Ground-Water Conditions in Las Vegas Valley, Clark County, Nevada

Part 2, Hydrogeology and Simulation of Ground-Water Flow

United States Geological Survey Water-Supply Paper 2320–B

Prepared in cooperation with the Clark County Department of Comprehensive Planning

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Part 2, Hydrogeology and Simulation of Ground-Water Flow

By DAVID S. MORGAN AND MICHAEL D. DETTINGER

Prepared in cooperation
with the Clark County
Department of
Comprehensive Planning

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2320–B

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

U.S. GEOLOGICAL SURVEY

GORDON P. EATON, Director

UNITED STATES GOVERNMENT PRINTING OFFICE : 1996

For sale by the
U.S. Geological Survey
Information Services
Box 25286, Federal Center
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Plume, Russell W.
Ground-water conditions in Las Vegas Valley, Clark County, Nevada.

(U.S. Geological Survey water-supply paper ; 2320–A–B)
"Prepared in cooperation with the Clark County Department of Comprehensive Planning."
Five folded maps in pocket, pt. 1.
Includes bibliographical references.
Contents: pt. 1. Hydrogeologic framework / by Russell W. Plume — pt. 2. Hydrogeology and simulation of ground-water flow / by David S. Morgan and Michael D. Dettinger.
1. Groundwater—Nevada—Las Vegas Valley. 2. Geology—Nevada—Las Vegas Valley. I. Morgan, David S. II. Dettinger, M.D. III. Clark County (Nev.). Dept. of Comprehensive Planning.
GB1025.N4P54 1989 87-600029

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CONVERSION FACTORS, ABBREVIATIONS, AND ACRONYMS

Multiply	By	To obtain
acre	0.4047	square hectometer
acre-foot (acre-ft)	0.001233	cubic hectometer
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year
acre-foot per month (acre-ft/mo)	0.001233	cubic hectometer per month
acre-foot per acre per year [(acre-ft/acre)/yr]	30.48	cubic hectometer per square hectometer per year
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.0929	meter square per day
foot per year (ft/yr)	0.3048	meter per year
gallon per day (gal/d)	0.003785	cubic meter per day
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
ton	907.2	kilogram

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

BMI	Basic Management, Inc.
ET	evapotranspiration
GWSI	Ground-Water Site-Inventory
LVVWD	Las Vegas Valley Water District
NWIS	National Water Information System
SNWP	Southern Nevada Water Project
TAZ	Traffic Analysis Zones

Ground-Water Conditions in Las Vegas Valley, Clark County, Nevada

PART 2, HYDROGEOLOGY AND SIMULATION OF GROUND-WATER FLOW

By David S. Morgan and Michael D. Dettinger

ABSTRACT

Ground-water withdrawals in Las Vegas Valley, Nevada, primarily for municipal supplies, totaled more than 2.5 million acre-feet between 1912 and 1981, with a peak annual withdrawal rate of 88,000 acre-feet in 1968. Effects of heavy pumping are evident over large areas of the valley, but are most pronounced near the major well fields, where water levels had declined as much as 280 feet by 1981 and where land subsidence totaled nearly 5 feet since development began in the early 1900's.

Secondary recharge from lawn irrigation and other sources is estimated to have totaled more than 340,000 acre-feet during 1972–81. Resulting rises in water-level in shallow, unconfined aquifers in the central and southeastern parts of the valley have caused: (1) Widespread water-logging of soils; (2) Increased ground-water discharge to Las Vegas Wash and its tributaries; and (3) Potential for degradation of water quality in deeper aquifers by accentuating downward vertical hydraulic potential in areas where shallow ground water has high concentrations of dissolved solids and nitrate.

A three-dimensional ground-water flow model of the valley-fill aquifer system was constructed for use in evaluating possible ground-water management alternatives aimed at alleviating problems related to overdraft and water-logging while maximizing use of the ground-water resources. In developing the computer model, concepts of the flow system were tested and verified, and data deficiencies were identified. The model simulates horizontal ground-water flow within, and vertical flow between, four geohydrologic units: The shallow unconfined aquifers, the near-surface aquifers, the developed-zone aquifers, and the deep-zone aquifers. The model also incorporates processes such as inelastic compaction of fine-grained sediments (land subsidence), discharge to washes, evapotranspiration, and springflow.

Transmissivities of the valley-fill sediments range from less than 100 feet squared per day (ft^2/d) to more than 800 ft^2/d within the near-surface aquifers and from 500 ft^2/d to more than 14,000 ft^2/d within the developed-zone aquifers. The elastic component of the storage coefficient in the developed-zone aquifers is estimated to range from 1×10^{-3} to 3×10^{-3}, whereas the inelastic component ranges from 7×10^{-4} to 3.2×10^{-2}. Average specific yield of the unconfined aquifers is approximately 0.08.

Natural recharge to the valley-fill aquifers is about 33,000 acre-feet per year; in 1979, an estimated 44,000 acre-feet of secondary recharge infiltrated to the near-surface and developed-zone aquifers. Peak water use for lawn irrigation during summer results in rates of secondary recharge that may increase threefold from winter rates. Simulated rates of seepage to washes in the valley increased correspondingly from an average of 850 acre-feet per month in winter to about 1,300 acre-feet per month in summer. Ground-water withdrawals by pumping totaled 620,000 acre-feet during 1972–81, and model results indicate that about 190,000 acre-feet of that total was derived from storage.

Use of the model as a predictive tool was demonstrated by simulating the effects of using most municipal wells only during the peak-demand season of June 1 through September 20. Results of the 9-year simulation indicated that (1) long-term rates of water-level decline near the municipal well field would be less than rates for 1972–81, but the magnitude of seasonal fluctuations would increase, and (2) total volume of water released from storage as a result of subsidence would be only 42,000 acre-feet per year, or about half the volume during 1972–81.

1.0 INTRODUCTION

In 1979, the U.S. Geological Survey and Clark County Department of Comprehensive Planning initiated a cooperative study of the ground-water flow system of Las Vegas Valley. This report details the methods used and results obtained in the principal effort of the study—development of a three-dimensional simulation model of ground-water flow in the valley. The following section describes the objectives and scope of this part of the study, as well as the problems and concerns that prompted this study and guided the development of the flow model. The general methods of study are outlined also.

1.0 INTRODUCTION—Continued

1.1 Objectives and Scope

Ground-Water Model of Las Vegas Valley Developed

Past and present ground-water conditions in Las Vegas Valley have been studied in the course of developing a mathematical simulation model; use of the model to predict future conditions is demonstrated for one development alternative.

Las Vegas Valley is in southern Nevada about 20 mi northwest of Lake Mead and the Colorado River (fig. 1.1-1). The Las Vegas metropolitan area, which includes the cities of Las Vegas and North Las Vegas and the populated surrounding areas, is near the center of the valley (fig. 1.1-1). The city of Henderson is in the southeastern part of the valley and Nellis Air Force Base (NAFB) is in the northeastern part.

This report presents the results of the second part of a study of ground-water conditions in Las Vegas Valley. During the first part of the study, the hydrogeologic framework of the valley, including the lithology, thickness, water-bearing characteristics, and configuration of the valley-fill deposits, was described by Plume (1989). The principal objectives of the second part of the study were to (1) refine the conceptual understanding of the ground-water flow system; (2) develop a mathematical model of the system; (3) identify data needs critical to an understanding of the system; (4) demonstrate the use of the model as a tool for analyzing the hydrologic effects of proposed land- and water-use strategies; and (5) develop a capability to estimate overdrafts of ground water, both local and basinwide, and to project large-scale implications of overdraft conditions. The mathematical model ultimately was intended for use in evaluating ground-water management alternatives in terms of compromises between alleviation of hydrogeologic hazards and water-supply maximization.

Geologic, hydrologic, and geophysical data were collected by several methods for the study. Geologic and hydrologic data sources consisted of well-drillers' logs, water-level measurements, seepage measurements, and records of ground-water withdrawals. Geophysical methods employed consisted of gravity and seismic-refraction surveys.

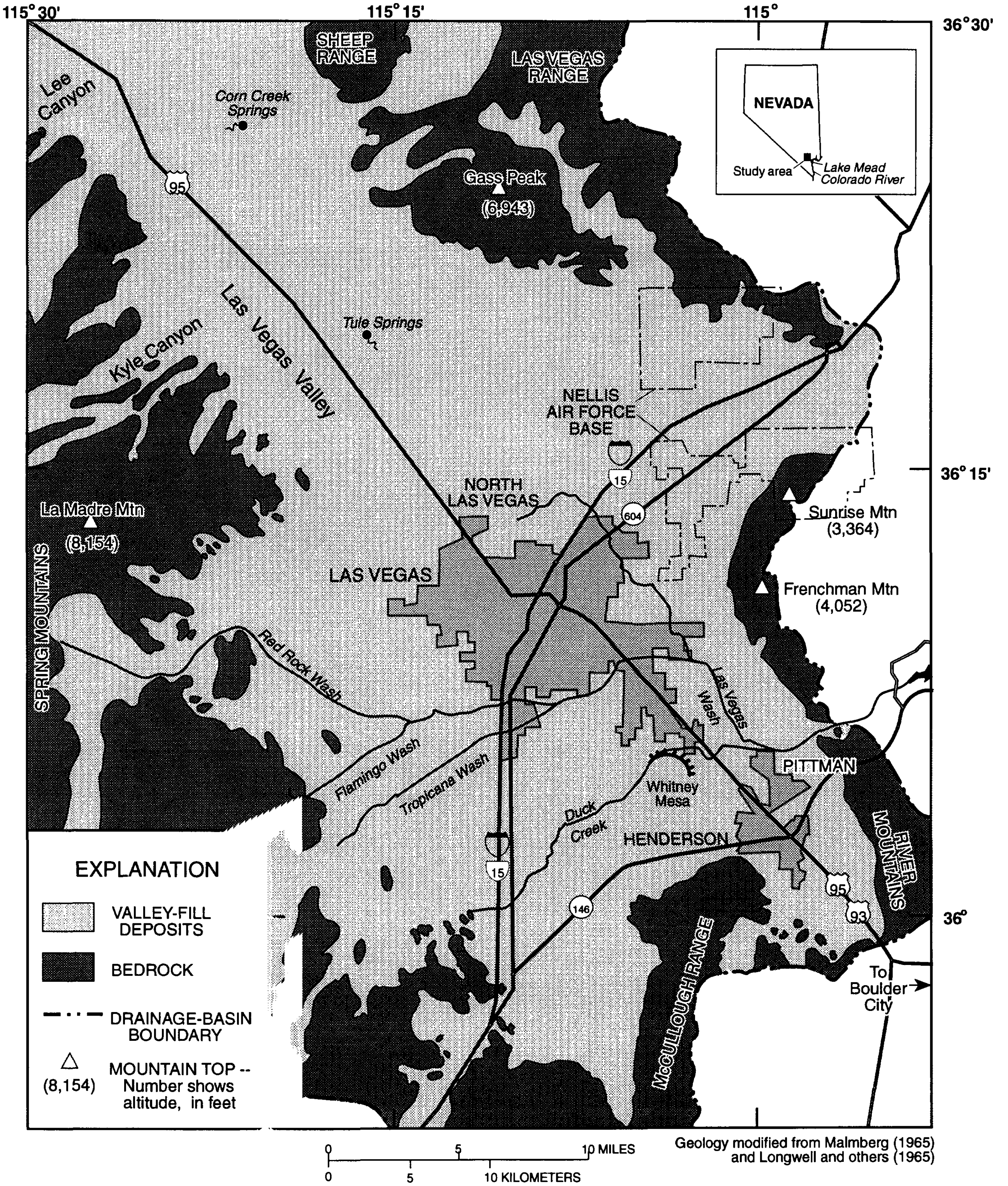


Figure 1.1-1. Location and general features of study area (from Plume, 1989, fig. 1).

1.0 INTRODUCTION—Continued

1.2 Problem Identification

1.2.1 Overdraft of Water from Aquifer

Overdraft has Induced Other Ground-Water Problems

Geographic concentration of pumping has produced localized overdraft of ground water and the problems of increased pumping lifts and land subsidence. A basin-wide overdraft has occurred since the mid-1940's.

Ground-water overdraft has been the precursor to most of the ground-water problems found to date in Las Vegas Valley—especially declining water levels, degradation of water quality by incursion of water having greater concentrations of dissolved solids and nitrate, land subsidence, and loss of ground-water dependent vegetation. Ground-water overdraft results when the pumping from the aquifer cannot be offset by reduction in natural discharge, an increase in recharge, or some combination of reduced discharge and increased recharge. When overdraft occurs, ground water is removed from storage, resulting in water-level declines. On the basis of this definition, overdraft of ground water from the Las Vegas Valley basin has been occurring since the first artesian wells were constructed in 1907.

Basin-wide overdraft results when ground-water pumpage exceeds inflow to the ground-water reservoir for a sustained period. Figure 1.2.1-1 shows that, by this definition, a condition of basinwide overdraft has existed in Las Vegas Valley since the mid-1940's. Malmberg (1965, p. 84) and Harrill (1976a, table 11) each used a conservative perennial-yield estimate of 25,000 acre-ft/yr and calculated the overdraft on the artesian aquifers to be 23,000 and 36,000 acre-ft in 1955 and 1974, respectively. The difference, 13,000 acre-ft, is attributable to an additional 29,000 acre-ft of pumpage in 1974 along with a 16,000-acre-ft reduction in the amount of natural discharge by upward vertical leakage.

Harrill (1976a, p. 63) proposed that overdraft be categorized as either basinwide or localized. Localized overdraft caused by the concentration of pumping on the west side of Las Vegas Valley has induced the most serious ground-water problems. Increased pumping lift is potentially one of the most costly overdraft-related problems, total water-level declines of as much as 280 ft had been measured by 1981 (Wood, 1988b, p. 21). Assuming an average water-level decline of 10 ft/yr at 1979 pumping rates, a study by URS Company and others (1983, p. 274) concluded that the increase in water cost per acre-foot due to additional pumping lift would be about $45 (1980 dollars) by the year 2000. This increase included the cost of lowering pumps by 1990. The study suggested that remedial actions required after the year 2000 might include new well-field development and blending or treatment due to degradation by downward leakage of saline or contaminated water.

Land subsidence in the valley, or local downwarping of the land surface, is a problem that has been induced by withdrawal of water from the valley-fill sediments and the resulting compaction of fine-grained inter-beds. The subsidence bowl formed by pumping in the valley is superimposed upon a broad regional depression centered on Lake Mead as shown by Bell (1981, fig. 18). Figure 1.2.1-2 shows the cumulative amount of land subsidence between 1935 and 1972 as interpreted by James R. Harrill (U.S. Geological Survey, written commun., 1982).

Damage to structures due to differential land subsidence and ground fissures has been widespread in Las Vegas Valley. Structures most commonly affected are the wells, pumps, storage tanks, and distribution pipes in the areas of most intensive pumping. Storm-drainage structures, roadways, and buildings also have been damaged in the vicinity of these pumping centers. The type and extent of damages are summarized by Bell (1981, p. 70–73) and by Mindling and others (1974).

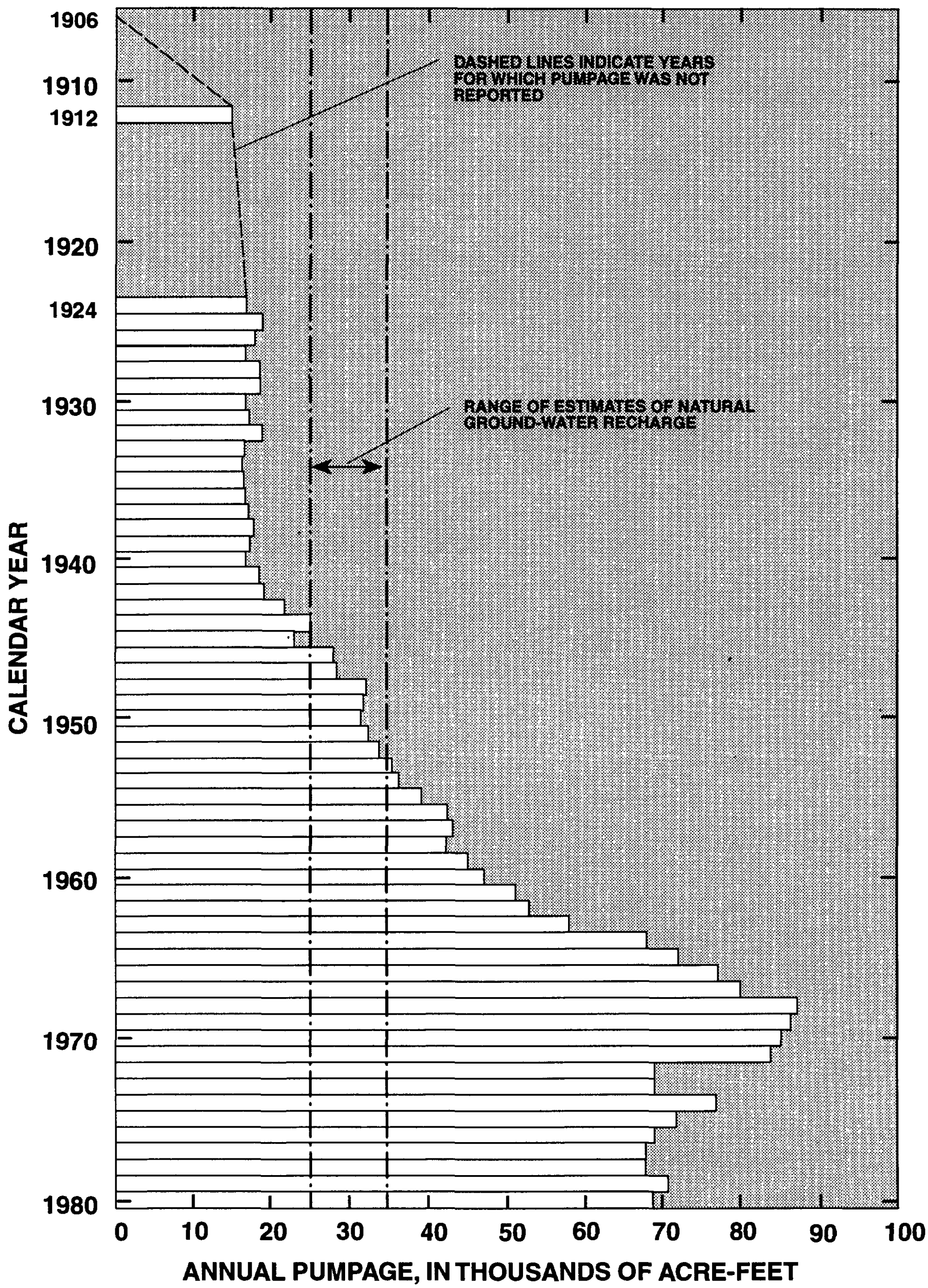


Figure 1.2.1-1. Estimated ground-water pumpage, 1906–80, and range of estimates of natural recharge. Pumpage estimates from unpublished pumpage inventories by office of Nevada State Engineer (written commun., 1980). Maximum estimated recharge from Maxey and Jameson (1948, p. 108); minimum from Malmberg (1965, p. 1).

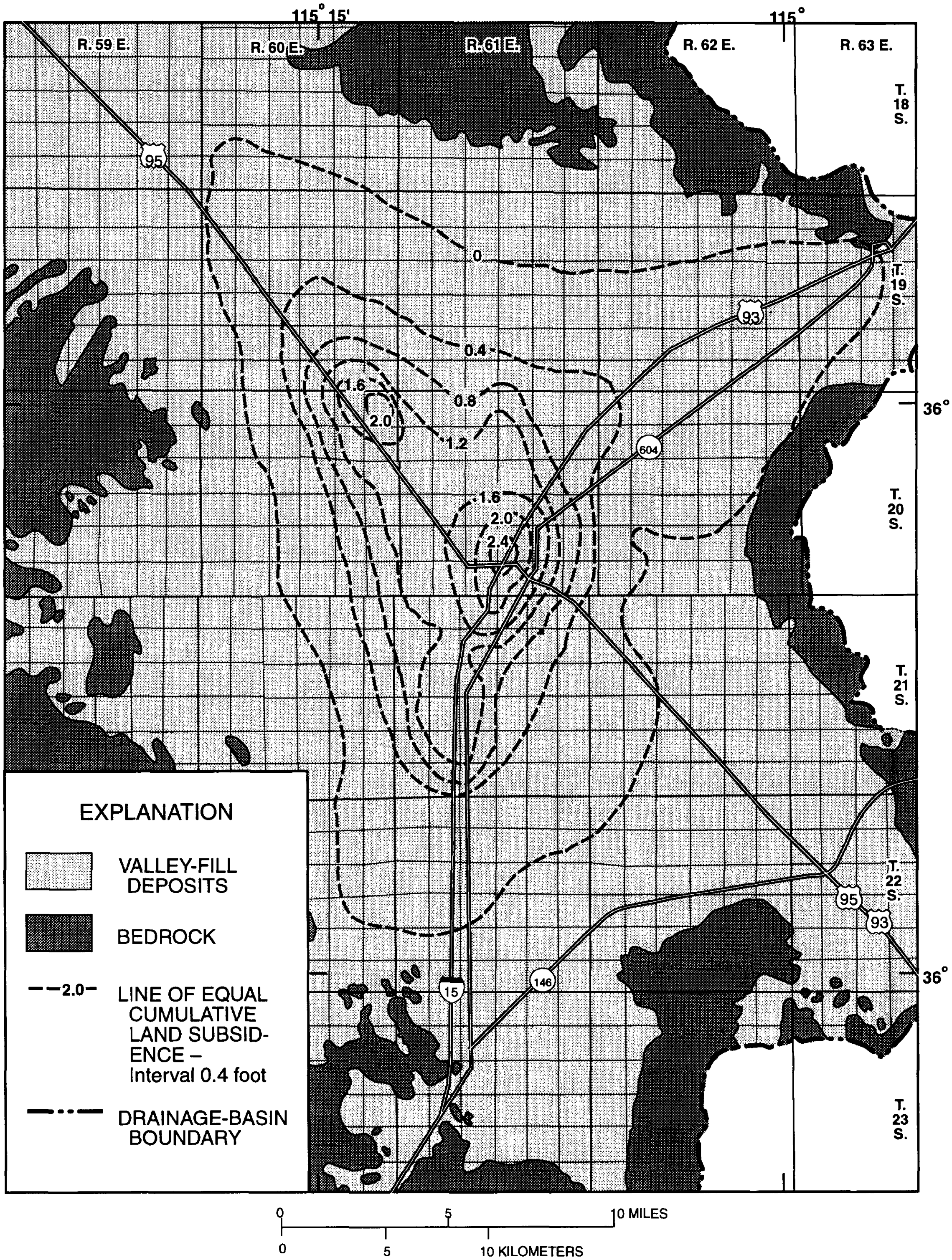


Figure 1.2.1-2. Cumulative land subsidence, 1935–72 (James R. Harrill, U.S. Geological Survey, written commun., 1982).

1.2.2 Water Logging and Water-Quality Degradation

Infiltration of Irrigation Water and Wastewater Results in Water Logging and Affects Water Quality

The water table is rising beneath most of the central and southeastern parts of the valley floor in response to infiltration of irrigation water and wastewater. Aquifer overdraft conditions, coupled with high rates of wastewater infiltration, can adversely affect the quality of deep ground water.

Under predevelopment conditions, the shallow ground-water system of Las Vegas Valley was recharged by upward leakage from the artesian aquifers and by infiltration of springflow and ephemeral streamflow. Development has resulted in a large net increase in the rates of recharge to the shallow ground-water system. This additional recharge—referred to here as secondary recharge—derives from infiltration of wastewater and deep percolation of excess lawn, park, and golf-course irrigation water (Patt, 1978, p. 32). Some of the effects of this additional recharge have been attenuated by a decline in the rate of natural recharge to the shallow ground-water system from 25,000 acre-ft in 1906 to 7,000 acre-ft in 1955 (Malmberg, 1965, p. 61, 72, 79, 83) to perhaps as little as 4,000 acre-ft in 1972 (Harrill, 1976a, p. 58). Infiltration of water associated with artesian springs ceased, as did upward leakage from the underlying artesian aquifers in large areas. During the same period, development led to the removal of large stands of phreatophytes, which were a major avenue of shallow ground-water discharge by transpiration.

The water table in most of the eastern part of the valley and locally in the central part was near the land surface under predevelopment conditions. Because low-permeability, near-surface sediments in the affected areas inhibit vertical and lateral ground-water movement, the changes in recharge and discharge have resulted in an increase in the amount of water stored near land surface, an increase in discharge to Las Vegas Wash (the surface drainage for the valley), and a rising water-table altitude. Figure 1.2.2-1 illustrates the rates of infiltration of wastewater and irrigation water in 1979 (as estimated during the present study and described in a later section) and the areas where the water table was rising between March 1977 and March 1978 (Wood, 1988a, p. 9). The correspondence between the two is apparent.

A shallow and rising water table can adversely affect structures, landscaping, agriculture, and sewage-disposal systems. Flooding and seepage into subsurface structures, weakening of concrete in structures, settling of foundation soils, increased alkalinity and salinity of soils, septic-system failures, and an increasing burden on wastewater disposal facilities by leakage into sewer lines may result from water logging (URS Company and others, 1983, p. 56).

Water at the water table was probably quite saline prior to urban growth in the valley and this condition may be (or may have been) aggravated by the addition of large volumes of secondary recharge. Secondary recharge may be contributing contaminants such as nitrate to the already saline ground water. Secondary recharge and a rising water table also saturate previously unsaturated soils and sediments and dissolve soluble salts present in the form of efflorescent crusts and evaporite deposits.

Most of the deeper ground water in the valley is suitable for domestic and other uses, but the water can be affected adversely by downward leakage of saline or contaminated water from the upper parts of the valley fill.

Of particular concern are the increasing nitrate concentrations that have been detected in the deep production wells of major water purveyors in the valley (Dettinger, 1987, p. 2). The probable source of nitrate is the ground water near the water table. Nitrate in the shallow ground water probably results from (1) leaching of nitrate from natural sources in the soil column, (2) onsite wastewater-disposal facilities, (3) land disposal of sewage, (4) irrigation with reclaimed wastewater, and (5) leachate from fertilizers. Figure 1.2.2-2 illustrates the areas identified by Kauffman (1978, p. 63) as potential nitrate sources, and the extent of the area in which the vertical hydraulic gradients between shallow and deep aquifers were downward in 1972 (Van Denburgh and others, 1982, p. 6). Lateral movement of water within the shallow sediments is inhibited somewhat by low horizontal permeability. The greatest potential source of contamination to deep water is, thus, associated with the localized areas of saline or contaminated water in the shallow zone where downward vertical gradients exist.

Rising water levels in the near-surface ground-water system have led to increased ground-water inflow to Las Vegas Wash. The inflowing ground water generally is highly mineralized and contributes to the large quantities of dissolved solids that are transported down the wash to Lake Mead (Kauffman, 1978, p. 4). The dissolved-solids content of the Colorado River is of great interstate and international concern, and so the quality of Las Vegas Wash is an important issue in local water-resource management (URS Company and others, 1983, p. 89–90).

The hydrodynamic relation between the shallow ground water and the water of deeper artesian aquifers in the valley was considered an important item of investigation in this study. The simulation analyses were therefore designed to address this relation. Results of the simulation analyses also may have implications with regard to waterlogging and water quality.

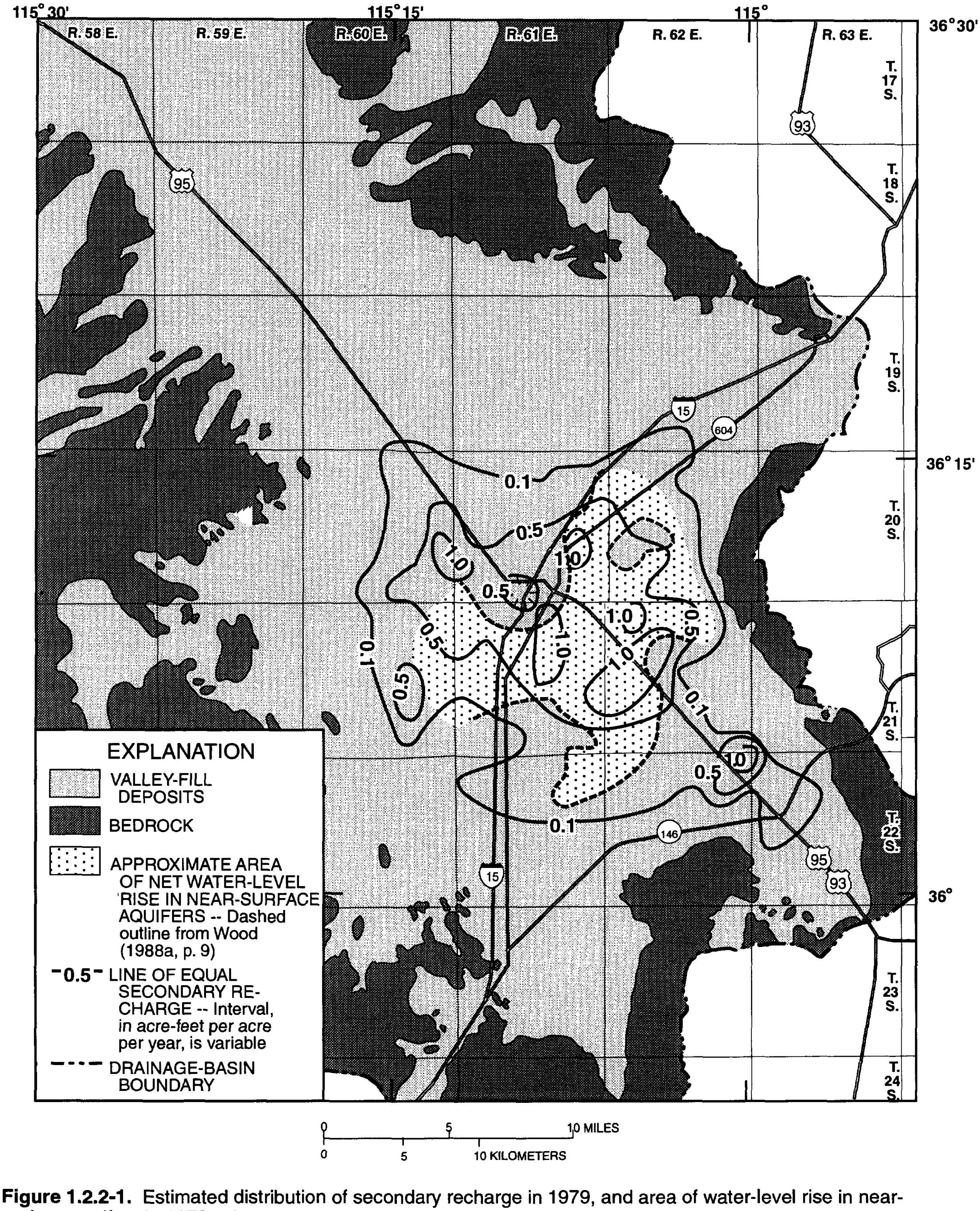


Figure 1.2.2-1. Estimated distribution of secondary recharge in 1979, and area of water-level rise in near-surface aquifers in 1978–79.

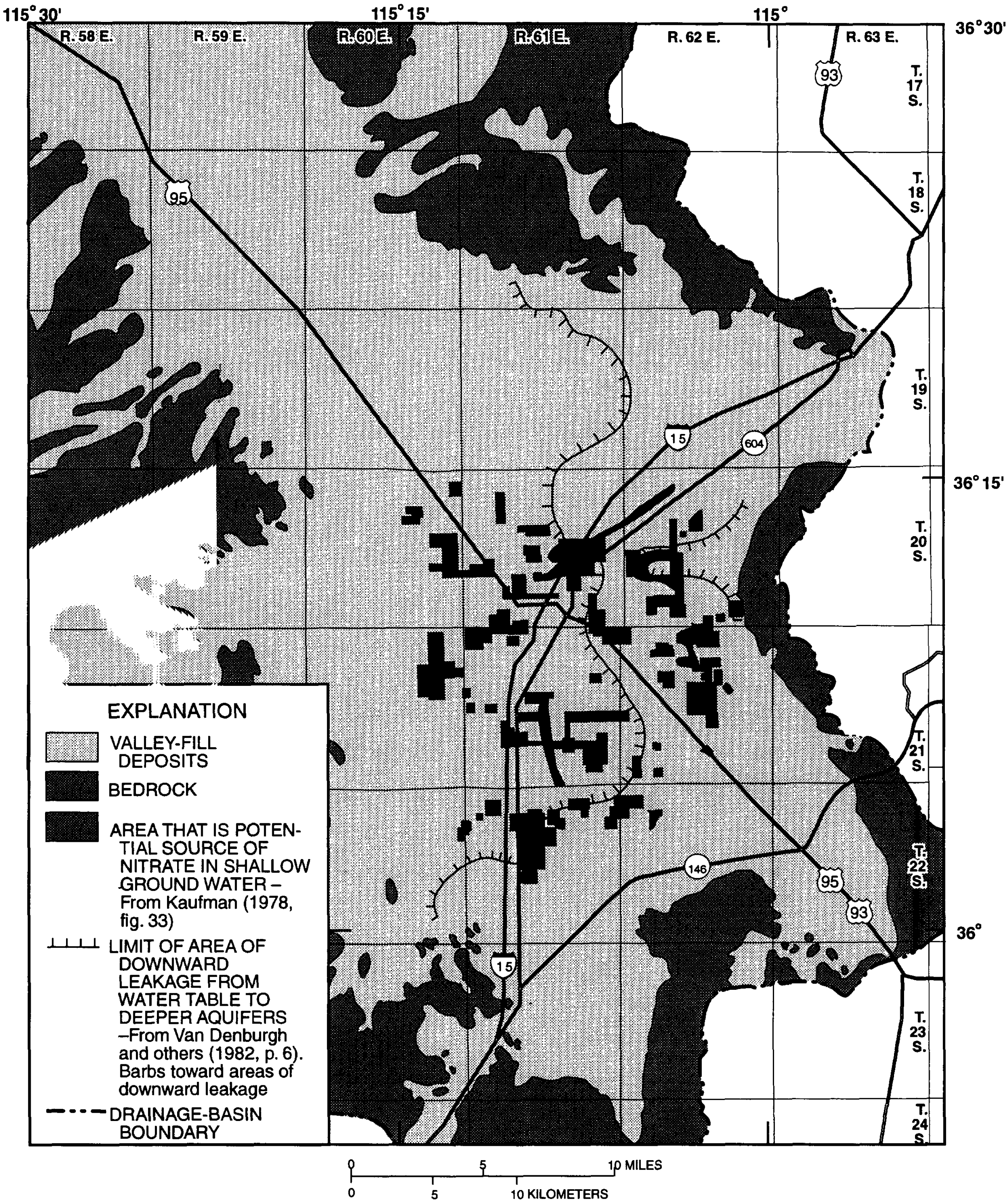


Figure 1.2.2-2. Distribution of potential sources of nitrate in shallow ground water, and areal extent of downward leakage from water table.

1.0 INTRODUCTION—Continued

1.3 Methods of Study

1.3.1 Field and Analytical Techniques

Field Data Collected for Model Development

Ground-water levels were measured either quarterly or annually and measurements or estimates of discharges in drains and washes were made. These data were collected, interpreted, and processed for input to the mathematical simulation model and comparison with results generated during calibration of the model.

Field studies for this investigation were directed at (1) gathering data, which would lead to a more accurate description of the hydrogeologic framework of the valley (Plume, 1989), and (2) making hydrologic measurements, which could be used for comparison with results of the simulation model (this study).

The location of observation wells and streams and drains in which discharge measurements were made are shown in figure 1.3.1-1. Existing water-level networks were expanded during the period of this study, with quarterly measurements made at about 65 wells and annual measurements made at about 200 wells between 1978 and 1982. The original network had been in existence since 1971, when it was established as a part of a cooperative study by the U.S. Geological Survey and the Nevada Division of Water Resources to evaluate the effects of pumping and large-scale importation of Colorado River water on the ground-water reservoir in Las Vegas Valley. In addition to measurements made by the U.S. Geological Survey, water-level measurements made by the Nevada Division of Water Resources, Las Vegas Valley Water District (LVVWD), City of North Las Vegas, Desert Research Institute at Las Vegas, and Nellis Air Force Base were used in this study.

Discharge measurements or estimates were made at about 50 sites on eight major streams and drains from June 1979 through March 1982. The measurements generally were made in early spring (prior to substantial runoff from residential water use) to estimate the location and magnitude of the ground-water contribution to flow in these drainages. Specific conductances of discharges also were measured and used to identify the source of the discharge.

Twenty-nine shallow observation wells were augered to depths of 12 to 90 ft, to define the water-table altitude and to observe the range of seasonal fluctuation in shallow ground-water levels. The principal investigative tool for this study was a ground-water flow model. All the data described in the preceding paragraphs, plus previously existing data, were used to construct and calibrate the mathematical simulation model. The details of the modeling approach are described in section 3.1.

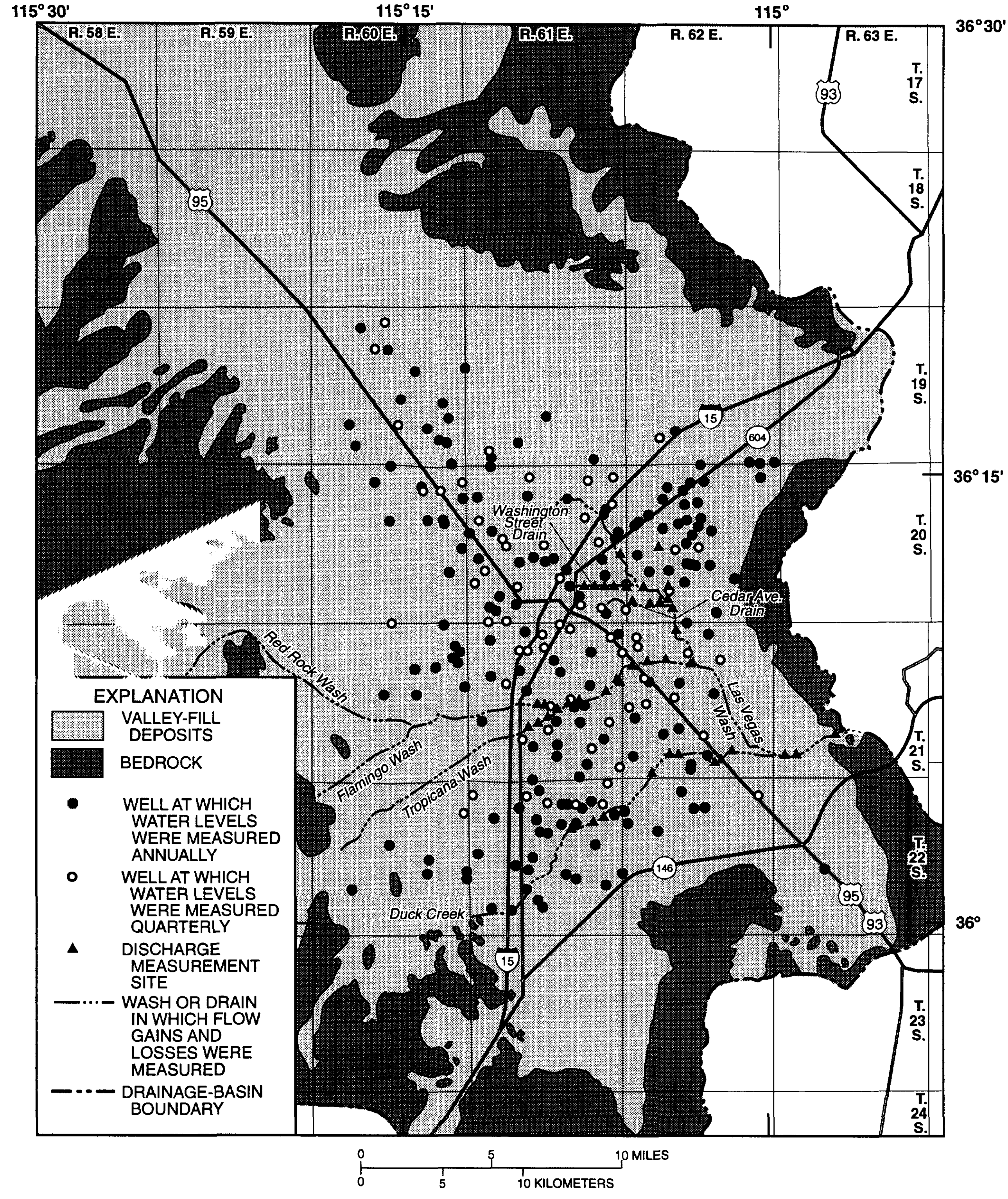


Figure 1.3.1-1. Locations of data-collection sites.

1.3 Methods of Study

1.3.2 Data Availability

Data Stored in National Water-Information System and Modeling Data Base

Well data used in this study, such as lithology, water levels, and construction details, are stored in the U.S. Geological Survey National Water-Information System (NWIS) data base. Spatial data describing aquifer properties and geometry are stored in a grid-based format that can be used to construct future models.

The U.S. Geological Survey's NWIS data base was used to store information for wells in the valley. NWIS consists of several files in which data are grouped and stored by common characteristics and data-collection frequencies. Data collected or compiled for this study were entered primarily into the Ground-Water Site Inventory (GWSI) file. The GWSI file contains site-location and identification information, well-construction data, reported lithologic logs, and individual field measurements such as water temperatures and water levels. About 1,150 wells in Clark County, 850 of which lie within the Las Vegas Valley hydrographic area, were listed in the GWSI file as of 1982. Over 9,400 intermittent and periodic water-level measurements are stored for wells within the hydrographic area. While the earliest measurements date back to 1907, few wells were periodically measured before the early to middle 1940's, and the first extensive network for periodic measurements was not established until 1971. In the course of Part I of this study, Plume (1989, p. A9) interpreted and entered over 240 well logs into the GWSI file.

The spatial distributions of aquifer properties and geometry, as well as system stresses such as recharge and pumping, are stored in grid-format data files. These files compose a modeling data base that can be used in future studies as described below. The data grid, as it is called, consists of 60 columns and 72 rows. Each cell in the grid has dimensions of 3,000 ft on each side (see fig. 1.3.2-1). Finite-difference ground-water flow models, such as the one used in this study, require that the region to be modeled be divided into rectangular cells. Each cell is assumed to be homogenous with respect to aquifer characteristics and these characteristics must be supplied to the model as data arrays. The finite-difference model grid designed for this study may not be suitable for future studies; the data-grid format for storing aquifer-characteristic and other model-related data will simplify the process of converting this model to one having an alternate grid design. Conversion would be accomplished through the use of preprocessing programs that access the data-grid files and (1) locate all data-grid cells constituting a model-grid cell, (2) compute central, average, or total values, depending on the type of data, and (3) transfer those values to a model-grid file. The modeling data base will be kept on file at the U.S. Geological Survey office in Carson City, Nev., for future studies.

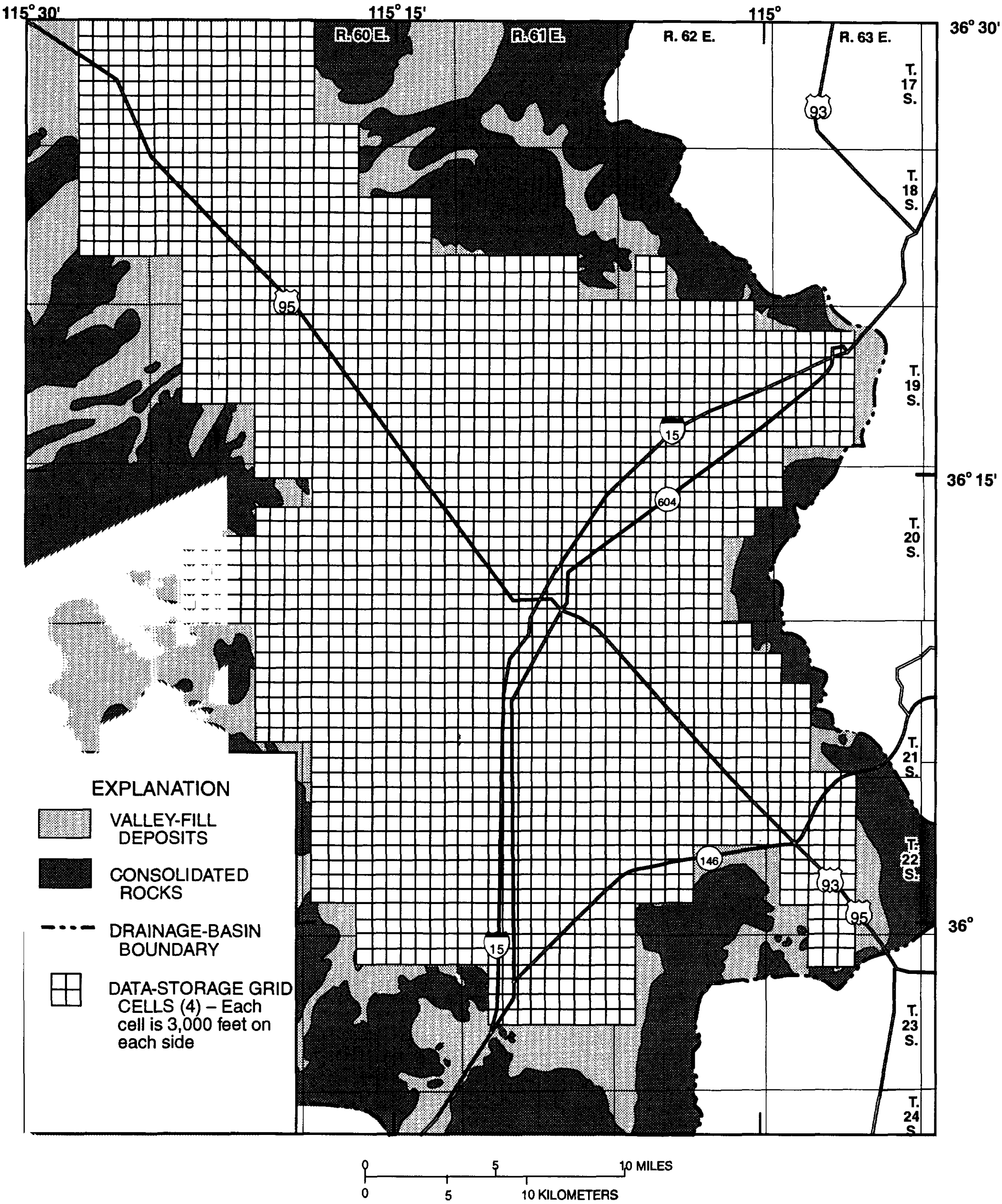


Figure 1.3.2-1. Extent and dimensions of data-storage grid.

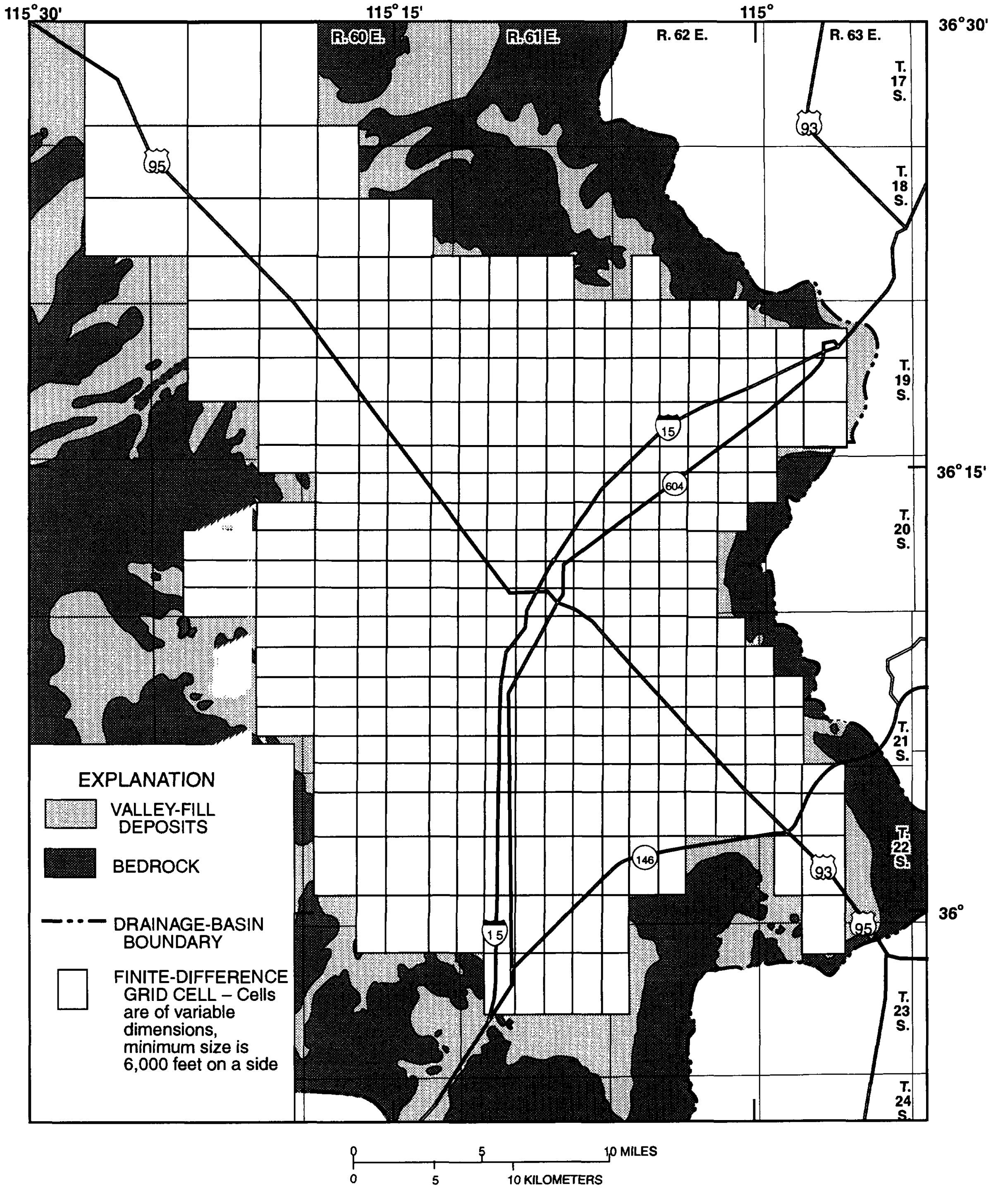


Figure 1.3.2-2. Extent and dimensions of finite-difference grid used in this study.

