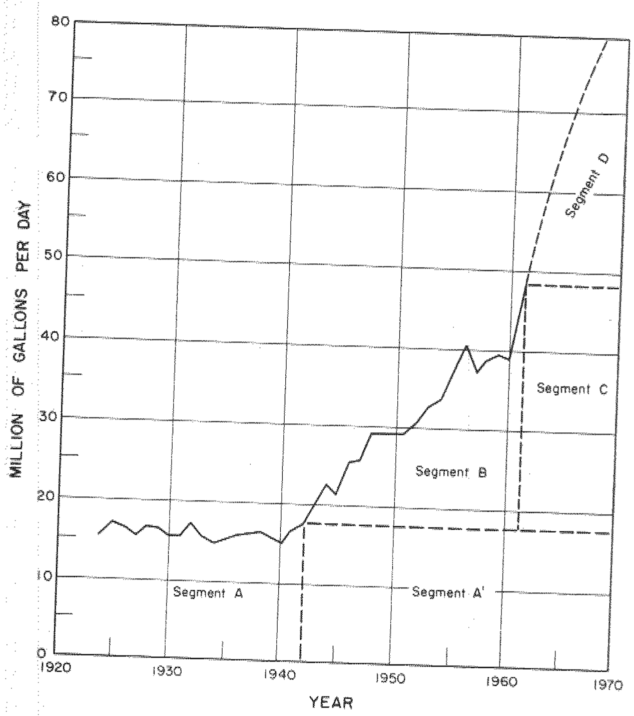


Figure 29. Method of approximating functions to simulate pumpage.

The regional changes in water levels that will occur over the period 1963 to 1970 depend on the transient behavior of water levels in response to pre-1963 as well as post-1963 pumpage. The procedure for analysis of the effects of this development is executed in the analog model with the aid of step functions, thus allowing a continuance of pre-1963 pumpage (illustrated as segment C in Figure 29) and the introduction of post-1963 pumpage (Segment D in Figure 29). Total drawdown is determined by superposition of increments.

Effect of Past (1941 to 1962) and Current (1962) Pumpage

Recapitulation of historic data provides a check on the accuracy of the modeled aquifer characteristics and boundary conditions. The historic data required are water-level change and pumpage identified in terms of rate, place, and time. The response of the electric model to excitation can be compared with the response of the ground-water system as measured in the field. If the comparison is favorable, that is, if the model faithfully recapitulates the past performance of the ground-water system, it can then be used to predict water-level response to new pumping stresses with approximately the same degree of accuracy.

Figure 30 shows the model recapitulation of water-level change over the period 1944 to 1963. Comparison of these results with the response of the ground-water system measured in the field over this same period (Fig. 25) is very close. Slight discrepancies occur north of the Las Vegas Valley Water District well field, in the Nellis Off-Base field, and the North Las Vegas area. These differences are minor, however, and further adjustment of the electrical network will not change appreciably the degree of accuracy. Indeed, the field data available to construct the actual change in the water-level map is sparse and not necessarily accurate to this degree.

The effect of a continuance of a segment of pre-1963 pumpage can be analyzed and presented graphically by a map showing predicted changes in water levels over a given period. Figure 31 shows the anticipated change in water levels in Las Vegas Valley as determined by the electrical analog model over the pumping period 1963 to 1969 if the following assumptions are made: (1) the annual pumpage over the period analyzed

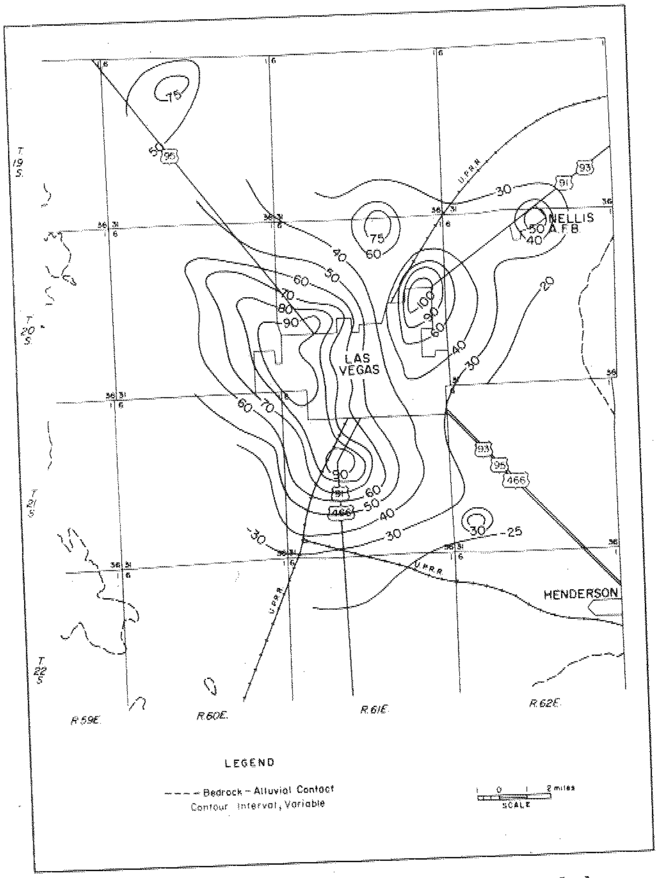


Figure 30. Analog recapitulation of water-level change, pumping period 1944 to 1962.

remains essentially the same as the pumpage in 1962; and (2) the points of ground-water extraction over the period analyzed remain essentially the same as the 1962 points of extraction. The water-level change map (Fig. 31) illustrates the combined effect of continuing decline as a result of pumpage from 1941 to 1962 plus the decline resulting from pumpage between 1963 and 1969 projected at the 1962 rate. If pumpage does not continue at the 1962 rate but increases from year to year, water-level changes will be greater than shown on Figure 31. As it is reasonably certain that pumpage will not decrease over the 1963 to 1969 period, Figure 31 shows the minimal change in water levels to be expected. Figure 31 shows the water levels as they would appear in non-pumping wells during the season of minimal pumping. Pumping-level changes will be approximately of the same magnitude.

Forecast of Water Requirements and Sources

At present, the principal source of water in Las Vegas Valley is the underground reservoir, augmented by a small amount of water imported from Lake Mead. Unprecedented growth since 1941 and especially in the last 5 years has caused considerable concern over the status of the ground-water reservoir. Plans for water importation have recently been implemented and estimates of the date of completion of the first stage of pipeline construction range from 1968 to 1970. Under the project plan, present distributors will contract for a supply of surface water and use ground water only for peaking. Bureau of Reclamation officials estimate that approximately 46,000 acre-feet of water annually will be withdrawn from the basin for peaking purposes after completion of the first stage of the project. (Bureau of Reclamation, 1963).

