HYDROGEOLOGY AND NUMERICAL MODELING OF THE BORREGO VALLEY AQUIFER SYSTEM

by

Thomas W. Henderson

Fall 2001

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HYDROGEOLOGY AND NUMERICAL MODELING OF THE BORREGO VALLEY AQUIFER SYSTEM

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Presented to the

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In Partial Fulfillment

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Master of Science

in

Geological Sciences

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by

Thomas W. Henderson

Fall 2001

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Fall 2001

DEDICATION

This thesis is dedicated to my family – Theresa, Tommy, and Hannah. Theresa – this work could not have been completed without your love, support, and understanding. Thank you for carrying me when my burden seemed too much. Your constant words of encouragement sustained me through lonely nights and weekends at the office. With your help, "I cracked the code". I am forever indebted to you for your support on this long road. Tommy and Hannah – this work has been in process since before either of you were born. I have completed this work to provide a brighter future for both of you. Thank you both for accepting my absence, and showering me with your unconditional love. My hope is that through this effort you will understand that any adversity can be overcome with persistence and hard work. I love you all.

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CHAPTER I

INTRODUCTION

The Borrego Valley aquifer system has been the principal source of water to the residents of Borrego, Borrego Springs, and the surrounding area since the late 1940s. Extensive use of groundwater from the aquifer system to support agriculture, recreation, and municipal use has led to an apparent overdraft condition. Groundwater extraction in excess of natural recharge over an extended period of time has led to depletion of the total quantity of groundwater in storage.

Purpose

The purpose of this study was to: (1) develop a conceptual model of the aquifer system, (2) develop a numerical model to represent the aquifer system, (3) utilize the numerical model to evaluate historic groundwater trends, and (4) utilize the numerical model to predict future conditions for two groundwater use scenarios.

Physiographic Description of the Basin

The following paragraphs provide background information relating to the physical description of the aquifer system in Borrego Valley and the surrounding area. Additional detailed information, relevant to this thesis is provided in subsequent chapters.

Location

Borrego Valley is located near the northeast corner of San Diego County, California, near the western border of Imperial County, California (Figures 1 and 2). This area of San Diego County is within the Colorado Desert geomorphic province of California. Borrego Valley is in the margin between the desert region to the east, and the mountains of the Southern California Batholith to the west.

Figure 1. Regional location map.

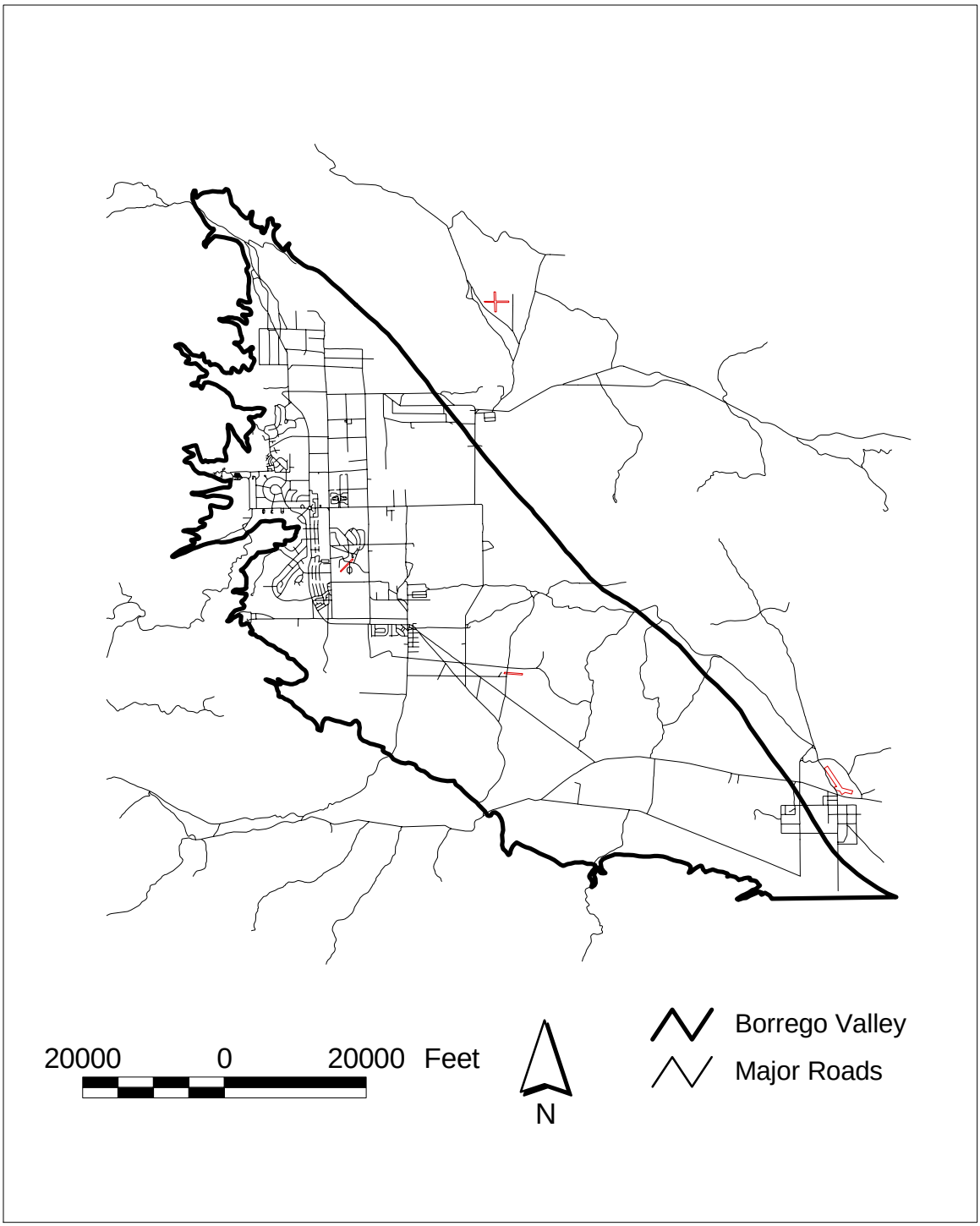


Figure 2. Basemap of Borrego Valley and vicinity.

Topography

Topography in the north portion of the floor of Borrego Valley ranges in elevation from approximately 1,100 feet above mean sea level (a.m.s.l.) around the margins of the basin (Figure 3) to 440 feet a.m.s.l. in the vicinity of Borrego Sink. Topography in the central and south portions of Borrego Valley ranges in elevation from approximately 700 feet a.m.s.l. to 100 feet a.m.s.l. at the southeast end.

Geologic Setting

Borrego Valley is bounded on the north, west, and south by mountains of the Southern California Batholith. East of Borrego Valley are the Borrego Badlands, and the desert region of Imperial Valley. Cretaceous-age granitic and metasedimentary rocks of the Southern California Batholith define the valley on three sides, and form its base. Sedimentary fill in Borrego Valley includes Tertiary marine and terrestrial deposits, as well as Quaternary alluvium of Holocene age.

Borrego Valley is in the San Jacinto Fault Zone, with a major splay of that fault (the Coyote Creek Fault) occurring along the eastern side of the basin. Faults in the San Jacinto Fault Zone are characterized (in general) as right-lateral strike-slip faults. Several other faults occur in the vicinity of Borrego Valley. Most of these faults are roughly coincident in strike (approximately northwest) to the San Jacinto Fault Zone.

Folds in Tertiary sedimentary rocks occur in Borrego Valley, both southwest and slightly north of Borrego Mountain. These folds appear to plunge in a southwesterly direction. Folds in the Borrego Badlands east of Borrego Valley are extensive, and complex. The geology of Borrego Valley and surrounding vicinity is described in greater detail in Chapter II.

Hydrogeology

The hydrogeology of Borrego Valley is characterized by four hydrogeologic units within the overall aquifer system. The hydrogeologic units include (from bottom to top) the Tertiary Palm Spring Formation (and other Tertiary marine and terrestrial deposits – if present), older Quaternary alluvium, intermediate-age Quaternary alluvium, and younger Quaternary alluvium. The principal water-bearing unit in Borrego Valley appears to be the older alluvium. The unit with the greatest thickness in Borrego Valley is the Tertiary Palm

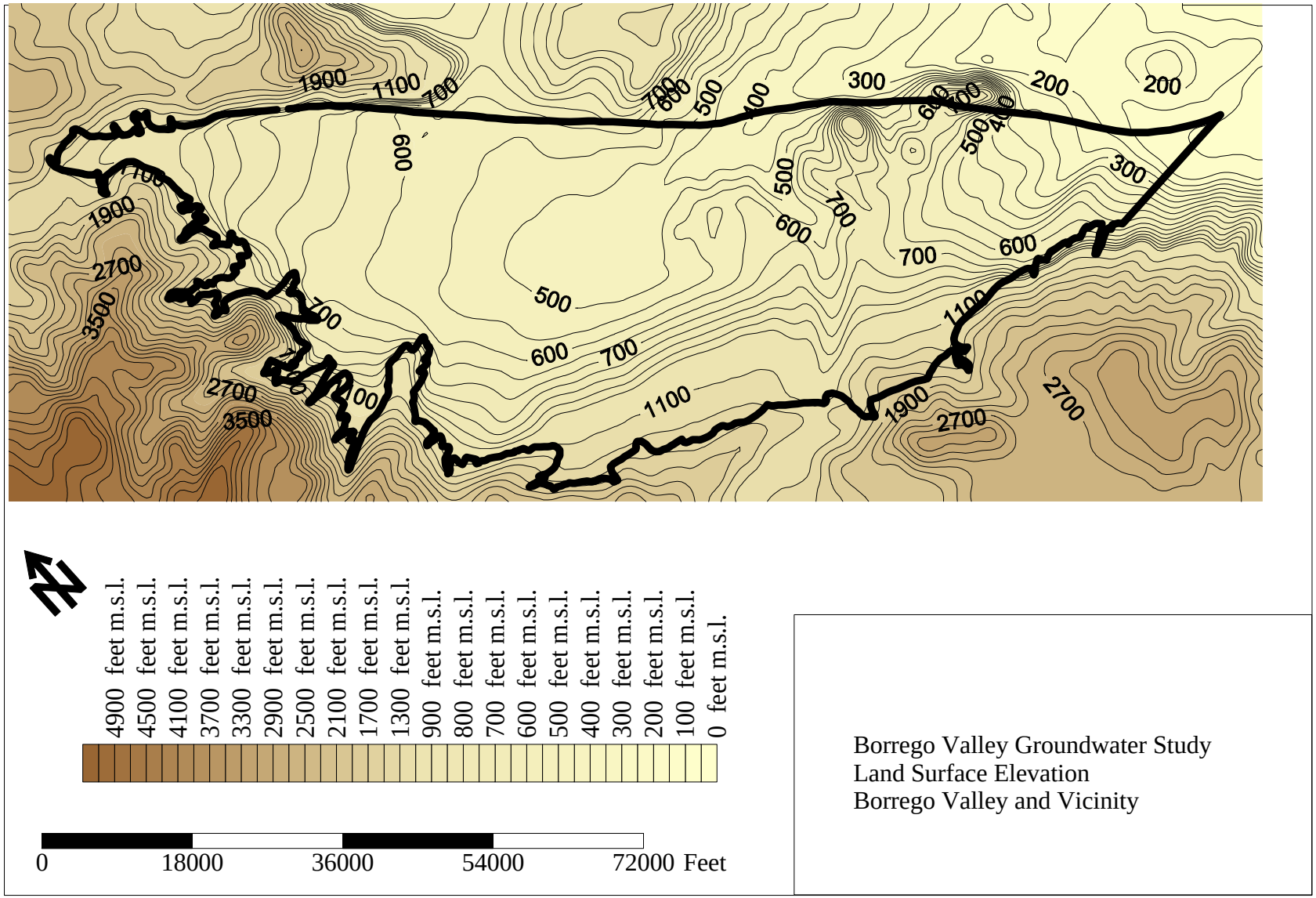


Figure 3. Land surface elevation in Borrego Valley and vicinity.

Spring Formation (and other Tertiary sedimentary formations - if present). These units are described in greater detail in Chapters III and IV.

Well Numbering System

Most of the wells used in this study are named according to their location in the rectangular system used for subdivision of public land. All wells are named based on the San Bernardino Base Line and Meridian. The first part of the well number preceding the slash (as in 10S/6E 21A1) indicates the Township. The number after the slash represents the Range. The number after the range indicates the section within that specific Township and Range. The letter after the Section number is the Tract. The last number is a serial number for wells in each tract, as assigned by the California Department of Water Resources (DWR) (Figure 4).

Several of the wells used in this study were named by Borrego Valley residents or San Diego County Department of Planning and Land Use (SD Co. DPLU) staff. These names may correspond with state well numbers assigned by DWR, but for clarity the names assigned by Borrego Valley residents or SD Co. DPLU staff are maintained.

Vegetation

Native vegetative cover in Borrego Valley consists of native scrub in the surrounding mountains of the Southern California Batholith and native phreatophytes.

Non-native vegetative cover includes agricultural crops, grass (associated with golf courses), and potentially exotic phreatophytes.

Land Use

The principal land uses in Borrego Valley include private residential, agricultural, and recreational. Most of Borrego Valley is owned by private individuals or corporations (Moyle, 1982). Nearly surrounding Borrego Valley are the public lands of the Anza-Borrego Desert State Park, and the Cleveland National Forest.

Climate

The climate in Borrego Valley is arid, consistent with the desert region located in the study area, and extending east. Average annual precipitation on the valley floor ranges from approximately 3 to 6 inches. Rainfall in the surrounding watersheds to the west is

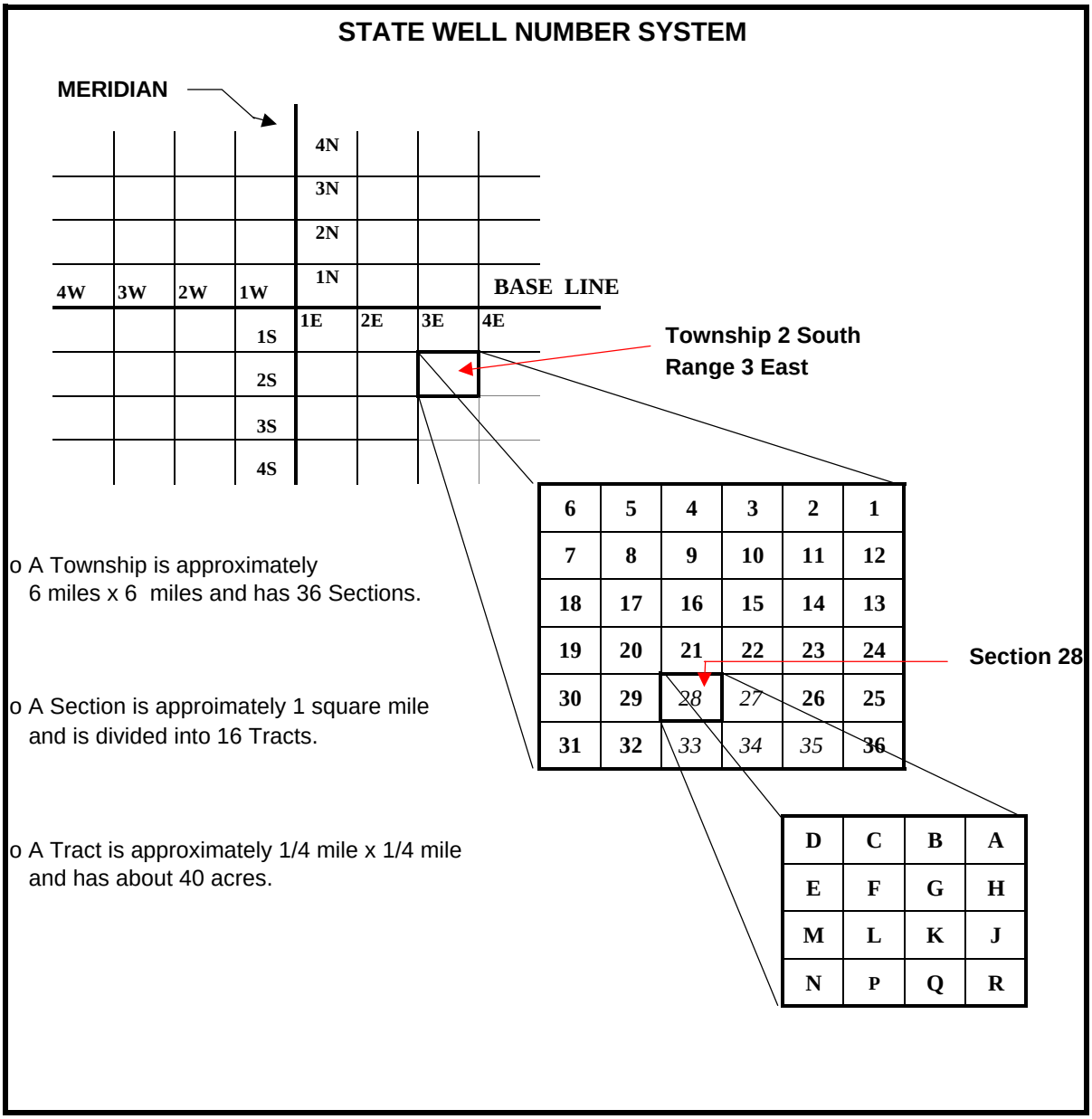


Figure 4. State well numbering system.

significantly higher, and averages approximately 16 inches (Moyle, 1982). Most precipitation occurs in the winter, generally distributed between November and April. However, summer thunderstorms, originating in Baja California to the southeast, do occur.

Surface Water Features

The primary sources of recharge in to Borrego Valley are the multiple creeks and intermittent streams that drain from the mountains of the surrounding watershed. Ten principal drainage areas were defined and informally named for the purposes of this study. Each of these drainages is described in greater detail by Netto (2001), and information about their surface water flow characteristics is provided in Chapter III.

Previous Work

Many authors have reported work associated with the geology or hydrogeology of Borrego Valley. Most of this work was reviewed, and those that provided useful information for this study are detailed below as they pertain to previous basin characterizations, previous water budgets, and previous groundwater modeling.

Burnham (1954) provided a tabulation of groundwater quality data and well information (e.g., year drilled and water level information). The report also included summaries of driller's logs for wells on file at the United States Geological Survey (USGS) at the time of the report.

California Department of Water Resources (1968) summarized a study conducted to collect and tabulate all available hydrologic data for several basins, including Borrego Valley. This study provided information to public agencies and the general public for planning water utilization and development work, and was also used as part of an overall groundwater investigation of the area. The most valuable data in this report were the multiple driller's log summaries which supplemented those provided by Burnham (1954).

Moyle (1982) was the most comprehensive and detailed study of the hydrogeology of Borrego Valley. Moyle's work included definition of a conceptual model for the aquifer system (including geologic descriptions of hydrostratigraphic units and an interpreted gravity survey), development of components of a water budget for the period 1945 through 1980, and evaluation of groundwater quality in Borrego Valley.

Moyle's work was intended to be the first phase of a study to: (1) develop a conceptual model and water budget for Borrego Valley, (2) develop a numerical model of the groundwater system in Borrego Valley, and (3) utilize the numerical for evaluation of future management scenarios for groundwater in Borrego Valley.

Moyle's work represents the starting point for the work described herein, as well as work completed by Netto (2001). Conclusions in this study are, in some instances, consistent with the work reported by Moyle. In other instances, the new work provides significantly different information and conclusions.

