

Appendix D

Coachella Valley Groundwater Model (Revised)

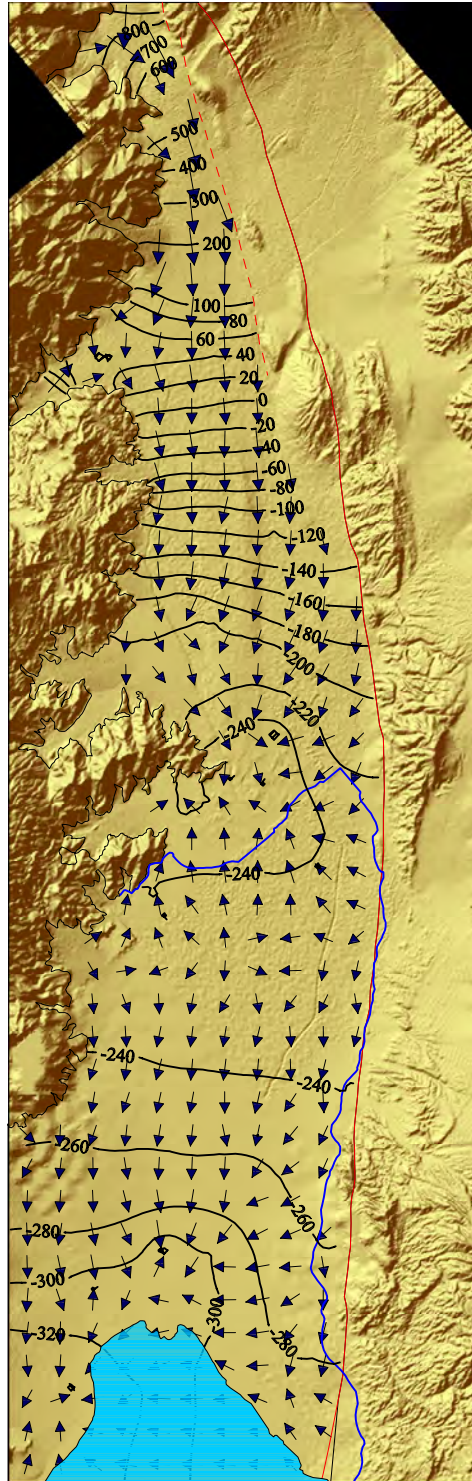
Appendix D of the Draft PEIR is hereby revised to include the two reports that follow:

Coachella Valley Groundwater Model, Peer Review Report, 1998.

Groundwater Flow Model of Coachella Valley, California: An Overview”
prepared by Graham E. Fogg, Gerald T. O’Neill, Eric M. LaBolle and David J.
Ringel,

Groundwater Flow Model of Coachella Valley, California: An Overview

Graham E. Fogg, Gerald T. O'Neill, Eric M. LaBolle, David J. Ringel



Prepared for
Coachella Valley Water District

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Groundwater Flow Model of Coachella Valley, California: An Overview

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November 2000

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Groundwater Flow Model of Coachella Valley, California: An Overview

1 EXECUTIVE SUMMARY

A three-dimensional, numerical groundwater flow model of the Coachella Valley, California was developed for Coachella Valley Water District (CVWD) to provide a scientific basis for managing groundwater in Coachella Valley into the next century. The purpose of the model is to test the effects of various management plan alternatives involving artificial recharge and reductions in pumpage on sustainability of groundwater levels, potential saline water intrusion from the Salton Sea, and potential land subsidence.

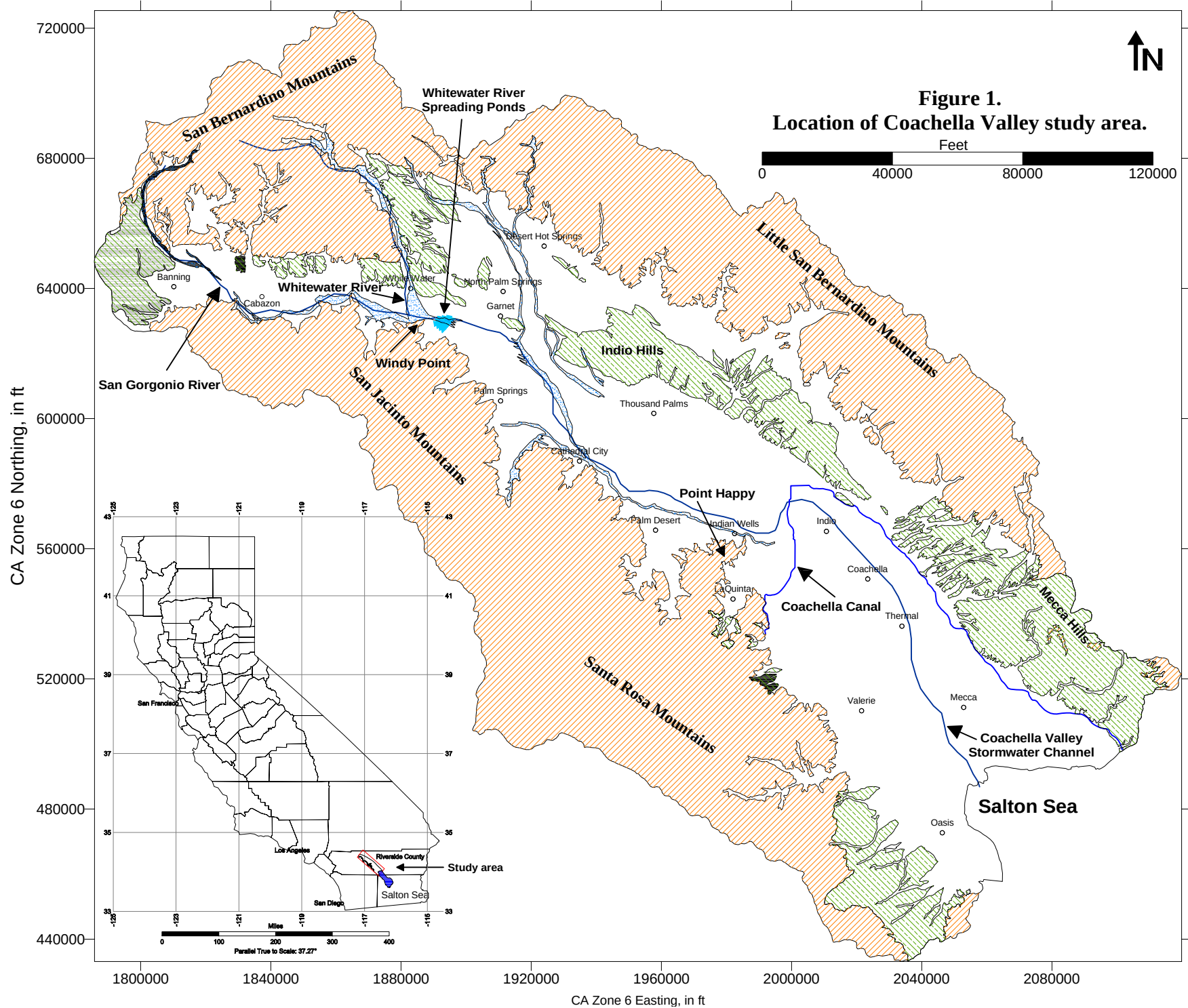
The model built upon previous modeling investigations by the United States Geological Survey (USGS) in the upper Coachella Valley. Tyley (1974), Swain (1978), and Reichard and Meadows (1992) all constructed two-dimensional groundwater flow models of the upper valley, each model representing an improvement over the previous. Tyley's model was an electric analog and the later efforts were based on the finite element method. Thus, the current three-dimensional model of the entire Coachella Valley is a logical extension of the previous models. The multiple layers of the present model are also necessary for representing multiple aquifer zones in the lower valley.

A historical period of 61 years, from 1936 through 1996, was used to calibrate the model. Comprehensive information on groundwater pumpage, natural recharge, and drain flows were compiled for this period. Data on groundwater parameters from well tests and records were interpreted together with regional geologic information to define the physical system within which the groundwater flows. Results are generally excellent, with groundwater levels computed by the model throughout the basin closely tracking the measured historical trends and elevations. Additionally, the model closely simulated historic trends and flows in measured agricultural drain discharges.

An independent committee consisting of three internationally recognized experts in the development and application of groundwater models conducted a peer review of the model. The committee concluded that the model is valid and could be used to evaluate the groundwater impacts of the management alternatives under consideration (Larson et. al, 1998).

2 INTRODUCTION

The Coachella Valley is a northwest-southeast trending valley over 50 miles in length (from the San Geronio Pass to the Salton Sea) and includes approximately 440 square miles. Coachella Valley lies in central Riverside County in the hot, arid Colorado Desert of California (Fig. 1). Precipitous and rugged mountains bound Coachella Valley, except to the southeast, where the valley drains into the Salton Sea. Elevations in the watershed range from over 10,000 ft above sea level in the San Bernardino and San Jacinto Mountains to lower than 200 ft below sea level at the Salton Sea. The valley floor ranges in elevation from over 1,200 ft above sea level in the San Geronio Pass to approximately 228 ft below sea level at the Salton Sea.



The valley is divided into an upper valley and lower valley near Point Happy (Fig. 1). The upper valley primarily consists of desert resort communities, while the lower valley has a predominantly, year-round, agricultural economy. These economies are dependent on water from surface water and groundwater sources. Resort communities in the upper valley rely on groundwater, which is supported by artificial recharge. Agricultural development in the lower valley uses groundwater as well as Coachella Canal water imported from the Colorado River. Surface water for artificial recharge and from the Coachella Canal was introduced to the valley after many years of groundwater pumping resulted in widespread declines in water levels throughout the basin. Still, demand on groundwater has increased over time, and has placed considerable stress on the aquifer system. These stresses have resulted in valley-wide overdraft and reversed hydraulic gradients in the lower basin. Additionally, potential land subsidence is a concern.

2.1 Previous Investigations

Previous hydrologic studies conducted in Coachella Valley include those of Mendenhall (1909), Kocher and Harper (1927), Pillsbury (1941), Huberty et al. (1948), and substantial work by California Department of Water Resources (1964; 1979). Detailed descriptions of the geology and hydrology of the Coachella Valley groundwater basin are provided in California Department of Water Resources (DWR, 1964) report *Coachella Valley Investigation*. USGS studies in the upper Coachella Valley, including the development of groundwater flow and transport models, include those of Tyley (1974), Swain (1978) and Reichard and Meadows (1992). These studies were motivated chiefly by the need to better understand and forecast effects of artificial recharge at the Whitewater River spreading ponds (Fig. 1), including water quality impacts of the recharge. However, no previous hydrologic modeling analysis had included the lower Coachella Valley, and very few estimates of pumpage or recharge from irrigated agriculture had been made. Consequently, the current study was designed to develop a model that included both the upper and lower Coachella Valley and estimates of historical agricultural groundwater pumpage in the lower valley for use in calibration.

2.2 Purpose and Scope

The purpose of the study was to (1) develop a comprehensive understanding of the groundwater hydrology of Coachella Valley, and (2) develop a three-dimensional groundwater flow model of the entire valley to provide a means of analyzing quantitatively the groundwater inflows and outflows in a management context.

The study consisted of extensive reexamination of the available groundwater data, developing improved estimates of pumpage and recharge, and construction of a three-dimensional groundwater flow model of most of the valley. The purpose of the model is to evaluate present and future management options in Coachella Valley. The model is designed to simulate groundwater flow throughout the basin, while addressing the limitations of previous models. The three-dimensionality of the model allows for good representation of the complex aquifer system in the lower valley. Furthermore, improved estimates of pumpage and recharge, representation of the massive drainage network underlying the agricultural lands, as well as interaction between the

groundwater system and the Salton Sea are significant improvements relative to previous investigations.

2.3 Well Numbering System

The well numbering system used in this report is based on the rectangular system for subdivision of public land. Wells are numbered according to their location; for example 04S05E15J01S indicates the township (T. 4 S.), range (R. 5 E.), section (15), 40-acre subdivision of the section (J), and a serial number for wells in each 40-acre subdivision (1). The model area lies south and east of the San Bernardino base line and meridian. Figure 2 shows an overlay of the rectangular system on a digital base map of the Coachella Valley area.

2.4 Hydrogeologic Setting

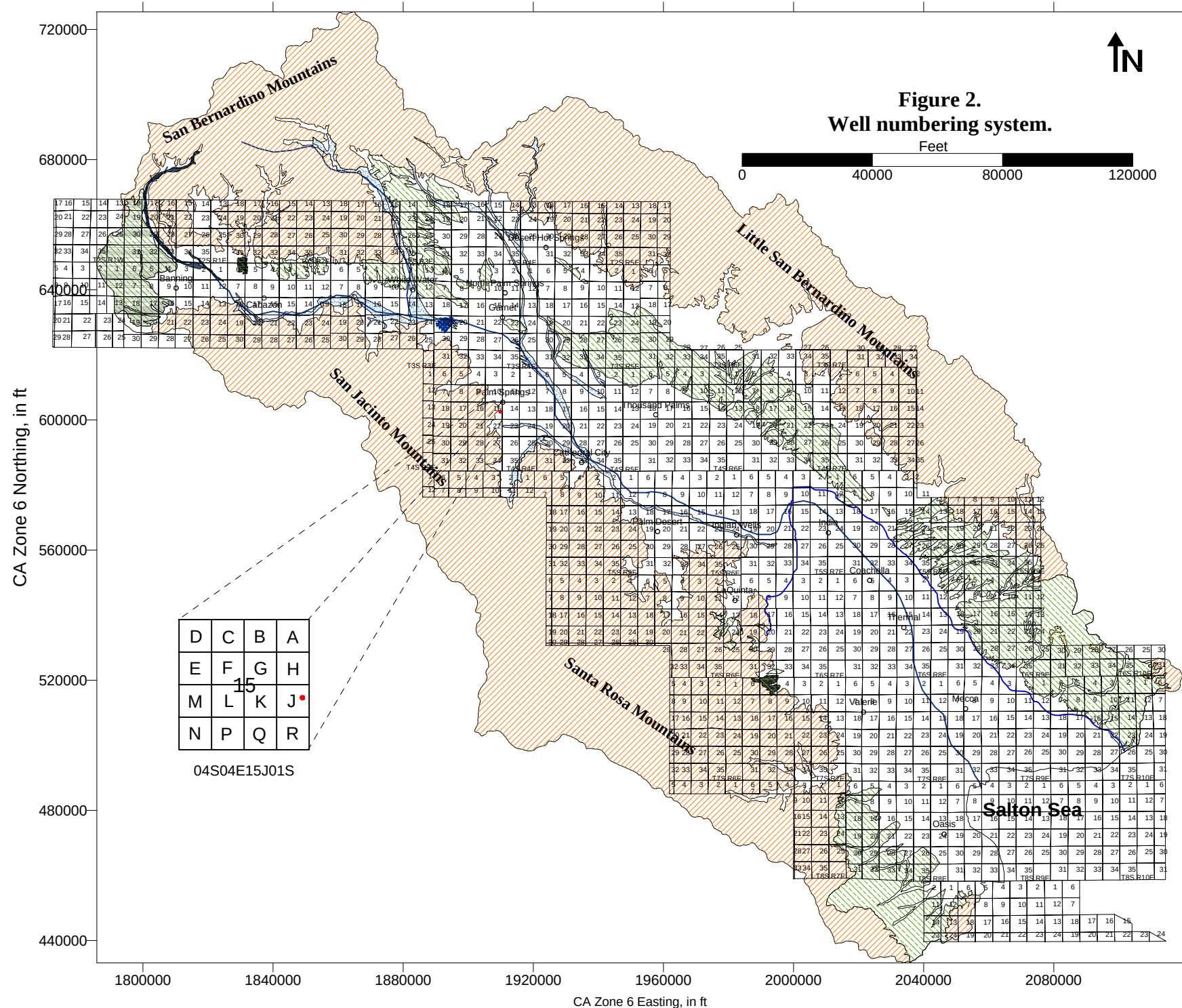
Coachella Valley is located in the northwestern corner of the Colorado Desert physiographic province. It is bounded by the Peninsular (San Jacinto and Santa Rosa Mountains) and Transverse (San Bernardino and Little San Bernardino Mountains) Ranges. Much of the valley floor lies at low elevation; from Indio south to the Salton Sea, valley floor elevations are generally below mean sea level. The dominant feature of the Colorado Desert is the Salton Trough, a large structural depression that extends from San Geronio Pass south to the Gulf of Mexico (Norris and Webb, 1976). The Salton Basin refers to the region of the trough that drains directly into Salton Sea. The lower portion of the trough is occupied by the Colorado River delta and is entirely in Mexico. The San Andreas fault zone extends along the northeastern side of the basin. Thick Cenozoic sedimentary materials of primarily continental (nonmarine) origin underlie the Salton Basin and contain the major aquifer systems.

Climate in the valley consists of hot, arid summers; however, summer convection storms from the Gulf of California contribute as much as 40 percent of the annual rainfall on the valley floor. Warm dry winters prevail in the valley. Average annual rainfall on the valley floor is less than 5 inches, and does not contribute significantly to the usable water supply. Average annual precipitation on the San Bernardino and San Jacinto Mountains ranges from 30 to 40 inches, and natural recharge to the groundwater basin occurs from infiltration of mountain runoff. The Whitewater River and its tributaries, and the Coachella Valley Stormwater Channel (CVSC), drain the watershed (Fig. 1).

2.4.1 Geology

The geology of the Coachella Valley area has been studied in detail and documented in previous reports, including DWR (1964) and others (see Tyley, 1974); therefore, this section contains information pertinent only to understanding the groundwater flow system.

Figure 2.
Well numbering system.



In general, the Coachella Valley is part of a great structural trough that includes the Gulf of California. The northwest trending valley is bounded on the northeast by Pre-Tertiary metasedimentary and igneous rocks of the Little San Bernardino Mountains, to the southwest by Pre-Tertiary metamorphic and igneous rocks of the San Jacinto and Santa Rosa Mountains, to the northwest by the San Gorgonio Pass, and to the southeast by the Salton Sea. Thus, crystalline Pre-Tertiary igneous and metamorphic rocks comprise the mountain ranges and underlie the valley floor at substantial depths.

The basin is filled with thousands of feet of sedimentary materials of continental origin, with the exception of some Pliocene marine sediments. Thick deposits of Tertiary and Quaternary sediments overlie the crystalline bedrock. These sediments generally consist of coarse, alluvial fan deposits on the periphery of the basin, grading basinward into fine-grained deposits laid down in an alluvial plain and shallow lake environment (DWR, 1964).

The northwesterly trending San Andreas fault zone (Fig. 3) extends along the northeastern side of the basin. Large subparallel and branching faults of the San Andreas fault system are present in Coachella Valley, and act as partial barriers to groundwater flow. These faults include the San Andreas, Mission Creek, Banning, Garnet Hill, Indio Hills and Mecca Hills Faults (DWR, 1964).

2.4.2 Aquifer System

The groundwater basin generally coincides with the valley floor and is bounded by high mountains and faults (Fig. 3). The groundwater basin boundary, and its subdivision into subareas and subbasins, was determined by DWR (1964) on the basis of formation permeability, faults, well yields and water quality. Tyley (1974) further generalized the basin for modeling purposes in the upper valley. The mountains are composed of relatively impermeable rocks that impede the movement of groundwater. Unconsolidated Recent and late Pleistocene alluvial deposits form a complex aquifer system in Coachella Valley. The Pleistocene Ocotillo Conglomerate is the principal water-bearing unit and consists of poorly consolidated sandstones and conglomerates with lenticular interbeds of silts and clays. This unit reaches at least 2,400 ft in thickness (DWR, 1964). In the lower valley, the upper part of the Ocotillo Conglomerate consists primarily of 100 to 200 ft of lake-deposited materials of low permeability, which form a confining unit (or aquitard) above the main or lower aquifer. Figure 4 illustrates the regional hydrostratigraphy, and Figure 5 shows a generalized stratigraphic column in the lower valley.

The San Gorgonio Pass is an east-west trending, narrow valley approximately 15 miles long between the San Jacinto and San Bernardino Mountains that provides Coachella Valley access to the coastal plains to the west. A coarse sandy alluvial fill chiefly underlies the pass area. Drillers' logs indicated very coarse and poorly sorted materials with little or no fines present through most of the pass area; these materials are more than 1,000 ft thick (DWR, 1964).

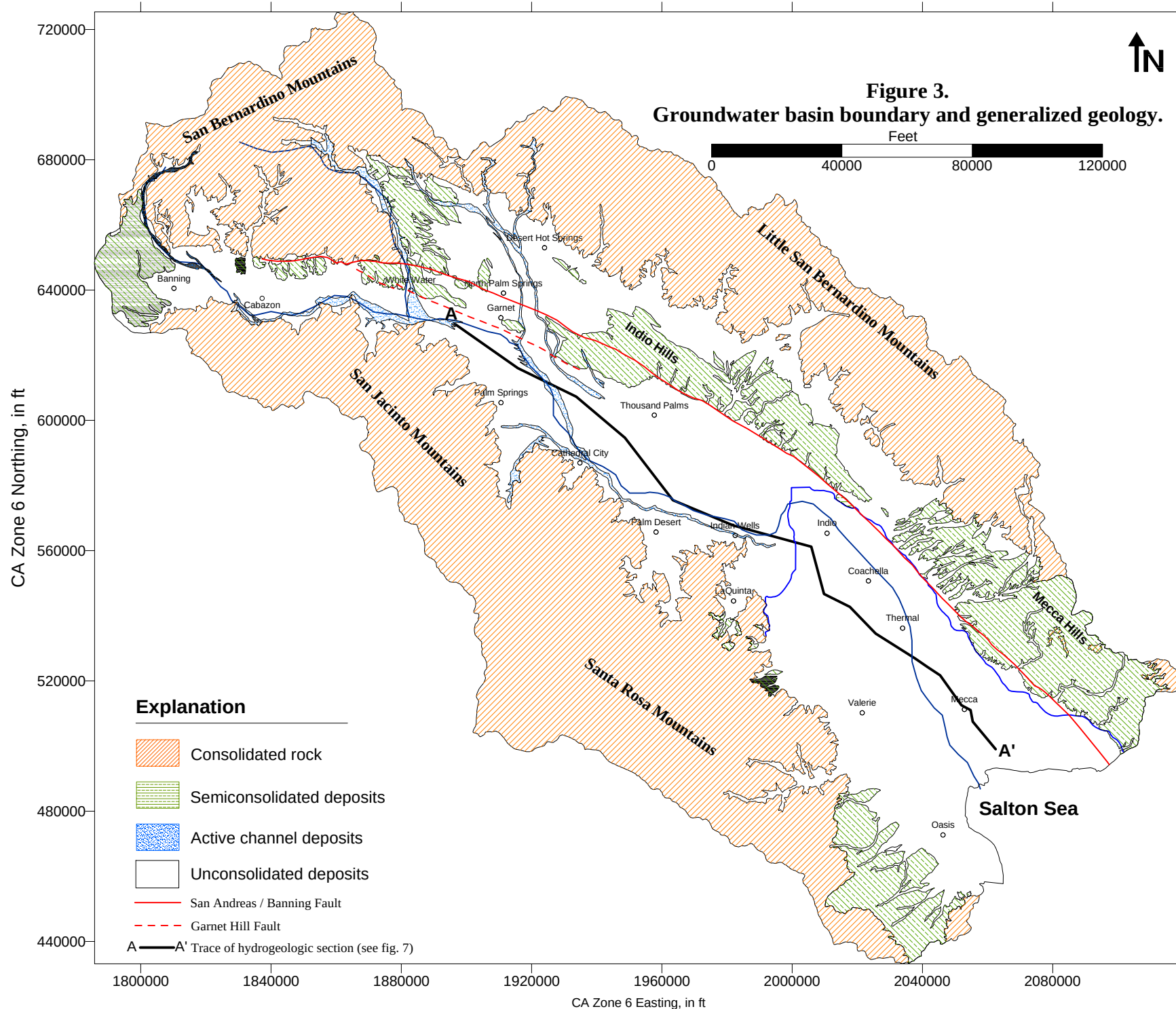


Figure 4.
Schematic geologic section through Coachella Valley.