According to the Bureau of Reclamation officials, future population to be served by the Las Vegas Valley Water District, City of North Las Vegas and the Nellis Air Force Base facilities will increase from 193,000 in 1970 to 418,000 in the year 2000. Using U.S. Bureau of the Census

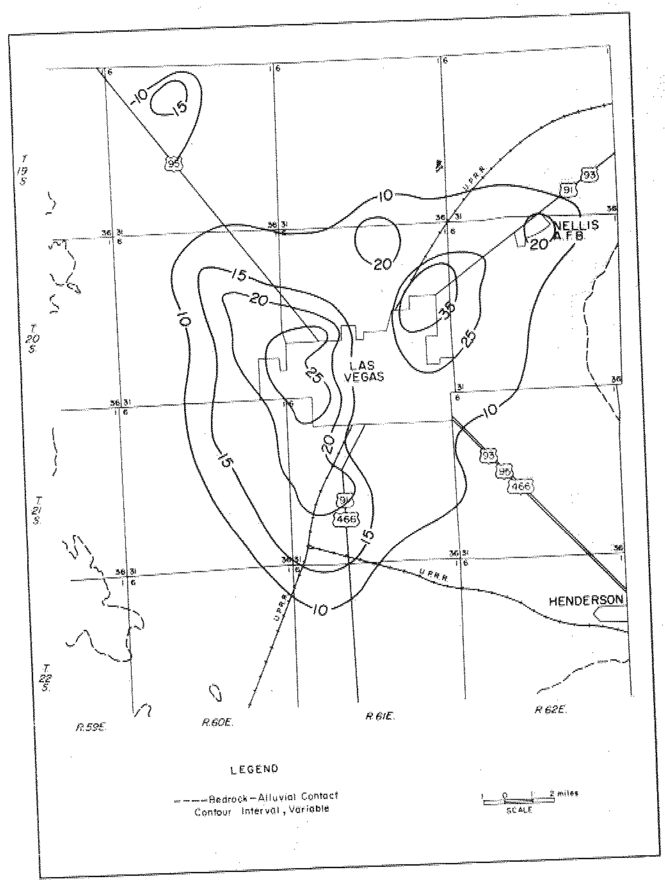


Figure 31. Water level change from 1963 to 1969, caused by the residual effect of pumpage from 1941 to 1963 and the effect of pumpage between 1962 and 1969 projected at the 1962 rate.

estimates for 1960 and 1962 population as reference points, this prediction may be low, at least until 1970.

Among basic factors in the determination of conjunctive use of surface and ground water are an understanding of both the ground-water system in the valley and the pipeline project, the latter including data on delivery schedules and distribution. As these factors are still in the planning stage, any predictions at this time are conjectural. However, after water is imported, it is certain that the time, rate, and points of ground-water extractions will be materially altered. Further, it is reasonably certain that the period 1963 to 1970 will continue to be one of rapid growth sustained primarily by ground-water supplies. Based on these factors a forecast of the consequences of increased withdrawals from the aquifers for water supply during the period 1963 to 1970 is a reasonable starting place in the analysis of a very complex and temporarily indeterminate problem. Therefore, this report considers possible effects of withdrawal on the ground-water levels only to 1970.

LAS VEGAS VALLEY WATER DISTRICT SERVICE AREA

The Las Vegas Valley Water District includes about 300 square miles extending from somewhat south of Henderson to a mile or so north of Tule Springs. However, all of this area is not now served by the district. Actually, only the City of Las Vegas, the area immediately contiguous to the west and south, and a few outlying areas receive water from the district. Within the district boundaries are the City of North Las Vegas, the City of Henderson, and Nellis Air Force Base which have independent water supplies, all except Henderson depending upon ground water.

Pumpage by the Las Vegas Valley Water District increased from 17,570 acre-feet in 1955 to 25,830 acre-feet in 1962. In 1962, the district used about 4,080 acre-feet of Lake Mead water and sold about 815 acre-feet to North Las Vegas. In 1963, the pumpage increased to 28,807 acre-feet, and 6,426 acre-feet were imported from Lake Mead. Gross water requirements for the Las Vegas Valley Water District Service Area in 1970 are estimated at about 86,000 acre-feet (28,000 million gallons). This estimate includes total water requirements in the 300 square-mile service area except requirements satisfied by North Las Vegas and Nellis Air Force Base.

Nearly all of the district withdrawals have been from 13 wells in the main district well field in the western part of the City of Las Vegas. During the course of this investigation, the following additional facilities have been added to the system:

1. Two wells have been drilled in the main well field with a total tested capacity of about 5,000 gallons a minute. These wells started producing water in 1963.

2. Four wells have been drilled south and west of McCarran Field. Total tested capacity is about 3,500 gallons a minute. Distribution lines lead from this well field to the southern part of the Strip. Production will start by July, 1964.

3. Two wells have been completed a few miles west of the main well field and will be in production by mid-1964. Combined production is about 5,000 gallons a minute. These wells will be used to supply the high-level areas to the west and northwest.

4. Two wells a few miles north of the main well field are scheduled to supply the west and northwest parts of the service area by mid-1964. Combined production is about 5,000 gallons a minute.

Despite the additional facilities listed above and the addition to the system of numerous wells formerly operated by local water companies within the service area, estimated water requirements to 1970 exceed present total production estimates. This is due chiefly to the large quantities of water required during peaking seasons and the lack of sizeable storage facilities. Based on present knowledge of subsurface conditions, it is reasonably certain that most of the additional pumping facilities to be constructed during the next few years will be west and northwest of the main well field.

CITY OF NORTH LAS VEGAS MUNICIPAL SUPPLY

The North Las Vegas service area recently expanded from less than seven square miles just east of Las Vegas to about 42 square miles east and north of Las Vegas. The area is surrounded by the Las Vegas Valley Water District and includes most of the territory north of Las Vegas as far west as U.S. Highway 95, in a strip about five miles wide.

Pumpage by North Las Vegas increased from about 2,051 acre-feet in 1955 to 4,508 acre-feet in 1962. In 1962, North Las Vegas purchased 815 acre-feet from the Las Vegas Valley Water District. In 1963, pumpage increased to 5,462 acre-feet and the imported water decreased to about

642 acre-feet. Gross water requirements for the North Las Vegas Service Area in 1970 are estimated at about 14,600 acre-feet (4,760 million gallons). This estimate includes the total water requirement of the 42 square-mile service area.