Mitten, Lines, Berenbrock, and Durbin's (1988) work was the second phase of a three-phase study conducted to evaluate groundwater in Borrego Valley. Mitten et al. developed a finite-element model of Borrego Valley utilizing the hydrogeologic information provided in Moyle's report of 1982. Mitten et al. constructed the model and used it to simulate water levels for the period 1946 through 1980 with two-year stress periods. Based on steady-state and transient calibration, Mitten et al. reported the calibrated physical properties of the aquifer system, based on Moyle's conceptual model.

The Phase 2 report by Mitten et al. was intended to be the second of three studies conducted relating to groundwater in Borrego Valley. A third report which intended to describe future groundwater management in Borrego Valley, could not be found, and was likely not completed.

The reports described above provided background information about the hydrogeology of Borrego Valley. These works helped to focus this author's efforts, as well as those of Netto (2001). This study includes similar independent analyses of the same hydrogeologic system, with, in some cases, different conclusions.

CHAPTER II

GEOLOGY

The geology of Borrego Valley and the surrounding area has been described by many authors. The following description of geologic units and processes for Borrego Valley are based on work by some of those authors. A limited (1-day) reconnaissance of the geology in Borrego Valley was conducted for gross confirmation of their observations.

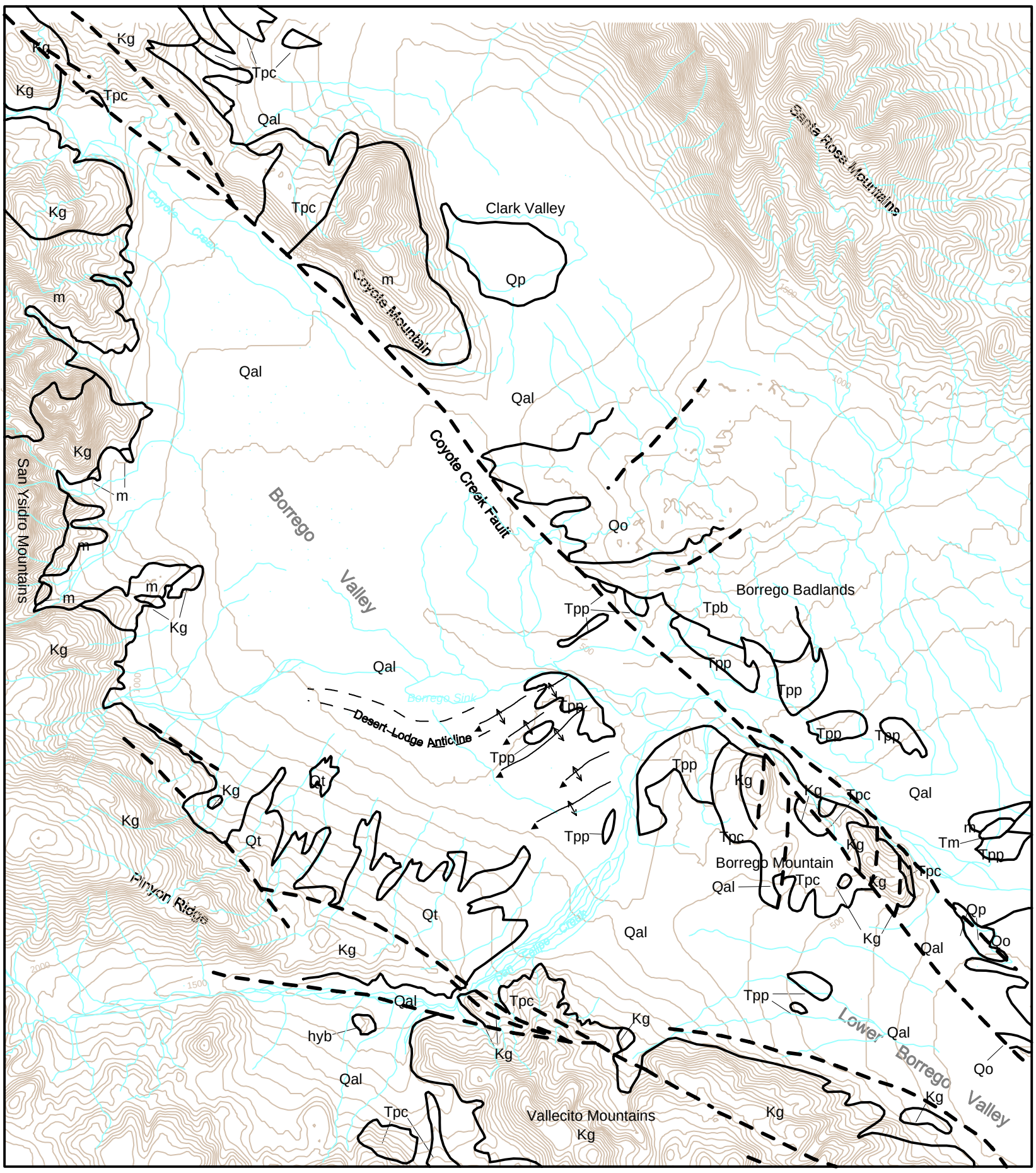
The geologic descriptions of Diblee (1986) are used extensively to describe geologic units and processes. In addition, limited information was taken from W.R. Moyle, Jr. (1982), R. Threet (personal communication, October 13, 1995), and the California Division of Mines and Geology (1959). Based on information provided by the previous authors, and the results of the field reconnaissance, a map of surface geology in the vicinity of Borrego Valley was constructed (Figure 5).

Geologic Units

Geologic units in Borrego Valley and the surrounding vicinity include crystalline rocks, consolidated sedimentary rocks, and poorly- to moderately-consolidated alluvium. Each of the geologic units recognized during the 1-day reconnaissance, or as described in the literature are discussed in the following sections.

Basement Complex

The oldest geologic unit in the vicinity of Borrego Valley are the Cretaceous-age granitic, and metasedimentary rocks of the Southern California Batholith. The batholith intruded what is now the area west of Borrego Valley, in the surrounding mountains and watersheds. Granitic rocks of the batholith form the basement complex of the aquifer system, and outcrop on the north, west, and southwest sides of the basin, as well as at Borrego Mountain (Figure 5).



Modified From: California Division of Mines and Geology, 1959

GEOLOGIC UNITS

Qal - Quaternary Alluvium
Qp - Quaternary Playa Deposits
Qt - Quaternary Terrace Deposits and Disected Alluvium
Qo - Ocotillo Conglomerate
Tpb - Borrego Formation
Tpp - Palm Spring Formation
Tpc - Canebrake Conglomerate
Tm - Imperial Formation
Kg - Granitic Rocks (undivided)
m - Metesedimentary Rocks (undivided)

Geologic Contacts

Faults

Intermittant Streams

Elevation Contour
(Contour Interval = 100 feet)

0 2 4
MILE

Figure 5. Geology of Borrego Valley and vicinity.

Imperial Formation

The Tertiary Imperial Formation crops out east of Borrego Valley in the Borrego Badlands. The Imperial Formation may occur in Borrego Valley at depth, overlying the basement complex. A driller's log for well 10S/5E 25R1 (near the west side of Borrego Valley) notes shells at a depth of 430 feet, which would be consistent with the Imperial Formation. No other evidence of the Imperial Formation in driller's logs has been found; however, the Imperial Formation is expected to underlie the Palm Spring Formation. Because the Palm Spring Formation has limited water bearing characteristics (described later), few wells have fully penetrated the Palm Spring Formation extensively. The Imperial Formation is characterized as "light gray claystone and lesser interbedded arkosic sandstones, with calcareous oyster-shell reefs" (Diblee, 1986, p. 3). According to Diblee, the Imperial Formation was deposited in a shallow marine environment.

Canebreak Conglomerate

The Tertiary Canebreak Conglomerate crops out east of Borrego Valley in the Borrego Badlands, north of Borrego Valley along the western slope of Coyote Mountain, and southeast of Borrego Springs in the vicinity of where San Felipe Creek enters Borrego Valley (Figure 5). The Canebreak Conglomerate may occur in Borrego Valley at depth, overlying the Imperial Formation (if present), or the basement complex. The Canebreak Conglomerate is interpreted by Diblee to be the "coarse marginal facies of the Palm Spring Formation" (Diblee, 1986, p. 3). The lithology of the Canebreak Conglomerate is described as "granitic fanglomerate and gray conglomerate" (Diblee, p. 3).

Palm Spring Formation

The Tertiary Palm Spring Formation crops out in Borrego Valley, south-southeast of the City of Borrego Springs (Figure 5). The Palm Spring Formation is the thickest sequence of sedimentary deposits in Borrego Valley (described later). The Palm Spring Formation also crops out extensively in the Borrego Badlands, east of Borrego Valley. Diblee described the Palm Spring Formation as "a thick series of land-laid arkosic sandstones and red clays of Pliocene age" (1986, p. 2). Diblee further indicated that the Palm Spring Formation grades westward into the Canebreak Conglomerate.

Older Alluvium

Older Quaternary alluvium is present, at depth, throughout most of the northern portion of Borrego Valley. It is absent, or very thin, in the middle portion of the aquifer system, and southward, in the vicinity of where the Palm Spring Formation crops out. This unit is of Holocene age, and is comprised of sediments ranging from clay-sized to cobble-sized clasts. The older alluvium was deposited primarily by alluvial fan and intermittent stream processes.

Lacustrine Deposits

Quaternary lacustrine deposits are present, at depth, throughout much of the northern portion of Borrego Valley. The lacustrine units are present at or near the surface, near the south-central portion of the basin, north of where the Palm Spring Formation crops out. This unit is of Holocene age, and is comprised primarily of fine-grained sediments (e.g., clay-sized to silt-sized particles). The lacustrine deposits were part of a shallow fresh water depositional system, such as a shallow lake or delta.

Younger Alluvium

Younger Quaternary alluvium is present at the surface throughout most of Borrego Valley (Figure 5). Exceptions are locations where the lacustrine unit or Palm Spring Formation are exposed near the surface in the central portion of Borrego Valley. This unit is of Holocene age and is comprised of sediments ranging from clay-sized to cobble-sized clasts. The younger alluvium was deposited primarily by alluvial fan and intermittent stream processes.

Additional Lithologic Units Within the Study Area, But Outside the Area of Interest

Several important geologic units occur within the general study area, but outside of the immediate area of interest. These units occur in the Borrego Badlands, east of Borrego Valley.

Borrego Formation

The Tertiary Borrego Formation crops out east of Borrego Valley in the Borrego Badlands. According to Diblee, the Borrego Formation is of Pliocene age. The Borrego Formation does not appear to occur in the Borrego Valley aquifer system. The Borrego Formation is interpreted by Diblee (1986) to be the fine grained lacustrine facies of the Palm Spring Formation. The lithology of the Borrego Formation is described as "light gray claystone and minor buff sandstones" (Diblee, p. 3).

Ocotillo Conglomerate

The Ocotillo Conglomerate overlies the Borrego Formation in the Borrego Badlands, east of Borrego Valley. According to Diblee, the Ocotillo Conglomerate is of Pliocene to Pleistocene age. The Ocotillo Conglomerate does not occur in the Borrego Valley aquifer system. The Ocotillo Conglomerate is described by Diblee as "gray conglomerate of granitic debris" (Diblee, 1986, p. 3).

Structural Features

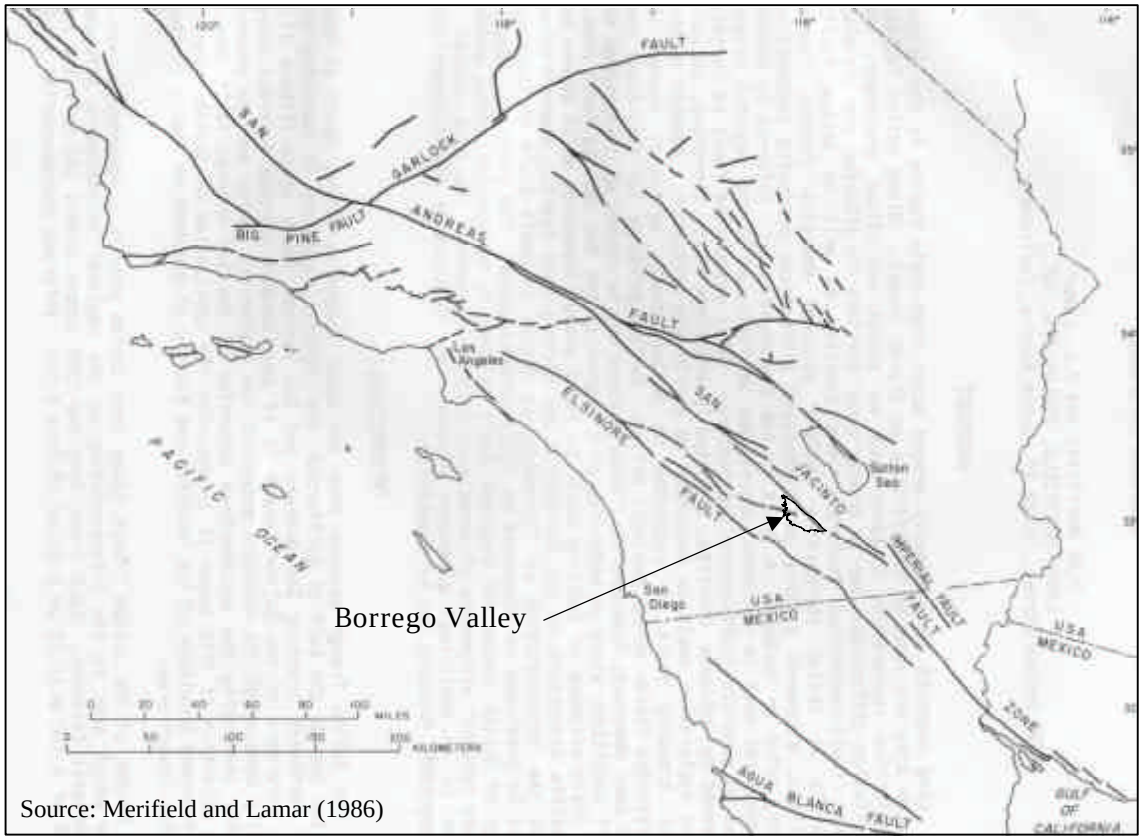
Structural features in Borrego Valley include faults and folds, associated primarily with regional tectonics, and specifically the San Jacinto Fault Zone.

Faults

Borrego Valley is located within the San Jacinto Fault Zone, which is characterized by a series of right-lateral, strike-slip faults which trend north-northwest (Figure 6). The Coyote Creek Fault, part of the San Jacinto Fault Zone runs along the interpreted east margin of the aquifer system (Figure 5). The Coyote Creek Fault was interpreted to be a barrier to groundwater flow by Moyle (1982). This interpretation was based on a few water levels, near the southern extent of Coyote Mountain. It is unclear whether the fault actually acts as a barrier to groundwater flow. The distinction may be unimportant, given the proximity of the Borrego Badlands east of the fault, which are expected to be a barrier to groundwater flow.

Folds

Folds in older sediments are common in the vicinity of Borrego Valley, particularly in the Borrego Badlands. Diblee reported a major synclinorium in the Borrego Badlands that he



Source: Merifield and Lamar (1986)

Figure 6. Major faults in southern California.

called the San Felipe Synclinorium. The major axis of this feature trends east-west through Borrego Mountain and the San Felipe Hills (Diblee, 1986). Dr. Richard Threet (personal communication, October 13, 1995) identified the Desert Lodge Anticline (probably a unit of the Sleepy Hollow Folds) as a westward plunging anticline within the Palm Spring Formation (Figure 5). The Desert Lodge Anticline appears to represent the northern-most surface or near-surface expression of folding in the Palm Spring Formation, in Borrego Valley. This anticline, and the series of folds it is associated with, appear to isolate groundwater in the northern portion of Borrego Valley from the southern portion, as is described in greater detail later. The surface expression of southwestward plunging synclines and anticlines south of Borrego Sink are obvious from inspection of topography and the surface outcrop pattern of the Palm Spring Formation (Figure 5).

Geologic Configuration of the Conceptual Model

The U.S. Geological Survey (USGS) reported the results of a gravity survey conducted for Borrego Valley, as part of their 1982 study. The gravity survey and subsequent interpretations were based on information available at that time. Since that time, new data have become available which have been integrated into a reanalysis by this author and others.

Original Interpretation of Gravity Data

As part of the 1982 study, the USGS collected gravity survey data from 223 stations in and around Borrego Valley (Moyle, 1982). Based on those data, and subsequent interpretations, the USGS derived an elevation of the top surface of the basement complex. The USGS also calculated a maximum thickness of sediments in the basin of 2,450 feet. Moyle cautioned that this estimated value may be subject to increasing error with distance from wells that were drilled to basement, which were used by the USGS for calibration.

The gravity data were reinterpreted in 1995, based on the addition of another data point (a new well drilled to basement near the west-central portion of the basin) (Martin, 1995). Based on this information, Martin calculated new density contrasts between saturated sediments and basement (approximately 0.41 gm/cc), and unsaturated sediments and basement (approximately 0.51 gm/cc), using the modeling program MagixPlus (Martin,

1995). These calculations were specific to an area in the vicinity of the wells drilled to basement.

New Interpretation of Gravity Data

The new information provided by Martin, as well as the need to develop a new conceptual model of the groundwater basin led to the re-evaluation of the USGS gravity data. Details of that re-evaluation are provided below.

Based on the new density contrasts calculated by Martin, a second reinterpretation of the residual gravity map presented by Moyle (1982) was completed. MagixPlus was utilized to calculate new basement depths along each of the 10 hydrogeologic cross-sections developed for this study (described later). MagixPlus is a software program that allows two-dimensional (2-D) interpretation of measured gravity data. The new density contrasts (Martin, 1995), an estimated water table elevation, the existing residual gravity map (Moyle), and information about where bedrock outcrops at the surface were utilized. Basement elevations were calculated along the profile of all 10 hydrogeologic cross-sections (Figures 97 through 106, Appendix A). Data from cross-sections that were not closely perpendicular to the contours of residual gravity on Moyle's map were excluded since they violated the 2-D assumption.

In addition to basement elevation reinterpretation utilizing MagixPlus, data provided by Agbabian and Associates were utilized for the area in the north portion of Borrego Valley. Agbabian and Associates conducted a focused tectonic study of north Borrego Valley. As part of their tectonic study, they drilled several wells to basement and conducted geophysical measurements (including gravity surveying) over a dense grid. While Agbabian and Associates would not release the data they collected for further interpretation, they did release their interpreted basement elevation in this area of Borrego Valley (Figure 107 – Appendix A). These data were utilized for determination of basement elevation in that portion of the aquifer system.

Data from select MagixPlus interpretations, the Agbabian and Associates data, and data reflecting bedrock outcrop locations were integrated, and contoured to estimate bedrock elevation throughout Borrego Valley (Figure 7).