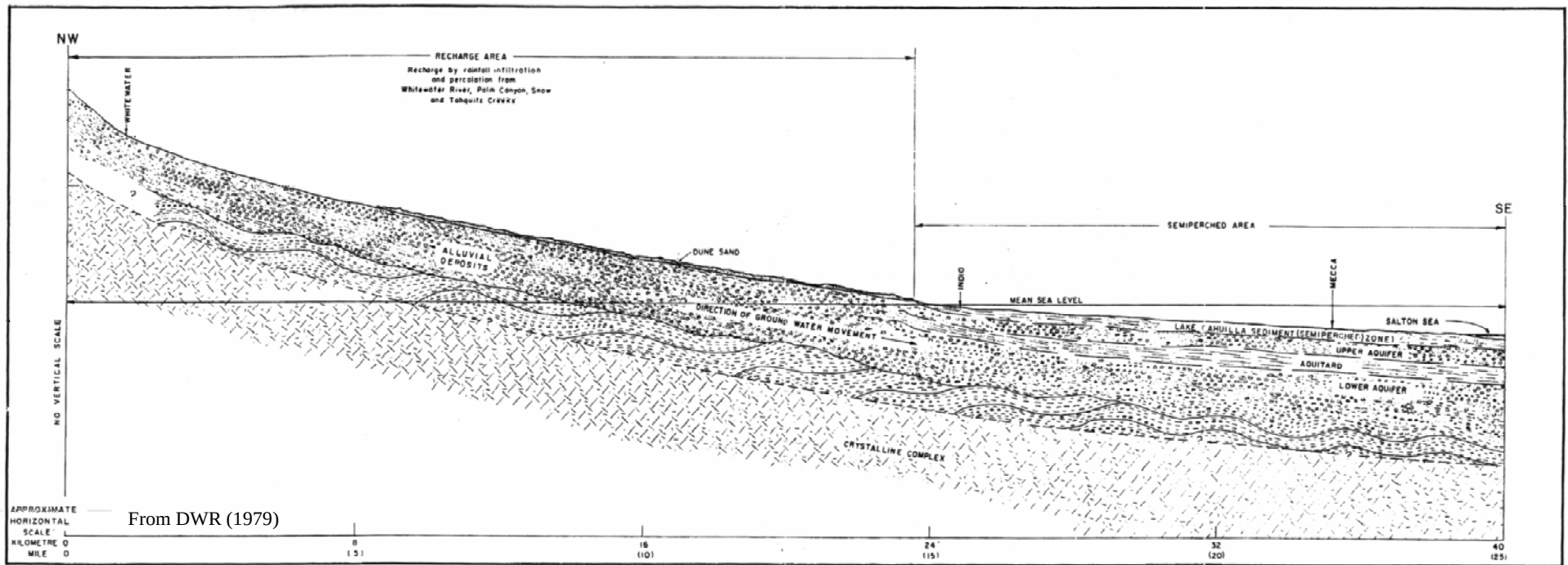
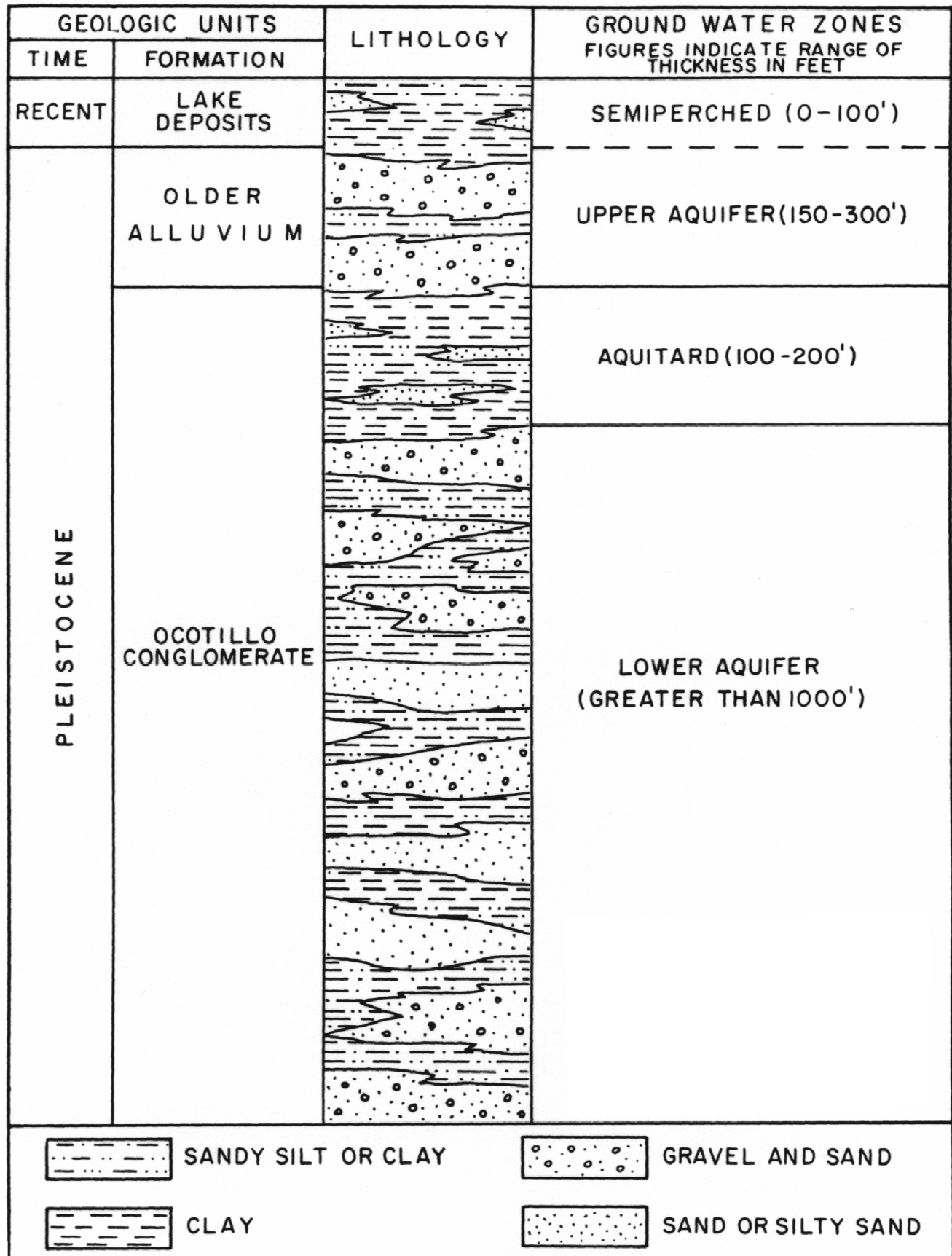


Figure 5.
Generalized stratigraphic column in lower Coachella Valley.



From DWR (1964)

Along the periphery of the entire valley, and in the upper valley from the San Gorgonio Pass to Cathedral City, are heterogeneous alluvial fan and stream wash deposits containing relatively small amounts of fine-grained materials. Thicknesses of the fan deposits commonly exceed 1,000 ft. Recent deposits, possibly 300 to 400 ft thick overlie the Ocotillo Conglomerate. In general, groundwater is unconfined, and the major sources of recharge to the aquifer are mountain-front recharge and streamflow infiltration, and subsurface inflow from San Gorgonio Pass.

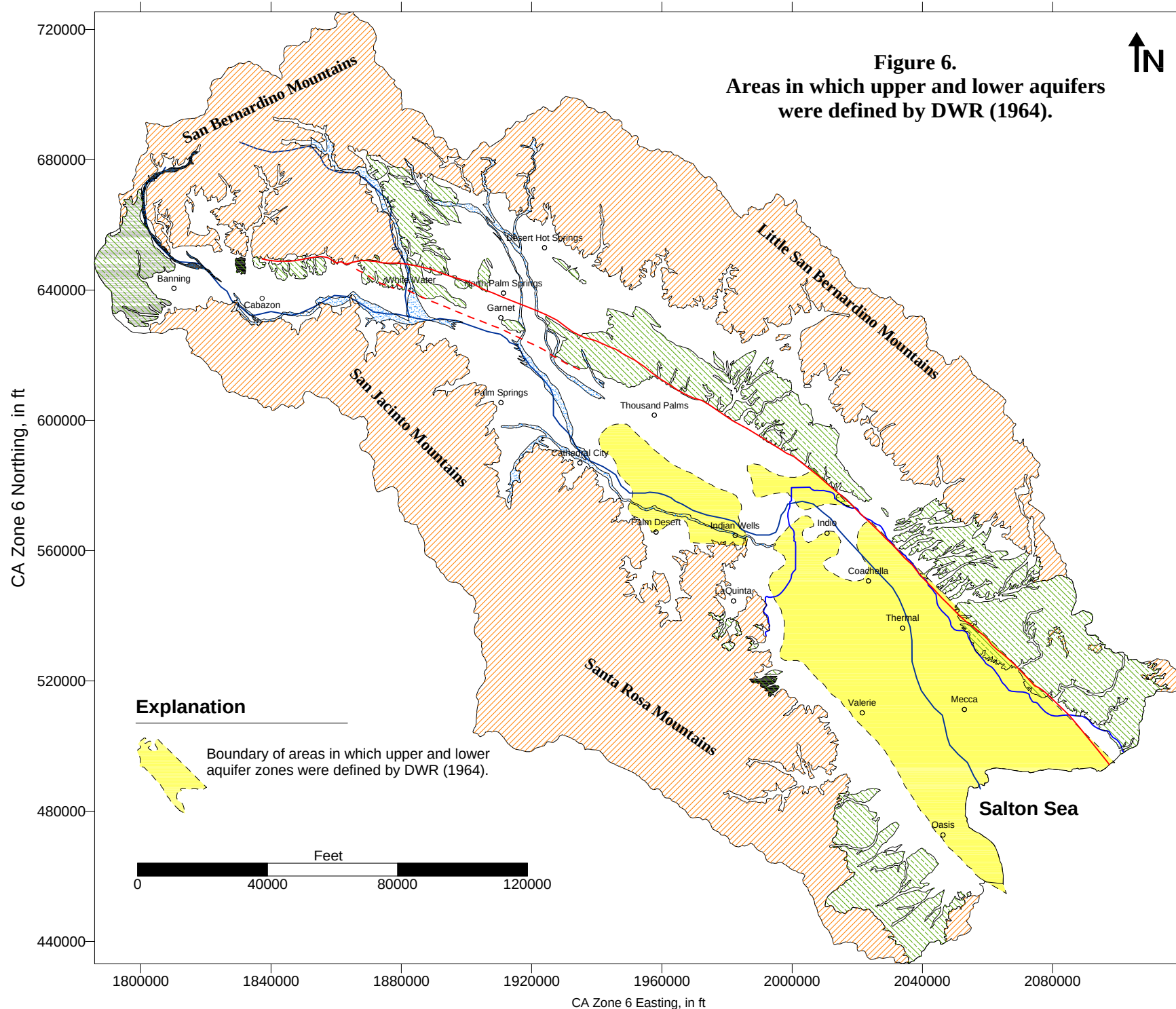
Alluvial plain and lake deposits (interbedded sand, silts and clays) underlie the center of the valley from as far north as Cathedral City to the Salton Sea. A large area in the center of the upper valley between Cathedral City and Point Happy is underlain by Recent dune sand. Active channel deposits (sand, gravel and boulders) are found along the Whitewater River and its tributaries (Fig. 3). Unconfined groundwater occurs in the alluvial fans at the base of the Santa Rosa Mountains, while confined or semiconfined conditions occur in the central part of the valley. Sand and gravel bodies are discontinuous and clay beds are often not extensive; however, two aquifer zones separated by a zone of fine-grained materials were identified from well logs (DWR, 1964). Figure 6 shows the extent of the zone where multiple aquifers were found. In a later report, DWR (1979) investigators found they could not correlate the aquitard throughout the lower valley.

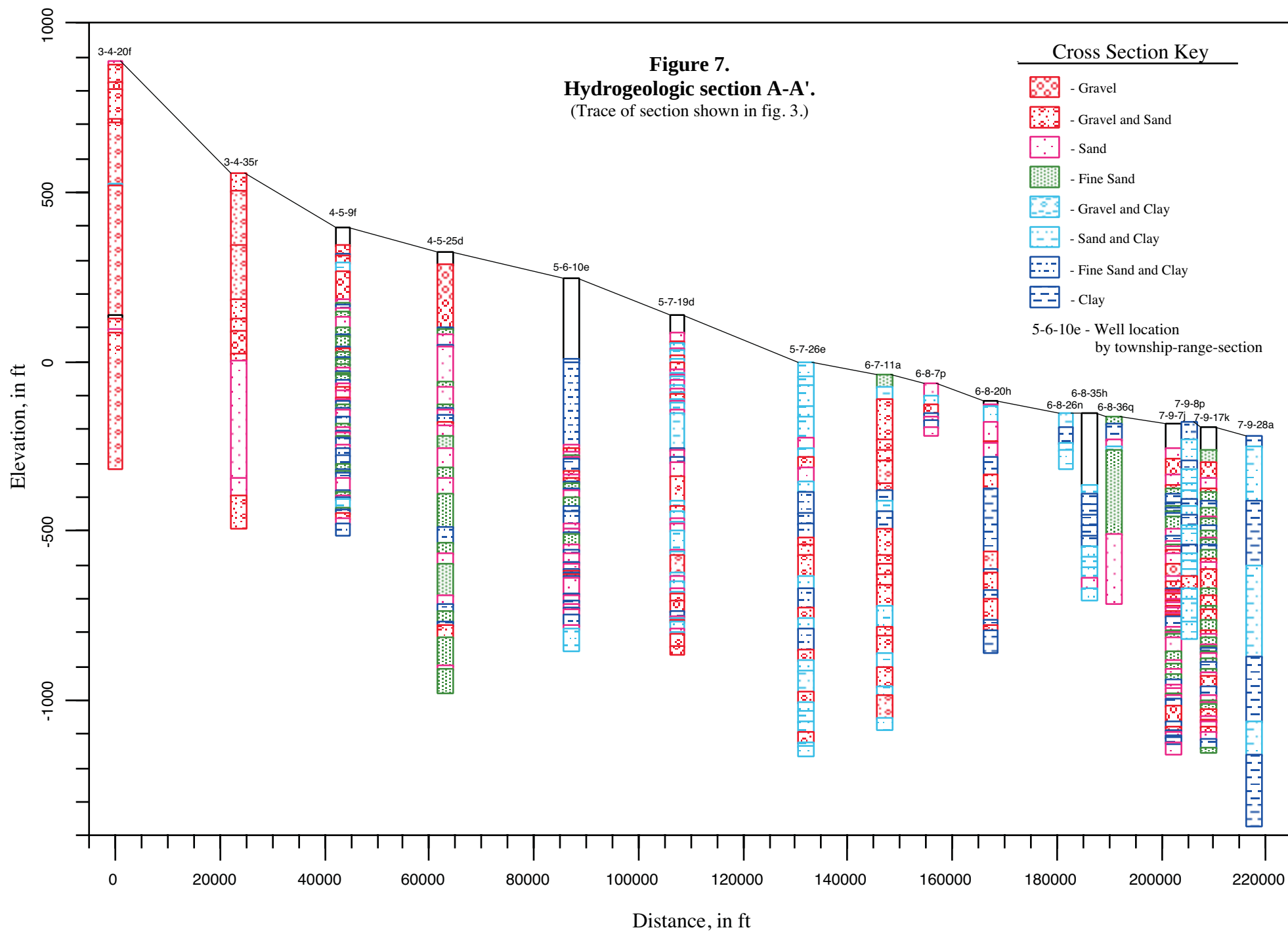
The present study found the geologic characterizations from DWR (1964; 1979) to be consistent with available electric and drillers log data; however, the data clearly show that the aquifers and aquitard in the multiple aquifer zones are complexly interbedded intervals of sand, gravel, silt and clay rather than distinct, coherent zones (Fig. 7). This is typical of the fluvial and alluvial fan depositional environments in which most of these sediments were deposited. Nevertheless, the conceptual model of an extensive confining unit of relatively low permeability (DWR, 1964) proved to be consistent with measured and model simulated water levels.

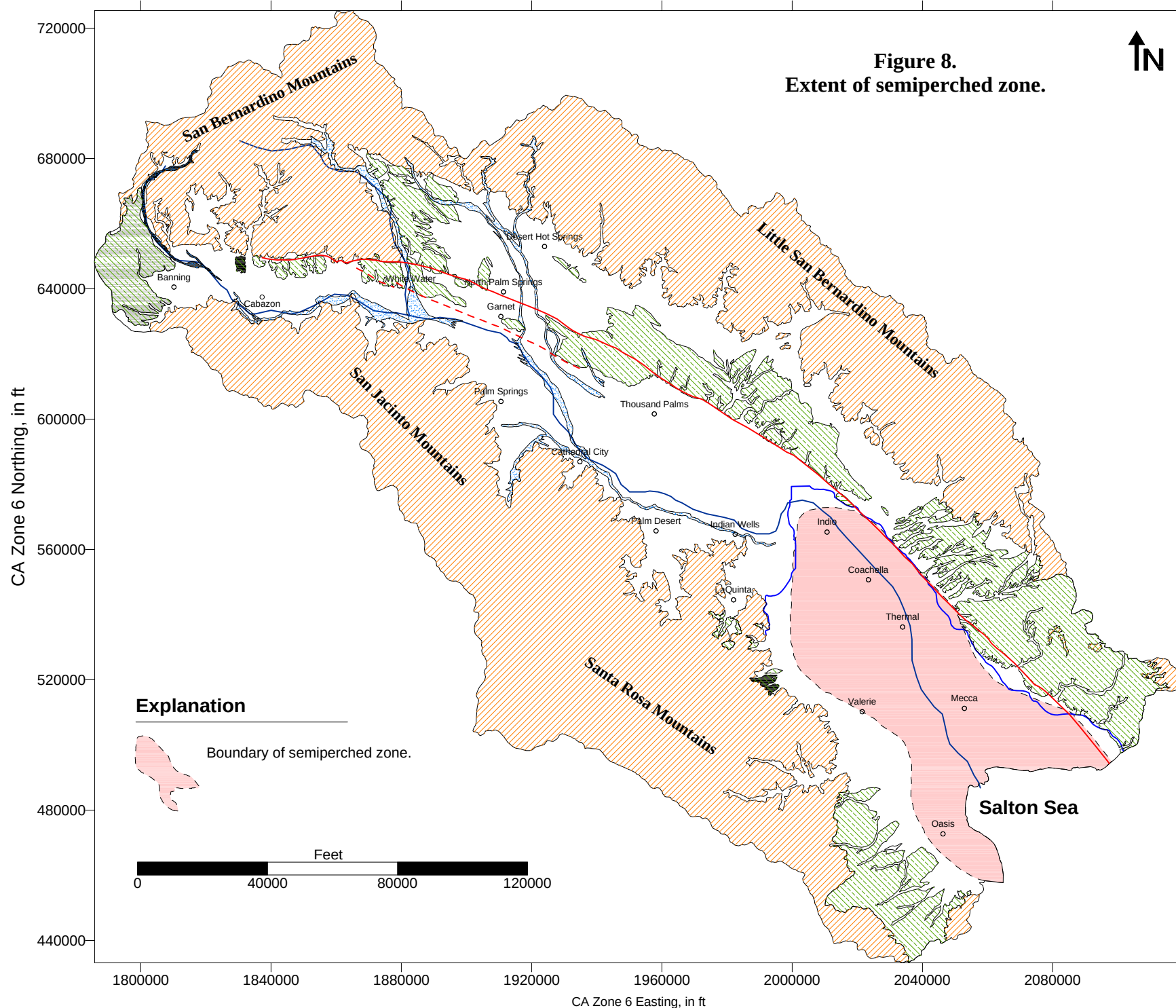
Southeast of Indio, Recent tight silts and clays up to 100 ft thick of the semiperched zone caps the upper aquifer. The low permeability of these materials retards deep percolation of irrigation water, causing drainage problems. Figure 8 shows the areal extent of the semiperched zone. No evidence has been found to suggest the semiperched zone is an actual perched aquifer; rather, conditions remain totally saturated below the semiperched aquifer.

Inflow to the aquifer system occurs as subsurface inflow and areal recharge. Subsurface inflow occurs from the San Gorgonio Pass and across the Banning Fault. Areal recharge includes streamflow infiltration, mountain-front recharge, irrigation return flow, sewage-effluent return flow, and artificial recharge. Streamflow infiltration and mountain-front recharge are the primary natural sources of water to the aquifer system.

The general direction of groundwater movement is southeastward toward the Salton Sea. Groundwater discharge from the aquifer system occurs from wells, drains, evapotranspiration from native vegetation, and as subsurface outflow to the Salton Sea.







The direction of vertical groundwater flow in the lower valley has changed over time due to development. DWR (1979, Plate 5) mapped the extent of flowing artesian conditions in 1905, 1946, and 1969. Artesian conditions were extensive in 1905, roughly equivalent to the area of the semiperched zone. By 1946, due to significant groundwater pumping from the lower aquifer, the area of artesian pressures had shrunk to less than half its 1905 extent. Since 1949, imported Colorado River water has been the principal irrigation water supply in the lower valley, and with reductions in agricultural pumpage, groundwater levels increased from 1950-75. Consequently, the extent of artesian conditions in 1969 had increased almost to 1905 conditions. However, since 1975 water levels have again been declining in the lower valley and the area of artesian conditions has declined significantly from its 1969 extent. Analysis of water level data suggests that the direction of vertical groundwater movement in the center of the lower valley has shifted from primarily upward in the early part of the century, to downward from the 1930's to the early 1950's, then upward again from the late 1950's through the mid-1970's, and mostly downward since.

Transmissive properties of the aquifer system are greatest in the upper alluvium along the Whitewater River channel in the upper valley, and within the alluvial fans along the southwestern boundary of the valley. Thus, except within Recent stream channel deposits, transmissivities are higher on the southwest margins of the basin grading to lower values in the center. Also, permeabilities tend to decrease southeastward toward the Salton Sea; well logs confirm the existence of low permeability silts and clays near, and presumably beneath, the Salton Sea. Additionally, low permeability materials characterize the semiperched zone and aquitard units in the lower valley.

Storage coefficients of the aquifer system are much greater in the upper unconfined alluvium than in the deeper confined units. The model computes the volume of water taken into and released from storage in the system with changes in hydraulic head.

2.5 Groundwater Development

A brief history of groundwater development in Coachella Valley through 1996 is presented here to document the significant natural events and human influences affecting groundwater in the basin. A review of these conditions aids in understanding the resulting groundwater levels in the basin and, in turn, performance of the model in the simulation of historical trends. Every major change in groundwater levels and flows computed by the model can be attributed directly to historical events in the basin.

The modern history of the Coachella Valley began with the completion of the Southern Pacific railroad in 1879 (DWR, 1964). The railroad used artesian wells, and farmland was put under production as settlement of the area began. Irrigation development did not advance rapidly because of the prohibitive cost of drilling and operating wells. But the development of economical well-drilling methods and pumping machinery around 1900 lessened the costs, and by 1906, 400 wells had been installed; by 1916, the irrigated land in Coachella Valley increased to 7,000 acres.

The Salton Sea was formed from 1904 to 1907 as a result of diversion of Colorado River water for irrigation in Imperial Valley, and the concurrent occurrence of floods in the Colorado River (Hely et. al, 1966). The present day Sea has been sustained chiefly by drainage from irrigated

lands in Imperial Valley. Figure 9 is a chart of Salton Sea water surface elevations showing how the present sea level has evolved since 1904.