In 1962, the City of North Las Vegas had 21 wells, practically all of which were within the original 7-square-mile area. Most of these wells have a low capacity, and up to 20 percent of the water used in North Las Vegas during the peaking period has been supplied by the Las Vegas Valley Water District. To meet expected water requirements, an intensified drilling program has been conducted over the past two years. Five wells have been drilled, two in the northern part of the service area, two in the western part of the service area east of U.S. Highway 95, and one within the main service area. In addition, at least two wells just north of the main service area have been purchased from private owners, and are now in production.

OTHER AREAS

Important areas of extraction other than the two major entities discussed above include Nellis Air Force Base, Tule Springs, the Strip, and Paradise Valley. These areas are briefly discussed in the following paragraphs.

Nellis Air Force Base has developed a ground-water supply from two well fields, one within the confines of the base and the other about 5 miles west of the base (the Off-Base well field). Quantities of water pumped from each field have been more or less equal since 1956.

Pumpage at Nellis Air Force Base increased from 1,324 acre-feet in 1955 to 2,068 acre-feet in 1962. In 1963, the pumpage increased slightly to 2,100 acre-feet. Gross water requirements for Nellis Air Force Base in 1970 are estimated at about 2,760 acre-feet (900 million gallons).

It is not possible to predict with any degree of accuracy the future development of ground-water within the other pumping entities in the valley either in time or place. In view of the historic and present development in the valley, however, certain speculations may not be unreasonable. For example, the development of additional irrigation water in the Tule Springs area is unlikely. However, the high productivity of the aquifers in that area present certain advantages to both major water utilities, and near-future development of municipal water may be a result. On the other hand, there is certain to be an increase in the use of irrigation, quasi-municipal, and domestic water in the Paradise Valley region, but extractions will be small and points of diversion widely scattered. Amounts and quality of the available water probably will limit large-scale production in Paradise Valley.

Certain pumpage increases in the Strip are likely as a result of expanding recreational facilities, but net increases in extraction may be inconsequential. The Las Vegas Valley Water District is now distributing water to entities that formerly developed their own, and the acquisition of additional accounts is certain.

According to the estimates given above, total water requirements for the area considered in this report for the year 1970 will be about 103,360 acre-feet and about 96,000 acre-feet in 1969. The latter represents an increase of about 41,000 acre-feet over the 1962 pumpage. These estimates do not include imported water through the B.M.I. pipeline for use in Henderson.

Effect of Increased Pumping

NONDIMENSIONAL ANALYSIS

Although increments in rate of future withdrawals have been estimated and locations of many additional pumping centers have been ascertained, the relationships between the two in time are unknown. That is, there is no way to determine the actual rate of pumping or increases in pumping for each new center, or exactly when this pumpage will occur. Some of these problems may at least in part be circumvented by analyzing alternate plans of development and evaluating the consequences of each plan. For this approach, a nondimensional analysis of drawdown is often the most useful (Skibitzke and da Costa, 1962). Contour maps representing proportional drawdown for specified periods of time may be constructed and any pumping rate for that period of time can be assumed and its effect analyzed. The analysis is made by relating the nondimensional contours with pumpage data. Where the water-level effects resulting from two or more pumping centers overlap, total drawdown is determined by adding the effects of each. As demonstrated by Skibitzke and da Costa (1962), it is expedient to assume that the withdrawal of water is concentrated at a point within the pumping center. The solution obtained therefore pertains only to regional water levels at some distance from the pumping center and to interference between pumping centers, but may not be applicable to local problems within a pumping center.

The contours shown in Figure 32 represent drawdown conditions for three pumping centers for a continuous two year pumping period. The contours show the proportional drawdown only. Any amount of water within the physical limits of the aquifer may be withdrawn from the selected points for two years and the proportional drawdown will remain the same. In Figure 33 the nondimensional contours have been given dimensional significance. In this analysis it is assumed that 1,580 million gallons represents total annual production, equally distributed between the three pumping centers. If annual pumpage is only one-half of the assumed rate, the water-level change represented by each contour would be only half as great as that shown. The response of different parts of the ground-water system to similar pumping stresses is not the same, as is evident in the figure.

The effect of numerous points of withdrawal for various periods of time have been analyzed

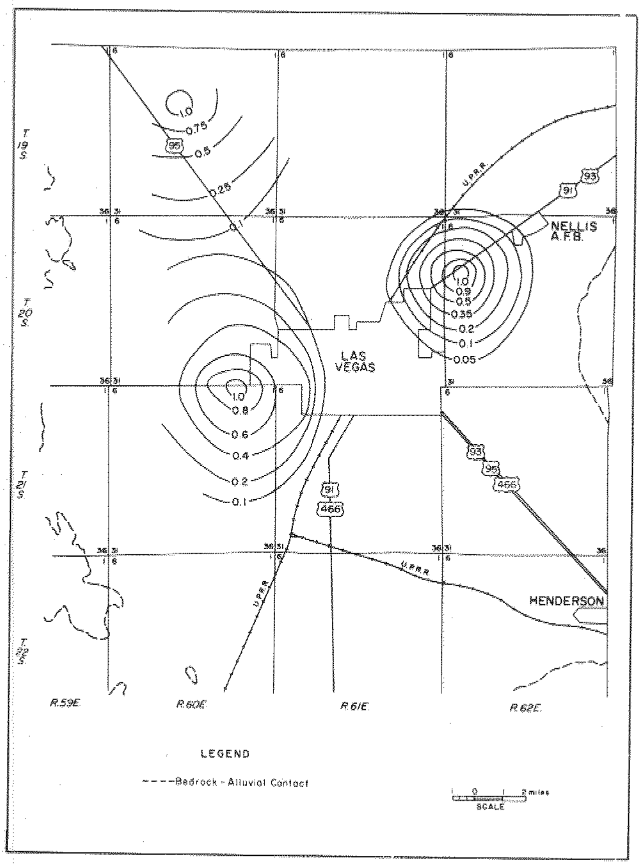


Figure 32. Transient drawdown caused by pumping Tule Springs, Las Vegas and North Las Vegas two years after pumping starts.