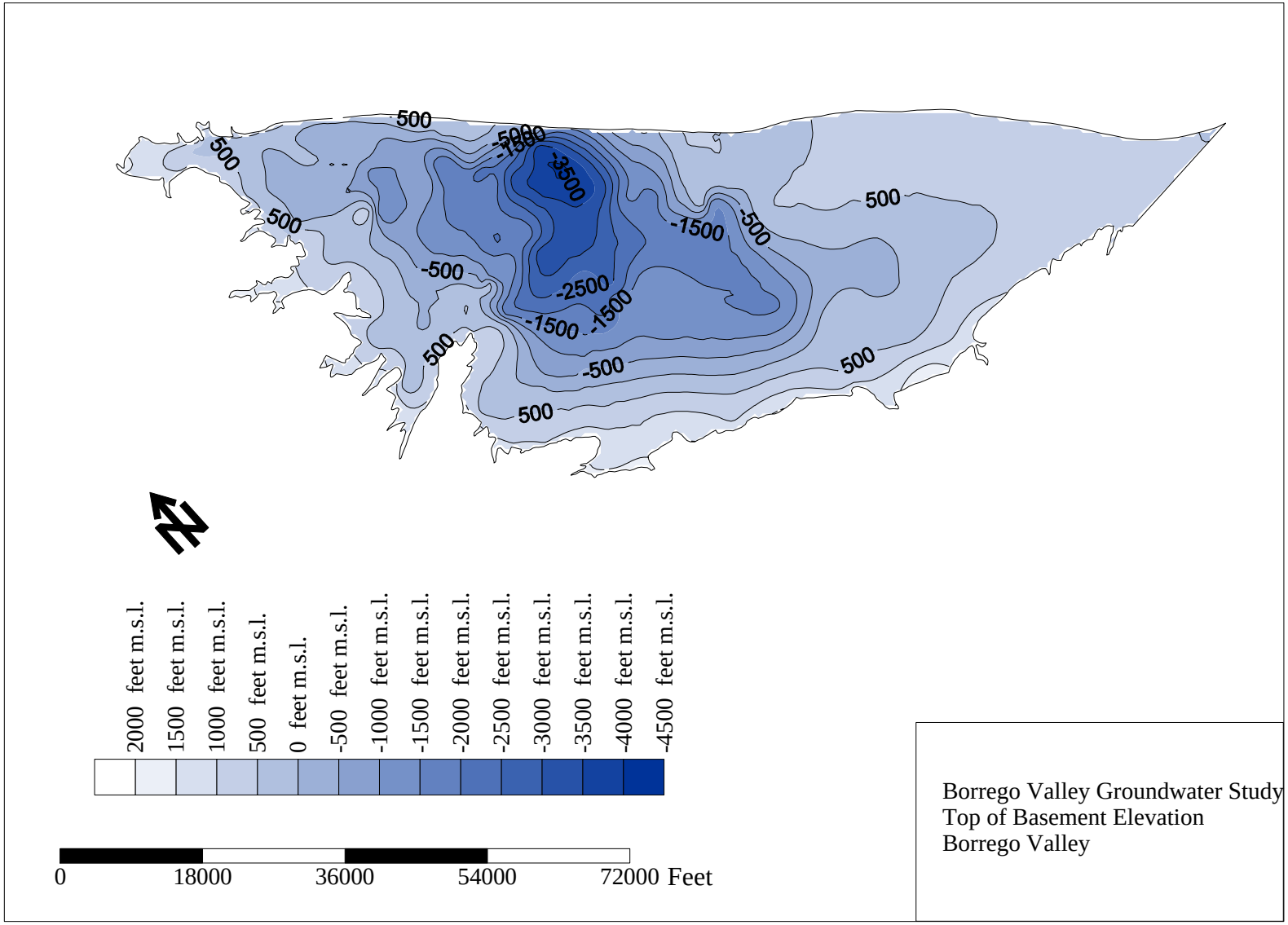


Figure 7. Estimated elevation of the top of basement.

Stratigraphic Interpretation of Boring Logs

To develop a numerical model of Borrego Valley, a conceptual model had to be established. Available driller's logs for borings in Borrego Valley and vicinity were provided by the California Department of Water Resources (DWR) and existing literature (DWR, 1995). Based on the density and location of driller's logs, 10 hydrogeologic cross-sections were oriented across Borrego Valley (Figure 8). Driller's logs from 133 wells were used to develop the conceptual model of the basin, as described in Chapter III. Discrete aquifer units were estimated based on the driller's logs (Plate 1 in back pocket). The information provided by each of the 10 hydrogeologic cross-sections was integrated, and a contour map of each conceptual hydrogeologic unit was created utilizing a thin-plate spline algorithm. Further information on the development of the conceptual model is provided in Chapter III.

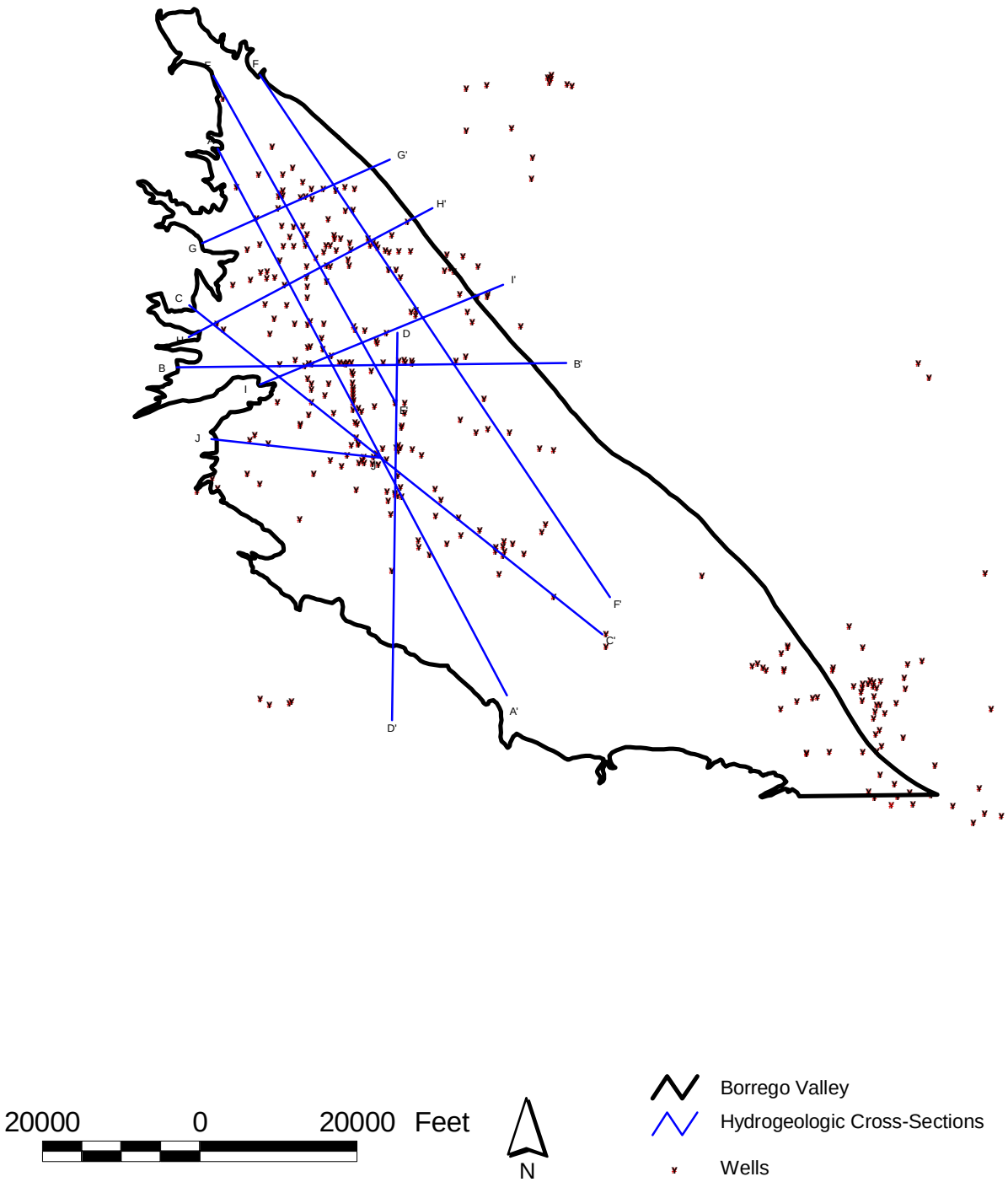


Figure 8. Hydrogeologic basemap with the locations of 10 hydrogeologic cross-sections.

CHAPTER III

HYDROGEOLOGY

The hydrogeology of the Borrego Valley aquifer system is described below. The defining components of the aquifer system include both physical characteristics, sources or recharge and discharge, and groundwater levels and movement.

Definition of the Aquifer System and Hydraulic Properties

Four primary aquifer system hydrogeologic units were defined by the interpretation of local geologic units described in the previous chapter and by the review of driller's logs. These four units were distinguished from one another based on their soil texture, color, and other pertinent geologic information, as described by driller's logs. In general, the four units are well-defined near the center of the groundwater basin, particularly in the vicinity of Borrego Sink – an historic groundwater discharge area. Around the margins of the basin, the distinction between several of the hydrogeologic units is less pronounced. Soil textures around the margin of the basin are dominated by sediments deposited as alluvial fans. This depositional environment provides for a wider range of soil textures spatially, limiting the ability to track continuous hydrogeologic units. Three of the described hydrogeologic units are Quaternary in age, and include both alluvium (e.g., alluvial fan and intermittent stream deposits) and an interpreted lacustrine unit, probably associated with fresh-water and/or playa lakes occurring historically in the vicinity of Borrego Valley. The last of the four described hydrogeologic units, the Palm Spring Formation, is Tertiary in age, and is ubiquitous throughout much of East San Diego County, Imperial County, and portions of Riverside County. As previously described, the Palm Spring Formation is an interbedded assemblage of freshwater sedimentary deposits.

Younger Alluvium

The younger Quaternary alluvium in Borrego Valley is primarily alluvial fan and intermittent stream deposits. The processes which created this hydrogeologic unit continue today, as sediment is eroded and transported from the mountains surrounding Borrego Valley

to the valley floor. The upper surface of the younger alluvium coincides with land surface where the alluvium is present (Figure 9). It is absent through much of the middle-portion of Borrego Valley and other localized areas. The younger alluvium is thickest near the margins of the basin, where it is under the most direct influence of deposition via alluvial fans and intermittent streams (Plate 1 in back pocket). It attains a maximum interpreted thickness in Borrego Valley of approximately 1,200 feet, south of San Felipe Creek (Figure 10), and ranges in thickness between 0 and 400 feet throughout the primary portion of the aquifer system.

Soil textures in the younger alluvium range from clay-sized to cobble-sized particles. The distribution of these units is generally erratic, a function of their alluvial fan and intermittent stream depositional environment. The generalized spatial distribution of the different soil textures in the younger alluvium is described in greater detail in Chapter IV. The water-bearing characteristics of the younger alluvium were based on interpretation of aquifer tests, and grain-size diameter relationships, as described by Netto (2001). Table 1 below, provides the interpreted values of hydraulic conductivity, specific yield, and elastic storage coefficient (as specific storage) based on that work. These values were later modified by model calibration, as described in Chapter V.

Table 1

Summary of Initial Estimates of Physical Properties of Hydrogeologic Units

Hydrogeologic Unit	Hydraulic Conductivity (ft/day)	Specific Yield (Percent)	Specific Storage (per foot of aquifer)
Alluvium (Younger, Intermediate-Age, and Older)			
Gravel	1,915	30	0.000002
Coarse Sand	342	25	0.000002
Medium Sand	85	15	0.000002
Fine Sand/Silt	15	10	0.000002
Clay	0.0002	5	0.000002
Interbedded Clay and Gravel	17	15	0.000002
Palm Spring Formation			
All	10	10	0.000002

Note. As estimated by aquifer tests and soil texture diameter relationships.

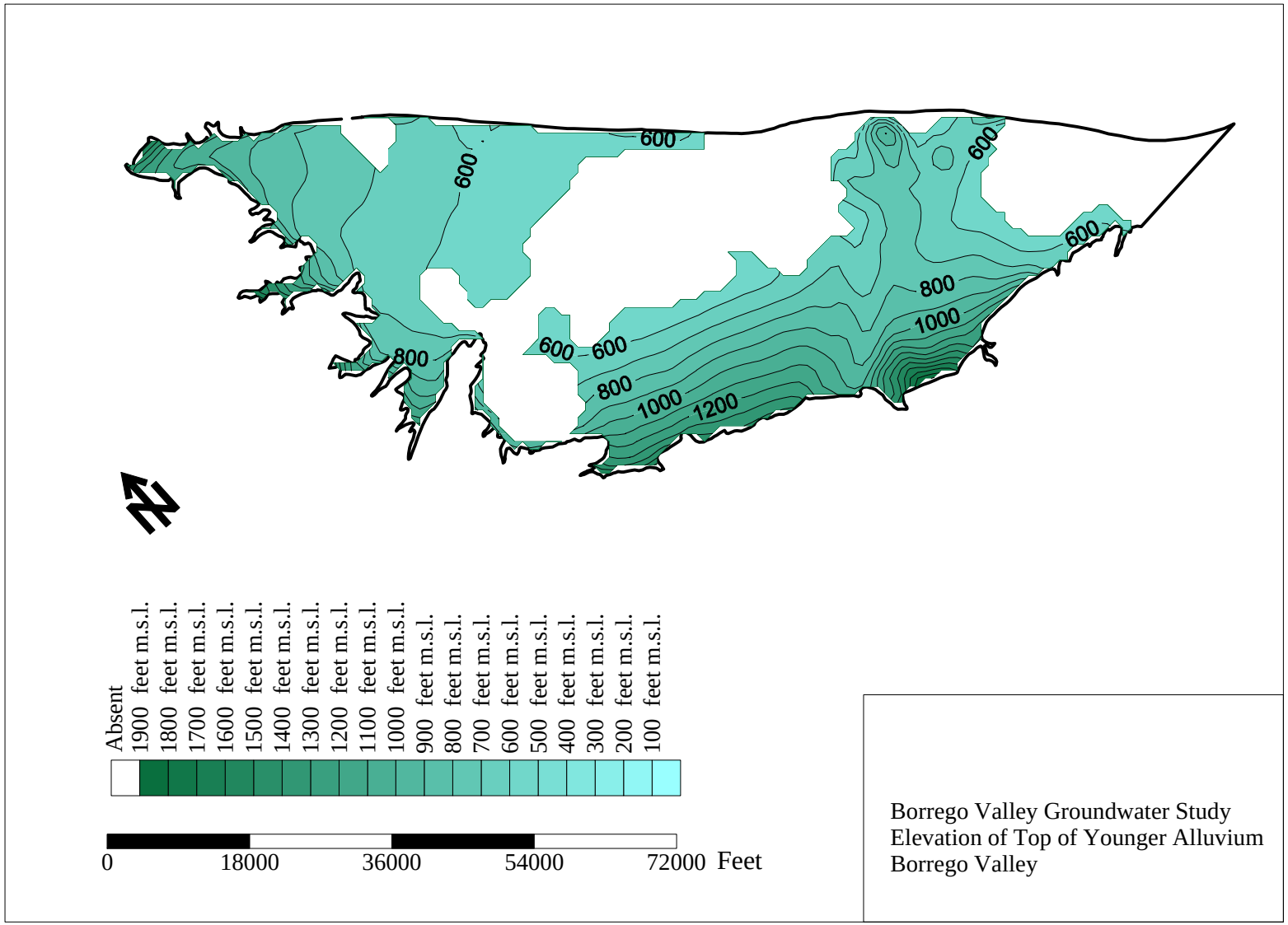


Figure 9. Elevation of top of younger alluvium.

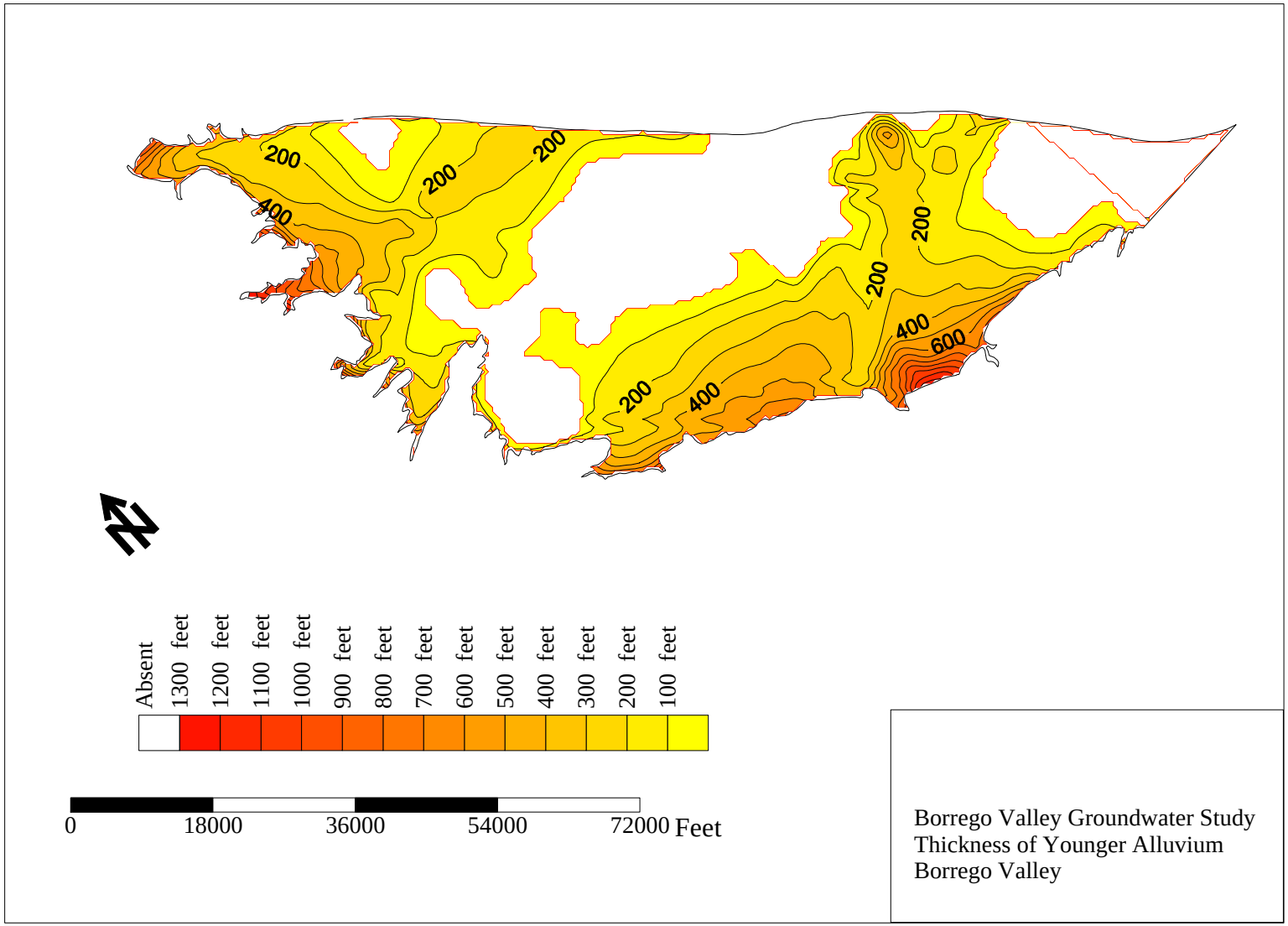


Figure 10. Thickness of younger alluvium.