Increasingly, more agricultural land was developed and the limitations of the natural water supply became evident as groundwater levels in the valley declined. In 1918, CVWD was formed to protect, conserve, and supplement Coachella Valley's water supplies. In 1919, CVWD built recharge ponds near Windy Point to capture and percolate runoff from the Whitewater River.

CVWD early recognized the need for additional water beyond the natural replenishment to support the continued development of the varied economies in the valley. In 1934, CVWD contracted to build the Coachella Branch of the All-American Canal to bring Colorado River water to Coachella Valley. Construction of the Coachella Canal began in 1938 when there were about 14,000 acres of land under irrigation, and was completed in 1948 when there were about 23,000 acres under irrigation. By then, increased pumping of groundwater for municipal and recreational use in the upper valley, and for agricultural use in the lower valley, had led to widespread water-level declines. Since 1948, irrigated agriculture has increased rapidly; today there are over 60,000 acres being farmed (Fig. 10).

With the completion of the Coachella Canal in 1948, imported water from the Colorado River began to supplement groundwater use for agriculture in the lower valley, and concurrent reductions in groundwater pumpage helped to alleviate the overdraft. As shown on Figure 11, annual deliveries of Colorado River water via the Coachella Canal rose from about 30,000 acre-ft per year in 1949 to over 300,000 acre-ft per year in 1958; also, between 1958 and 1975, Coachella Canal deliveries averaged about 325,000 acre-ft per year, reaching a high value of nearly 370,000 acre-ft in 1975. However, since the late 1970's, the demand for water in the lower valley has increased relative to the deliveries of imported surface water. As a result, groundwater levels have again been declining in the lower valley, due to decreasing annual deliveries of water from the Coachella Canal, and concomitant increases in groundwater production necessary to meet the demand. In fact, from 1976 to 1996, annual canal deliveries declined and averaged less than 300,000 acre-ft per year (Fig. 11).

Figure 12 shows a typical hydrograph for a well in the lower valley. Note that water levels declined from the late 1920's until groundwater pumpage decreased when Coachella Canal water became available in 1949. Higher water levels, from the late 1950's to the late 1970's resulted from a combination of decreased pumpage and the use of imported water as the primary source for irrigation. Water levels have declined since the 1970's due to declining deliveries of imported water for irrigation, and associated increasing rates of groundwater pumpage.

Beginning in 1950 and largely completed by 1975, CVWD installed and maintains a system of 166 miles of pipe and 21 miles of open drains that serve as a drainage network for irrigated lands. Subsurface tile drains intercept high groundwater and irrigation return flows while controlling soil salinity. Most of the drainage empties into the CVSC and ultimately to the Salton Sea. Figure 13 charts the total acreage served by drains over time. Figure 14 charts the total annual measured agricultural drain flows.

Figure 9.
Historic surface elevation of Salton Sea.

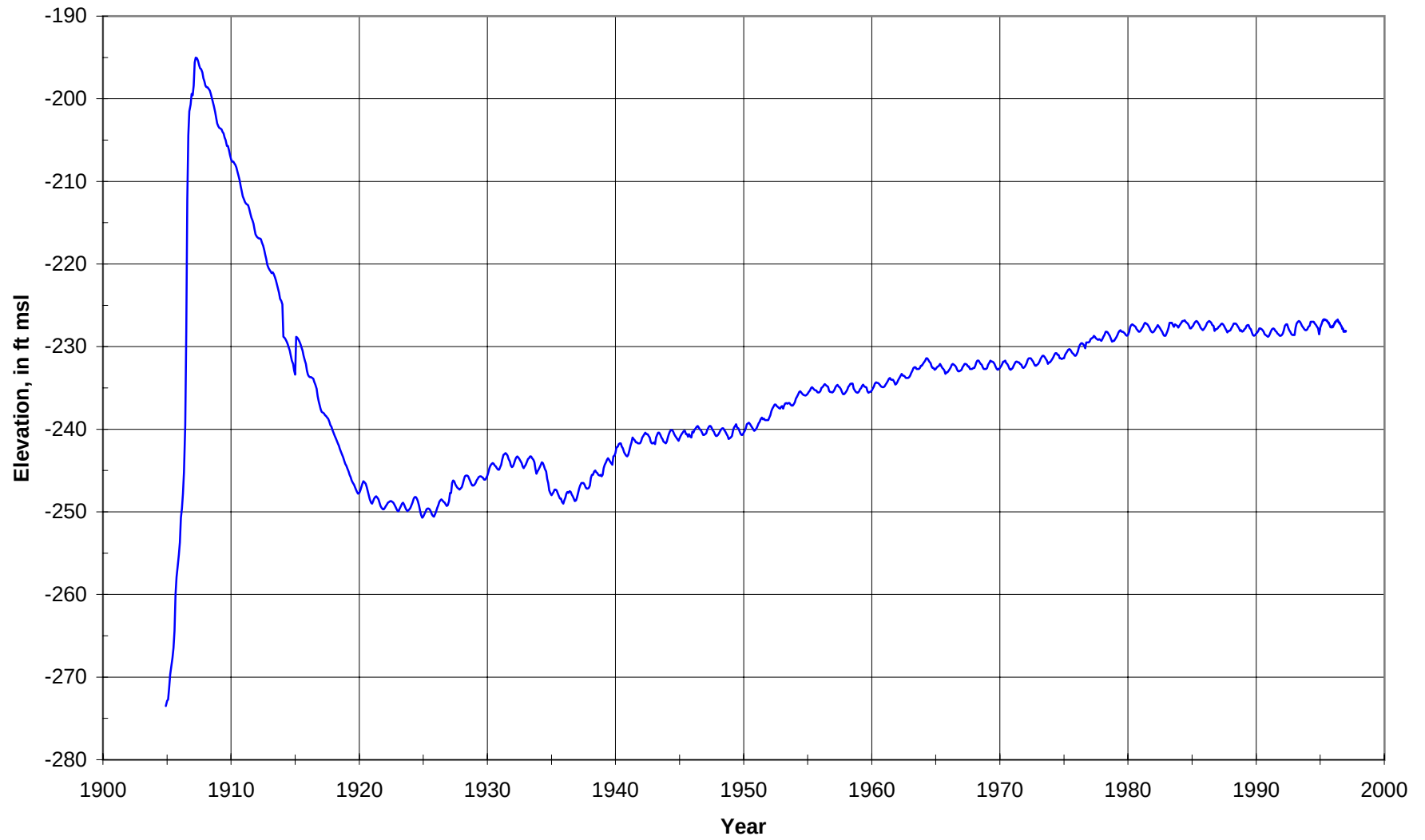


Figure 10.
Agricultural acreage in Coachella Valley.

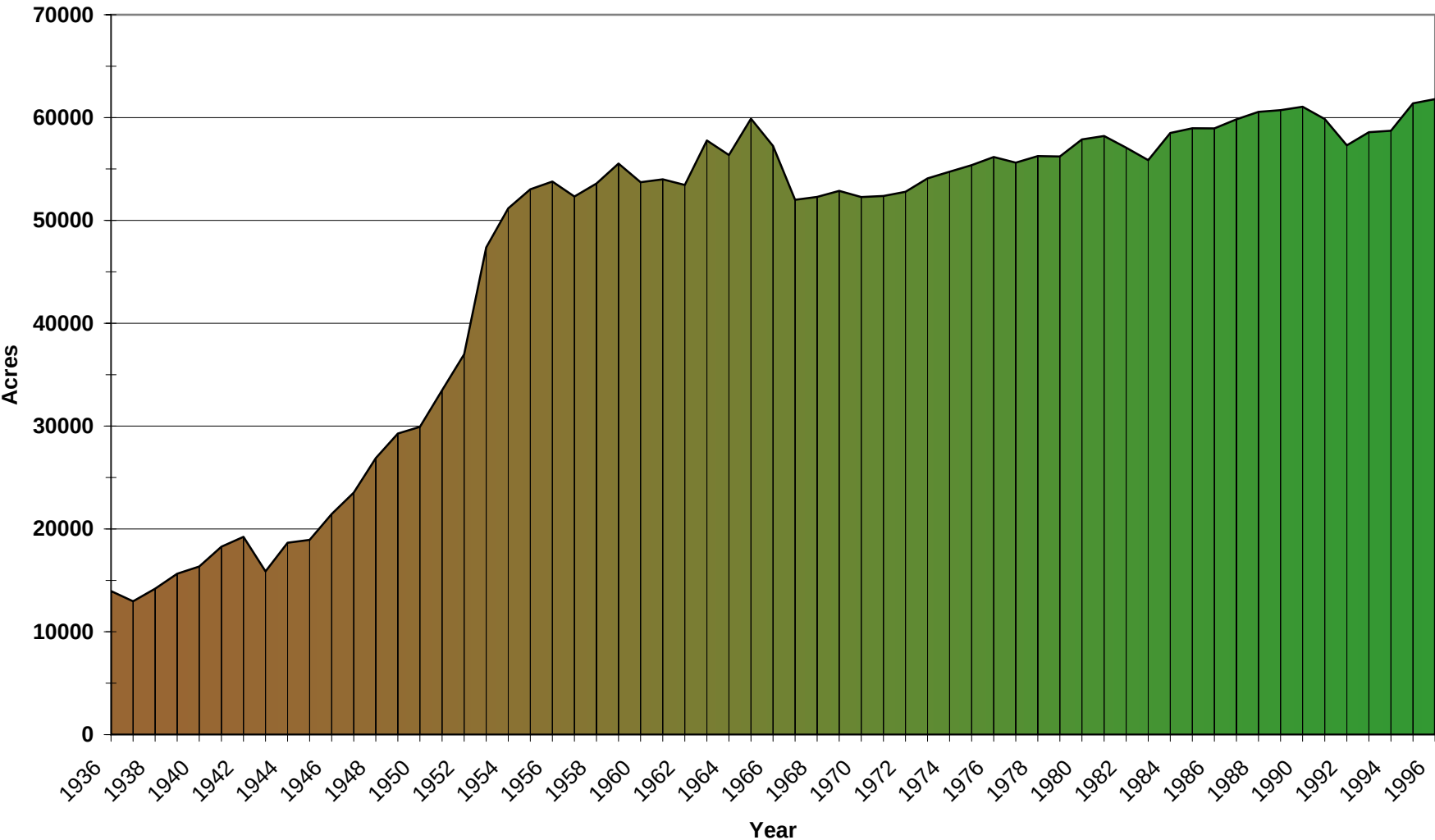


Figure 11.
Total annual farm deliveries from Coachella Canal.

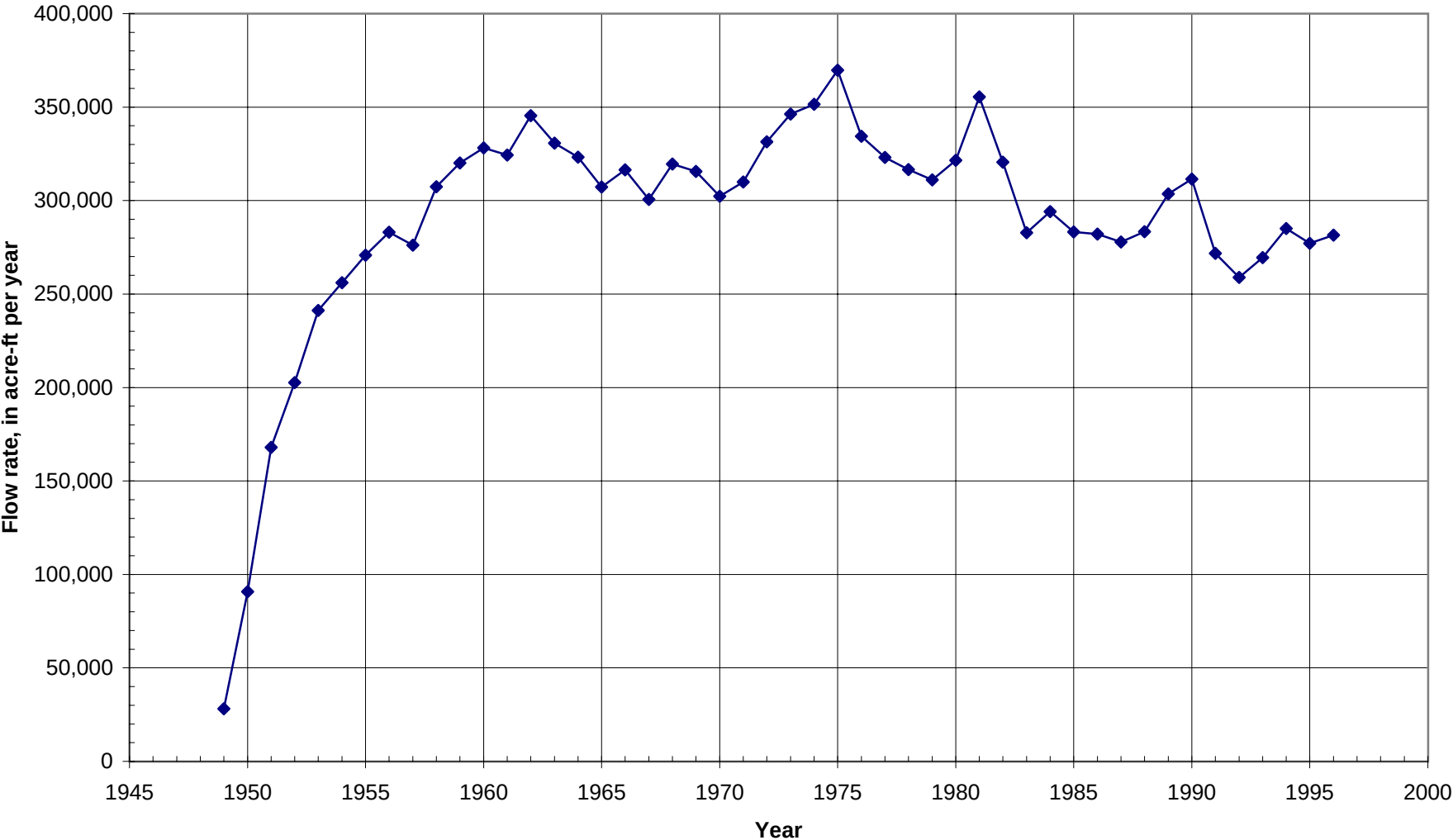


Figure 12.
Hydrograph of lower valley well 06S07E22B01S.

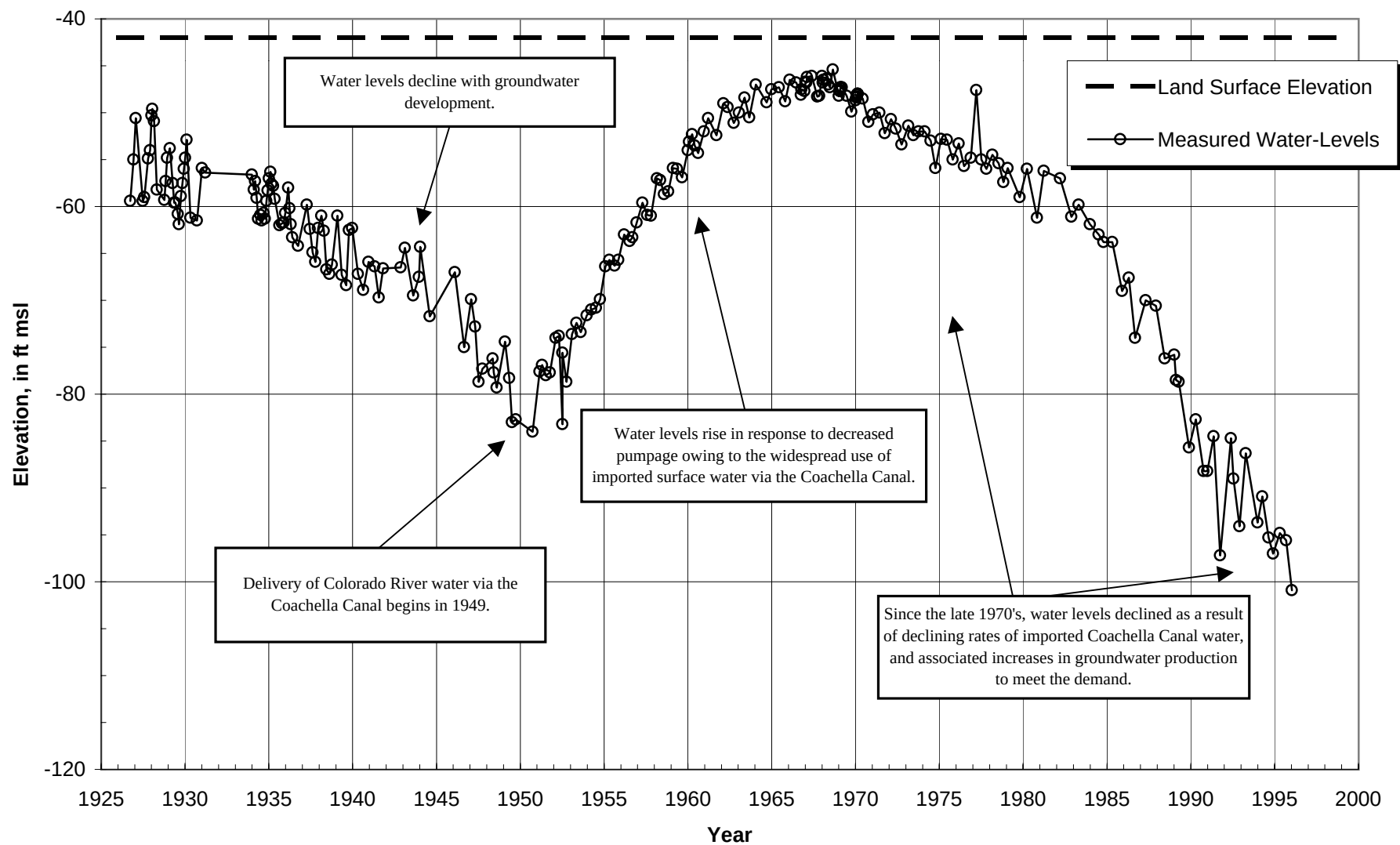


Figure 13.
Total farm acreage served by drains.

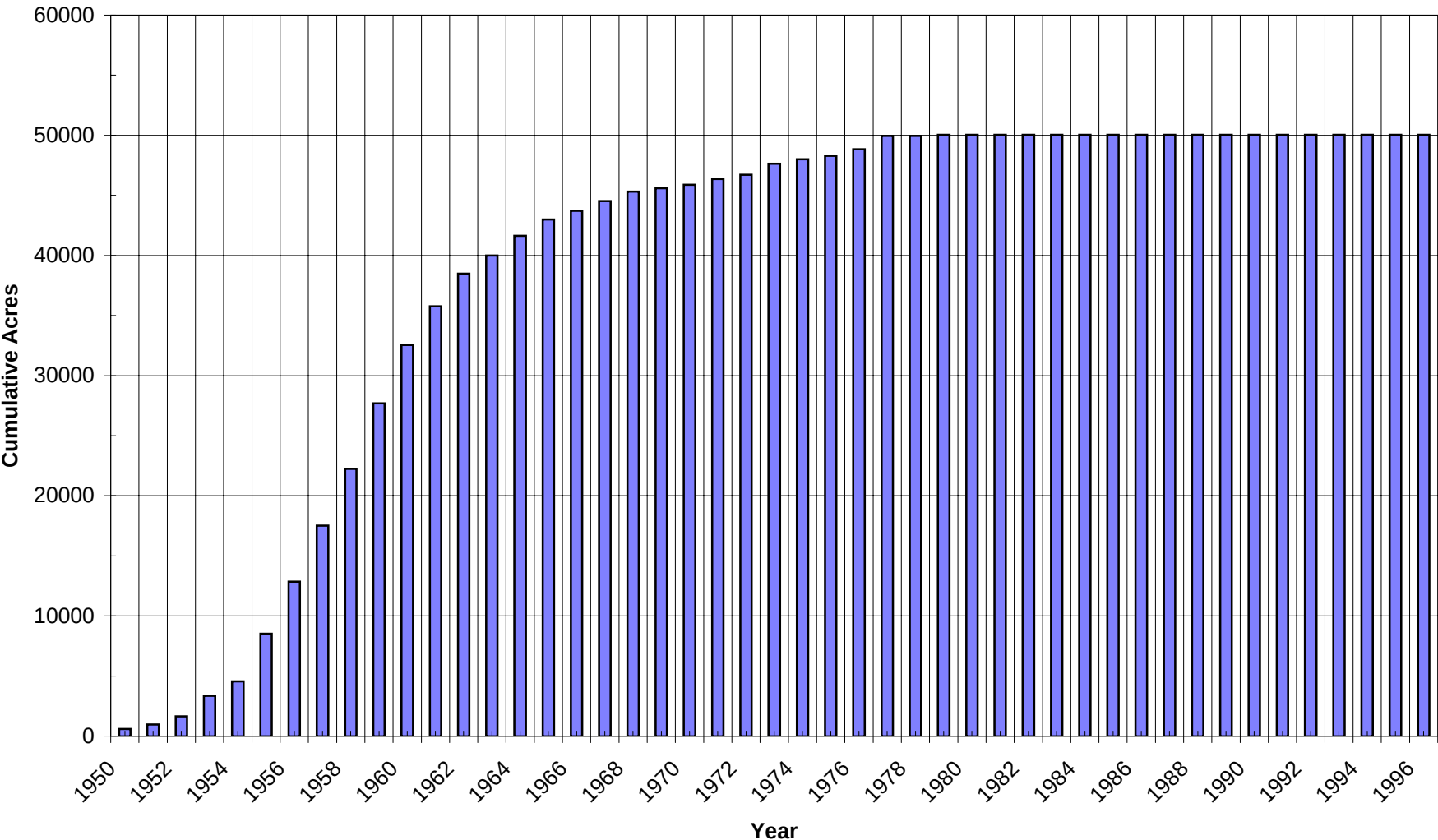
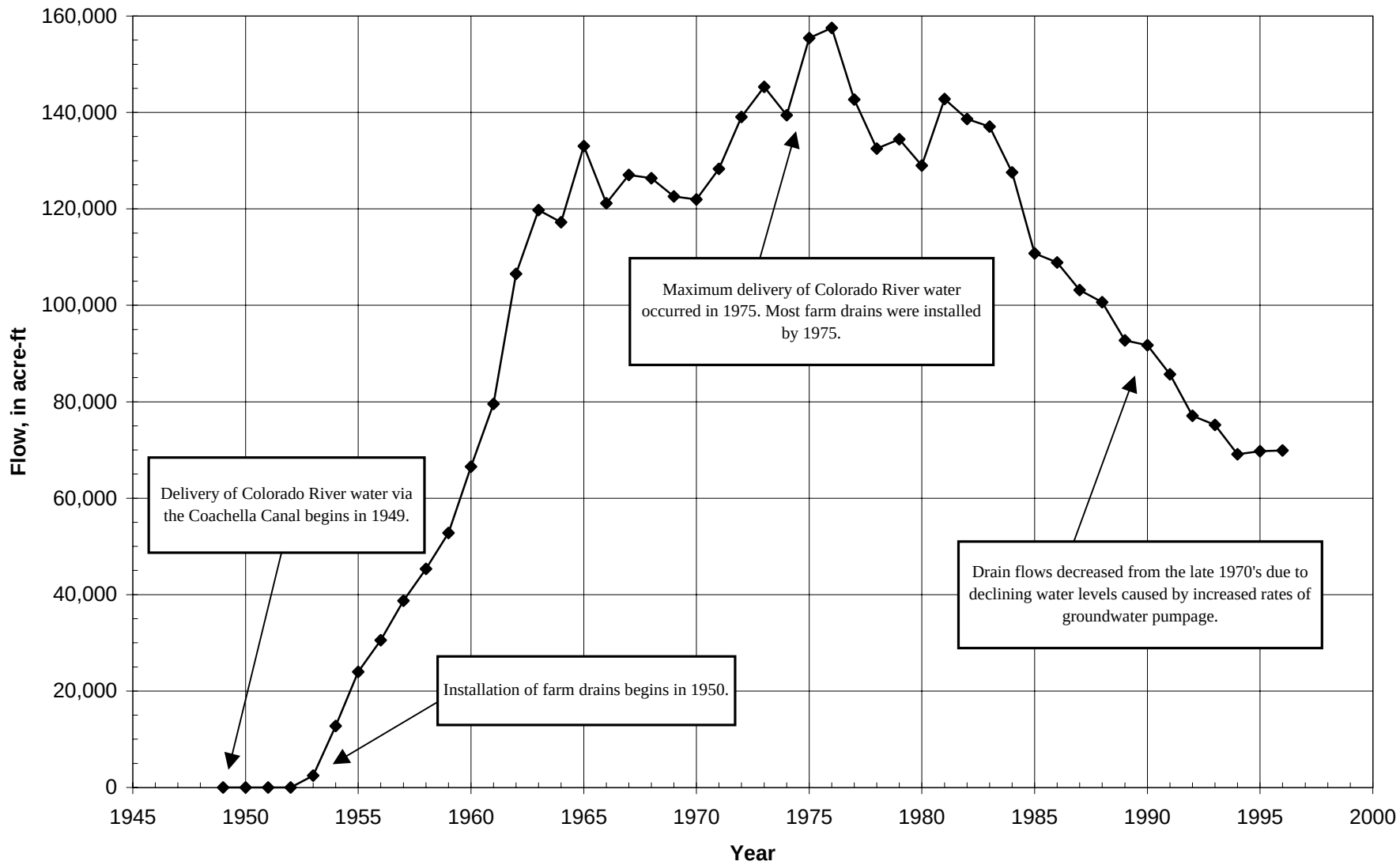


Figure 14.
Total annual agricultural drain flows.