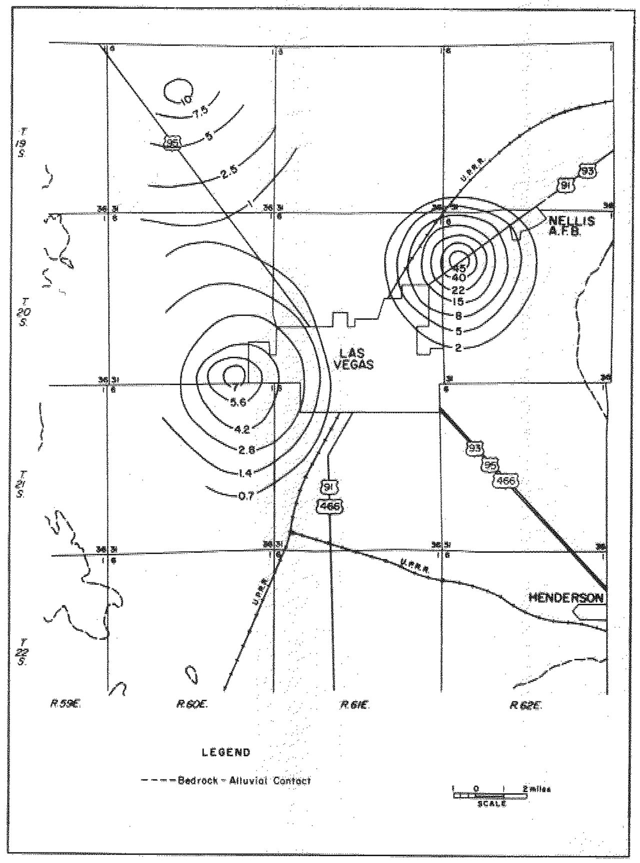


Figure 33. Transient water-level change, in feet, caused by pumping Tule Springs, Las Vegas, and North Las Vegas, two years after pumping starts.

similarly. For example, the drawdown contours for the Tule Springs and North Las Vegas pumping centers previously shown in Figure 32 and 33 are shown for a continuous five year pumping period, Figure 34. Identical assumptions regarding pumpage were employed to obtain the dimensional drawdowns.

EFFECT OF PUMPING IN THE AREA OF PRINCIPAL WITHDRAWALS

The predictable effect of continued production from all existing wells at the 1962 rate of pumping under certain idealized assumptions has already been estimated (Fig. 31). Increased water requirements in the area of principal development will likely be satisfied by either major water utility, except at governmental establishments such as Nellis Air Force Base. The effect of these pumpage increments on water levels may be analyzed separately if they can be identified in terms of rate, time, and place. In this analysis consideration must be given both to recently completed pumping centers discussed in the section on water

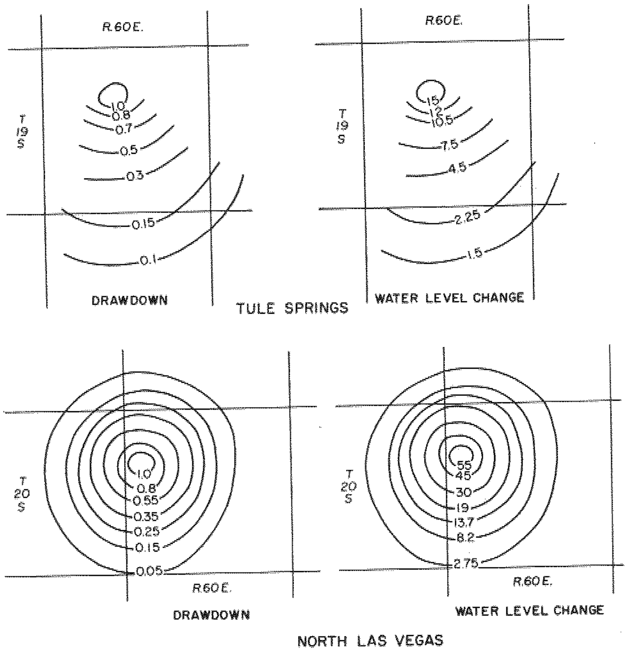


Figure 34. Transient drawdown and water-level change caused by pumping Tule Springs and North Las Vegas, five years after pumping starts.

requirements and sources and to additional pumping facilities yet to be developed in the 1960 decade. In the case of the former, identification of pumpage in the terms required offers little problem as the peaking and average production potential of the new multiple-well centers are reasonably known and their locations are known exactly. Time of use must necessarily coincide with the peaking season, as present ground-water pumping and storage facilities are inadequate during this period to meet water demand. Their use during most of the seven month non-peaking season is not required and therefore is not likely because of economic limitations, such as lift and yield. Selection of locations for additional multiple-well centers yet to be developed during the 1960 decade to meet anticipated peaking requirements has been based on the developmental pattern most likely to be followed by water developers.

Table 8 shows a particular scheme of development in Las Vegas Valley during the period 1963 to 1969 that is possible if the water demand increases at the predicted rate discussed in this report. For this presentation it is convenient to classify present and predicted pumping centers indicated by the numbers 1 to 13 and according to the cone of depression in the area of principal use that is most likely to be affected materially by the development.

Eight multiple-well centers have been classified in western Las Vegas Valley, four of which are already completed (Numbers 1, 2, 3, and 5, Table 8). It is assumed that both base and peaking requirements for the City of Las Vegas will be supplied by the high-yield, more efficient wells in the main district well field and the other centers will be used for peaking only. Maximum production figures assigned to the completed multiple-well centers shown in Table 8 are based on production-test results. Two additional well fields assumed to be operated by the Las Vegas Valley Water District have been placed northwest of the main field. Low static lifts to the west and historically low production capability to the south are deterrents to the placement of additional wells in these areas, and the selected locations appear to be logical. The Tule Springs area offers certain advantages for large-scale municipal ground-water development, but probably will not be required for a few years.

Large-scale depletion and low production capability in eastern Las Vegas Valley has resulted in a wider distribution of the North Las Vegas water facilities. Thus, two of the multiple-well fields are in the western part of the valley. As there is yet no pipeline available to convey this water eastward to the area of principal use, it has been assumed that large-scale production will not begin until 1965 (Table 8).

One multiple-well center of the Las Vegas Valley Water District has been classified in southern Las Vegas Valley. The wells are already completed and will start production by mid-1964. Maximum pumpage figures in Table 8 are based on test production data.

Four multiple-well centers are in eastern Las Vegas Valley, all of which are completed and have been in production since 1963. It is assumed that both base and peaking requirements for the City of North Las Vegas and Nellis Air Force Base will be supplied by the most efficient facilities (Numbers 10 and 11, Table 8), and the other centers will be used for peaking only.