Intermediate-Age Alluvium

The intermediate-age alluvium in Borrego Valley is an assemblage of low- and high-energy depositional environment alluvium. Near the center of the basin, in the vicinity of the historic groundwater discharge area and the topographic low, the depositional environment is interpreted to be lacustrine deposits. In these areas, the unit is thickest, indicating depositional in-filling of historic topographic lows. Around the margins of Borrego Valley, the lithology of this unit is similar to the younger alluvium, and is characterized by fine to coarse grained sediments associated with high-energy depositional environments, such as alluvial fans and intermittent streams. The upper surface of the intermediate-age alluvium coincides with land surface in areas where the younger alluvium is absent (Figure 11). The intermediate-age alluvium is interpreted to be absent throughout much of the southwestern and the northern-most portions of Borrego Valley. As with the other three hydrogeologic units, the interpreted thickness and lateral extent of this unit is based primarily on lithologic descriptions from driller's logs. As such, the intermediate-age alluvium may be present in those areas where it is shown as absent, but is indistinguishable, from the overlying younger alluvium and underlying older alluvium. Additionally, the intermediate age alluvium is absent in the vicinity of Borrego Mountain due to the localized bedrock highs, and absent where the Palm Spring Formation (described later) is present at land surface. It attains a maximum interpreted thickness of approximately 600 feet, near the middle of the aquifer system, southeast of the City of Borrego Springs (Figure 12). This unit ranges in thickness between 0 and 600 feet throughout the primary portion of the aquifer system.

Soil textures in the intermediate-age alluvium range from clay-sized to cobble-sized particles. The finer grain sediments occur near the middle of the aquifer system, in the historic groundwater discharge area, as lacustrine type deposits. Coarser sediments occur along the margins of the groundwater basin, under the influence of alluvial fan deposition. The spatial distribution of the different soil textures in this unit is described in greater detail in Chapter IV. The estimated water-bearing characteristics of the intermediate-age alluvium are provided in Table 1.

Older Alluvium

The older Quaternary alluvium in Borrego Valley is primarily comprised of alluvial fan and intermittent stream deposits. The interpreted surface of the older alluvium is

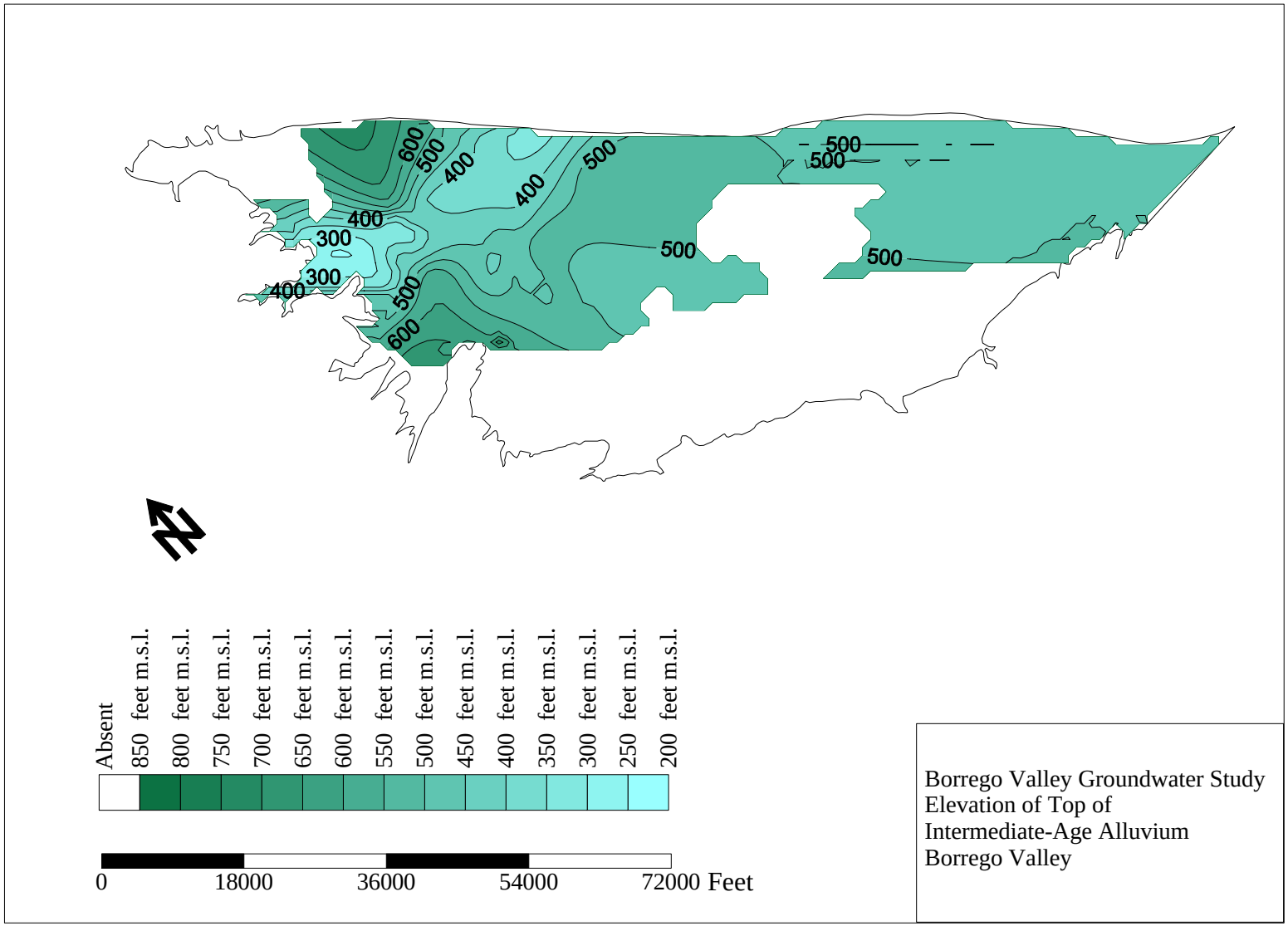


Figure 11. Elevation of top of intermediate-age alluvium.

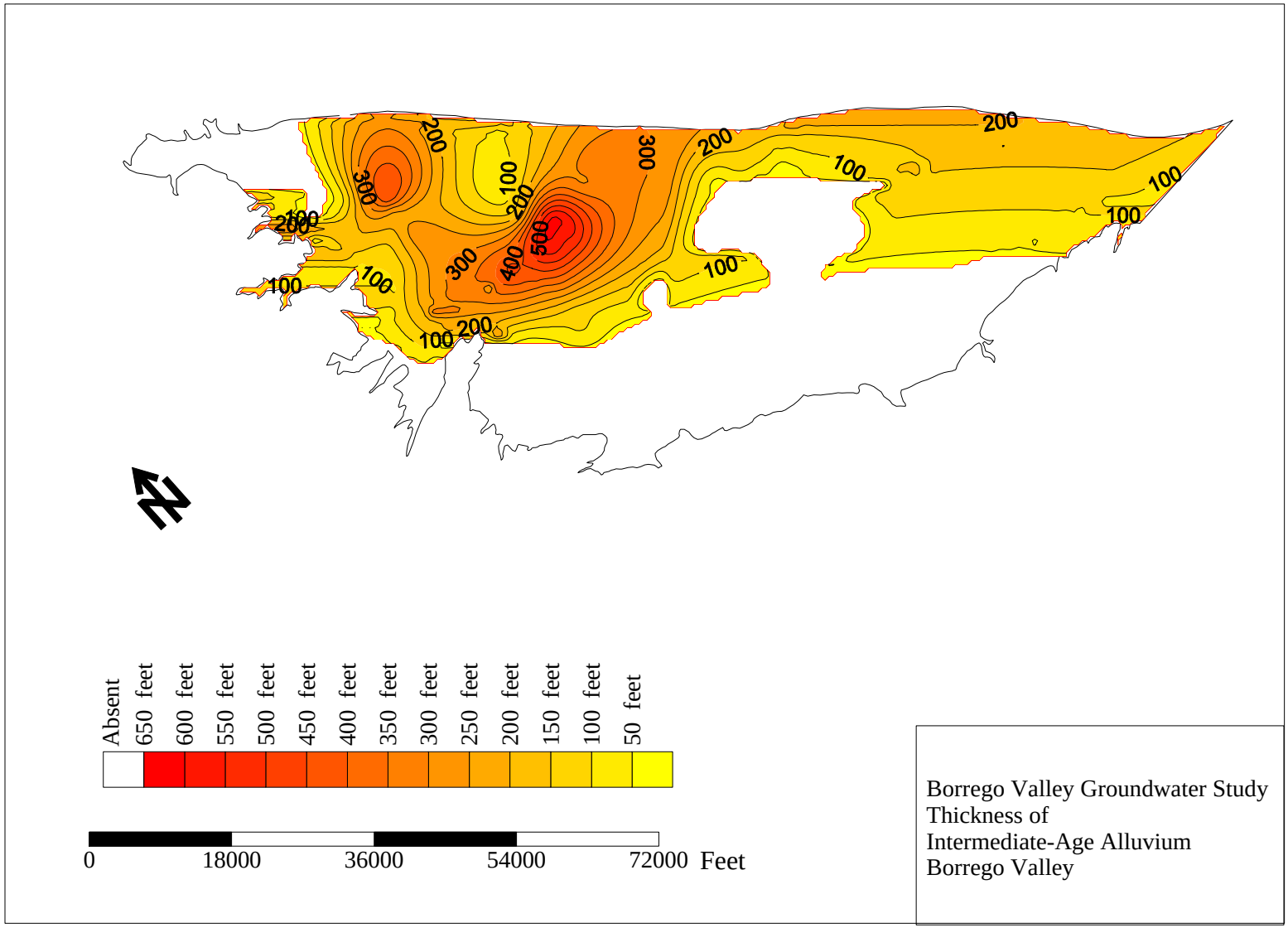


Figure 12. Thickness of intermediate-age alluvium.

provided in Figure 13. This unit is absent through much of the middle-portion of Borrego Valley (where the Palm Spring Formation crops out), and other localized areas. This unit is thickest near the margins of the basin, particularly in the vicinity of Coyote Creek, where it is under the most direct influence of deposition via alluvial fan deposits and the stream deposits of Coyote Creek. It attains a maximum interpreted thickness of approximately 1,400 feet, near the mouth of Coyote Creek (Figure 14), and ranges in thickness between 0 and 1,000 feet throughout the primary portion of the aquifer system.

Soil textures in the older alluvium are like those of the younger alluvium, and range from clay-sized to cobble-sized particles. The distribution of these textures is generally erratic, a function of their alluvial fan and intermittent stream depositional environment. The spatial distribution of the different soil textures in the older alluvium is described in greater detail in Chapter IV. The water-bearing characteristics of the older alluvium are provided in Table 1.

Palm Spring Formation

The Tertiary Palm Spring Formation is a shallow-water (e.g., lake or delta) deposit. Throughout much of its area of occurrence, the Palm Spring Formation is stratified, and distinct depositional facies can be interpreted. The presence of the Palm Spring Formation in Borrego Valley is based primarily on the work of others, as well as driller's log notations (e.g., soil texture and color). The interpreted surface of the Palm Spring Formation is provided in Figure 15. This unit is interpreted to overlie both the crystalline basement complex as well as any other older sediments that may be in the aquifer system, but not identified in driller's logs. This unit is present throughout much of the middle portion of Borrego Valley, and crops out northwest of Borrego Mountain. The geometry of this unit is not fully known due to data limitations. However, based on driller's logs, the northern portion of this unit occurs as a thickening wedge, starting near the north-central portion of the basin, proceeding southeastward. It attains a maximum interpreted thickness of approximately 4,000 feet, southeast of the City of Borrego Springs (Figure 16) and ranges in thickness between 0 and 4,000 feet throughout the primary portion of the aquifer system.

Interpretation of the driller's logs did not allow identification of stratigraphy or facies within this unit so, for the purposes of this study, it is "lumped" into one soil texture,

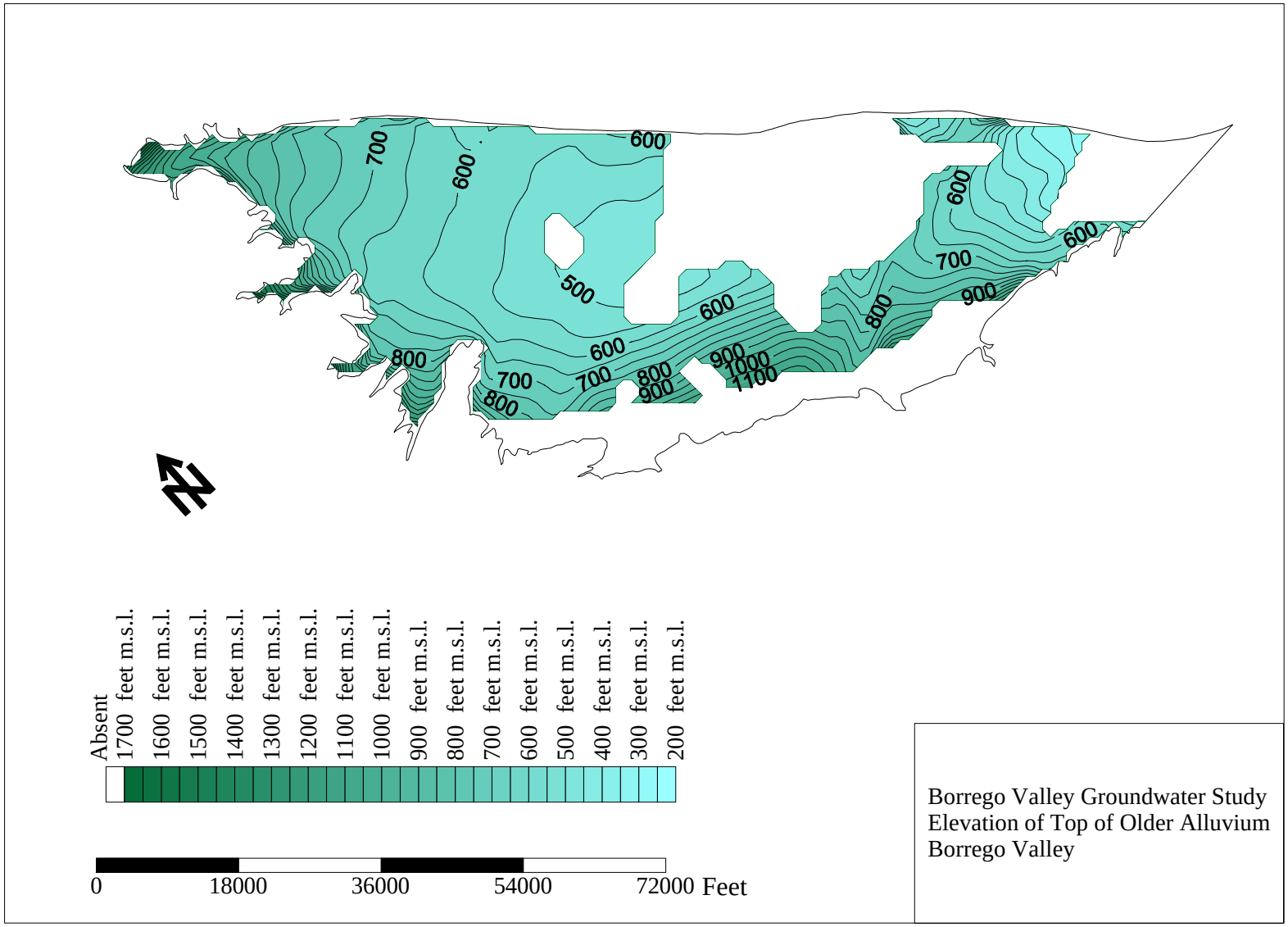


Figure 13. Elevation of top of older alluvium.

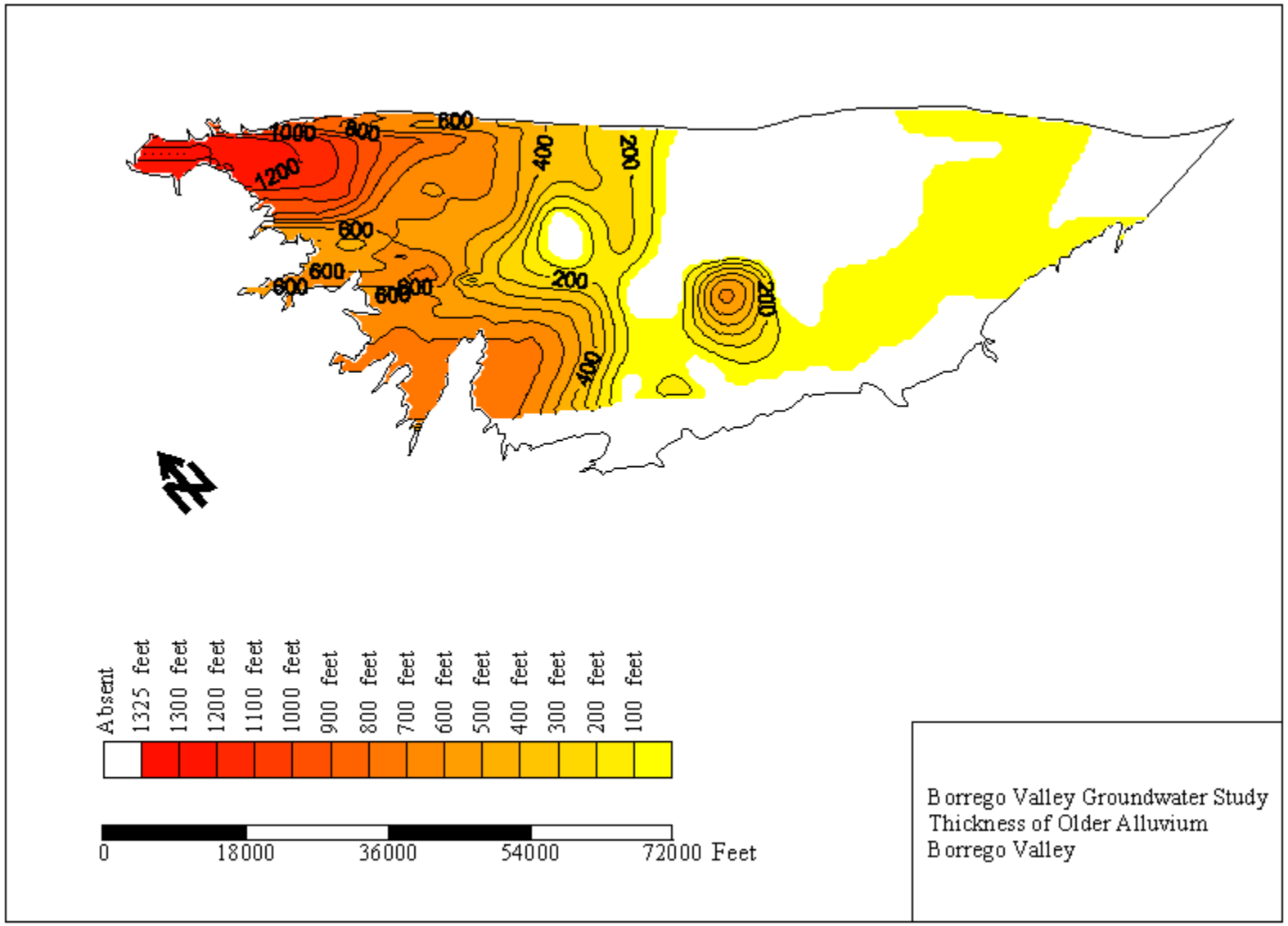


Figure 14. Thickness of older alluvium.