In 1963, CVWD and Desert Water Agency (DWA) entered contracts with the state for entitlements to State Water Project (SWP) water. CVWD and DWA entered an exchange agreement with Metropolitan Water District of Southern California (Metropolitan) to trade their SWP entitlement for the same amount of Colorado River water (from Metropolitan's Colorado River Aqueduct, which crosses Coachella Valley near White Water). In 1972, CVWD expanded the percolation ponds near Windy Point, and in 1973, CVWD and DWA began to receive these exchange waters. Figure 15 shows the total annual diversions from the Colorado River Aqueduct into the Whitewater River for artificial recharge at Windy Point.

By 1974, groundwater levels had declined from 60 to over 100 ft below their 1936 levels in the upper valley. Groundwater pumpage has continued to increase in the upper valley; however, above average precipitation in the late 1970's, early 1980's and mid-1990's, combined with significant artificial recharge in the 1980's, temporarily slowed the rate of water-level declines. Nevertheless, water levels are presently declining in the upper valley. Figure 16 shows a characteristic hydrograph for a well in the upper valley. Note that water levels declined from the beginning period of measurement until the late 1970's and early 1980's when significant precipitation and artificial recharge occurred in the upper valley.

3 MODEL CONSTRUCTION

The model is implemented with the computer code MODFLOW (McDonald and Harbaugh, 1988), which simulates groundwater flow in three dimensions using a block-centered finite-difference approach. The code conforms to modern theory and standard practice for solving the equations of groundwater motion and provides an excellent means of representing the complex aquifer system in Coachella Valley.

The area covered by the groundwater model is shown on Figure 17. The upstream and downstream ends of the model correspond to the San Gorgonio Pass area and Salton Sea, respectively. The southwest flank of the model represents the interface between the unconsolidated sedimentary fill and consolidated to semi-consolidated rocks of the San Jacinto and Santa Rosa Mountains. The northeast flank of the model represents the interface between the unconsolidated sedimentary fill and consolidated to semi-consolidated rocks of the Little San Bernardino Mountains, Indio Hills, and Mecca Hills. Most of the ephemeral stream flow into the basin originates along the southwest flank. Note that the San Gorgonio Pass, Mission Creek and Desert Hot Springs subbasins are not explicitly modeled; subsurface outflow from these subbasins into the main basin is included in the boundary conditions at the Pass, and along the Banning and San Andreas faults.

3.1 Finite-Difference Mesh

The model consists of a three-dimensional, finite-difference mesh of blocks called cells, the locations of which are described in terms of the 270 rows, 86 columns and 4 layers in the mesh. At the center of each cell there is a point called a node at which head is calculated. The model has a node spacing of 1,000 ft in the x-y plane, and variable vertical node spacing representing variable thicknesses of the corresponding aquifer or aquitard intervals. The mesh is oriented along the length of the valley, coinciding with the principal direction of regional groundwater flow.

Figure 15.
Total annual water diverted from Colorado River Aqueduct to Whitewater River.

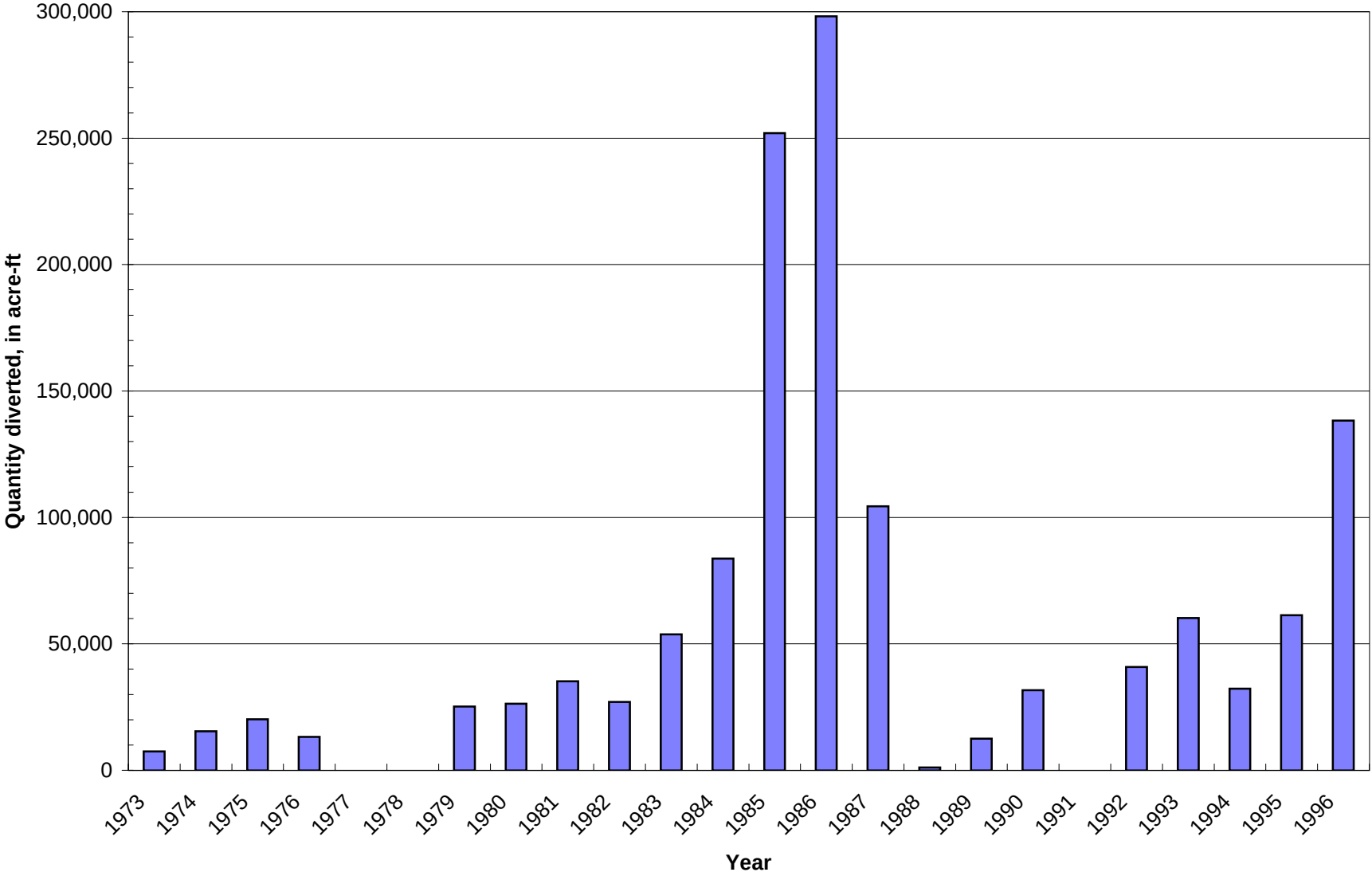
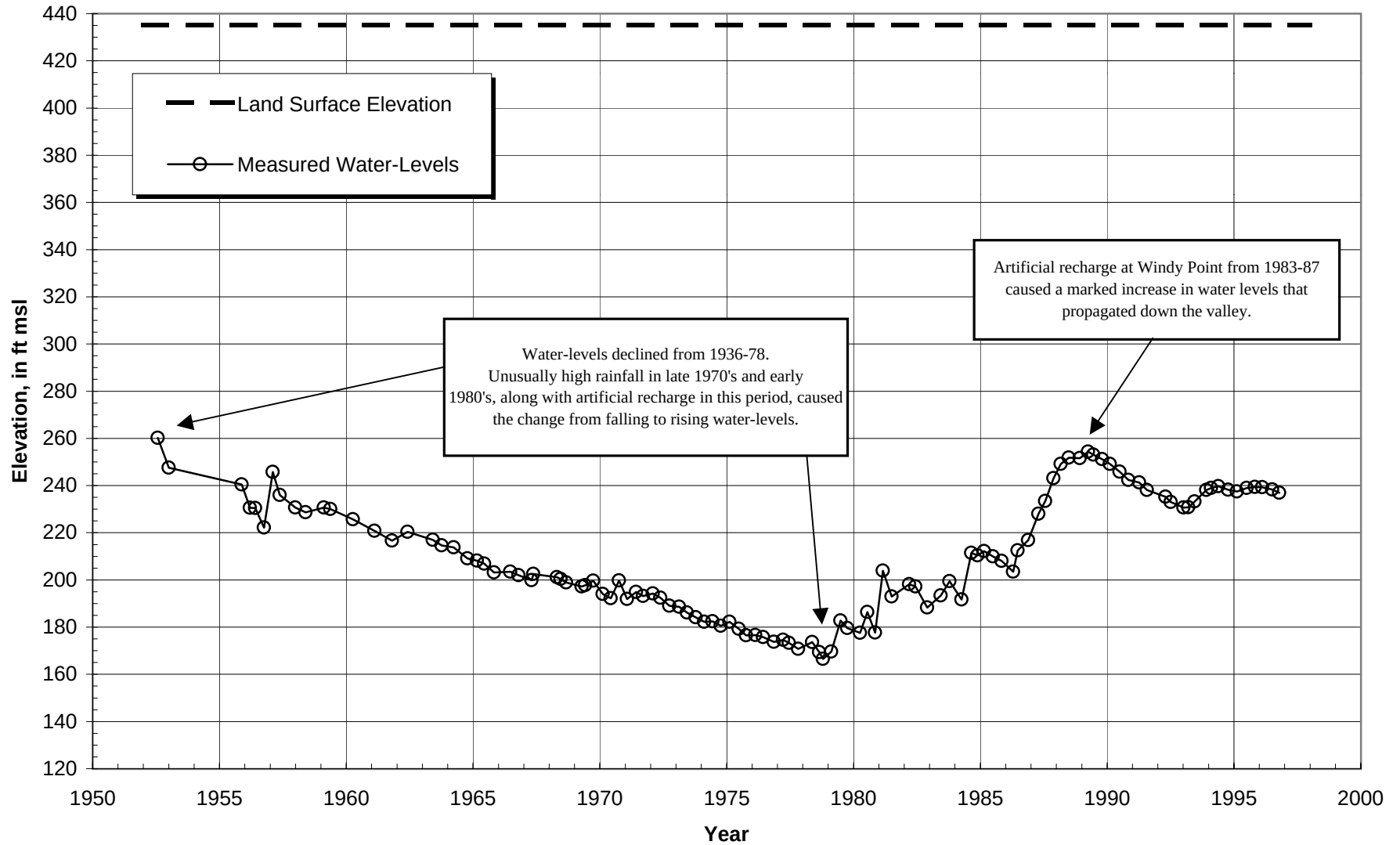


Figure 16.
Hydrograph of upper valley well 04S04E15J01S.



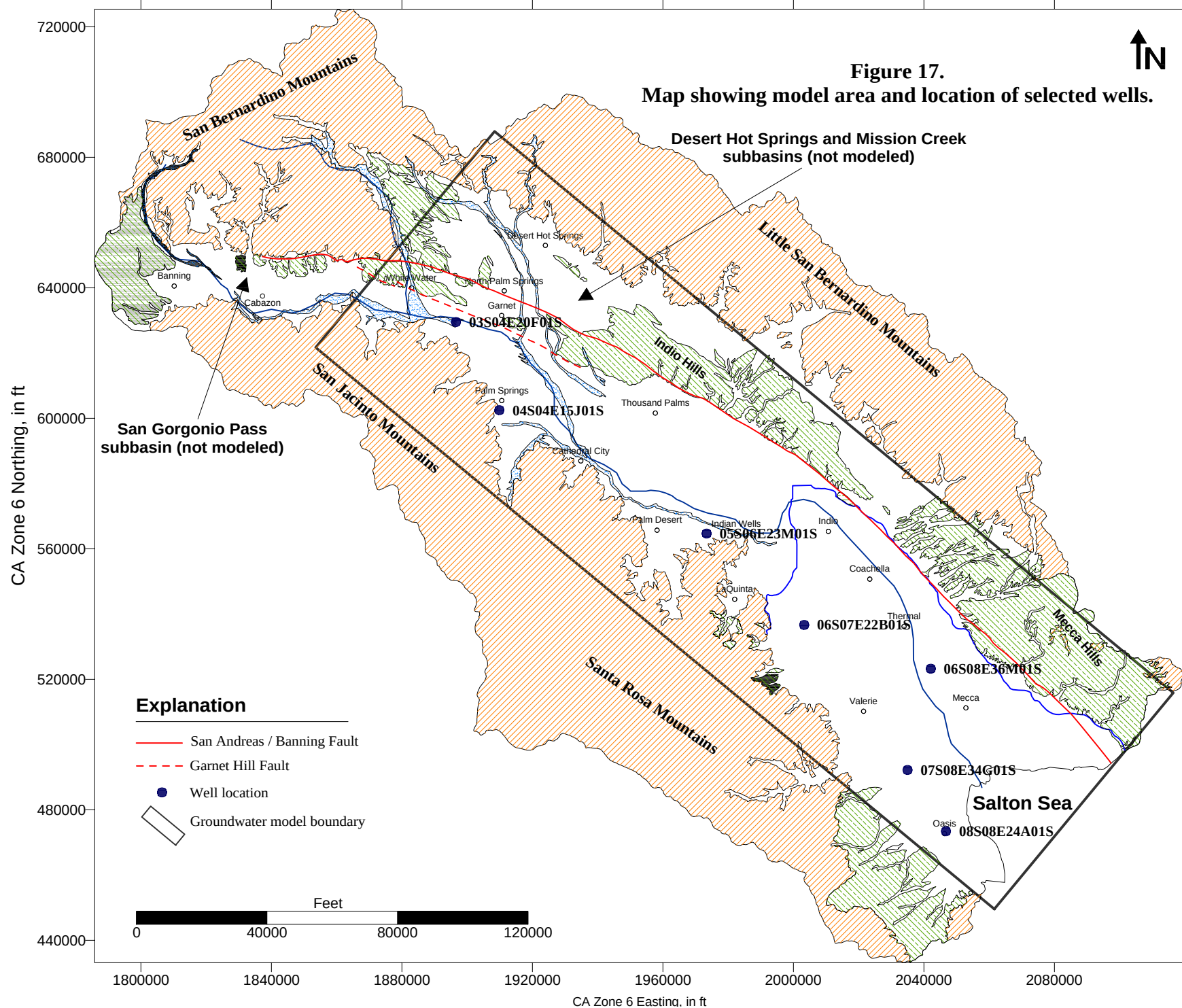


Figure 18 shows the horizontal layout of the mesh for layer 1, the uppermost layer. The shaded cells around the perimeter are inactive (no-flow) cells and define the x-y plane geometry of the flow region. The inactive cells lie in areas of low-permeability, consolidated to semiconsolidated rocks or in subbasins of Coachella Valley that are substantially isolated from the main basin by faults (see Tyley, 1974). The 48,396 active cells represent unconfined and confined aquifer systems in the Recent and Pleistocene sedimentary fill.

Figure 19 shows a cross-section of the groundwater model mesh along the length of the valley, roughly through its center; Figure 20 shows a section that crosses the valley near the city of Coachella. Top and bottom elevations of the four model layers are placed mainly to represent the multiple aquifer zones present in the lower valley and were derived from USGS digital elevation models (DEM), and hydrogeologic characterizations from DWR (1964; 1979).

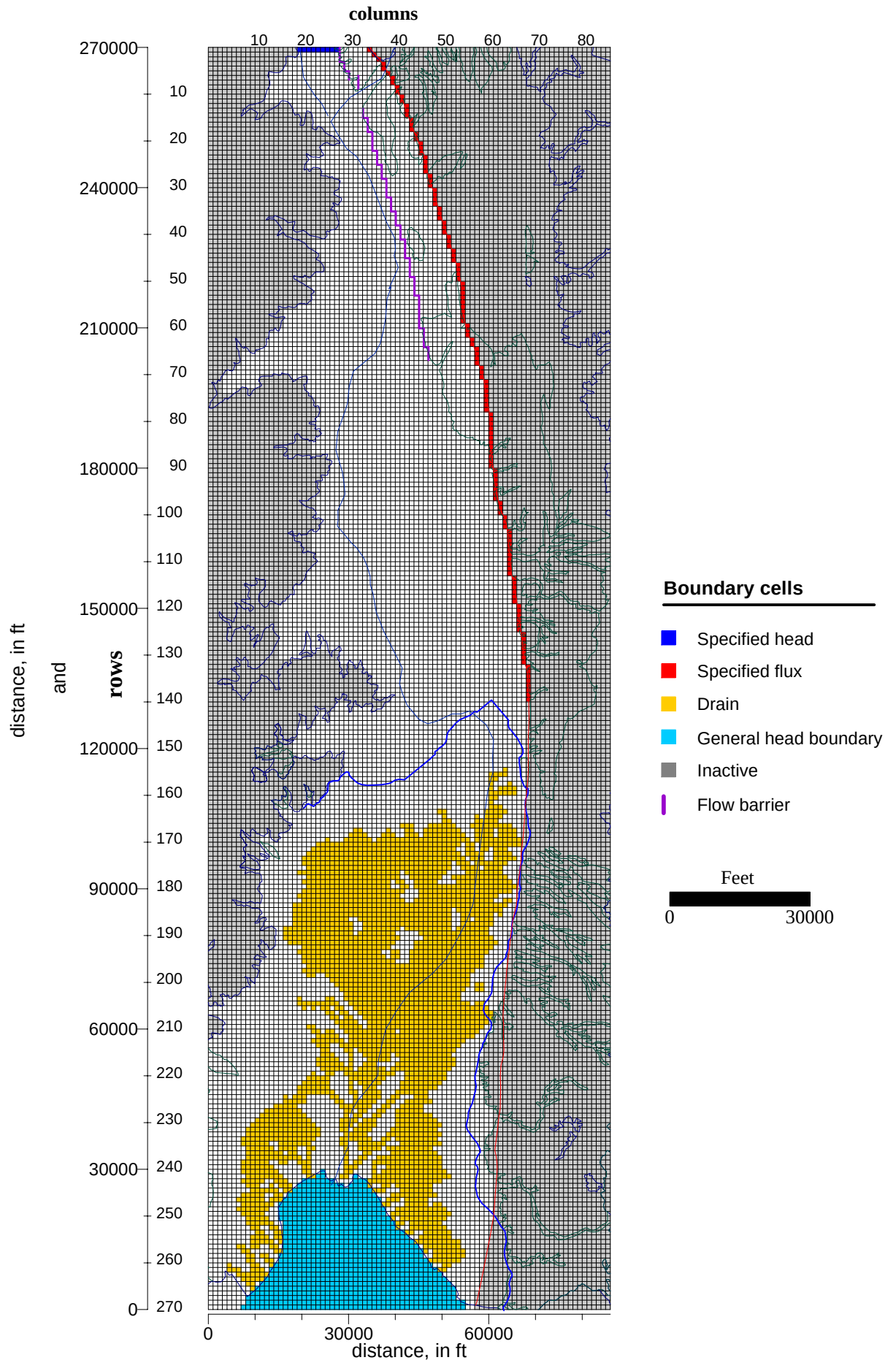
In the areas containing multiple aquifers (Fig. 6), layer 4 represents the lower aquifer, layer 3 represents an aquitard zone, layer 2 represents an upper aquifer, and layer 1 represents the semiperched zone (Fig. 8) in the lower valley and a shallow aquifer interval elsewhere. Near the southwest margin, total thickness of the layers slightly thins toward the San Jacinto and Santa Rosa Mountain front, where thickness of the sedimentary fill decreases. Outside the multiple aquifer zones, the four layers have no particular geologic significance but allow computation of vertical flow components in areas like the Whitewater River spreading ponds. No laterally extensive confining beds were found to exist outside the multiple aquifer zones. All the pumpage in the model comes from layers 4 and 2.

3.2 Boundary Conditions

Boundary conditions are used anywhere in the model domain to account for water entering or leaving that domain. Boundary conditions account for sources of water such as recharge ponds and subsurface inflow from adjacent basins, and wells and drains where groundwater discharges from the flow system. Model input data describing each set of boundary conditions were developed for the 51 stress periods that define conditions from 1936-96.

The active area of the model is bounded by the San Gorgonio Pass up slope (northwest) and the Salton Sea down slope (southeast), the San Jacinto and Santa Rosa Mountains and associated canyons along the southwest margin, and the Banning and San Andreas faults along the northeast margin. The base of the model represents the depth to which fresh water actively circulates. In the upper valley, the thickness of the active flow system is approximately 1,000 ft, based on observed decreasing resistivity with depth in geophysical logs and on maximum well depths (Reichard and Meadows, 1992). In the lower valley, thickness of the active flow system ranges from 1,000 ft to over 1,500 ft based on well logs and geologic characterizations from DWR (1964). The upper boundary of the flow system is the water table; processes affecting this boundary include recharge, drains, and evapotranspiration from natural vegetation.

Figure 18.
Model mesh and boundaries in uppermost layer.