In this analysis, or scheme of development, it has been assumed that pumpage will increase over the 1962 rate to 41,000 acre-feet by 1969. Table 8 shows that no further annual increments are assumed to occur in southern Las Vegas Valley beyond 1966 and in eastern Las Vegas Valley beyond 1965. In southern Las Vegas Valley the limitation is based on the production capability of the multiple-well center. In eastern Las Vegas

TABLE 8

Estimated Withdrawals and Withdrawal Pattern in Las Vegas Valley, 1963 to 1969 (pumpage increases only). Numbers 1 to 13 Correspond to Multiple-Well Centers Shown on Figures 35, 36, and 37.

Cone of Depression	1963	1964	1965	1966	1967	1968	1969	Total
Western Las Vegas Valley								
1) Main District Field	5.0 MGD	5.0 MGD	6.0 MGD	8.0 MGD	9.0 MGD	10.0 MGD	11.0 MGD	
2) District North Field		4.8 MGD*	7.2 MGD*	7.2 MGD*	7.2 MGD*	7.2 MGD*	7.2 MGD*	
3) District West Field		4.8 MGD*	7.2 MGD*	7.2 MGD*	7.2 MGD*	7.2 MGD*	7.2 MGD*	
4) District Northwest Field			3.6 MGD*	5.0 MGD*	7.2 MGD*	7.2 MGD*	7.2 MGD*	
5) N. Las Vegas West Field			2.0 MGD*	3.0 MGD*	4.0 MGD*	5.0 MGD*	6.0 MGD*	
6) District Northwest Field				5.0 MGD*	7.2 MGD*	7.2 MGD*	7.2 MGD*	
7) Tule Springs						7.2 MGD*	12.0 MGD*	
8) N. Las Vegas Northwest Field				1.0 MGD*	2.0 MGD*	3.0 MGD*	4.0 MGD*	
Total Million Gallons	1,825	3,265	5,190	7,180	8,500	10,250	11,650	47,860
Total Acre-feet	5,600	10,000	15,800	22,000	26,000	31,400	35,700	146,500
Southern Las Vegas Valley								
9) District South Field		2.4 MGD*	3.6 MGD*	5.0 MGD*	5.0 MGD*	5.0 MGD*	5.0 MGD*	
Total Million Gallons		360	540	750	750	750	750	3,900
Total Acre-feet		1,100	1,660	2,300	2,300	2,300	2,300	11,960
Eastern Las Vegas Valley								
10) N. Las Vegas Field	1.1 MGD	1.1 MGD	1.1 MGD	1.1 MGD	1.1 MGD	1.1 MGD	1.1 MGD	
11) Nellis Air Force Field	0.7 MGD	0.8 MGD	1.1 MGD	1.1 MGD	1.1 MGD	1.1 MGD	1.1 MGD	
12) N. Las Vegas Field	0.5 MGD*	0.5 MGD*	0.5 MGD*	0.5 MGD*	0.5 MGD*	0.5 MGD*	0.5 MGD*	
13) N. Las Vegas Field		0.7 MGD*	0.7 MGD*	0.7 MGD*	0.7 MGD*	0.7 MGD*	0.7 MGD*	
Total Million Gallons	731	872	980	980	980	980	980	6,503
Total Acre-feet	2,240	2,670	3,000	3,000	3,000	3,000	3,000	19,910
Total Million Gallons	2,556	4,497	6,710	8,910	10,230	11,980	13,380	58,263
Total Acre-feet	7,840	13,770	20,460	27,300	31,300	36,700	41,000	178,370

*Peaking well field only.

Valley the imposed limitation is arbitrary. In this area the development of additional water may occur largely at the expense of the yield of present wells.

Most wells are closely spaced and yield less than one or two gallons of water a minute for every foot of drawdown. Because of the quantities of water required, pumping lifts exceed two to three hundred feet and interference between wells is great. Hence, it is possible to develop larger quantities of water for very short times only, and then only at the expense of other wells.

Because of the imposed limitations on two of the three areas considered in this report, most of the additional ground-water withdrawal will probably occur in western Las Vegas Valley. In Table 8, for example, approximately 83 percent of the pumpage in 1967 is assigned to pumping centers in the western part of the valley. Whether this water is used in the western part of the valley or transported to other parts of the valley is of no consequence.

The pumpage data listed in Table 8 constitutes a cause—that is, an anticipated withdrawal of water at a designated rate or change in rate, at a designated place, and for a designated period of time. Figure 35 shows the estimated effect expressed in terms of water-level change over the period 1963 to 1964 in response to the cause listed in Table 8 for this period of time. As the withdrawal of water is assumed to be concentrated at a point within the pumping center, only regional water-level response is accurately depicted. Smaller quantities of water withdrawn at each multiple-well center will result in proportionally less drawdown attributed to each center, and therefore less drawdown regionally, but the pattern of the affected area will be as shown in the figure. The effect of additional wells brought into production at any time during the period 1963 to 1964 plus the effect of previous (pre-1963) pumpage must be added to the effect attributed to this pumping scheme. The figure shows water levels as they would appear in non-pumping wells during the season of minimal pumping.

Figure 36 shows the estimated effect expressed in terms of water-level change in response to the cause listed in Table 8 over the period 1963 to 1968. The qualifying conditions stipulated above also hold in this analysis. In addition, designated pumping centers 4, 6, and 8 constitute a large part of the cause, and if their locations or pumping schedules are not as shown, the system response will differ. If they are located closer to the pumping centers in western Las Vegas Valley, the water-level change in that part of the area will be greater than shown. If additional water is withdrawn in eastern Las Vegas Valley, the water-level change in that area will be proportionally greater than shown. As there is minimal interference between pumping centers in the eastern and western part of the valley over pumping periods as short as five or seven years, the addition to or subtraction from assigned pumping stresses in either of these areas will not materially affect the estimated response of the other.

Figure 37 shows the estimated water-level change over the period 1963 to 1970 in response to the assumed pumpage data in Table 8. Most noteworthy is the effect on the regional water-level decline pattern due to postulated development in the Tule Springs area and the continued decline of water levels. When or whether Tule Springs is developed depends upon the availability of less expensive water in the area of principal use.