1.0 INTRODUCTION—Continued

1.4 Acknowledgments

The following individuals and organizations are gratefully acknowledged for their contributions to this study. Dennis Bechtel, then with the Clark County Department of Comprehensive Planning, assisted with aspects of model development and provided maps and statistical land-use summaries. The City of Las Vegas Department of Public Services and the Clark County Department of Parks and Recreation gave permission to drill test wells at local parks. The Nevada Department of Transportation allowed the use of some of their test holes as observation wells. The Las Vegas Valley Water District, the City of North Las Vegas, Nellis Air Force Base, the Desert Research Institute, and the Clark County District Health Department provided valuable information on water levels and well construction. The Las Vegas office of the Nevada Division of Water Resources supplied pumpage inventories from which water-use data were compiled. Finally, local residents made an important contribution by allowing access to their wells for water-level measurements.

2.0 DESCRIPTION OF THE AREA

Problems identified in section 1.2 are the result of complex cause-and-effect relations between natural hydrogeologic conditions in the valley and stresses on the ground-water system induced by human activities. The extent to which these problems have developed or will develop depends on the geometry and hydraulic characteristics of the valley-fill aquifers, and the rates and patterns of natural recharge, secondary recharge, and pumping.

The following sections describe the general features and hydrologic conditions in the study area. Discussions of the land forms, hydrogeology, and water budget of the valley are presented. The history of land and water use are discussed also.

2.1 Land Forms

Three Physiographic Units in Las Vegas Valley

Las Vegas Valley is surrounded by mountain blocks that are separated from the valley lowlands by long, gently sloping piedmont surfaces. The valley is drained by Las Vegas Wash, which is fed by ground-water seepage, runoff, sewage-treatment effluent, and power plant coolant water.

The following description, taken from Plume (1989, p. A2), is repeated here to acquaint the reader with the most prominent physiographic features of the study area. Figures 1.1-1 and 2.1-1 show the extent of these features.

The study area can be divided into three physiographic units: mountains, piedmont surfaces, and valley lowlands. Valley lowlands are surrounded by gently sloping piedmont surfaces, and by mountains that rise 5,000–6,000 ft above the valley floor. Las Vegas Valley is bounded on the west by the Spring Mountains, on the north by the southern ends of the Sheep and Las Vegas Ranges, on the east by Frenchman and Sunrise Mountains (collectively), and on the south by the River Mountains and McCullough Range. The highest points in the study area are the summits of La Madre Mountain, at an altitude of 8,154 ft above sea level on the east side of the Spring Mountains, and Gass Peak, at an altitude of 6,943 ft at the south end of the Las Vegas Range. Where mountain blocks meet piedmont surfaces, the change in slope is abrupt. This change in slope occurs at altitudes ranging from about 2,000 ft at Frenchman Mountain to about 4,000 ft at the base of the Spring Mountains and Sheep Range.

Mountain blocks are separated from valley lowlands by long, gently sloping surfaces that are collectively referred to as piedmont surfaces (Bell, 1981, p. 10). These surfaces are nearly 10 mi wide on the western side of the valley and from 2 to 5 mi wide on the northern, southern, and eastern sides of the valley. The piedmont surfaces were interpreted as coalescing alluvial fans in early investigations (Maxey and Jameson, 1948, p. 32; Longwell and others, 1965, p. 6; and Malmberg, 1965, p. 11, 12). More recent studies, however, indicate that the piedmont surfaces are in part pediments (Dinger, 1977, p. 18; Bell, 1981, p. 10; Martin D. Mifflin, Desert Research Institute, written commun., 1981).

Piedmont surfaces terminate at the edge of the valley lowlands at altitudes ranging from 1,500 ft a few miles northeast of Henderson to about 2,900 ft near Corn Creek Springs. Valley lowlands slope gently to the east and southeast except in the vicinity of fault scarps, where local relief is as much as 100 ft or, at Whitney Mesa, about 200 ft.

Las Vegas Valley is drained at its southeast end by Las Vegas Wash to Lake Mead on the Colorado River. Most tributaries to that stream are relatively small unnamed washes. Exceptions are the larger streams at the southern end of the valley, which include Flamingo Wash, Tropicana Wash, and Duck Creek. The lower ends of these tributaries and Las Vegas Wash are now perennial streams for four reasons: (1) Their channels intersect the water table; (2) storm drains collect excess lawn irrigation water and other urban runoff and discharge into major drainages; (3) sewage-treatment plants discharge into Las Vegas Wash; and (4) a power plant discharges coolant water into Duck Creek. In the upper parts of Las Vegas Wash and its tributaries, flow occurs only during and shortly after heavy rains.

The valley lowlands historically have been the most heavily populated of the three physiographic areas, although Las Vegas is growing rapidly to the south, west, and northwest onto the piedmont surfaces. In addition, Henderson is situated entirely on a piedmont surface.

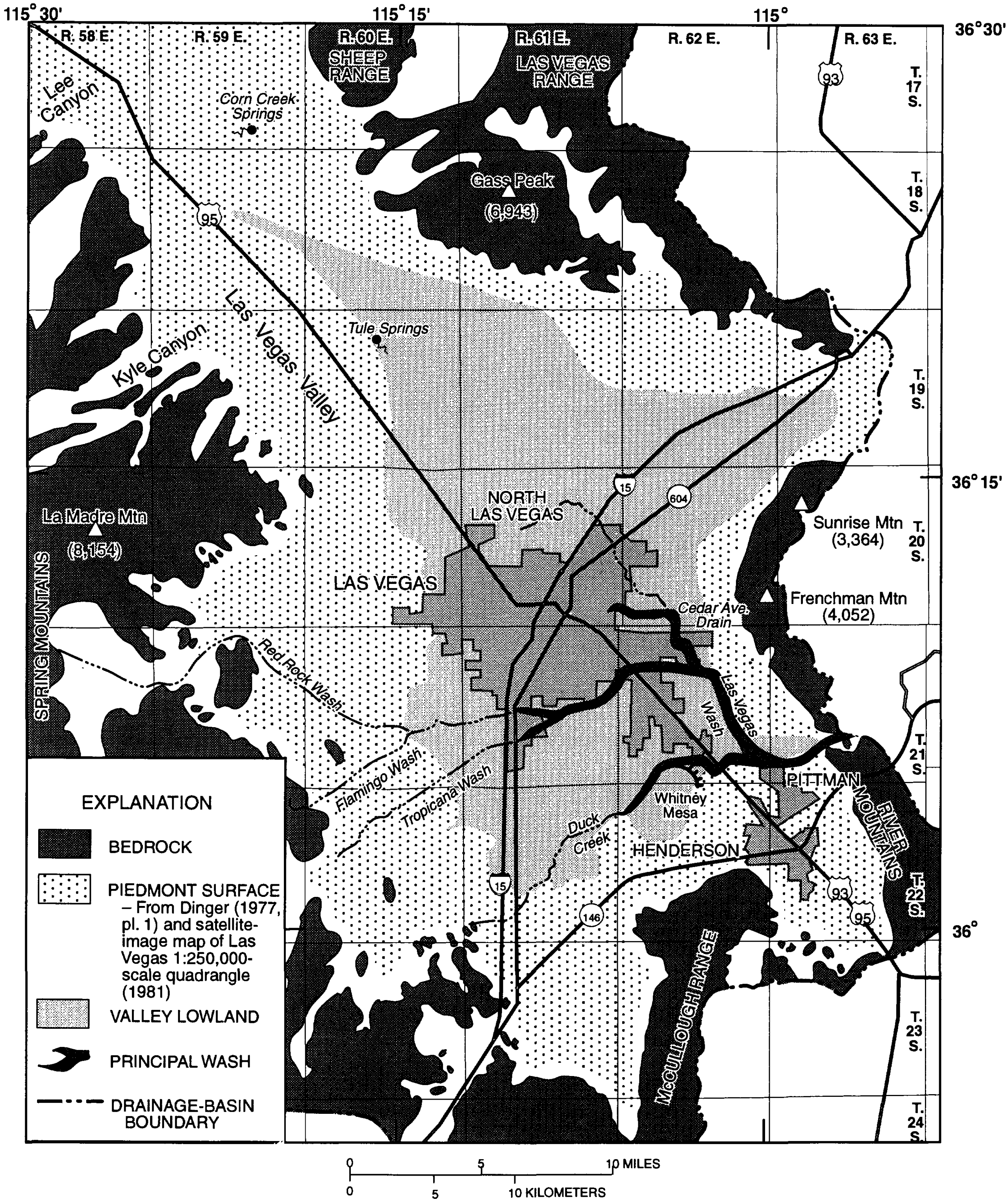


Figure 2.1-1. Physiographic features of study area.

2.2 Hydrogeologic Framework

Basin Filled with Complexly Interbedded Sediments

The uppermost 1,000 ft of sediments underlying the western and northwestern parts of the valley contain the most productive aquifers. Eastward gradation from gravels to predominately fine-grained deposits is a prominent hydrogeologic feature of the valley-fill aquifers.

The stratigraphy, lithology, thickness, and extent of the valley-fill deposits, which are discussed in detail by Plume (1989), are summarized below. The terminology presented herein to describe the various zones of aquifers and confining beds is used throughout the remainder of this report.

Las Vegas Valley is underlain by a structural basin composed of Precambrian and Paleozoic carbonate rocks, Permian through Jurassic clastic rocks, and early Tertiary igneous rocks. [The predominant carbonate rocks are components of the southern Nevada carbonate-rock aquifers described by Dettinger (1989b).] The carbonate and noncarbonate units form a bedrock basin in which as much as 5,000 ft of mostly clastic sediments were deposited. The age of these sediments is believed to range from Miocene through Holocene.

Interpretations of geophysical data indicate that the bedrock basin generally conforms to the shape of the valley, but it consists of two parts: a deep (2,000 to 5,000 ft) depression beneath most of Las Vegas Valley and a relatively shallow (less than 1,000 ft) bedrock surface on the western side of the valley near Red Rock Wash (fig. 2.2-1). The deep part of the basin is bounded on the east and possibly on the west by normal faults, and on the north by the Las Vegas shear zone, along which strike-slip displacement and perhaps vertical displacement have taken place.

The Muddy Creek Formation, of late Miocene and early Pliocene age, consists of valley-fill deposits that are coarse near mountains and progressively finer toward the valley center (Longwell and others, 1965, p. 48). The thickness of the Muddy Creek Formation is not well established in Las Vegas Valley. Early interpretations of drillers' logs placed the top of the formation at a depth ranging from land surface in southern parts of the valley to more than 1,000 ft below land surface at Las Vegas (Domenico and others, 1964, p. 10; Malmberg, 1965, p. 20, 21; Mindling, 1965, p. 36). However, no as-yet-identified faults account for such a great difference in altitude. Estimates of the thickness of the Muddy Creek Formation near Las Vegas range from 500 to 3,000 ft (Domenico and others, 1964, p. 12; Malmberg, 1965, p. 21).

The uppermost 700 to 1,000 ft of valley-fill deposits generally are younger than the Muddy Creek Formation throughout most of the valley. These deposits are bounded laterally by large, coalescing alluvial fans emanating from the surrounding mountain ranges and descending to the valley floor over distances of up to 10 mi. The fans consist of heterogeneous, poorly sorted mixtures of boulders, gravel, sand, silt, and clay. They are incised and imbedded with gravel trains that absorb and transmit recharge to the main ground-water reservoir (Malmberg, 1965, p. 22). Beneath the central part of the valley floor, the fans grade into more uniform deposits that can be described in terms of specific zones of aquifers. The most productive zones within the main ground-water reservoir are principally within the uppermost 1,000 ft of sediments; however, lateral variation in lithology is large. The sharp eastward gradation from coarse to fine deposits, shown in fig. 2.2-1, is one of the most striking and well documented hydrogeologic features in the valley (Domenico and others, 1964, table 1; Harrill, 1976a, p. 13; Plume, 1989, p. A10).

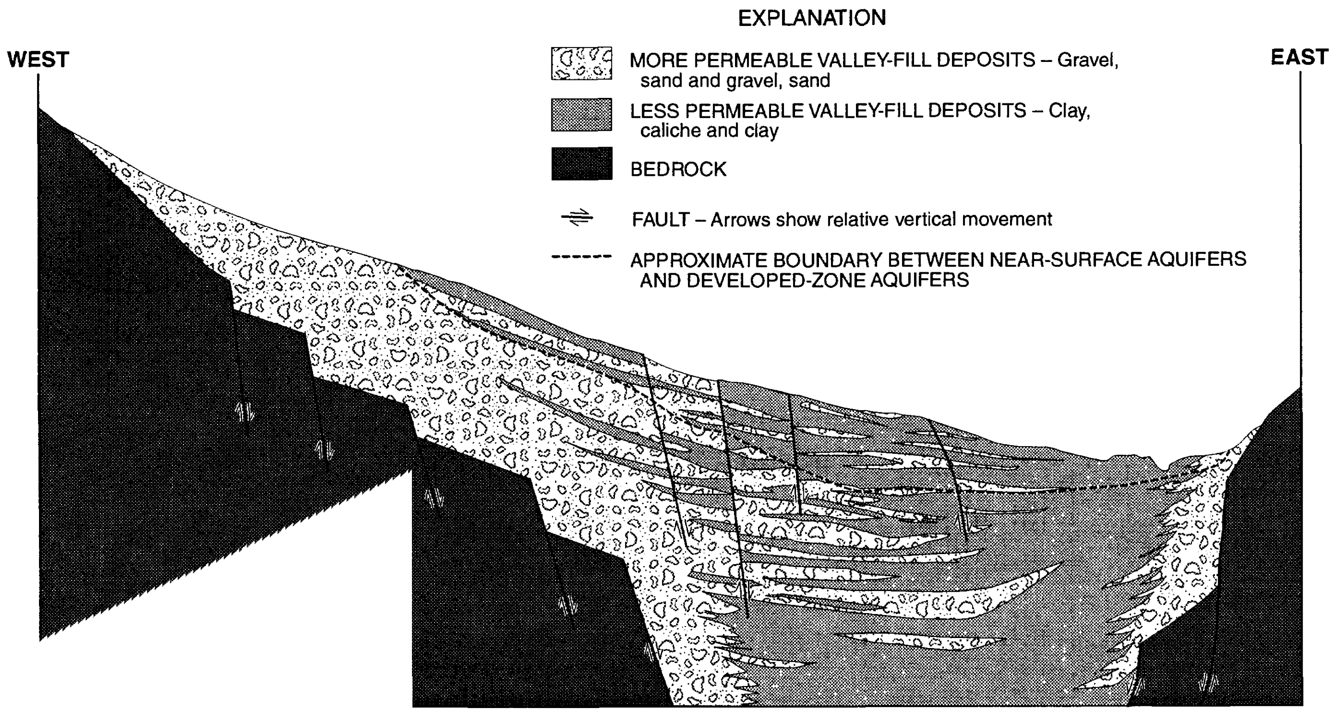
In this report, the valley-fill aquifers are discussed in terms of a zone of near-surface aquifers, a zone of developed aquifers, and a zone of deep aquifers.

The zone of near-surface aquifers underlies the central part of the valley, where it forms the uppermost 200 to 300 ft of valley fill. The term "near-surface aquifers" as used in this report refers to virtually the same sequence of deposits described by Harrill (1976a, p. 11). The interval consists of complexly interbedded clay, silt, sand, and gravel, and constitutes a semi-confining unit relative to the underlying zone of developed aquifers. The assumed thickness and extent of the semi-confining unit is highly dependent on the definition of its lower boundary. Data collected for this study did not warrant modification of the definition used by Harrill (1976a, p. 11)—

the first indication of significant water-bearing material. Interpretation of drillers' logs by Plume (1989, p. 15) did, however, allow a more accurate delineation of its thickness and extent.

The zone of developed aquifers consists of the interval of valley fill most likely to be affected by pumping; these sediments will be referred to in this report as the "developed-zone aquifers." The valley-fill sediments of the developed-zone aquifers consist mostly of lenses of sand and gravel separated by differing amounts of clay and silt. In the central part of the valley, the developed-zone aquifers generally extend from depths of about 200 to 300 ft to about 1,000 ft beneath land surface. In peripheral parts of the valley, the developed-zone aquifers extend from the water table to depths of about 1,000 ft below land surface. This zone correlates with the "shallow and middle zones of artesian aquifers" described by Maxey and Jameson (1948), and the upper parts of Malmberg's (1965) "artesian aquifers" and Harrill's (1976a) "principal aquifers."

The zone of deep aquifers consists of the valley-fill sediments deeper than 1,000 ft and will be described herein as the "deep-zone aquifers." The deep-zone aquifers are characterized by their relatively low permeability. Their lithology is largely unknown but they probably contain more fine-grained sediments than the developed-zone aquifers. Despite lower permeabilities, the deep-zone aquifers probably constitute much of the ground-water storage capacity of the valley-fill deposits. This zone of aquifers is evaluated in this report to the extent that data allow. The deep-zone aquifers generally correspond to Maxey and Jameson's (1948) "deep zone," and the lower parts of Malmberg's (1965) "artesian aquifers" and Harrill's (1976a) "principal aquifers."



Not to scale

Figure 2.2-1. Generalized west-to-east hydrogeologic section of Las Vegas Valley. Modified from Maxey and Jameson (1948, pl. 6b).

2.3 Hydrogeologic Conditions and Water Budget

2.3.1 Predevelopment Conditions

Predevelopment Conditions Dominated by Flow From Mountains Toward Valley Floor

Under predevelopment conditions, the aquifers of Las Vegas Valley were recharged primarily by precipitation in the surrounding mountains and discharged primarily at large springs and by phreatophytic transpiration.

Under predevelopment conditions, nearly all water entering the ground-water system of Las Vegas Valley originated as precipitation in the mountains surrounding the valley. The Spring Mountains on the western boundary and the Sheep and Las Vegas Ranges on the northern boundary of the valley are the highest, receive the most precipitation, and, consequently, contribute most of the natural recharge to the valley. Exactly how and where natural recharge takes place at a local scale is not certain. Some of the recharging water probably percolates through porous sections of the mountain blocks, and some runs off to percolate through the extensive piedmont deposits that flank the mountain blocks. Regardless, the bulk of this recharge is assumed to enter the valley-fill sediments near the foot of the mountains.

Discharge from the ground-water system of Las Vegas Valley is assumed to have been in a dynamic equilibrium with natural recharge under predevelopment conditions. Ground water from the developed-zone aquifers leaked upward into the near-surface aquifers beneath the lowest parts of the valley floor, and it reached land surface at large springs along fault scarps (Malmberg, 1965, p. 58–59). This leakage of water upward into the near-surface aquifers and to springs from the developed-zone aquifers was the primary source of recharge to the near-surface aquifers. Discharge from the near-surface aquifers was mostly by phreatophytic transpiration where the water table was within a few tens of feet of land surface. Finally, Loeltz (1963, p. Q5) and Harrill (1976a, p. 50) concluded that a small amount of water also may have leaked through the consolidated rock under Frenchman Mountain.

Components of the predevelopment ground-water budget have been estimated by various authors. The resulting estimates differ greatly for some components, as indicated in table 2.3.1-1. Some of the differences may be attributable to improvements in understanding of the ground-water system, but some depend more on what parts of the hydrologic system a given author focused on and what methods were used to estimate the various components. For example, Maxey and Jameson (1948, p. 120) estimated total recharge to be 30,000 to 35,000 acre-ft on the basis of rough estimates of precipitation and recharge efficiency. Malmberg (1965, p. 57) revised that estimate to 25,000 acre-ft on the basis of natural-discharge estimates, estimates of subsurface flow toward the areas of discharge near the valley floor, and hydrograph analyses of selected wells. Simulation analyses by Harrill (1976a, p. 49), however, indicated an annual recharge rate of 30,000 acre-ft/yr, which is closer to the earlier estimates by Maxey and Jameson (1948, p. 120). Because uncertainties concerning some of the components, such as recharge and phreatophytic transpiration, remain large, and because data that describe the natural condition of Las Vegas Valley are limited, choosing a "best" set of budget estimates could be misleading. Estimates of the ground-water budget determined from this study were compared to the range of previous estimates rather than to any single estimate.

Table 2.3.1-1. Components of the ground-water budget under predevelopment and early development conditions

[All figures in acre-feet, rounded to nearest thousand; numbers in parentheses are page or plate numbers in original reference; <, less than; >, greater than; —, not estimated]

Budget item	Conditions and reference: Predevelopment (Malmberg, 1965)	Predevelopment (Harrill, 1976a)	1944 (Maxey and Jameson, 1948)
Developed-Zone Aquifers			
Estimated average annual recharge	25,000 (57)	30,000 (49)	30,000–35,000 (108)
Estimated annual discharge:			
Wells	0 (63)	0	15,000 (94)
Springs	6,000 (63)[a]	6,000 (41)	6,000 (95)
Net leakage	19,000 (pl 1)	23,000 (80)	<8,000 (95)
Subsurface outflow	—	1,000 (50)	0 (94)
Unaccounted-for difference between recharge and discharge	0	0	1,000–6,000
Near-Surface Aquifers			
Estimated annual recharge:			
Infiltration from wells and springs	6,000 (61, 79)	—	—
Infiltration of precipitation	0 (38)	—	0 (90)
Infiltration of imported water	0	0	0
Net leakage	19,000 (80)	23,000 (pl 1)	5,000–8,000 (91)
Estimated annual discharge:			
Phreatophytes	25,000 (80)[b]	—	5,000–8,000 (86)
Shallow wells	0 (82)	0	0 (85)
Seepage to washes	flood runoff (9)	—	—
Unaccounted-for difference between recharge and discharge	>0	—	>0 (91)

[a] Figures were modified wherever possible to account for the fact that Malmberg includes Red Rock Canyon, southern Three Lakes Valley, and southern Indian Spring Valley in his estimates.

[b] Evapotranspiration by phreatophytes excluding direct consumptive use of precipitation.

2.3.2 Postdevelopment Conditions

Hydrologic Conditions Changed Drastically With Development

Development of the land and water resources of the valley has led to marked changes in the water budget and to dramatic alteration of rates and means of recharge and discharge. Upward leakage from the developed-zone aquifers into the near-surface aquifers declined and even reversed, and perennial streamflow began in some washes in response to a rising water table.

With development of land and water resources in the valley, the natural rate and mechanisms of recharge from precipitation in the surrounding mountains probably remained unchanged. The potential for subsurface outflow near Frenchman Mountain also may be unaffected. Otherwise—as a result of years of pumping ground water and, more recently, importing water—the hydrogeologic conditions have changed drastically relative to conditions that prevailed prior to development. Some of the differences between hydrogeologic conditions under predevelopment conditions and those during the subsequent development become evident by comparing the water budgets in tables 2.3.1-1 and 2.3.2-1.

The natural recharge to the aquifers of the valley has been supplemented by large volumes of secondary recharge entering the near-surface aquifers. This secondary recharge originates either as ground water or as water imported from Lake Mead. After use, the part of this water that has not been consumptively used or discharged to sewers may percolate to the water table. By the early 1970's, the rate of percolation may have been between 0.2 and 1.5 times as large as the natural recharge rate (table 2.3.2-1). At the same time that secondary recharge to the shallow ground water was increasing dramatically, water-level declines in the principal aquifers were reducing and even reversing upward leakage. Thus, the sources of recharge to the near-surface aquifers changed radically.

Water levels within the near-surface aquifers have risen in many areas, and previously dry washes that flowed intermittently now drain ground water and flow year-round. Still, the total rate of discharge from the near-surface aquifers probably remained relatively constant because the effects of land-use changes that resulted in clearing of some stands of phreatophytes probably have been offset by rising water tables in many areas. In contrast, discharge from the developed-zone aquifers has changed dramatically. Ground-water pumpage from the aquifers is the overwhelmingly predominant form of discharge, exceeding spring discharge and upward leakage.

Finally, the water budget has changed drastically from the dynamic equilibrium between recharge and discharge described in the preceding section. The estimates of net discharge shown in table 2.3.2-1 mostly reflect the estimated imbalances between recharge and discharge. These imbalances represent water being released from or put into storage. Storage depletion of the same magnitude as the natural recharge-discharge rates was induced by the early 1970's. With rising water levels in the near-surface aquifers, storage in the shallow system may have increased.

The increases in secondary recharge and ground-water pumpage resulted in perennial surface-water outflow from the valley by way of Las Vegas Wash, cessation of flow at all major springs, and net downward leakage from the near-surface aquifers into the developed-zone aquifers. The uses of land and water that resulted in these hydrogeologic conditions are described in the next sections.

Table 2.3.2-1. Components of the water budget under developed conditions

[All figures in acre-feet, rounded to nearest thousand; numbers in parentheses are page or plate numbers in original reference; —, not estimated]

Budget item	Mid 1950's			Early 1970's	
	1955 (Malmberg, 1965)	1955 (Harrill, 1976a)	1958 (Patt, 1978)	1972 (Harrill, 1976a)	1973 (Patt, 1978)
Developed-Zone Aquifers					
Estimated average annual recharge	25,000 (84)	30,000 (49)	—	30,000 (49)	—
Estimated annual discharge:					
Wells	39,000 (63)	39,000 (22)	42,000 (36)	63,000 (22)	63,000 (32)
Springs	2,000 (63)[a]	1,000 (41)	—	minor (43)	—
Net leakage[b]	6,000 (84)	13,000 (58, pl 1)	—	−2,000 (58)	—
Subsurface outflow	—	1,000 (50)	—	1,000 (50)	—
Net discharge	22,000	24,000	—	32,000	—
Near-Surface Aquifers					
Estimated annual recharge:					
Infiltration from wells and springs	14,000 (72)	3,000 (58)[c]	13,000 (36)[d]	4,000 (58)[c]	17,000 (32)[d]
Infiltration of precipitation	0 (38)	—	2,000 (36)	—	2,000 (32)
Infiltration of imported water	5,000 (72)	2,000 (58)[c]	7,000 (36)[d]	2,000 (58)[c]	27,000 (32)[d]
Net leakage[b]	6,000 (83)	13,000 (pl 1)	—	−2,000 (pl 1)	—
Estimated annual discharge:					
Phreatophytes	24,000 (77)[e]	—	—	—	—
Shallow wells	1,000 (84)	1,000 (22)	1,000 (36)	7,000 (22)	7,000 (32)
Seepage to washes	— (71)	—	10,000 (36)	—	16,000 (32)
Net discharge	0	—	−11,000[f]	—	−23,000[f]

[a] Figures were modified wherever possible to account for the fact that Malmberg includes Red Rock Canyon, southern Three Lakes Valley, and southern Indian Spring Valley in his estimates.

[b] Negative values indicate recharge.

[c] Referred to as the minimal quantity, and includes some infiltration of imported water.

[d] Assumes that Henderson and Basic Management Inc. (BMI), sources (entirely imported water) do not contribute to septic tank, Las Vegas sewage connections, golf courses, or agricultural return flows, and that all other non-Henderson/BMI wastewater returns represent a uniform mix of imports and ground water.

[e] Evapotranspiration by phreatophytes excluding direct consumptive use of precipitation.

[f] Change in shallow ground-water storage, corrected for seepage to washes.

2.4 Land Use

Expanding Residential and Commercial Acreages Dominated Land-Use Trends

Since the construction of the Basic Management, Inc., industrial complex in Henderson during World War II, the major land-use trends have been an increase in suburban residential areas, and an expansion of commercial and resort enterprises.

The first nonaboriginal settlers in Las Vegas Valley were Mormon missionaries who built a fort in 1855. Thereafter, ranches were established and prospered (Patt, 1978, p. 7). By 1912, a number of wells had been constructed in the valley to supplement springs as sources of water for domestic use and irrigation. Between 1912 and 1944, the irrigated acreage remained almost constant and the population increased several-fold to approximately 30,000 persons (Maxey and Jameson, 1948, p. 1).

In the 1930's and 1940's, following the construction of Hoover Dam on the Colorado River and the Basic Magnesium, Inc., (later, Basic Management, Inc.; hereafter abbreviated BMI) industrial complex at Henderson, Las Vegas Valley underwent a period of rapid growth in population (Paher, 1971, p. 120). This growth has continued and has been reflected in substantial expansions in the number and extent of residential areas in the valley. Most of this growth has been in the suburban communities of the City of Las Vegas. The growth of residential areas in Las Vegas Valley is shown in figure 2.4-1.

Since the 1930's, Las Vegas has grown to be a thriving resort, drawing tourists from throughout the world. Most resort activities are, and historically have been, concentrated in downtown Las Vegas, near the center of the valley, and along the "Strip," which parallels Interstate Highway I-15 south of downtown.

Aside from variations in the level of activity at BMI at Henderson, industrial growth in Las Vegas Valley has been slow compared to the phenomenal growth of commercial and resort activities.

As of 1979, land uses in Las Vegas Valley were divided between residential areas (26,000 acres); resort and commercial areas (5,580 acres); industrial areas (2,692 acres); and public facilities such as schools, waste-water treatment plants, and airports (13,000 acres; URS Company and others, 1983, p. 142). Agricultural uses constitute a small part of the total [less than 2,000 acres in 1973 (Patt, 1978, p. 16, 17)].

The distribution of land uses in the valley as of 1979 are shown in figure 2.4-2. Most of the residential acreage surrounds downtown Las Vegas, with a smaller concentration around the city of Henderson. Downtown Las Vegas itself is devoted primarily to resort and commercial operations. Of the industrial land uses, 1,143 acres were concentrated in the heavy-industrial complex at Henderson. Most of the remaining industrial acreage is in the vicinity of the railroad, which parallels Interstate Highway I-15.

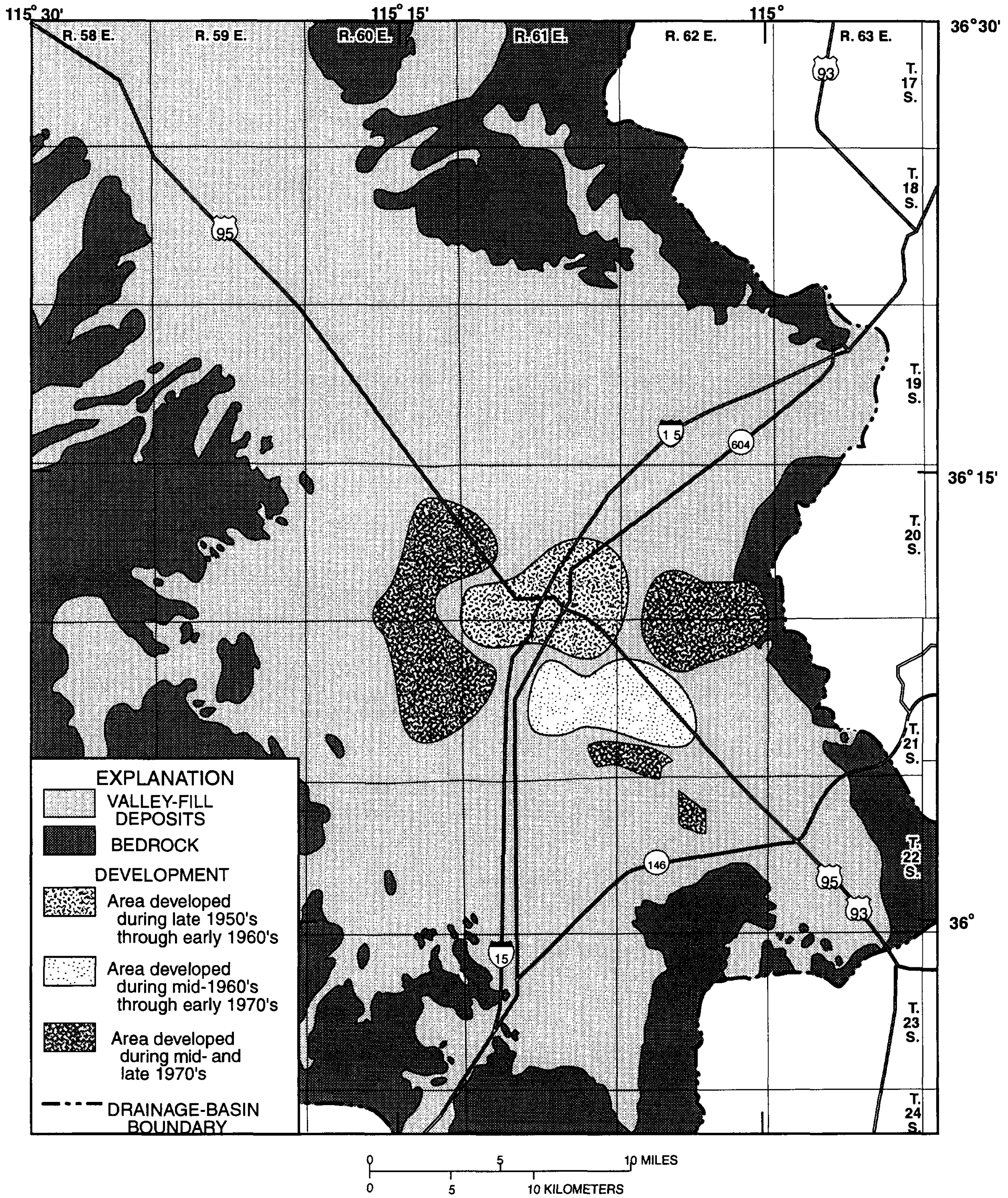


Figure 2.4-1. General pattern of urban and suburban development between late 1950's and late 1970's. Based on information from Clark County Department of Comprehensive Planning (1981, p. 159).

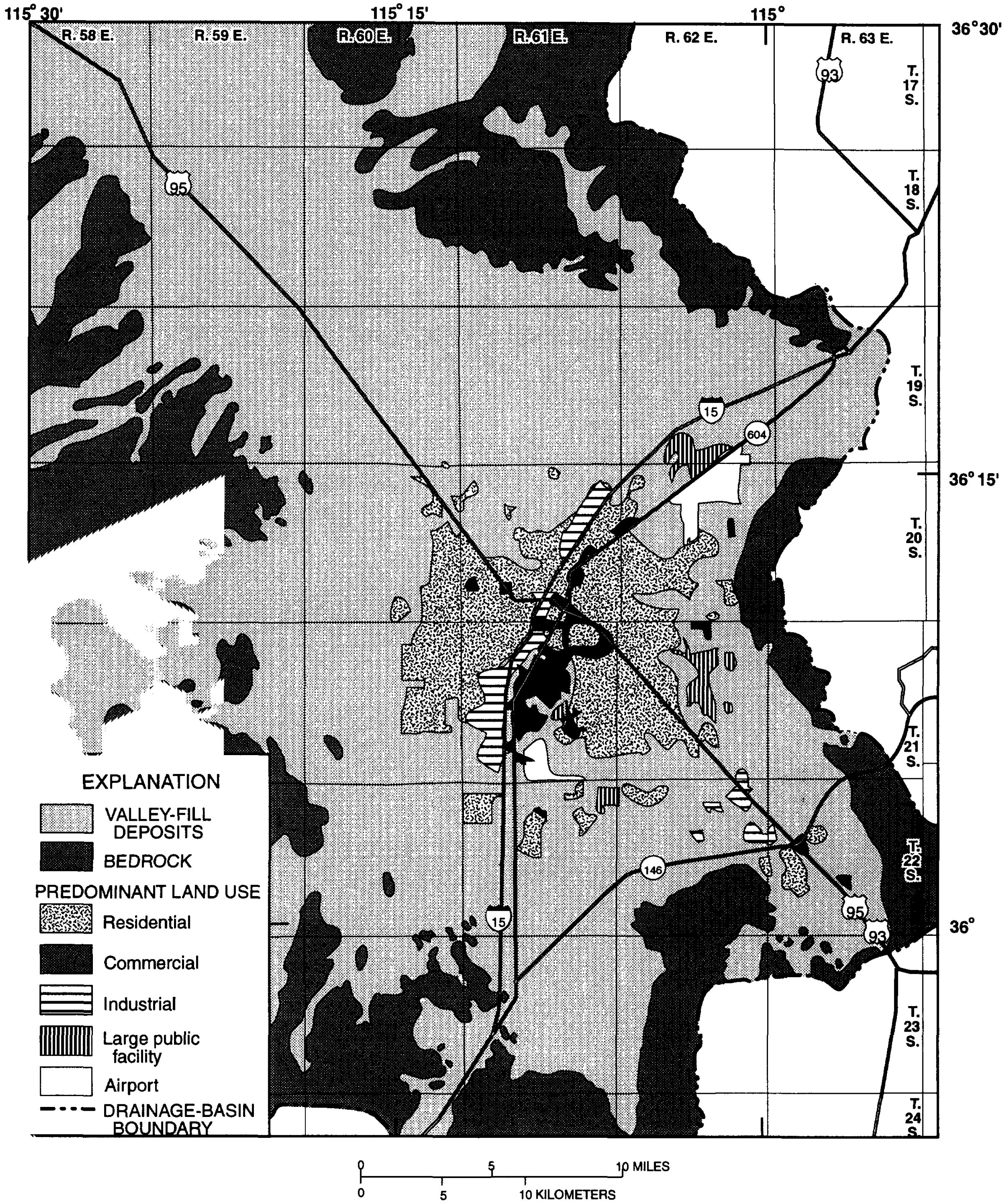


Figure 2.4-2. Major land uses as of 1979 (modified from Clark County Department of Comprehensive Planning, 1981, fig. 3-2).

2.5 Water Use

Growth in Water Demand, Primarily for Municipal Use, Has Led to Increasing Reliance on Imports

The history of water use in Las Vegas Valley has been one of large-scale and, at times, rapid growth. Demands have been met using springs, wells, and, more recently, imported water from Lake Mead.

Springs provided water supplies for the first settlers in Las Vegas Valley, but by 1912, wells had been constructed in the valley to supplement these supplies. The total discharge from these wells and the springs was 20,500 acre-ft in 1912 (Maxey and Jameson, 1948, p. 96). The rate of ground-water production remained near this level until 1941, when pumping rates began to increase rapidly. After 1941, as a result of war-time activities in the valley, the growth of BMI in Henderson, and a growing tourist industry, the population of the valley began to increase rapidly (Paher, 1971, p. 120). By 1955, the population was 50,000 and water use had grown to 57,000 acre-ft/yr (Harrill, 1976a, p. 19).

Between 1942—when it was first imported into the valley—and 1955, water from Lake Mead (17,000 acre-ft/yr by 1955, Harrill, 1976a, p. 22) was used only in the Henderson area, and the additional valley-wide demand for water was met by ground-water pumpage. In 1955, the LVVWD began to purchase limited amounts of Lake Mead water from BMI for public use. Figure 2.5-1 illustrates the history of water use, by source, since 1955. In 1956, effluent from the large sewage-treatment plants serving the valley was first used as cooling water at nearby power plants and for irrigation (Orcutt, 1965, p. 52–54). These practices have continued since then.

Population growth and consequent growth in the demand for ground-water continued during the 1950's and 1960's. In 1971, the first phase of the Southern Nevada Water Project (SNWP) became operational, permitting large imports of Lake Mead water to the LVVWD distribution systems. Since that time, the imports have satisfied the growing water demands, and ground-water pumpage has remained at about 70,000 acre-ft/yr (Wood, 1988b, p. 3; URS Company and others, 1983, p. 36). A total of more than 2.5 million acre-ft was pumped from the valley-fill aquifers of Las Vegas Valley between 1912 and 1981 (fig. 1.2.1-1). Water from Lake Mead became the dominant source for the valley in 1975, when 81,000 acre-ft was imported (Wood, 1988b, p. 4). In 1979, the 185,000 acre-ft of water used in the valley was supplied by: Lake Mead, 105,000 acre-ft; ground-water pumpage, 72,000 acre-ft; and wastewater reuse, 8,000 acre-ft (Wood, 1988b, p. 3–4; URS Company and others, 1983, p. 51).

Legal constraints ultimately will limit the use of surface water and ground water in the valley. Imports from Lake Mead to Nevada were limited to 300,000 acre-ft/yr by the Boulder Canyon Project Act of 1928. The Supreme Court Decree in *Arizona* v. *California* (1964) increased that total by an amount equal to the return flows to the lake by way of Las Vegas Wash (URS Company and others, 1983, p. 74-77 and 89-91). Presently, the amount of additional, or "return-flow-credit," water due Nevada is uncertain because, among other reasons, the amount of ground water discharged to Las Vegas Wash (as subsurface inflow to the Wash, and as a contributor to sewage effluent discharged to the Wash) needs to be subtracted from the total flow to calculate return-flow credit. For this reason, ground-water discharge can only be approximated.

Las Vegas Valley has been identified by the Nevada State Engineer as a "designated" basin—that is, one in which water rights are fully appropriated. As a result, all new wells drawing more than 1,800 gal/d require permits from the State Engineer. In recognition of the ground-water overdraft in Las Vegas Valley, all well permits and domestic-use appropriations since 1955 have been issued on revocable terms, and are revoked when municipal water supplies become available to users (URS Company and others, 1983, p. 80). Wastewater management agencies still have the right to use, sell, or distribute sewage effluent, subject to endorsement of the State Engineer.

Economic considerations also will play a role in future water-resource development in the valley. The

1982 cost for Lake Mead water was about $90 per acre-foot and is expected to grow to nearly twice that amount by the year 2000. Wastewater for reuse costs from $85 to $124 per acre-foot to produce. Ground water costs approximately half as much as either of these sources to produce, and thus is more desirable economically (URS Company and others, 1983, p. 108–109 and 117).

Ground water has other advantages as a source of supply in most of the valley. It is generally of better quality than water from Lake Mead or recycled wastewater and is more readily available for distribution through municipal supply systems or from private wells in most of the valley. The completion of the second phase of the SNWP in 1981 has allowed the municipal water systems to deliver Lake Mead water to almost all users within their boundaries (Roger Freeman, Las Vegas Valley Water District, oral commun., 1983), which largely negates the last-stated advantage of ground-water supplies within the municipalities of the valley. The second phase also increased the delivery capacity of the Lake Mead water-importation system to a full 300,000 acre-ft/yr, so that legal constraints may now be expected to limit importation before logistics do. Wastewater for reuse is still available on a large scale only near the wastewater treatment plants. Use of imported water and reuse of wastewater have a major advantage in that they can replace existing or additional extractions of ground water from the overdrafted aquifers of Las Vegas Valley.

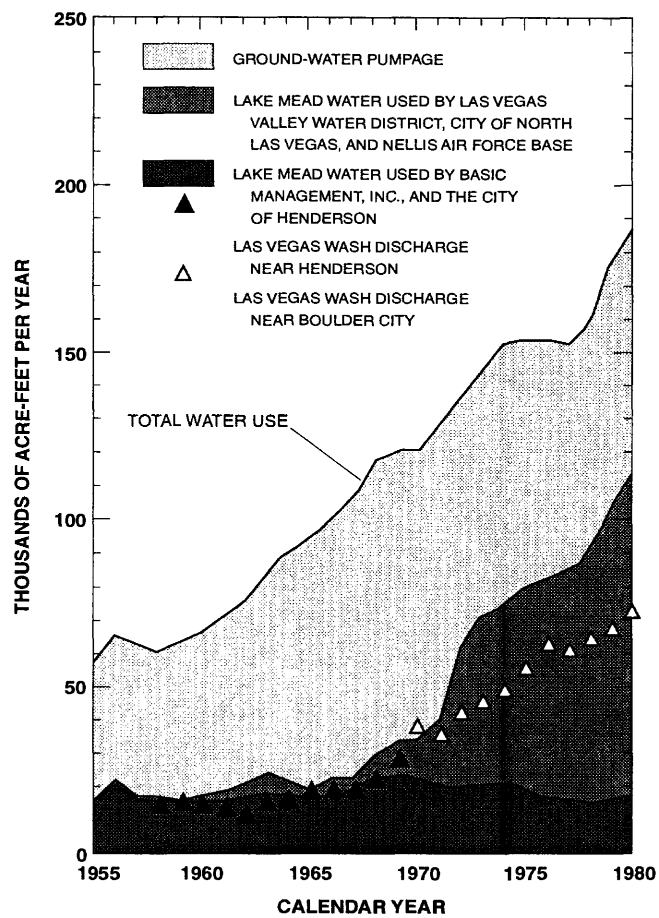


Figure 2.5-1. Ground-water pumpage, imports of water from Lake Mead, and surface-water outflow in Las Vegas Wash, 1955–80 (Wood, 1988b, fig.1).

3.0 MODEL DEVELOPMENT

The following sections describe the approach used in developing a model of the ground-water flow system of Las Vegas Valley. Specifically, they describe the conceptual and mathematical models of the physical system, the physical and hydrologic processes represented by the model, and the hydraulic characteristics of the valley fill.

Development of a conceptual model of the ground-water system is a goal in any hydrologic study, regardless of whether a mathematical simulation model is to be developed. The conceptual model is an assemblage of hydrologic cause-and-effect relations superimposed upon a geologic framework. The interdependency of the cause-and-effect relations and their mutual dependency on the geometry and water-bearing character of the aquifer system result in a physical system that is extremely complex. The conceptual model is, of necessity, a simplification of that system. This simplified concept forms the foundation of a mathematical simulation model.

An important step in the development of a mathematical simulation model is the calibration procedure. During that procedure, hydraulic properties of, and hydrologic stresses on, the aquifer system are modified until the simulation results acceptably match observed historical ground-water conditions. Most commonly, the estimated hydraulic characteristics of the basin are adjusted, and the model-computed water levels are then compared to measured or estimated water levels. Further adjustments are made until a reasonable match is obtained. Other hydrologic conditions such as the distribution and rate of evapotranspiration, the magnitude and extent of subsidence, ground-water seepage to washes, and springflow may also be used for comparison. If adjustment of hydraulic characteristics within reasonable or known bounds does not produce a satisfactory match between observed and computed conditions, the conceptual model may need reevaluation, or the simulation program may be inadequate, or both.

Section 3.1 describes the conceptual model for the Las Vegas Valley ground-water basin, the simulation program employed, and the synthesis of conceptual model and simulation program to form the mathematical simulation model. Section 3.2 describes the physical and hydrologic processes included in the conceptual model and how they are simulated. Section 3.3 describes the hydraulic characteristics of the valley fill.

3.1 Modeling Approach

3.1.1 Conceptual Model of Ground-Water Flow System

Hydrology and Geology Combined in Conceptual Model

A complex geologic framework, and dramatic changes in relations between ground-water recharge and discharge caused by overdraft and imports of water, have resulted in a dynamic conceptual model of the system.

The structural basin that underlies Las Vegas Valley is bounded by consolidated rocks on the sides and bottom and is filled to a depth as great as 5,000 ft with partly consolidated and unconsolidated valley-fill sediments (Plume, 1989, p. 1). These sediments store and transmit the ground water within the basin. The sediments exhibit a wide range of lithologies, reflecting an equally wide range of depositional modes and environments. The primary hydrogeologic divisions of the conceptual model developed during this study are: (1) the near-surface aquifers, (2) the developed-zone aquifers, and (3) the deep-zone aquifers. These divisions are discussed in section 2.2. The following paragraphs summarize the components of the conceptual model, and figure 3.1.1-1 shows the relation between components.

The near-surface aquifers contain both sand and gravel beds that transmit moderate amounts of water to shallow wells, and clay lenses that effectively impede vertical movement of ground water. The uppermost 20 to 50 ft of the saturated part of the near-surface aquifers is mostly unconfined (Westphal, 1977, p. 26). Below this interval, clay and extensive caliche deposits create confined (or perched) ground-water conditions.

Under natural conditions, ground water in the basin recharged the near-surface aquifers by leaking upward from what is now the developed-zone aquifers before being discharged by evapotranspiration. The exploitation of the developed-zone aquifers and the accompanying declines in artesian water level, coupled with increasing secondary recharge and rising water tables in the near-surface aquifers, have resulted in reversal of the direction of net leakage toward the developed-zone aquifers. Rising water levels in the near-surface aquifers in the eastern and southeastern parts of the valley resulted in enough seepage to Las Vegas Wash to cause perennial flow beginning in about 1944 (Patt, 1978, p. 10).

The developed-zone aquifers are, by definition, underlain by the deep-zone aquifers or by bedrock on the margins of the basin. Bedrock forms the lateral boundaries of the developed-zone aquifers except at the northwestern and northeastern extremities of the valley where topographic highs probably form ground-water flow divides. The top of the developed-zone aquifers is formed by the bottom of the near-surface aquifers where they overlie the developed-zone aquifers; where the near-surface aquifers are absent, the developed-zone aquifers are unconfined and the top of the unit is the water table.

Under natural conditions, the ground water of the developed-zone aquifers was recharged by infiltration of precipitation and snowmelt in the Spring Mountains and Sheep Range, and was discharged by spring flow, by upward leakage into the near-surface aquifers, and by small quantities of underflow through Frenchman Mountain (fig. 1.1-1). Since development of the basin, this hydrologic regime has been altered extensively. Natural recharge is now augmented by downward leakage from the near-surface aquifers and, in some areas, by direct secondary recharge. Although greatly reduced in extent, areas of upward vertical leakage still exist in parts of the valley. Water levels and spring discharge have declined steadily in response to pumping and by 1975, none of the larger springs were flowing.

The deep-zone aquifers are a poorly defined sequence of sediments bounded laterally and below by bedrock and overlain by the developed-zone aquifers. The deep-zone aquifers are defined in this study as the sediments more than 1,000 ft below land surface. Where the depth to bedrock is less than 1,000 ft, the deep-zone aquifers do not exist. The deep-zone aquifers have low permeability and yield little water to wells but have large storage capacity (Malmberg, 1965, p. 24). Discharge from the deep-zone aquifers is by upward leakage to the developed-zone aquifers, and possibly by underflow through adjacent bedrock.

Recharge processes and flow paths for the valley-fill deposits are not fully understood. Infiltration through channels of ephemeral streams at the heads of alluvial fan deposits is an observable process but may not account for much of the total recharge to the system. Infiltration of precipitation and snowmelt, flow through fractured carbonate rocks, and subsequent recharge to the valley-fill deposits is a reasonable conceptual model for most recharge to the system; however, little information is available to delineate source areas and flow paths and to quantify travel times.

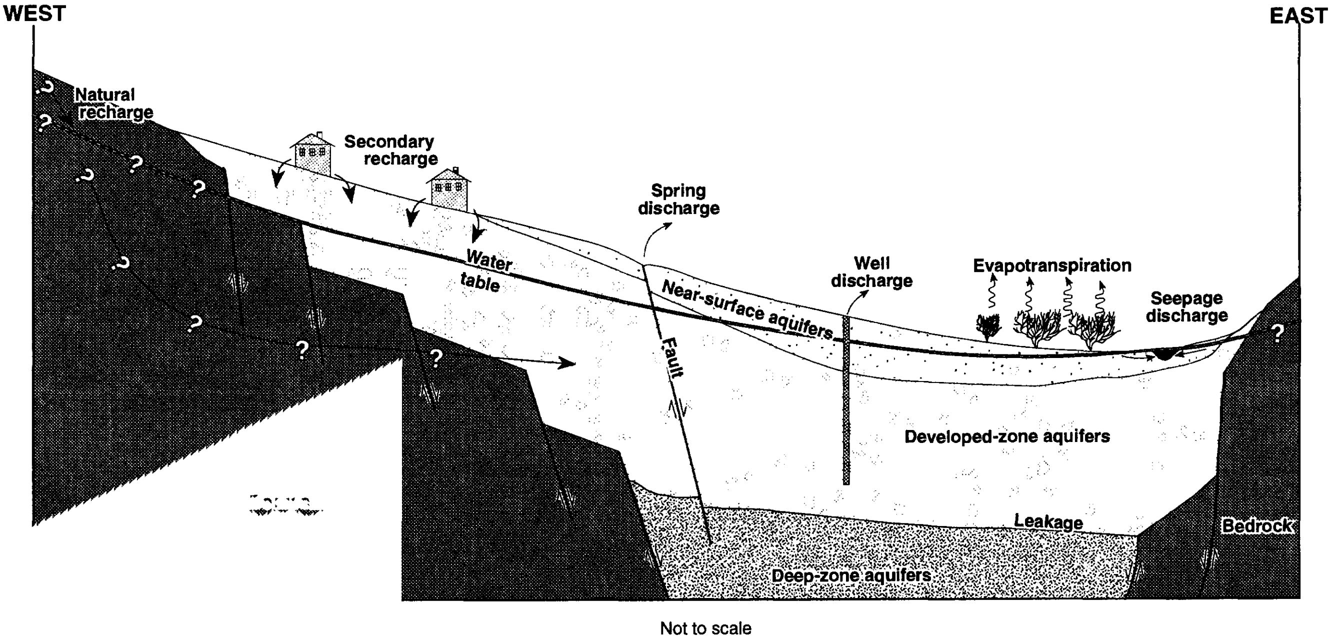


Figure 3.1.1-1. Schematic west-to-east hydrogeologic section.