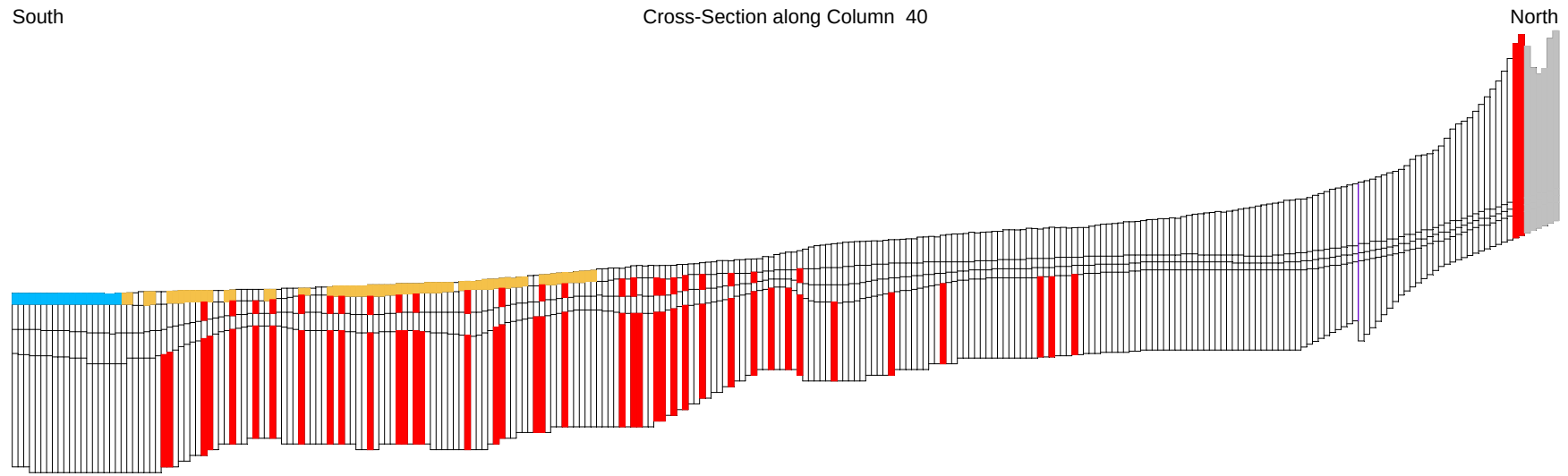


Figure 19.
Cross-section of model mesh along length of valley.

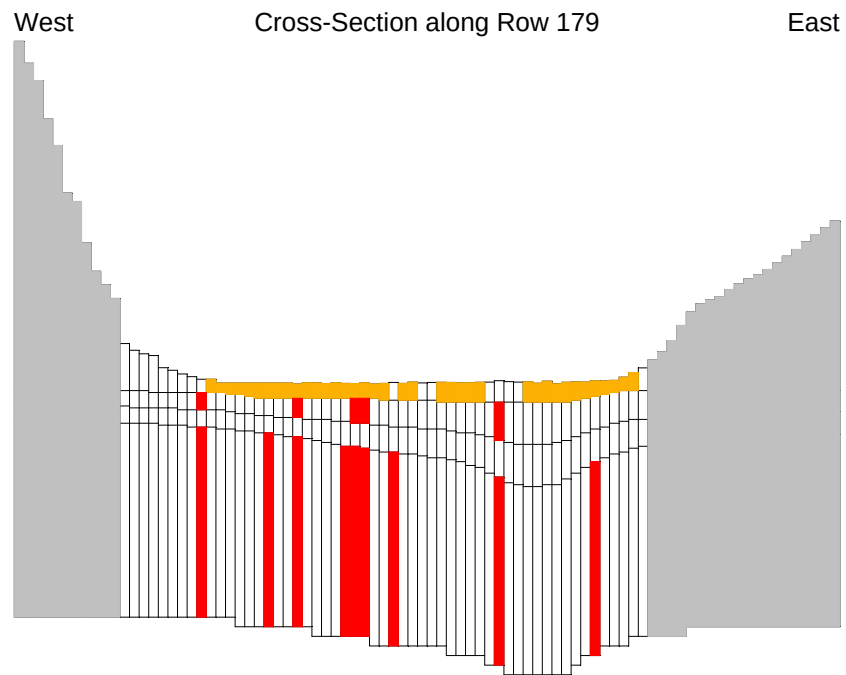


Figure 20.
Cross-section of model grid near Coachella. Vertical Exaggeration: 20x

Brief descriptions of the model boundary conditions and the methods used to estimate the boundary heads and fluxes are discussed in this section. Some boundary conditions represent flows that are input to the model, such as pumpage and recharge. Others, such as drains, evapotranspiration, and the Salton Sea boundary, are head-dependent boundaries where flows are computed by MODFLOW.

3.2.1 Natural Recharge

Recharge to the groundwater system from natural sources includes precipitation on the valley floor, infiltration of runoff from precipitation in the mountains, and inflows from adjacent groundwater basins.

3.2.1.1 Inflow from San Gorgonio Pass Area

The San Gorgonio Pass subbasin (DWR, 1964) is located northwest of the valley proper; groundwater flows from the subbasin into the model area across a buried bedrock ridge about one mile west of the junction of Interstate 10 and State Highway 111. Drainage within the pass area is tributary to Coachella Valley via the San Gorgonio River that enters the Whitewater River channel above Windy Point. However, there are no data available on streamflow in the San Gorgonio River near Windy Point.

A time-variant specified head boundary condition was used to model inflow from the San Gorgonio Pass for the period 1936-96. Measured groundwater levels in the vicinity of the boundary were used to specify the time-dependent head.

3.2.1.2 Inflow Across Banning and San Andreas Faults

Subsurface inflow occurs across the Banning and San Andreas faults, which form the northeasterly boundary of the main groundwater basin. These faults are segments of the San Andreas Fault zone, which consists of several parallel faults, some of which diverge from the main fault system.

The Banning Fault extends from the west end of San Gorgonio Pass easterly and then curves southeasterly along the Indio Hills. The Banning Fault is considered an effective, but imperfect, barrier to groundwater movement based on significant groundwater level and quality differences across the fault. In the portion extending southeasterly from the San Bernardino Mountains to the Indio Hills, the Banning Fault separates the Mission Creek subbasin to the northeast from the Garnet Hill subbasin on the southwest. Groundwater level differences across the Banning Fault in this area are on the order of 200-250 ft. Along the Indio Hills, springs, cienegas and dense vegetation in canyon oases stem from the barrier effects of the fault. Tyley (1974) estimated flow across the Banning Fault into the Garnet Hill Subbasin to be 2,000 acre-ft per year. This value was assigned uniformly to specified-flux cells along the fault in the current model.

The Banning Fault merges with the Mission Creek Fault in the central Indio Hills. From this point southeasterly, the fault is generally referred to as the San Andreas Fault. The presence of palm tree oases along the southwest flank of the Indio Hills and abrupt changes in vegetation southeast of the Indio Hills are indicative of the effectiveness of this zone as a barrier to

groundwater flow (DWR, 1964). Additionally, contour maps of groundwater elevations in the lower valley over time generally show equipotential lines terminating at the San Andreas Fault at right angles, supporting the designation of the fault as a no-flow boundary. No recent water level data across the fault are available in this region; however, DWR reported water level differences of about 50 ft in 1961.

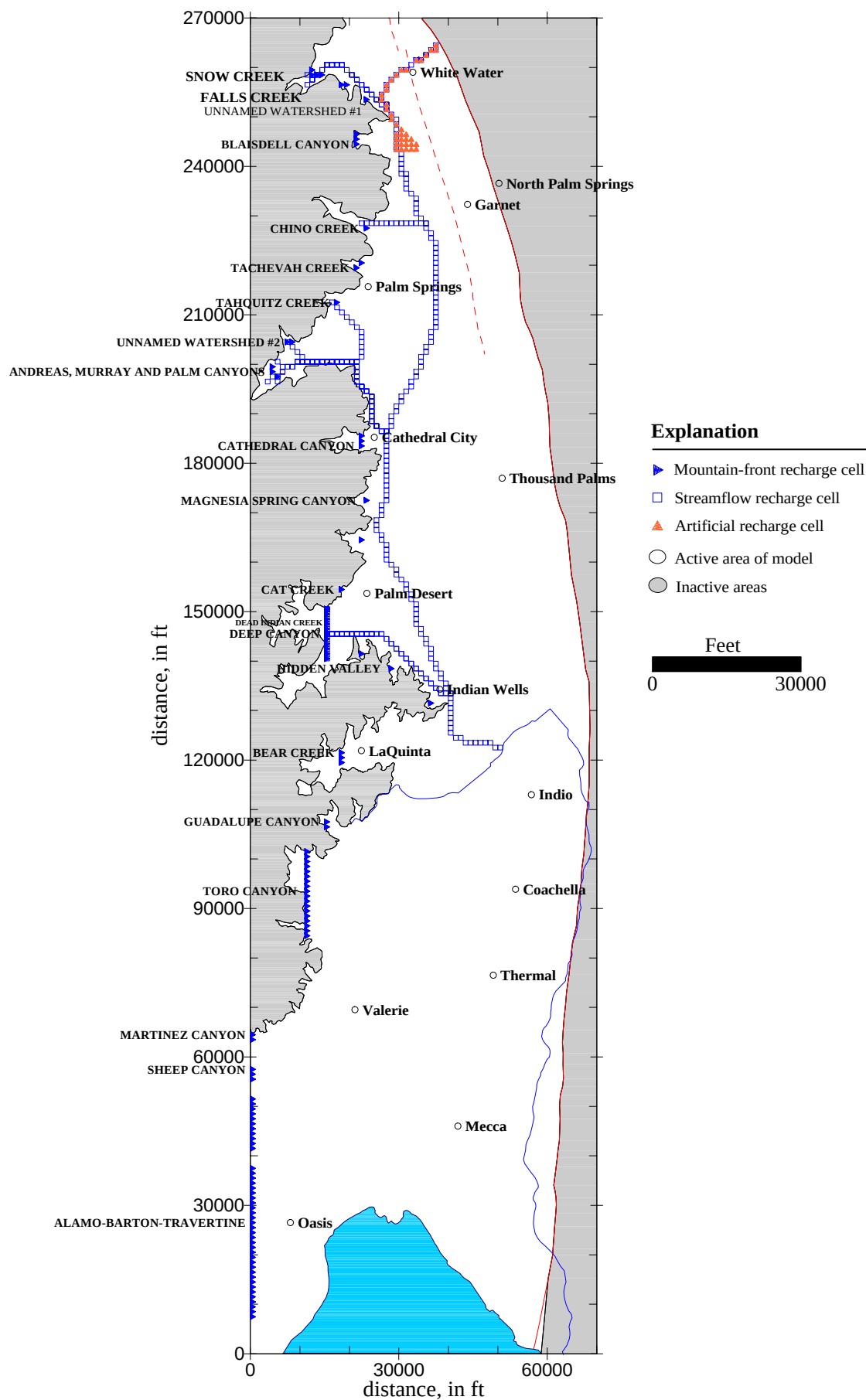
3.2.1.3 Infiltration of Mountain Runoff

Streamflow infiltration and subsurface inflow from mountain watersheds (or mountain-front recharge) from precipitation in the San Bernardino, San Jacinto and Santa Rosa Mountains are the primary natural sources of water to the aquifer system in Coachella Valley. Additional recharge may be derived from precipitation in the Little San Bernardino Mountains. The total volume of tributary inflow varies dramatically from season to season and year to year, due to wide variations in precipitation; perennial streamflow from the mountain watersheds is practically non-existent.

The average annual tributary inflow to the study area during the 61-year model calibration period was estimated for each of the mountain watersheds. Recharge from mountain runoff was estimated by an approach similar to that used by DWR (1964), which involves correlating annual watershed precipitation and runoff. In wet periods, considerably larger amounts of runoff are produced per unit of precipitation than in dry periods. Evapotranspiration and other losses consume a larger fraction of precipitation in dry years than in wet years. In addition, in dry periods, substantial precipitation is required to overcome soil moisture deficits before runoff occurs. Where available, gauged streamflow was used. The method used to estimate runoff from ungauged watersheds involved defining watershed boundaries and determining tributary areas, estimating the average precipitation for the base period 1931-61 for each watershed (DWR, 1964), estimating the annual precipitation (1936-96) for each watershed using precipitation indices, and estimating the annual runoff for each watershed using rainfall-runoff curves. Except for the Whitewater River watershed, 90 percent of the estimated runoff was attributed to streamflow infiltration, and 10 percent of the estimated runoff was attributed to mountain-front recharge. The Whitewater River canyon is suspected to have a greater subsurface flow into the model area than the other mountain tributary watersheds, hence a greater percentage of the estimated runoff was attributed to mountain-front recharge for this watershed.

Subsurface inflow from mountain watersheds was distributed to perimeter cells of the model located in canyons and along mountain fronts as shown on Figure 21. Recharge from infiltration of streamflow was distributed to model cells differently depending on if the year was relatively wet (greater than 1,000 acre-ft of Whitewater River flow at Indio), or relatively dry. With the exception of the Whitewater River, flow beyond mountain-front areas is normally limited to infrequent storm events in wet years. Therefore, recharge from infiltration of streamflow during dry years on major tributaries, and for all years on minor tributaries, was distributed to the perimeter model cells shown on Figure 21. During wet years, there is normally significant tributary flow beyond the mountain-front areas and eventually to the Whitewater River. In these years, recharge from streamflow on major tributaries was distributed to the streamflow recharge cells (Fig. 21) according to a basic river routing model.

Figure 21.
Distribution of mountain-front, tributary
and artificial recharge in model.



3.2.1.4 Precipitation on the Valley Floor

Precipitation on the valley floor is not a major source of groundwater recharge due to the low annual rainfall. According to DWR (1964), the average annual precipitation on the valley floor for the 30-year period 1930-60 is about 4.5 inches. This amount of precipitation is normally consumed by direct evaporation or by evapotranspiration from native desert vegetation. During extremely wet periods, precipitation in excess of evapotranspiration and soil moisture deficits may result in both runoff and groundwater recharge; however, this occurs infrequently, and the anticipated recharge rates are small. Thus, such recharge is neglected in the model. These assumptions are consistent with the results of deep percolation studies reported by DWR (1930; 1964).

Within the San Geronio Pass area, the greater annual precipitation probably results in some limited groundwater recharge. Estimated annual groundwater recharge in this area is approximately 4,000 acre-ft/year (DWR, 1964).

3.2.2 Artificial Recharge

Since 1973, CVWD and DWA have received SWP water through an exchange agreement with Metropolitan. Water released from Metropolitan's Colorado River Aqueduct flows down the Whitewater River channel to the recharge ponds near Windy Point. A portion of the water infiltrates along the channel, and some evaporates from the ponds before percolating to the water table. Estimates of the amount lost to infiltration in the channel and that to evaporation from the ponds were made for the model. Figure 15 charts the annual amounts of water released from the Colorado River Aqueduct to the Whitewater River. Recharge rates were computed for the infiltration along the channel and at the recharge ponds, and applied in the model as time-dependent specified flux boundaries. Note that in the three years 1985-87, over 650,000 acre-ft of water was released to the Whitewater River. From 1980-87, groundwater levels in the artificial recharge area increased over 350 ft.

3.2.3 Pumpage

Pumpage by wells is by far the largest component of discharge from the groundwater system. Other components of discharge include native vegetation evapotranspiration, flow to drains, and subsurface outflow to the Salton Sea.

Historical pumpage in the upper valley was obtained primarily from previous USGS modeling efforts up to 1967, and from CVWD well discharge meter data for 1984-96. Annual pumpage data not available throughout the historic period were estimated in this study. Principal components of groundwater production in the upper valley include municipal and domestic use, and golf course irrigation.

Historical pumpage in the lower valley is comprised mostly of unmetered agricultural pumpage; accordingly, substantial effort was devoted to estimating the historical agricultural pumpage in this study. Estimates of the volume of surface water delivered to, and crop water use

in, each section (one square mile) as a function of space and time were developed in this study to enable calculation of the agricultural pumpage by the consumptive use method (e.g., Diamond and Williamson, 1983). Pumpage in each section was estimated for a number of key years in the historical period from 1936-96. Key years are those that coincided with changing trends in groundwater levels in the lower valley (e.g., 1958, 1968, 1975, 1980, 1987, 1992), and the simulation starting and ending years 1936 and 1996, where sufficient land use data, i.e., crop reports and canal water deliveries, were also available. Pumpage at in-between years was interpolated from the key year estimates.

Agricultural groundwater pumpage in each section was estimated in key years by the following equation:

$$GW = \frac{CU - EP}{IR} - SW$$

where

GW = groundwater pumpage,
 CU = consumptive use,
 EP = effective precipitation,
 IR = irrigation efficiency, and
 SW = surface water delivered.

Consumptive use was estimated for each section from crop evapotranspiration (ET) and leaching requirement (LR) data and detailed crop acreage by section records developed in this study. Consumptive use was calculated for each section by multiplying the total acreage of each crop within that section by the sum of its ET and LR and then summing these results for all the crops in that section:

$$CU_{\text{section}} = \sum_i \text{CropAcreage}_i \times (ET_i + LR_i)$$

where the index i refers to a specific crop type.

Effective precipitation is precipitation that meets the demands of consumptive use, the fraction of annual precipitation that is available for use by crops during the growing season. Effective precipitation was assumed to be negligible. Irrigation efficiency is the percentage of water delivered to the farm that is available for consumptive use.

Total monthly-metered flows for the key years and a map and index sheet identifying the locations of the surface water meters by township, range, and section are maintained by CVWD for lands receiving water from the Coachella Canal. These data were organized into a database and annual totals were calculated for each meter; total metered flows into each section were then computed.

Estimates of golf course demand and some metered municipal and fish farm pumpage data were also factored into the lower valley pumpage database. Additionally, historical unmetered domestic, fish farm and duck club use was estimated.

3.2.4 Return Flows

Return flows are that part of the applied water that percolates back into the groundwater system. Some types of return flows, such as irrigation return and golf course return, can have more than one source of water. For example, Colorado River water from the Coachella Canal is used along with groundwater pumped from wells to supply the needs of agriculture. Thus, agricultural return flows are computed from the total applied water less the water consumed by crop evapotranspiration. Golf course return flows are estimated in a similar manner. Return flows from municipal pumpage were estimated to be a percentage of pumping rates based on assumptions made in the USGS modeling studies, and an analysis of return flows in the upper valley from this study. Other return flows in the model include irrigation returns from diversions of streamflow, and returns from recycled wastewater. Return flows were assigned as infiltration rates to the uppermost model layer.

3.2.5 Evapotranspiration

Groundwater losses to evapotranspiration (ET) by phreatophytes on undeveloped lands are accounted for with an ET boundary condition in the model. Native vegetation on undeveloped lands receives its water supply from direct precipitation and soil water. High evaporation rates and deficient soil water are conditions common to much of the undeveloped land of the Coachella Valley that is underlain by a deep water table. Plants on these lands will transpire little water. However, on undeveloped lands underlain by a shallow water table, phreatophytes receive much of their water from groundwater within reach of their roots and the quantities of water transpired can be substantial.

The ET component of the model is limited to the undeveloped lands within the semiperched zone for the following reasons: (1) significant ET losses are likely to occur only in areas where the water table is shallow, and (2) historically, the only significant areas of undeveloped land within the model domain that are also underlain by a shallow water table lie within the semiperched zone. Development in the semiperched zone is primarily agricultural and total developed area has increased significantly since the early part of the century. Since the 1950's, these developed lands have been generally underlain by agricultural drains at a depth of approximately 10 ft. As the installation of farm drains proceeded, the ET boundary was replaced with a drain boundary condition as described in the next section.

3.2.6 Drain Flows

Effects of agricultural drains in the lower valley were simulated as a function of space and time by building a database of drain locations, depths, and dates of construction from CVWD records. These data were input to the model to specify the drain boundary conditions, which allow computation of flow to drains. Computed and measured drain flows serve as an important benchmark for evaluating accuracy of the model simulations.

The basis for the design of the agricultural drains is described in the CVWD *Drainage Report* (CVWD, 1954). That report and CVWD drain construction records are the primary data sources for establishing the drain boundary conditions. The current drainage system consists of CVWD and on-farm drains. On-farm drains are those constructed by the farmers, at approximately

6-ft depths, and are connected to the CVWD drains. CVWD drains are typically installed at depths of 8 to 10 ft to ensure proper drainage of farm parcels. CVWD operates about 21 miles of open drains (primarily in the Oasis area) and about 166 miles of pipe drains. These drains flow either into the CVSC or directly into the Salton Sea.

The first farm drainage systems were installed in February 1950. With the increased agricultural development made available by Coachella Canal water, installation of both on-farm and CVWD drains progressed rapidly. CVWD records document the location (township, range, section and subdivision), the acreage served, and the date of installation of the drains. Figure 13 shows the cumulative acreage of parcels with drains installed. Currently, drains serve over 50,000 acres of farmland.

Drain boundary conditions were defined by identifying the year when drains were installed, and by mapping drain locations to each model cell. Development of the drain boundary conditions is depicted on Figure 22. Initially, the undeveloped land within the semiperched zone is described with an ET boundary condition; following the installation of farm drains, the ET boundary is replaced by a drain boundary.

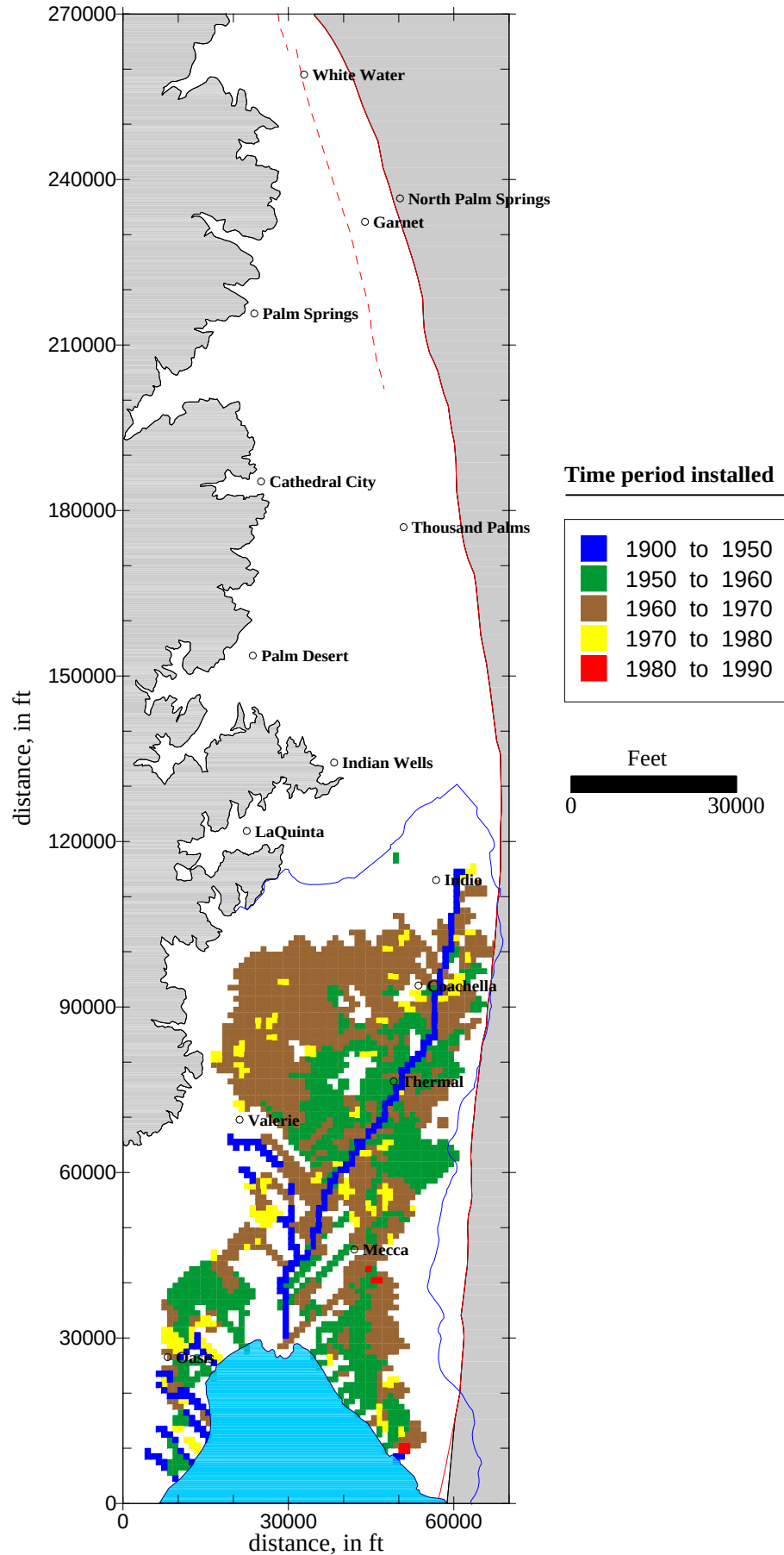
CVWD monitors the flow in each of the drains discharging directly into the Salton Sea and in the CVSC. Data are also collected on direct discharges into the CVSC from sources other than drains. These other discharges include treated wastewater from municipal wastewater reclamation plants, discharges from fish farms, and regulatory releases from the Coachella Canal. The total agricultural drainage is determined from these measured data for comparison with that computed by the model.