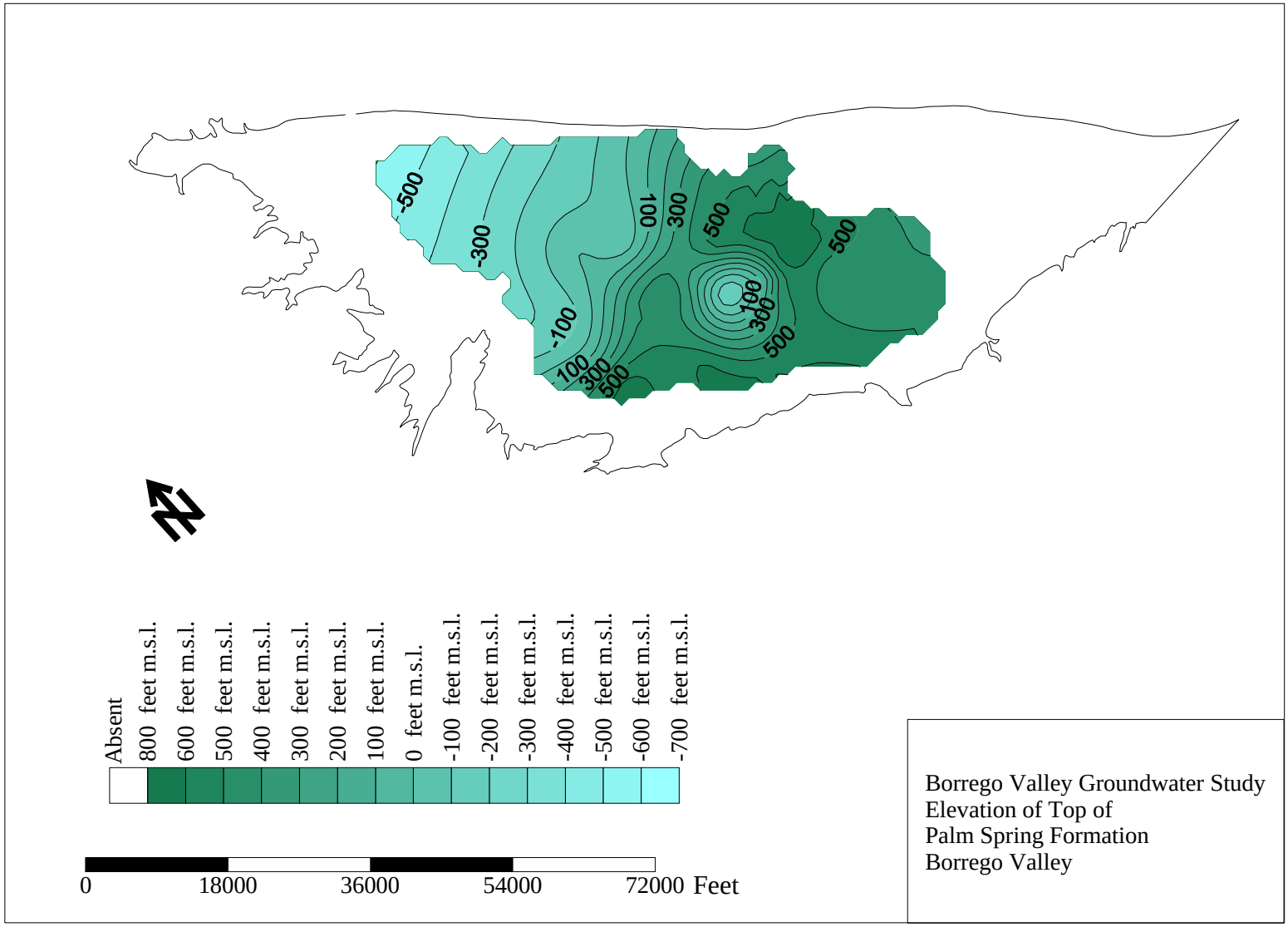


Figure 15. Elevation of top of Palm Spring Formation.

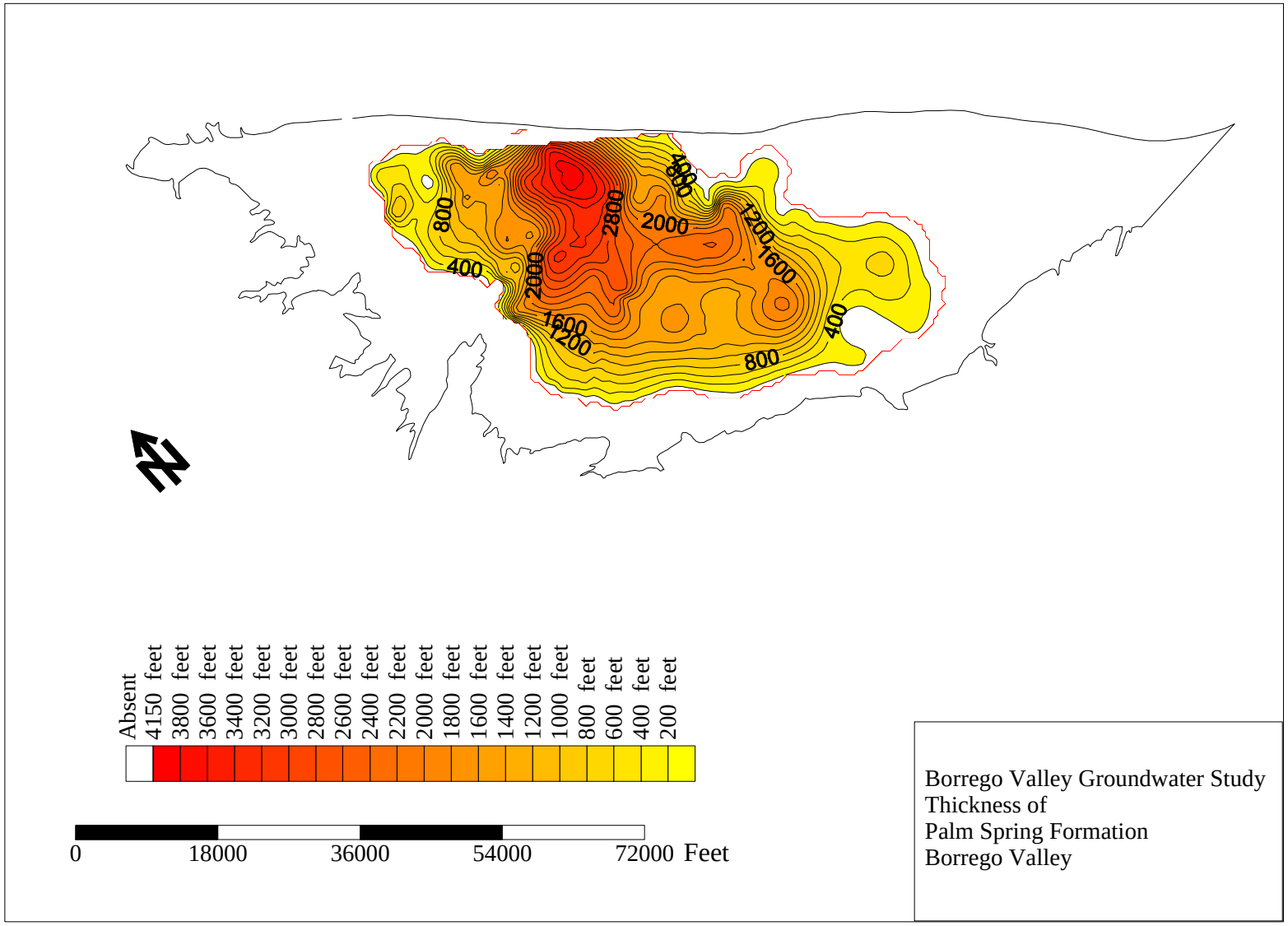


Figure 16. Thickness of Palm Spring Formation.

representing the most-common sediment grain sizes. The water-bearing characteristics of the Palm Spring Formation are provided in Table 1.

Basement Complex

The base of the aquifer system is the crystalline bedrock of the Southern California Batholith. The basement complex is Cretaceous in age, and intruded into what is now Southern California as a northwest trending feature, composed primarily of granitic rock. The water-bearing characteristics of this feature are expected to be orders of magnitude lower than those of both the alluvium and formational materials described above. The top of the basement complex forms the base of the aquifer system. The top of the basement complex (Figure 7) was interpreted based on field mapping, and re-interpretation of existing gravity data, as described in Chapter II.

Sources of Recharge

Recharge to groundwater in the Borrego Valley occurs as meteoric water enters the system via several pathways. Meteoric water in the surrounding watershed becomes recharge as infiltrating surface water, as bedrock recharge, or as underflow into the immediate vicinity of the valley. All of these sources of recharge result from rainfall in the surrounding watershed area. Rainfall that occurs on the floor of Borrego Valley itself is assumed to not infiltrate and become a source of recharge, due to high evaporation rates and low quantities of actual rainfall. Recharge in Borrego Valley is directly linked to yearly distributions of rainfall in the surrounding watershed, as well as long-term trends in climatic cycles.

Quantification of recharge to the Borrego Valley for the period 1945 through 2000 was accomplished by evaluating discreet sources of recharge. To the extent possible, historically observed, or measured data were utilized to quantify the amount of each of these sources. Where observed data are absent, source amounts were estimated utilizing empirical and/or analytical relationships, as described below.

Surface Water Infiltration

Infiltration of surface water into the Borrego Valley groundwater basin was estimated using observed data and empirical and analytical relationships. This source of recharge to

the groundwater basin originates as rainfall in the mountains of the surrounding watershed (Figure 3). A portion of the volume of water which falls in discrete drainage areas within the watershed becomes runoff. Runoff leaves the watershed and drainage area as creeks or streams. These streams enter the Borrego Valley along its margins and flow until it infiltrates into the groundwater basin, or, in rare instances, exits the valley as surface water flow. Fifteen sources of surface water infiltration were considered for an analysis of recharge to Borrego Valley for the period 1945 through 2000. Each of these sources correspond to a discrete portion of the surrounding watershed, which drains toward Borrego Valley. Of these fifteen sources of recharge, observed surface water discharge records exist for three for various periods of time. These records provide the basis for empirically derived values of surface water discharge at the other 12 sources, as described by Netto (2001). A summary of surface water and bedrock recharge (described later) for select periods of time is provided in Table 2. This table is a companion to Table 5 (p. 40), which summarizes groundwater discharge during select years with aerial photo coverage, or other sources of discharge data. The estimates of groundwater discharge for those select years are expected to be more accurate than estimates for the intervening years which were quantified via indirect methods. Estimated quantities of surface water recharge on a yearly basis for the period 1946 through 2000 are summarized in Table 9 (Appendix B).

Gauged watersheds. Three streams were historically gauged by the USGS. Of those three, collection of gauging data continues today at only one (Borrego Palm Creek). Observed daily values of average instantaneous discharge were used to calculate the quantity of water reaching Borrego Valley originating from these three sources. A summary of surface water discharge data for these three stations is provided in Table 3.

Because observed discharge at these three stations was used to estimate discharge at the other 12 sources, full records for these stations during the period 1945-2000 had to be established. These “full records” include both observed and estimated data, as described below. A full explanation of the process utilized to develop “full records” for these three stations is provided by Netto (2001).

Table 2

Summary of Groundwater Recharge for Select Years

Year	Surface Water Recharge (Total) (AF/Yr)	Bedrock Recharge (Total) (AF/Yr)	Underflow Recharge (San Felipe Creek) (AF/Yr)	Total Recharge (AF/Yr)
1953	3,100	630	32	3,760
1959	2,690	0	32	2,720
1963	2,170	0	32	2,200
1966	2,500	3,750	32	6,280
1968	1,580	0	32	1,610
1979	7,550	2,030	32	9,610
1992	3,470	3,440	32	6,940
1995	3,850	4,590	32	8,470
1997	2,610	2,090	32	4,730
1998	8,590	1,600	32	10,220
2000	2,200	500	32	2,730

Table 3

Summary of Surface Water Sources with Historic Gauged Data

Creek or Stream	Period of Gauging	Number of Years	Minimum Discharge (A-F/Yr)	Maximum Discharge (A-F/Yr)	Average Discharge (AF-Yr)
Borrego Palm Creek	1951-2000	50	10	5,700	680
Coyote Creek	1951-1982	32	350	11,260	1,750
Upper San Felipe Creek	1959-1982	24	70	4,820	430
Note. Includes only gauged data.					
Borrego Palm Creek	1945-2000	56	10	5,700	680
Coyote Creek	1945-2000	56	350	11,260	1,890
Upper San Felipe Creek	1945-2000	56	0	4,820	470

Note. Includes both observed gauge data and calculated data.

The Borrego Palm Creek station had the most complete record, with observed data from 1951 through 2000. For the period 1945 through 1950, surface water discharge was estimated based on the rainfall to runoff relationship estimated for this drainage area during the period 1951 through 2000 (Netto, 2001).

The Coyote Creek station had the second most complete record, with observed data from 1951 to 1982. For the period 1945 through 1950, surface water discharge was estimated based on the rainfall to runoff relationship estimated for this drainage area during the period 1951 through 1982 (Netto, 2001). For the period 1983 through 2000, surface water discharge at this station was estimated based on the discharge relationship between this station and the Borrego Palm Creek station. This relationship assumes that runoff in one drainage can be related to runoff in another, for the same discrete time period (Netto).

Observed data exist for the Upper San Felipe Creek for the period 1959 through 1982. For the period 1945 through 1950, surface water discharge was estimated based on the rainfall to runoff relationship for this drainage area during the period 1959 through 1982 (Netto, 2001). For the period 1951 through 1958, surface water discharge at this station was estimated based on the estimated discharge relationship between this station and the other two stations actively gauged (Borrego Palm Creek and Upper San Felipe Creek). For the period 1983 through 2000, surface water discharge at this station was estimated based on the discharge relationship between this station and the Borrego Palm Creek station (Netto).

A summary of discharge for these three sources during the period 1946 through 2000 is provided in Table 9 (Appendix B) and is comprised of both observed and estimated data.

Ungauged watersheds. As previously described, 12 of the 15 sources of groundwater recharge (as surface water infiltration) are drainage areas without any historic stream discharge gauging measurements. The three sources with observed or calculated stream discharge data were used to estimate discharge on the ungauged streams. A relationship describing runoff as a function of drainage area was defined for the three gauged streams. In addition, a relationship describing runoff as a function of precipitation volume (precipitation x drainage area) was also defined for the three gauged streams. Neither of these two methods were significantly more accurate, so the average of the two was used to estimate discharge at the 12 ungauged sources on a yearly basis for the period 1945 through 2000 (Netto, 2001). A summary of estimated data for these 12 sources is provided in Table

4. Quantities of estimated discharge for these three sources during the period 1945 through 2000 are provided in Table 9 (Appendix B).

Table 4

Summary of Surface Water Sources Without Historic Gauged Data

Drainage Area, Unnamed Creek or Stream	Period of Estimation	Length of Est. Period (Yr)	Est. Min. Discharge (AF/Yr)	Est. Max. Discharge (AF/Yr)	Est. Avg Discharge (AF/Yr)
Coyote Mountain	1945-2000	56	9	390	54
South Coyote Canyon	1945-2000	56	6	250	35
Northwest Slopes	1945-2000	56	5	220	31
Henderson Canyon	1945-2000	56	9	400	56
Indian Head Mountain	1945-2000	56	2	90	12
South Borrego Palm Canyon	1945-2000	56	1	60	9
Hellhole Canyon	1945-2000	56	22	960	130
Dry Canyon	1945-2000	56	3	150	21
Culp/Tubb Canyon	1945-2000	56	22	940	130
Pinyon Ridge	1945-2000	56	14	620	87
Lower San Felipe Creek	1945-2000	56	120	5,210	730
East San Felipe Creek	1945-2000	56	3	110	15

Bedrock Recharge

Bedrock recharge to the Borrego Valley groundwater basin was estimated for the period 1945 through 2000. Previous studies have either ignored or overly simplified this source of recharge to the groundwater basin. Previous simplifications appear to have greatly understated the quantity of recharge contributing to the groundwater basin from this pathway. For this evaluation, bedrock recharge was estimated utilizing a mass balance approach – that is, an attempt to fully account for all meteoric water introduced into the surrounding watershed.

Conceptually, once meteoric water has reached a watershed or drainage, its ultimate fate is along one of several pathways. Some fraction of the meteoric water exits the drainage area as surface water (runoff), some is consumed by direct evaporation and/or transpiration

by plants, some is stored as moisture in the soil profile, and some has the potential to become recharge to the bedrock system underlying the drainage area. All of these pathways are interdependent, and change with time. For the purposes of this study, bedrock recharge was calculated for the period 1945 through 2000 utilizing the computer program Recharg2 (Huntley, 1990). A full explanation of the calculation of bedrock recharge is provided by Netto (2001).

Groundwater flow through bedrock in the surrounding watershed is expected to approximately mirror topography, and discharge to the regional topographic low – Borrego Valley. Sources of bedrock recharge in this study are those drainage areas in the surrounding watershed whose bedrock topography is expected to drain directly to the groundwater basin. Of the 15 surface water discharge drainage areas, nine were considered to be sources of bedrock recharge to the groundwater basin. Bedrock recharge in the remaining six drainage areas were expected to recharge Borrego Valley as surface water discharge due to bedrock highs at the toe of the drainage areas, or due to the geometry of the drainage basin.

Calculated bedrock recharge to the Borrego Valley groundwater basin ranged from 0 to 19,860 acre-feet per year, and averaged 1,790 acre-feet per year during the period 1945 through 2000. A summary of total yearly bedrock recharge from the nine sources for select periods of time is presented in Table 2. Bedrock recharge on a yearly basis for the period 1945 through 2000 for all nine sources is summarized in Table 10 (Appendix B).

Underflow Recharge

Recharge to the Borrego Valley groundwater basin occurs where the San Felipe Creek exits the surrounding watershed and enters the alluvial portion of the Valley. Recharge as underflow was estimated by the USGS to be approximately 32 acre-feet per year (Moyle, 1982). No attempts to refine this estimate were made.

Summary of Groundwater Recharge

Groundwater recharge to Borrego Valley is related to the multiple pathways of meteoric water once it has entered the watershed. The combined recharge of meteoric water to the Borrego Valley for the period 1945 through 2000 ranged from approximately 760 acre-feet per year to approximately 51,000 acre-feet per year, and averaged 6,170 acre-feet per year.

Sources of Discharge

The primary sources of discharge from Borrego Valley include groundwater extraction in support of agricultural, recreational, and municipal use. In addition to these activities, natural discharge occurs from transpiration by native phreatophytes and as underflow out of the valley. Previous work indicates that steady-state conditions existed prior to about 1945 (Moyle, 1982). Discharge due to man-made activities was estimated by the same source to be less than 100 acre-feet per year in 1945.

A combination of data sources were used to determine historic discharge from Borrego Valley during the period 1945 through 2000. Aerial photos were reviewed to estimate discharge during discreet intervals of time. The San Diego County Department of Planning and Land Use (SD Co. DPLU) provided access to aerial photos for the years 1953, 1959, 1963, 1968, 1979, 1992, and 1995. These photos were evaluated to determine the acreage and crop or groundcover type on developed land. Estimates of net discharge required to support the crops or groundcover were calculated based on their area, their estimated consumptive use rate, and estimated irrigation efficiencies. These photos were also used to determine the approximate extent of acreage that historically supported native phreatophytes. Verbal communication with several farmers, golf course representatives, water purveyors, and other citizens provided additional information relative to historic land coverage and estimated consumptive use rates. In addition, SD Co. DPLU staff provided information on general historic land use patterns.