The figures shown in this section of the report record the effect of a predetermined cause, or causes, identified in Table 8. The number of alternate schemes of development, or causes, utilizing both existing and potential multiple-well fields are too numerous to enumerate. Hence, it would indeed be fortuitous if ground water were developed in the exact manner expressed in the table. However, this does not detract from the value of the analog analysis. The pumpage scheme analyzed depicts the water-level change in response to an additional 41,000 acre-feet of ground water developed primarily in the area of principal use. Much of any future development is certain to occur within this area. By considering the drawdowns yet to be registered due to pre-1963 pumpage (Fig. 31) and those that may be registered due to maximum pumpage increases in this decade (Fig. 37), non-pumping water levels in the main area of principal use will still be well above the top of the aquifers identified by subsurface mapping in western Las Vegas Valley. In eastern Las Vegas Valley the aquifers are no longer identified and most of the water is obtained from a large thickness of saturated, low permeability silts and gravelly sands. A wider distribution of pumpage than that analyzed or drawing water from areas utilized to a limited extent will result in even less localized water-level change and higher heads in the area of principal use. Hence, except for eastern and southern Las Vegas Valley where limitations were imposed

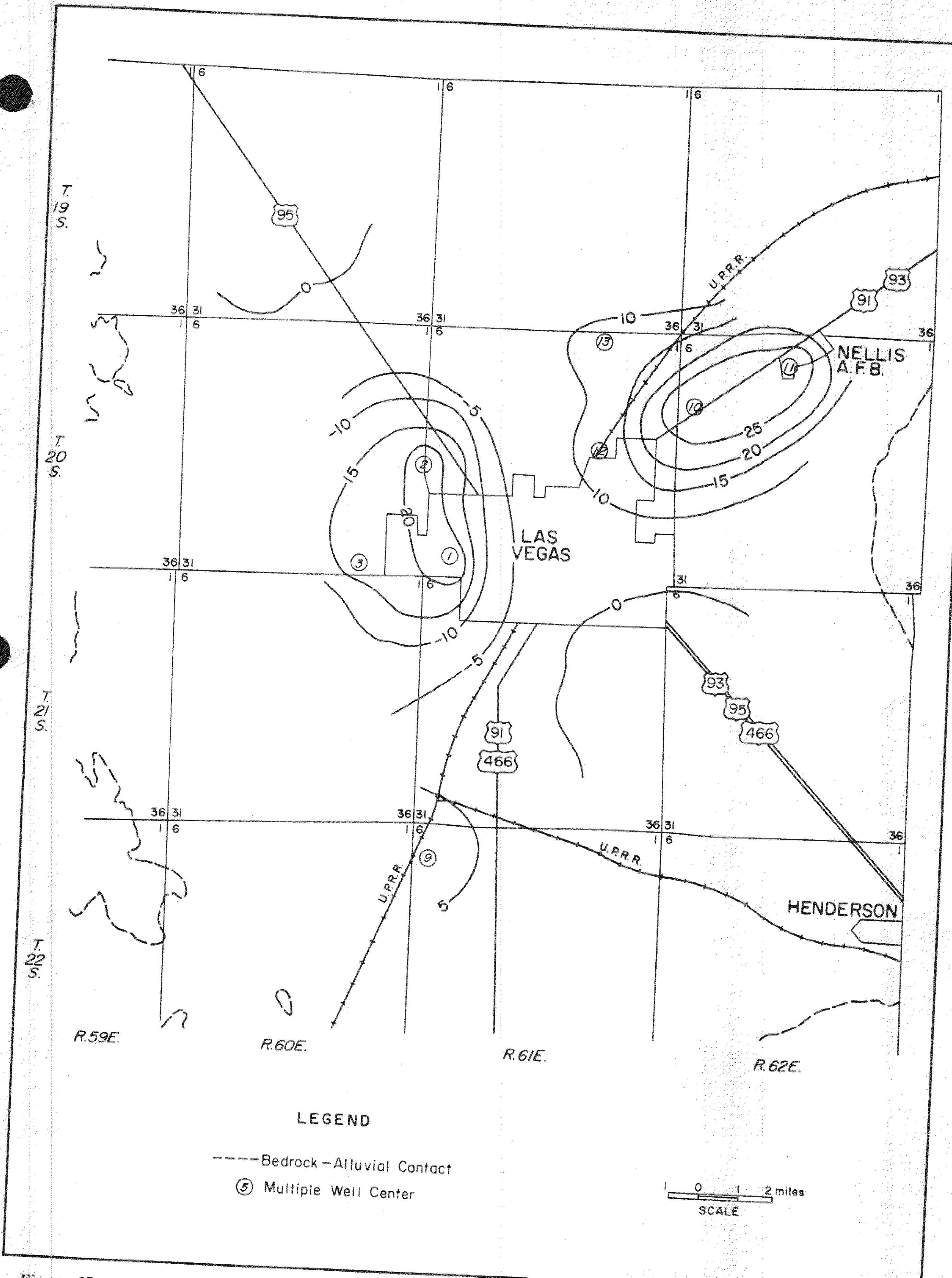


Figure 35. Transient water-level change, January 1963 to January 1965, caused by estimated increased pumping in Las Vegas, North Las Vegas, and Nellis Air Force Base (effect of antecedent and other pumping ignored).