3.2.7 Salton Sea

The Salton Sea forms the southeastern boundary of the groundwater basin and the model. Current elevation of the Salton Sea is approximately -228 ft below mean sea level and its average depth is about 30 ft. Evaporation, and the lack of outflow, from the Salton Sea and ancestral seas before it has concentrated salts in water and in alluvial deposits underlying the Sea. Currently, the salinity of the Salton Sea is approximately 43,000 mg/L.

Transient head boundaries were assigned to model layer 1 cells within the Sea (Fig. 18). This type of boundary condition allows recharge from, and discharge to, the Sea. Heads on the Salton Sea boundary are specified as equivalent freshwater heads to account for the density of the seawater. The southeast edge of the model extends more than 5 miles into the Sea and is a no-flow boundary. This configuration allows groundwater to flow underneath the sea and discharge upward. Furthermore, this allows the model to simulate groundwater flow from beneath the Sea into the fresh groundwater basin.

Figure 22.
Development of drain boundary conditions.



3.3 Initial Conditions

Simulation of groundwater flow in Coachella Valley begins in 1936 when sufficient water level data and data needed to estimate pumpage throughout the valley were available. The year 1936 was also the starting time for the USGS model simulations in the upper valley (Tyley, 1974). Additionally, the first extensive study of water levels and pumpage in the lower valley provided these data for 1936 (Pillsbury, 1941).

A groundwater elevation contour map of the entire valley was created for 1936 and heads from this map were input as initial conditions to the model (Fig. 23). These heads are based on water level measurements in wells tapping the unconfined and lower aquifers, and were assigned to model layers 2, 3 and 4, as well as the unconfined areas of layer 1. Initial water levels within the semiperched zone of layer 1 were estimated from these data and adjusted where necessary to not exceed land surface elevation.

3.4 Parameters

Aquifer parameters include thickness, hydraulic conductivity and storage coefficient. These parameters affect the rate of groundwater movement and the volume of water taken into and released from storage. General descriptions of the data and methods used to estimate the initial parameter values in the model are given in this section. Refinements to initial parameter values were made during model calibration.

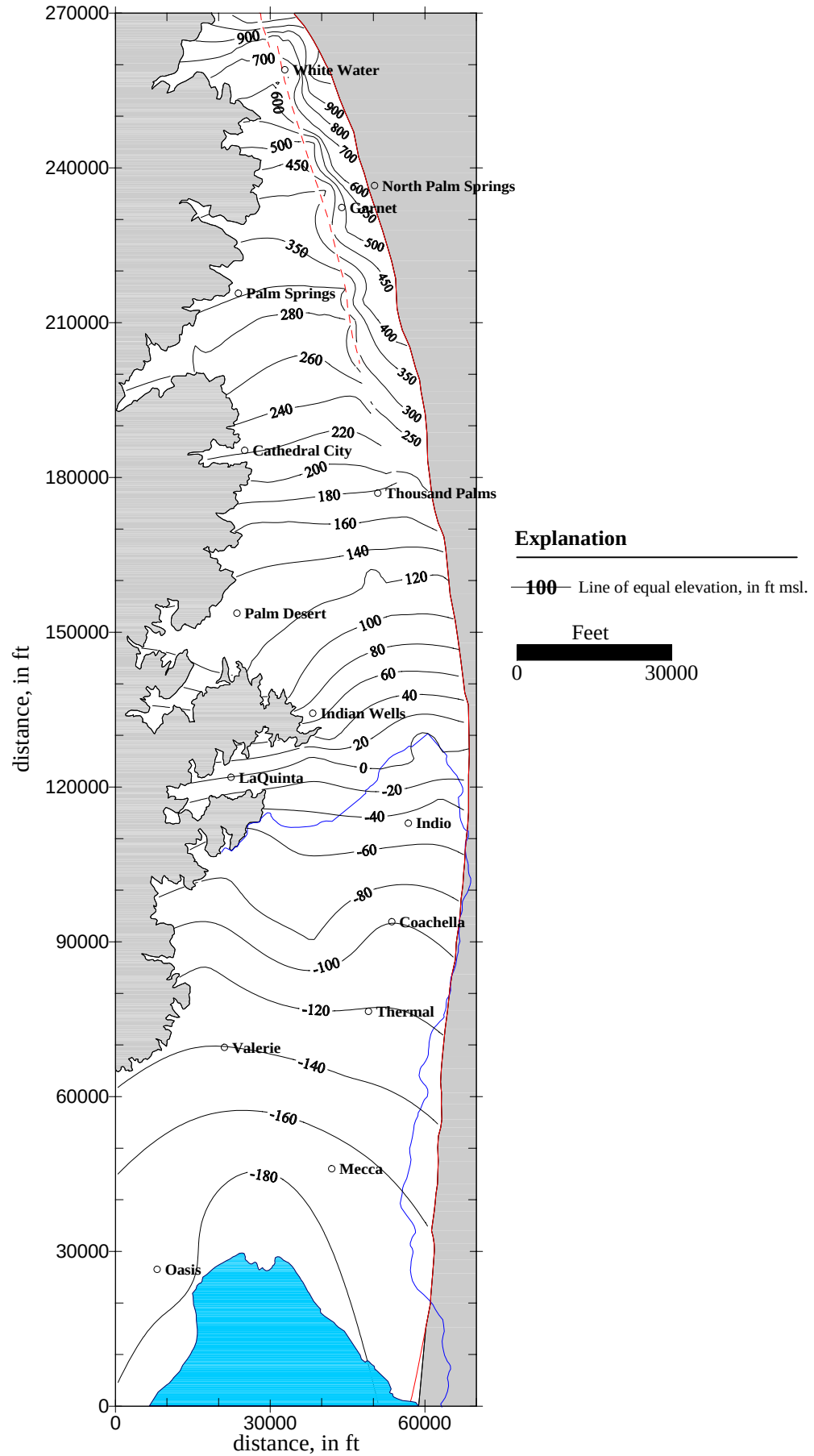
3.4.1 Aquifer Thickness

Elevation of the tops and bottoms of model layers are referenced to land surface elevations, and hence the topography, obtained primarily from USGS digital elevation models (DEM) and topographic maps of the Coachella Valley area. Total aquifer and hydrostratigraphic unit thickness then follows from elevations assigned to the mesh layers.

In the lower valley, layer thickness follows geologic characterizations by DWR (1964; 1979) that were corroborated by analysis of subsurface data in this study; the layers were designed to closely approximate the main aquifer units in the lower valley. For example, layer 1 approximately corresponds with the semiperched zone (100 ft thick), layer 2 with an upper aquifer unit (80 to more than 240 ft thick), layer 3 with an aquitard (80 to more than 240 ft thick), and layer 4 with a lower aquifer unit (1,000 ft thick). In the upper valley, aquifer thickness estimated by USGS (Reichard and Meadows, 1992), was initially used and later revised during model calibration.

The model tracks the location of the water table relative to the layer elevations. If the water table drops below the bottom of a layer at a location, the corresponding cell in that layer is made inactive. If the water table later rises above the layer bottom, the cell is reactivated. Outside the semiperched zone, thickness of layers 1, 2, and 3 were adjusted to minimize this conversion to dry cells.

Figure 23.
Contours of measured groundwater elevations in 1936.



3.4.2 Hydraulic Conductivity

Initial estimates of aquifer transmissivity (T) were obtained in part from previously calibrated values used in Reichard and Meadows (1992) for the upper valley, some pumping test results for the lower valley, and fairly abundant specific capacity data for the entire valley. Hydraulic conductivity (K) of the confining bed in multiple aquifer zones was estimated based on the sediment texture and heterogeneity and was treated as a calibration parameter. Similarly, vertical K (K_v) of the aquifer zones was based on the degree of fine-grained bedding present in electric and drillers logs as well as past experience with three-dimensional heterogeneity in sedimentary basins; this parameter was also adjusted in calibration.

Time, drawdown and discharge data from 50 short-term pumping tests (generally of 3-hour duration) on CVWD wells were analyzed for transmissivity using the graphical method of Cooper and Jacob (1946). Due to incomplete well development or other unknown test conditions, half of the tests were rejected for analysis. Transmissivity estimates determined from the analyses were plotted against specific capacity (S_c) and regression was used to develop an equation describing the relationship between T and S_c . This equation was then applied to other wells throughout the valley having S_c test data in the database. Transmissivity can be expressed as the product of hydraulic conductivity and aquifer thickness, or $T = K \times b$, where b is the aquifer thickness. Thus, initial values of K were determined from the T estimates.

3.4.3 Specific Yield and Specific Storage

Distribution of specific yield (S_y) from Reichard and Meadows (1992) was initially used in the upper valley for model layer 1; these values were subsequently modified slightly during calibration. Similar specific yield values were initially estimated for the unconfined areas and semiperched zone in the lower valley; these values were later adjusted during calibration.

Specific storage (S_s) values were estimated for each of the model layers 2, 3 and 4, and were multiplied by layer thickness to obtain storage coefficient (S) for each model layer. S_s varied in confined vs. unconfined areas.

3.5 Garnet Hill Fault

The Garnet Hill Fault (Fig. 3) is located about 1.5 miles south of, and is oriented generally parallel to the Banning Fault. DWR (1964) suggested that the fault has not displaced Recent alluvium, but is effective as a barrier to groundwater flow below depths of 100 ft, based on water-level measurements at the fault. The area between the Garnet Hill Fault and the Banning Fault is named the Garnet Hill Subarea (DWR, 1964). The few wells present in the Garnet Hill Subarea indicate that water levels are higher in the subarea than in the adjacent Palm Springs Subarea opposite the Garnet Hill Fault.

The Garnet Hill Fault is simulated using the Horizontal Flow Barrier Package (Hsieh and Freckleton, 1993). Model-calibrated transmissivities along the Garnet Hill Fault from Swain (1978)

were used to compute initial estimates of hydraulic conductivity of the fault barrier. These estimates were modified slightly during calibration.

3.6 Land Subsidence

Groundwater levels throughout most of Coachella Valley are nearing or have already fallen below historic lows, causing concern about potential land subsidence. Thus, CVWD entered into a cooperative agreement with USGS in 1996 to establish a network of geodetic monuments for monitoring potential subsidence in the lower valley (Ikehara et al., 1997). Capability for modeling of subsidence exists in the present model via implementation of the Interbed-Storage Package (Leake and Prudic, 1991). Because evidence for subsidence in the valley is unclear, however, the parameters in the Interbed-Storage Package have been set so that simulated subsidence remains small (less than approximately 1 ft). It is suspected that substantial drawdown northwest of Point Happy, near the transition between the upper and lower valley, induced some subsidence that was not detected. Continuing overdraft raises the probability of future subsidence, calling attention to the importance of future monitoring of the established network.

4 CALIBRATION AND HISTORICAL SIMULATION RESULTS

Model calibration is the process of refining the model representation of the hydrogeologic framework, estimates of boundary condition heads and fluxes, and aquifer parameters to improve correspondence between measured data and simulated results. Successful calibration demonstrates the ability of the model to simulate historical water levels and fluxes throughout the basin.

The model was calibrated, using standard methods (ASTM D5490, D5981), to measured water levels and drain flows in the period 1936-96. Measured data on groundwater levels, artificial recharge amounts, drain flows, and elevation of the Salton Sea were available in this historical period. The data show significant changes in groundwater levels, both up and down, owing to major historical shifts in both pumpage and recharge. Thus, a major goal has been to simulate these important historical changes, thereby providing a rigorous test of the ability of the model to adequately simulate effects of future fluctuations in pumpage and recharge. The results are generally excellent, despite the complexities inherent to the Coachella Valley groundwater system.

The modeling effort has been devoted more to estimating historical pumpage and recharge, and to hydrologic data analysis, than to fine-tuning of model parameters during calibration. The following paragraphs briefly discuss the main boundary conditions and parameters adjusted during calibration:

- Although some metered pumpage data and previous estimates of pumpage were available for various time periods, historical pumpage and return flows in the current model were largely estimated in this study through a phased approach. In each phase, improvements in the model databases on historical pumpage and recharge produced improvements in the agreement between measured and historical water levels and drain flows. For example, in the upper valley, initial calibration runs lacked adequate pumpage data for the period 1969-83. When these data were developed and included in the model, much closer agreement between measured and observed groundwater levels was achieved.

- Ephemeral streamflow recharge was at first simulated as constant in time, but test runs of the model showed that some of the major trends in water levels could not be reproduced without varying the recharge in accordance with infrequent but significant flood events. The data for time-varying ephemeral streamflow recharge was based on a hydrologic analysis of precipitation and runoff in watersheds sourced in the San Jacinto and Santa Rosa Mountains as well as the Whitewater River watershed.
- The main parameters adjusted in the calibration were K , S_s , S_y , and vertical hydraulic conductivity (K_v). For example, K estimates were refined in regions where well test data were sparse. Magnitudes of all such adjustments were small to moderate and were consistent with available data and conceptual models.
- Measured semiperched zone water levels and CVWD monitored drain flows were important calibration targets for the boundary condition representing evapotranspiration from native vegetation.

Model results include computed water levels for each active node in the model mesh. Computed water levels were plotted for many wells at various depths and locations throughout the valley and were compared with measured water levels in the wells. Locations of some representative wells are shown on Figure 17. Charts of measured and simulated water levels are shown on Figure 24 for several representative wells in the valley. These charts demonstrate that the model accurately simulates the varied historical changes in water levels in wells at widely different locations in the valley.

Two years, 1968 and 1992, were selected from two dissimilar hydrologic periods to present model results for groundwater elevations throughout the valley. Figure 25 shows contours of measured water levels and a plot of residual values in the upper aquifer for 1968. A *residual* is the difference between the computed and measured water level at a well location. Figure 26 shows contour plots of measured and simulated groundwater elevations (a) and residuals (b) in the lower aquifer in 1968. Similar plots for 1992 are shown on Figures 27 and 28. These maps show that the model very closely simulates the observed water level patterns throughout the valley. Additionally, most of the residuals are within 20 ft, in very good agreement with the measured data.

Simulated versus measured water levels for wells in the valley with water level data in the years 1968 and 1992 are shown on Figures 29 and 30, respectively. The one-to-one correspondence line is plotted for comparison. The close agreement between the water level data and the line of zero residuals indicates a successful calibration. Further, there is little or no pattern (correlation) between positive and negative residuals (above and below the line), and the magnitude of the residuals is very small (usually less than 2 percent) compared to the total change in head along the valley.

Figure 24.
Measured and simulated groundwater levels in selected wells.

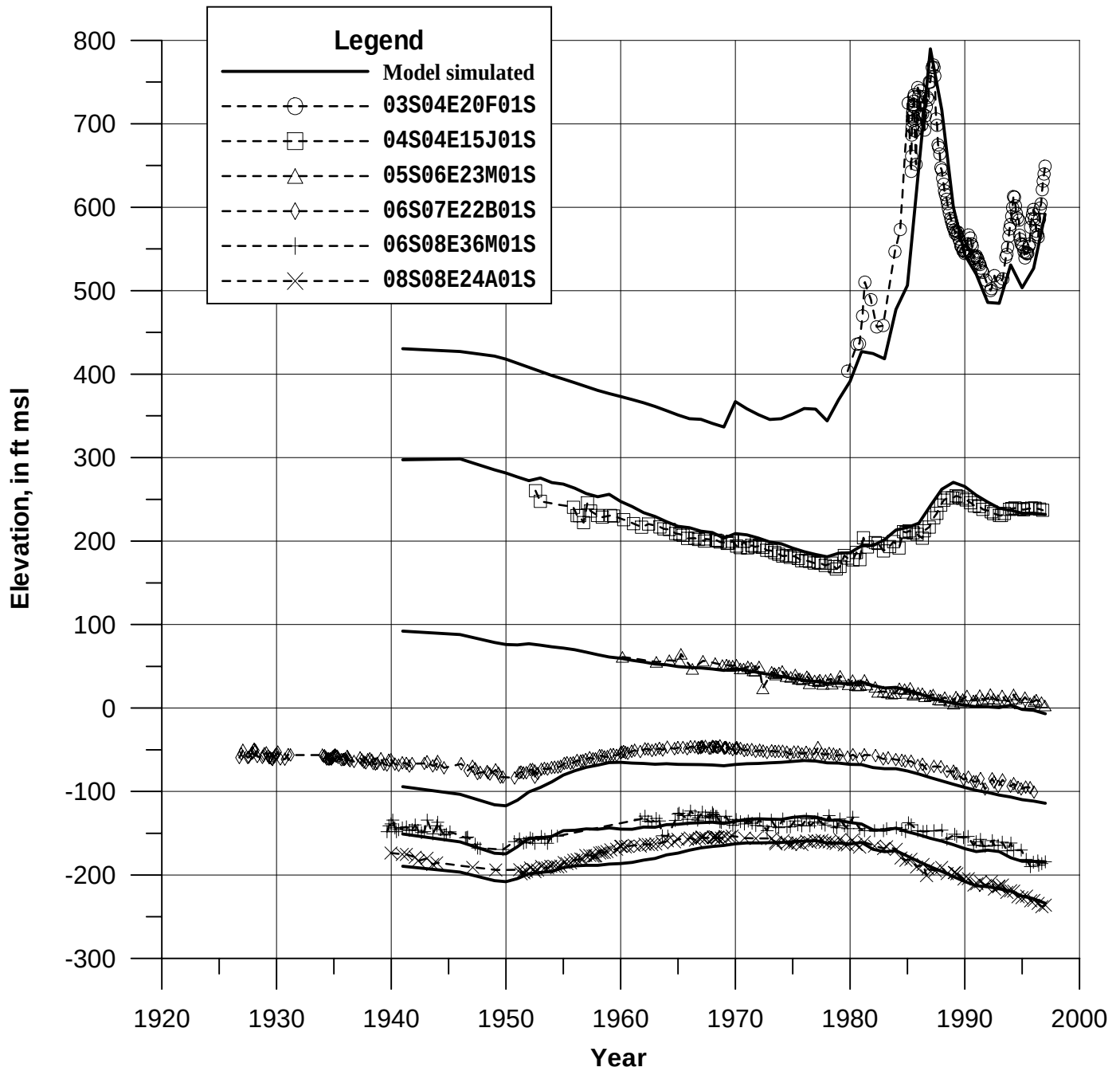


Figure 25.
Measured groundwater levels and residuals in the upper aquifer, 1968.

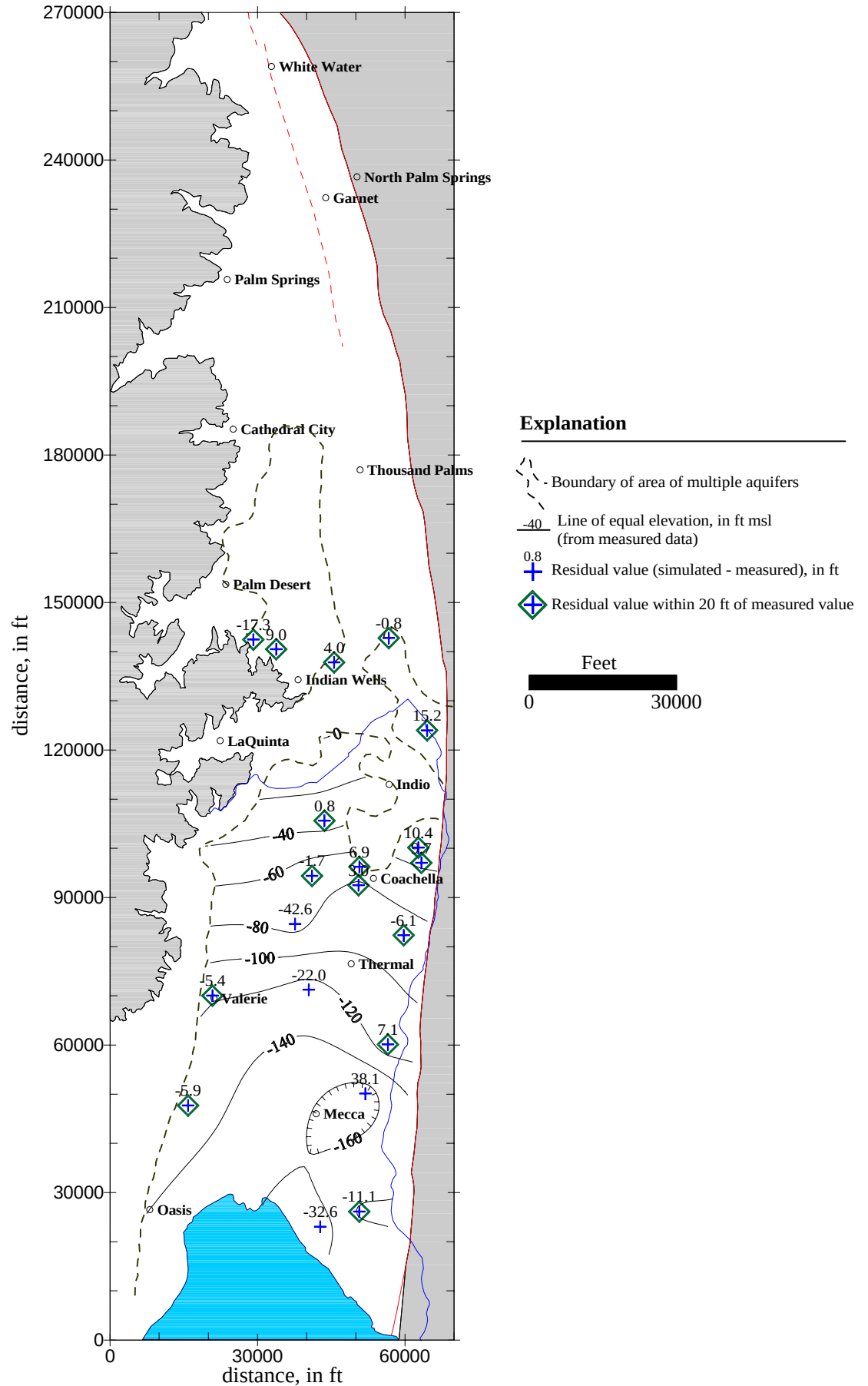


Figure 26.

Measured and simulated groundwater levels and residuals in the lower aquifer, 1968.