3.1.2 Mathematical Simulation Program

Simulation Program is a Three-Dimensional, Finite-Difference Model

The mathematical simulation program numerically solves a finite-difference approximation of the ground-water flow equation for multi-layer aquifer systems. The program uses hydrogeologic data that describe the extent, properties, and boundary conditions of an aquifer system to simulate the movement of ground water through that system.

The simulation program is the set of Fortran computer instructions that solves an approximation of one form of the ground-water flow equation. The basic program, developed and documented by Trescott (1975) and Trescott and Larson (1976), is capable of simulating ground-water flow in the vertical and horizontal directions. Trescott's program was modified to allow construction of the simulation model for this analysis of the Las Vegas Valley ground-water flow system.

The form of the ground-water flow equation solved by the program, which is identical to Trescott's eq 4 (1975, p. 4), is as follows:

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(bK_{zz}\frac{\partial h}{\partial z}\right)= S'\frac{\partial h}{\partial t}+bW(x,y,z,t)$$

where h = hydraulic head (L);
T_{xx}, T_{yy} = principal components of the transmissivity tensor (L^2/t);
K_{zz} = principal component of the vertical hydraulic-conductivity tensor (L/t);
b = thickness of the hydrologic unit (L);
S' = storage coefficient (dimensionless); and
$W(x,y,z,t)$ = volumetric flux per unit area (L/t).

This is considered a "quasi-three-dimensional model" (Bredehoeft and Pinder, 1970) because confining beds are not represented by layers. The resistance of the confining beds to vertical flow is incorporated in the approximation of this equation by the vertical leakance, $\frac{K_{zz}}{b}$.

To solve the equation for a heterogeneous, anisotropic, porous medium with irregular boundaries, the aquifer system is subdivided into rectilinear cells within which the hydrologic properties of the system are assumed to be uniform. Cells differ in dimension but are a minimum of 6,000 ft on a side. These cells form a grid (see fig. 3.1.2-1) in three dimensions, allowing replacement of the continuous derivatives in the above equation by expressions for the ratios of the changes in hydraulic head over small but finite intervals. The resulting system of finite-difference equations (one equation for each cell) describes horizontal flow within each layer and vertical flow or leakage between the layers. The equations are solved numerically by the Strongly Implicit Procedure (SIP) described by Remson and others (1971, p. 219).

The source term, $W(x,y,z,t)$, of Trescott's simulation program can include well discharge (or well recharge) and recharge from precipitation. Most of the modifications made to the program for this study involved additions to or subtractions from the source term that reflect the influences of spring discharge, ET, and seepage of ground water to washes. The methods of computing discharge for each of these processes are similar to those used by McDonald and Harbaugh (1988). The effects of land subsidence are also accounted for in the model. The semi-empirical method of estimating subsidence is based on changes in specific storage with decreasing hydraulic head. The methods and assumptions used in implementing these modifications to the basic simulation program are described later in section 3.2.

Additional modifications to the program are:

1. Water budgets may be listed for each model layer.
2. Areal recharge rates may vary with time; changes to the areal (secondary) recharge distribution are allowed at each stress period.
3. Hydraulic head, drawdown, and subsidence may be saved for subsequent processing by a contouring program.

4. Water-level data may be saved after each time period for individual cells.
5. Flow-vector data may be saved for subsequent processing by a plotting program.

The hydrologic data requirements of the simulation program can be divided into two groups: Those data that quantify, directly and indirectly, the hydrologic fluxes to and from the ground-water system (Group I) and those data that describe how the porous medium stores and transmits ground water (Group II). The members of each group are listed in table 3.1.2-1. Group-I data need be specified only where a flux to or from the system occurs; for example, secondary recharge is usually specified only in urban or agricultural areas where runoff infiltrates to the water table. In contrast, Group-II data need to be specified at each node. Group-I data, their distribution, and how they were estimated, are described in section 3.2. Similar information for Group-II data is given in section 3.3.

Table 3.1.2-1. Model input data

Parameter	Units
Group I (specified only when necessary)	
Las Vegas Wash node:	
Leakance	1 per second
Streambed altitude	feet above sea level
Maximum rate of evapotranspiration	feet per second
Effective depth of evapotranspiration	feet below land surface
Inelastic storage coefficient	dimensionless
Secondary recharge	feet per second
Natural recharge	cubic feet per second
Pumping	cubic feet per second
Group II (needs to be specified at each active cell)	
Transmissivity	feet squared per second
Vertical leakance	1 per second
Elastic storage coefficient	dimensionless
Initial hydraulic heads	feet above sea level
Land-surface altitude	feet above sea level

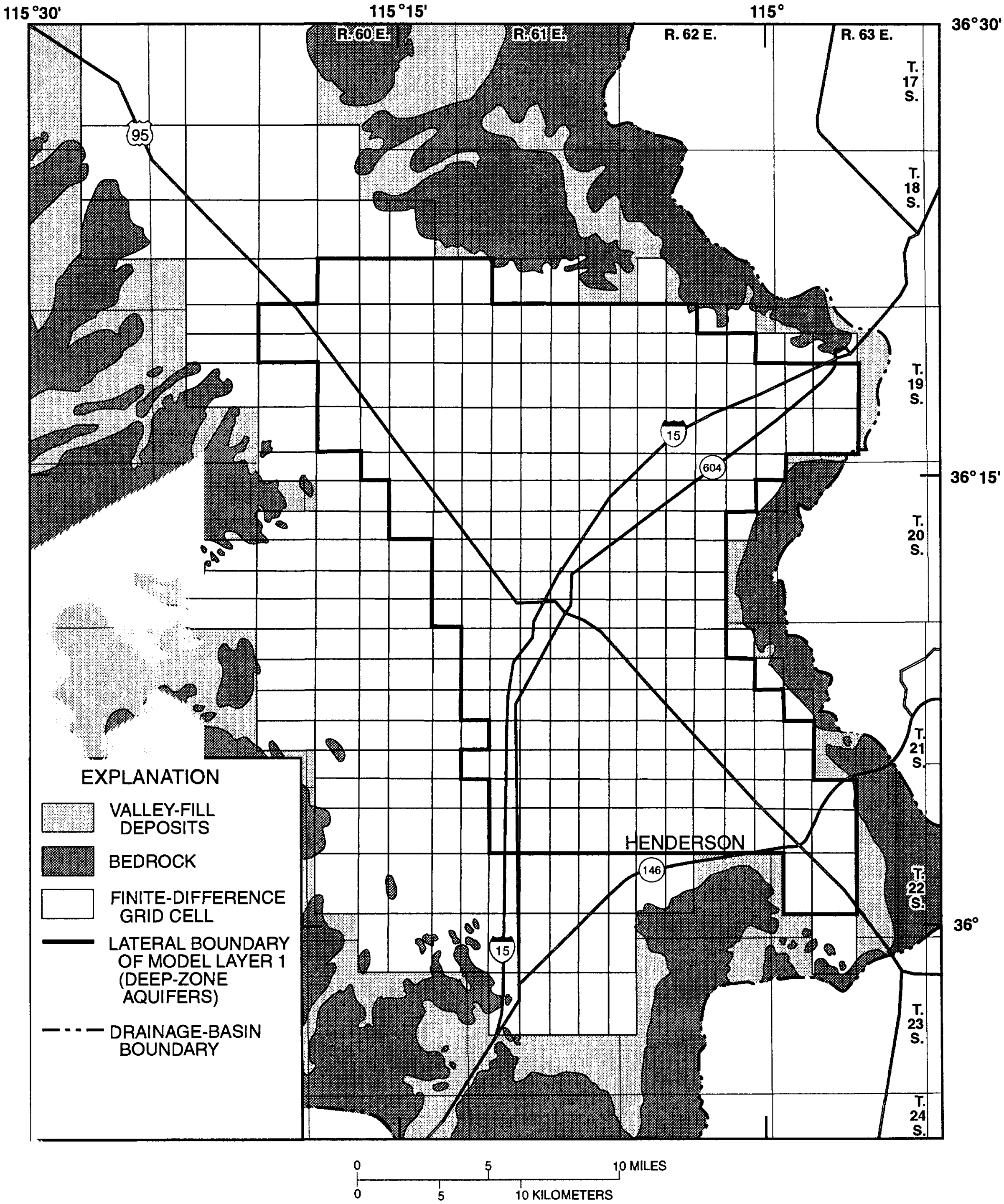


Figure 3.1.2-1. Finite-difference grid, and lateral boundary of deep zone as represented by model layer 1.

3.1.3 Mathematical Simulation Model

Multi-Layer Model Used to Simulate System

The boundary conditions used in the model were selected to provide as accurate a representation of the conceptual model as the available data permit. Four model layers were used, to represent (1) the deep-zone aquifers, (2) the developed-zone aquifers, (3) the confined part of the near-surface aquifers, and (4) the unconfined part of the ground-water system.

The simulation model represents the synthesis of the simulation program, the boundary conditions, the hydraulic characteristics of the aquifer system, and the hydrologic stresses on the flow system.

How the hydrogeologic units of the conceptual model are represented in the simulation model is shown in figure 3.1.3-1. The lowest unit of the valley-fill sediments, the deep-zone aquifers, is layer 1 of the simulation model. The lower and lateral boundaries of layer 1 are formed by bedrock that is assumed to be impermeable throughout the basin. The contacts between the valley-fill deposits and bedrock are treated as zero-flux boundaries in the simulation model; that is, boundaries across which no flow is allowed. This assumption was tested during the predevelopment simulation analysis to assess the validity of a conceptual model that included a deep flow path for recharge from bedrock into the valley-fill deposits. As shown in figure 3.1.3-1, the shape of the bedrock basin and the thickness of fill therein dictate that the areal extent of layer 1 is not as great as that of the overlying layers. The actual areal extent of layer 1 is shown in figure 3.1.2-1.

The boundary between the deep- and developed-zone aquifers could not be well defined on the basis of lithology, hydraulics, geochemistry, or any other commonly used criteria for delineating ground-water flow systems. Well-log data indicate a generalized downward gradation from coarse-grained to fine-grained sediments through the depth interval of 600 to 1,000 ft in the central part of the valley. This is corroborated by drillers' logs for the few wells that are completed below this interval. These observations led to the selection of a boundary based on the depth to which aquifers had been developed (about 1,000 ft below land surface). The definition of this boundary is appropriate because the primary intended use of the simulation model is to predict water-level changes resulting from future ground-water withdrawals from the developed-zone aquifers.

The lateral boundaries of layer 2—the developed-zone aquifers—lie at the contact between bedrock and valley fill except in the extreme northwestern and northeastern corners of the valley where ground-water divides probably coincide with topographic divides. Treatment of the lateral boundaries of layer 2 differ with location. Where natural recharge or underflow are thought to be substantial, specified flux boundaries are used; elsewhere, zero-flux boundaries are assumed. This choice of boundary conditions implicitly assumes that no additional natural recharge or underflow from or to the bedrock can be induced by stresses in the valley-fill aquifers.

Where layer 2 is underlain by bedrock, ground water cannot leak upward into the layer. Where layer 2 is in contact with layer 1, leakage may move in the direction of the hydraulic gradient at a rate dependent on the specified vertical leakance.

The upper boundary of layer 2 is (1) the water table in areas where the layer is unconfined, and (2) the bottom of the near-surface aquifers in areas where that unit is present. The rate of vertical leakage between the developed-zone aquifers (layer 2) and the near-surface aquifers (layer 3) is dependent on the direction and magnitude of the vertical hydraulic gradient and the assigned vertical leakance.

Layer 3 of the model represents the near-surface aquifers. It is underlain by layer 2 and can receive leakage from above or below. Because the simulation program will not allow a layer to pinch out, as the near-surface aquifer does, layer 3 must contact active grid cells in areas outside the lateral extent of the near-surface aquifers. In these areas, layer 3 is assigned hydraulic properties that ensure its mathematical invisibility to the model.

Layer 4, shown in figure 3.1.3-1, represents the unconfined part of the ground-water system, valley wide. The parameters assigned to it in the simulation model represent those of the upper 20 ft of saturated thickness throughout the valley. Its function in the model is that of a medium through which hydrologic inputs and outputs (such as secondary recharge and evapotranspiration) may pass. Its use is necessitated by the inability of the simulation program to simulate a system where the uppermost hydrogeologic unit (in this instance, layer 3) is not present valley wide.

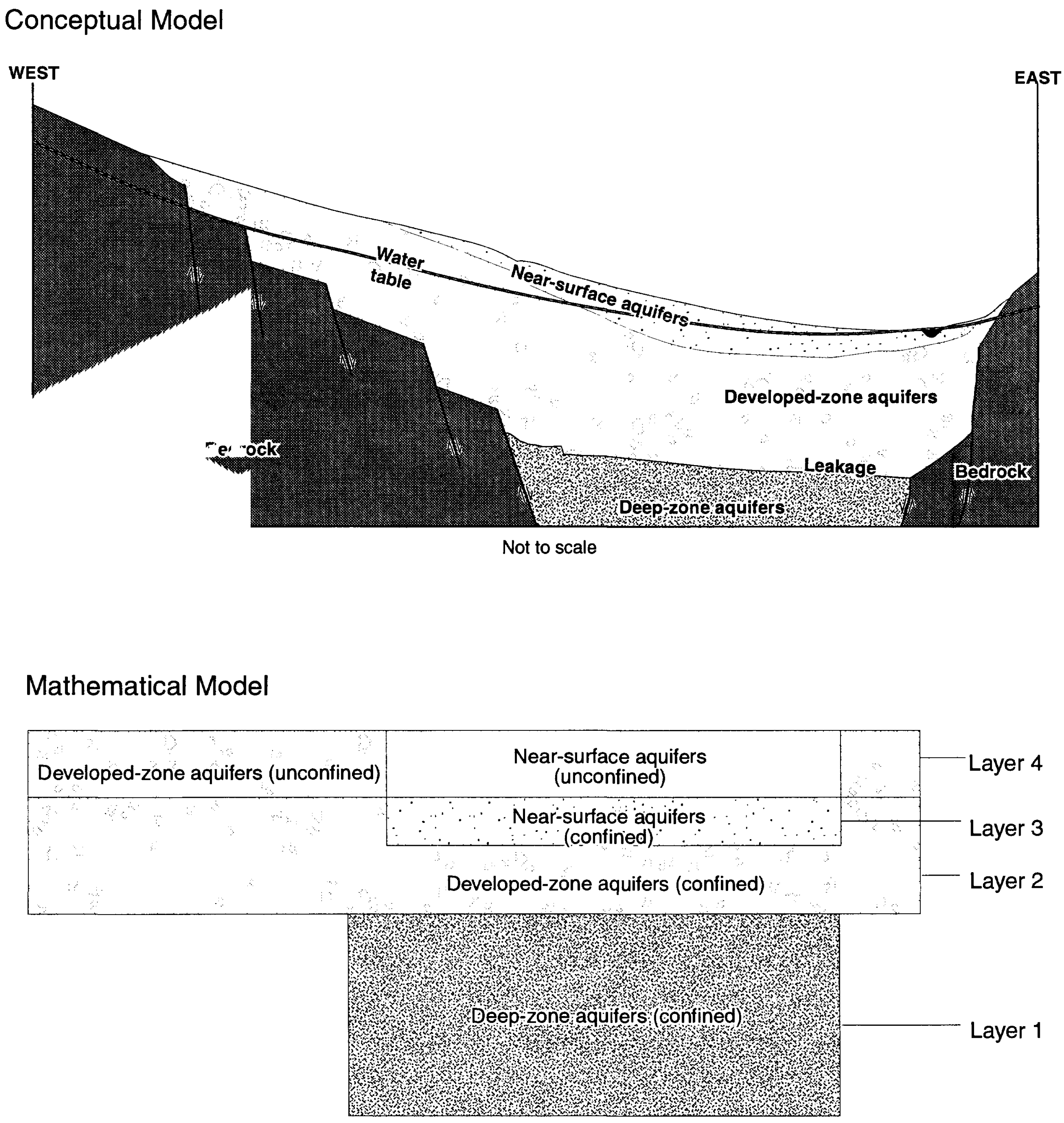


Figure 3.1.3-1. Vertical layering of the flow system in conceptual and mathematical models.

3.0 MODEL DEVELOPMENT—Continued

3.2 Physical and Hydrologic Processes

3.2.1 Evapotranspiration

Discharge by Evapotranspiration Simulated as Linear Function of Depth to Water

Ground water discharged by evapotranspiration consists mostly of pumped or imported water that has reached the near-surface aquifers as secondary recharge from a previous use. Under predevelopment conditions, all phreatophytes were supported by upward leakage and spring discharge.

Evapotranspiration (ET) includes (1) evaporation from open water bodies and (where the water table is near land surface) from soil surfaces, and (2) transpiration by phreatophytes. Most land-surface discharge of ground water in Las Vegas Valley is by transpiration; in fact, Malmberg (1965, p. 73) states that total discharge by evaporation is probably less than the overall error associated with estimates of discharge by transpiration.

Phreatophytes are plants that obtain much of their water supply from the zone of saturation (below the water table). In Las Vegas Valley, these plants include (in approximate order of abundance) saltgrass, mesquite, tule, marshgrass, cottonwood, and willow (Malmberg, 1965, p. 73). The distribution and abundance of each type have changed relative to predevelopment conditions because of changes in the source and location of recharge to the near-surface reservoir. Total consumptive use by ET (less precipitation) was 27,000 acre-ft/yr over 8,400 acres in 1906, and had been reduced to only 22,000 acre-ft/yr over 8,100 acres by 1955 (Malmberg, 1965, p. 77–80). Total upward leakage decreased during the same time period from about 19,000 acre-ft/yr (Malmberg, 1965, p. 80) to between 6,000 acre-ft/yr (Malmberg, 1965, p. 72) and 13,000 acre-ft/yr (Harrill, 1976a, p. 58). Thus, in 1955, between one-quarter and one-half of phreatophyte growth was supported by secondary recharge to the near-surface reservoir. According to Harrill (1976a, p. 45), phreatophyte stands in 1976 were as vigorous as, or more vigorous than, under predevelopment conditions because secondary recharge was either equal to or exceeding any downward leakage to the developed-zone aquifers.

The model used in this study computed discharge of shallow ground water by ET as a linear function of the depth to the water table (fig. 3.2.1-1). This method is predicated on the assumption that depth to ground water is the main determinant of the occurrence, type, and density of phreatophytes found in an area. The method has been used in similar hydrologic settings in Nevada with good results (Harrill, 1986, p. 31; Thomas and others, 1989, p. 25). The function depicted in figure 3.2.1-1 is:

$$Q = \frac{QET}{ETDIST}(ETDIST - Z),$$

where Q = rate of evapotranspiration (L/t);
QET = maximum ET rate allowed (when the water table is at land surface) (L/t);
$ETDIST$ = effective depth of ET (L); and
Z = depth to water (L).

The maximum rate, *QET,* was specified as 6.3 ft/yr at each cell in agreement with Harrill (1986, p. 31), who applied this rate in nearby Pahrump Valley. The effective depth was specified generally as 20 ft; where more deeply rooted phreatophytes (cottonwood, mesquite) were shown to exist (Malmberg, 1965, pl. 9), effective depths as great as 30 ft were used.

Both the maximum rate *(QET)* and the effective depth *(ETDIST)* need to be specified at each cell in the uppermost layer and may be varied areally. The computed hydraulic head *(PHI)* and the land-surface altitude *(GRND)* are used to determine depth to water. Although this method was adequate for simulating ET under predevelopment conditions, urbanization and accompanying reductions in phreatophyte densities required a modification to the method of calculating ET. Under these conditions, the presence of the water table within 20 ft of land surface is no longer a reliable indicator of ET. A reduction in the maximum rate of ET *(QET)* is used to account for reductions in phreatophyte density due to urbanization. On the basis of the assumption that there is an inverse relation between secondary recharge rates (urbanization) and maximum ET rates, the maximum ET rate was estimated at each cell, using the relation:

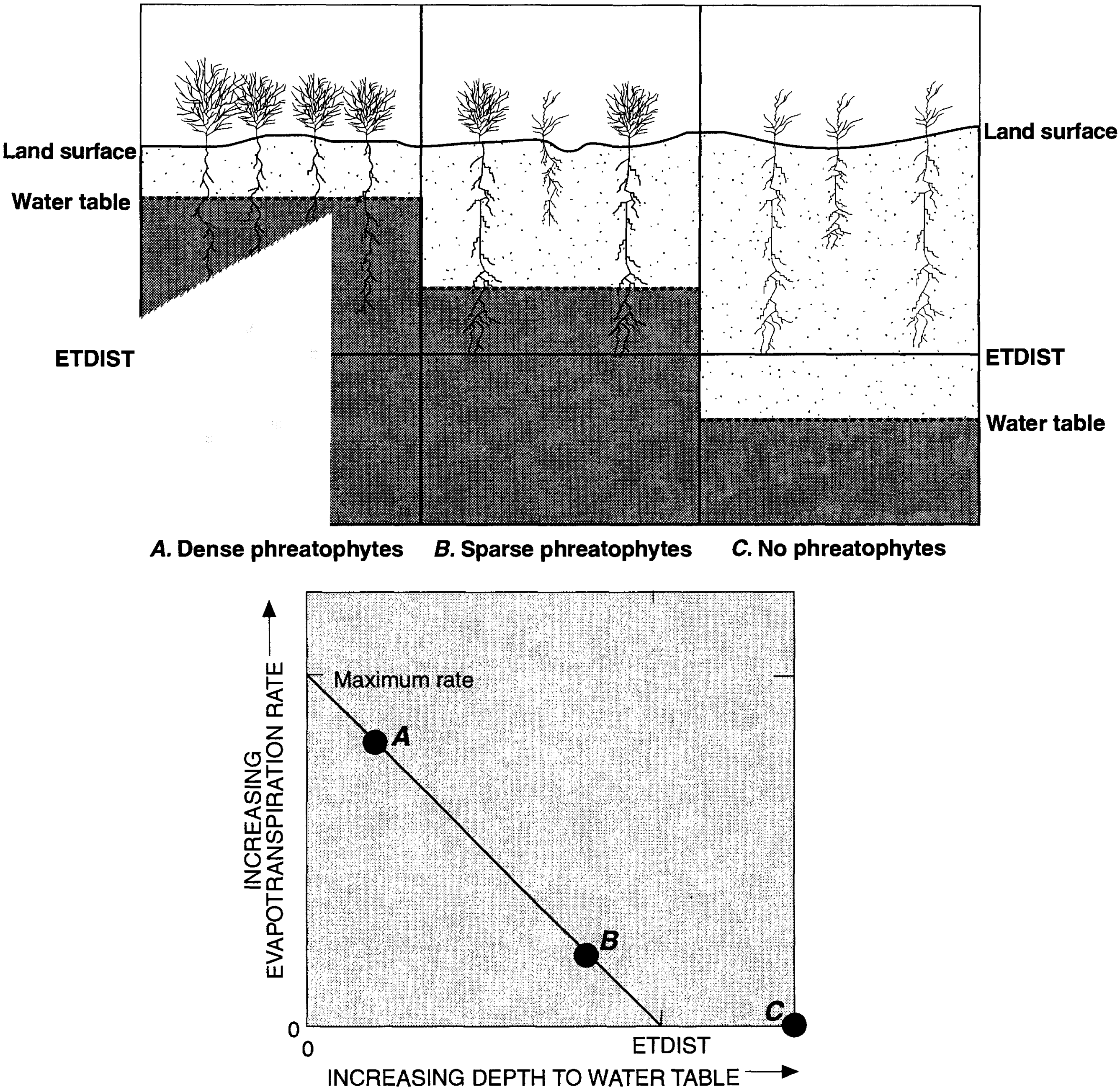
$$QET_{new} = -3.0(QRE) + QET,$$

where QET_{new} = the adjusted maximum rate of ET (L/t), and

QRE = the estimated rate of secondary recharge (L/t).

The constant −3.0 was chosen so that QET_{new} would be zero in the areas where the secondary-recharge rates were equal to the 1979 maximum (2.1 ft/yr). This constant is valid only when QET and QET_{new} are expressed in feet per year.

During the calibration, total discharge by ET, the shape of the discharge area, and, to a lesser extent, the distribution of discharge within that area were compared with observations made by Maxey and Jameson (1948) and Malmberg (1965), as discussed in later sections.



EXPLANATION

ETDIST EVAPOTRANSPIRATION EXTINCTION DEPTH

A RATE OF EVAPOTRANSPIRATION BY PHREATOPHYTES IS NEAR MAXIMUM WHEN WATER TABLE IS SHALLOW

B RATE OF EVAPOTRANSPIRATION BY PHREATOPHYTES APPROACHES ZERO AS DEPTH TO WATER TABLE APPROACHES ETDIST

C EVAPOTRANSPIRATION BY PHREATOPHYTES CEASES WHEN DEPTH TO WATER TABLE EXCEEDS ETDIST

Figure 3.2.1-1. Linear function between depth to ground water and rate of evapotranspiration at each grid cell.

3.2.2 Spring Discharge

Simulated Decline in Artesian Spring Flows

The major springs in Las Vegas Valley flowed under artesian pressure and were associated with fault scarps. Flow from these springs ceased with the development of the artesian system and consequent reduction of hydraulic head. Spring flow is simulated as a discharge from the developed-zone aquifers that is linearly related to the head in that zone.

The major springs in Las Vegas Valley were along the bases of scarps in the valley fill. The largest were the Las Vegas, Kyle, Tule, Corn Creek, Stevens, and Grapevine Springs. Malmberg (1965, p. 59) hypothesized that the offset of permeable aquifers against less permeable beds may impede lateral flow across the fault zones associated with the scarps, which in turn may facilitate flow upward along those zones to the near-surface reservoir and land surface. Maxey and Jameson (1948, p. 64) suggest that cementation within the fault zones also may impede lateral flow, and force water upward to springs. The location and predevelopment discharge rates of the major springs are shown in figure 3.2.2-1.

Many gravity-fed springs emerge along the margins of the valley fill and in the surrounding mountains. These springs occur where the water table intersects the land surface, and are common near the recharge areas for the developed zone in the remote sections of the valley (Maxey and Jameson, 1948, p. 74). Gravity springs and seeps also occur within the valley along the scarps.

With development, the discharge rates from the major springs declined in response to declining artesian pressures. In 1912, artesian spring discharge totaled approximately 6,400 acre-ft/yr. By 1941, the flow had declined to 3,400 acre-ft/yr; by 1955, the discharge rate from major artesian springs was 1,400 acre-ft/yr; and by 1975, all major artesian spring flow in the vicinity of Las Vegas had ceased (Malmberg, 1965, p. 59 and 63; Harrill, 1976a, p. 43).

In the simulation model, discharge from springs in Las Vegas Valley was directly related to the artesian head at a cell according to the following equations:

$$Q(I,J) = [PHI(I,J,2) - GRND(I,J)]\,(SPQ)\,[AREA(I,J)],$$
$$\text{when } PHI(I,J,2) > GRND(I,J) \text{ and}$$
$$Q(I,J) = 0, \text{ when } PHI(I,J,2) \le GRND(I,J),$$

where I = row number of cell,
J = column number of cell,
$Q(I,J)$ = spring flow at cell (L^3/t),
$PHI(I,J,2)$ = hydraulic head (L),
$GRND(I,J)$ = average land-surface altitude (L),
SPQ = leakance coefficient between the developed-zone aquifers and the spring orifice ($1/t$), and
$AREA(I,J)$ = area of the model cell (L^2).

The coefficient SPQ is conceptually equivalent to the average vertical hydraulic conductivity along the fault zone (or other spring flow path through the semiconfining layers) divided by the length of the flow path leading to the orifice from artesian aquifers. Values of SPQ were estimated at cells that included major scarps, according to the equation:

$$SPQ = \frac{Q(I,J)}{(\Delta H)\,[AREA(I,J)]}$$

where ΔH = estimated predevelopment difference between the artesian head in layer 2 and land-surface altitude. $Q(I,J)$ was assumed equal to pre-development spring-flow rates.

Spring flow was assumed to be discharged from the system instantaneously; that is, the flow was not recirculated through the near-surface reservoir before being lost to ET.

At major springs, dense stands of phreatophytes were present (Maxey and Jameson, 1948, pl. 7). In estimating SPQ, the measured spring flows were increased slightly to account for upward-moving ground water that never reached the land surface but leaked directly into the near-surface aquifer. The flows of some springs and seeps were never measured under predevelopment conditions. Flows assumed in calculating SPQ at these small springs and seeps were estimated on the basis of the estimated evapotranspiration by the stands of phreatophytes associated with them, as mapped by Malmberg (1965, pl. 7).

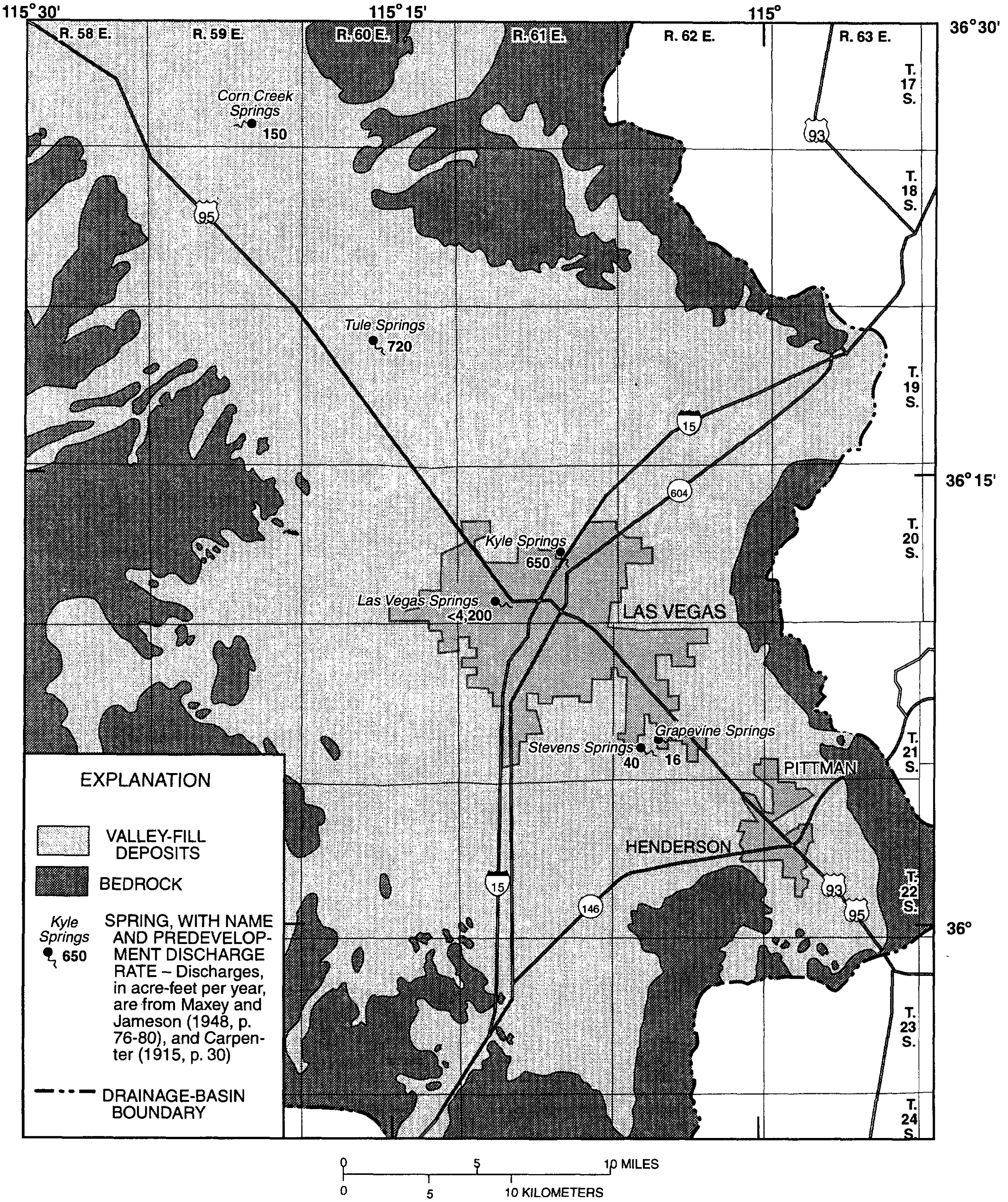


Figure 3.2.2-1. Location and predevelopment discharge of major springs.

3.2.3 Interaction Between Ground Water and Surface Water

Ground Water Discharges into Several Streams in Las Vegas Valley

Certain small streams or washes in Las Vegas Valley drain ground water from the shallowest parts of the near-surface aquifers. The simulated rate of drainage was assumed to be linearly related to the difference between the water-surface altitude in the stream and the hydraulic head in the shallowest aquifers. Streams and washes were assumed to function only as drains, which do not lose water to the near-surface aquifers.

Under predevelopment conditions, the stream channels of Las Vegas Valley were generally dry except during periods of flood. Las Vegas Wash, in the southeastern part of the valley, descended to the Colorado River through a narrow canyon. Las Vegas Wash was the only surface outlet by which water could flow from the valley. Flow occurred only during infrequent, severe floods (Malmberg, 1965, p. 9).

With development, surface-water flow in the washes of the valley became more common, and in some places was perennial. These flows are fed by inflow from the rising ground water under the lower parts of the valley and by surface discharges of sewage-treatment effluent, power-plant coolant water, wastewater, and flood water. These flows eventually are drained from the valley by way of Las Vegas Wash, which in 1982 discharged 39,800 acre-ft to Lake Mead (U.S. Geological Survey, 1984, p. 55).

In general, streams and washes may contribute water to or drain water from underlying aquifers. The direction and rate of flow between surface water and ground water are related to the permeability of the streambed and the difference between the hydraulic heads in the stream and the underlying ground-water reservoir.

In Las Vegas Valley, the major streams function primarily as ground-water drains, and this condition is expected to continue with further development; therefore, the simulation analyses allow only ground-water drainage to the streams. Streamflow routing was not incorporated in the ground-water flow simulations reported here. The rate of drainage was assumed to be linearly related to surface-water and ground-water head differences, according to the equation:

$$WAQ(I,J) = [WALK(I,J)]\,[PHI(I,J,4) - WAEL(I,J)]\,[AREA(I,J)],$$

where $WAQ(I,J)$ = rate of ground-water discharge (L^3/t) to the stream at cell (I,J),
$WALK(I,J)$ = streambed leakance ($1/t$),
$WAEL(I,J)$ = channel altitude (L),
$PHI(I,J,4)$ = water-table altitude (L), and
$AREA(I,J)$ = area of the cell (L^2).

Drainage to the stream is assumed to cease when the water table falls below $WAEL(I,J)$. Under extreme conditions—when the water-table altitude is projected as being higher than the general interchannel land-surface altitude at a cell (and thus, much higher than the altitude of the channel)—discharge of ground water to the stream is automatically (and arbitrarily) limited to a maximum rate defined by the equation:

$$WAQ(I,J) = [WALK(I,J)]\,[GRND(I,J) - WAEL(I,J)]\,[AREA(I,J)],$$

where $GRND(I,J)$ = the interchannel land-surface altitude (L).

The streambed leakance is a measure of the hydraulic connection between the stream and the near-surface aquifers, and is a function of the hydraulic conductivity and geometry of the streambed and underlying aquifer materials. It needs to be reduced to account for the difference between the wetted area of the stream and the area of the cell as a whole. In the Las Vegas Valley model, the streambed leakance for each cell that contained a length of stream was assumed to be 0.0016 per day. This leakance estimate is primarily a product of the model calibration process. The cells containing streams that were assumed to have a potential to drain water from the shallowest parts of the near-surface aquifers are shown in figure 3.2.3-1.

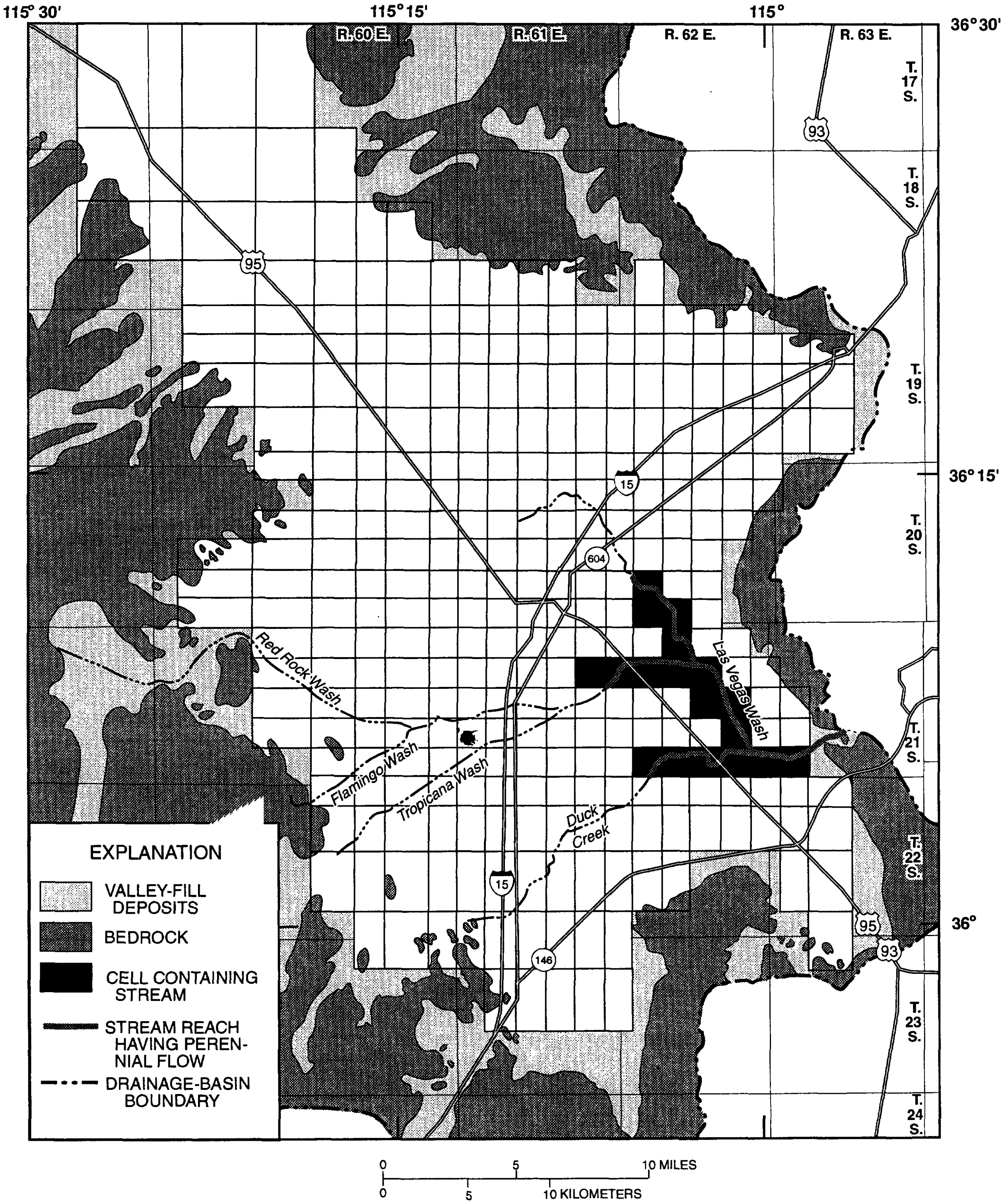


Figure 3.2.3-1. Model grid showing cells containing streams with potential to drain ground water from shallowest parts of near-surface aquifers.

3.2.4 Subsidence

Water from Compaction of Clays Important Component of Ground-Water Resource

The storage properties of aquifers that include fine-grained sediments change considerably when hydraulic heads are lowered sufficiently to cause nonrecoverable compaction.

The two major causes of land subsidence in Las Vegas Valley are (1) compaction of the aquifer system as a result of the lowering of hydraulic heads and (2) regional loading caused by the filling of Lake Mead. The 23 million acre-ft (30 billion tons) of water stored in Lake Mead are causing regional downwarping in parts of Utah, Arizona, California, and Nevada (Bell, 1981, p. 32). This downwarping is sufficiently small and constant in the Las Vegas area so that damage to structures resulting from it is unlikely. A third process that may be occurring is hydrocompaction. This settlement of near-surface soils occurs where dry, loose, low-density sediments are wetted and undergo compaction due to loss of intergranular strength (Bell, 1981, p. 36). Examples of subsidence by this latter process have not been documented in Las Vegas Valley but may be masked by subsidence due to other causes.

The most active period of subsidence in Las Vegas Valley was 1963–72, when the three depressions shown in figure 1.2.1-2 developed around the local centers of intensive pumping. By 1980, the total area affected by subsidence was 400 mi^2, double the area affected in 1963 (Bell, 1981, p. 47). Maximum measured subsidence as of 1980 was 3.9 ft at the Las Vegas Post Office (T. 20 S., R. 61 E., sec. 35). However, interpolations using discontinuous records from adjacent benchmarks indicate a maximum of 4.8 to 5.0 ft immediately east of the Post Office.

The most important mechanism for subsidence in Las Vegas Valley, which has been incorporated into the simulation model, is compaction of fine-grained interbeds within the aquifer materials. This compaction results from the increased effective stress on the intergranular matrix when hydraulic heads within adjacent coarse-grained sediments are reduced by pumping. The intergranular spaces yield "water of compaction" as they collapse, and are considered a one-time source of water to wells because their collapse is largely nonrecoverable, or inelastic. The specific storage of these deposits prior to compaction may be as much as 100 times greater than that for coarse-grained deposits where compaction is less and is recoverable, or elastic (Lofgren, 1979, p. 30).

Compaction begins when a level of stress called the preconsolidation stress is exceeded. Thus, preconsolidation stress can be expressed in terms of feet of water or hydraulic head and represents the stress or head at which inelastic deformation begins (Poland and others, 1972, p. 7). A detailed discussion of the stresses that cause subsidence is given by Poland and Davis (1969).

Following a prolonged drawdown cycle, water-level recovery can be rapid because less than 5 percent of intergranular pore storage is regained in the fine-grained deposits (Lofgren, 1979, p. 31). Lofgren notes, however, that in the central parts of ground-water basins and especially within extensive areas of subsidence, the effects of rising heads may require a long time to reach the interior parts of thick clay beds. Consolidation may therefore continue long after seasonal or long-term recoveries in water levels begin. These conditions might exist in Las Vegas Valley, where slow-draining clay beds continue to compact despite rising water levels in localized areas of reduced pumping. Poland and others (1975, fig. 61) recorded compaction and water levels at a site in the San Joaquin Valley, Calif., where subsidence of the entire system did not cease until water levels had made an 8-year recovery of about 240 ft from their all-time low.

Compressible, clayey beds are numerous and extensive throughout the valley-fill sediments in Las Vegas Valley. Materials classified by Plume (1989, pl. 3) as "fine-grained" compose as much as 90 percent of the total thickness within the 0- to 700-ft depth interval. Studies of the vertical distribution of compaction (Domenico and Maxey, 1964, p. 8; Mindling, 1971, p. 12–18) indicate that compaction may occur anywhere within this interval, but that its occurrence is mostly dependent on the location of maximum head changes due to pumping.

The importance of the water of compaction as a component of the ground-water resource and the destructive effects of land subsidence required that the simulation model be capable of projecting compaction due to water-level decline. The method used is similar to that used by Prudic and Williamson (1989), which was modified from that of Meyer and Carr (1979).

Elastic and inelastic storage coefficients were specified at all model cells representing the confined part of the near-surface aquifers (layer 3) and the developed-zone aquifers (layer 2). The initial preconsolidation head at each cell was estimated by model calibration and comparison with estimates from other studies. The values that best reproduced consolidation rates and water-level changes were 40 ft below the predevelopment heads. Meyer and Carr (1979, p. 13) used a preconsolidation stress of 70 ft in the Houston area, and Prudic and Williamson (1989) used a preconsolidation stress of 85 ft in the Central Valley of California. The computed head within each cell is compared with a threshold level, the preconsolidation head, after each simulated time increment as the system is stressed. When the head declines below the preconsolidation head at a cell (that is, when the preconsolidation stress is exceeded), the elastic storage coefficient is replaced by the inelastic coefficient, and the current head becomes the new preconsolidation head. If the water level should recover, the storage coefficient may revert to the elastic value, depending on the magnitude of the recovery, but the lowest head is retained as the preconsolidation head.

Thick, slow-draining clay beds may continue to compact inelastically long after heads recover to levels above preconsolidation heads. User-defined, delayed-drainage intervals can be specified for layers 2 and 3 to account for the continued compaction. These intervals help the model to reach a stable solution by not allowing large water-level oscillations that would be triggered when small head increases cause large decreases (to the elastic values) in storage coefficients. The water-level response of a typical model cell to cyclical pumping (reflecting seasonal changes in demand for water) and conversion to and from the inelastic storage coefficient is illustrated in figure 3.2.4-1.

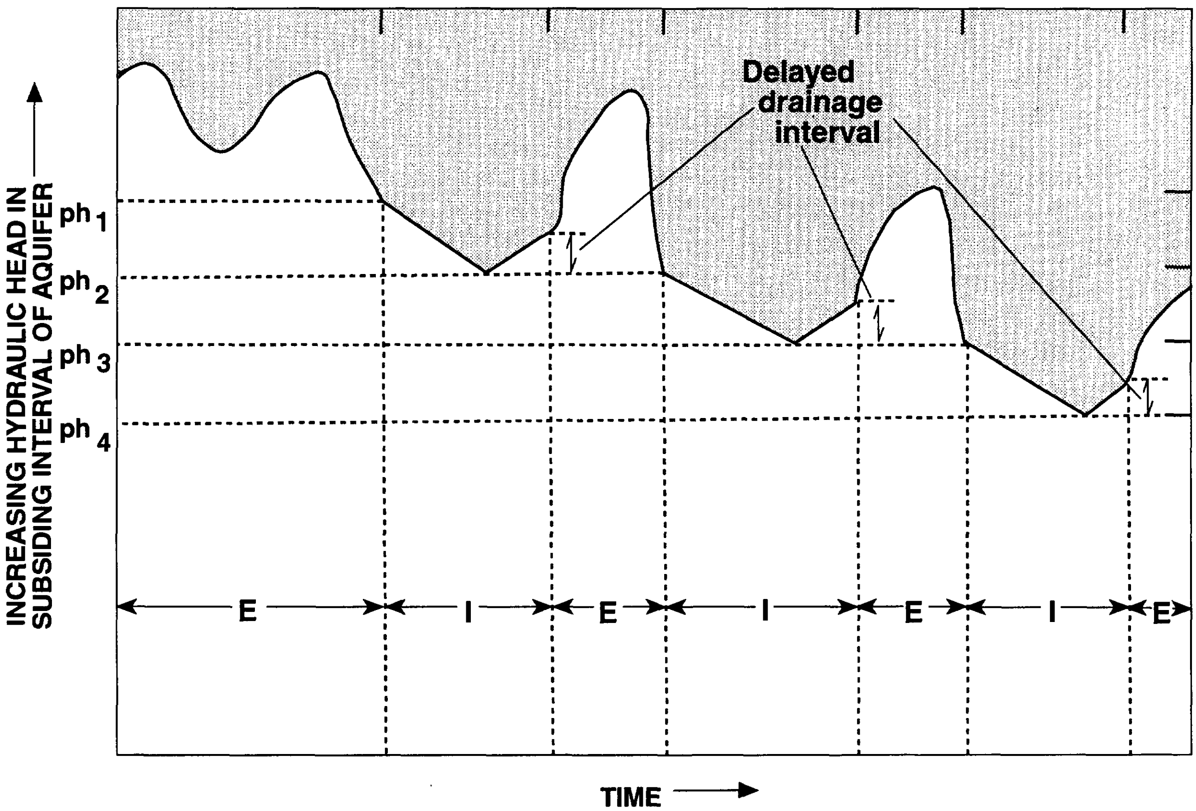


Figure 3.2.4-1. Hypothetical change in hydraulic head within an aquifer undergoing inelastic compaction in response to cyclical pumping. Periods of elastic (E) and inelastic (I) changes in storage are indicated. Successive pre-consolidation head values are designated as ph_1–ph_4.

3.2.5 Secondary Recharge

Amount of Secondary Recharge to Water Table Differs with Land Use

Much of the water applied in lawn irrigation and agriculture, the domestic wastewater disposed of in septic-tank leach fields, and the domestic and industrial wastewater disposed of in evaporation/percolation ponds in the valley percolates downward to become recharge at the water table.

Three major sources of secondary recharge have accompanied urban growth in the valley: (1) lawn and turf watering in residential areas, at golf courses, and on public facilities such as school yards; (2) discharge and disposal of industrial wastewater in unlined ditches and ponds at the Henderson industrial complex; and (3) discharge of domestic wastewater to septic-tank leach fields, primarily at the margins of the valley floor and on the fans outside sanitation-district boundaries. These three categories contributed 58, 30, and 4 percent, respectively, of the total secondary recharge in 1973 (Patt, 1978, p. 32). Other sources have included agriculture, water-supply transmission losses, and storm runoff.