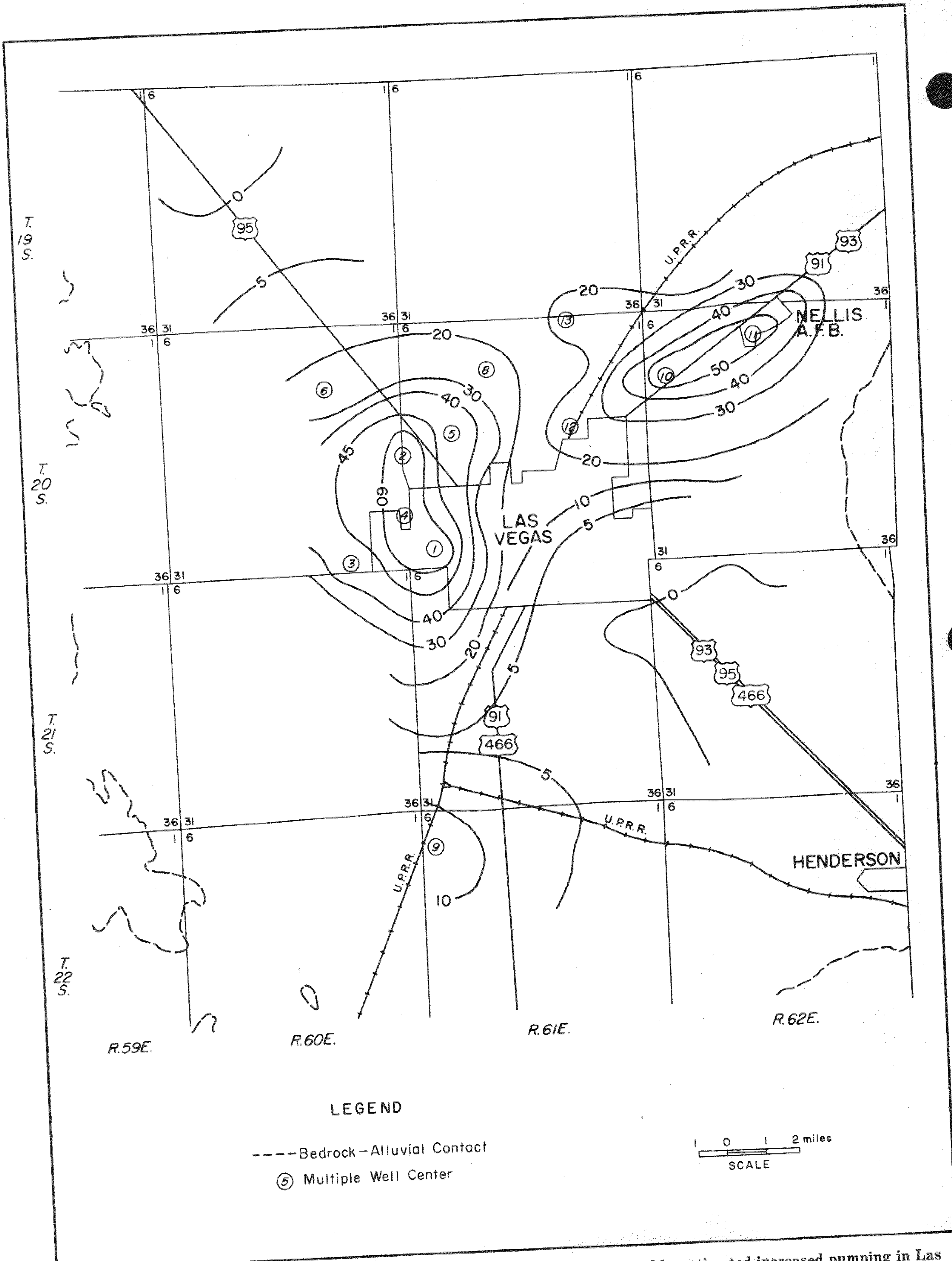


Figure 36. Transient water-level change, January 1963 to January 1968, caused by estimated increased pumping in Las Vegas, North Las Vegas, and Nellis Air Force Base (effect of antecedent and other pumping ignored).

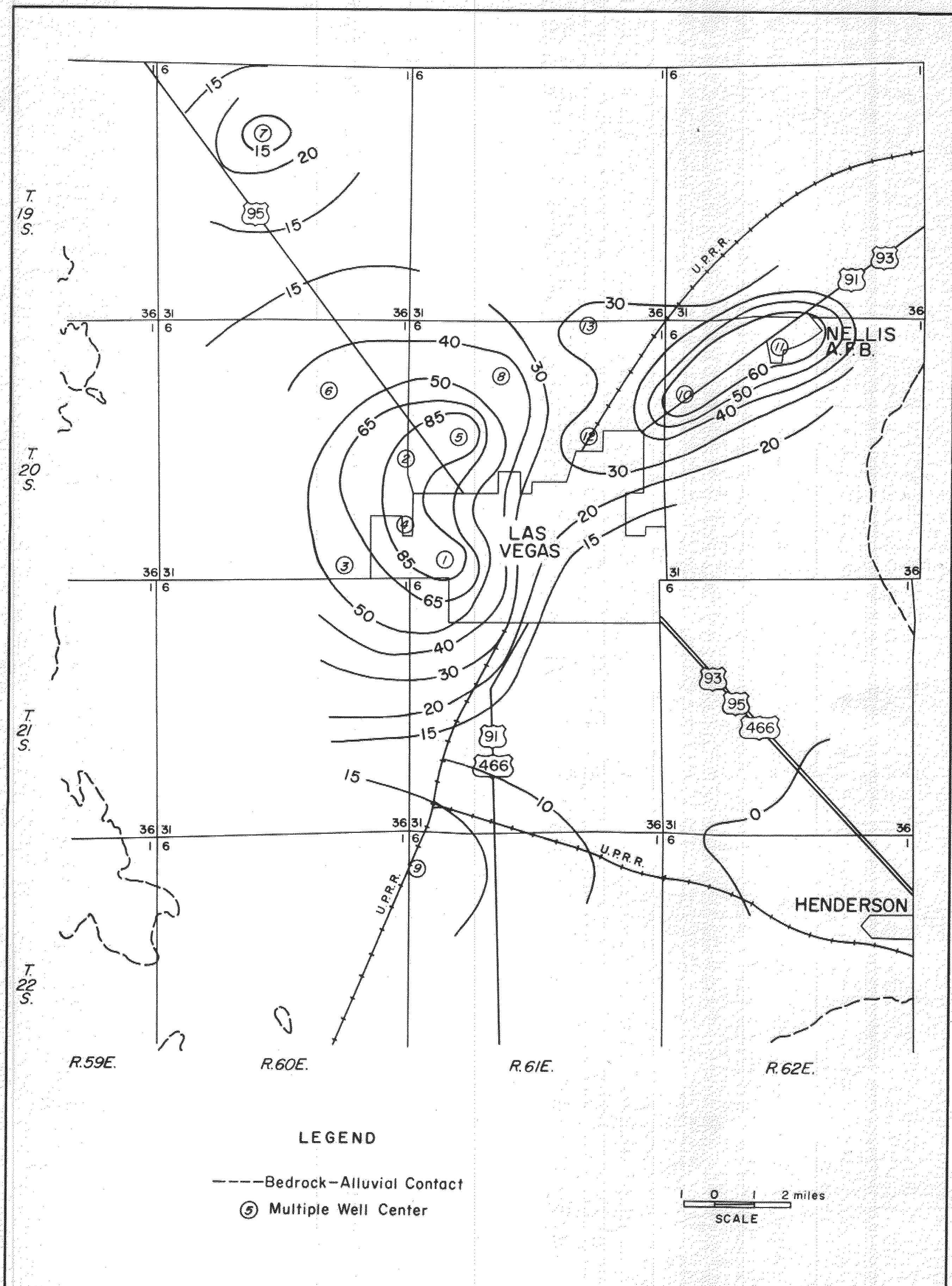


Figure 37. Transient water-level change, January 1963 to January 1970, caused by estimated increased pumping in Las Vegas, North Las Vegas, Nellis Air Force Base, and Tule Springs (effect of antecedent and other pumping ignored).

on quantities of water pumped the developmental pattern postulated and analyzed is one in which minimal consideration is given to well field spacing, and therefore one in which localized effects are at a maximum.