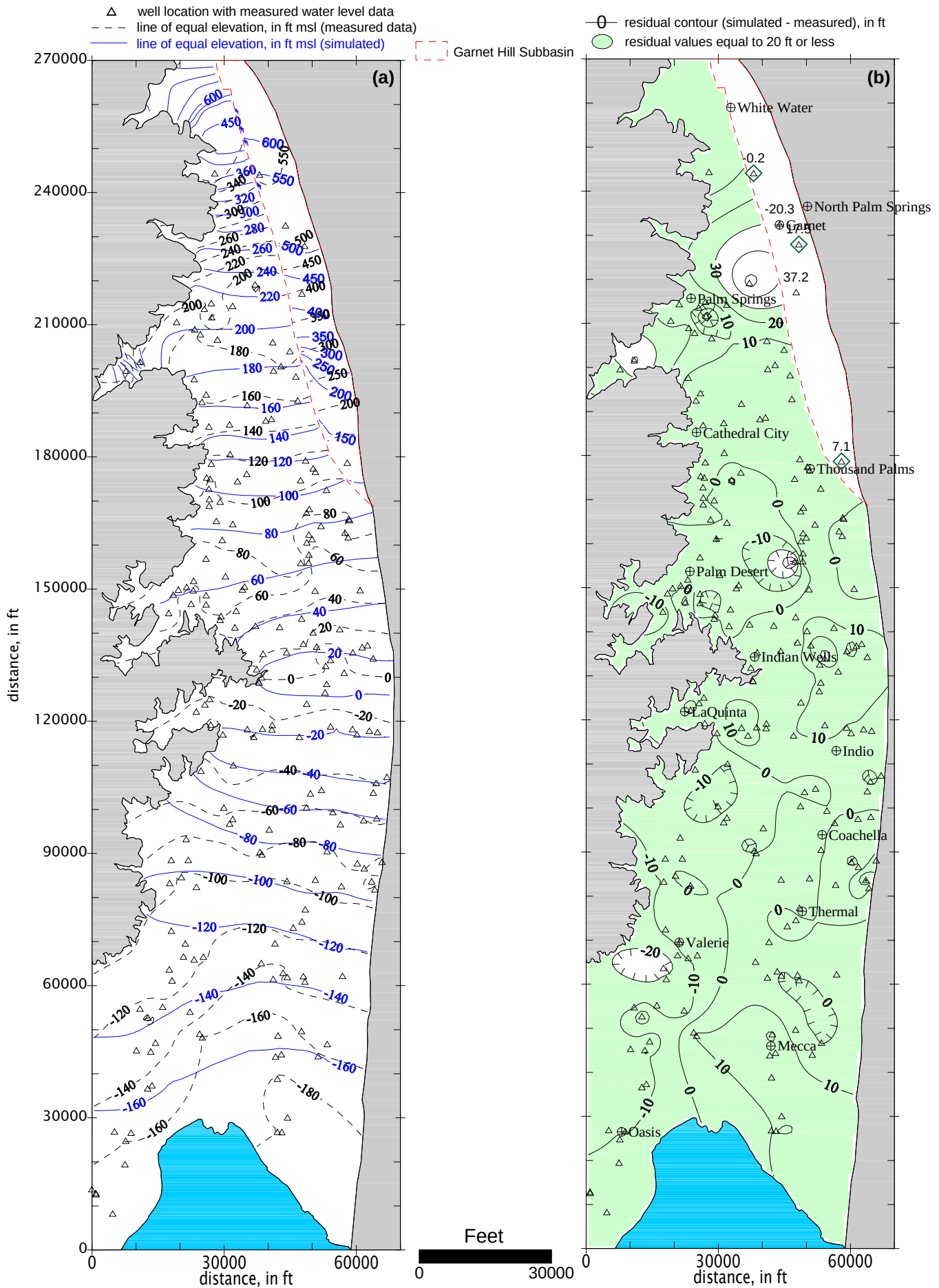


Figure 27.
Measured groundwater levels and residuals in the upper aquifer, 1992.

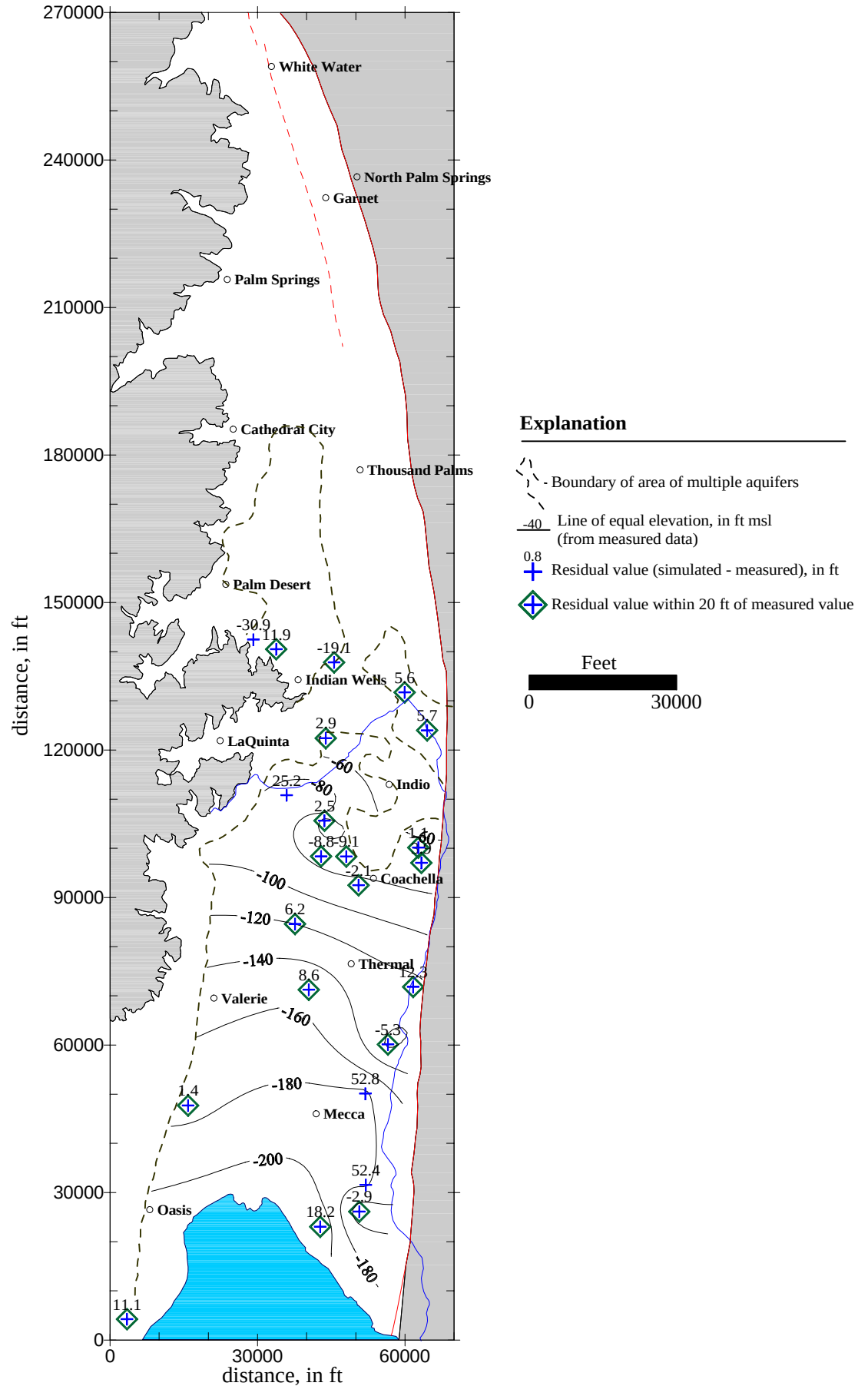


Figure 28.

Measured and simulated groundwater levels and residuals in the lower aquifer, 1992.

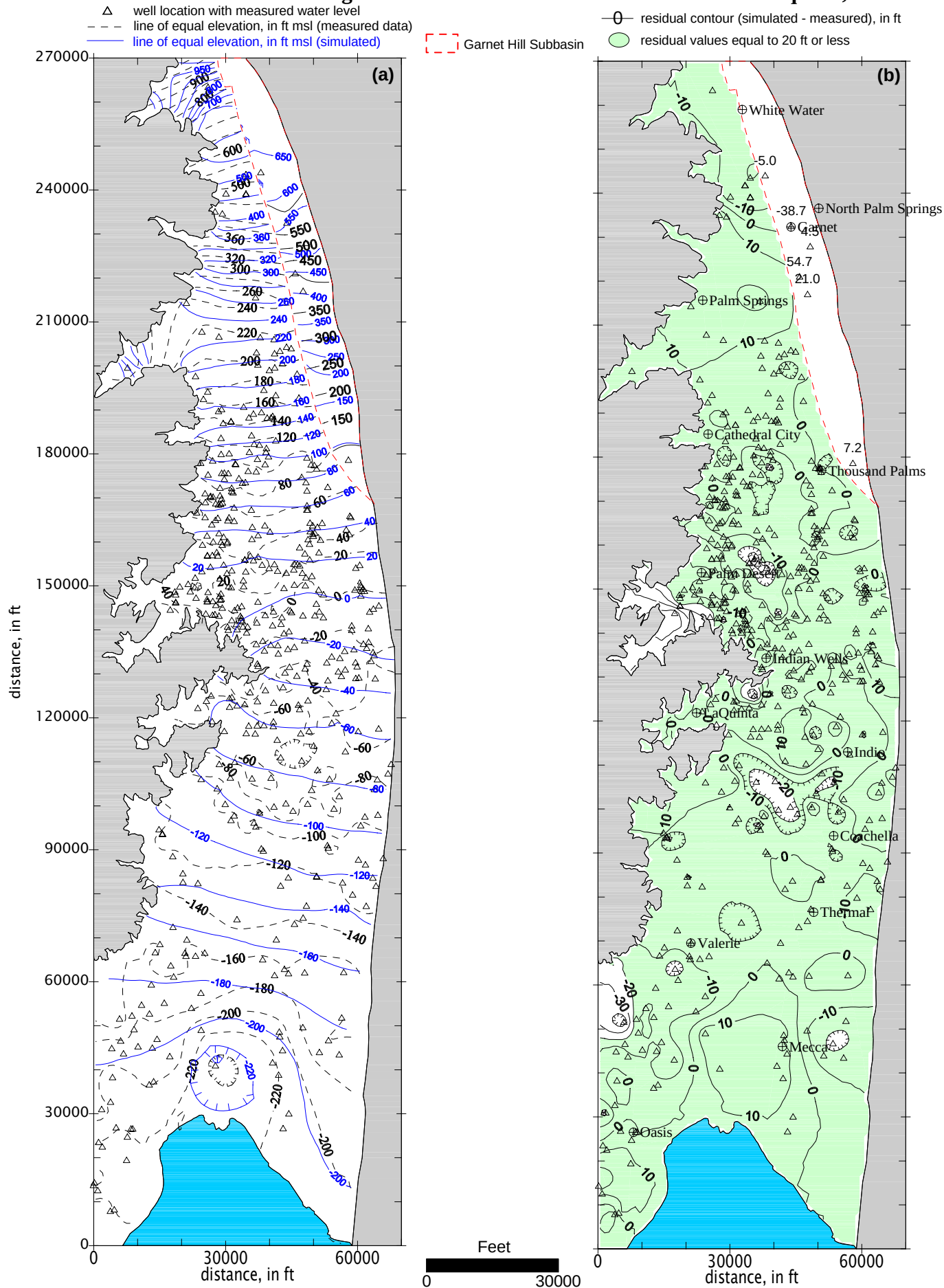


Figure 29.
Measured versus simulated groundwater levels in the upper and lower aquifers, 1968.

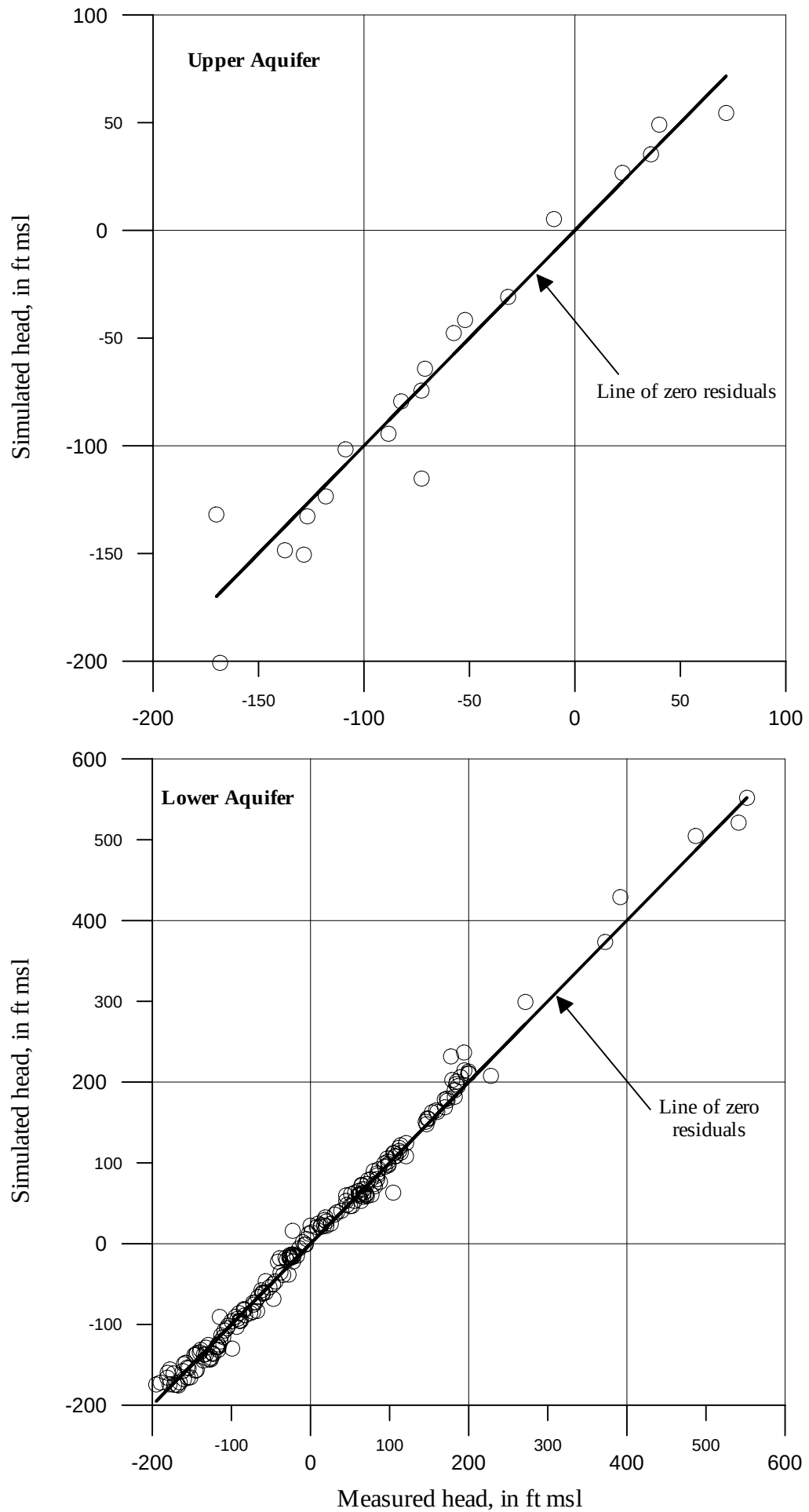


Figure 30.
Measured versus simulated groundwater levels in the upper and lower aquifers, 1992.

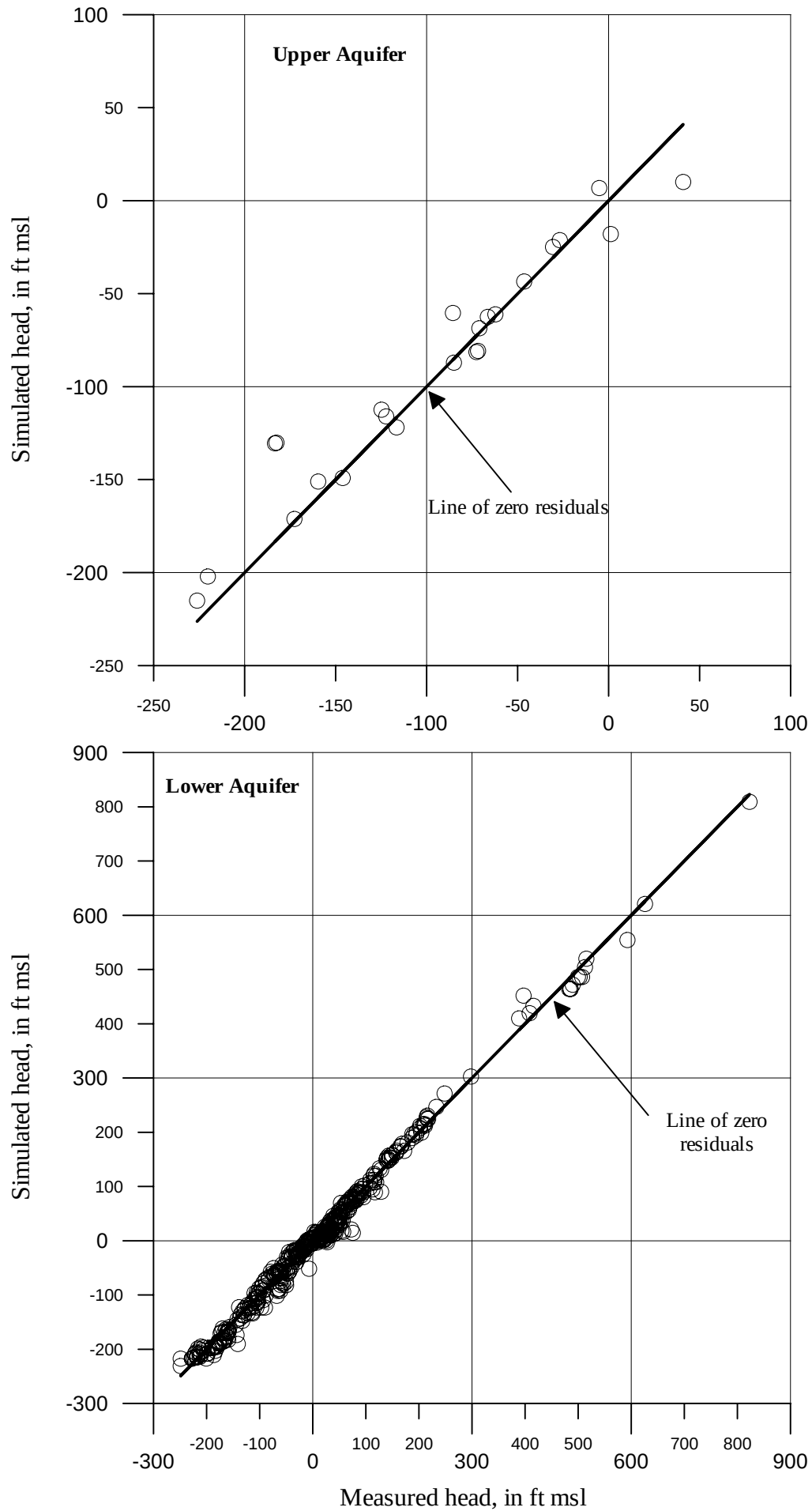


Figure 31 shows a histogram of the model deviations (residuals) from annual average groundwater elevations for all available measured water level data from wells in the period 1936-96. Where measured groundwater level data were available in a well, an annual averaged data value was compared with the model-simulated value at the mid point of the year. This chart is convenient for showing the distribution of model residuals for the entire calibration period. Note that approximately 86 percent of the residuals in the upper aquifer and 85 percent of the residuals in the lower aquifer are within 20 ft. The mean of the residuals for the upper aquifer is 3.86 ft and that for the lower aquifer is 3.39 ft. These are excellent results, considering the long historical period, the great number and varied location of wells, and the large range in measured water levels (over 1,100 ft) along the basin.

Model computed drain flows are compared with measured agricultural drain flows in Figure 32. The very good agreement provides additional, strong evidence that the model is capable of simulating real trends in both water levels and flow rates.

In summary, progressive improvements in the model by inclusion of increasing amounts of data and a refined conceptual model, produced excellent agreement between measured and simulated groundwater levels and drain flows for the period 1936 to 1996. These results indicate the model is valid for simulating the kinds of fluctuations and trends experienced by the system in the past.

5 PEER REVIEW

CVWD commissioned three internationally respected experts in groundwater hydrology and modeling to conduct a peer review of the groundwater model. The committee included Dr. Irwin Remson, Mr. Steven P. Larson, and Dr. James W. Mercer. Given the purpose of the model to aid CVWD in managing groundwater resources in Coachella Valley, the following goals were established for the peer review process:

1. Given the conceptual model, numerical model construction and performance in historical simulation, comment on model reliability.
2. Evaluate suitability of model to simulate prevention of intrusion of groundwater from the Salton Sea and stabilization of groundwater levels in response to management options of artificial recharge.
3. Recommend changes, if needed, to achieve the above.

The peer review process consisted of a review of background materials, site reconnaissance, and participation in a series of meetings with the groundwater modeling team. Three meetings took place over the course of seven months, and consisted of presentations by the modeling team on conceptual and technical aspects of the model. The peer review panel recommended some modifications to the model at the first meeting that were completed and reviewed at the second; additional calibration was recommended at the second meeting that was completed and reviewed at the third. In this way, comments by the panel were considered and the modeling approach was modified as appropriate.

Figure 31.
Histogram of residuals, 1936-96.