The contributions of lawn watering and domestic wastewater to secondary recharge were estimated for input to the model on the basis of estimated acreages of residential, commercial, and municipal lawns, numbers of residential units, and numbers of unsewered homes in various geographic units called traffic-analysis zones (TAZ's). These statistics were provided by the Clark County Department of Comprehensive Planning for 1979 and by Patt (1978, appendix 1) for 1972. The area of residential lawns for 1979 was calculated by assuming that between 5 and 15 percent of residential areas were devoted to lawns, with the assumed percentage depending on the density of housing. The secondary recharge contributed by lawns in the TAZ's was estimated by assuming that residential lawns contribute 11.2 (acre-ft/acre)/yr and other public lawn areas contribute 2.5 (acre-ft/acre)/yr (on the basis of information given by Patt, 1978, p. 17–23). Outside sanitation-district boundaries, and in a few other areas pinpointed by Kauffman (1978, p. 63), domestic septic tanks were assumed to contribute between 0.25 and 0.55 acre-ft/yr per dwelling unit to secondary recharge, depending on dwelling-unit type. These factors are based on the assumptions that consumptive use is insignificant during in-house water uses, and that the per capita indoor water use is 108 gal/d (Patt, 1978, p. 23). These contributions were totaled by TAZ, and distributed to the model grid cells at rates proportional to the fraction of each TAZ that lies within a cell.

Prior to 1972, no land-use statistics were available, so estimates for 1955 and 1965 were generated solely on the basis of the areal extent of urban residential development as determined from a map of the history of recorded subdivisions (see fig. 2.4-1) and a few old aerial photographs.

Total recharge rates for major secondary-recharge sources at Henderson and along Las Vegas Wash were assumed equal to the rates estimated by Patt (1978, p. 32–39), and were distributed among cells that contained recharge source areas. The source areas were delineated approximately and the rates of recharge were estimated for wastewater-treatment plants, wastewater-disposal ponds, and unlined industrial ditches and ponds. During the mid-1970's, wastewater flow to unlined industrial ponds was greatly reduced and, as a consequence, estimated recharge rates in the Henderson area were drastically decreased.

Estimated recharge rates in the Henderson area were added to the matrices of estimated recharge from lawn watering and domestic wastewater throughout the valley to yield the secondary-recharge rates used in the simulations. Recharge rates applied in the simulations for 1955, 1972 (the year that Lake Mead water first became available in large quantities), and 1979 are presented in figures 3.2.5-1, 3.2.5-2, and 3.2.5-3. These estimates totaled about 12,000 acre-ft for 1955, 30,000 acre-ft for 1972, and 44,000 acre-ft for 1979. Patt (1978, p. 32) estimated that the secondary recharge in 1973 totaled 43,000 acre-ft, which is considerably more than the estimate presented here.

The difference may be attributed to the additional sources of recharge that Patt considered and to differences in assumptions about water use employed in arriving at the two sets of estimates. Assumptions in this study were designed to allow estimates based on the data and projections available to Clark County planners for 1979 and subsequent years. The assumptions were then modified to allow application of the estimation procedure with as few changes as possible to Patt's data for 1973. Simulations for the period from 1972 through 1979 employed additional rate matrices for secondary recharge that were calculated by linear interpolation between the years 1972 and 1979, and by extrapolation of the 1972–79 trend to 1981 to yield a smoother response. Figure 4.2.1-1*A*, *B* show the total estimated rates of secondary recharge used to simulate the periods 1912–71 and 1972–81. Secondary-recharge matrices appear in the model as the two-dimensional variable *QRE* (dimensions, *L/t*), and the rates are applied to the unconfined part of the near-surface reservoir (layer 4).

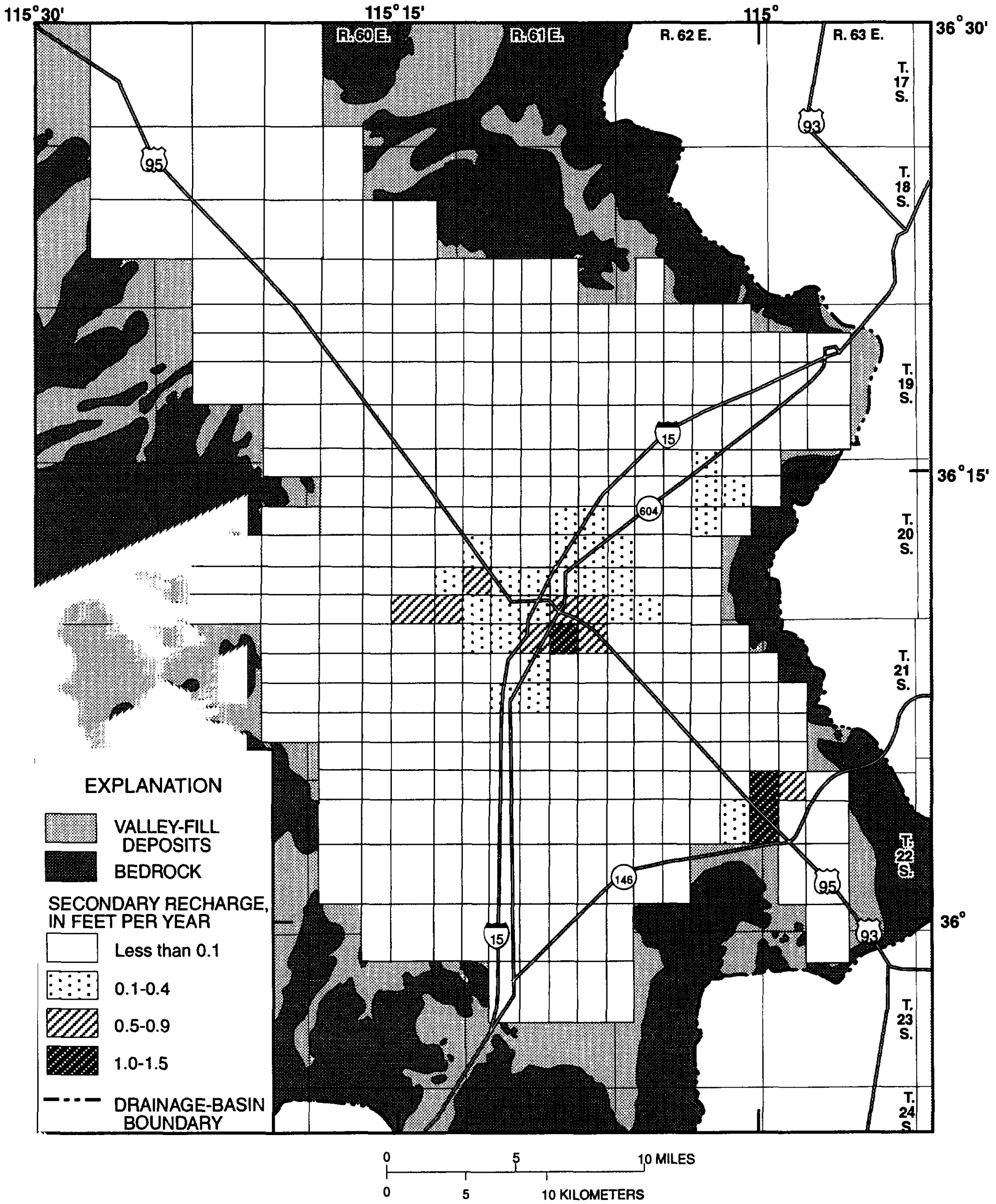


Figure 3.2.5-1. Estimated secondary recharge in 1955.

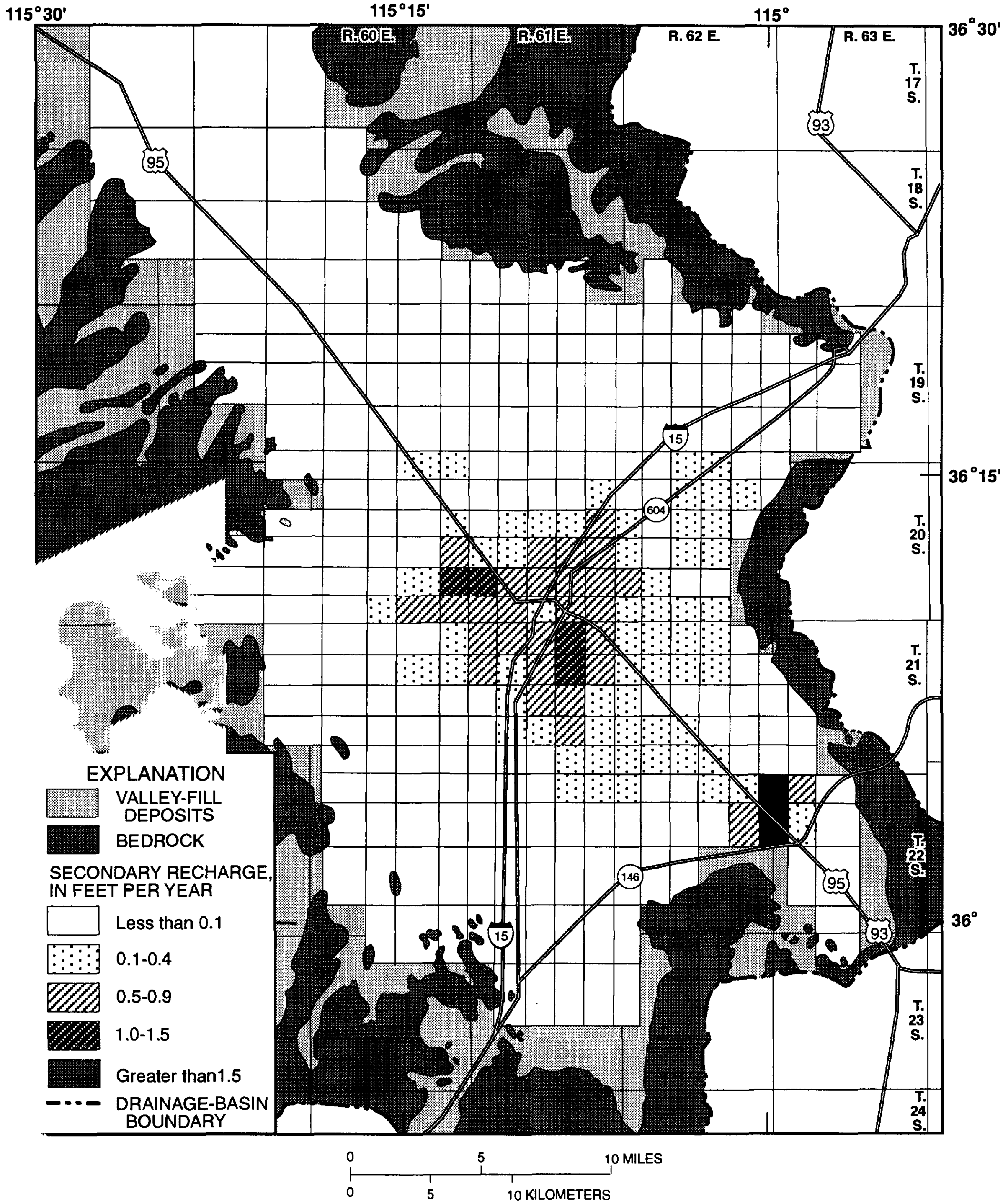


Figure 3.2.5-2. Estimated secondary recharge in 1972.

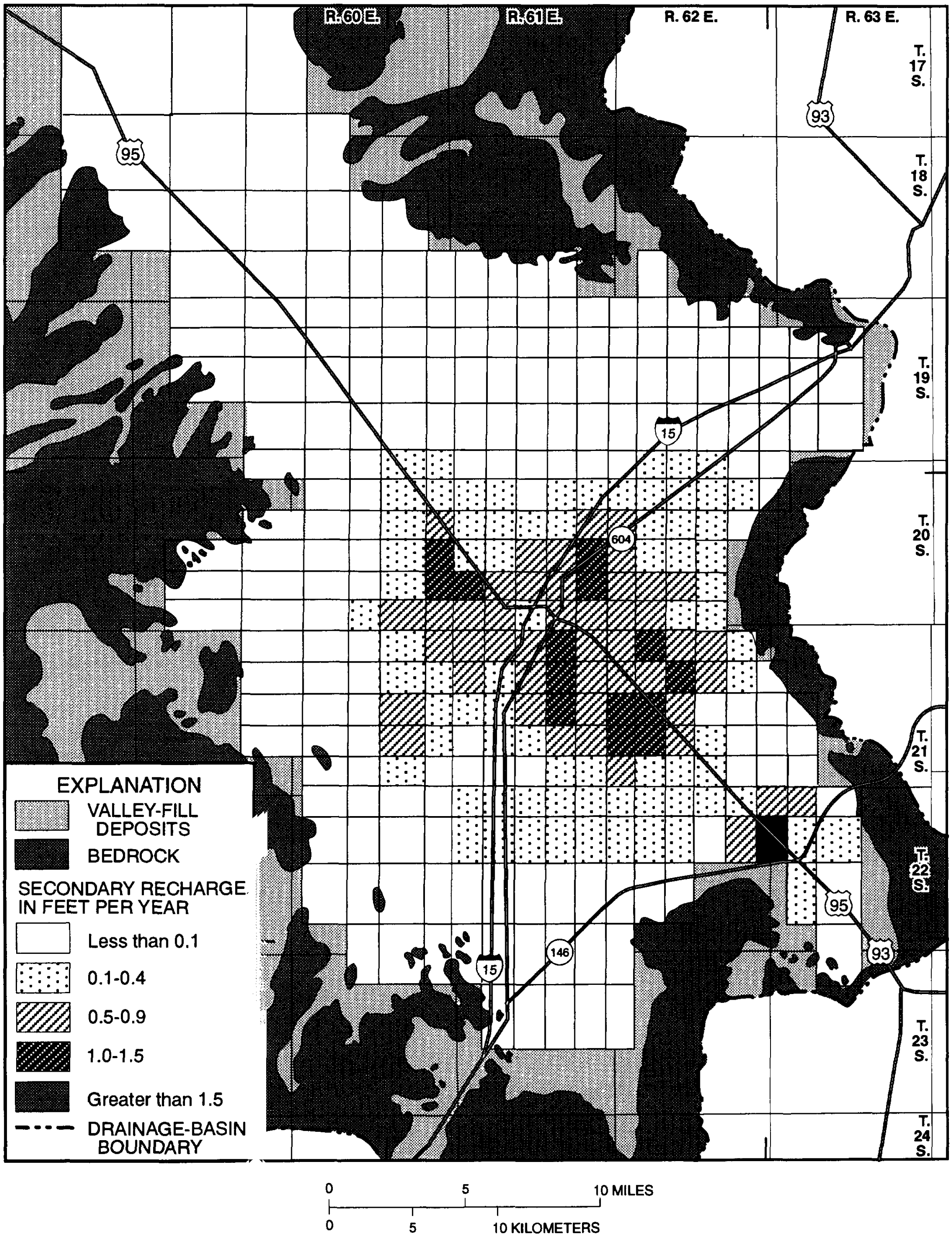


Figure 3.2.5-3. Estimated secondary recharge in 1979.

3.2.6 Ground-Water Pumpage

Ground Water Used for Many Purposes

Ground water for commercial, domestic, irrigation, and industrial use is pumped primarily from the deeper developed-zone aquifers with lesser amounts drawn from the near-surface aquifers. Major pumping centers in 1980 included the large municipal water-district well fields, large golf courses and parks, and agricultural enterprises near Tule Springs.

Ground water is the source of supply for a large part of the domestic, irrigation, and commercial water use in the valley. Pumpage totaled 70,000 acre-ft in 1980. During that year, municipal water-supply systems pumped 51,000 acre-ft for distribution to their customers. Private ground-water consumption (uses not served by the major water districts) totaled 5,000 acre-ft for domestic indoor and outdoor use, 8,600 acre-ft for irrigation (in addition to residential-lawn irrigation), 4,000 acre-ft for commercial use, and 700 acre-ft for industrial-water use. An estimated 400 acre-ft of ground water was extracted for other uses.

Most of the ground water pumped from Las Vegas Valley is extracted from the developed-zone aquifers. Generally, the total pumpage from the near-surface aquifers is estimated as equal to the total pumpage from private domestic wells. In 1980, approximately 4,000 acre-ft—6 percent of the total pumpage—was drawn from these wells.

The distribution of ground-water pumpage in 1955, 1968 (the year of maximum pumpage, totaling 88,000 acre-ft), and 1980 is shown in figure 3.2.6-1. The main pumping centers shown were associated with municipal well fields. Historically, the distribution of ground-water pumpage has become more diffuse, with the individual pumping centers contributing a smaller fraction of the total pumpage. The major pumping centers in Las Vegas Valley have been the well fields of the LVVWD. Originally the main well field in T. 20 S., R. 61 E., sec. 31 provided most of the water for the District, and at one time was responsible for more than half the total draft on the valley aquifers (URS Company and others, 1983, p. 56). In response to concerns about land subsidence and the logistics of water delivery, LVVWD ground-water pumpage was gradually distributed among additional newly constructed well fields, most of which were west of the main well field. LVVWD pumpage has stabilized at approximately 40,000 acre-ft/yr in recent years (URS Company and others, 1983, p. 57).

As Lake Mead water became available to most of the valley through the Southern Nevada Water Project (SNWP) and other distribution systems since 1972, municipal pumpage for the City of North Las Vegas and Nellis Air Force Base has decreased. The City of North Las Vegas now relies primarily on Lake Mead water, with smaller volumes drawn from wells on the west side of the valley floor. Existing pumping centers in the southern half of the valley are generally associated with irrigation wells serving large resort golf courses and public parks. Since 1942, the amount of pumpage in the vicinity of Henderson has been small as a result of the availability of Lake Mead water through the BMI delivery system.

Overall, ground-water pumpage for municipal uses in the northeastern quarter of the valley has decreased since 1972. Municipal wells are heavily pumped to meet peak demands during the summer months. Agricultural and turf-irrigation wells also tend to be pumped heavily in the summer.

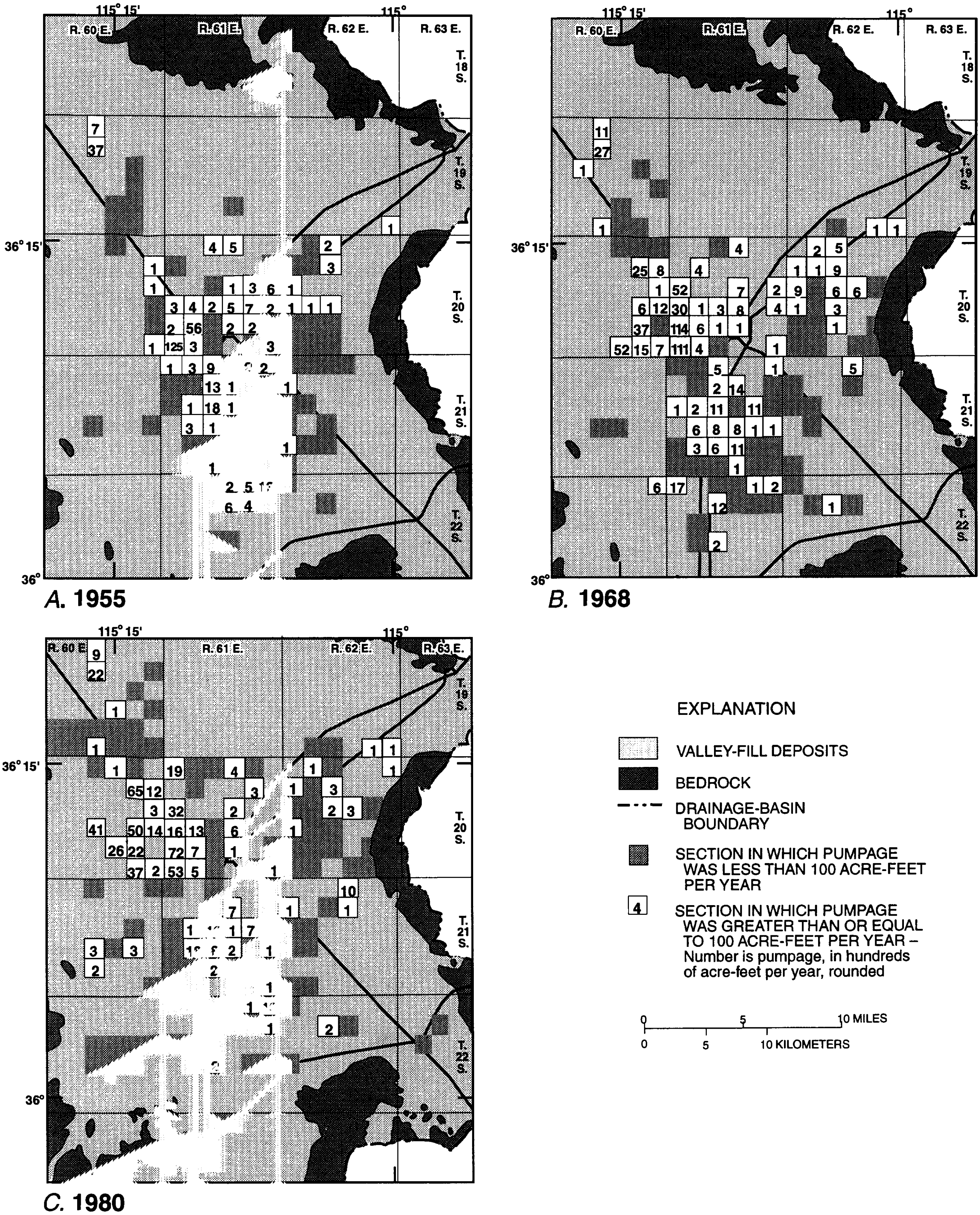


Figure 3.2.6-1. Ground-water pumpage, by square-mile section. *A*, 1955, *B*, 1968, and *C*, 1980.

3.3 Hydraulic Characteristics of Valley Fill

3.3.1 Transmissivity

Transmissivity Greatest on West Side of Valley

Transmissivity differs over wide ranges, both vertically and horizontally. The most productive aquifers are within the developed zone on the west side of the valley.

Transmissivity is a property of an aquifer that describes its ability to transmit water. By definition, it is the rate at which water of the prevailing kinematic viscosity is transmitted horizontally through a unit width of the aquifer under a unit hydraulic gradient (Lohman and others, 1972, p. 13). The transmissivity of an aquifer is dependent on both its hydraulic conductivity and its saturated thickness.

Precalibration transmissivity estimates for the simulation model were developed using regression analysis of pumping-test and lithologic data from drillers' logs for selected wells. An equation was developed for each of 25 wells for which (1) transmissivity could be estimated from well-test data and (2) the total saturated thicknesses of coarse, medium, and fine sediments could be estimated from lithologic logs. Because transmissivity (T) is the product of horizontal hydraulic conductivity (K) and saturated thickness (b), the total transmissivity of a section of mixed lithology is:

$$T = K_c b_c + K_m b_m + K_f b_f ,$$

where T = transmissivity (L^2/t),
K_c, K_m, K_f = hydraulic conductivities of coarse, medium, and fine sediments (L/t), and
b_c, b_m, b_f = respective saturated thicknesses (L).

The solution of the 25 regression equations (R^2=0.75) yielded conductivities of 15 ft/d, 1 ft/d, and 0.1 ft/d for coarse, medium, and fine sediments, respectively.

Transmissivities were estimated over the entire model area using lithologic data interpreted by Plume (1989, p. A10–A11) from 240 well logs. The logs were used to generate sediment-thickness maps by average grain size within each model layer. The estimated transmissivities at each model cell were the sum of the products of hydraulic conductivity and sediment thickness for each grain-size category. This method yielded a distribution that was related closely to the extent and thickness of sediments considered to be coarse grained.

During the calibration process, the initial estimates were increased near the northern, eastern, and southern margins of the valley, and in other areas where there are large thicknesses of fine-grained sediments. In the Henderson area, where large thicknesses of the Muddy Creek Formation underlie the valley, initial estimates of transmissivity in all layers had to be increased by a factor of 3 to 4 during calibration. The initial underestimates of transmissivity in this area could have been caused by underestimation of the horizontal hydraulic conductivity for fine-grained sediments (K_f), or K_f may differ within the valley, and fine-grained sediments in the Henderson area have higher hydraulic conductivities than those in other parts of the valley. Another explanation may be that ground-water movement in this area is predominantly through thin lenses of sand and gravel that frequently are not reported in the logs used to generate the sediment-thickness maps. This would cause consistent underestimation of transmissivity in these areas. Less dramatic alterations were made in other areas during both steady-state and transient calibrations to account for the effects of geologic structure and other factors not related exclusively to grain size.

The transmissivity distributions used to model the near-surface and the developed-zone aquifers are shown in figure 3.3.1-1 and 3.3.1-2. These distributions have retained their similarity to the distribution of coarse-grained materials and seem to further support the conclusion of Plume (1989, p. A11) that the Spring Mountains have been the major source of clastic material to the valley fill. Transmissivities shown in figure 3.3.1-2 for the developed-zone aquifers are quite similar to those estimated by Harrill (1976a, fig. 6) for his simulation analysis. This is noteworthy because Harrill's transmissivities were estimated from aquifer-test data rather than lithologic logs.

Insufficient data were available to estimate transmissivity by the above method for the deep-zone aquifers (layer 1). Therefore, a distribution similar to that for the developed-zone aquifers was used initially and then modified during calibration. The best model results were obtained when values for the deep zone were reduced to about 20 percent of those in the developed zone.

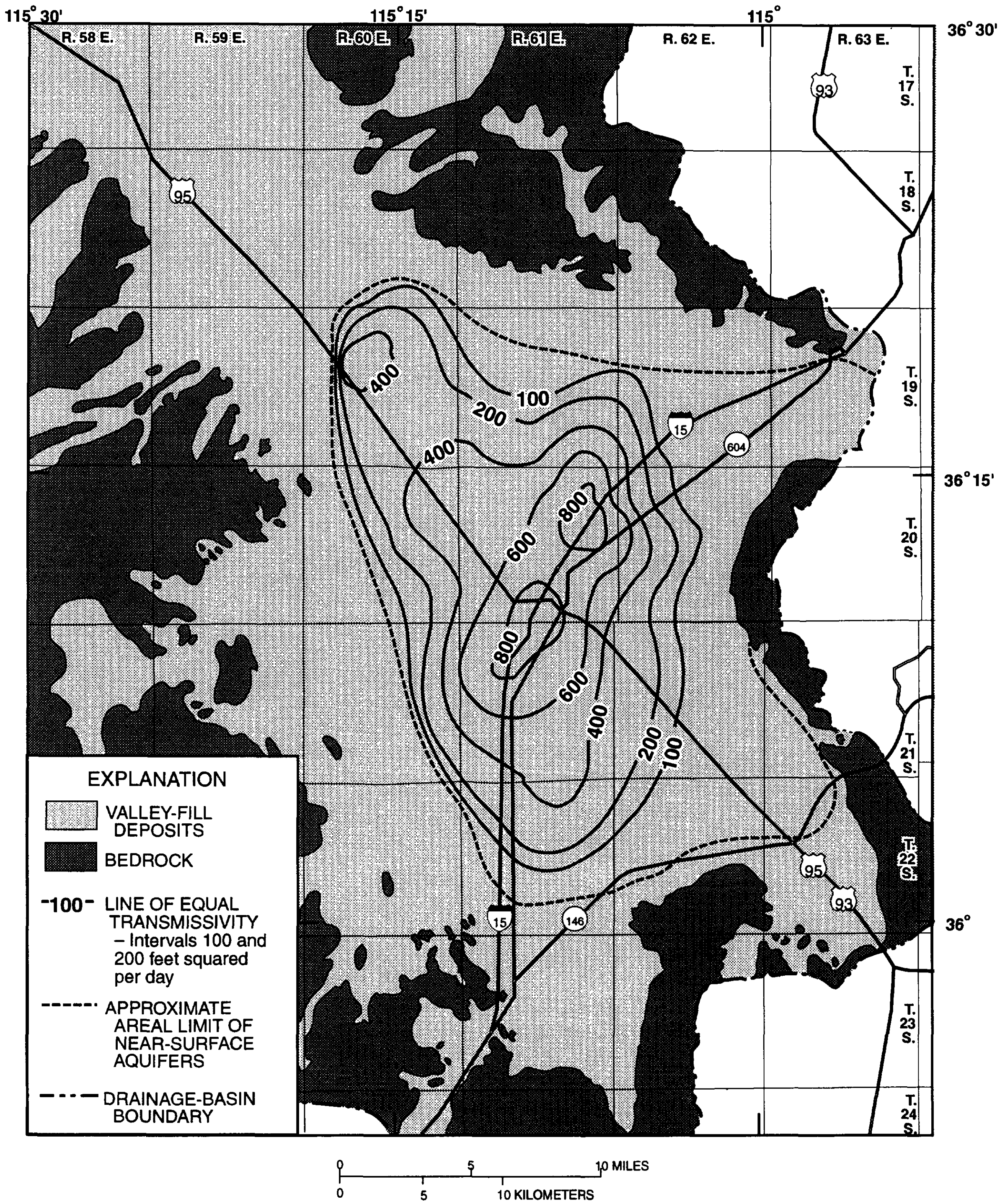


Figure 3.3.1-1. Estimated transmissivity in near-surface aquifers.

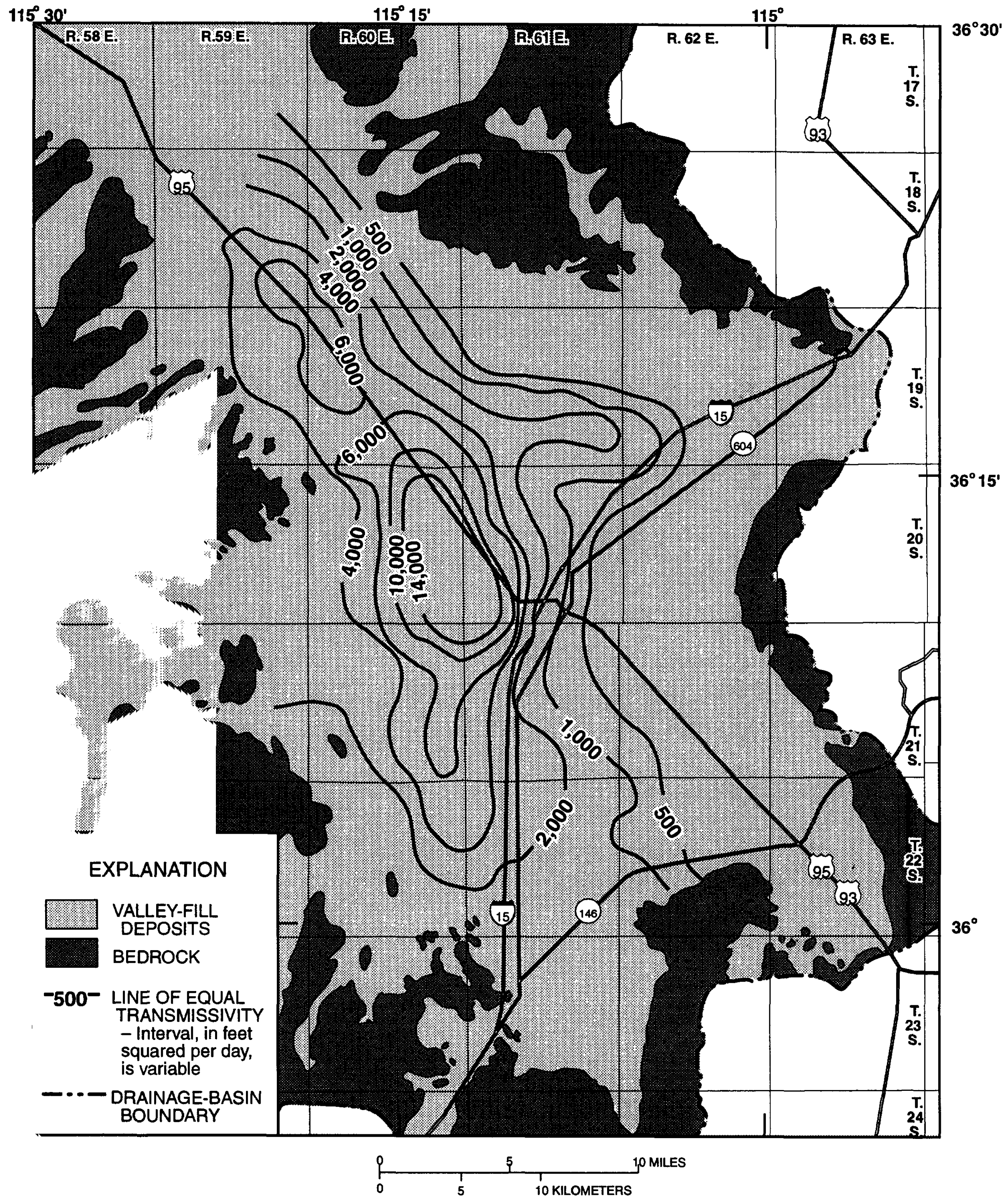


Figure 3.3.1-2. Estimated transmissivity in developed-zone aquifers.

3.3.2 Vertical Leakance

Vertical Leakance Controls Rate of Flow and Hydraulic Gradient in Vertical Direction

Vertical leakance is the physical property of an aquifer system that describes the resistance of the system to vertical movement of ground water; it is estimated from the vertical hydraulic conductivity and thickness of the fine-grained sediments.

Vertical leakance determines the rate of ground-water movement between two adjacent model layers for a given head difference between the layers. Leakance may be thought of as the resistance to vertical flow within the aquifer system. Leakance is calculated by dividing vertical hydraulic conductivity by the length of the flow path. The flow-path length is usually defined as the thickness of the fine-grained deposits between two layers. The thickness of coarse-grained materials along the flow path can normally be neglected because they pose little resistance to vertical ground-water movement.

The thickness of fine-grained sediments was mapped for both the near-surface aquifers and the developed-zone aquifers using well-log data from Plume (1989, p. A9). The length of the vertical flow path between the near-surface and the developed-zone aquifers was computed at each model cell by assuming that the fine-grained deposits were evenly distributed within each layer and adding half the thickness of fine-grained materials within the near-surface aquifers to half the thickness of those within the developed-zone aquifers. Thus, an effective thickness of fine-grained sediments between layer centers at each cell was estimated.

Harrill (1976a, fig. 8) estimated vertical hydraulic conductivities for these clay beds that ranged from 7×10^{-4} to 7×10^{-3} ft/d. Dividing these conductivities by the effective thicknesses of fine-grained sediments yielded an initial distribution of vertical leakance, which was refined during model calibration. The final areal distribution of leakances between the near-surface aquifers and the developed-zone aquifers is shown in figure 3.3.2-1.

A similar method was used to make the initial estimates of vertical leakance between the developed-zone and the deep-zone aquifers (fig. 3.3.2-2). However, only limited data were available on the extent and thickness of clay beds within the deep-zone aquifers. The thickness of fine-grained sediments along the vertical flow path between the middle of the developed-zone aquifers and the middle of the deep-zone aquifers was estimated as half the thickness of fine-grained sediments within the developed-zone aquifers plus the total thickness between depths of 700 and 1,000 ft. The 700- to 1,000-ft interval is the deepest extent of available data on grain-size distribution, but represents only a small fraction of the thickness of the deep-zone aquifers in many parts of the valley. Thus, a more conservative estimate of vertical leakance may result from using the total clay thickness within the 700- to 1,000-ft interval. The conservative estimate was considered favorable given the uncertain lithology at depths greater than 1,000 ft and the relative insensitivity of the model response to changes in this parameter.

Refinements to vertical leakance between the deep- and developed-zone aquifers during calibration consisted mainly of increases near the western boundary of the deep zone. During transient simulations, the model was comparatively sensitive to increases in upward leakage in this area.

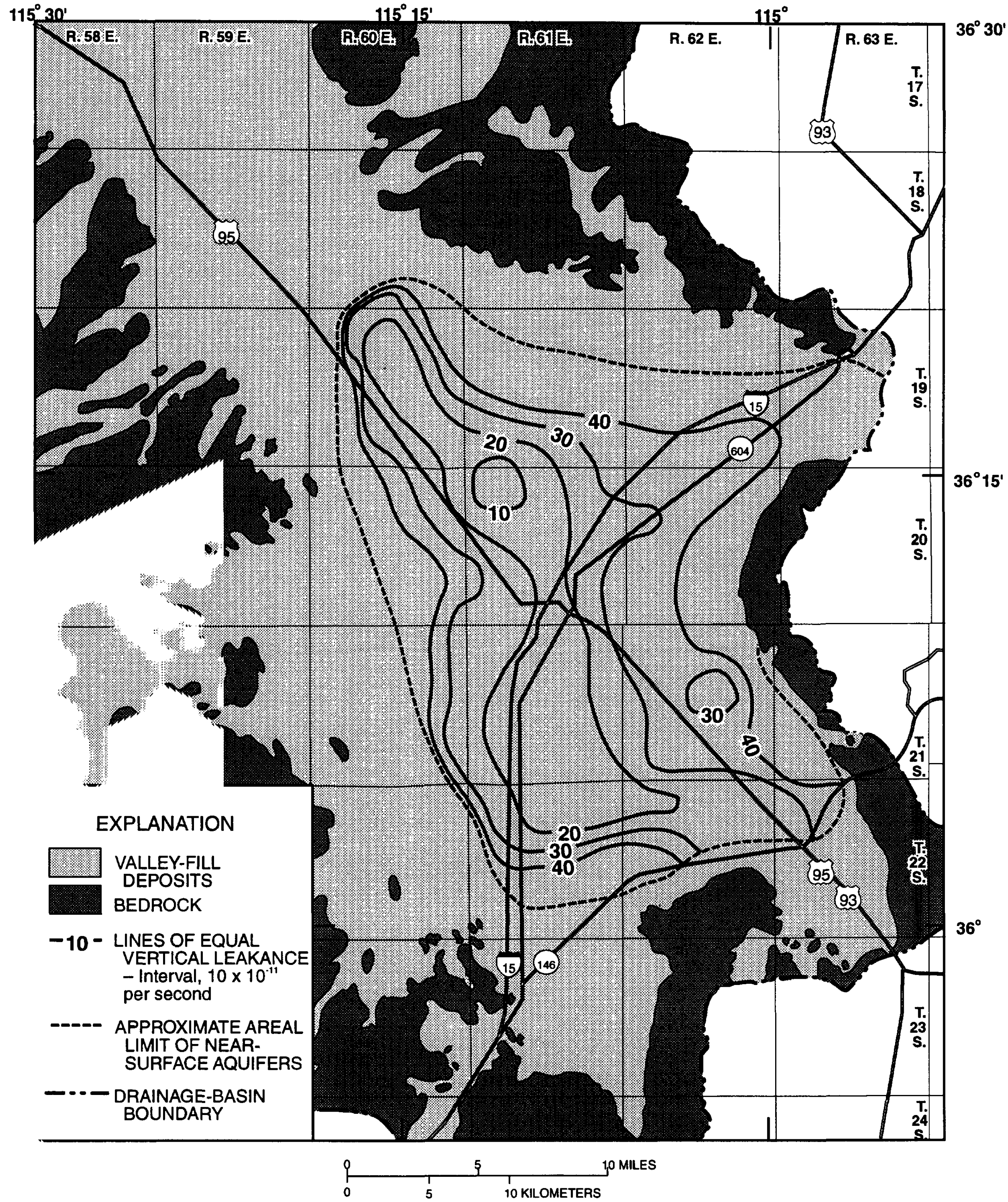


Figure 3.3.2-1. Vertical leakance between near-surface and developed-zone aquifers.

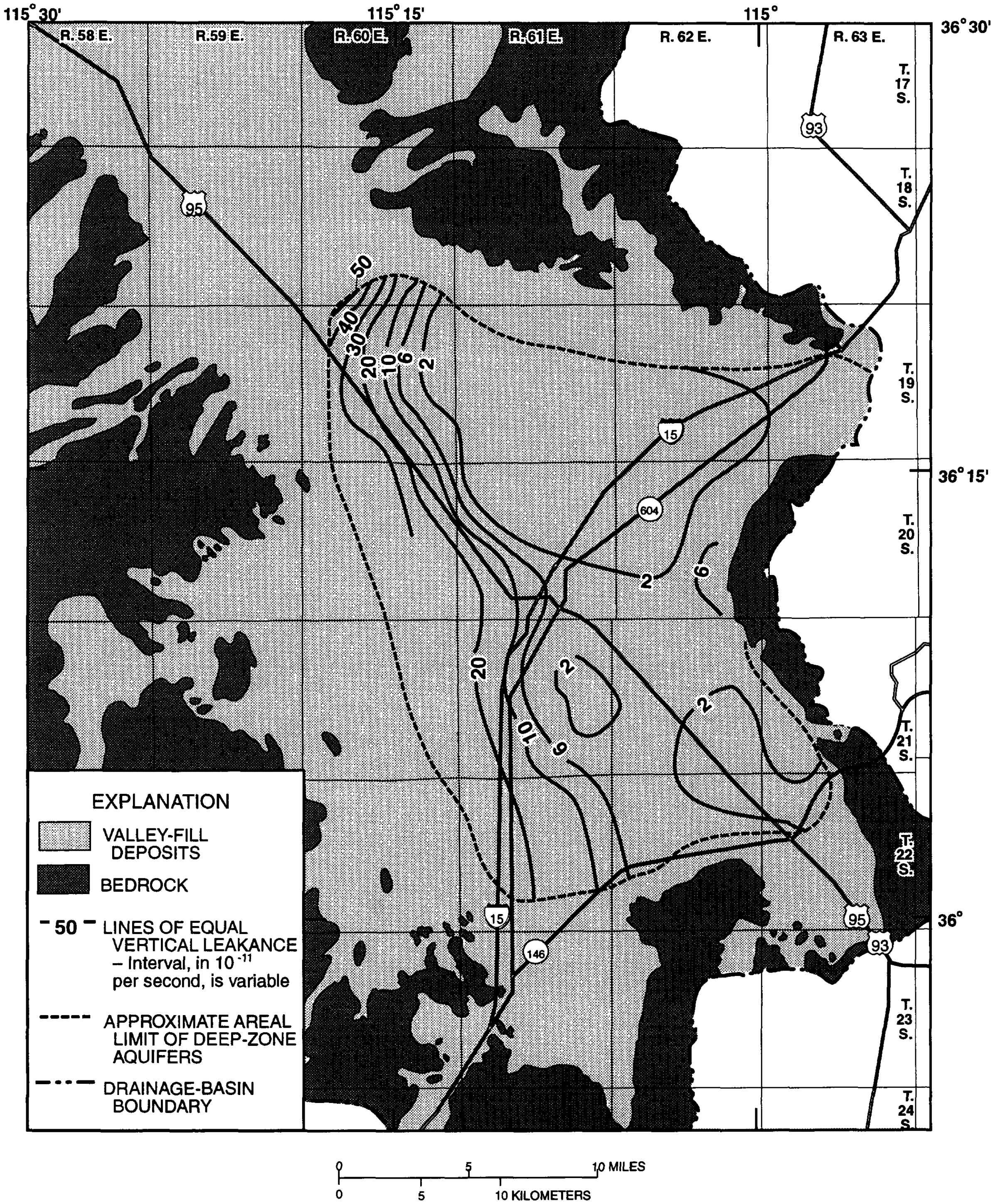


Figure 3.3.2-2. Vertical leakance between developed-zone and deep-zone aquifers.

3.3.3 Elastic-Storage Coefficient and Specific Yield

Gravity-Drainage Yields Exceed Those of Elastic Storage

Water is stored in an artesian ground water aquifer in volumes proportional to the hydraulic head and the intergranular storage capacity of the aquifer. The elastic-storage coefficient describes that part of the storage capacity that can be attributed to the expansion of the water itself and the elastic compression of the artesian aquifer. Specific yield is the equivalent property for water-table aquifers, in which most water from storage is derived from simple gravity drainage.

The term elastic-storage coefficient is used in this report to describe the volume of water a confined aquifer releases from or takes into storage per unit surface area, per unit change in head. Ground water from this source is derived solely from expansion of water, from elastic compression of the aquifer, and from elastic compression of adjacent and interlayered fine-grained beds. This component of storage is completely recoverable because deformation of the granular matrices of the aquifer and fine-grained beds is, by definition, elastic.

Fine-grained confining beds release considerable volumes of water from storage when they undergo inelastic compaction during sustained periods of head decline. This component of the overall storage capacity of an aquifer, which may be much greater than the elastic component, is discussed in detail in section 3.3.4.

The lower part of the near-surface aquifers, the area of the developed-zone aquifers overlain by the near-surface aquifers, and the entire deep-zone aquifers are all assumed to be confined and were therefore assigned elastic-storage coefficients. The coefficients were calculated using estimated elastic specific-storage values appropriate for fine- and coarse-grained sediments. The specific storage used for coarse-grained deposits (1×10^{-6}) was identical to that estimated by Riley and McClelland (1972, p. 77D) from aquifer tests in the San Joaquin Valley, Calif. Elastic specific-storage values for fine-grained deposits in the San Joaquin Valley averaged 4.5 times that for coarse-grained deposits, according to Helm (1978, p. 193). For the confined areas of each aquifer zone, these specific-storage values were multiplied by computed thicknesses of fine-grained and medium- to coarse-grained deposits to estimate elastic-storage coefficients. The resulting estimates ranged from 1×10^{-3} to 3×10^{-3}. These estimates are generally larger than six estimates based on pumping tests reported by Malmberg (1965, p. 42). However, model results were found to have low sensitivity to errors in elastic-storage coefficient and initial estimates were adjusted little during calibration.

Water-table conditions exist over a large area of Las Vegas Valley, and a large volume of ground water has been obtained from gravity drainage (dewatering) of these deposits resulting from water-table declines. This volume of water is called the specific yield; it is equal to the volume of ground water yielded by gravity drainage, divided by the volume of aquifer material drained. The time required for complete drainage differs greatly, depending upon grain size and sorting, the degree and extent of aquifer cementation, and the presence of caliche or clay layers, all of which can impede drainage and create areas of perched ground water.

The uppermost part of the near-surface aquifers (layer 4) was assumed to be under water-table conditions. Initial estimates for specific yield were made by using maps of the percentage of fine-, medium-, and coarse-grained sediments within the uppermost 50 ft (Plume, 1989, pl. 3). Initial specific-yield values were assigned solely on the basis of the predominant grain size. This method generated a distribution that ranged from 3 percent in areas underlain mostly by fine-grained sediments to 25 percent in areas underlain mostly by coarse-grained sediments. During model calibration, specific yields were decreased in many areas. Extensive caliche zones and numerous clay lenses are known to exist, and they probably reduce the effective gravity-drainage yield significantly.

Reductions to this parameter resulted in a valley-wide average specific yield of about 8 percent, with a standard deviation of 5 percent.

The distribution of elastic-storage coefficients and specific yields used in modeling the developed zone are shown in figure 3.3.3-1.

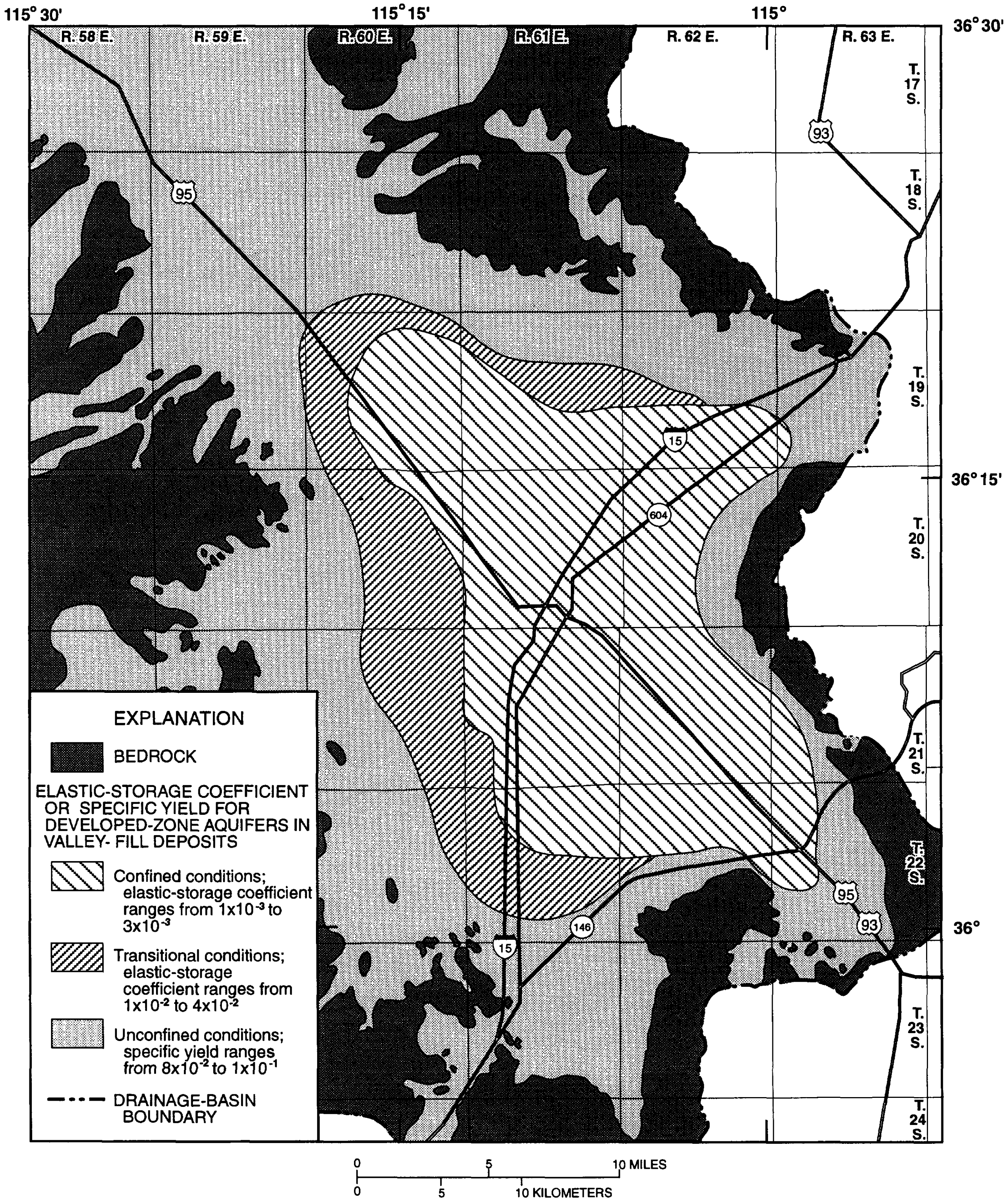


Figure 3.3.3-1. Elastic storage coefficient and specific yield for developed-zone aquifers (model layer 2).

3.3.4 Inelastic-Storage Coefficient

Inelastic-Storage Coefficients up to Thirty Times Greater than Elastic Coefficients

Values of the specific unit compaction were estimated for the near-surface aquifers (9.2×10^{-5} per foot) and the developed-zone aquifers (7.1×10^{-5} per foot). These values are assumed to approximate inelastic specific storage. Estimated inelastic-storage coefficients range from 9.0×10^{-4} to 1.4×10^{-2} for the near-surface aquifers and from 7.0×10^{-4} to 3.2×10^{-2} for the developed-zone aquifers.

The inelastic component of the storage coefficient describes water released from storage as a result of compaction of the fine-grained interbeds of the aquifer system. As described in section 3.2.4, this component is small until the head declines below the preconsolidation head. For head changes within the range above the preconsolidation head, water released from storage comes mostly from the elastic expansion of water and elastic compression of the aquifer materials (see section 3.3.3). The inelastic-storage coefficients used for this study are the product of the thickness of fine-grained beds and the mean inelastic specific storage.