Evapotranspiration of Native Phreatophytes

Native phreatophytes occur primarily in two major areas, along undeveloped areas between irrigated land in the northern portion of the valley, and in the vicinity of Borrego Sink. Native phreatophytes in the northern portion of Borrego Valley probably transpire irrigation water in the vadose zone in close proximity to irrigated lands. The depth to the water table in the northern portion of Borrego Valley is relatively deep, and is expected to preclude transpiration directly from the surface of the water table. Native phreatophytes in the vicinity of Borrego Sink occur in an historic groundwater discharge area. Transpiration by native phreatophytes in this area is expected to be directly from both the water table and the vadose zone. Historic evapotranspiration was initially estimated (for the purposes of

developing a conceptual water budget). These estimates were refined through numerical modeling, as described in Chapters V and VI. Evapotranspiration estimates in Table 5 are based on the results of that modeling. Discharge from Borrego Valley associated with evapotranspiration ranged from 3,960 acre-feet per year in 1946 to 132 acre-feet per year in 2000, and averaged 1,330 acre-feet per year for the period 1946 through 2000. A summary of net discharge associated with evapotranspiration on a yearly basis, based on the results of modeling, is provided in Table 10 (Appendix B).

Table 5

Summary of Groundwater Discharge for Select Years (acre-feet per year)

Select Year	Evapo-transpiration	Underflow Out at Lower Borrego Valley	Agriculture (Row Crops)	Agriculture (Citrus)	Agriculture (Table Grapes)	Agriculture (Miscellaneous)	Recreational	Municipal	Total
1953	2,990	4,870	4,110	150	11,110	0	210	430	23,870
1959	1,940	4,280	4,570	270	11,190	0	420	670	23,340
1963	1,410	3,980	3,120	510	10,030	11	590	930	20,580
1966	1,070	3,790	3,600	530	0	4	640	1,050	10,680
1968	880	3,690	4,320	550	0	0	830	1,140	11,410
1979	600	3,250	1,390	1,990	0	48	1,180	1,580	10,040
1992	250	2,930	0	3,800	0	2,600	2,440	2,830	14,850
1995	230	2,870	0	6,280	0	3,000	2,090	2,890	17,360
1997	210	2,830	0	6,280	0	3,000	2,090	2,890	17,300
1998	190	2,810	0	6,280	0	3,000	3,090	2,890	18,260
2000	130	2,780	0	6,280	0	3,000	3,090	2,890	18,170

Note. Evapotranspiration and Underflow Estimated with Numerical Model

Underflow Out of Borrego Valley

Groundwater travels from the principal recharge areas, through Borrego Valley, and discharges primarily to the lower end of the valley in the vicinity of Ocotillo Wells. At this location, groundwater is expected to no longer be influenced by discharges concentrated in the vicinity of Borrego Springs, and is lost from the system. Discharge due to underflow out

of Borrego Valley was calculated through numerical modeling, as described in Chapters V and VI. Underflow discharge estimates in Table 5 are based on the results of that modeling. The quantity of underflow out of Borrego Valley ranged from 6,050 acre-feet per year in 1946 to 2,780 acre-feet per year in 2000, and averaged 3,780 acre-feet per year for the period 1945 through 2000. A summary of underflow discharge from Borrego Valley on a yearly basis, based on the results of modeling, is provided in Table 10 (Appendix B).

Groundwater Discharge Due to Agricultural Activities

One of the primary sources of groundwater discharge in Borrego Valley is groundwater extraction associated with agriculture. Major agricultural development in Borrego Valley began after 1945, and continues today. The primary crops developed include row crops, citrus orchards, table grapes, and assorted other agriculture (e.g., tree farms and ornamental nurseries). The pattern of agricultural use has shifted several times throughout that period, as is reflected in Table 5. As previously described, groundwater discharge resulting from agricultural use was estimated using aerial photos from seven discreet time periods, as well as from personal communication with others. In general, agricultural use for years with available aerial photos was integrated into the water budget as a known quantity of discharge. The aerial distribution of irrigated agricultural lands for the years with aerial photo coverage are provided in Figures 108 through 114 (Appendix B). For the intervening years, agricultural use was estimated by interpolating on a crop-by-crop, and irrigated parcel-by-parcel basis. A summary of discharge estimates for each major crop type on a yearly basis, based on the aerial photos and interpolation, is provided in Table 11 (Appendix B). Provided below are crop specific discussions and assumptions for each of the primary crop types historically present in Borrego Valley.

Row crop irrigation evaluation. Based on aerial photos, undifferentiated row crops were present and actively irrigated in Borrego Valley during the period 1953-1979. Row crop irrigation between 1945 and 1953 was assumed to increase linearly from zero to the values estimated from the 1953 aerial photo. Row crop irrigation in the 1992 aerial photo was absent or negligible. Irrigation of row crops during the period 1979-1992 was assumed to decrease linearly from the values estimated for 1979 to zero in 1992. The gross irrigation

demand for undifferentiated row crops (applied quantity of water) was estimated to be 2 feet per year (Van Der Leeden, Troise & Todd, 1990). Net discharge values are based on an estimated irrigation efficiency of 87%, with 13% of the gross applied water returning to the groundwater basin as irrigation return flows (Netto, 2001). Estimated net discharge from Borrego Valley associated with row crop irrigation ranged from 110 acre-feet per year in 1992 to 4,570 acre-feet per year in 1960, and averaged 2,180 acre-feet per year during the period 1945 through 1992. A summary of net discharge associated with irrigation of row crops on a yearly basis is provided in Table 11 (Appendix B).

Citrus orchard irrigation evaluation. Citrus orchards were present and actively irrigated in Borrego Valley during the period 1953-2000. Citrus orchard irrigation between 1945 and 1953 was assumed to increase linearly from zero to the values estimated from the 1953 aerial photo. Citrus irrigation was the dominant agricultural use in Borrego Valley in 2000. The gross irrigation demand for citrus orchards was differentiated based on the maturity of the orchard. The maturity of the orchard was determined historically based on a parcel-by-parcel analysis of aerial photos, interviews with current farmers, and field confirmation (for recent years). The gross irrigation demand for young citrus orchards (applied quantity of water) was estimated to be 1 foot per year (S. Bauer, personal communication, February 3, 1997; S. Fortiner, personal communication, August 15, 1997). The gross irrigation demand for mature citrus orchards (applied quantity of water) was estimated to be 3.25 feet per year based on the same sources, as well as the previous report by the USGS (Moyle, 1982). Net discharge values are based on an estimated irrigation efficiency of 87%, with 13% of the gross applied water returning to the groundwater basin as irrigation return flows. Net discharge from Borrego Valley associated with citrus orchard irrigation ranged from 20 acre-feet per year in 1946 to 6,280 acre-feet per year in 2000, and averaged 1,820 acre-feet per year for the period 1946 through 2000.

Table grape irrigation evaluation. Table grapes were present and actively irrigated in Borrego Valley during the period 1953-1966. Table grape irrigation between 1945 and 1953 was assumed to increase linearly from zero to the values estimated from the 1953 aerial photo. Table grape irrigation ceased in 1966 following a labor dispute (Moyle, 1982). The gross irrigation demand for table grapes (applied quantity of water) was estimated to be 6

feet per year (S. Fortiner, personal communication, August 15, 1997; R. Zinzer, personal communication, May 6, 1997). Net discharge values are based on an estimated irrigation efficiency of 87%, with 13% of the gross applied water returning to the groundwater basin as irrigation return flows. Net discharge from Borrego Valley associated with table grape irrigation ranged from 1,390 acre-feet per year in 1946 to 11,190 acre-feet per year in 1959, and averaged 8,440 acre-feet per year during the period 1946 through 1959.

Miscellaneous other agriculture irrigation evaluation. Several miscellaneous agricultural crops were present and actively irrigated in Borrego Valley during the period 1963-2000. Miscellaneous agricultural crop irrigation between the period 1960 and 1963 was assumed to increase linearly from zero to values estimated from the 1963 aerial photo. Interpolation of yearly values of discharge associated with irrigation of these crops was performed by interpolating between aerial photo years, and with a parcel-by-parcel assessment. Miscellaneous agricultural crop types include tree farms and nurseries, alfalfa, palms and ornamentals, and potatoes. The gross irrigation demand for tree farms and nurseries, palms and ornamentals, and potatoes was estimated to be 2 feet per year (Van Der Leeden et al., 1990). The gross irrigation demand for alfalfa was estimated to be 6.2 feet per year (Van Der Leeden et al.). Net discharge values are based on an estimated irrigation efficiency of 87%, with 13% of the gross applied water returning to the groundwater basin as irrigation return flows. Net discharge from Borrego Valley associated with miscellaneous agricultural irrigation ranged from 0 acre-feet per year in 1968 to 3,000 acre-feet per year in 2000, and averaged 1,030 acre-feet per year during the period 1960 through 2000.

Groundwater Discharge Due to Recreational Activities

One of the primary sources of groundwater discharge from Borrego Valley is groundwater extraction in support of recreational activities. The primary recreational land use in Borrego Valley is several golf courses. Golf courses in Borrego Valley include the De Anza Country Club, the Borrego Springs Park and Community Service District (BSPCSD) golf courses, the Road Runner Country Club, and the Ram’s Hill Development. The gross irrigation demand for all golf courses (greens, fairways, and miscellaneous other areas combined) in Borrego Valley is approximately 6 feet per year (S. Fortiner, personal

communication, August 15, 1997; A. Gorton, personal communication, August 16, 1997; J. Peterson, personal communication, July 8, 1997). A summary of total net groundwater discharge associated with golf courses for select years is provided in Table 5.

De Anza Country Club. Net groundwater extraction at the De Anza Country Club (gross demand minus irrigation return) was approximately 210 acre-feet per year between 1953 and 1958, and 420 acre-feet per year between 1958 and 1962. Net groundwater extraction during 1979 was approximately 700 acre-feet per year, based on estimates from areas in aerial photos, and continues at that rate today. Net groundwater extraction between 1962 and 1979 was assumed to increase linearly from the 1962 rate to the 1979 rate, reflecting development and improvement of the golf course and associated areas to the 1979 acreage. A summary of estimated net discharge associated with irrigation in support of recreational activities at De Anza Country Club is provided in Table 11 (Appendix B).

Borrego Springs Park and Community Service District. Prior to 1998, the Borrego Springs Park and Community Service District (BSPCSD) had one golf course. Net groundwater extraction for this course was estimated to be approximately 170 acre-feet per year for the period 1963 through 2000. In 1998, a large 18-hole golf course and associated developments were put in place in the vicinity of the BSPCD. This golf course is similar in nature to the Ram's Hill development, and has more acreage per hole than several of the older courses in Borrego Valley. Net groundwater demand at this course has been likened to that of the Ram's Hill development, which requires approximately 1,000 acre-feet per year, as described later. The net discharge associated with this new golf course is estimated to be approximately 1,000 acre-feet per year (J. Peterson, personal communication, June 18, 2001).

Ram's Hill. The Ram's Hill Development (golf course and housing tracts) was completed in 1983. The Borrego Water District (BWD) provides groundwater for this development. The Borrego Water District extracts water from approximately seven wells to meet the recreational and municipal demands of Ram's Hill. The net groundwater use dedicated to irrigation of the golf course and associated areas is estimated to be approximately 1,000 acre-feet per year (J. Peterson, personal communication, July 8, 1997). The balance of the water extracted from BWD wells is used to satisfy municipal demand.

Total gross extraction from BWD wells used for irrigation purposes during the period 1983-2000 ranged from 1,020 acre-feet in 1994 to 1,530 acre-feet in 1991, and averaged approximately 1,180 acre-feet per year for the period 1983 through 2000 according to records provided by BWD.

Roadrunner Country Club. Net groundwater extraction at the Roadrunner Country Club (gross demand minus irrigation return) was approximately 160 acre-feet per year in 1968, the year it was completed. Net groundwater extraction in 1979 was approximately 310 acre-feet per year, based on estimates from areas in aerial photos, and continues at that rate today. Net groundwater extraction between 1968 and 1979 was assumed to linearly increase from the 1968 rate to the 1979 rate, reflecting development and improvement of the golf course and associated areas to the 1979 acreage.

Groundwater Discharge Due to Municipal Demand

A growing component of groundwater discharge from the Borrego Valley is municipal demand, based on population increases and subsequent development. Various agencies provide water to meet municipal demand, including Borrego Water District (as previously described), Borrego Water Company, Borrego Springs Park and Community Service District, and Borrego Air Ranch. Municipal demand for the period 1945 through 2000 has been estimated from pumping records, and communication with local municipality representatives, local residents, and SD Co. DPLU staff. Total municipal demand for that period was estimated to range from 100 acre-feet per year to approximately 2,200 acre-feet per year. Estimates of net groundwater discharge due to municipal demand for select years are provided in Table 5.

Some portion of groundwater pumped for municipal purposes has the potential to become recharge to the groundwater basin. Municipal water which is utilized by residents and then discharged to septic systems would recharge the aquifer system. Municipal water collected by a sewering agency (e.g., Borrego Water District) could also become aquifer recharge, based on the wastewater treatment technique utilized. According to information provided to Steve Netto (author of a related thesis) by Mr. Casey Rodriguez of the Borrego Water District, the district collects wastewater from both its own service area, and that of the

Borrego Springs Park and Community Services District. This wastewater is discharged to unlined evaporation ponds. According to Mr. Rodriguez, the vast majority of water discharged to these ponds evaporates, and infiltration of wastewater to the aquifer system is expected to be minimal. Mr. Rodriguez further stated that Borrego Water District has not attempted to quantify this potential source of recharge. Recharge due to this source is expected to be minimal. In addition, the range of potential recharge from this source (100 to 2,200 acre-feet per year, averaging 1,200 acre-feet per year) is much less than observed and/or calculated natural recharge for the period of record so error in the calculated water budget or numerical model is considered minimal.

Borrego Water District. The Borrego Water District supplies municipal water to the Ram's Hill development. The Ram's Hill Development was completed in 1983. Based on records of total extraction provided, coupled with estimates of the fraction used for golf course irrigation, the yearly quantities of water used for municipal distribution during the period 1983 through 2000 were estimated, and are summarized in Table 11 (Appendix B).

Borrego Water Company. A portion of the historic municipal demand has been satisfied by distribution of groundwater by the Borrego Water Company. Groundwater extraction records for their seven wells were provided for the period 1983 through 1995. Municipal demand in Borrego Valley prior to 1983 was estimated to increase linearly from 100 acre-feet per year (Mitten et al., 1988) to 2,190 acre-feet per year in 1995. A summary of estimated groundwater extraction to meet municipal demand for Borrego Water Company and its predecessors for the period 1945 through 2000 is provided in Table 11 (Appendix B).

Borrego Springs Park and Community Service District. The BSPCSD has been in operation since 1963. The BSPCSD provides water to residents in its service area to meet municipal demand. Groundwater production records for BSPCSD were not available. Estimated net groundwater extraction to satisfy municipal demand in the BSPCSD were estimated to be approximately 100 acre-feet per year for the period 1963 through 2000 (R. Zinzer, personal communication, May 6, 1997). A summary of estimated groundwater discharge to meet municipal demand for BSPCSD for the period 1945 through 2000 is provided in Table 11 (Appendix B).

Borrego Air Ranch. A small portion of the historic municipal demand has been in the vicinity of Borrego Air Ranch – a small community southeast of Borrego Springs. Groundwater production records for Borrego Air Ranch were not available. Estimated net groundwater extraction to satisfy municipal demand at Borrego Air Ranch were estimated to be approximately 10 acre-feet per year for the period 1945 through 2000 (Rowling, 1999). A summary of estimated groundwater discharge to meet municipal demand for BSPCSD for the period 1945 through 2000 is provided in Table 11 (Appendix B).

Summary of Groundwater Discharge

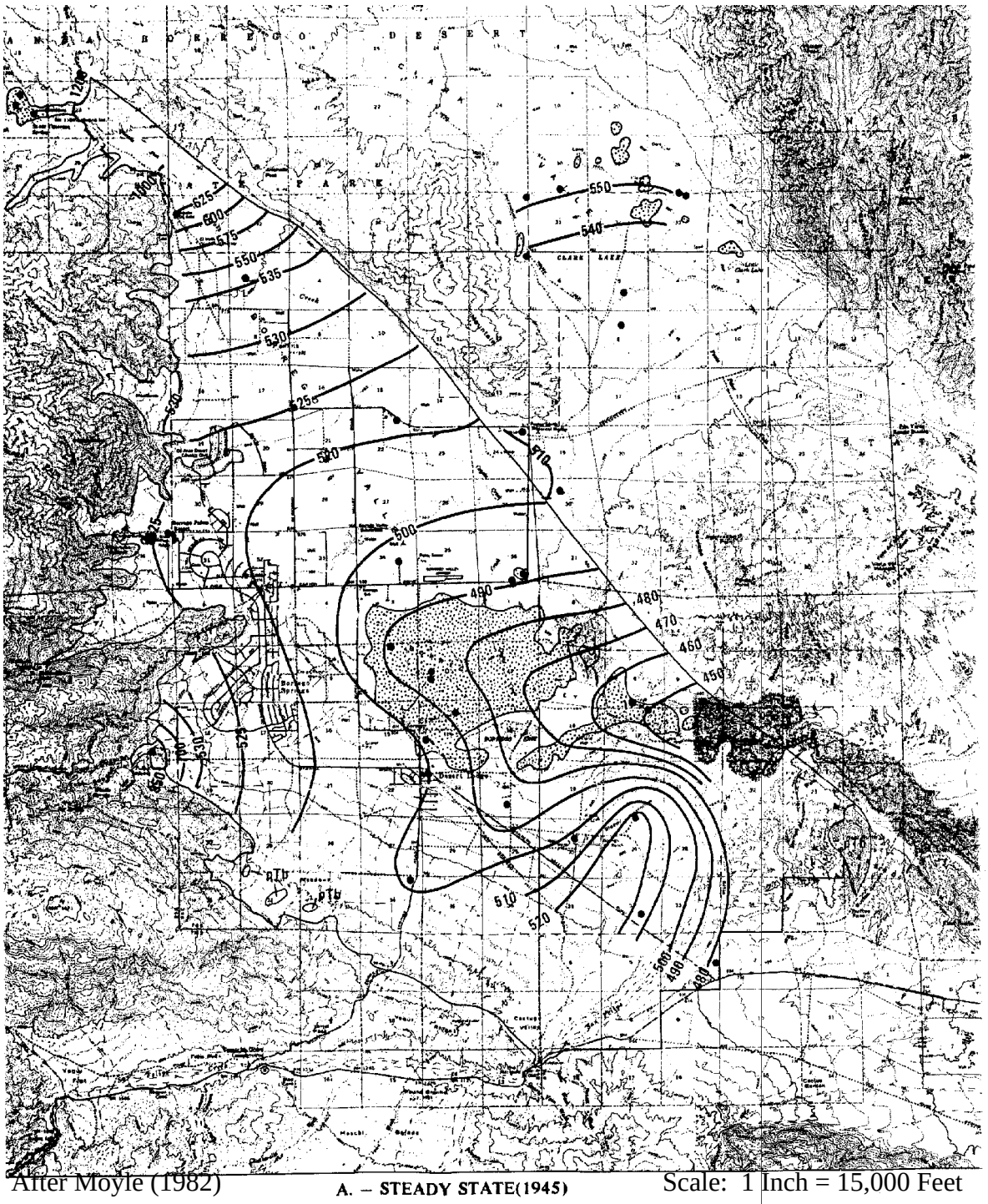
Groundwater discharge from Borrego Valley is related to multiple activities including agriculture, recreation, population, and natural processes such as evapotranspiration and underflow out of the valley. The combined total net discharge from Borrego Valley resulting from these activities ranges from approximately 8,470 acre-feet per year to 23,870 acre-feet per year, and averaged 14,520 acre-feet per year for the period 1945 through 2000.