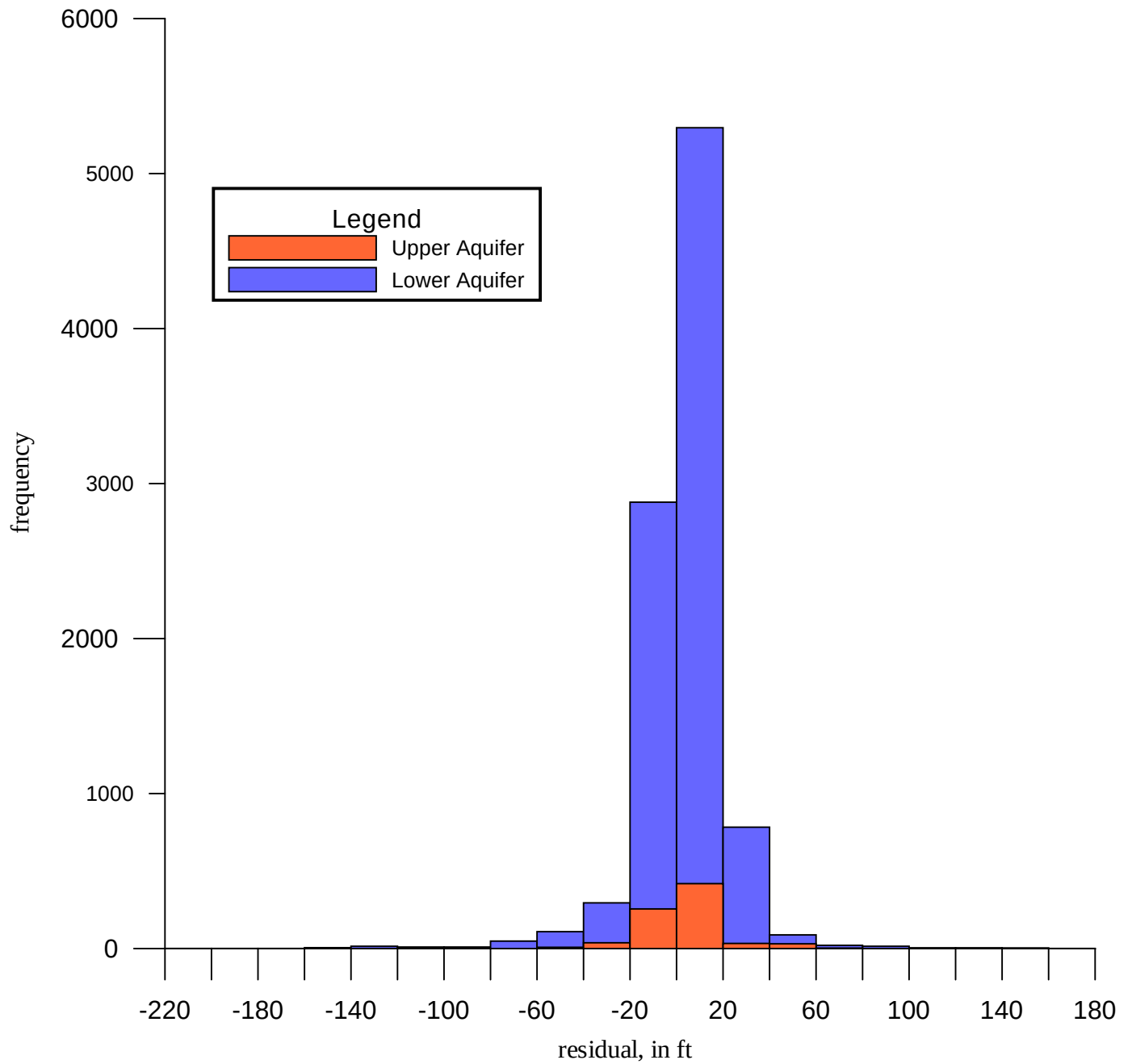
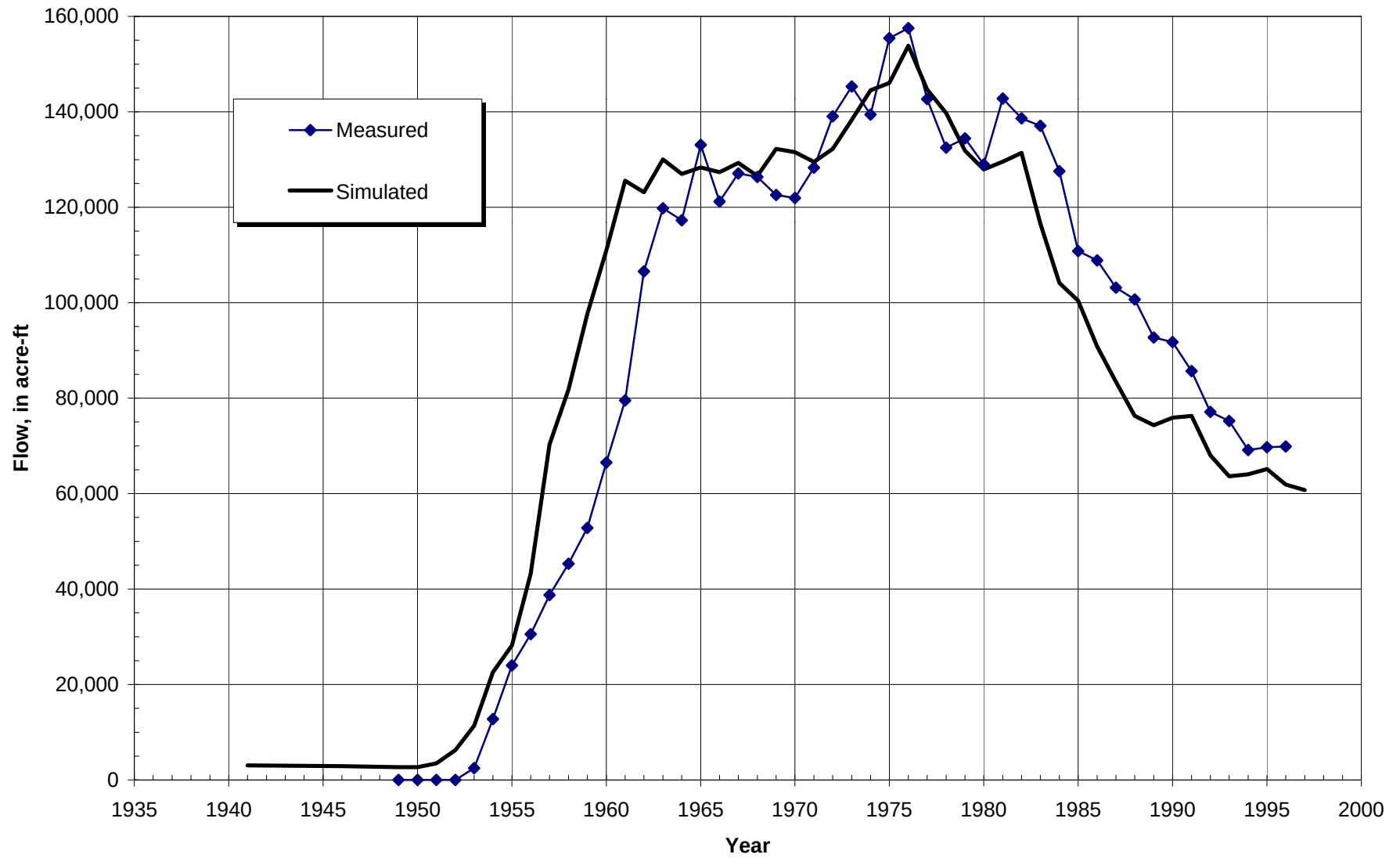


Figure 32.
Measured and simulated agricultural drain flows.



The peer review committee concluded the model calibration is excellent based on the calibration results, the nature of the hydrogeologic system, and the fact that the model is calibrated using databases that are extensive in both space and time (Larson et. al, 1998). The committee concluded “the overall model is valid” and further that “continued study should be restricted to specific local problems.” The committee also noted that any changes in local areas would not affect the overall model, and that the model may be used to help evaluate and compare the proposed water management plan alternatives.

6 RESULTS OF PREDICTIVE SIMULATIONS

The model was used to simulate numerous different water management plan alternatives under consideration by CVWD. Water use for each alternative from 1997 to 2035 was estimated, and appropriate model boundary conditions were developed for this period. Results of the predictive simulations were analyzed in terms of (1) sustainability of groundwater levels and (2) maintenance of net groundwater discharge to the Salton Sea.

In developing the model boundary conditions for the planning period 1997-2035, the following assumptions were made:

- Average recharge rates from infiltration of streamflow and mountain runoff over the 61-year history-matching period from 1936-96 are applicable to the simulation period 1997-2035.
- Actual Salton Sea elevation was used in 1997-99 and held constant at 1999 levels for 2000-2035.
- Minimum SWP inflows were assumed to be 50,000 acre-ft per year
- No additional drains were installed after 1996.

Pumpage and recharge estimates were made separately for each alternative as discussed in the Water Management Plan¹. To demonstrate the model application, two of the alternatives under consideration are briefly discussed in the following sections. Model results are presented including contour plots of simulated groundwater levels in the main aquifer system (layer 4) for the year 2035 and contour plots of the difference between these and simulated groundwater levels at the end of 1999.

6.1 Alternative 1 – No Project

The No Project alternative would not involve any additional management actions beyond CVWD’s ongoing activities. These include:

- continued groundwater recharge in the upper valley at historical rates (approximately 50,000 acre-ft per year),

¹ Contact CVWD for more information.

- minimal reduction in groundwater use by providing alternative sources of water to golf course and agriculture,
- current levels of domestic, golf course, and agricultural water conservation, and
- information and education programs would be maintained at existing levels.

Figure 33 shows a contour plot of simulated groundwater levels in 1999; vectors indicate the general direction of groundwater flow. Figure 34 shows a contour plot of simulated groundwater levels for 2035. Figure 35 shows a contour plot of the difference in heads between 1999 and 2035; the shaded areas indicate water level declines greater than 200 ft. The continuing overdraft conditions simulated in Alternative 1 raise the concern for potential land subsidence in the area between Palm Desert and Indian Wells. This is due to the existence of significant fine-grained materials at depth in this area (Fig. 6) and because the simulated water-level declines fall well below historical lows.

6.2 Alternative 4 – Combination Alternative

Alternative 4 is a combination of the most feasible and cost-effective measures evaluated by CVWD. It includes maximizing the use of Coachella Canal water and recycled water, urban and agricultural conservation measures, increasing upper valley groundwater recharge by approximately 40,000 acre-ft per year, and recharging the lower valley groundwater with imported Coachella Canal water by approximately 80,000 acre-ft per year.

Alternative 4 results are identical to those for Alternative 1 in the year 1999. Figure 36 shows a contour plot of simulated groundwater levels in 2035 for Alternative 4. Figure 37 shows a contour plot of the difference in heads between 1999 and 2035; under this alternative, groundwater levels would rise near the proposed artificial recharge areas, and over much of the lower valley.

7 CONCLUSIONS

Excellent agreement, both valley-wide and throughout the 61-year history-matching period, between measured and model simulated water levels and drain flows, demonstrates that the Coachella Valley groundwater model has been calibrated successfully. The excellent match between measured and simulated conditions was based on a sound conceptual model, and was obtained largely through (1) careful, methodical development of progressively more accurate databases on groundwater pumpage and recharge estimates, and (2) hydrogeologically prudent, moderate adjustments in aquifer parameters.

Results indicate that the model is valid for analysis of regional management problems provided the imposed stresses on the system are similar to those during the calibration period. Regarding field applications of the management alternatives, infiltration rates for artificial recharge projects should be verified by pilot tests, and review of local hydrogeologic conditions should accompany any proposed plans. Any improvements in local hydrogeologic information can readily be included in the model, enhancing the predictive capability of the model locally, without affecting the overall results.

Figure 33.
Alternative 1 simulated groundwater levels in layer 4, 1999.

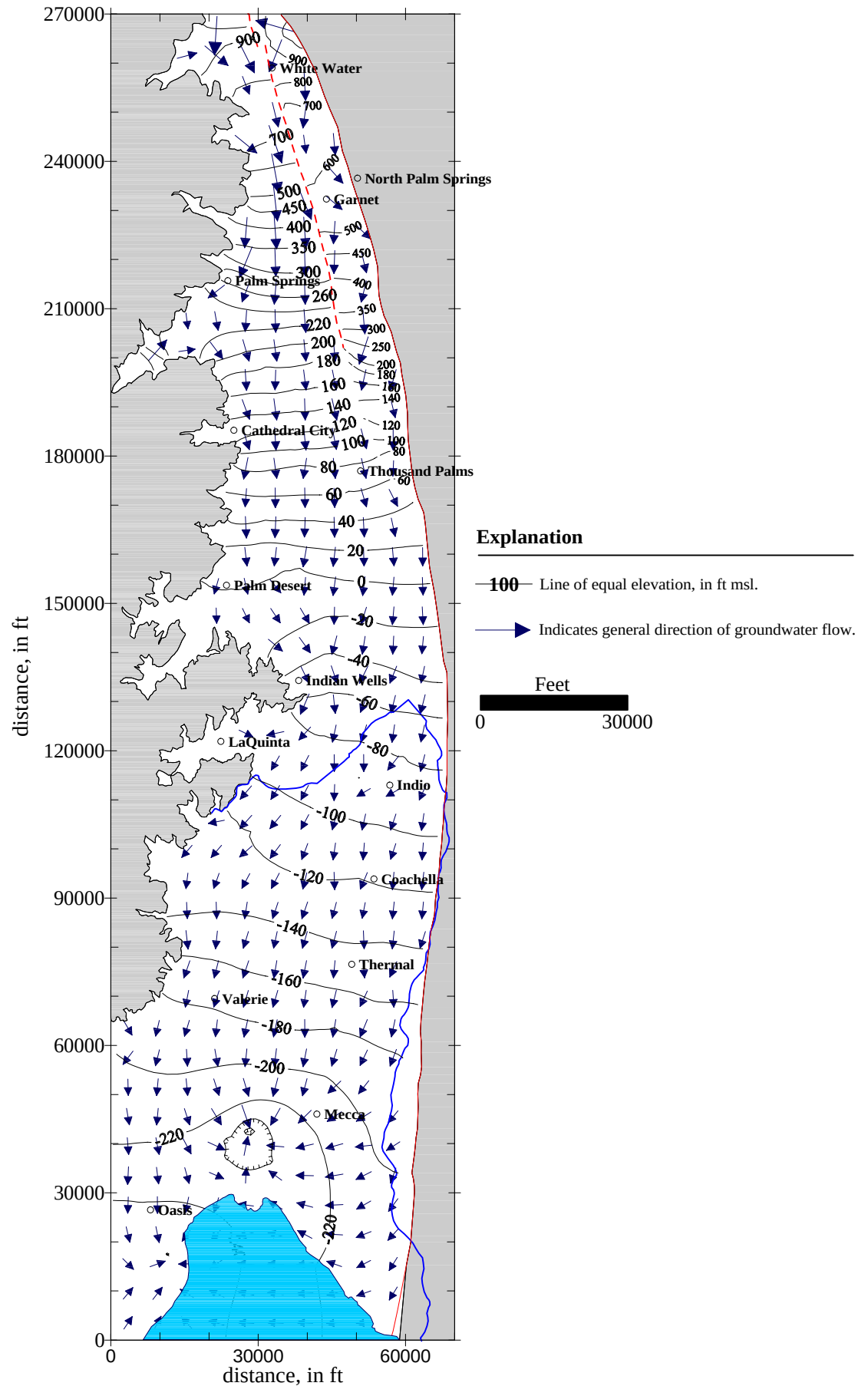


Figure 34.
Alternative 1 simulated groundwater levels in layer 4, 2035.

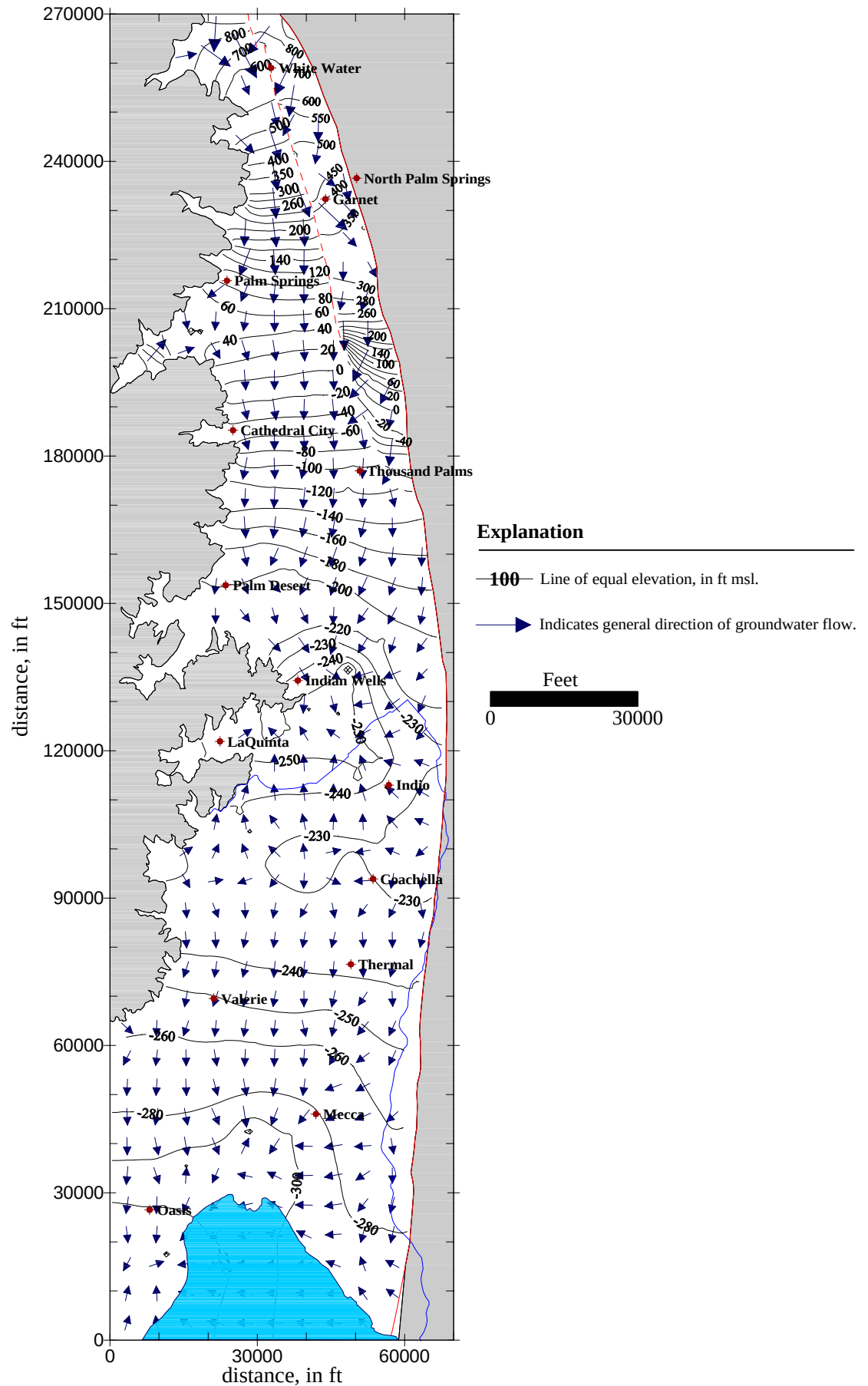


Figure 35.
Alternative 1 potential water-level decline in layer 4, 1999-2035.

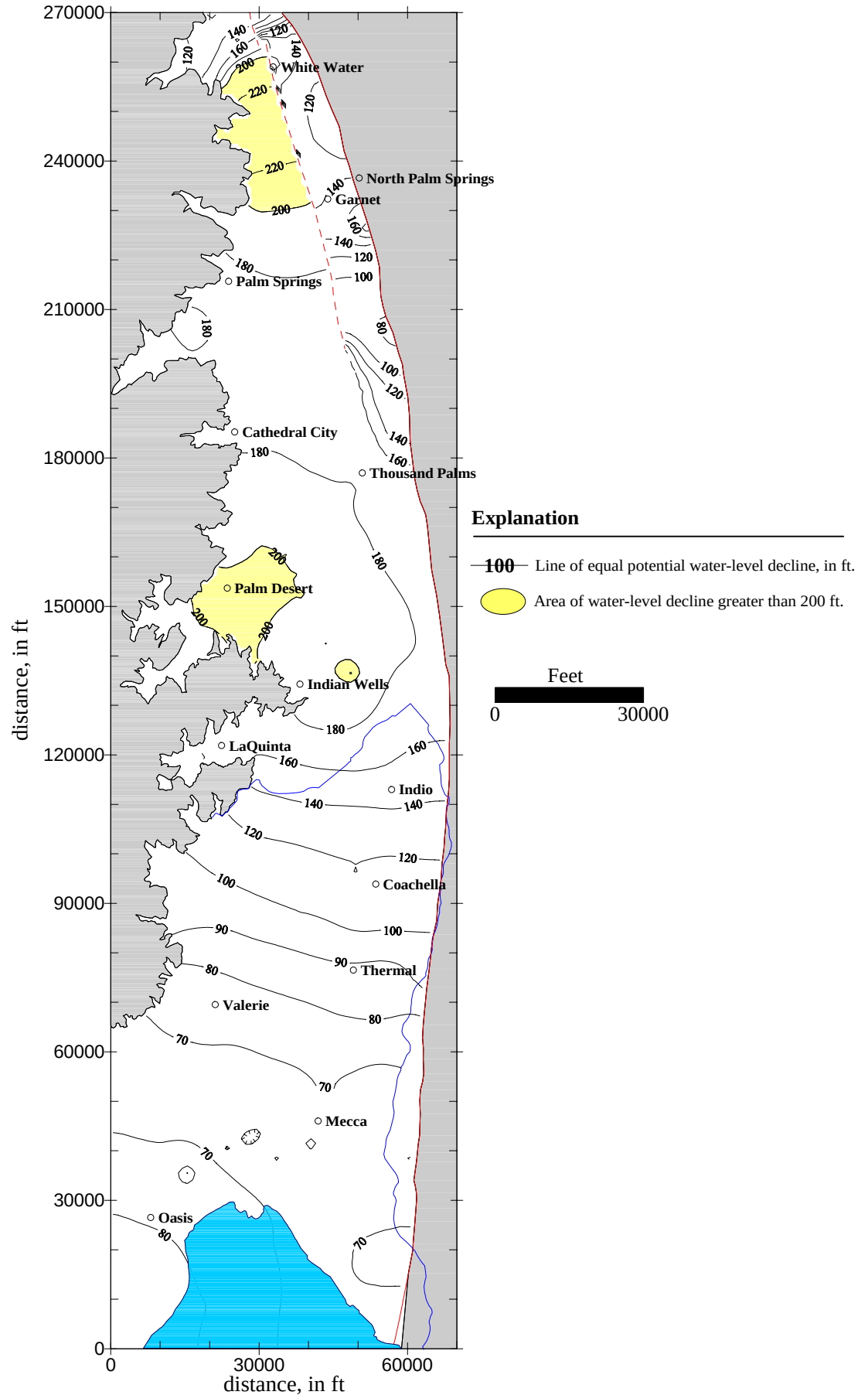


Figure 36.
Alternative 4 simulated groundwater levels in layer 4, 2035.

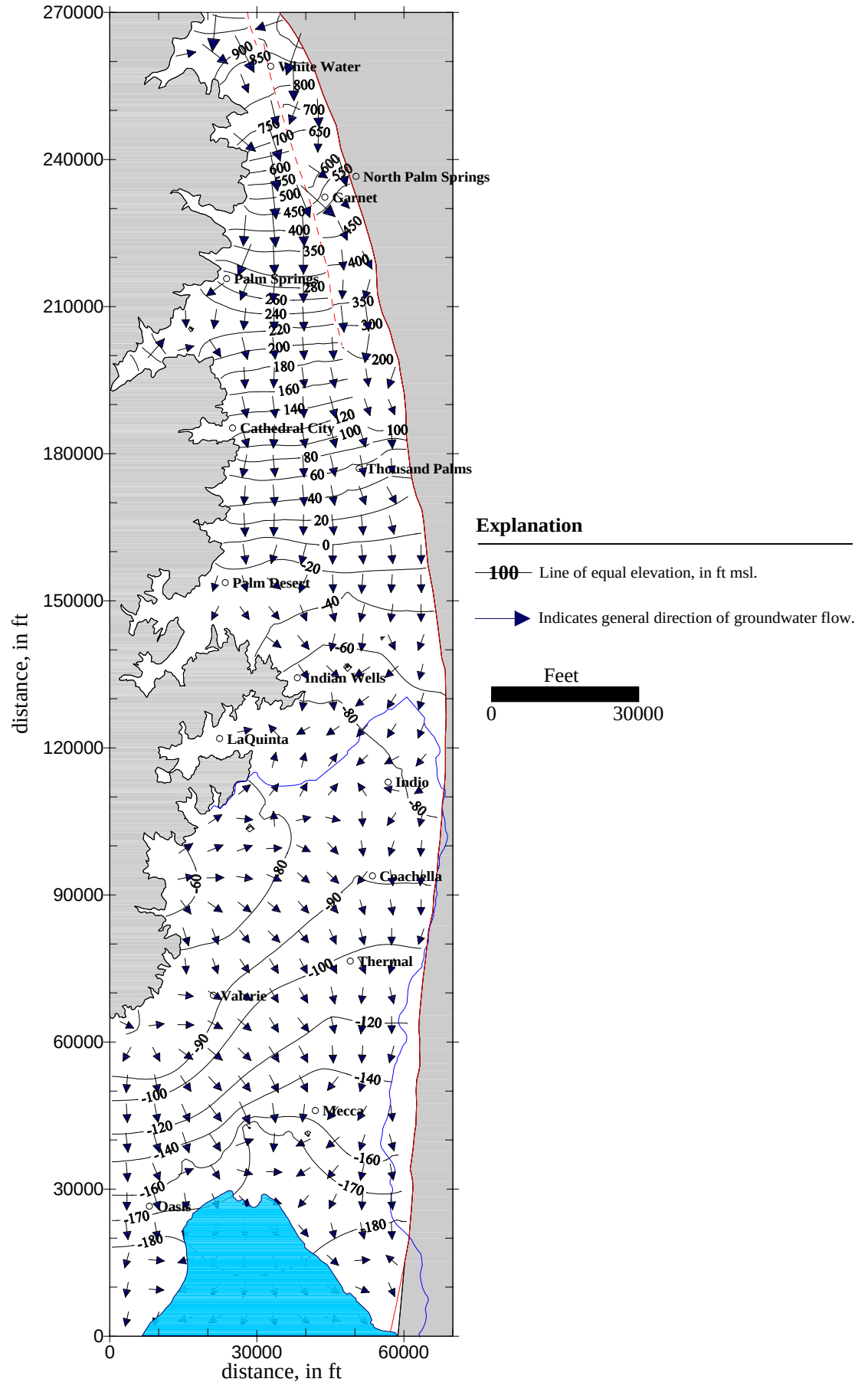


Figure 37.
Alternative 4 potential water-level difference in layer 4, 1999-2035.