The term specific unit compaction is defined as the compaction of a unit thickness of deposits, per unit of increase in applied stress (lowering of head), during a specified time period (Poland and others, 1972, p. 3). Specific unit compaction is considered to be an approximation of inelastic specific storage if compaction, during the specified time period, approximates the compaction resulting from a long-term reduction in head. Poland and others (1972, p. 3) describe this as "ultimate" specific unit compaction, which is attained only when pore pressures in the fine-grained beds have reached hydraulic equilibrium with pore pressures in the adjacent aquifers.

Values of specific unit compaction were calculated by two methods: (1) a valley-wide volumetric analysis of subsidence, head decline, and clay thickness and (2) calculations at four individual sites based on field measurements of subsidence, water-level decline, and clay thickness. For the volumetric analysis, valley-wide subsidence during the period 1963–72 was used because this was the period of most active subsidence (see fig. 4.2.2.4-1B) and because head-decline and subsidence data were available from Harrill (1976a, p. 42). Clay thicknesses for the near-surface aquifers (approximately 10–150 ft) and the developed-zone aquifers (approximately 200–450 ft) shown in figures 3.3.4-1 and 3.3.4-2 were estimated from maps of valley-fill lithology (Plume, 1989, pl. 3). The mean area-weighted clay thicknesses are 85 and 220 ft for the near-surface aquifers and developed-zone aquifers, respectively. To calculate values of specific unit compaction for each depth interval, the proportion of overall subsidence occurring in each interval must be assumed.

Data from Mindling (1971, p. 12–18) and Domenico and Maxey (1964, p. 8) show that the vertical distribution of subsidence is most dependent on vertical distribution of head decline. Head declines have historically been greatest adjacent to the perforated intervals of deep, heavily pumped wells. Assuming a subsidence ratio of 7:3 between the developed-zone and the near-surface aquifers, the values of specific unit compaction computed on a valley-wide, volumetric basis are 3.4×10^{-5} per foot and 9.2×10^{-5} per foot, respectively. Thus, despite the lesser proportion of overall subsidence attributed to the near-surface aquifers, the specific unit compaction is greater there. This seems to support data from Mindling (1971, p. 13) that indicate higher compressibilities for sediments of the near-surface aquifers.

Water-level declines and clay thicknesses within the developed-zone aquifers were used with subsidence data at the four benchmarks shown in figure 3.3.4-2 to calculate local values of specific unit compaction ranging from 5.7×10^{-5} to 9.6×10^{-5} per foot, with a mean of 7.1×10^{-5} per foot. Water levels in the near-surface aquifers rose at three of these sites during most of the period of record (1935–72) and all subsidence therefore was assumed to have occurred within the underlying developed-zone aquifers. These values are slightly higher than those derived from the volumetric method, but nonetheless agree well.

Comparison with estimates of inelastic specific storage for the San Joaquin Valley, Calif., which had a mean of 3×10^{-4} per foot (Helm, 1978, p. 193), suggests that values for Las Vegas Valley do not represent "ultimate" specific unit compaction or inelastic specific storage. This would imply that most of the fine-grained beds had not reached hydraulic equilibrium with adjacent coarse-grained beds by 1972, and that a subsequent period of prolonged drawdown might result in greater subsidence-to-head-decline ratios. This disequilibrium may explain the discrepancy between estimates by the volumetric method and those calculated at specific sites within high-subsidence areas. Locally, compaction may be occurring at a rate closer to its maximum.

For these simulations, the estimated specific unit compaction was assumed to be equal to the inelastic specific storage. The estimate from the volumetric method, 9.2×10^{-5} per foot, was used for the near-surface aquifers; when multiplied by clay thicknesses in this interval, it resulted in a range of inelastic-storage coefficients from 9.0×10^{-4} to 1.4×10^{-2}. The mean of the site-specific estimates, 7.1×10^{-5} per foot, was used for the developed-zone aquifers, where inelastic-storage coefficients ranged from 7.0×10^{-4} to 3.2×10^{-2}.

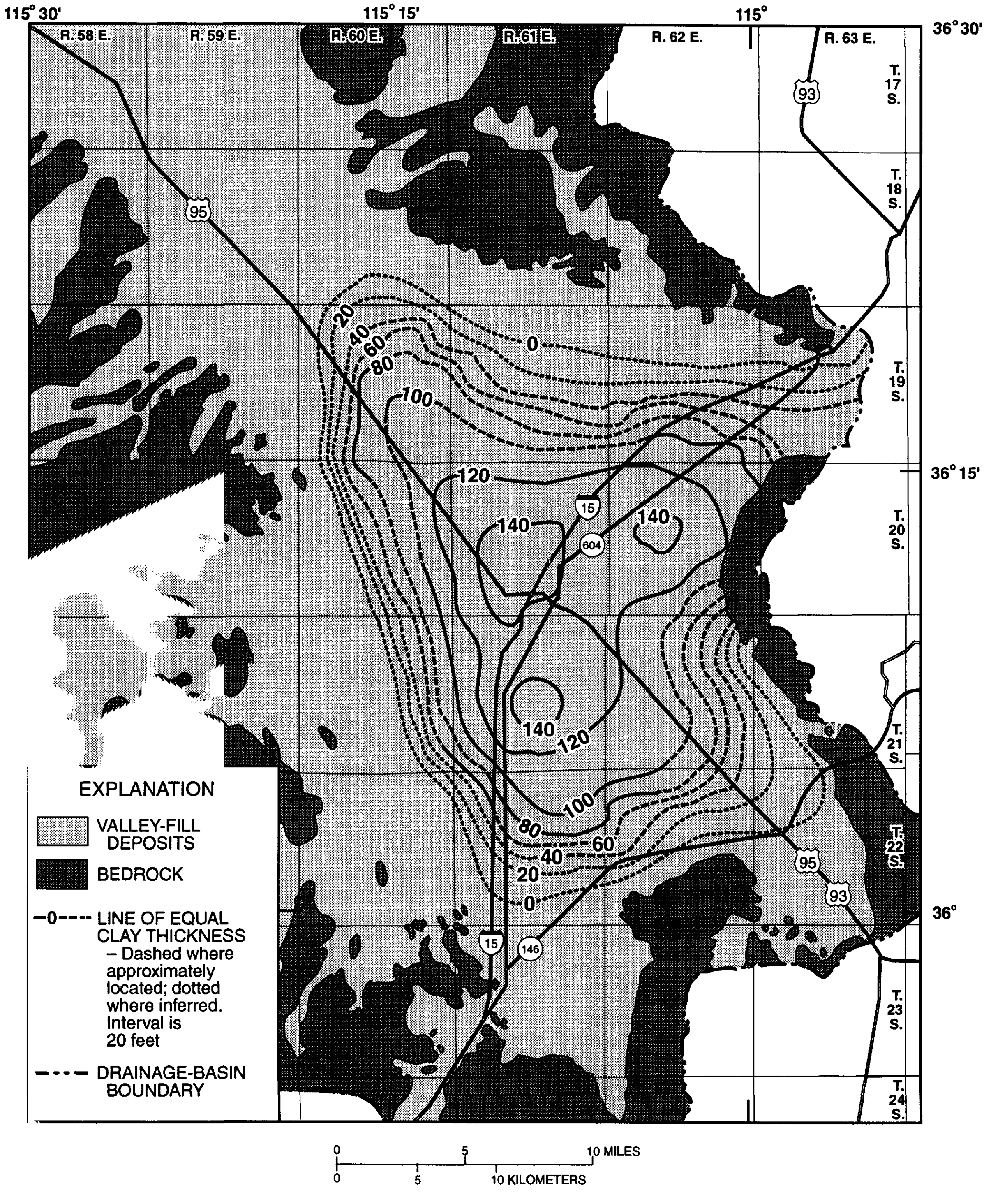


Figure 3.3.4-1. Approximate thickness of clay within near-surface aquifers.

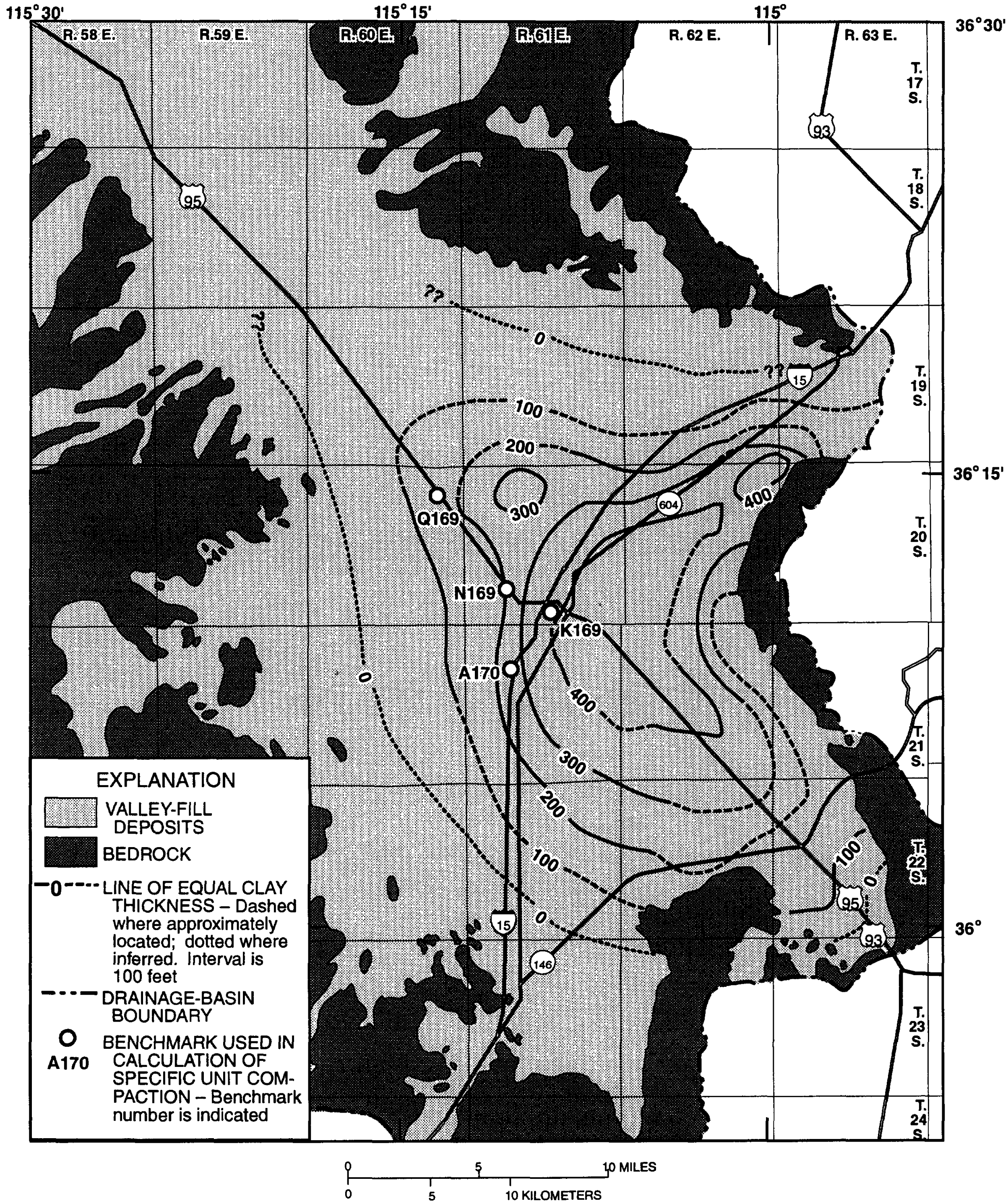


Figure 3.3.4-2. Approximate thickness of clay within developed-zone aquifers.

4.0 SIMULATION OF PAST CONDITIONS

Simulation of past ground-water conditions is an integral part of model development. During this history-matching process (commonly referred to as model calibration), the model boundaries and hydraulic characteristics are evaluated and adjusted until the model's computed responses match the measured response of the ground-water system.

In this study, the history-matching procedure consisted of two steps. First, predevelopment conditions were simulated and initial estimates of aquifer parameters, boundary locations, and boundary types were adjusted until the model was capable of simulating historical hydrologic conditions within acceptable tolerances.

These results were used as the initial conditions for the second step in the history-matching procedure—simulation of responses to development (nonequilibrium conditions). Calibration of the model to observed responses to development required division of the period, 1912 through spring 1981, into two simulation periods (1912 through spring 1972, and summer 1972 through spring 1981). Available data on pumping, recharge, and water levels for the first period are sparse through 1955. Although more data are available after 1955, information was not collected regularly or systematically until the late 1960's and early 1970's. An increased interest in data collection coincided with, and to some extent resulted from, full implementation of Phase I of the Southern Nevada Water Project in 1972. The hydrologic effects of this shift from local ground water to imported surface water were the most significant since the 1960's, when ground-water development grew at its highest rate. The sharp increase in data availability and quality, and the major changes in the stresses on the ground-water system, favored splitting the transient calibration period. The data for 1912–72 were used for a preliminary calibration, whereas the more accurate and plentiful data for 1972–81 were used for final calibration of the model.

The acceptability of the model response was judged against the uncertainties associated with the data for each period. These uncertainties, the closeness of model-calculated results to observed conditions, and interpretations of aquifer-system behavior on the basis of simulation of past conditions are presented in the following sections.

4.1 Simulation of Predevelopment Conditions

4.1.1 Recharge and Boundary Conditions

Natural Recharge of 33,000 Acre-Feet per Year Used in Simulation

Recharge by runoff from precipitation and snowmelt, which totals about 33,000 acre-ft/yr, is derived mainly from the northern Spring Mountains.

Ground-water recharge into the valley-fill aquifers was specified at the edges of the model grid to represent (1) natural recharge to the ground-water aquifer by runoff from snowmelt and rainfall and (2) ground-water outflow in the vicinity of Frenchman Mountain. The magnitude and distribution of these flows were estimated by comparison with the work of previous investigators and calibration of the model. The distribution of recharge and discharge by source area is shown in figure 4.1.1-1. Total natural recharge estimated by this method is 33,000 acre-ft/yr. This estimate is within the range proposed by previous workers: from 25,000 acre-ft/yr (Malmberg, 1965, p. 65) to 35,000 acre-ft/yr (Maxey and Jameson, 1948, p. 21). Harrill (1976a, p. 50) used simulation analysis and the Maxey-Eakin method (Eakin and others, 1951, p. 79–81) to derive an estimate of 30,000 acre-ft/yr, and Dettinger (1989a) used a chloride-balance method to compute a value of 28,000 acre-ft/yr from the northern Spring Mountains, Sheep Range, and Las Vegas Range. The Maxey-Eakin and chloride-balance methods, which are based on precipitation and altitude relations, indicate that the amount of recharge from the Spring Mountains is comparable with that from the Sheep and Las Vegas Ranges. Harrill's two-dimensional finite-difference model (1976a, p. 50), however, required that a much higher proportion of total recharge originate in the northern Spring Mountains. Figure 4.1.1-1 shows a distribution of recharge similar to that used by Harrill. This distribution suggests that recharge source-area boundaries, which must be well defined to permit the effective use of precipitation/altitude-based methods, have not yet been fully delineated for Las Vegas Valley.

Plume (1985, table 2) estimated that Lee and Kyle Canyons in the northern Spring Mountains contribute a total of 8,000 acre-ft/yr to the Las Vegas Valley ground-water system. The combined areas of the canyons cover most of the northern Spring Mountains within the modeled area north of T. 20 S. The most reasonable simulations were obtained from the model when recharge specified for this area was 8,500 acre-ft/yr.

As previously discussed (section 3.1.1), recharge pathways from the source areas to the valley-fill deposits are not well understood. The concept of a deep flowpath through fractured carbonate rocks underlying the west side of the basin was tested during the predevelopment analysis. The test consisted of redistributing to the deep zone a part of the Spring Mountain recharge previously apportioned to the developed zone. The resulting simulation showed that the layer (or depth) at which the recharge entered the system had much less effect on simulated heads than did the quantity of recharge.

Ground-water outflow through the consolidated rocks near Frenchman Mountain (1,500 acre-ft/yr) and the southern part of T. 21 S., R. 63 E. (500 acre-ft/yr) was inferred from the results of calibration, from sparse water-level data west of Frenchman Mountain (Loeltz, 1963, p. Q5), and from similar data between the mountain and Lake Mead, which all indicate a hydraulic gradient in this direction. The sensitivity of model results to outflow in this area was noted by Harrill (1976a, p. 50), who pointed out that total outflow (1,200 acre-ft/yr for his model) amounts to less than 5 percent of the ground-water budget under predevelopment conditions and has a minimal effect on the overall flow regimen of the valley.

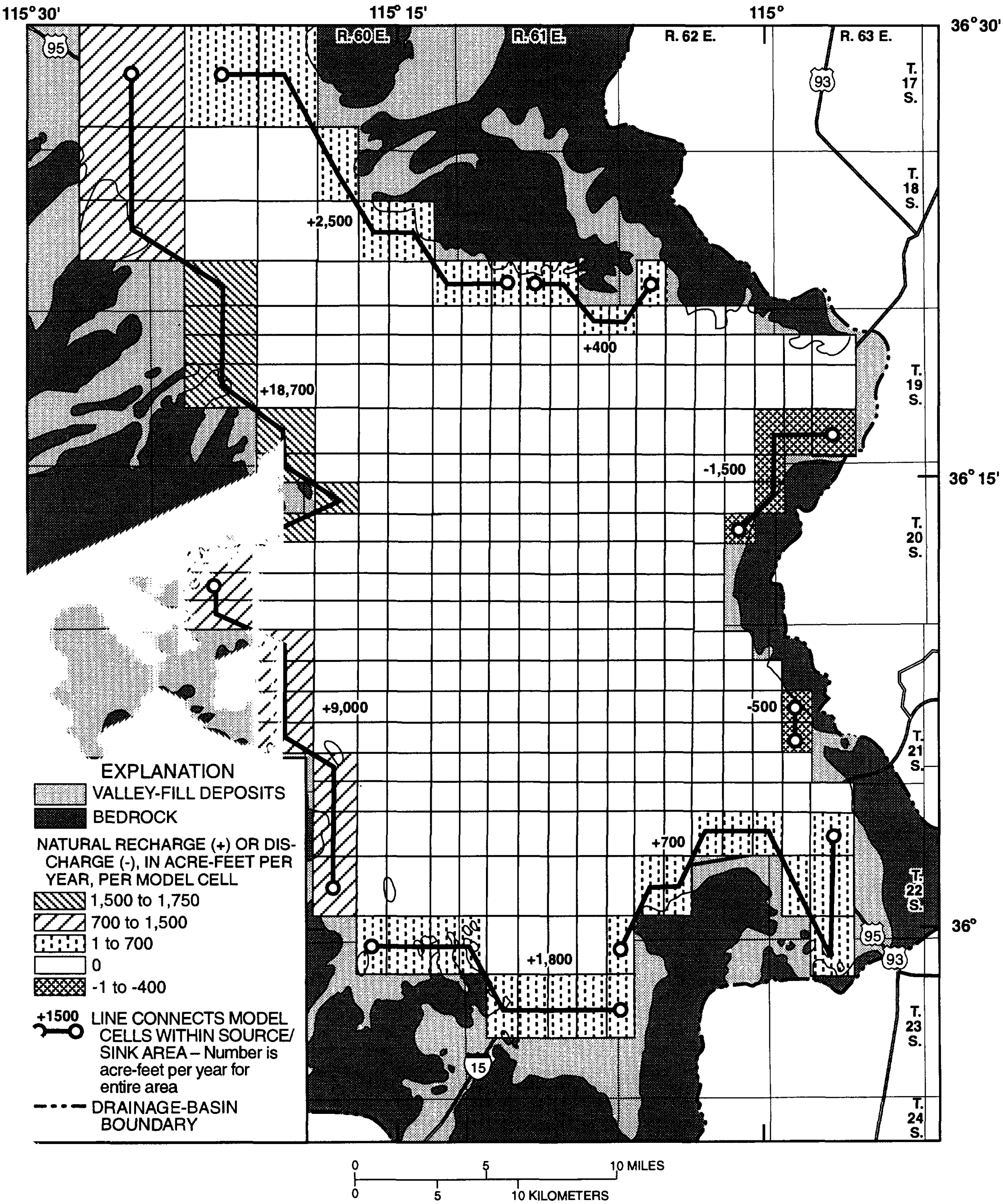


Figure 4.1.1-1. Distribution of estimated natural ground-water recharge and subsurface discharge.

Equilibrium Flow Conditions Assumed for 1912

The flow system was assumed to be in dynamic equilibrium in 1912 and a potentiometric surface map for that period was used to calibrate the model for predevelopment conditions.

The underlying assumption for the simulation of predevelopment flow conditions was that the flow system was in a state of dynamic equilibrium in 1912, the year for which Malmberg (1965, pl. 7) constructed the potentiometric contours for what is now known as the developed-zone aquifers [later expanded by Harrill (1976a, fig. 23) as shown in fig. 4.1.2.1-1]. Dynamic equilibrium, or as it is sometimes called, steady-state, is the condition an aquifer reaches when recharge and discharge balance, and no water is added to or lost from storage. It is considered a dynamic equilibrium because short-term or seasonal extremes in precipitation may cause temporary disequilibrium, but long-term variation is negligible. The term "predevelopment conditions" will be used to describe the conditions of dynamic equilibrium that are assumed to have prevailed in and prior to 1912.

The general direction of ground-water flow indicated by the contours in figure 4.1.2.1-1 is from the major source areas for recharge in the Spring Mountains and Sheep Range in the west and north, toward the discharge areas in the lower part of the valley to the southeast. The potentiometric surface ranges in altitude from approximately 1,500 ft to 2,900 ft above sea level within the study area.

The simulated predevelopment potentiometric surface (fig. 4.1.2.1-2) closely matches the general shape of the observed surface. Maximum difference between observed and simulated hydraulic heads were at the margins of the valley where few wells were available to estimate the position of potentiometric contours. Throughout most of the valley, simulated hydraulic heads were within 50 ft of observed hydraulic heads.

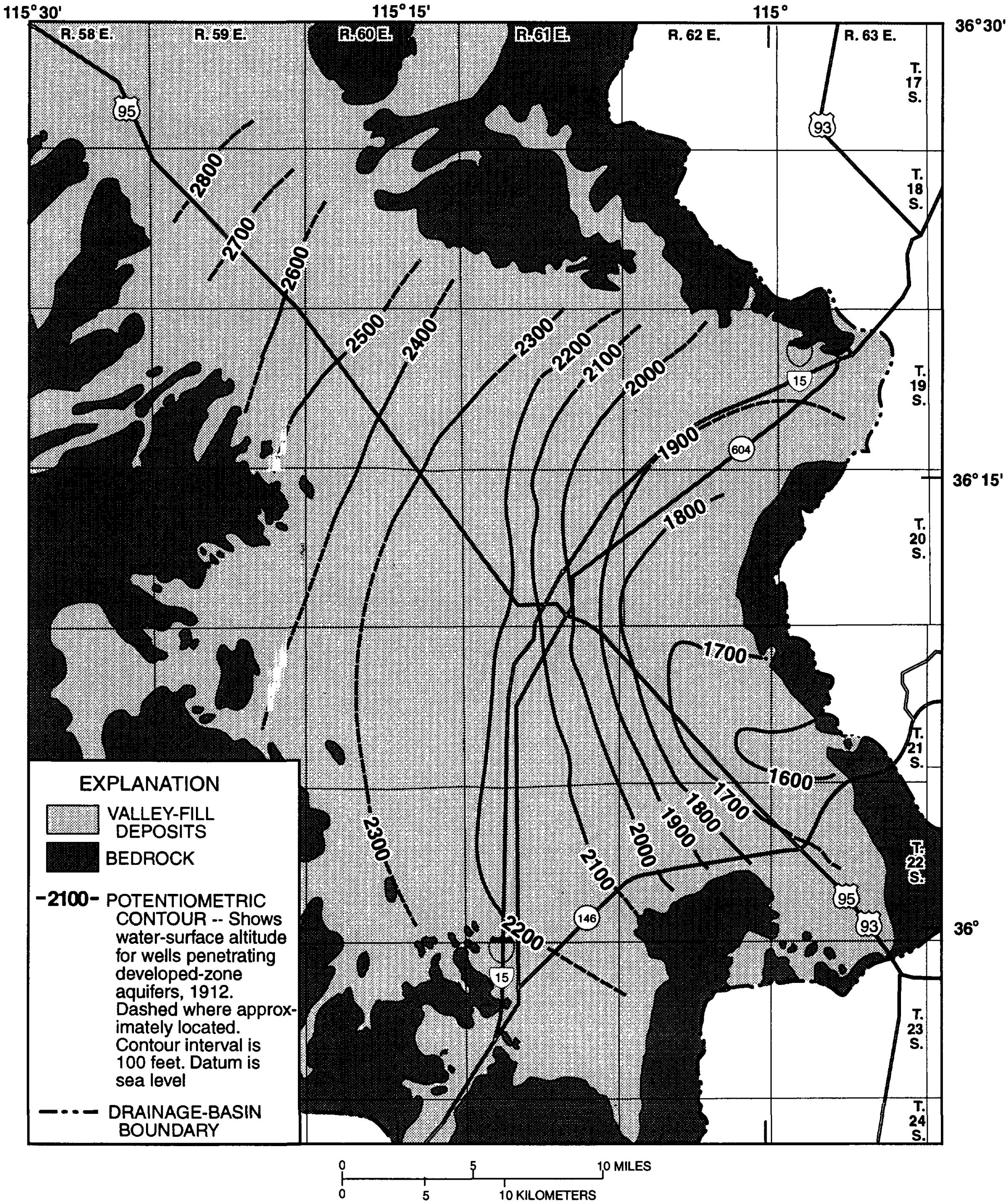


Figure 4.1.2.1-1. Approximate potentiometric surface in developed-zone aquifers, under predevelopment conditions (from Harrill, 1976a, fig. 23).

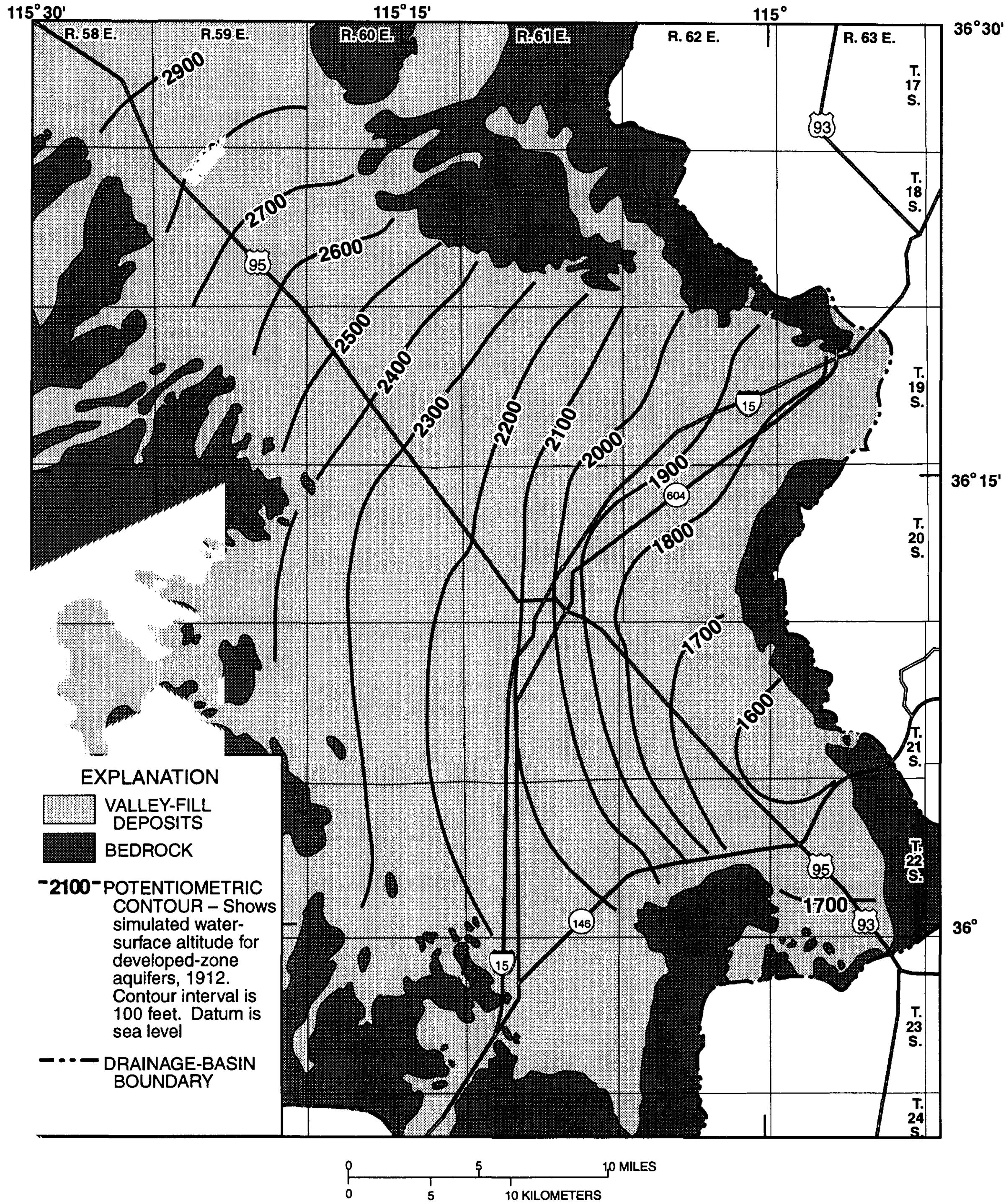


Figure 4.1.2.1-2. Simulated potentiometric surface in developed-zone aquifers, under predevelopment conditions.

4.1.2.2 Near-Surface Aquifers

Close Agreement Between Observed and Simulated Conditions

The model reproduced the general shape of the water-level surface, rates of evapotranspiration and spring discharge, and the distribution of phreatophytes reasonably well. Water-level contours from 1946 were used for comparison with simulated water levels because of insufficient data for the 1912 predevelopment period.

Water-level data for the near-surface aquifers are not available for the 1912 "predevelopment" period. Nonetheless, it was considered important to have some means of measuring the model's performance with respect to simulating the near-surface aquifers during predevelopment conditions. Therefore, the assumption was made that the near-surface aquifers had not as yet been significantly affected by development as of March 1946, and that the shape of the water-level surface contoured by Maxey and Jameson (1948, pl. 7; fig. 4.1.2.2-1) is a good approximation of that for predevelopment conditions.

Assuming that changes in storage were minor compared to the overall water budget, the shape of the surface described by the contours was controlled by the transmissivity of the aquifers, vertical leakance of the confining beds, and the flow rates within the aquifer. The heterogeneity and faults within the sediments and the distribution of recharge and discharge are thus responsible for the irregularity of the contours. The lower hydraulic gradient (wide contour spacing) to the west of the 2,100-ft equipotential contour reflects higher transmissivities in this area. High positive (upward) vertical hydraulic gradients existed at the lower altitudes in the area of ground-water discharge. The simulated water-level distribution is shown in figure 4.1.2.2-2 for comparison.

Discharges of 24,000 acre-ft/yr by evapotranspiration and 6,000 acre-ft/yr from springs were simulated by the predevelopment model; the simulated evapotranspiration rate agrees closely with the 1912 evapotranspiration rate estimated by Malmberg (1965, table 17) of 27,000 acre-ft/yr. The distribution of simulated discharge by evapotranspiration also agreed closely with the distribution of phreatophytes mapped by Malmberg (1965, pl. 1). The observed and simulated water-level surfaces shown in figures 4.1.2.2-1 and 4.1.2.2-2 also agree closely, supporting the conclusion that the conceptual model of the flow system is represented accurately by the mathematical model.

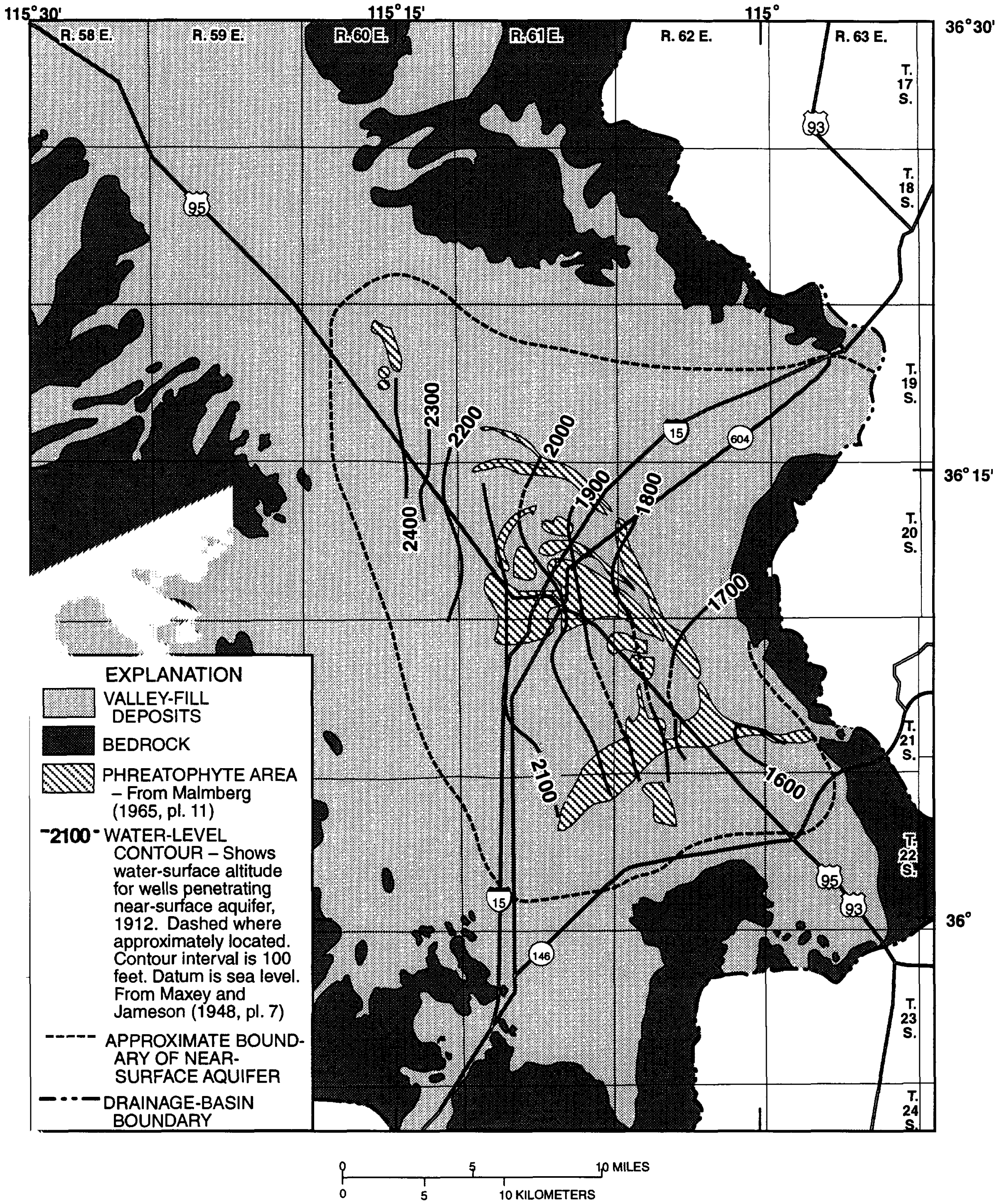


Figure 4.1.2.2-1. Approximate water levels in near-surface aquifers, under predevelopment conditions.

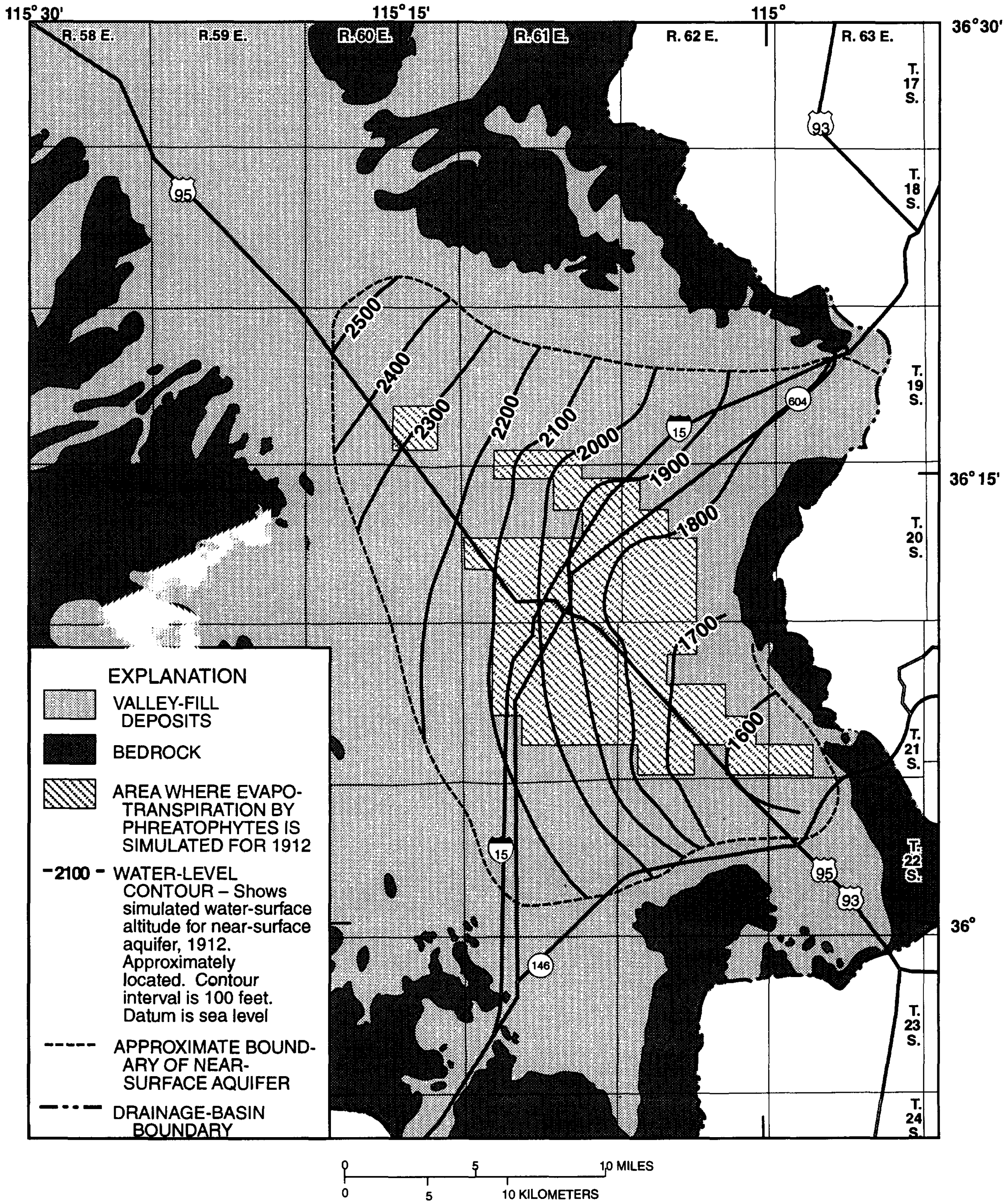


Figure 4.1.2.2-2. Simulated water levels in near-surface aquifers, under predevelopment conditions.

4.2 Simulation of Responses to Development, 1912–81

4.2.1 Boundary, Initial, and Stress Conditions

Pumping and Recharge Rates Estimated for Several Multiyear and Seasonal Periods

Pumping and recharge rates were estimated for 8 multiyear periods from 1912 through spring 1972 and 18 seasonal periods from summer 1972 through spring 1981. Initial water-level conditions for the simulation of responses to development for 1912–72 were computed using the predevelopment model. Simulated water levels for spring 1972 were used as initial conditions for the period 1972–81.

The term "hydrologic stress" refers here to any change in natural or induced recharge or discharge that causes change in the direction and rate of ground-water flow in the ground-water system. Man-induced hydrologic stresses on the Las Vegas Valley ground-water system include pumping and secondary recharge. The magnitude and distribution of these stresses were estimated for 8 multiyear periods during 1912–72 and for 18 seasonal periods (2 per year) during 1972–81. The valley-wide magnitude of stresses is shown in figure 4.2.1-1. A total of more than 2.5 million acre-ft was pumped from the Las Vegas Valley ground-water basin between 1912 and 1981 (fig. 1.2.1-1) and about 620,000 acre-ft between 1972 and 1981 (fig. 4.2.1-1).

The hot, dry summers common to Las Vegas Valley stimulate a highly seasonal demand for water. This demand generally peaks in July in response to domestic water use for lawn irrigation. Each year of the 1972–81 simulation period was divided into peak and low water-use seasons. Total annual pumpage for each year was apportioned to the peak-use (June 1 to September 20) and low-use (September 21 to May 31) seasons on the basis of average LVVWD monthly ground-water production data for 1978–80. Seasonal average pumping rates, shown in figure 4.2.1-1*B*, varied from about 4,000 acre-ft/mo during low-use months (October–May) to about 9,000 acre-ft/mo during peak-use months (June–September).

Estimated annual rates of secondary recharge were seasonally apportioned according to monthly rates of outdoor residential water use in 1979. In 1979, 56 percent of outdoor water use was between June 1 and September 20 (URS Company and others, 1983, table B-3); the same percentage of total annual secondary recharge was assumed for that 3 $^2/_3$-month period. This resulted in a recharge rate for the peak-use season that was nearly three times the rate for the low-use season. The seasonal rates of ground-water pumpage and secondary recharge used to simulate the period 1972–81 are shown in figure 4.2.1-1*B*.

The areal distributions of secondary recharge and pumping are described in sections 3.2.5 and 3.2.6, respectively. The estimated temporal changes in total secondary recharge and pumping are shown for 1912–72 in figure 4.2.1-1*A* and for 1972–81 in figure 4.2.1-1*B*. Secondary recharge during 1912–81 is estimated to total more than 840,000 acre-ft, of which about 340,000 acre-ft infiltrated during 1972–81. The data shown in these figures were used as input to the model.

Figure 4.2.1-1*A*, *B* also shows the fluxes specified at the model boundaries to approximate natural recharge from mountain-front runoff and ground-water outflow. The rates were derived during calibration of the predevelopment model (see section 4.1.1) and were assumed to be constant, both from season to season and from year to year.

Initial estimates of the water level at each model cell are required for any simulation. However, in simulating predevelopment (steady-state) conditions, when water levels do not change with time, these estimates do not affect the final calculated water levels; they affect only the time required for the model to reach a solution. The closer the initial estimates are to the final calculated values, the more rapidly the solution will be reached.

In simulating transient conditions, calculated differences between initial and final water levels are of principal interest. Thus, initial water-level estimates can have a significant effect on results. If the initial water levels are calculated by the model using aquifer characteristics (transmissivity, storage coefficients) and boundary conditions consistent with those in the predevelopment model, then the initial water levels will not cause errors in calculated water-level changes. If, however, the initial estimates are generated externally (for example, from a contour map) or by a model with different aquifer characteristics or boundary conditions, significant errors in computed water-level changes may be generated due to what has been called "numerical equilibration" of water levels. To avoid this problem, initial water levels for each of the calibration periods in this study were those generated by the model as final water levels for the previous time period. The predevelopment model was used to calculate initial conditions for the 1912–72 period and the computed water levels for spring 1972 were used as initial conditions for the 1972–81 period.

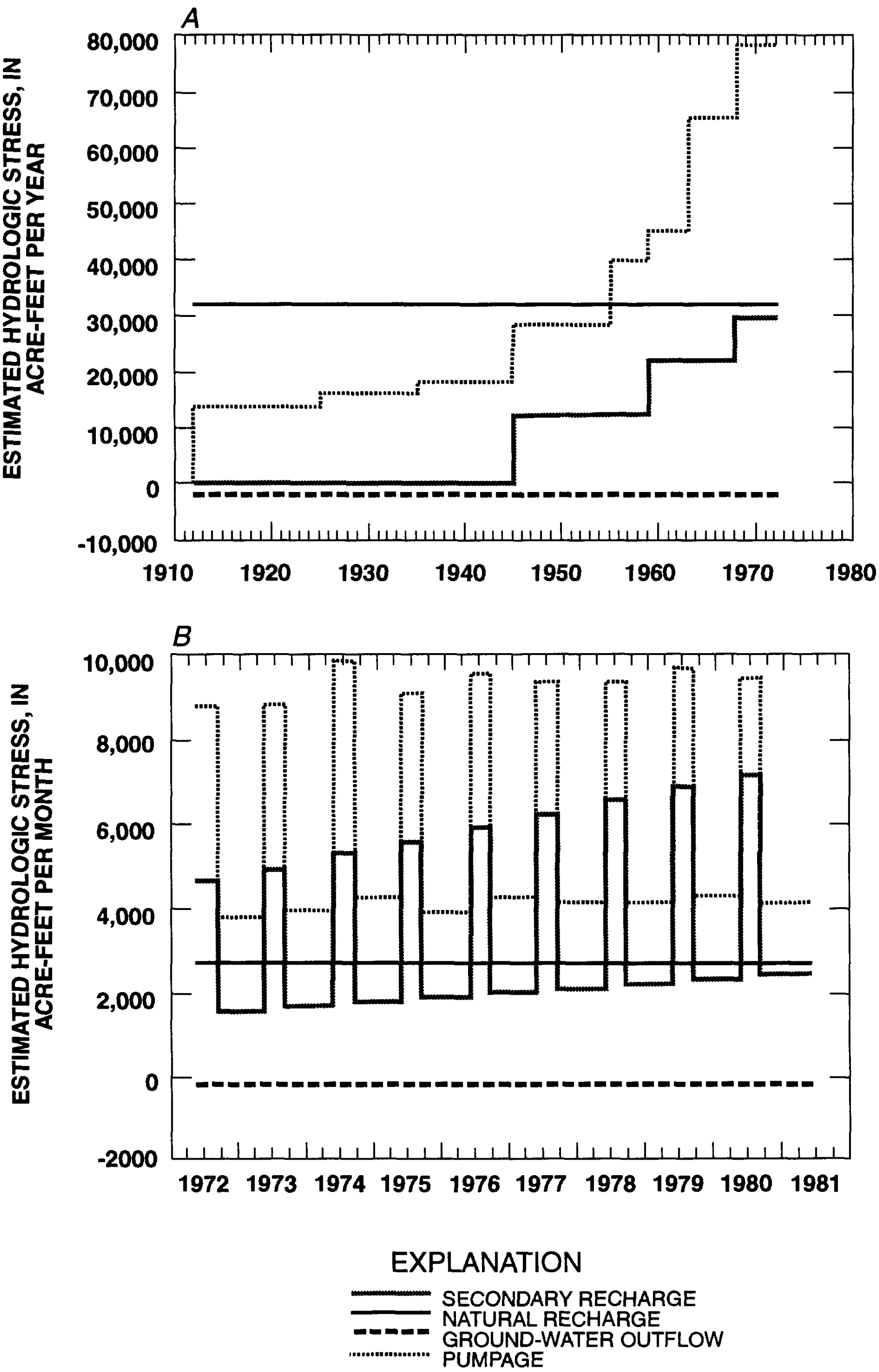


Figure 4.2.1-1. Estimated pumping, recharge, and boundary flux rates for simulation of aquifer response to development, *A*, 1912–72, and *B*, 1972–81. Negative value for ground-water outflow indicates discharge of ground water from model area.

4.2.2 Effects of Development, 1912–72

4.2.2.1 Effects in Developed-Zone Aquifers

One-Third of Pumpage from Developed-Zone Aquifers is from Storage Depletion

Water-level declines of as much as 240 ft centered on the western side of the valley reflect depletion of about 600,000 acre-ft of storage in the developed-zone aquifers between 1912 and 1972. The simulated declines and depletion agree with results from previous studies.

Water levels in the developed-zone aquifers declined substantially on the west side of the valley between 1912 and March 1972. The pumping of high-yield, municipal-supply wells concentrated in this area produced maximum declines of about 240 ft. The measured and simulated water-level changes in the developed-zone aquifers between 1912 and 1972 are shown in figures 4.2.2.1-1 and 4.2.2.1-2, respectively. The distribution of simulated declines agree with measured changes, although the simulated declines are commonly smaller than measured declines in the major cone of depression on the west side of the valley.

The location, depth, and shape of the cone of depression are influenced by many factors, including (1) location of heavily pumped wells, (2) distribution of hydraulic characteristics (such as transmissivity and storage coefficient), (3) location of physical boundaries, (4) location and magnitude of recharge, and (5) vertical leakage from adjacent aquifers.

These factors are listed in approximate order of decreasing significance in Las Vegas Valley. Elongation of the cone about a northwest-southeast axis is largely due to a similar distribution of the most permeable sediments in the valley; these deposits are bounded to the east by great thicknesses of less permeable sediments and to the west by extreme thinning of alluvial-fan deposits. Figure 4.2.2.1-1 shows that the cone of depression has intercepted the bedrock-alluvium boundary on the west side of the valley. No evidence supports or refutes the possibility of additional recharge being induced by this condition, and in this analysis, no additional recharge is assumed to be induced from the bedrock.

Few high-yield wells have been drilled in the southeastern part of the valley because of the scarcity of productive aquifer zones. Consequently, the Henderson-Pittman area has relied on imported water from Lake Mead rather than local ground water for its municipal and industrial supplies. Recharge to the near-surface aquifers by infiltration of excess irrigation water, industrial process water, and wastewater, in combination with the area's position at the lowest point in the flow system, resulted in water-level increases between 1912 and 1972 and downward vertical leakage.

Harrill (1976a, table 10) estimated storage depletion in the developed-zone aquifers for the period 1955–72 by three methods: (1) computing recharge minus discharge; (2) multiplying water-level declines by area and storage coefficient; and (3) using a simulation model. The average of these estimates was 460,000 acre-ft. The present simulations calculated a storage depletion of 360,000 acre-ft for 1955 through March 1972, and do not include the peak-demand summer months of 1972. For comparison with Harrill's estimate, the simulated rate of storage depletion for 1971 (30,000 acre-ft) is assumed as the 1972 rate, and the resulting total for 1955–72, an estimated 390,000 acre-ft, is in reasonable agreement with Harrill's estimate.

Between 1912 and 1972, storage depletion in the developed-zone aquifers is simulated as totaling 600,000 acre-ft. Storage depletion, therefore, supplied about one-third of the pumpage from this zone; the rest came from recharge or storage depletions in the overlying near-surface aquifers.