Groundwater Movement and Levels

Groundwater in the Borrego Valley aquifer system flows from the principal areas of recharge toward the center of the valley. Groundwater discharges in various locations due to groundwater extraction, in the vicinity of Borrego Sink due to transpiration by native phreatophytes, and in Lower Borrego Valley as underflow out of the aquifer system. The following sections describe the characteristics of groundwater flow and levels in the Borrego Valley aquifer system.

Groundwater Movement

Groundwater in the north and central parts of Borrego Valley travels from the primary sources of recharge along the margins of the basin, to the central part of the basin in the vicinity of Borrego Sink (Figure 17). Historically, the ground surface in the vicinity of Borrego Sink was saturated (due to high groundwater levels), and the area currently supports a large number of native phreatophytes. From there, groundwater discharges across the Coyote Creek Fault, and then proceeds southeast toward Ocotillo Wells. The Borrego Badlands (fine-grained sedimentary formational material) is expected to be a barrier to further eastward flow of groundwater. Groundwater in the south portion of Borrego Valley



After Moyle (1982) A. – STEADY STATE(1945) Scale: 1 Inch = 15,000 Feet

Figure 17. USGS interpreted water level elevations (feet m.s.l.) – 1945.

(particularly in the vicinity of San Felipe Creek) moves primarily southeast toward of Ocotillo Wells. The presence of the relatively low-permeability Palm Spring Formation between the north and south portions of Borrego Valley is thought to contribute to this. Groundwater exits the aquifer system in the Lower Borrego Valley, and is expected to proceed to the regional topographic low. Previous studies, and numerical modeling described in Chapters V and VI, show this pattern of groundwater flow through Borrego Valley.

Groundwater Levels

Water level elevation data has been collected sporadically since development began to occur in Borrego Valley in the late 1940s. Several wells have sufficient data for definition of water level trends within discrete areas of Borrego Valley. The focal points of groundwater extraction during the period 1945 through 2000 were in the north and northwest portion of Borrego Valley, associated primarily with agricultural and recreational demands. The generalized water levels trends in the extensively developed portion of the basin (north of where the Palm Spring Formation crops out) are reasonably represented by water levels observed in wells 10S/6E 21A1 and Fortiner (Figures 18 and 19). Water levels in these two wells show four temporal trends relating to groundwater use and climate, as described below:

1945-1965 - Groundwater discharge in excess of groundwater recharge lead to declining groundwater levels in much of the north and north-central portions of the basin (Figure 18).

1965-1975 - Groundwater levels in Borrego Valley during this period appear to stabilize and, in some cases, begin to rebound a small amount (Figure 18). Groundwater extraction appears to be in balance with groundwater recharge for that period. This change may be associated with the discontinuation of table grape production in Borrego Valley. Cultivation of table grapes was replaced by other crops and, by 1975, a new period of imbalance between groundwater extraction and recharge began (Figure 18).

1975-1987 - Increased groundwater extraction lead to a resumption of water level declines in Borrego Valley (Figures 18 and 19). The rate of water level decline during this period is not as severe as during the period 1945 through 1965, and probably reflects a relatively wetter, short-term climatic cycle.

Figure 18. Water level elevation hydrograph - 10S/6E 21A1.

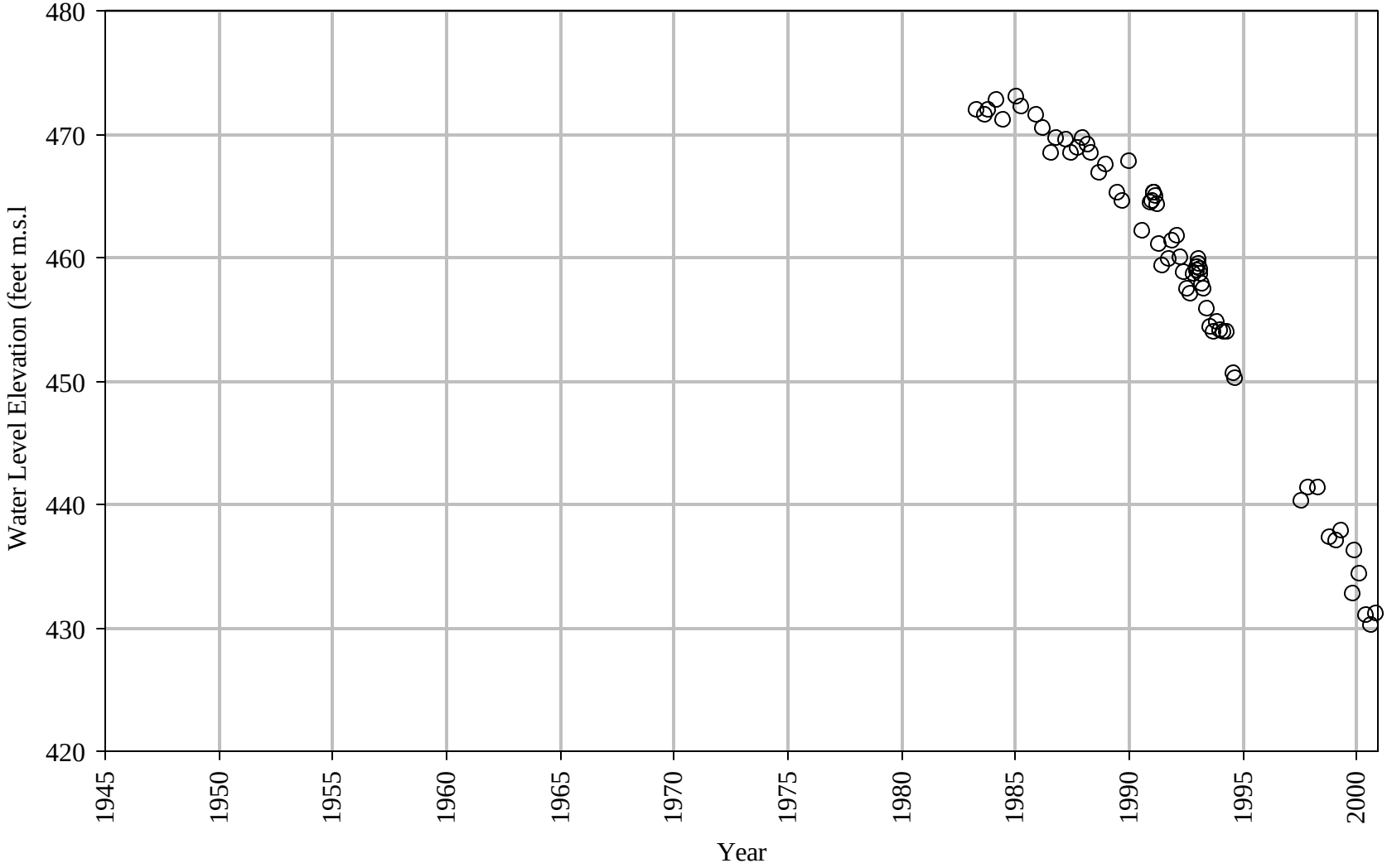


Figure 19. Water level elevation hydrograph well - Fortiner.

1987-2000 - The rate of decline appears to steepen between 1987 and 2000 (Figures 18 and 19), indicating either an ever-increasing deficit between groundwater discharge and recharge, or the impact of the geometry of the aquifer system as water levels decline (e.g., nonlinear decrease in available groundwater storage with depth).

The study by Moyle (1982) provided interpreted distributions of water levels in the aquifer system for select years. The water level trends reflected in wells 10S/6E 21A1 and Fortiner (Figures 18 and 19) show general conditions in the north and north-central portions of the basin. The water level contour maps constructed by Moyle (1982) provide snapshots of water levels throughout much of the basin for select periods. These maps allow identification of specific areas of water level decline that may be more dramatic than basin-wide trends, which are discussed below:

1945 – Water Levels are interpreted to be at steady-state condition. The general groundwater flowpaths are as shown in Figure 17. Water level elevations range from 480-feet a.m.s.l. near San Felipe Creek to 625-feet a.m.s.l. near the mouth of Coyote Creek.

1952-1953 – Water levels in the south-central portion of the Valley are similar to those described for the 1945 condition. In the north and north-central portions of the basin, several cones of depression in the groundwater table were noted, near areas of intense agriculture and other development (Figure 20). Water level elevations range from 470-feet a.m.s.l. near San Felipe Creek to 525-feet a.m.s.l. near the north portion of the Valley. The most severe cone of depression includes a water level elevation of 440-feet a.m.s.l. This location is in the vicinity of intense agriculture. The water level elevation at this location in 1945 was approximately 520-feet a.m.s.l.

1965 – Water levels throughout the basin had generally the same configuration as during the 1952-1953 condition. Water level elevations range from 470-feet a.m.s.l. near San Felipe Creek to 490-feet a.m.s.l. near the north portion of the Valley (Figure 21). The cone of depression noted in the north portion of the Valley still existed, at approximately the same magnitude. In addition, a new cone of depression developed near the western margin of the basin, southwest of the City of Borrego Springs. The water level elevation at this location during this period is 440-feet a.m.s.l. (down from approximately 490-feet a.m.s.l. in 1952-1953).

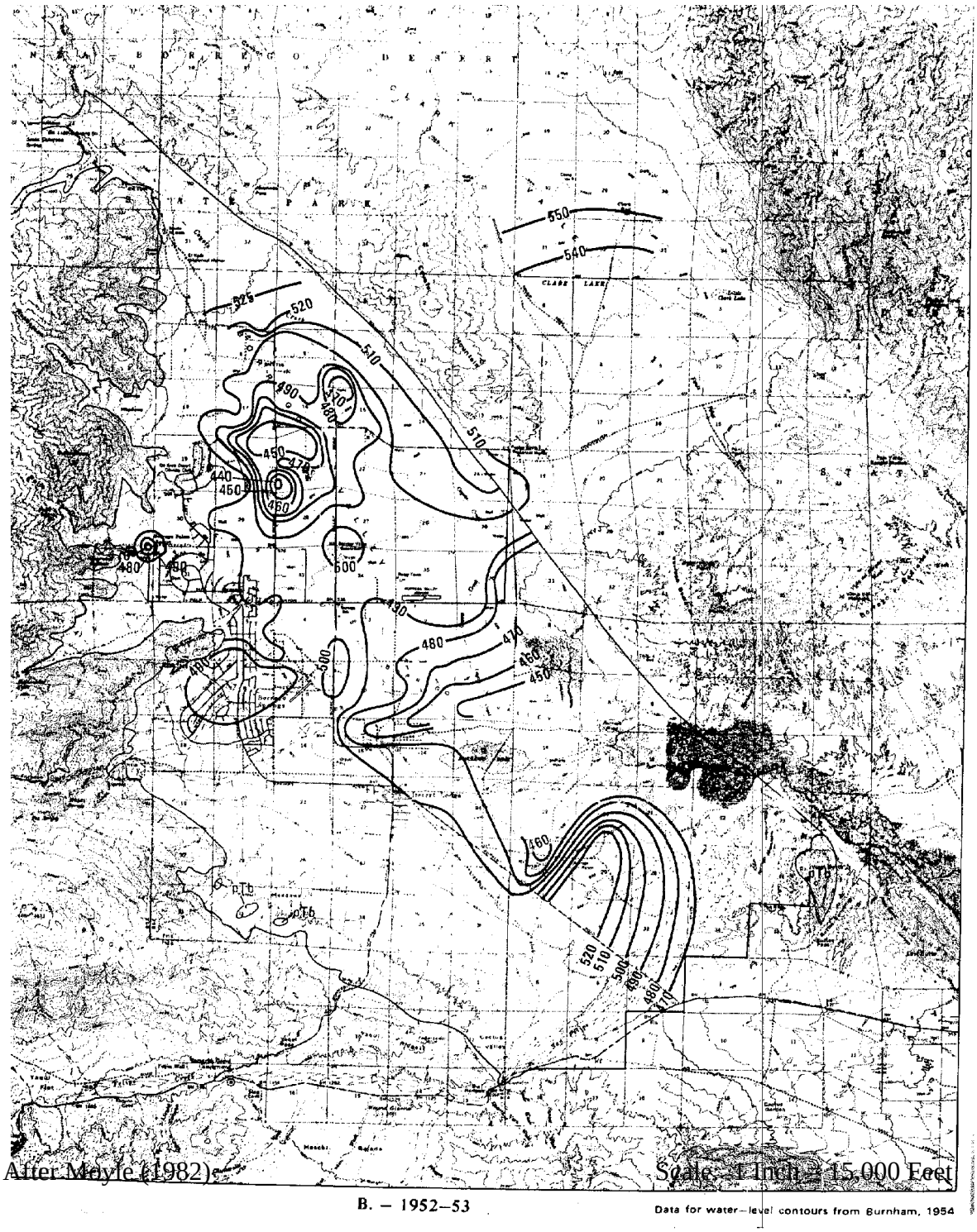


Figure 20. USGS interpreted water level elevations (feet m.s.l.) – 1952-1953.

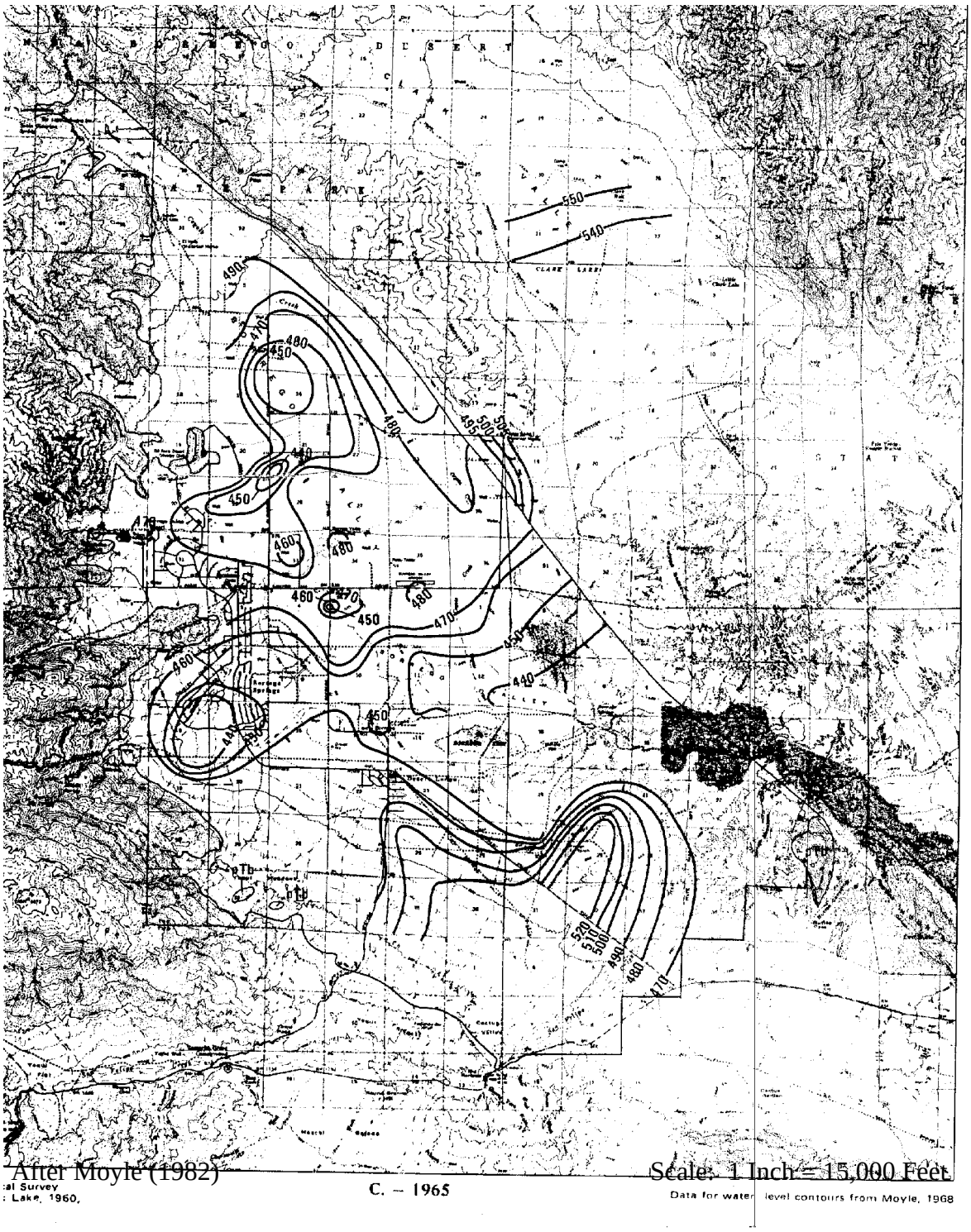
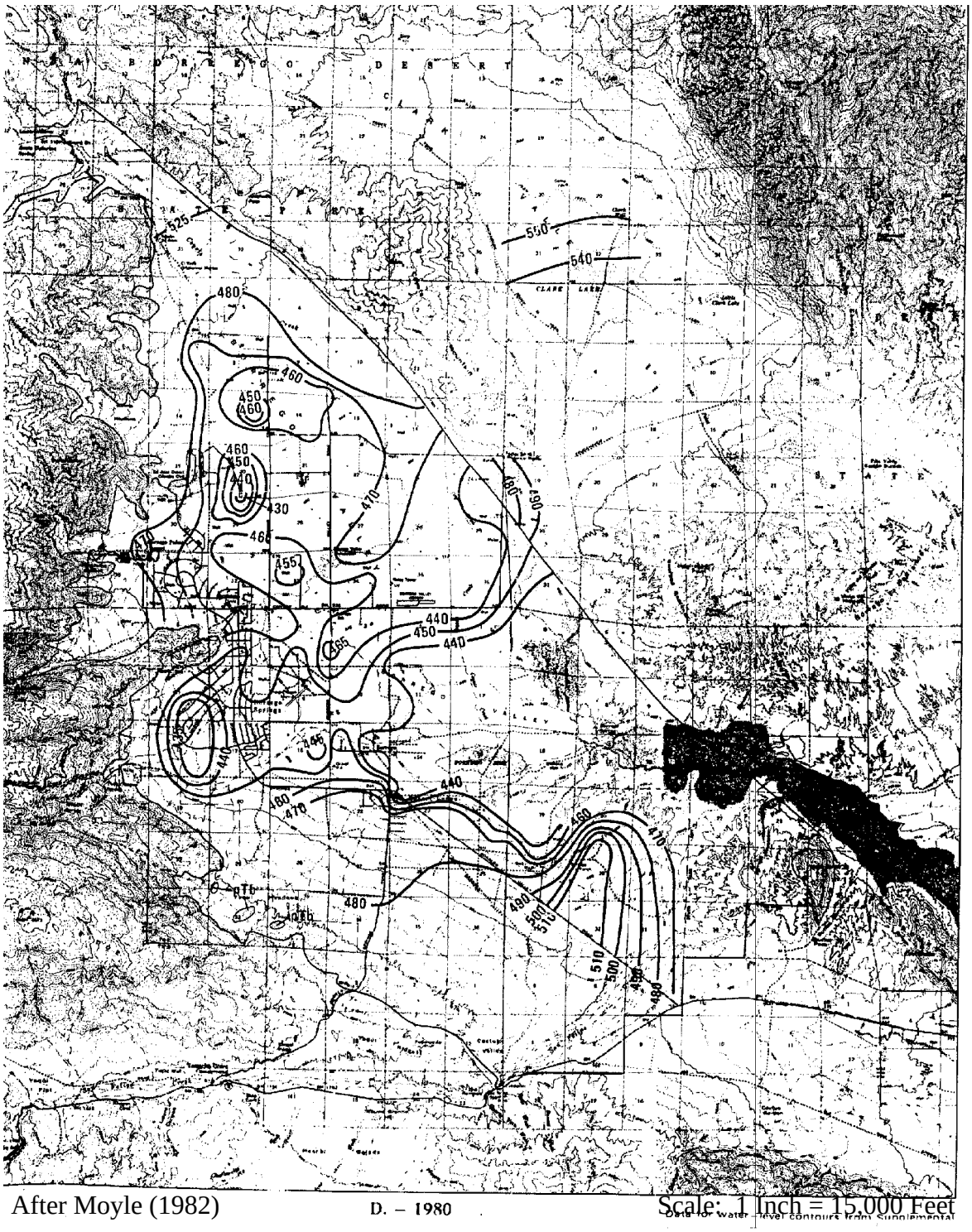


Figure 21. USGS interpreted water level elevations (feet m.s.l.) – 1965.