EFFECT OF DEVELOPMENT ON SHALLOW WELLS

Although the occurrence of ground-water in Las Vegas Valley has been the subject of several studies and is relatively well understood, very little is known regarding the response of the "near-surface" aquifers to deep pumping from the artesian basin. In the past, recycled water has prevented any material change in storage in the near-surface aquifers. In 1962 there were over 2,500 domestic wells in the valley, most of which pump water from the near-surface aquifers.

Many domestic and permitted wells in the northwestern and some other parts of the valley average less than 300 to 350 feet in depth, and pump primarily from the artesian aquifers identified by geologic mapping. The general order of magnitude of water level change anticipated in western and eastern Las Vegas Valley and especially the lowered position of water levels during peaking seasons will unquestionably affect many of these wells. Shallow wells pumping from near-surface waters just east of the Las Vegas Valley Water District and east of North Las Vegas may not be materially affected provided recycling of water is not eliminated.

EFFECT OF DEVELOPMENT ON AREA OF ARTESIAN FLOW

Other than the Las Vegas Valley Water District southern well field, large-scale withdrawal of ground water in southern Las Vegas Valley is not anticipated. The effect of pumping by the Las Vegas Valley Water District on the area of artesian flow will not be great, at least during this decade (Fig. 37). Some wells will cease to flow in parts of central Las Vegas Valley prior to 1969. The southern Boulder Highway area and parts of southeastern Paradise Valley will not be materially affected by the development of additional municipal water. Ultimately, wells in this area may cease to flow, probably more in response to the local development of domestic water supplies.

EFFECT OF DEVELOPMENT OF MUNICIPAL WATER FROM TULE SPRINGS AREA

The effect of past withdrawal of ground water in the Tule Springs area can be analyzed separately with the electric model. Studies show that the elongation in a northwestern direction of the water-level change pattern for the period 1944 to 1963 (Fig. 25) is due primarily to development of irrigation water in the Tule Springs area. Isolation of the effects of ground-water withdrawal in the Tule Springs area is shown on Figures 32 and 34.

When or whether the Tule Springs area is developed depends upon the availability of less expensive water closer to the area of principal use. The amount of water that might be developed depends upon the hydrologic properties of the sediments and the interference between the Tule Springs and western Las Vegas Valley cones. It is not unreasonable that an additional 4,000 million gallons may be developed annually during this decade without excessive interference with the western Las Vegas Valley cones.

CONCLUDING REMARKS

The application of analog techniques to ground-water supply problems in Las Vegas Valley has provided information pertaining to effect of withdrawals on potential or head and the concluding remarks will be limited to this subject.

Head is most often evaluated in terms of lifting water or, in increasingly more common instances, in terms of ultimate depletion of the resource by dewatering. The economic aspects of ground-water development becomes a controlling factor in the community's effort to manage its resource only when a potentially less expensive or more dependable source of water may be available. In agricultural communities management becomes paramount when the cost of pumping water approaches the gross receipts obtained from wholesaling crop production. In that part of Las Vegas Valley presently affected by continually declining water levels, there is neither significant crop production nor cheaper available water. That a more dependable supply of water will be required is reflected in the community's plans to import surface water from Lake Mead. Therefore, at least during the 1960 decade, the only water-supply problem of economic dimensions in Las Vegas Valley is that the people are willing to pay an increased price for water in order to continue to enjoy the benefits they may derive from living in a desert community. On the other hand, a critical problem is presently facing officials who must decide and implement conjunctive use practices, and much more is involved in this problem than the cost of lifting water.

To speak quantitatively of depletion of the resource in terms of time requires considerably more information than is available. Among factors that are unknown are the amount of ground-water recharge to the aquifers from sources other than underflow, the relationship between consumed water and return flows, and the effective bottom of the ground-water reservoir in the western half of the valley. Because of these and other factors, it is not possible to closely estimate the amount of water that could be safely developed in Las Vegas Valley. All data available from this and other studies strongly indicate that the quantities of water presently developed, if removed entirely from the ground-water reservoir on a permanent basis, would eventually result in critical depletion.

The Muddy Creek Formation, where it is known to be used for water supply, is of little or no value for municipal water, and may indicate the effective bottom of the ground-water reservoir. Its position in the system may therefore suggest the maximum water-level change that would render the aquifer useless. The depths to this formation where they are known have been indicated. It is significant that in some parts of western Las Vegas Valley, highly permeable sands and gravels are known to occur as deep as 1,200 feet, and low-permeability Muddy Creek sediments have not been encountered. Muddy Creek sediments have been recognized at about 700 feet in North Las Vegas. However, the permeability of the sediments underlying North Las Vegas is not great, and probably Muddy Creek sediments are not appreciably less permeable.

With the completion of the Southern Nevada Pipeline Project, approximately 13,000 to 14,500 million gallons of water will be required annually from the ground-water reservoir on a five-or-six month pumping schedule. This is about two-thirds of the water pumped in 1962. It is recognized that this quantity of water exceeds the estimated annual replenishment to the basin and ultimately may result in depletion. However, because of the size of the underground storage reservoir, this demand should present no problem for the amortization period of the pipeline project.

Local problems may arise in areas such as North Las Vegas in eastern Las Vegas Valley where large-scale depletions have already taken place and those predicted for the future will not allow the required pumping rate to be maintained although the valley as a whole will not be excessively overdeveloped. The remedy may be found by distributing the pumping more widely or drawing water from areas now utilized to a limited extent. Distribution of pumpage in this area will also tend to alleviate some effects of land subsidence. Hence, for the next 50 years or so, if surface water is imported, the limits of ground-water production in Las Vegas Valley depend merely upon the economics of wider distribution and the productivity of the aquifers to be developed.

The analog analysis of the consequences of ground-water development presented in this report is by no means complete. Questions yet to be answered relate to the consequences of ground-water contributions in the conjunctive use practices anticipated beyond 1970. Once surface water is imported, the cause to be dealt with is readily identifiable in terms of the amounts, places of diversion and time of withdrawals. That is, the pumping centers to be used for peaking loads will be fixed and their pumping schedules known exactly. Thus, there is only one scheme of development to be dealt with—an exact one—and the effect of this scheme can be analyzed within the limits of analog accuracy for as much as 20 years in advance. The technical facility is now available to answer these questions once it is decided how and in what manner the ground-water resource will be developed.

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