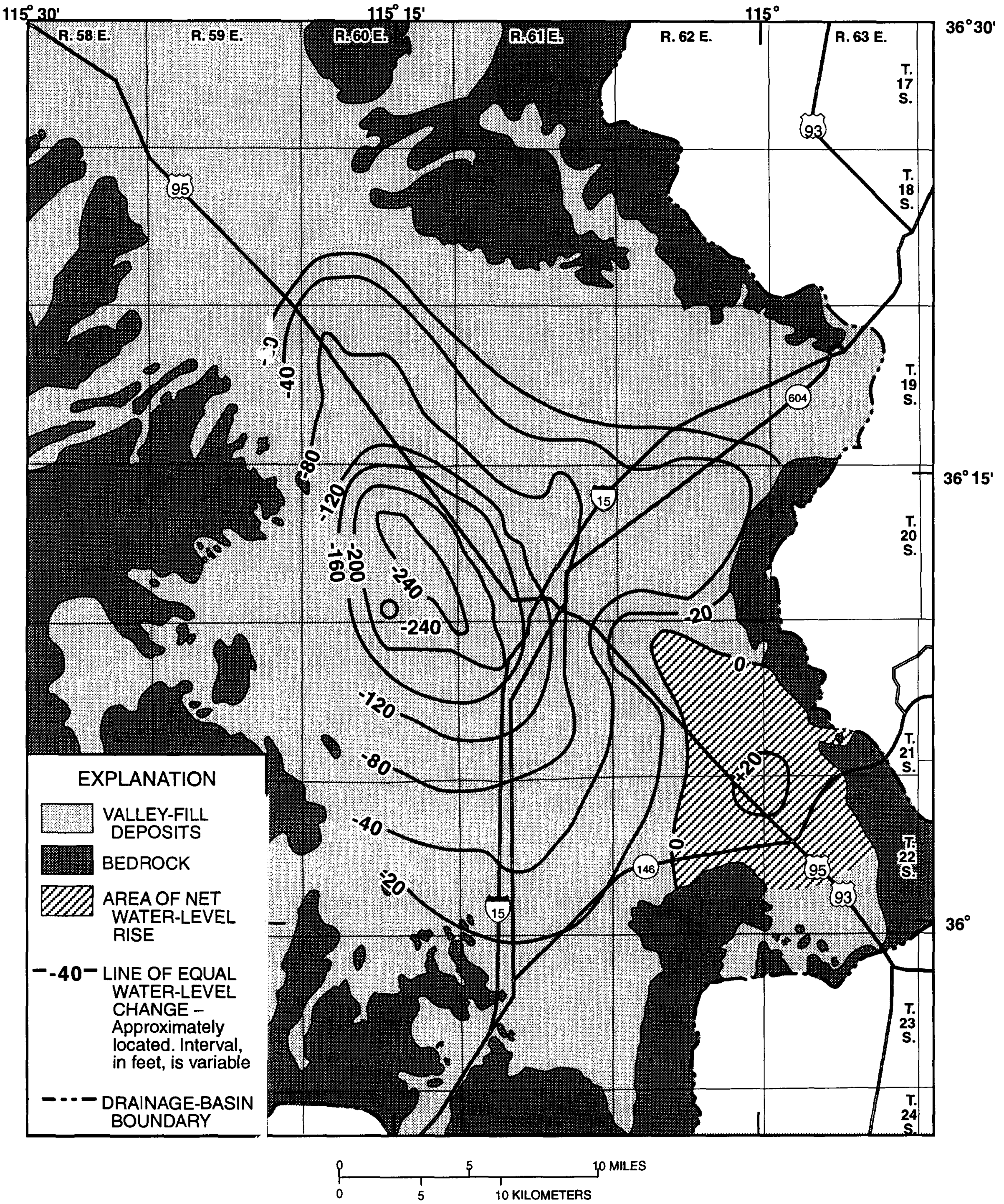


Figure 4.2.2.1-1. Approximate water-level change in developed-zone aquifers, 1912–72 (from Harrill, 1976a, figs. 15, 17).

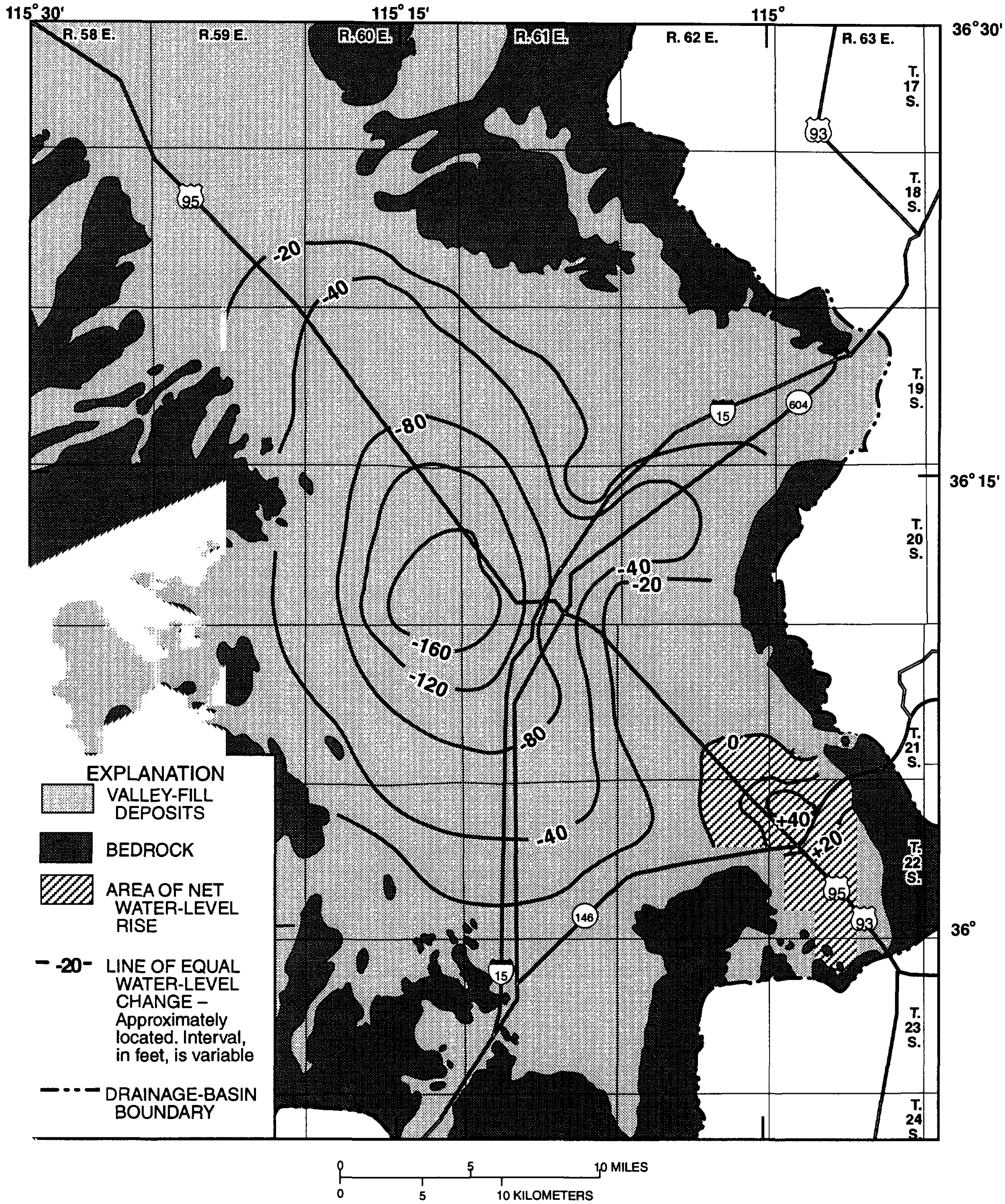


Figure 4.2.2.1-2. Simulated water-level change in developed-zone aquifers, 1912–72.

4.2.2.2 Effects in Near-Surface Aquifers

Secondary Recharge Partly Offsets Induced Leakage to Developed-Zone Aquifers

From 1912 to 1972, water levels in the near-surface aquifers in the central and southeastern parts of the valley were stabilized or raised by secondary recharge. This partly offset the large storage depletion at the western edge of the near-surface aquifers.

Water-level changes in the near-surface aquifers were generally in the same direction as those in the developed-zone aquifers between 1912 and spring 1972, but were either greater or smaller depending on the area of the valley, the magnitude of the stress imposed, and the quantity of secondary recharge reaching the near-surface aquifers locally. On the west side of the valley, water levels declined greatly in response to (1) declining hydraulic heads in the heavily pumped, underlying developed-zone aquifers and (2) the absence of significant clay beds to restrict downward movement. Drawdown in the near-surface aquifers was less toward the center of the basin, where thick clay beds restrict vertical movement of ground water.

Secondary recharge from high-density housing tracts, golf courses, parks, irrigated acreage, and industrial waste ponds stabilized or caused increasing water levels in a large part of the near-surface aquifers between 1912 and 1972. Measured water-level changes in the near-surface aquifers for the period 1955–73 and simulated water-level changes for the 1912–72 period are shown in figures 4.2.2.2-1 and 4.2.2.2-2, respectively. Although the measured water-level changes are for the period 1955–73, they are probably representative of the distribution and magnitude of changes during the simulation period 1912–72. Changes between 1912 and 1955 are assumed to be small relative to changes between 1955 and 1972, and changes during 1973 can only be assumed small (due to lack of data for that year).

Harrill (1976a, table 6) estimated that 130,000 acre-ft of water was depleted from storage in the near-surface aquifers between 1955 and 1972. This estimate is the sum of the products of water-level decline, area, and average storage coefficient (0.05). The estimate from this study, adjusted as in section 4.2.2.1 for comparison, is 160,000 acre-ft. The extent of the near-surface aquifers used by Harrill and that used in the model are nearly equal, and the model-simulated water-level declines are reasonable approximations of observed declines for this period. Thus, the discrepancy between storage-depletion estimates probably results from the storage coefficients used. Calibrated specific yields in the unconfined, upper part (layer 4) of the near-surface aquifers range from 0.01 to 0.09, with a mean of about 0.08. The semiconfined part (layer 3) was assigned coefficients in the "leaky artesian" range of 0.001 to 0.009; the resulting contribution from layer 3 was only about 10 percent of the total water derived from storage between 1912 and 1972. Thus, the effective storage coefficient for the near-surface aquifers averages about 0.09, almost twice that used by Harrill. The difference in estimated storage depletion in the near-surface aquifers can be fully accounted for by the difference in estimated specific yield used in each calculation.

From 1912 to 1972, the total storage depletion from the near-surface aquifers was simulated as 280,000 acre-ft. This depletion occurred along the west and northwest parts of the aquifer, where the near-surface aquifers are closely tied to the developed-zone aquifers. In the central part of the valley, secondary recharge partly offset leakage downward from the near-surface aquifers to the developed zone induced by water-level declines in the developed zone, and as a consequence storage depletion was small. Still farther east, secondary recharge caused rising water levels and actually increased the volume of water stored.

During 1912–72, the total simulated storage depletion from the basin-fill aquifers of Las Vegas Valley was 880,000 acre-ft, or about 50 percent of pumpage. Roughly 50 percent of the depletion occurred after 1955.

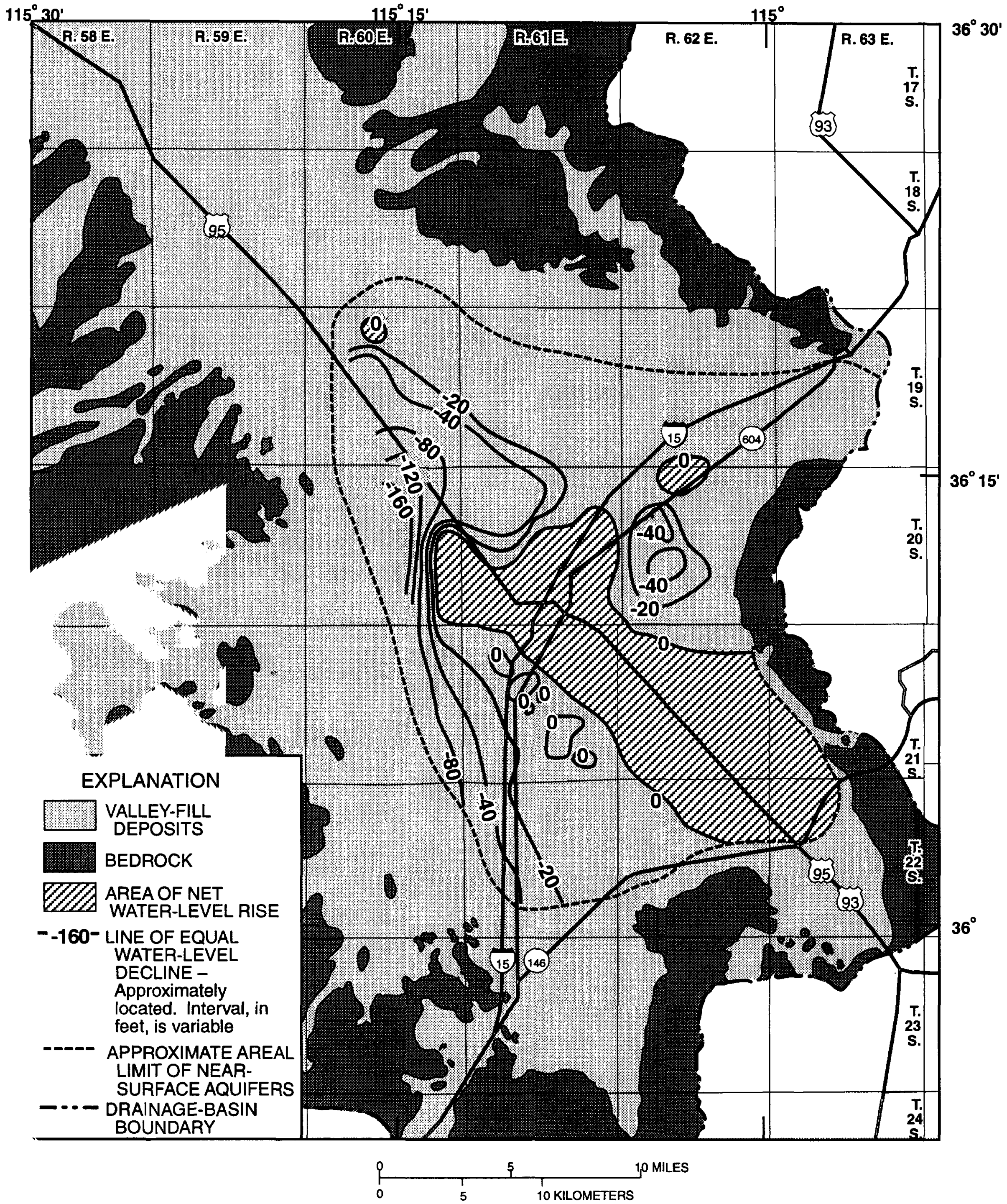


Figure 4.2.2.2-1. Approximate water-level change in near-surface aquifers, 1955–73 (from Harrill, 1976a, fig. 12).

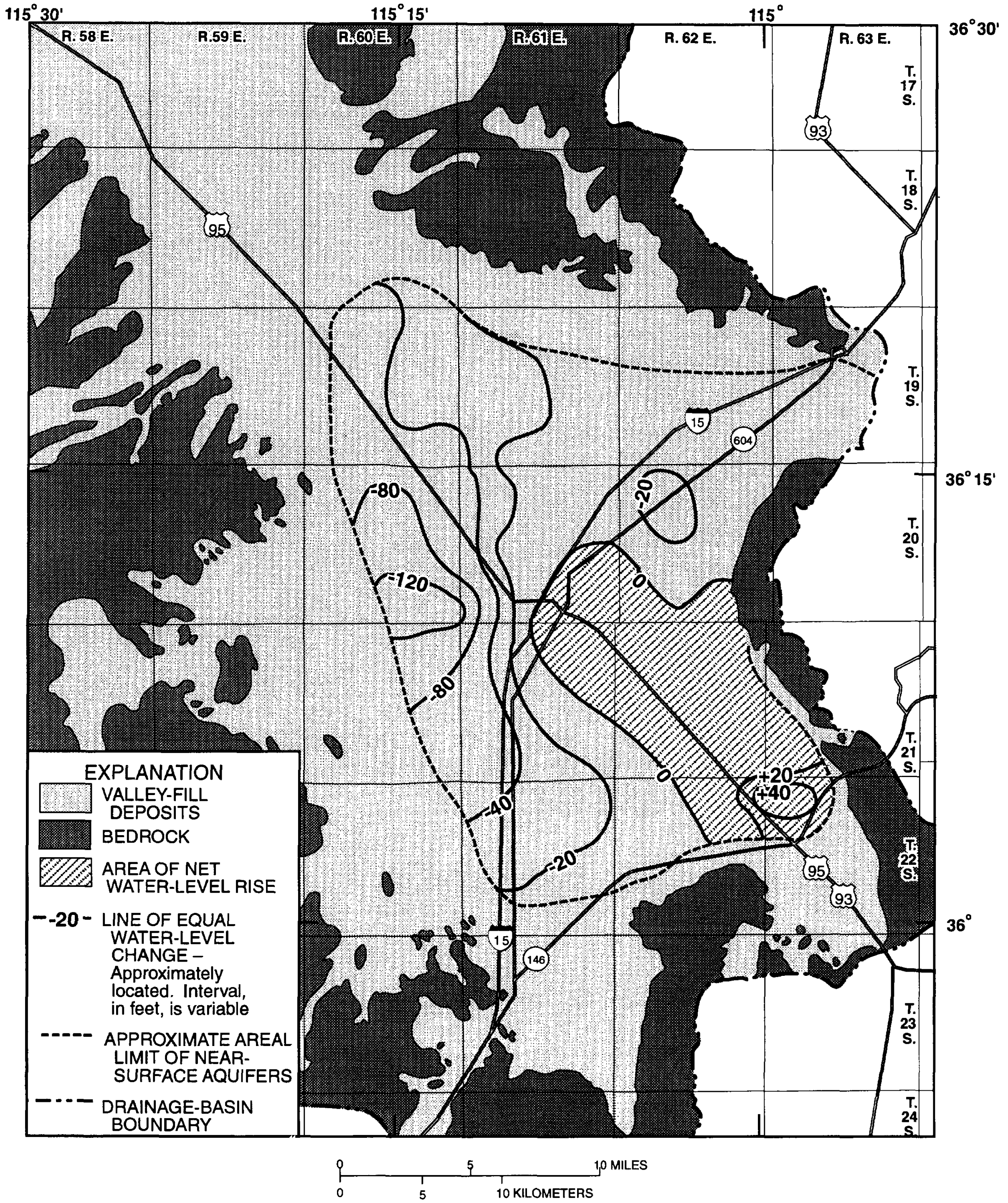


Figure 4.2.2.2-2. Simulated water-level change in near-surface aquifers, 1912–72.

4.2.2.3 Subsidence

Six Percent of 1955–72 Pumpage Derived from Compaction of Fine-Grained Beds

Subsidence can be reasonably well predicted in Las Vegas Valley on the basis of relations between head decline and inelastic specific storage; however, geologic controls also affect the location and extent of subsidence.

Land subsidence measured between 1935 and 1972 and simulated land subsidence between 1912 and 1972 are shown in figures 4.2.2.3-1 and 4.2.2.3-2, respectively. Until 1945, when pumping rates began to increase rapidly, little if any subsidence is likely to have taken place. Model simulations confirm this, and thus, 1935–72 measured subsidence is considered a reasonable approximation of total subsidence for the postdevelopment period. The general pattern and magnitude of subsidence was reasonably well reproduced by the model. Local areas of simulated maximum subsidence, however, were offset from their true locations. The areas of heaviest subsidence are controlled by head decline, thickness and compressibility of sediments, and geologic structure. The method of computing subsidence used in the model does not allow for the effects of buried fault escarpments or other structural features which might control the distribution of subsidence. This is evident in the southern part of T. 20 S., R. 61 E., where the area of greatest measured subsidence is centered under downtown Las Vegas, yet the area of highest simulated compaction is 3 mi west, at the site of the original LVVWD well field. Holzer (1978, p. 7) presents evidence linking this zone of differential subsidence to a north-trending fault (see fig. 4.2.2.3-1) first mapped by Maxey and Jameson (1948, pl. 1). The simulated maximum subsidence is offset 3 mi west at the old LVVWD well field because the apparent control of geologic structure is not accounted for in the model.

The following table lists model-derived estimates of the water volumes (in acre-feet) released from storage during 1912–72 due to compaction of compressible clay beds. The table is divided into periods that coincide with model simulation periods to facilitate comparison with estimates by previous investigators.

	1912–54	1955–62	1963–72	Total, 1912–72
Developed-zone aquifers	4,000	11,000	36,000	51,000
Near-surface aquifers	0	1,000	9,000	10,000
Total	4,000	12,000	45,000	61,000

Mindling (1971, table 3) reported the volume of compaction during the period 1957–63 to be approximately 28,000 acre-ft. Model-computed compaction totaled only 12,000 acre-ft for the period 1955–62. The model results for 1963–72 showed 45,000 acre-ft of compaction, which was 5,000 acre-ft more than Harrill's estimate for the same period (1976a, p. 41). Total-compaction estimates agree well if a total of 68,000 acre-ft is assumed for 1955–72 (summing the estimates of Mindling and Harrill), compared with an adjusted, model-computed volume of 62,000 acre-ft. The model-computed total volume of subsidence was adjusted to match the time period of the Mindling-Harrill total by (1) adding 5,000 acre-ft (the computed 1971 volume) to account for subsidence during the peak-demand months of 1972 included in Harrill's estimate, and (2) subtracting the computed 4,000 acre-ft simulated during the period prior to Mindling's estimate. The basinwide average percentage of pumpage derived from compaction was about 6 percent between 1955 and 1972. Mindling (1971, table 3) reported that this ranged from 2 to 19 percent between 1935 and 1963; the maximum percentage of pumpage was derived from compaction during 1957–63.

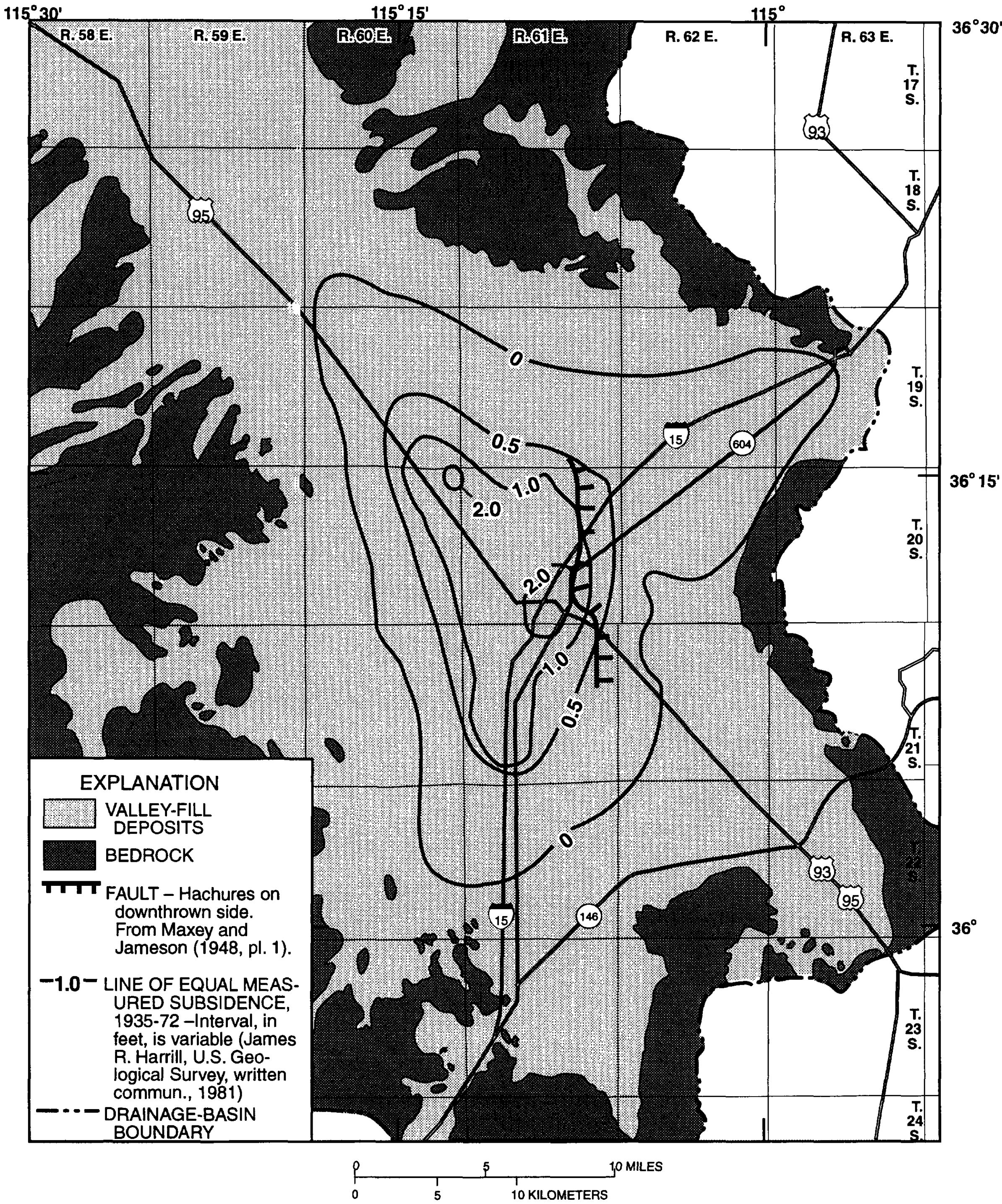


Figure 4.2.2.3-1. Measured land subsidence due to ground-water withdrawals, 1935–72.

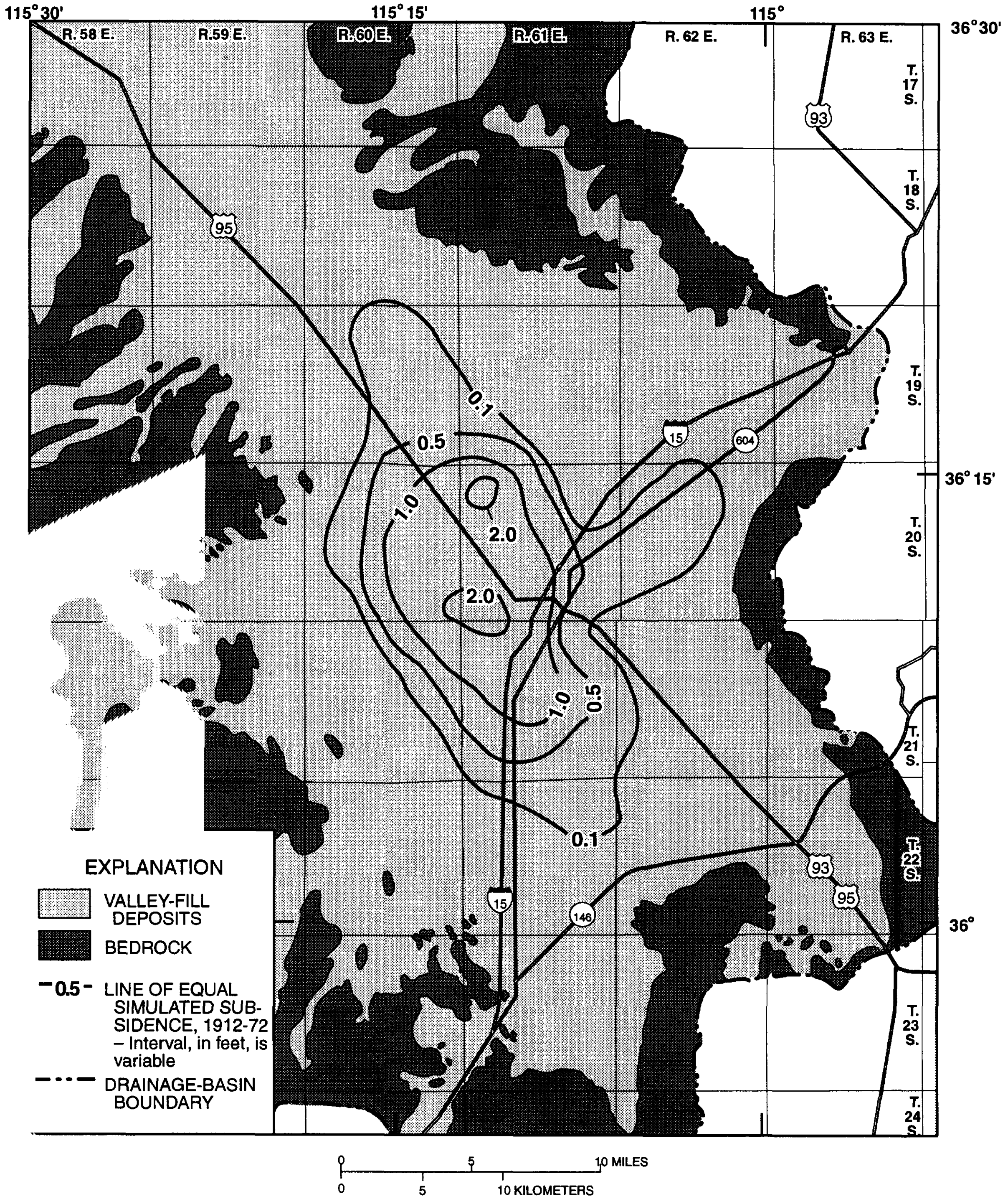


Figure 4.2.2.3-2. Simulated land subsidence due to ground-water withdrawals, 1912–72.

4.2.2.4 Ground-Water Movement and Discharge

Net Vertical Ground-Water Flow Reversed from Upward to Downward

The vertical hydraulic gradient between the developed-zone and the near-surface aquifers has reversed from upward to downward over much of the valley due to pumping from the developed-zone aquifers and secondary recharge to the near-surface aquifers. Excluding pumpage, ground-water discharge was greater in 1972 than under predevelopment conditions; most pumpage was derived from storage.

Ground-water movement in both the vertical and horizontal directions was significantly altered between 1912 and 1972. Pumping and secondary recharge were the major causes of the changes in natural flow paths and discharge patterns.

Under predevelopment conditions, all natural recharge to the developed-zone aquifers eventually moved upward into the near-surface aquifers under the vertical hydraulic gradient that existed throughout most of the lower altitude parts of the valley. Pumping wells within the developed-zone aquifers captured a progressively greater percentage of upward leakage as the cone of depression expanded, causing the area of upward hydraulic gradient to dwindle. Figure 4.2.2.4-1*A* shows the gradual reversal of leakage from the developed-zone into the near-surface aquifers. Declining water levels in the developed-zone aquifers also induced a minor amount of net upward leakage from the deep-zone aquifers since the mid-1950's (fig. 4.2.2.4-1*A*) and the release of water by compaction of fine sediments (fig. 4.2.2.4-1*B*).

Simultaneously, heads in the near-surface aquifers increased over large areas (especially in the central and southeast parts of the valley) in response to increasing secondary recharge. Figure 4.2.2.4-1*A* shows the important effect secondary recharge has had on ground-water movement between aquifer zones. For the near-surface aquifers, the net upward flow comprises evapotranspiration plus seepage to washes, minus secondary recharge. Before 1945, pumping from the developed zone was gradually reducing the amount of vertical flow from the developed-zone to the near-surface aquifers. After 1945, when secondary recharge became significant, the upward flow rate decreased rapidly until 1962, when net flow reversed from upward to downward. Model results indicate that secondary recharge to the near-surface aquifers first exceeded discharge (that is, evapotranspiration plus seepage) from the aquifers in about 1970.

The effects of secondary recharge also can be seen in the simulated rates of discharge to washes and by evapotranspiration in figure 4.2.2.4-1*C*. Seepage was stable prior to 1945, but increased sharply between 1945 and 1972. A rising water table over large areas of the near-surface aquifers resulted in significant seepage to washes and drains, and the advent of perennial flow in many of them. According to Patt (1978, fig. 12-15), 15 to 50 percent of total secondary recharge to the near-surface aquifers originated from infiltration ponds at the BMI plant between 1943 and 1973. A proportionately large percentage of the total ground-water seepage occurred along Las Vegas Wash immediately north of the BMI ponds. Few estimates of the ground-water contribution to Las Vegas Wash are available for years prior to 1972; however, the quantity and general distribution of seepage to washes computed using the model are in good agreement with inferences based upon water-level changes in the near-surface aquifers.

Changes in spring discharge with time were not reproduced accurately by the model. Actual discharge did not diminish as rapidly as depicted in figure 4.2.2.4-1*C*; in 1955, measured discharge from Las Vegas, Kyle, Tule, and Corn Creek Springs totaled 1,400 acre-ft, whereas the simulated value was only 400 acre-ft. This disagreement may be attributed to the modeling assumption that all flow is horizontal within the developed-zone aquifers (layer 2). In the physical system, pumping did not lower the heads equally throughout the thickness of the developed zone (as the model simulates)—instead, hydraulic heads within parts of the zone probably remained above land surface, causing spring discharge for longer periods than model results indicate.

Simulated evapotranspiration (fig. 4.2.2.4-1*D*) gradually declined in response to declining water levels from 1912 to 1945. After 1945, phreatophytes were sustained in some areas by secondary recharge.

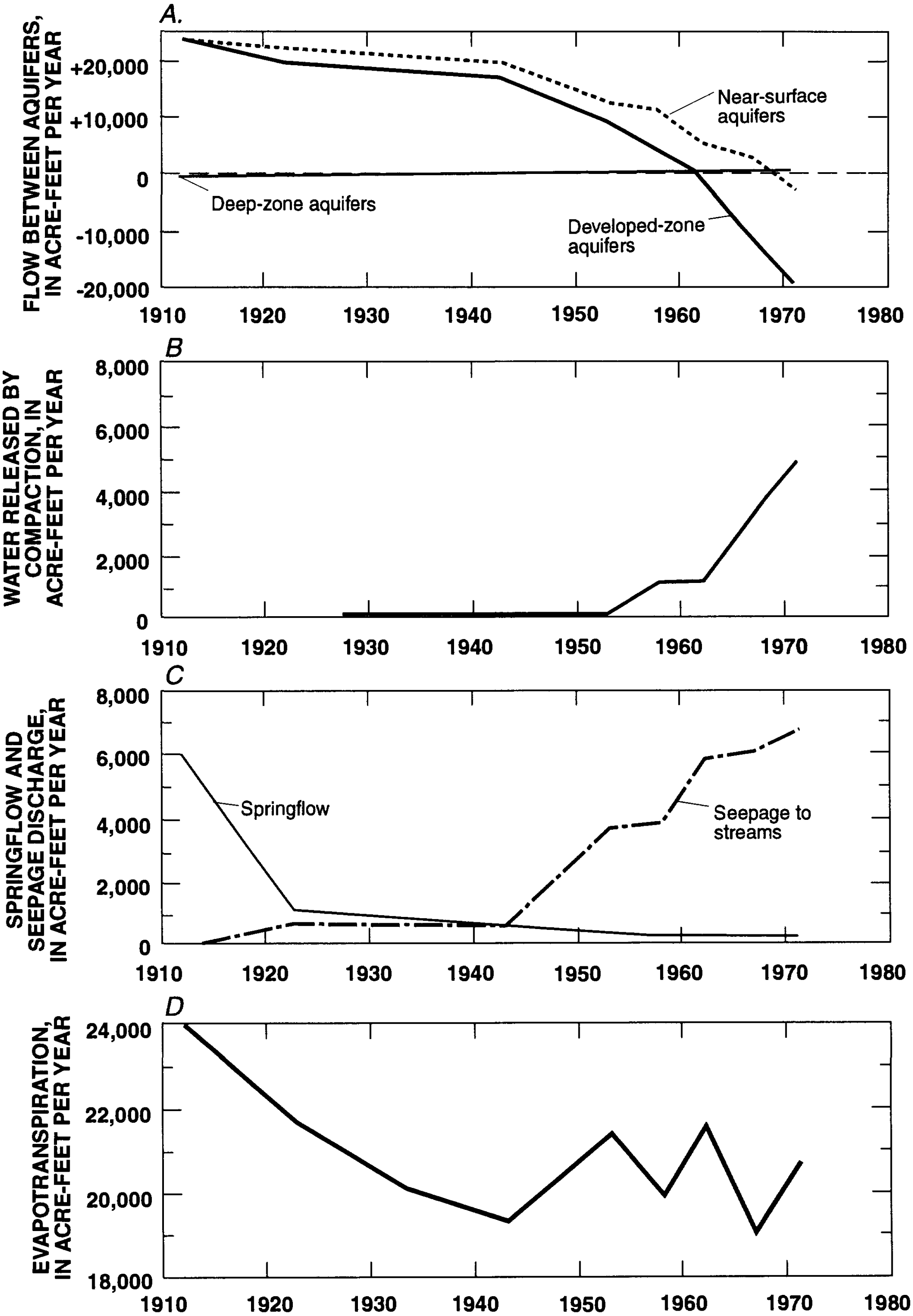


Figure 4.2.2.4-1. Simulated ground-water movement and discharge, 1912–72. *A*, Upward (+) and downward (–) flow between aquifers (shows net flow across upper boundary of indicated aquifer). *B*, Water released by compaction. *C*, Spring discharge and seepage to streams. *D*, Evapotranspiration.

4.2.3.1 Water-Level Changes

Water-Level Changes Reflect Long-Term Pumping Patterns

Water levels continued to decline at rates of as much as 5 ft/yr in local areas of heavy pumping. In the southeast and central parts of the valley, water levels showed a net rise.

The model reliably simulated water-level changes between 1972 and 1981 in the near-surface and developed-zone aquifers in much of the valley. To evaluate the model's reliability, water-level changes measured at 46 wells in the developed-zone aquifers between March 1972 and March 1981 were compared with model-computed water-level changes. Figure 4.2.3.1-1 shows the distribution of the differences between measured and computed changes. At about one-half of the wells, the computed changes were within 5 ft of the measured changes. Measured and simulated water-level changes for selected wells and corresponding model cells are shown in plate 1.

Water-level changes from summer 1972 to 1981 were characterized by declines on the west side of the valley and rises on the east side. This general statement applies for both the developed-zone and the near-surface aquifers. The simulated changes in water level for the developed-zone and near-surface aquifers are shown in figures 4.2.3.1-2 and 4.2.3.1-3, respectively.

A prominent feature on both maps is the large area of water-level rise centered near Nellis Air Force Base. Water levels in this area recovered more than 40 ft in response to increases in secondary recharge and marked reductions in pumpage locally and valley-wide. Water levels declined in the Henderson-Pittman area following cessation of disposal of industrial-process effluent to unlined infiltration/evaporation ponds. Estimates of secondary recharge used in the model are more uncertain in this area; the estimates for 1973 through 1981 were derived by extrapolating Patt's (1978, p. 32–39) 1972 estimates forward in time (section 3.2.5). Despite the uncertainty of the recharge estimates, computed water-level changes generally agree with the results of Westphal and Nork (1972), whose simulations of the shallow aquifer in this area suggest that water levels would drop 30 to 40 ft within 2 years of the time when use of the infiltration ponds was terminated. Other areas of Henderson have shown water-level rises related to residential growth (Wood, 1988a, p. 9). These changes would not be simulated by the model because the estimates of secondary recharge were not prepared at this scale.

The largest simulated water-level declines were more than 70 ft and were centered near the heavily pumped municipal well fields on the west side of the valley. Localized declines of 20 ft and more have been induced by pumping of new domestic wells in the northern half of T. 22 S., R. 61 E.

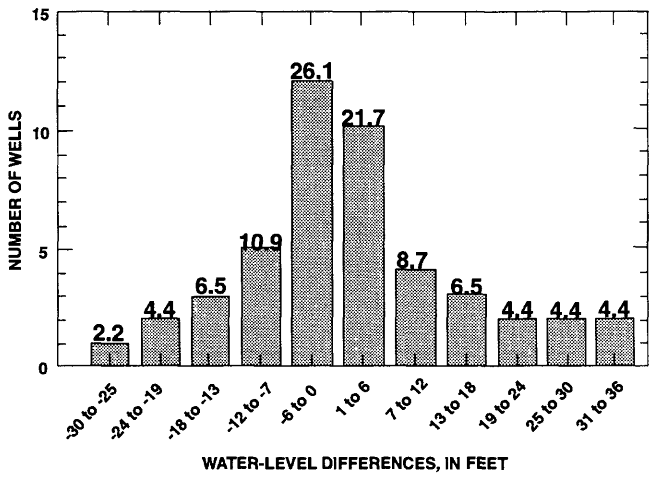


Figure 4.2.3.1-1. Difference between measured and simulated water-level change at selected wells, 1972–81. Value above bar indicates percentage of total wells in class.

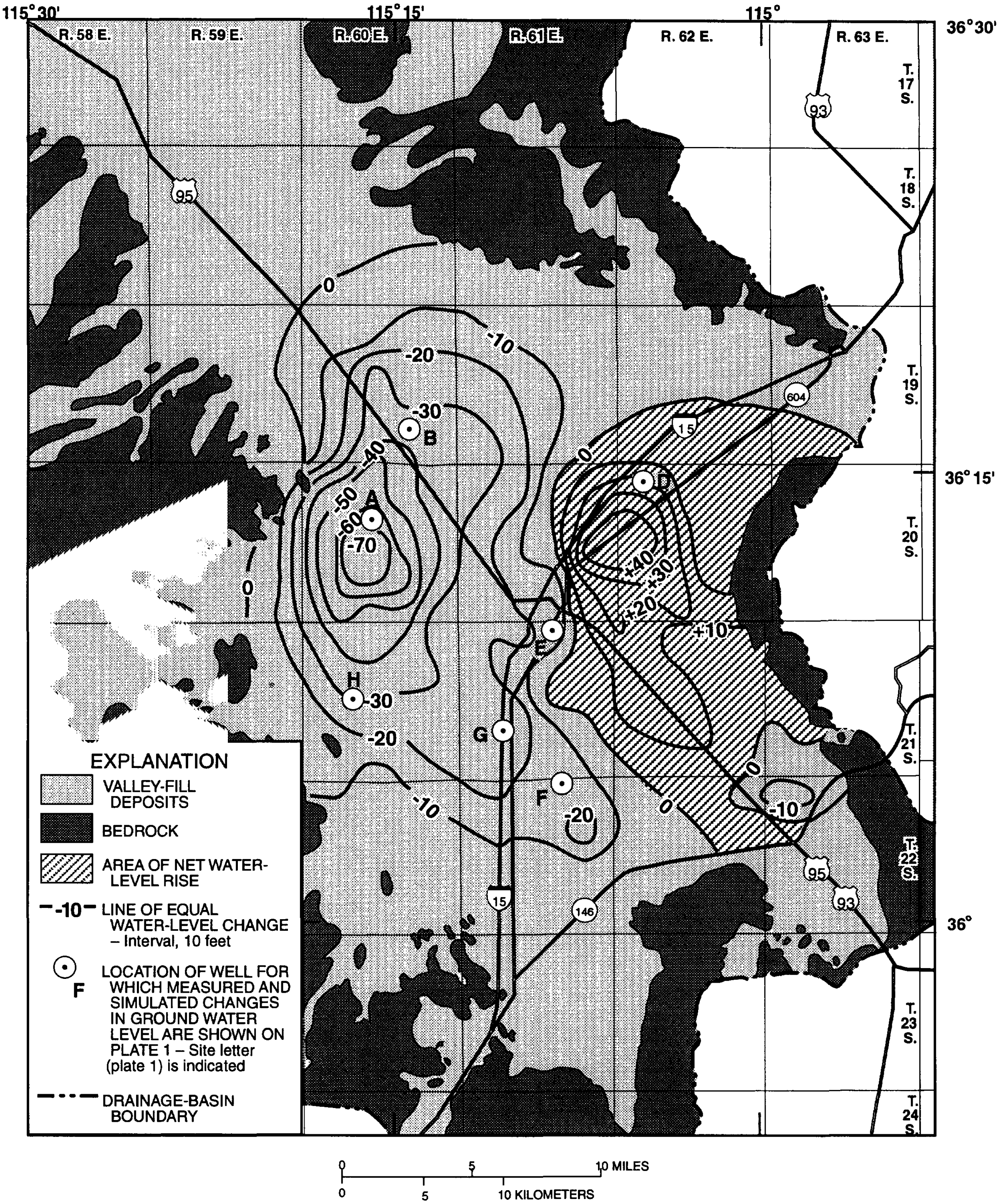


Figure 4.2.3.1-2. Simulated water-level changes in developed-zone aquifers, 1972–81.

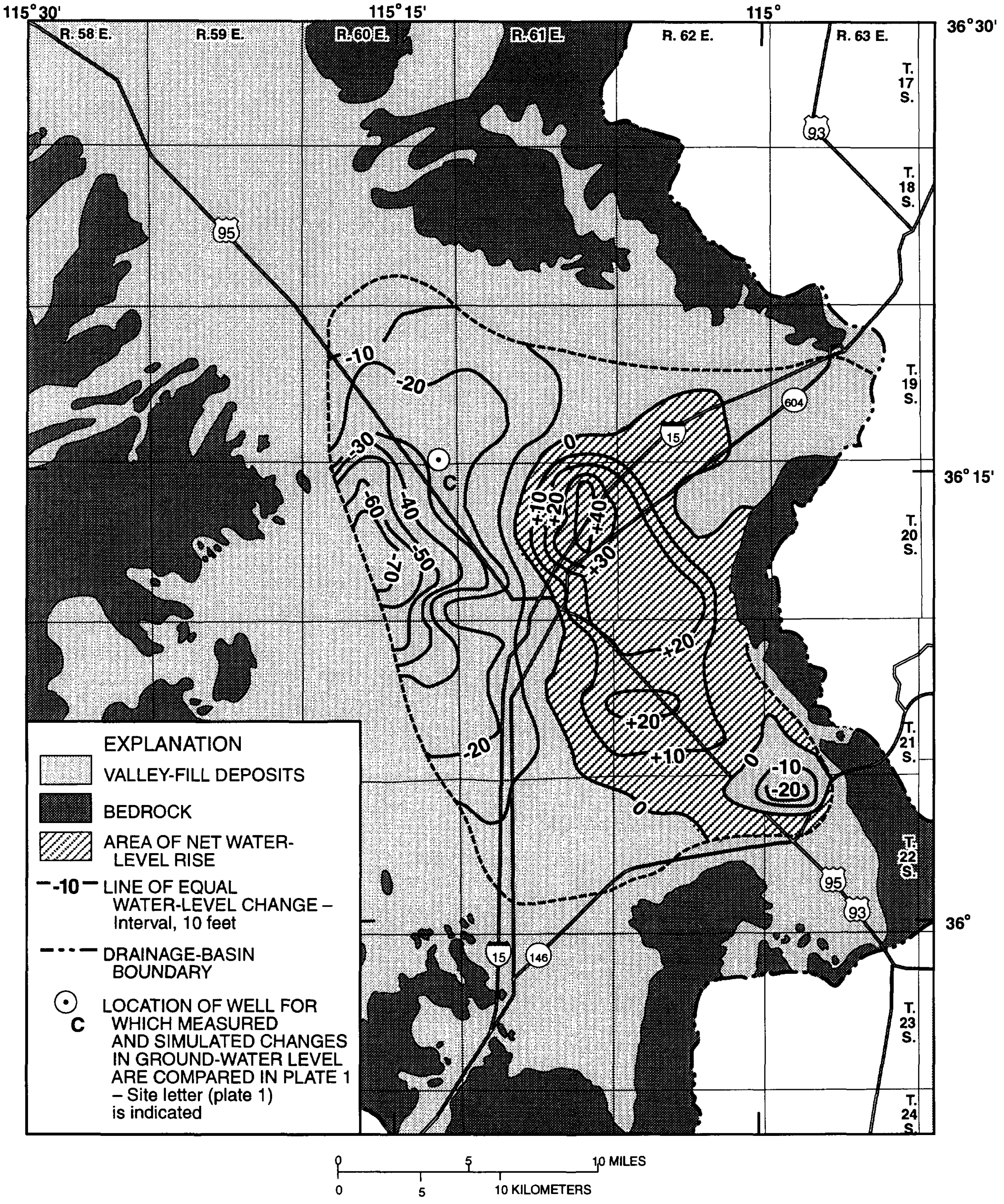


Figure 4.2.3.1-3. Simulated water-level changes in near-surface aquifers, 1972–81.

4.2.3.2 Storage Depletion

Ground-Water Storage Changes Reflect Pumping and Irrigation Periods and Conditions

The percentage of pumpage supplied by storage depletion was smaller between 1972 and 1981 than between 1912 and 1972 because of increased secondary recharge. Seasonal fluctuations in storage in the near-surface aquifer and developed-zone aquifers reflect the interaction of pumping and secondary recharge.

Substantial volumes of water, about 190,000 acre-ft, were removed from storage in the aquifers beneath Las Vegas Valley during 1972–81. The developed- and deep-zone aquifers contributed about 100,000 acre-ft from storage and the near-surface aquifers contributed about 90,000 acre-ft. The simulated volume of ground water removed from elastic storage was 112,000 acre-ft basinwide (about 39,000 from the developed-zone and deep-zone aquifers, and about 73,000 from the near-surface aquifers) and additional 78,000 acre-ft was released by inelastic compaction of fine-grained sediments. These storage depletions together account for 30 percent of the 620,000 acre-ft of pumpage during this period; the remainder of the pumpage was supplied principally by natural and secondary recharge. During the period 1912–72, storage depletion supplied 50 percent of pumpage. The decreasing percentage of pumpage that is supplied by storage depletion in the 1972–81 simulation period reflects an increase in secondary recharge rates from about 30,000 acre-ft/yr in 1972 to 46,000 acre-ft/yr in 1981. Increases in secondary recharge are due to suburban growth and larger imports of water from Lake Mead after 1972.

Figure 4.2.3.2-1*A* shows the simulated monthly rates of change in storage for the near-surface, deep-zone, and developed-zone aquifers from June 1972 through May 1981. This figure illustrates the seasonal changes in ground-water storage caused both by pumping in the developed-zone aquifers and by secondary recharge to the near-surface aquifers. During the summer, storage in the developed-zone aquifers is depleted by heavy pumping; at the same time, outdoor water use is contributing sufficient infiltration to the near-surface aquifers to cause an increase in the volume of stored water. As pumping rates and outside water use decrease in the fall and winter, downward leakage from the near-surface aquifers to the developed-zone aquifers causes storage depletion in the near-surface aquifers and reduced depletion or small gains in storage in the developed-zone aquifers. Figure 4.2.3.2-1*B* shows that the long-term result of these seasonal changes in storage is a net decline in ground-water stored in both shallow and deep aquifers.

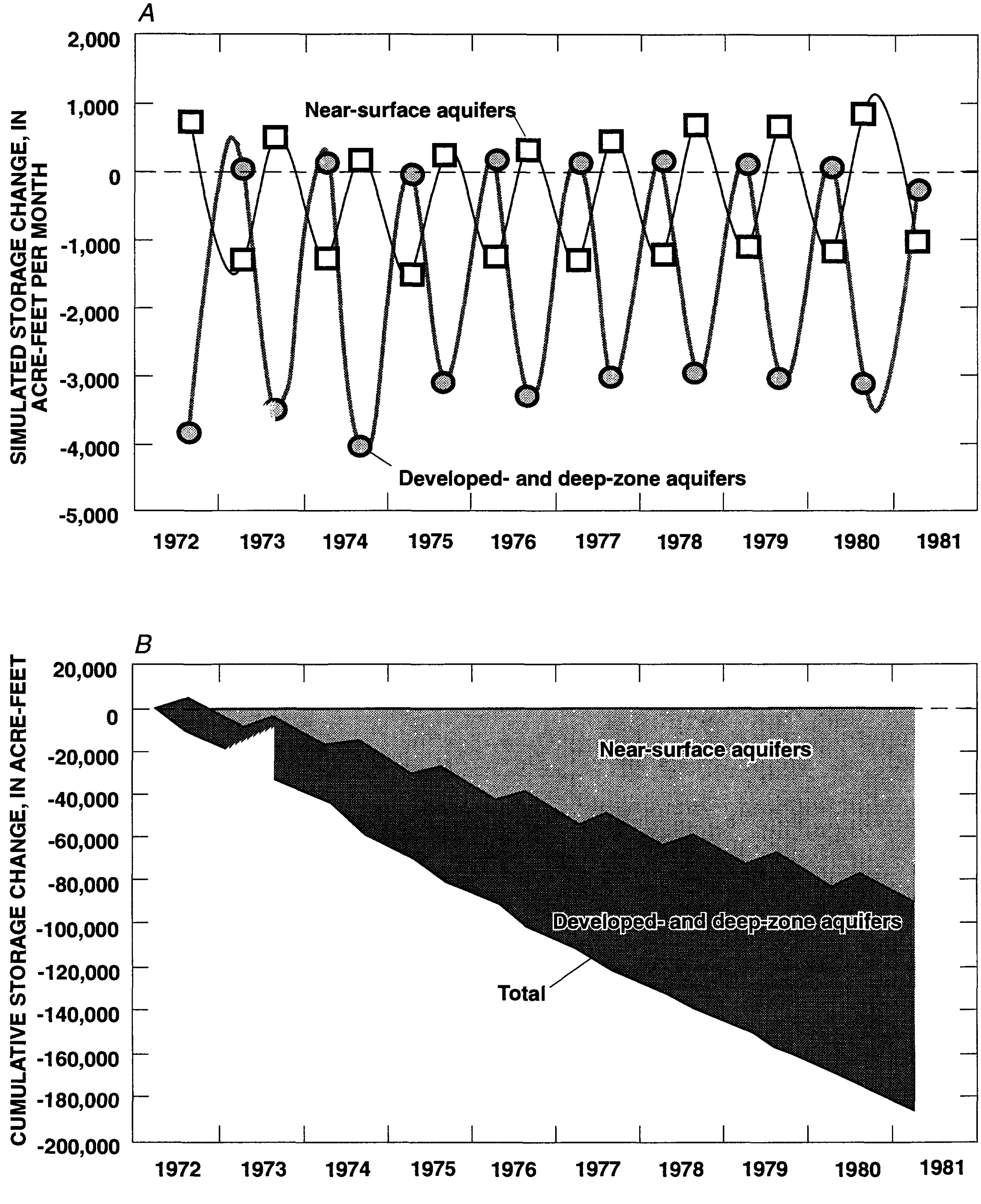


Figure 4.2.3.2-1. Simulated changes in storage, 1972–81. *A*, Monthly rates; *B*, cumulative declines. In *A*, symbols are calculated values; curves are interpolated values. Negative values indicate storage depletion.

4.2.3.3 Subsidence

Land Subsidence Continued Despite Reduced Pumpage

Land subsidence related to ground-water withdrawal continued during the period 1972–81. Local subsidence maximums of 0.6, 0.8, and 1.0 ft were measured near the locations of pre-1972 subsidence maximums.

Measured land subsidence between 1972 and 1980 is shown in figure 4.2.3.3-1. The areal distribution was interpreted from level lines surveyed by the Nevada Department of Transportation in 1972 and by the National Geodetic Survey in May and June of 1980. Bell (1981, fig. 24) reported the 1980 data and recalculated all altitude changes relative to a benchmark set in bedrock near the mouth of Lee Canyon; these recalculated altitudes were used to construct figure 4.2.3.3-1.

The area affected by subsidence in 1980 (200 mi^2) had grown considerably from that affected in 1972 and, according to Bell (1981, p. 47), was twice the area affected in 1963. Pre- and post-1972 subsidence patterns are similar. The greatest subsidence measured since 1972, however, has been near the northeast corner of T. 20 S., R. 60 E., in the vicinity of the City of North Las Vegas well field. This reflects a shift from the center of Las Vegas (near the intersection of Fremont Street and Las Vegas Boulevard), where the greatest subsidence had previously been recorded. This trend, which was first detected after a 1963 releveling (Bell, 1981, p. 47), apparently was the result of relocation of major pumping centers to the more permeable sediments north and west of downtown Las Vegas. Secondary subsidence bowls near The Strip and at the Nellis Air Force Base well field (north and northeast parts of T. 20 S., R. 61 E.) also continued to develop between 1972 and 1980. These changes could not be well delineated because the 1980 survey did not include previously surveyed east-west lines along Craig and Flamingo Roads.

Simulated subsidence generally exceeded measured subsidence in areas where leveling data were available, as shown in figures 4.2.3.3-1 and 4.2.3.3-2. However, the general shape and extent of the anomaly were well reproduced by the model. More important, the location and magnitude of the subsidence maximums matched well. Although the computed maximums are within approximately 0.4 ft of the measured maximums, the total valley-wide volume of subsidence computed by the model was 78,000 acre-ft, compared with an estimate of 50,000 acre-ft based on lines of equal subsidence in figure 4.2.3.3-1. Compaction of fine-grained beds within the developed-zone aquifers contributed 61,000 acre-ft to the model-generated total, while 17,000 acre-ft were derived from the near-surface aquifers.

The simulated valley-wide rate of compaction declined somewhat steadily from 8,300 acre-ft/yr in 1972 to 4,500 acre-ft/yr in 1980. Large seasonal water-level fluctuations within the developed zone induced similar fluctuations in the rate of compaction. In the near-surface aquifer, the compaction rate remained relatively steady seasonally. The simulated seasonal rates of release of water due to compaction from both the developed-zone and the near-surface aquifers are shown in figure 4.2.3.3-3.

Subsidence rates have not declined uniformly throughout the valley. In fact, evidence shows that they have remained constant in at least one area. During the period 1974–81, casing-separation measurements at well S20 E61-17CDBB1 show that compaction continued at a nearly constant rate of 0.2 ft/yr during that period (James R. Harrill, U.S. Geological Survey, written commun., 1981). Pumping rates within 2 to 3 mi of this well have declined only slightly, and the water level has declined 60 ft at a fairly constant rate during the same period.

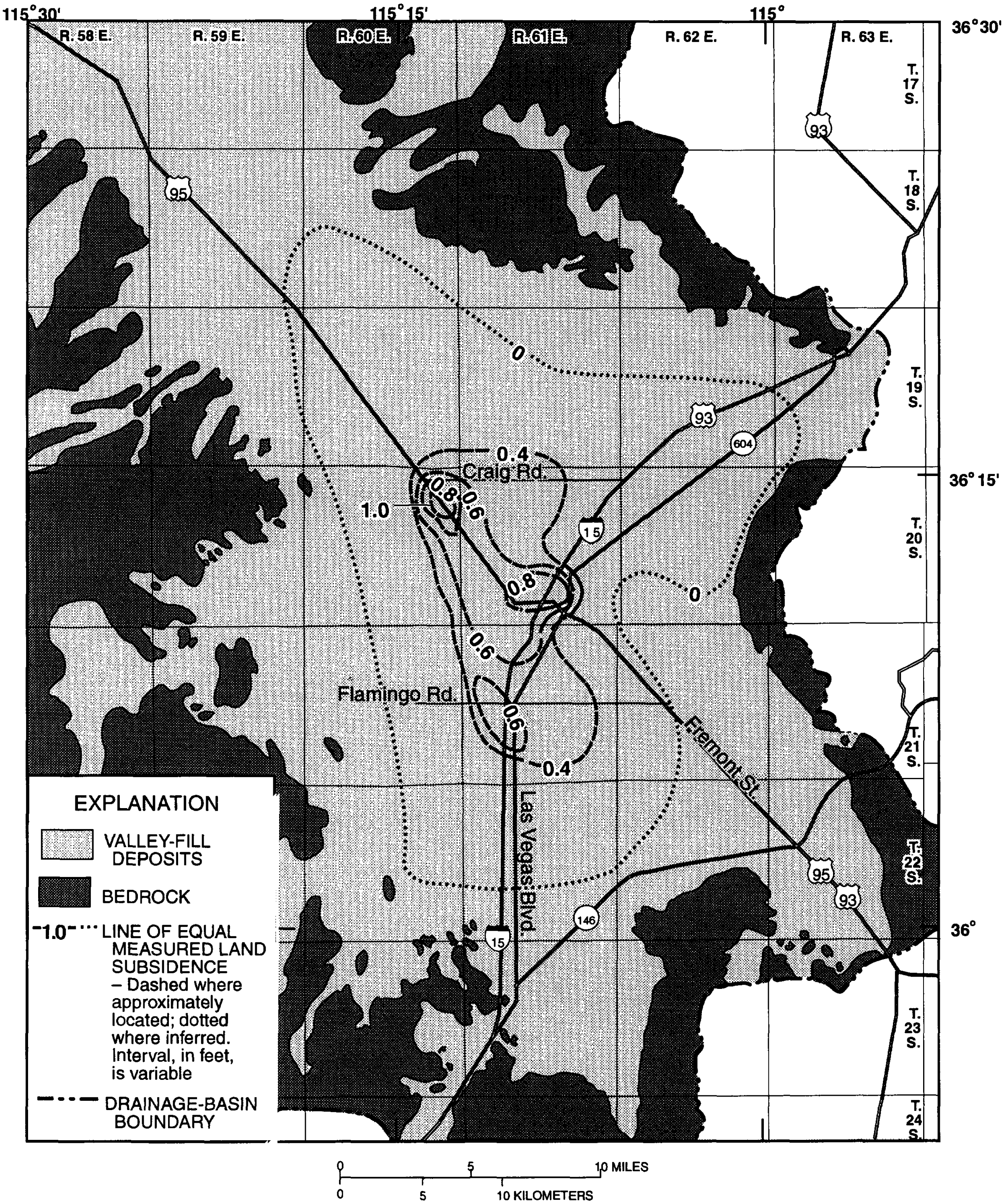


Figure 4.2.3.3-1. Approximate measured land subsidence, 1972–80. Based on data collected by Nevada Department of Transportation in November 1972 and by National Geodetic Survey in 1980.

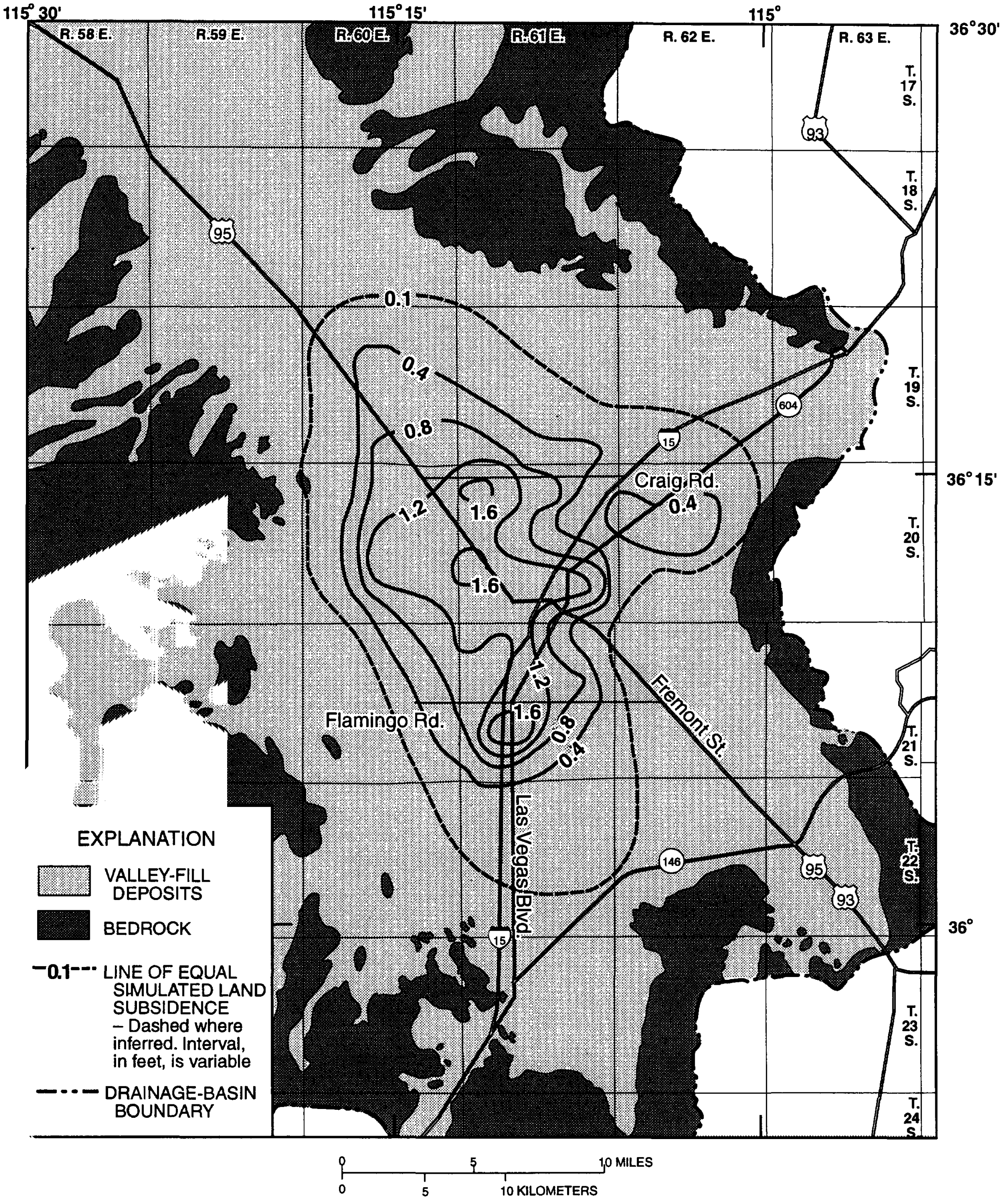


Figure 4.2.3.3-2. Simulated land subsidence, 1972–81.

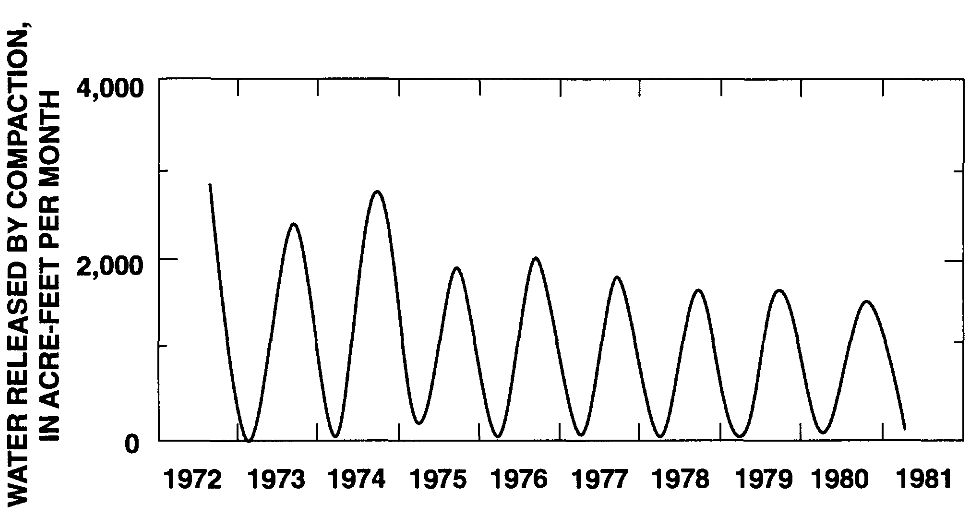


Figure 4.2.3.3-3. Simulated rates of release of water from storage due to compaction, 1972–81.

4.2.3.4 Ground-Water Movement and Discharge

Urban Growth, Surface-Water Imports Alter Hydrology of Near-Surface Aquifers

Evapotranspiration by phreatophytes has been reduced by urbanization; however, discharge by seepage to washes has steadily increased due to rising water levels in the near-surface aquifers.

Pronounced changes in the ground-water flow regime of Las Vegas Valley began during 1972, the first full year of operation of the SNWP. These changes resulted primarily from the 15,000-acre-ft/yr reduction in pumping, which was made possible by the availability of additional imported water. Water levels rose as much as 10 to 15 ft in the developed-zone aquifers from February 1972 to February 1973 (Harrill, 1976b, fig. 6). Lesser recoveries occurred over a large area of central, east, and southeast Las Vegas Valley. These trends in water level were relatively short-lived, however, and reversion to pre-1972 rates of water-level decline first became evident in 1975, when a year-round depression and ground-water divide formed just east of the main well field of the LVVWD (Harrill, 1976a, p. 43). Vertical gradients in the downward direction continued to develop in magnitude and extent.

Figure 4.2.3.4-1*A* shows the simulated monthly rates of vertical flow between model layers. The widest range in seasonal rates is for vertical flow into or out of the near-surface aquifers. These rates are equivalent to evapotranspiration plus seepage, minus secondary recharge. The wide range is due to large seasonal fluctuations in the amount of secondary recharge from lawn irrigation. Downward leakage to the developed-zone aquifers occurred year-round between 1972 and 1981; however, calculated rates reached maximums during the peak-pumping summer months and minimums during the intervening low-demand periods. Seasonal variation also is shown in rates of vertical flow between the deep- and developed-zone aquifers; maximum upward flows from the deep-zone aquifers coincide with the peak-pumping seasons.

The simulated seasonal rates of discharge by evapotranspiration and by seepage to washes and drains are shown in figure 4.2.3.4-1*B*. Between 1972 and 1981, about 190,000 acre-ft of ground water was discharged from the near-surface aquifers in nearly equal proportions by evapotranspiration and seepage, while about 340,000 acre-ft of secondary recharge infiltrated to the water table.

The total area in the model receiving secondary recharge increased considerably in 1972, probably because the pre-1972 secondary recharge area was underestimated due to incomplete land-use data. This resulted in a pronounced decrease in the computed rate of evapotranspiration between the end of the 1912–72 simulation and the start of the 1972–81 simulation due to the method used to account for phreatophyte removal in developed areas (section 3.2.1). Computed evapotranspiration rates declined from 13,000 acre-ft/yr in 1972 to 10,000 acre-ft/yr in 1980, but showed little seasonal variation. Actual seasonal variations probably are greater than indicated by the computations; for modeling purposes, however, the potential rate of evapotranspiration was assumed to be constant. Thus, seasonal variation in evapotranspiration was related solely to variations in the depth to water, and not to variations in potential evapotranspiration rates.

The seepage rate increased both seasonally (during the periods of peak demand) and annually over the calibration period (fig. 4.2.3.4-1*B*), as the rate of secondary recharge increased. By 1980, about 13,000 acre-ft/yr of near-surface ground water was discharging to the major washes. Most of this discharge was along the lower reaches of Las Vegas Wash and Duck Creek. Discharge to Flamingo and Tropicana Washes and the upper part of Las Vegas Wash is much more dependent on seasonal increases in secondary recharge, whereas seepage rates to lower Las Vegas Wash and Duck Creek are relatively constant year-round. In the early 1970's, when industrial wastewater disposal in the Henderson area was mostly to unlined ponds, nearly all seepage was to the lower Las Vegas Wash. When the waste ponds were lined and water use in the valley increased in conjunction with population increases, a larger proportion of the total seepage occurred in the upper reaches of Las Vegas Wash as well as Flamingo and Tropicana Washes, and it was more seasonally variable.

Estimated ground-water seepage to washes in 1973 was about 16,000 acre-ft, on the basis of water budgets for the near-surface aquifers by Patt (1978, fig. 11; see table 2.3.2-1). Model-simulated seepage was in fair agreement at about 10,000 acre-ft annually. From 1972–81, the simulated seepage increased to about 14,000 acre-ft/yr and varied seasonally between 850 acre-ft/mo during the low-demand period and 1,300 acre-ft/mo during the peak-demand period. The curve showing the simulated rate of seepage to washes in figure 4.2.3.4-1*B* follows the trend and seasonal character of secondary recharge shown in figure 4.2.1-1*B*. This relation is not coincidental; as water levels rise in the near-surface aquifers in response to increasing volumes of secondary recharge, the channels of washes and drains intercept the rising water table at points farther upstream, and seepage thereby occurs over a larger area. Future modeling may require that additional grid cells, at upstream reaches, be specified as "stream cells" (see section 3.2.3) to accurately simulate this condition.

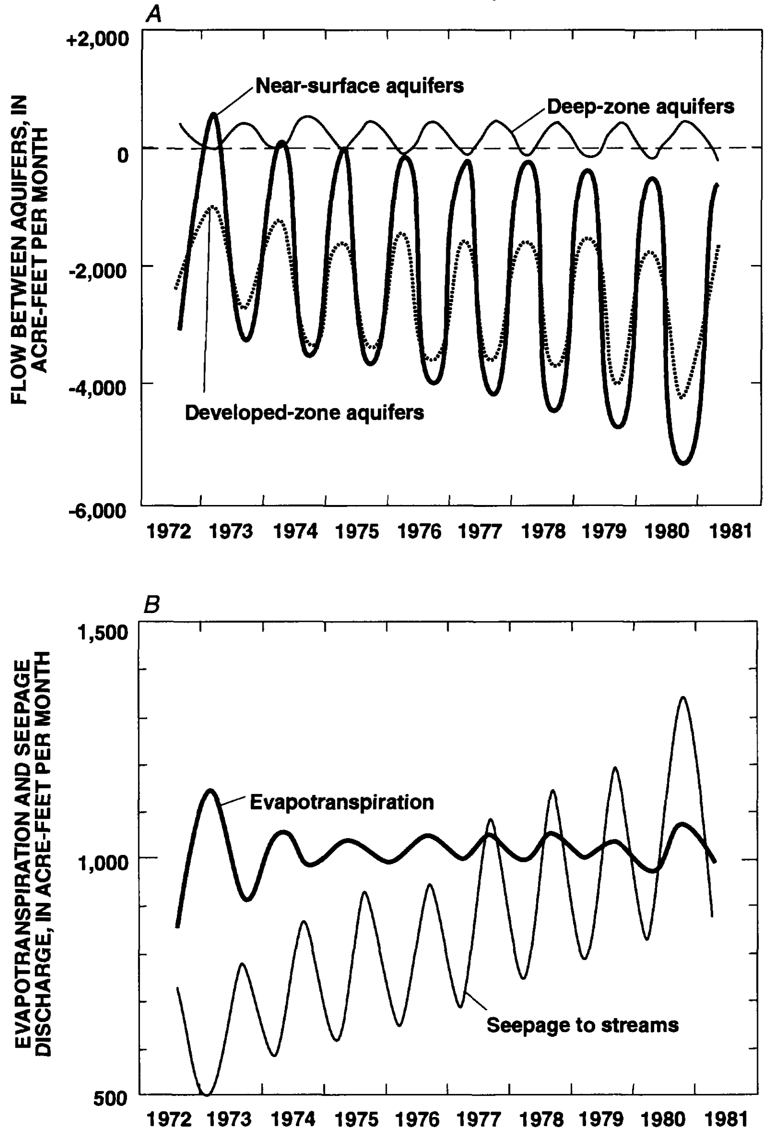


Figure 4.2.3.4-1. Simulated ground-water movement and discharge, 1972–81. *A*, Upward (+) and downward (–) flow between aquifers (shows net flow across upper boundary of indicated aquifer). *B*, Evapotranspiration and seepage to streams.

5.0 SIMULATION OF FUTURE CONDITIONS

Computer models are valuable tools in ground-water resource appraisals—helping the hydrologist to develop conceptual models of flow systems, to evaluate available data, and to design effective data-collection plans. As an investigative tool, the model is used to reproduce historical flow conditions; the model becomes a predictive tool when used to simulate future conditions.

The purpose of the following sections is to (1) demonstrate the use of the model developed for this study as a predictive tool, (2) point out the sources of error in and limitations on the predictive use of the model, and (3) present suggestions for further study of the hydrogeologic system that would improve the predictive capability of the model.

5.0 SIMULATION OF FUTURE CONDITIONS—Continued

5.1 Example: Ground-Water Use Primarily for Peak Demand Only

5.1.1 Description of Aquifer-Management Scenario

Seventy-Eight Percent of Total Pumpage Assumed to be Withdrawn During Summer

Predictions were made of hydrogeologic response to the following scenario: (1) total annual ground-water withdrawals and secondary recharge were assumed to remain constant at 1980 rates, and (2) ground-water withdrawals equal to the Las Vegas Valley Water District's permanent water right (39,400 acre-ft/yr) were assumed to be made between June and mid-September to meet peak water-use demand.

Satisfying the peak seasonal and daily water demands has been cited as "the real near-term water supply problem in southern Nevada" (URS Company and others, 1983, p. 9). Ground water has been identified as the best alternative for supplying the part of the peak demand that exceeds the capacity of the SNWP. Principal components of one strategy for long-term ground-water management that has been suggested for the valley are (1) dedication of municipal ground-water resources to periods of peak demand and (2) reduction of the total annual extraction from the developed-zone aquifers to a maximum of 50,000 acre-ft/yr (URS Company and others, 1983, p. 284).

The model developed for this study was used to simulate the hydrogeologic effects of the first component: using LVVWD wells only during the peak seasonal demand period, from June 1 through September 20, to supplement SNWP supplies. This mode of operation was simulated for 9 years using model-computed water levels for May 1981 as initial conditions. A simulation period of 9 years was chosen to allow direct comparison of results from this simulation to results of the 9-year, 1972–81 calibration period described in section 4.2.3.

For the simulation, annual ground-water pumpage from the valley was held constant at the 1980 level of 71,000 acre-ft. LVVWD wells were allowed to pump for 110 days (June 1–September 20) each year at a constant rate that yielded a total of nearly 40,000 acre-ft. The locations of model-grid cells containing LVVWD wells, and the assumed peak-season production from each cell, are shown in figure 5.1.1-1. This production scheme is not necessarily feasible to implement with the wells and distribution system that existed in 1981. For this simulation, however, each well was assumed to be capable of producing its entire 1980 pumpage volume within the 110-day peak period. This amount (40,000 acre-ft) approximates the average annual pumpage for the LVVWD during 1975–80 as well as their total permanent water right (39,400 acre-ft/yr).

The remaining 31,000 acre-ft/yr of non-LVVWD pumping was distributed seasonally according to average monthly pumpage data from the LVVWD during 1978–80. Accordingly, about 15,500 acre-ft (50 percent) of all non-LVVWD pumping was assumed to occur between June 1 and September 20 each year.

Secondary recharge also was assumed to remain constant annually at the estimated 1980 rate (about 45,000 acre-ft/yr). The seasonal distribution of secondary recharge was assumed to be closely related to the seasonal distribution of residential outdoor water use. In 1979, about 56 percent of outdoor water use was between June 1 and September 20 (URS Company and others, 1983, table B-3). Thus, roughly 25,000 acre-ft of secondary recharge was assumed to occur during each period of peak water demand.

All other model input data developed from the 1972–81 calibration period were used for this predictive simulation.

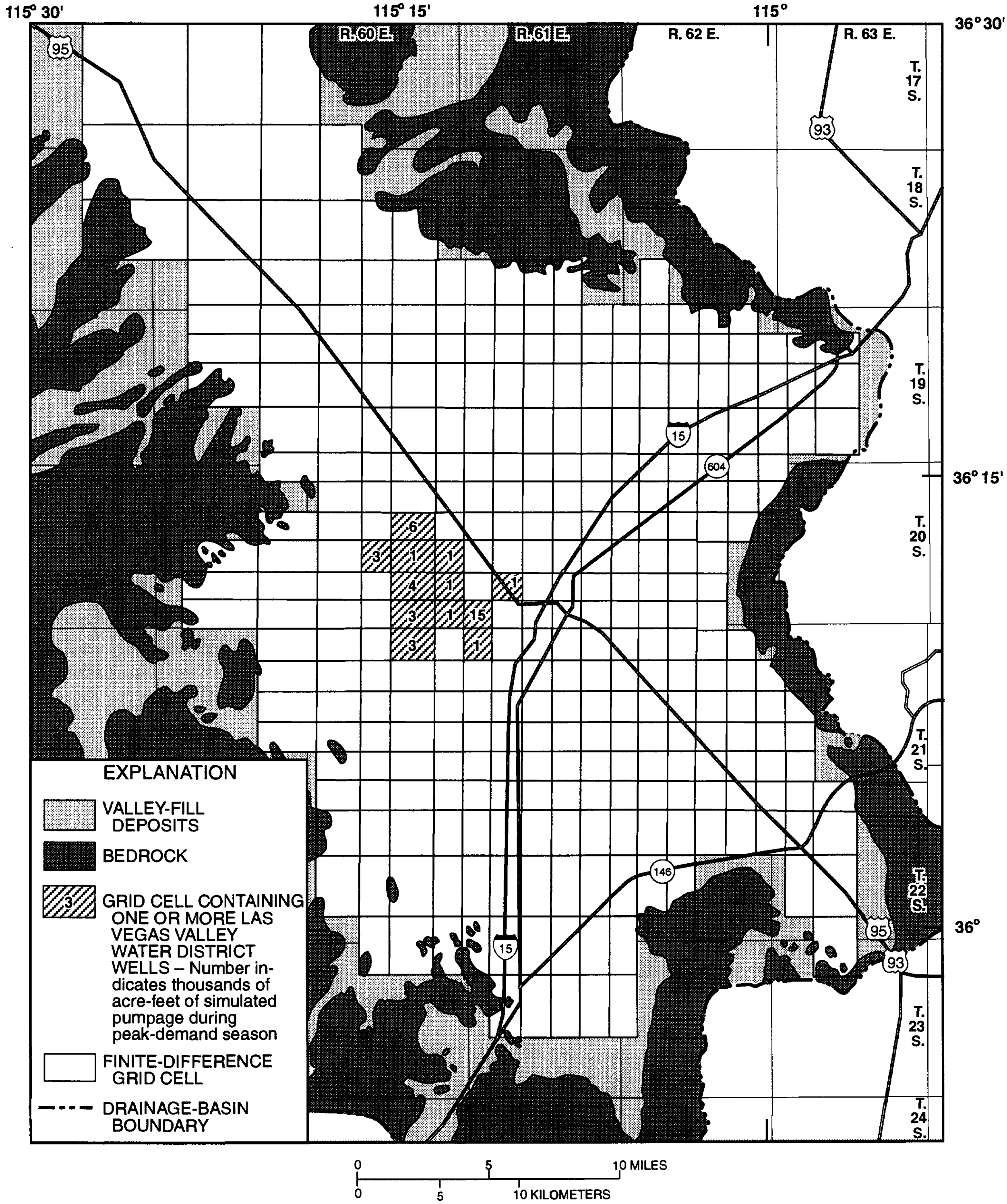


Figure 5.1.1-1. Simulated Las Vegas Valley Water District pumpage during peak-demand season.

5.1.2 Results of Simulation

Rates of Water-Level Decline and Subsidence Reduced

Simulation results show that using LVVWD wells only during peak-demand season would increase seasonal water-level changes, but would reduce the rate of annual water-level decline in some areas. The rate and annual volume of subsidence also would decrease, but seepage to washes and drains would increase by 40 percent.

The objective of this simulation is to demonstrate the use of the computer model as a predictive tool. The aquifer-management scenario is intended to provide insight into the hydrologic effects of altering the timing of ground-water withdrawals by the LVVWD. In this section, results of the simulation are presented and, in some cases, compared with the effects of ground-water development during 1972–81. Differences between the simulated effects for 1972–81 and those for this 9-year predictive simulation cannot be wholly attributed to the seasonal timing of ground-water withdrawals for the following two reasons:

First, annual pumping rates varied during 1972–81, ranging from 69,000 to 78,000 acre-ft/yr; in contrast, the rate assumed for this simulation is constant at about 71,000 acre-ft/yr. Coincidentally, however, total withdrawals for the 9-year period 1972–81 and for this 9-year predictive simulation are equal (620,000 acre-ft).

Second, estimated secondary recharge varied from 30,000 to 46,000 acre-ft/yr during 1972–81, whereas the 1980 rate (45,000 acre-ft/yr) is used for the entire 9-year predictive simulation. As a result, there is 18 percent more secondary recharge during the 9-year simulation period than during 1972–81.

The simulated water-level changes in the developed-zone aquifers and near-surface aquifers during the 9-year scenario are shown in figures 5.1.2-1 and 5.1.2-2. The changes were calculated by subtracting the computed water levels, after 9 years, from the computed May 1981 initial conditions. Note that these figures show the computed changes in water levels at their peaks during the year—in the early spring before heavy pumping begins. The simulated water-level changes in selected cells during the 9-year period are shown in plate 2.

In the management scenario used in this simulation, summer pumping in the LVVWD well fields is much greater than that during the summers of 1972–81. In this scenario, proportionately less pumping is simulated during the remainder of the year, resulting in a wider range of seasonal water-level changes. Computed springtime water levels in the developed-zone aquifers after 9 years are as much as 30 ft higher than those computed for May 1981 in a large area in southeast T. 20 S., R. 60 E. (fig. 5.1.2-1). Many LVVWD wells are in this area and the simulation projected severe effects in the area as a result of this seasonal redistribution of pumping. The apparent rise in water levels in this area actually results from the wide range of seasonal water level fluctuations and because seasonal maximum water levels were used to construct figures 5.1.2-1 and 5.1.2-2. If, instead, seasonal minimum water levels (which occur at the end of the summer pumping period) had been used to construct the figures, a decline would have been indicated in the same area. Inspection of computed hydrographs for this area (cell H in pl. 2) shows a net decline in average annual water levels of 20 to 30 ft in that area for the 9-year period.

Larger net declines are predicted in the west half of T. 20 S., R. 60 E., the southwest part of T. 19 S., R. 60 E., and the northwest part of T. 21 S., R. 60 E. These areas are west of the most highly urbanized parts of the valley, and projected water levels there are not sustained by vertical leakage of secondary recharge to the extent that they are farther east. The greatest net water-level rises predicted in the developed zone for the 9-year period are in the eastern part of the valley, where downward leakage from the near-surface aquifer resulted in net rises of 10 to 20 ft (pl. 2, fig. 5.1.2-1). Within this area, in the eastern half of

T. 20 S., R. 61 E., water levels recovered 20 to 40 ft during 1972-81, primarily in response to reduced pumping.

Comparison of figures 4.2.3.1-2 and 5.1.2-2 indicates that the pattern of water-level changes predicted in the near-surface aquifers is similar to that for the 1972–81 period. Large declines may be induced on the west edge of the near-surface aquifers as a result of heavy pumping in the underlying developed-zone aquifers and limited replenishment by secondary recharge. Concentrated secondary recharge in the southeast part of T. 20 S., R. 61 E., continues to cause rising water levels (fig. 5.1.2-1). The seasonal maximum levels (fig. 5.1.2-2) show a net rise of more than 30 ft for the 9-year predictive period.

Predicted cumulative ground-water seepage to washes and drains is 120,000 acre-ft for the 9-year period, which is about 40 percent more than the estimated total during 1972–81. This increase is largely unrelated to the seasonal redistribution of LVVWD pumping. Instead, the increase mostly reflects the greater total secondary recharge in the 9-year scenario than in the simulation of the 1972–81 period. Secondary recharge in the 9-year scenario was assumed equal to the 1980 rate for each of the 9 years, whereas the secondary recharge assumed in the 1972–81 simulation gradually increased throughout the period (fig. 4.2.1-1*B*).

Estimated rates of evapotranspiration did not change significantly from those of 1972–81. The computed average annual rate in the predictive scenario was 11,000 acre-ft/yr. An assumption of the model is that maximum potential evapotranspiration rates in Las Vegas Valley are controlled by the degree of urbanization and not by the water-table depth alone. By the end of the 1972–81 simulation, calculated maximum potential evapotranspiration rates had been reduced to minimum values. (See the explanation of the assumed inverse relation between potential evapotranspiration rates and urbanization in section 3.2.1.)

The predicted total volume of water released by compaction of fine-grained beds is 42,000 acre-ft. This is only 54 percent of the computed total for 1972–81. Maximum cumulative subsidence of the land surface occurs in the heavily pumped LVVWD well fields, but totals only 0.8 to 1.0 ft, compared with computed maximums of 1.2 to 1.6 ft during 1972–81. Model-predicted subsidence is less than that for the 1972–81 period because (1) preconsolidation stresses are exceeded for a shorter period when all LVVWD pumping is during the peak-demand summer months and (2) net declines for this predictive simulation are less.

In summary, predictive simulation indicates the following changes in ground-water conditions after 9 years as a result of using LVVWD wells only to satisfy seasonal peak demand: (1) water-level declines would continue on the west side of the valley in the developed-zone and near-surface aquifers, but at a slower rate than those of 1972–81; (2) the range of seasonal water-level changes would increase in the vicinity of LVVWD well fields; and (3) subsidence would be reduced by as much as 50 percent.

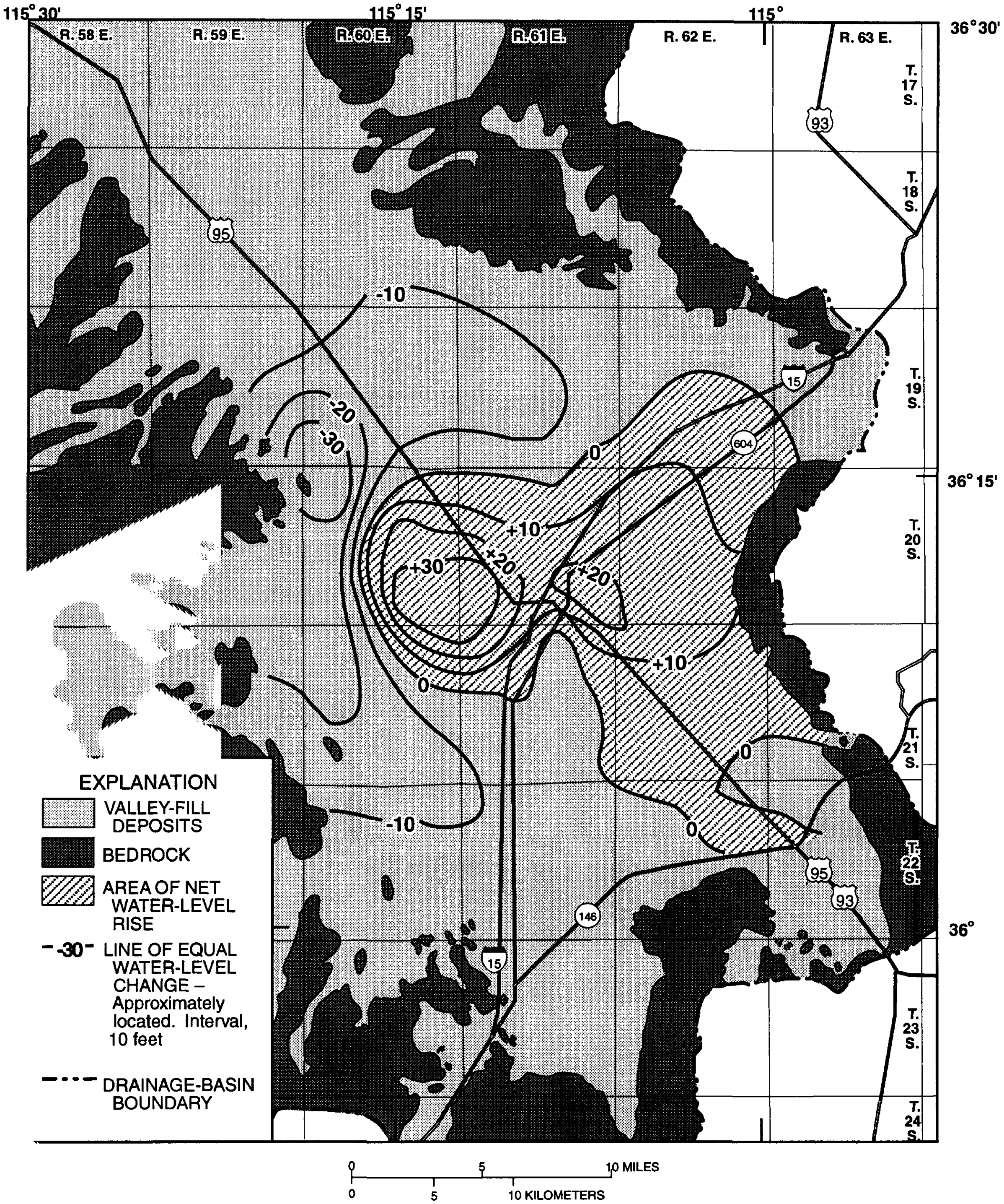


Figure 5.1.2-1. Simulated water-level changes in developed-zone aquifers after 9 years of Las Vegas Valley Water District pumpage for peak demand only.

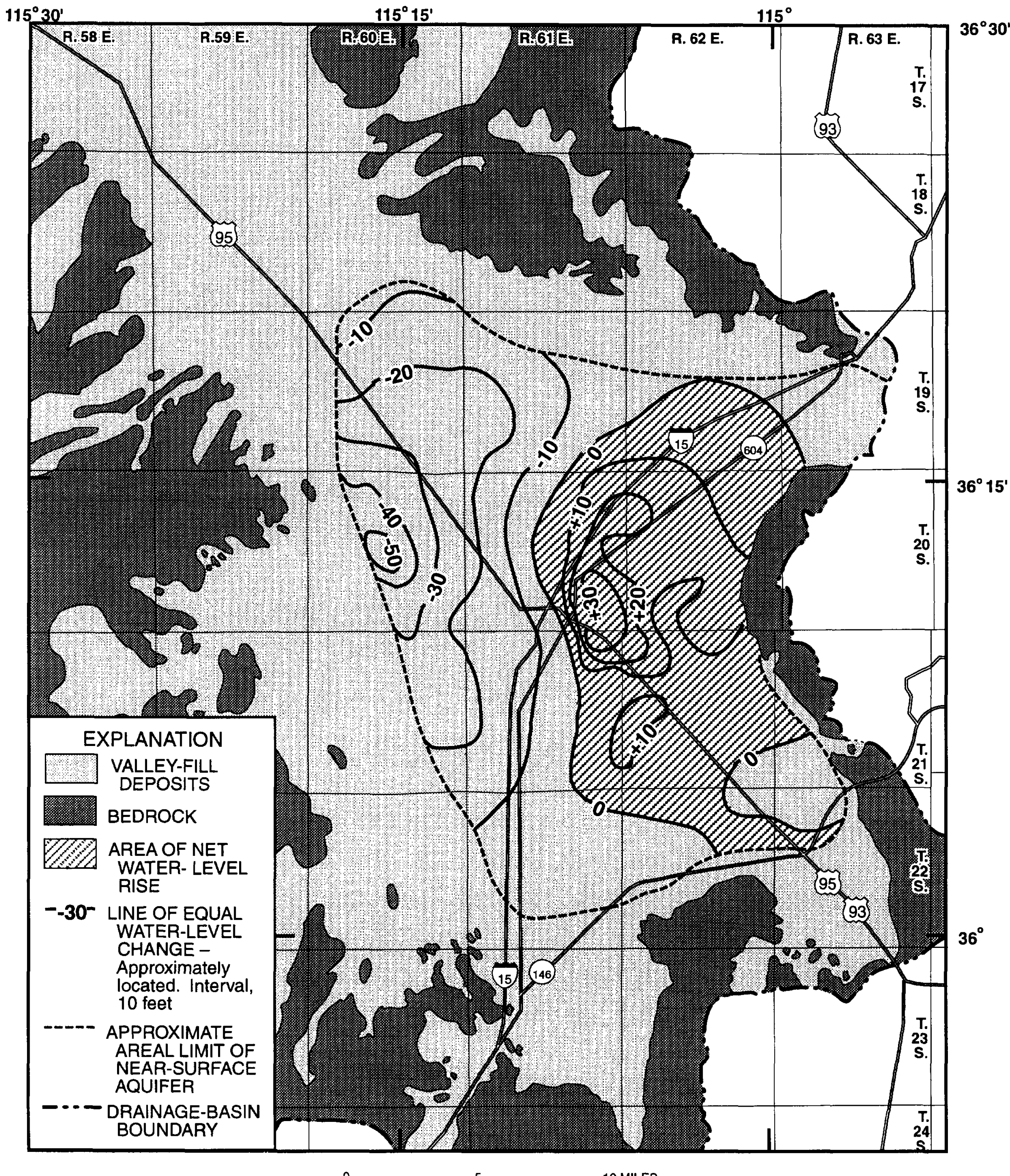


Figure 5.1.2-2. Simulated water-level changes in near-surface aquifers after 9 years of Las Vegas Valley Water District pumpage for peak demand only.

5.2 Sources of Error and Model Limitations

Principal Sources of Error in Recharge Estimates and Observed Water-Level Altitudes

The predictive accuracy of the model is diminished by errors associated with the conceptual model of the system, the computational scheme, and the input data. These errors and the limitations they impose on the predictive capability of the model need to be recognized.

To avoid misapplication of the model, it is important to recognize and understand the sources of error and the limitations inherent in this model and in numerical models in general. The deviation of simulated water levels from measured water levels is the result of errors associated with the (1) conceptual model, (2) computational scheme, (3) estimated hydraulic characteristics of the aquifers, (4) estimated water-budget data, (5) estimated initial conditions, and (6) observed water-level altitudes. The relative importance of these sources of error for the predevelopment and postdevelopment models in this study is indicated in figure 5.2-1. The relative importance is judged partly on the basis of experimentation with the model to determine the sensitivity of results to changes in aquifer characteristics, and partly from the reported experience of other investigators (Durbin, 1978, p. 30; Mercer and Faust, 1980, p. 115).

Conceptual errors result mainly from simplifying assumptions used, of necessity, in conceptualizing the aquifer system. The assumptions that are most likely to result in significant errors are: (1) intra-aquifer flow is limited to the horizontal plane; (2) the transmissivities and storage coefficient of the near-surface and developed-zone aquifers are time-invariant; and (3) the boundaries of the aquifer system coincide with the interface between consolidated rocks and unconsolidated sediments.

Errors associated with the computational scheme result from truncation and rounding. Truncation errors can be substantial if the space or time increments used in the algebraic approximations of the differential equations are too large. Round-off errors are introduced due to the finite accuracy of computer calculations. However, the computational scheme is not a serious source of error in the model.

The hydraulic characteristics of the aquifer system include transmissivity, storage coefficient (both elastic and inelastic), specific yield, and vertical leakance. Initial estimates of these characteristics were adjusted during calibration of the model, with the objective of minimizing the deviation of simulated water levels from observed water levels. These adjustments were assumed to improve the initial estimates. Adjustments were constrained so that final values of characteristics remained within reasonable limits.

The hydraulic characteristics derived through calibration are highly dependent on estimated natural recharge, pumpage, and secondary recharge. Errors in these estimates are transferred to the hydraulic characteristics through the calibration process and can be significant.

Simulation of responses to development requires that initial conditions (water levels) be specified. Errors in initial conditions result in errors in the simulated water levels. The magnitude of these errors is rapidly attenuated, however, as duration of the simulation increases.

Field water-level measurements can generally be made with accuracies of ±0.1 ft; this is considerably more accurate than required for most models. Large errors in water-level altitudes, however, probably result from locating wells inaccurately on topographic maps, which results in incorrectly estimated altitude of land surface, and thus, of the water level at the well. Many water-level measurements represent composite water levels because the wells are open to more than one aquifer. Additionally, some measurements may not be representative of static aquifer conditions because of effects of nearby pumping. Finally, extrapolation of contours in areas without data introduces errors. These errors do not contribute to the deviation of simulated water levels from measured water levels; obviously the model can, through calibration, be forced to reproduce the observed water levels. The error introduced by observed water levels contributes to the deviation of simulated water levels from the "true" hydraulic water levels in the aquifer. Observed water level altitudes can be a major source of error in this sense.

The model needs to be used selectively in predictive applications if the reliability of those predictions is to be assumed equal to the reliability achieved during the calibration process. This can generally be assumed if the magnitude and duration of hydrologic stresses are similar to those imposed during postdevelopment calibration (Durbin, 1978, p. 35; Mercer and Faust, 1980, p. 115).

The model for Las Vegas Valley was calibrated using a set of assumptions based on field conditions observed during the calibration period. The continuing validity of those assumptions needs to be re-evaluated for the period of prediction. A good example is the assumption that the transmissivity and storage coefficient of the developed zone in Las Vegas Valley are time-invariant. Future water-level declines in the developed-zone aquifers may invalidate this assumption if large areas change from confined to water-table conditions.

Finally, the mathematical model developed in this study can predict the results of hydrogeologic effects only at a coarse scale. The finite-difference grid represents all features (water levels, hydraulic properties, and fluxes) in cells no less than 6,000 ft on a side. Further analyses and calibration could readily narrow the scale of analysis, but until such calibrations are complete, model predictions should not be misinterpreted as providing more detail than indicated by the current grid.

Many assumptions and approximations are necessary in developing numerical models. In addition, models require input data that commonly are difficult to obtain or estimate. Either of these factors can lead to inaccuracies in model output; therefore, models need to be used with a large measure of subjective technical interpretation. If they are not, grossly inaccurate conclusions may result. Finally, models need to be viewed as just one of a series of tools to be judiciously used by scientists and managers in making decisions.

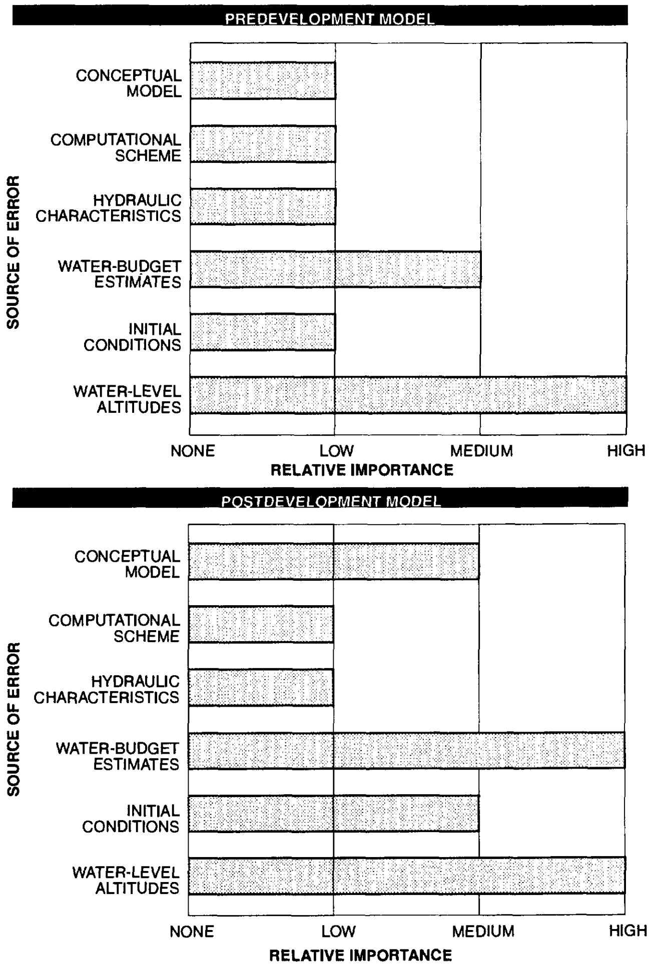


Figure 5.2-1. Relative importance of sources of modeling error.

5.3 Suggestions for Further Study

Near-Surface Aquifers and Bedrock-Alluvium Boundary Candidates for Additional Study

More detailed hydrogeologic characterizations of the near-surface aquifers and the bedrock-alluvium boundary would greatly improve the ability to accurately model the ground-water system in Las Vegas Valley.

One of the important results of this investigation was the identification of hydrogeologic factors that need more detailed study. These factors are identified in figure 5.3-1 and are discussed in this section. Also considered are some possible applications of the model developed for this study to the process of making ground-water management decisions.

Many ground-water problems in the Las Vegas Valley are manifested within the near-surface aquifers. In spite of this, the near-surface aquifers are poorly defined. Historically, the near-surface aquifers have not been considered an important source of drinking water; therefore, little information has been acquired to describe the unit. Some new hydrogeologic data were collected for this study from 29 shallow wells; however, deeper wells and greater areal coverage are needed to define the water-bearing character of the complicated sequences of caliche, sand, gravel, and clay within the upper 200 to 300 ft. The model developed during this study was the first regional-scale, three-dimensional model of the valley-fill aquifers; however, the near-surface aquifers were represented by only two layers of grid cells (for the confined and unconfined portions) due to data limitations. This approach was adequate for approximating the overall ground-water fluxes between the near-surface and developed-zone aquifers, but the approach required an assumption that all flow is horizontal within most of the unit. If more detailed analyses of (1) development of near-surface aquifers and (2) the effects of lawn irrigation and land application of wastewater are to be attempted using this model, an improved description of the near-surface aquifers is necessary. The initial need is for more accurate estimates of the amount and distribution of secondary recharge and pumpage in the near-surface aquifers.

A second, critical area for model refinement is the hydrogeology of the deep-zone aquifers. The deep-zone aquifers were included in this model, but their characteristics were estimated solely by extrapolation of data from the overlying developed-zone aquifers and by model calibration. The model results lacked the sensitivity to define accurately the hydraulic characteristics within the deep-zone aquifers; however, this insensitivity may have been a side effect of assumptions made in the conceptual model.

Ground water from the carbonate-rock aquifer systems of southern Nevada has been identified as a potential supplement to the water supplies of Las Vegas Valley (URS Company and others, 1983, p. 264–265). Evaluations of carbonate-rock aquifers surrounding Las Vegas Valley need to focus on (1) delineating source areas for recharge to the carbonate aquifers, (2) defining flow paths and rates between carbonate and valley-fill aquifers, and (3) quantifying storage capacities of and obtainable water from carbonate aquifers.

A carefully designed, long-term water-quality monitoring network would provide a continuous record of changes in ground-water chemistry in critical areas of the near-surface and developed-zone aquifers. This network could give an early warning of water-quality degradation in the developed-zone aquifers by downward movement of water from the near-surface aquifers. Such a data base also could be used to support future modeling of the transport of ground-water solutes.

An objective of this study was to provide a model that embodied a quantitative understanding of the ground-water system and could be used after the study to evaluate proposed solutions to present and future ground-water problems. The one predictive simulation presented in this report represents a simplistic management alternative in which ground water pumped by the LVVWD is used to satisfy only the peak seasonal water-use demands, with the bulk of the year-round demand being met using SNWP water.

Other questions that would be appropriate applications for the model might involve aquifer yield, well yield, well-field location, pumping schedules, and conjunctive-use alternatives. All these questions may be evaluated on the basis of the simulated effects and the costs of those effects. In Las Vegas Valley, the principal effects are water-level declines, waterlogging, subsidence, and water-quality changes. Given the close relation between land-use type and secondary recharge, the model may be used to evaluate the effects of future development patterns and proposed land-use on the ground-water system.

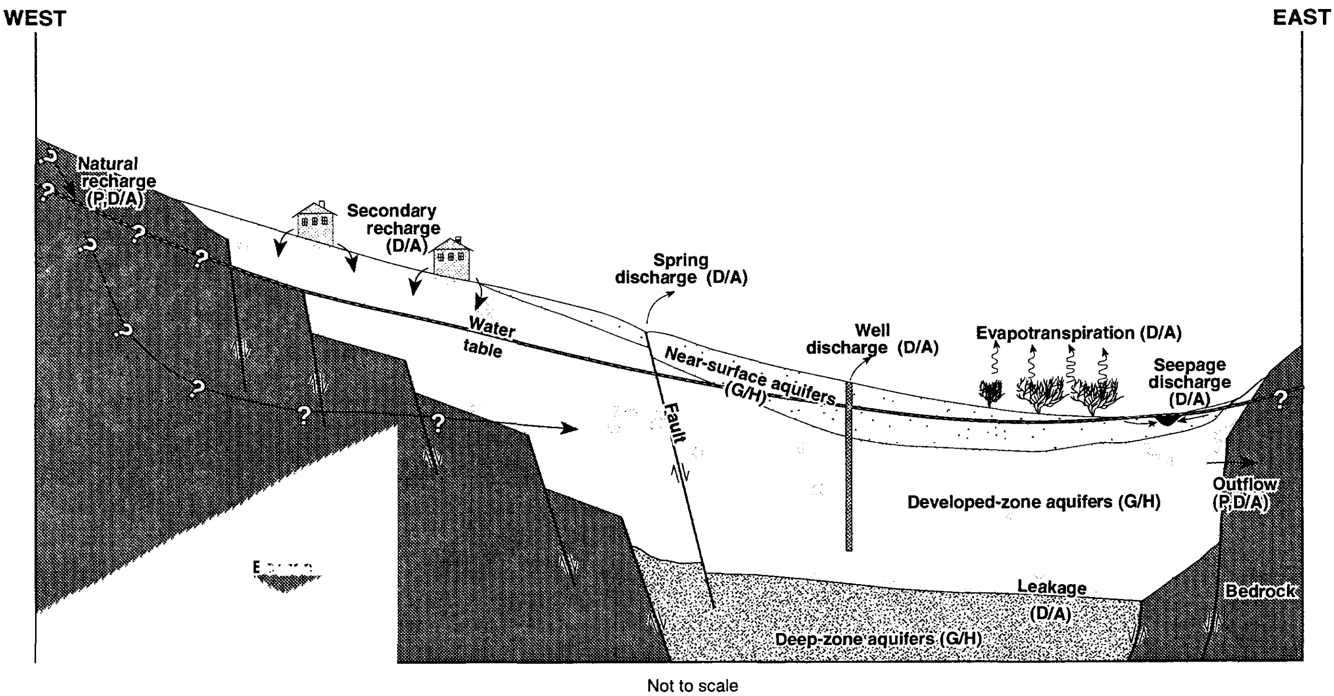


Figure 5.3-1. Aspects of conceptual model of flow system that would benefit from further study. Some aspects involve distribution and amount (*D/A*) of recharge or discharge, some involve geologic and hydrologic characteristics (*G/H*) of the system, and some involve study of processes (*P*) such as recharge.

6.0 SUMMARY

Las Vegas Valley is in Clark County, in southern Nevada. The metropolitan areas of Las Vegas and North Las Vegas lie near the center of the valley. Valley lowlands are surrounded by gently sloping piedmont surfaces, and by mountains that rise 5,000 to 6,000 ft above the valley floor. The valley is drained to Lake Mead on the Colorado River by Las Vegas Wash. The Las Vegas structural basin is filled by as much as 5,000 ft of Miocene and younger sediments. The most productive valley-fill aquifers are on the western side of the valley within the uppermost 1,000 ft of sediments. Beneath much of the central part of the valley, fine-grained sediments within the upper 200 to 300 ft of valley fill are sufficiently abundant to restrict the vertical movement of ground water. This shallow zone is referred to as the near-surface aquifers because it contains lenses of sand and gravel that transmit moderate amounts of water to wells. The deeper, more productive aquifers lie within what is called the developed-zone aquifers. These developed-zone aquifers are confined where overlain by the near-surface aquifers.

Pumpage from the valley-fill aquifers of Las Vegas Valley between 1912 and 1981 totaled more than 2.5 million acre-ft. The maximum annual pumpage was 88,000 acre-ft in 1968. Ground-water development remained modest in the valley until the early 1940's, when war-time industry and tourism spurred rapid population growth. Water levels declined greatly in response to ground-water development beginning in the 1940's, particularly in the municipal well-field areas in the west-central part of the valley. This trend was reversed for the first time in 1972, when ground-water withdrawals were reduced as a result of water imports starting in 1971 from Lake Mead through the Southern Nevada Water Project. During the 1972–81 period, imports of Lake Mead water largely satisfied most of the increasing demands for water, and ground-water pumpage remained at about 70,000 acre-ft/yr.

Pumpage from the developed-zone aquifers has exceeded estimated natural recharge since the mid-1940's. This has led to a condition of basinwide water overdraft. Local water overdraft has occurred in areas of heavy pumping for municipal supply, causing water-level declines as great as 280 ft since the early 1900's. Land subsidence related to the ground-water withdrawal has caused considerable damage to buildings, drainage structures, and wells. Much of the water used in the valley eventually infiltrates to the near-surface aquifers. This has resulted in a rising water table over most of the central and southeastern parts of the valley floor. Water-logged soils may lead to structural damage and increase the burden on wastewater disposal facilities in the valley.

A three-dimensional, finite-difference computer model was developed and used to determine the properties of the aquifer system and evaluate changes in the system caused by development of the valley's water resources. Preliminary model calibration was done for predevelopment conditions and for flow-system responses to development between 1912 and 1972. The final model calibration was made using data for the period 1972–81, because well-discharge and water-level data were much more complete for this period than for previous years.

Transmissivities of the valley-fill sediments range from less than 100 feet squared per day (ft^2/d) to more than 800 ft^2/d within the near-surface aquifers and from 500 ft^2/d to more than 14,000 ft^2/d within the developed-zone aquifers. The elastic component of the storage coefficient in the developed-zone aquifers is estimated to range from 1×10^{-3} to 3×10^{-3}, whereas the inelastic component ranges from 7×10^{-4} to 3.2×10^{-2}. Average specific yield of the unconfined aquifers is approximately 0.08.

Approximately 620,000 acre-ft of ground water was pumped during the 1972–81 calibration period. Seasonal average pumping rates ranged from 4,000 acre-ft/mo during the low-use months (October–May) to 9,000 acre-ft/mo during the peak-demand months (June–September). Simulation results indicate that about 190,000 acre-ft of ground water was released from elastic and inelastic storage during 1972–81. The developed- and deep-zone aquifers contributed about 100,000 acre-ft, of which 61,000 acre-ft came from the inelastic compaction of fine-grained beds. Nearly 90,000 acre-ft was contributed from storage change in the near-surface aquifers, and about 17,000 acre-ft of that total resulted in permanently lost storage capacity as a result of inelastic compaction.

Excess from lawn watering, wastewater returns, industrial process-water returns, septic-tank leachate, and transmission losses supplied recharge of about 340,000 acre-ft during 1972–81. Nearly one-half this total is estimated to have come from residential lawn watering. Thus, secondary recharge is closely related to the highly seasonal rate of outdoor water use. Annual rates of secondary recharge used to simulate the system ranged from 30,000 acre-ft/yr in 1972 to 46,000 acre-ft/yr in 1981, with rates for the peak-use season being nearly three times those for the low-use season.

During 1972–81, about 190,000 acre-ft of ground water was discharged from the near-surface aquifers in nearly equal proportions by evapotranspiration and seepage to washes and drains. Simulated seepage rates during 1972–81 varied seasonally between 850 acre-ft/mo during low-use months and 1,300 acre-ft/mo during the peak-use months. Simulated evapotranspiration decreased from 13,000 acre-ft/yr in 1972 to about 10,000 acre-ft/yr in 1980 and showed little seasonal variation.

Water levels recovered throughout the central and southeastern parts of the valley during 1972–81 in response to (1) reduced pumping valley-wide, (2) reduced pumping near Nellis Air Force Base, and (3) increased secondary recharge to the near-surface aquifers. Over the 9-year period, 1972–81, water levels rose more than 40 ft in areas where reductions in pumping and increases in secondary recharge coincided. Declines continued on the western side of the valley near pumping centers; simulated average declines there were 30 to 70 ft.

The hydrologic effects of altering the timing of ground-water withdrawals by Las Vegas Valley Water District (LVVWD) were assessed by simulating a hypothetical 9-year period during which LVVWD wells were used only during the peak-demand summer months. No reduction in total pumpage from 1980 rates (71,000 acre-ft) was assumed, and the annual rate and seasonal distribution of all non-LVVWD pumping were held at 1980 levels. The estimated 1980 seasonal rate and distribution of secondary recharge also were used for the entire 9-year period. Results indicated that water-level declines would continue on the western side of the valley in response to pumping, but with a long-term rate of decline less than that during the 1972–81 period. Seasonal water-level fluctuations would be greater than those during 1972–81 in the LVVWD well fields. Rising water levels in the near-surface aquifers would continue in the central, eastern, and southeastern parts of the valley, and would cause increases in the total seepage to washes and drains by as much as 40 percent (although this would not be attributable to the pumping of LVVWD wells for peak use only). Predicted subsidence is about half that computed for 1972–81, as a result of shorter periods of heavy pumping and reduced water-level declines.

The model needs to be used selectively as a prediction tool if the accuracy of the predictions is assumed to be comparable with the accuracy achieved during the calibration. The accuracy of the computer model is limited by errors associated with the conceptual model of the flow system, the computational scheme, the hydraulic characteristics of the aquifers, the hydrologic flux data, the initial water levels, and the measured water levels.

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8.0 SUPPLEMENTAL INFORMATION

8.1 Data Input Instructions for Simulation Program

These instructions are for the Las Vegas Valley ground-water flow model as modified from Trescott (1975) for this study. The modifications are described in detail within this report, and listings of the source code and data are on file at the U.S. Geological Survey office in Carson City, Nev. Some of the generality of the original program has been lost as a result of modifications to account for the effects of subsidence. The restrictions imposed by these changes are on the vertical layering of the system because subsidence might occur only in layers 2 and 3. Changes to the source code would be required to use the model with any other layering system than that described in this report. The flexibility of the model with respect to areal grid design and most other features has been retained.

Variables and arrays that were added to the sources code are enclosed in brackets. Pay special attention to comments preceded by an asterisk (*). They denote variables or arrays that are not required in all simulations. Abbreviations: *L*, length; *t*, time.

Group I: *Title, simulation options, and problem dimensions*

This group of cards, which are read by the main program, contain data required to specify dimensions of the model. To specify an option on card 4, type the characters underlined in the definition. When an option is not used, leave that section of card 4 blank.

CARD	COLUMNS	FORMAT	VARIABLE	DEFINITION
1	1-80	20A4	HEADING	Any title the user wishes to print on one line at the start of output.
2	1-52	13A4	HEADING	
3	1-10	I10	I0	Number of rows.
	11-20	I10	J0	Number of columns.
	21-30	I10	K0	Number of layers.
	31-40	I10	ITMAX	Maximum number of iterations per time step.
	41-50	I10	NCH	Number of constant head cells.
	51-60	I10	[ICHM1]	Beginning column number for composite head printout.
	61-70	I10	[ICHM2]	Ending column number for composite head printout.
4	1-4	A4	IDRAW	<u>DRAW</u> to print drawdown.
	6-9	A4	IHEAD	<u>HEAD</u> to print hydraulic head.
	11-14	A4	IFLOW	<u>MASS</u> to compute a mass balance.
	16-19	A4	IDK1	Not used.
	21-24	A4	IDK2	Not used.
	26-29	A4	IWATER	<u>WATE</u> if the upper hydrologic unit is unconfined.
	31-34	A4	IQRE	<u>RECH</u> for recharge to the uppermost layer that may be a function of space and time.
	36-39	A4	IPU1	<u>PUN1</u> to read initial head, elapsed time, and mass balance parameters from cards.
	41-44	A4	IPU2	<u>PUN2</u> to write constant head fluxes, computed heads, elapsed time, and mass balance parameters on unit 7. If SUBS is also specified, preconsolidation heads are written on unit 8.
	46-49	A4	ITK	<u>ITKR</u> to read the value of *TK(I,J,K)* for simulations in which confining layers are not represented by layers of cells. $TK(I,J,K)=K_{zz}/b$
	51-54	A4	IEQN	Determines flow equation solved by model. (See Trescott, 1975, p. 3–4.)
	56-59	A4	[ISUBS]	<u>SUBS</u> to simulate subsidence in layers 2 and 3.
	61-64	A4	[IEVT]	<u>IVET</u> to simulate evapotranspiration from uppermost layer.
	66-69	A4	[IHYD]	<u>IHYD</u> to output computed water levels at selected cells to unit 9 for each time step.
	71-74	A4	[IWSH]	<u>IWSH</u> to simulate discharge to wash cells from the uppermost layer.
	76-79	A4	[ISPG]	<u>ISPG</u> to simulate head-dependent spring discharge from layer 2.
5	1-10	F10.0	[DLAT]	Decimal latitude of lower left corner of model grid.
	11-20	F10.0	[DLNG]	Decimal longitude of lower left corner of model grid.

Group II: *Scalar parameters*

The parameters required in every problem are underlined. The other parameters are required as noted; when not required, their location on the card can be left blank. The G format is used to read E, F, and I format data; always right-justify data in the field. If F format data do not contain significant figures to the right of the decimal, the decimal point can be omitted.

CARD	COLUMNS	FORMAT	VARIABLE	DEFINITION
1	1-10	G10.0	<u>NPER</u>	Number of pumping periods for the simulation.
	11-20	G10.0	<u>KTH</u>	Number of time steps between printouts.
	NOTE: To print only the results for the final time step in a pumping period, make KTH greater than the expected number of time steps. Program always prints results for the final time steps.			
	21-30	G10.0	<u>ERR</u>	Error criteria for closure (*L*).
	NOTE: When the head change at all cells on subsequent iterations is less than this value (for example, 0.01 ft), the program has converged to a solution for the time step.			
	31-40	G10.0	<u>LENGTH</u>	Number of iteration parameters.
	41-50	G10.0	[KPH]	Number of pumping periods between printouts.
	NOTE: To print only the results for the final pumping period, make KPH greater than the expected number of pumping periods. The program always prints results for the final pumping period.			
2	1-10	G10.0	XSCALE	Factor to convert model length unit to unit used in X direction on maps (for example, to convert from feet to miles, XSCALE = 5280).
	11-20	G10.0	YSCALE	Factor to convert model length unit to unit used in Y directions on maps.
	21-30	G10.0	DINCH	Number of map units per inch.
	31-38	A8	MESUR	Name of map length unit.
	41-45	I5	[NPL]	Number of layers for which specific discharge vector data are requested.
	46-55	F10.0	[SCM]	Scaling factor for vector plots, feet per inch.
	56-65	F10.0	[VLI]	Max vector length (inches) on plots.
	66-70	I5	[NODFLX]	If equal to 1, fluxes to each cell from each adjacent cell are printed. Set to zero for no output.
3	1-10	G10.0	FACT1	Factor to adjust value of drawdown printed on maps.
	11-19	9I1	LEVEL1(I)	Layers for which drawdown maps are to be printed. List the layers starting in column 11; first zero entry terminates printing of drawdown maps.
	21-30	G10.0	FACT2	Factor to adjust value of head printed on maps.
	31-39	9I1	LEVEL2(I)	Layers for which head maps are to be printed (input as for drawdown).
	40-48	9I1	[LEVEL(3)I]	Select cell by cell output of water levels, land-surface altitude, subsidence, and evapotranspiration for any layer. List layers starting in column 40, first zero or blank entry terminates output. Output is to external files, one for each layer. The unit written is equal to the layer number plus 10 (that is, layer 4 is written to unit 14).
	50-58	9I1	[LEVEL(4)I]	Select ground-water specific discharge output for any layer. List layers as above starting in column 50. An external file is written to unit 19, which can be post-processed by a vector plotting program.

* If IHYD was not specified, skip to card 5.

CARD	COLUMNS	FORMAT	VARIABLE	DEFINITION
4	1-5	I5	[NUMNOD]	Number of cells for which hydrographs are to be output. Input one 4A card per cell with the row, column and layer numbers.
4A	1-4	I4	[LCN(I,1)]	Row number.
	5-8	I4	[LCN(I,2)]	Column number.
	9-12	I4	[LCN(I,3)]	Layer number.
	*If IWSH was not specified, skip to card 6.			
5	1-5	I5	[NUMWSH]	Number of cells where discharge to streams is computed. Input one 5A card per cell with location, reach, altitude, and leakance data.
	6-10	I5	[NUMRCH]	Number of stream reaches used.
5A	1-5	I5	[IWASH(K)]	Row number.
	6-10	I5	[JWASH(K)]	Column number.
	11-15	I5	[IRCH(K)]	Reach number.
	16-25	F10.0	[WAEL(K)]	Channel altitude.
	26-35	F10.0	[WALK(K)]	Streambed leakance.
	36-45	F10.0	[WACUT(K)]	Headcutting rate (feet per year).
	* If ISPG was not specified, skip to card 7.			
6	1-5	I5	[INSP]	Number of spring cells in layer 2. Input one 6A card per cell with row, column, and leakance of spring.
6A	1-10	I10	[IZ]	Row number.
	11-20	I10	[VZ]	Column number.
	21-35	F15.10	[SPQ(IZ,JZ)]	Spring leakance (*L*,*t*).
	*If SUBS was not specified, skip to card 8.			
7	1-10	I10	[ILHEAD]	If greater than 0, preconsolidation heads are printed.
	11-20	F10.0	[SUBH2]	Depth to preconsolidation head below predevelopment head for layer 2.
	21-30	F10.0	[SUBH3]	Same as above for layer 3.
	31-40	F10.0	[DELAY2]	Distance in feet that water level in layer 2 must recover before subsidence ceases.
	41-50	F10.0	[DELAY3]	Same as above for layer 3.
8	1-20	G20.10	SUM	Parameters in which elapsed time and cumulative volumes for mass balance are stored. For the start of a simulation, insert three blank cards. For continuation of a previous run using cards as input, replace the three blank cards with the first three cards of punched output from the previous run. By use of data from disk for input, leave the three blank cards in the data deck.
	21-40	G20.10	SUMP	
	41-60	G20.10	PUMPT	
	61-80	G20.10	CFLUXT	
9	1-20	G20.10	QRET	
	21-40	G20.10	CHST	
	41-60	G20.10	CHDT	
	61-80	G20.10	FLUXT	
10	1-20	G20.10	STORT	
	21-40	G20.10	ETFLXT	
	41-60	G20.10	FLXNT	

GROUP III: *Array Data*

Each of the following data sets (except data set 1) consists of a parameter card and, if the data set contains variable data, a set of data cards for each layer in the model. Each parameter card contains at least three variables.

CARD	COLUMNS	FORMAT	VARIABLE	DEFINITION
Every parameter card	1-10	G10.0	FAC	If IVAR=0, FAC is the value assigned to every element of the matrix for this layer. If IVAR=1, FAC is the multiplication factor for the following set of data cards for this layer.
	11-20	G10.0	IVAR	=0 if no data cards are to be read for this layer. =1 if data cards for this layer follow.
	21-30	G10.0	IPRN	=0 if input data for this layer are to be printed. =1 if input data for the layer are *not* to be printed.
Transmissivity parameter cards	31-40	G10.0	FACT (K,1)	Multiplication factor for transmissivity in x direction.
	41-50	G10.0	FACT (K,2)	Multiplication factor for transmissivity in the y direction.
	51-60	G10.0	FACT (K,3)	Multiplication factor for hydraulic conductivity in the z direction. (Not used when confining bed cells are eliminated and TK values are read).

GROUP III: *Array Data—Continued*

When data cards are included, start each row on a new card. To prepare a set of data cards for an array that is a function of space, the general procedure is to overlay the finite-difference grid on a contoured map of the parameter, and record the average value of the parameter for each finite-difference block on coding forms according to the appropriate format. In general, record only significant digits and no decimal points (except for data set 2); use the multiplication factor to convert the data to their appropriate values. For example, if DELX ranges from 1,000 to 15,000 ft, coded values should range from 1–15; the multiplication factor (FAC) would be 1000.

DATA SET	COLUMNS	FORMAT	VARIABLE	DEFINITION
1	1-80	8 F10.4	PHI(I,J,K)	Head values (*L*) for continuation of a previous run. PUN1 needs to be specified.
	NOTE: For a new simulation, this data set is omitted. Do not include parameter card with this data set.			
	*If IEVT was not specified, skip to data set 5.			
2	1-80	20 F4.0	[GRND(I,J)]	Land-surface altitude (*L*).
3	1-80	20 F4.0	[QET(I,J)]	Evapotranspiration rate (*L/t*).
4	1-80	20 F4.0	[ETDIST(I,J)]	Effective depth of evapotranspiration (*L*).
5	1-80	20 F4.0	STRT(I,J,K0)	Starting head matrix (*L*).
6	1-80	20 F4.0	S(I,J,K0)	Elastic storage coefficient (dimensionless).
	NOTE: This matrix also is used to locate constant head boundaries by coding a negative number at constant head cells. At these cells, t *must* be greater than zero. *If SUBS was not specified, skip to data set 11.			
7	1-80	20 F4.0	[SI2(I,J)]	Inelastic storage coefficient, layer 2 (dimensionless).
8	1-80	20 F4.0	[SI3(I,J)]	Inelastic storage coefficient, layer 3 (dimensionless).
9	1-80	20 F4.0	[LHEAD2(I,J)]	Preconsolidation head matrix, layer 2 (*L*).
10	1-80	20 F4.0	[LHEAD3(I,J)]	Preconsolidation head matrix, layer 3 (*L*).
	NOTE: (1) Zero values in LHEAD2 and LHEAD3 matrices cause STRT minus SUBH2 or SUBH3 to be used as the preconsolidation head. (2) A value of 999 in LHEAD2 or LHEAD3 matrices causes substitution of the inelastic storage coefficient prior to the first time step.			
11	1-80	20 F4.0	T(I,J,K)	Transmissivity (*L/t*).
	NOTE: (1) Zero values are required around the perimeter of the T matrix for each layer for reasons inherent in the computational scheme. This is done automatically by the program. (2) See the previous page for additional requirements on the parameter cards for this data set. (3) If the upper active layer is unconfined and PERM and BOTTOM are to be read for this layer, insert a parameter card for this layer with only the values for FACT on it.			
	* If ITKR was not specified, skip to data set 13.			
12	1-80	20 F4.0	TK(I,J,K)	K_{zz}/b
	*If WATE was not specified, skip to data set 15.			
13	1-80	20 F4.0	PERM(I,J)	Hydraulic conductivity (*L/t*). (See note 1 for data set 4.)
14	1-80	20 F4.0	BOTTOM(I,J)	Altitude of bottom water table unit (*L*).
15	1-80	8 G10.0	DELX(J)	Grid spacing in *x* direction (*L*).
16	1-80	8 G10.0	DELY(I)	Grid spacing in *y* direction (*L*).
17	1-80	8 G10.0	DELZ(K)	Grid spacing in *z* direction (*L*).

Group IV: *Parameters that change with the pumping period*

The program has two options for the simulation period:

1. To simulate a given number of time steps, set TMAX to a value larger than the expected simulation period. The program will use NUMT, CDLT, and DELT as coded.
2. To simulate a given pumping period, set NUMT larger than the number required for the simulation period (for example, 100). The program will compute the exact DELT (which will be less than or equal to the DELT coded) and NUMT to arrive exactly at TMAX on the last time step.

CARD	COLUMNS	FORMAT	VARIABLE	DEFINITION
1	1-10	G10.0	KP	Number of the pumping period.
	11-20	G10.0	[KPM1]	If RECH was specified, input as 1 to read in QRE array after last well card. Input as 0 (zero) if RECH was not specified or QRE is not to be changed for this pumping period.
	21-30	G10.0	NWEL	Number of wells for this pumping period.
	31-40	G10.0	TMAX	Number of days in this pumping period.
	41-50	G10.0	NUMT	Number of time steps.
	51-60	G10.0	CDLT	Multiplying factor for DELT.
	NOTE: 1.5 is commonly used			
	61-70	G10.0	DELT	Initial time step in hours.

Well data (Input one record per well—that is, NWEL records.)

COLUMNS	FORMAT	VARIABLE	DEFINITION
1-10	G10.0	K	Layer in which well is located.
11-20	G10.0	I	Row location of well.
21-30	G10.0	J	Column location of well.
31-40	G10.0	WELL(I,J,K)	Pumping rate (L/t), negative for a pumped well.

Recharge data (Input if KPM1=1 for this pumping period.)

The recharge matrix is read in the same way as Group III array data. The parameter card should follow the last well card. As with other array data, recharge may vary areally; if it does, follow the parameter card with data cards in 20F4.0 format.

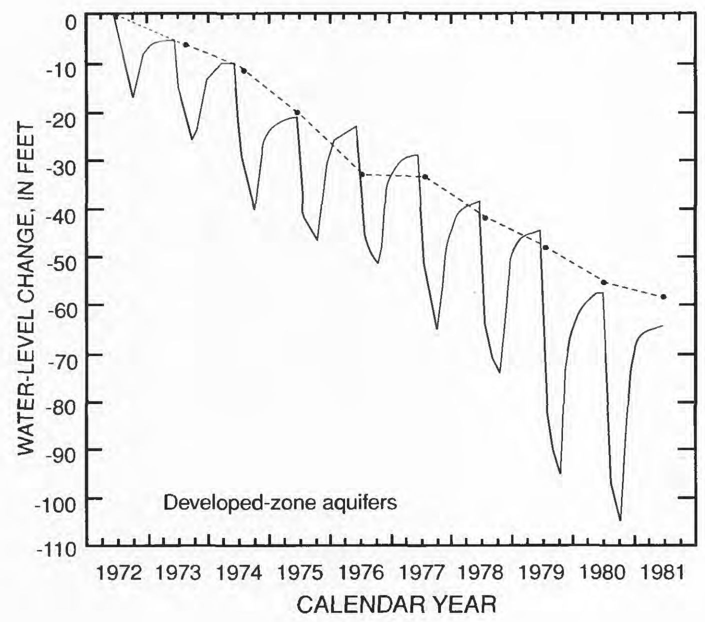
* For each additional pumping period, another set of Group IV cards is required (that is, NPER sets of Group IV cards are required).

☆ U.S. GOVERNMENT PRINTING OFFICE: 1996 - 774-045 / 20017 REGION NO. 8

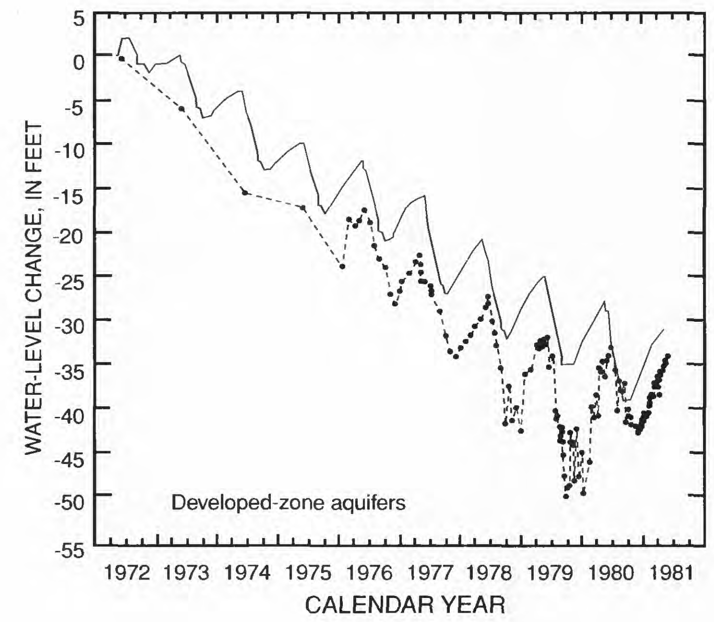
PREPARED IN COOPERATION WITH THE
CLARK COUNTY DEPARTMENT OF COMPREHENSIVE PLANNING

Morgan, D.S., and Dettinger, M.D., 1995, Ground-water conditions in Las Vegas Valley, Clark County, Nevada–Part II, Hydrogeology and simulation of ground-water flow

Site A



Site B



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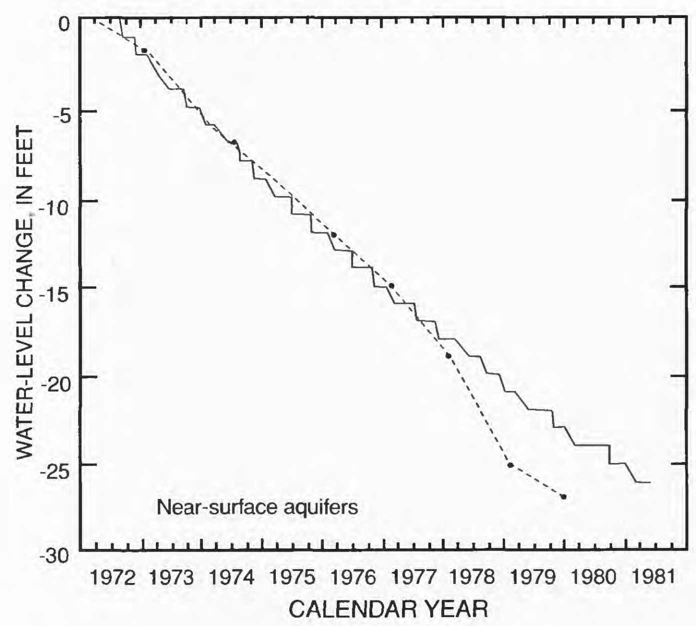

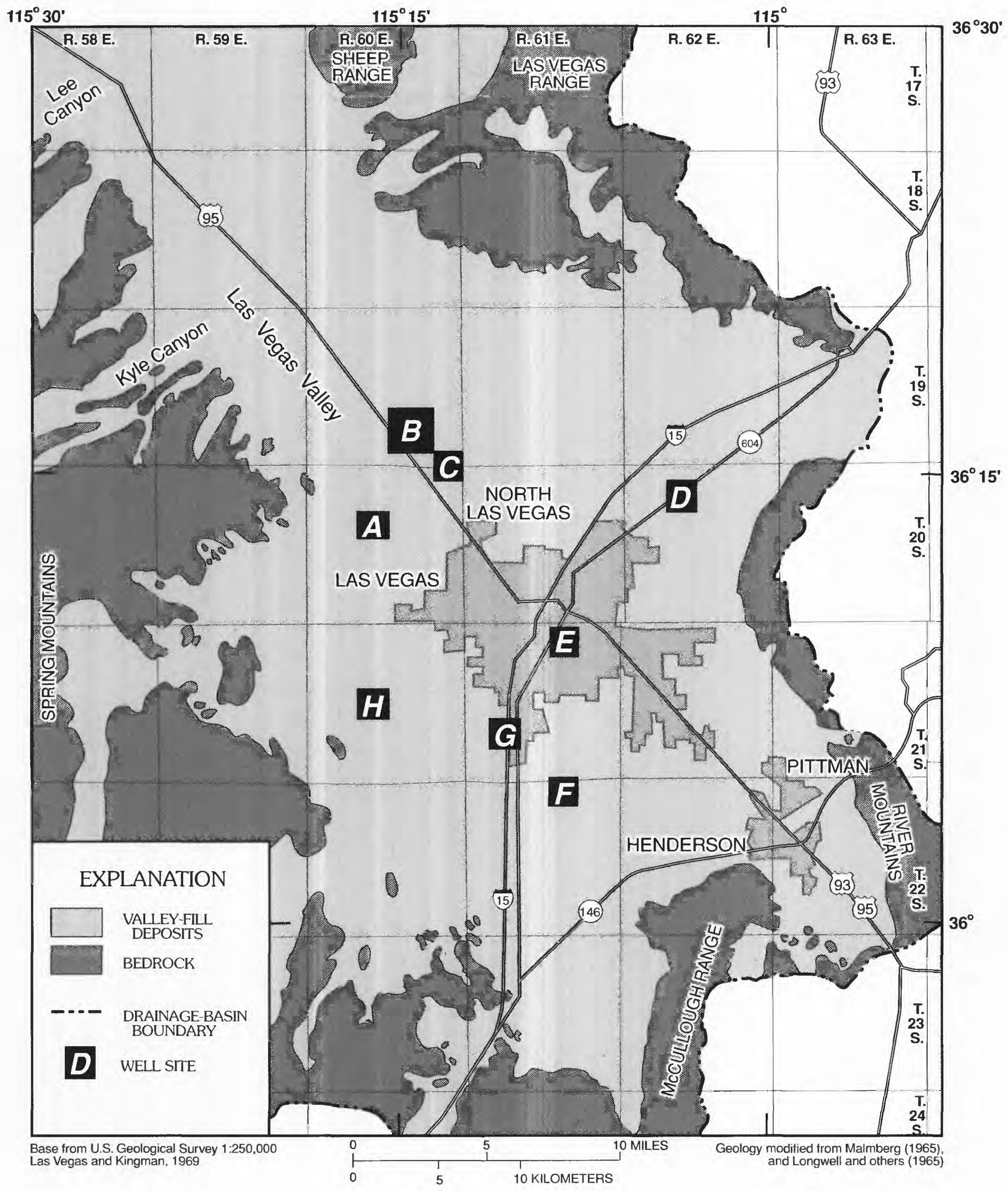

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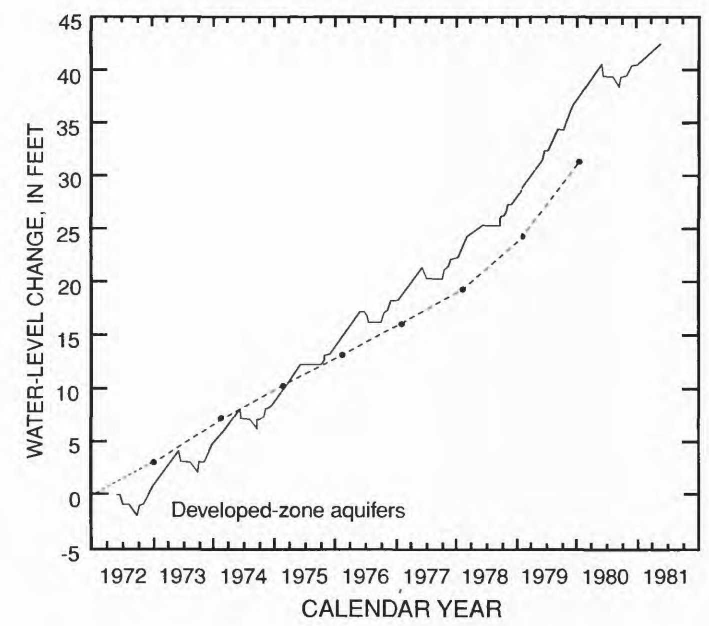

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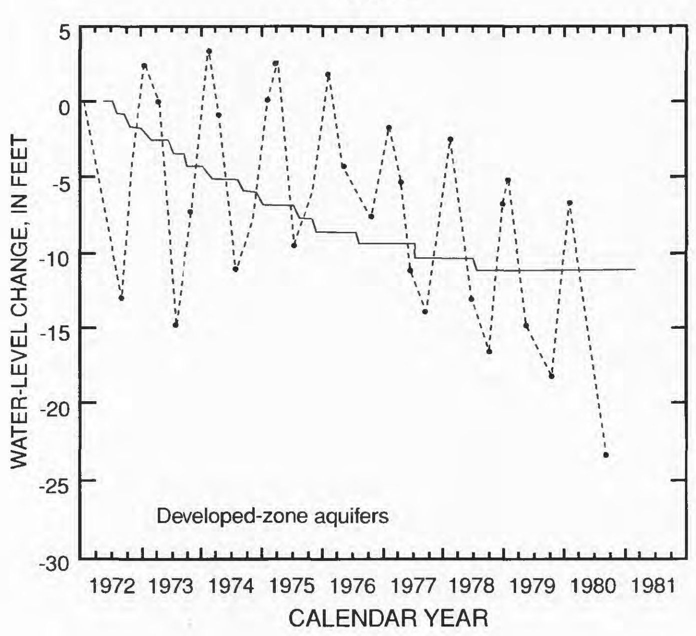
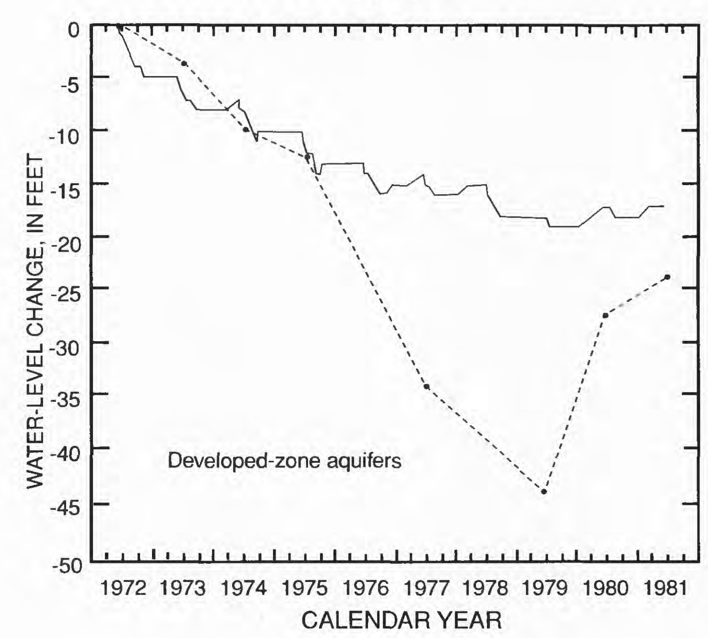


Site F



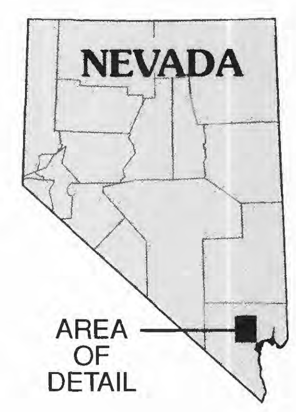
GRAPH SYMBOLS AND
WELL-SITE INFORMATION

MEASURED WATER LEVEL -- Dotted line indicates inferred water-level change; dashed line connects measured water levels

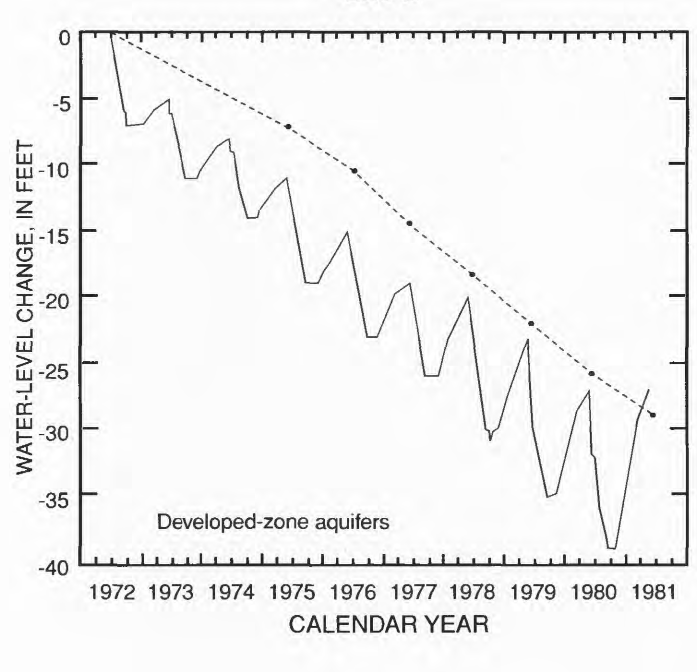
SIMULATED WATER-LEVEL CHANGE

Site	Well number [1]	Model cell (row, column, layer)
A	20/60-09DCC1	12, 6, 2
B	19/60-27BDC1	9, 7, 2
C	19/60-36CBB1	10, 8, 3
D	20/62-05CAA1	11, 15, 2
E	21/61-03ABB2	16, 12, 2
F	22/61-02CDCC1	21, 12, 2
G	21/61-19CBA1	19, 9, 2
H	21/60-16BDDB1	18, 6, 2

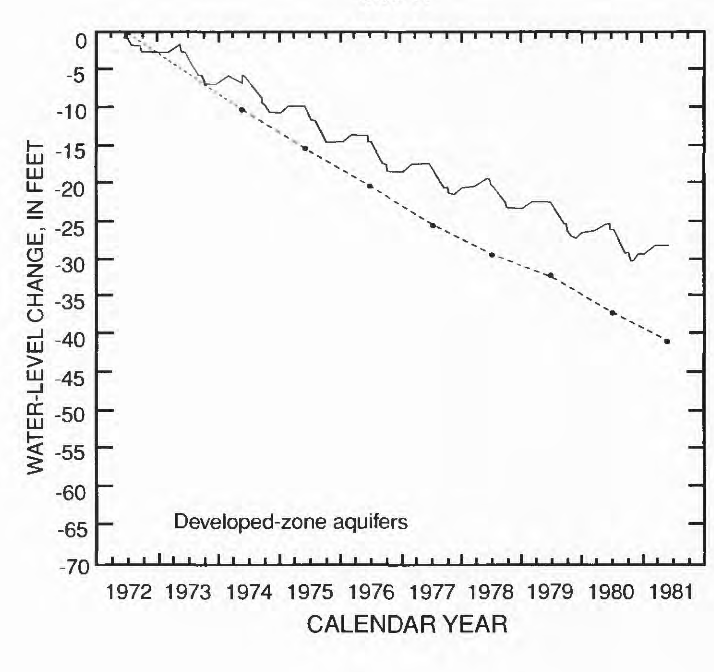
[1] Indicates (from left to right) township number, range number, section number, letters identifying location of well site within section, and site-sequence number.



Site G



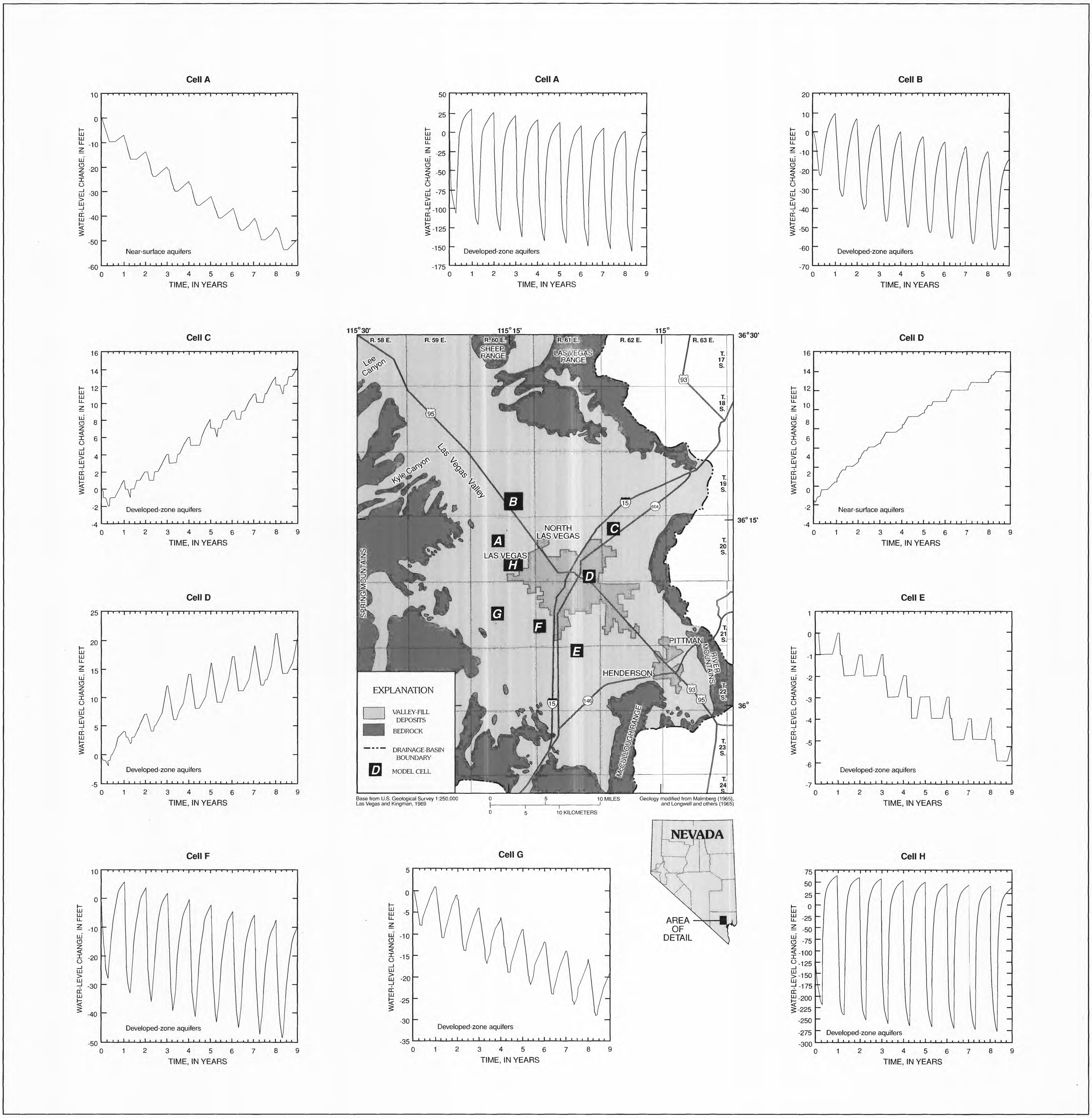
Site H



MEASURED AND SIMULATED CHANGES IN GROUND-WATER LEVEL, 1972-81, LAS VEGAS VALLEY, NEVADA

By
David S. Morgan and Michael D. Dettinger
1995

Morgan, D.S., and Dettinger, M.D., 1995, Ground-water conditions in Las Vegas Valley, Clark County, Nevada–Part II, Hydrogeology and simulation of ground-water flow



SIMULATED CHANGES IN GROUND-WATER LEVEL FOR 9-YEAR PERIOD DURING WHICH GROUND WATER IS PUMPED BY LAS VEGAS VALLEY WATER DISTRICT FOR PEAK DEMAND ONLY, LAS VEGAS VALLEY, NEVADA

By
David S. Morgan and Michael D. Dettinger
1995