1980 – Water levels throughout the basin generally had the same configuration as during the 1965 condition, with slightly more drawdown (approximately 10-feet) noted throughout the majority of the area (Figure 22).

Water level hydrographs for the period 1945 through 2000, and water level elevation contour maps for select years during that period demonstrate the long-term deficit between groundwater discharge and recharge. It is clear that mining of groundwater has occurred, and continues to occur. Some of the negative impacts associated with this overdraft condition are already occurring (e.g., decreased well efficiency and increased pumping costs due to lower water levels). Other, potentially more dramatic impacts (e.g., intrusion of low-quality connate groundwater from formational materials) may be occurring now, and is expected to increase in quantity in the future. These negative impacts, as wells as others not explicitly discussed will be exacerbated by the geometry of the aquifer system. Basin-wide rates of water level decline are expected to increase with ongoing groundwater mining, even without any change in the deficit between groundwater discharge and recharge, due to the decreased volume of available groundwater storage with depth of the water table.



After Moyle (1982)

Scale: 1 Inch = 15,000 Feet

Figure 22. USGS interpreted water level elevations (feet m.s.l.) – 1980.

CHAPTER IV

NUMERICAL GROUNDWATER MODELING

A numerical groundwater flow model was developed to simulate historic conditions, and to use as a tool for evaluation of future predictive use scenarios for Borrego Valley. Simulation of groundwater flow in Borrego Valley was completed using a six-layer, three-dimensional finite-difference groundwater flow model.

Description of the Model

The Fortran based modular computer code MODFLOW used for this study to simulate groundwater flow in Borrego Valley was developed by McDonald and Harbaugh (1988). This code was modified to include the preconditioned conjugate gradient 2 (PCG2) method for the solution of the finite difference approximating equations generated by MODFLOW (Hill, 1990). This method solves the finite difference equations over a network of rectangular blocks that represent the area to be modeled. Solutions to the finite difference equations are hydraulic head in the various model cells at specific times. A detailed explanation of the physical and mathematical concepts of MODFLOW are described in the code documentation (McDonald & Harbaugh).

Simplifying Assumptions and Limitations

A mathematical model is an approximation of the real aquifer system because not all of the characteristics of the actual system can be adequately determined, or represented. In addition, simplifying assumptions are required to make the problem more manageable. Some of the more important simplifying assumptions that relate to the model are:

1. The aquifer system is bounded by no-flow cells which cannot contribute any flow of water to the groundwater system. Therefore, potential flux from Clark Lake or the Borrego Badlands is considered negligible and is not represented.
2. The older, intermediate-age, and younger alluvium are modeled as discrete, but hydraulically connected, layers. In reality, particularly near the margins of Borrego Valley, these units are not well differentiated, and likely behave hydraulically as one unit.

3. All soil textures, in all model layers are horizontally isotropic. Horizontal and vertical hydraulic conductivity may differ..
4. The storage coefficients of the hydrogeologic units do not change with water-level changes.
5. Model layer 1 is unconfined, and transmissivity varies as a function of saturated thickness of the model layer. All other model layers are confined, but are convertible, and have the ability to become partially saturated (unconfined), in which case the transmissivity of those layers also varies as a function of saturated thickness.
6. Recharge occurs instantaneously.
7. The model cannot calculate the water level at individual pumping wells due to the finite-difference cell size (2000-feet by 2000 feet) and because pumping is distributed uniformly throughout the cell.

Model Structure

To represent the generalized physical system described in Chapter III, as well as to provide mathematical solution stability, the Borrego Valley aquifer system was modeled utilizing a six-layer MODFLOW model. In general, layers 1 through 3 of the numerical model are the same as the three Quaternary hydrogeologic units described in Chapter III. Specifically, however, model layers 1 through 3 were not allowed to have a thickness of less than 0.5 feet. For example, the younger alluvium is absent in an area near the north end of Borrego Valley, adjacent to the Coyote Creek fault (Figure 10). To represent this area, model layer 1 is present at a minimal thickness, and was assigned the physical properties of the intermediate-age alluvium (which in reality, is exposed at the surface). Model layers 1-3 were modified by this technique to maintain a minimum thickness, and to accurately represent the physical properties of the hydrogeologic units to the extent possible.

Model layers 4, 5, and 6 represent the Palm Spring Formation. As previously described, this hydrogeologic unit attains a maximum thickness of approximately 4,000 feet, which is quite large relative to the maximum thickness of the other three hydrogeologic units in the primary aquifer system. Because MODFLOW calculates the finite difference equations in the center of each calculation cell, this unit was subdivided into three model layers. The top of layer 4 is coincident with the top of the Palm Spring Formation hydrogeologic unit. However, the bottom of model layer 4 is set universally at –700-feet a.m.s.l. The bottom of model layer 5 is set at –2400 feet a.m.s.l., and the bottom of model

layer 6 is set at –4100-feet a.m.s.l. The lateral extent of layers 5 and 6 are defined by the presence or absence of bedrock adjacent to the Palm Spring Formation.

Three types of boundary conditions were used in the model. No-flow boundaries were used to represent barriers to groundwater flow. Constant-head boundaries were used near the southern end of Borrego Valley to represent the aquifer system discharge area. Specified-flux boundaries were used to represent recharge to and discharge from the aquifer system. Each of these boundary conditions is described in greater detail in the following sections.

The model domain is defined by the 60,000 foot by 150,000 foot area surrounding the Borrego Valley aquifer system. Each model layer has 2,250 cells which are each 2000 feet wide and 2000 feet long. The 2,250 calculation cells in each model layer include no-flow, active, and constant-head cells. No-flow cells were distributed around the margins of the aquifer system to represent the crystalline basement exposed at ground surface (bounding model layer 1) and at depth adjacent to model layers 1 through 6. In addition, no-flow cells were placed in the south-central portion of the aquifer system to represent Borrego Mountain, and the corresponding bedrock high. Constant-head cells were placed near Lower Borrego Valley, in the vicinity of Ocotillo wells, as water levels from well 12S/8E 22E1 (approximately mean sea level) indicate a steady-state condition (Figure 23). Based on data from this well, this area of Borrego Valley does not appear to be influenced by water-level fluctuations or variations in groundwater discharge and recharge in the upper portion of the aquifer system, and can be treated as a constant-head boundary.

Model Layer 1

Model layer 1 represents the younger alluvium hydrogeologic unit and is modeled with 1,173 active cells (Figure 24). Eighteen cells in model layer 1 are used to represent the boundary condition in Lower Borrego Valley, as previously described. The surface of model layer 1 is coincident with land surface throughout the model domain (Figure 25). The thickness of each cell in model layer 1 is defined by the top of model layer 1 (land surface) and the top of model layer 2 (Figure 26). Soil textures in model layer 1 range from fine sand and silt to gravel, with medium sand being the most prevalent texture (Figure 27). The distribution of soil textures in model layer 1 show the “inward-fining” of alluvial sediments

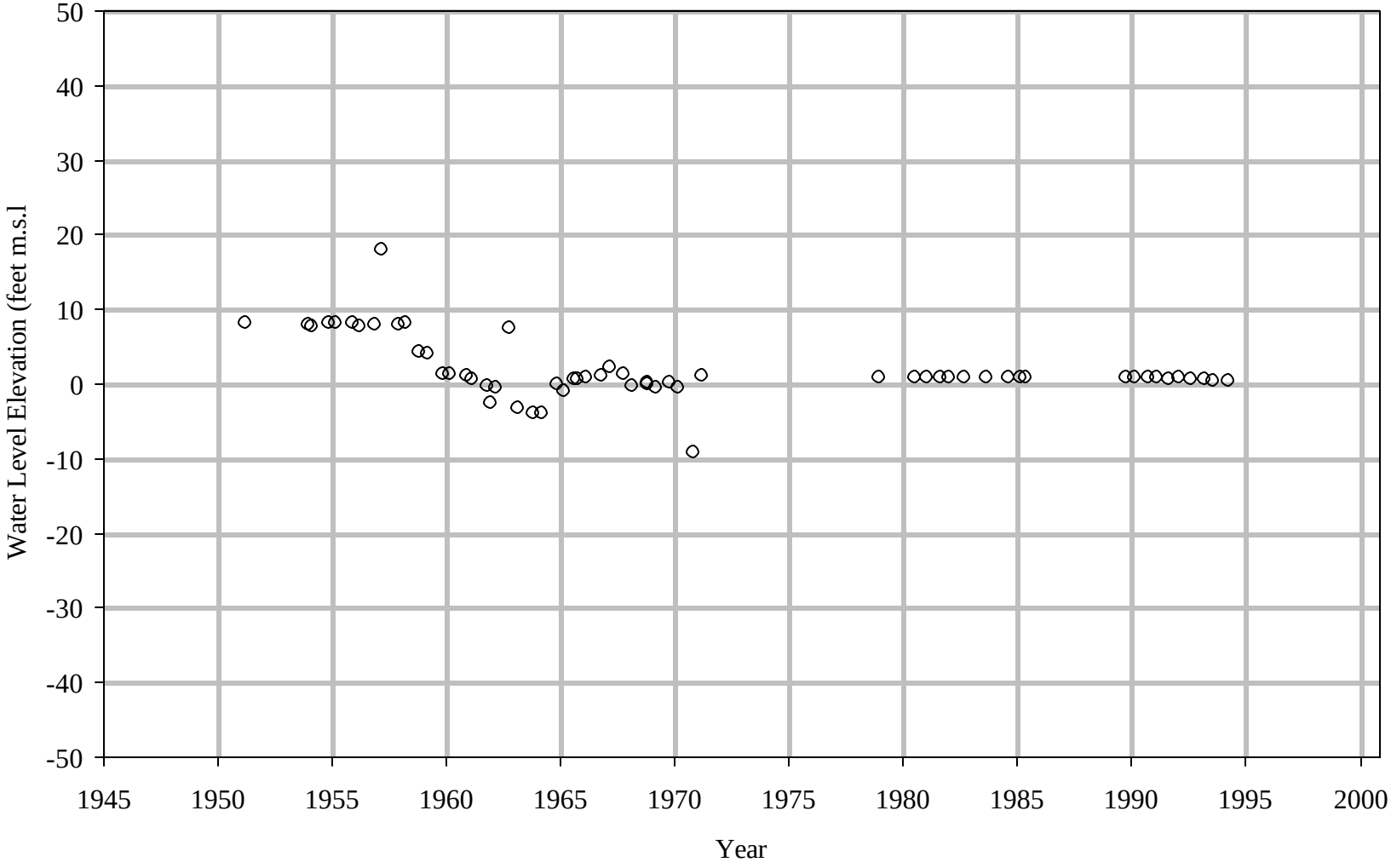


Figure 23. Water level hydrograph for well 12S/8E 22E1.

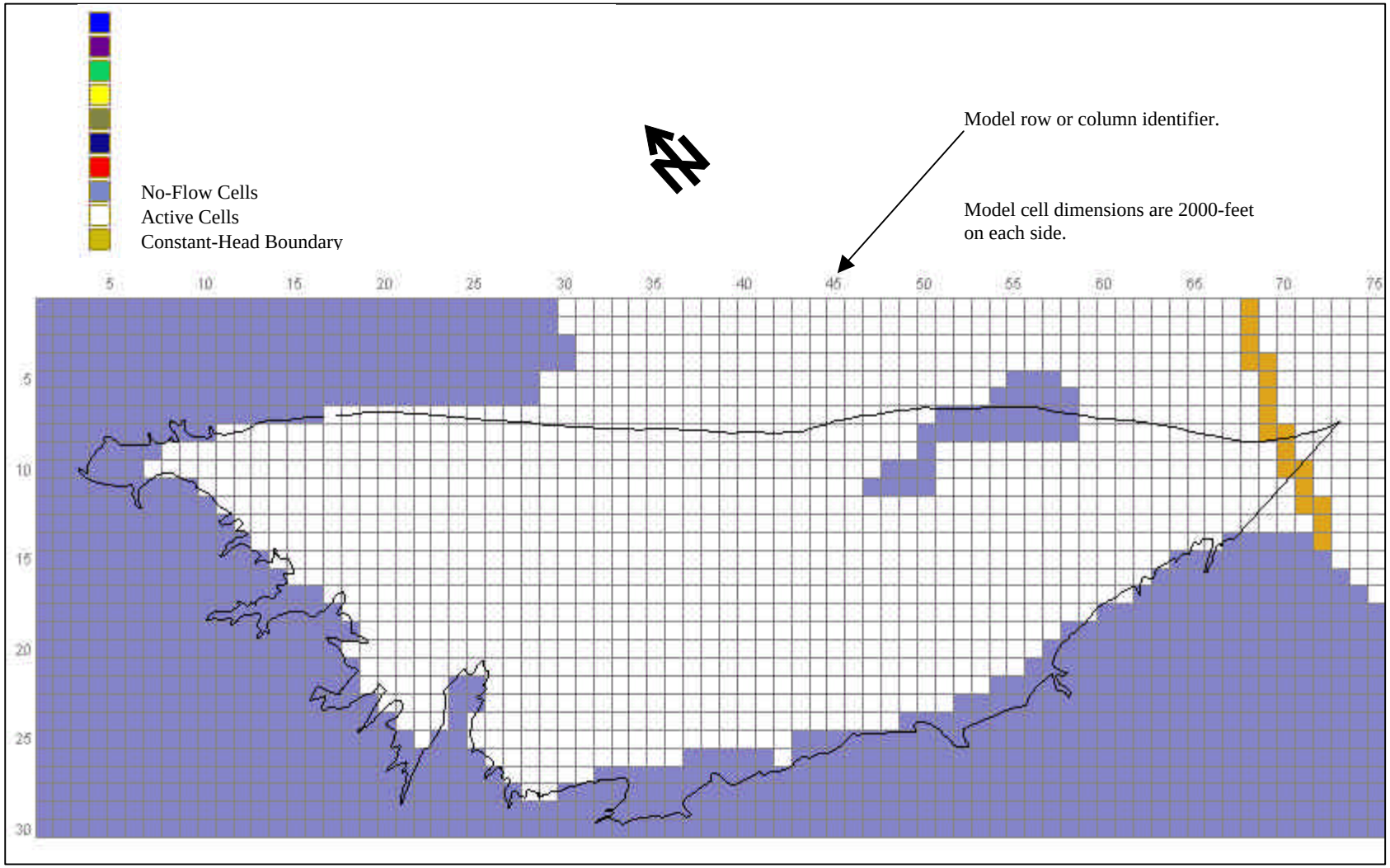


Figure 24. Model layer 1 no-flow, active, and constant-head cells.

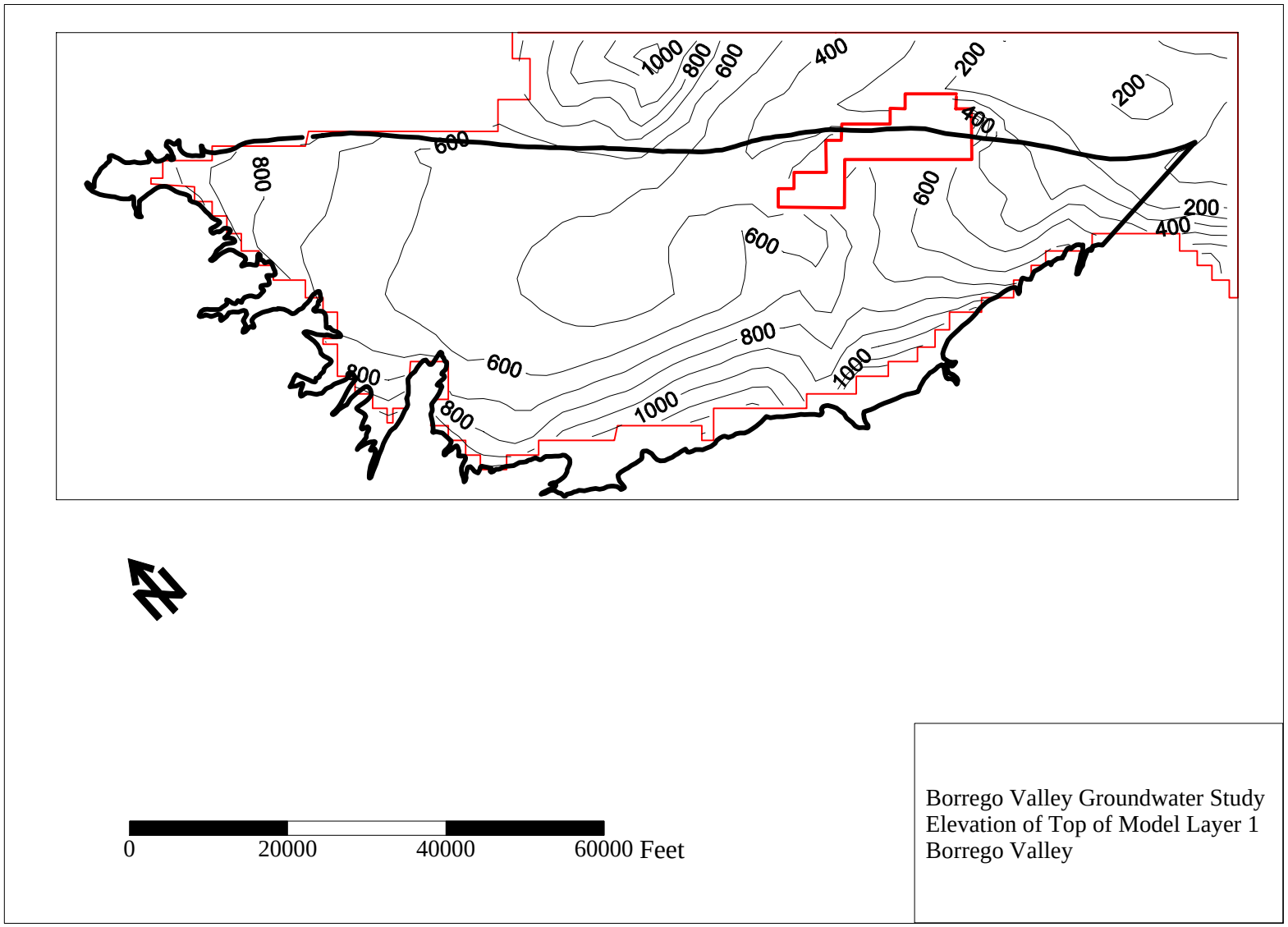


Figure 25. Elevation (feet m.s.l.) of top of model layer 1.

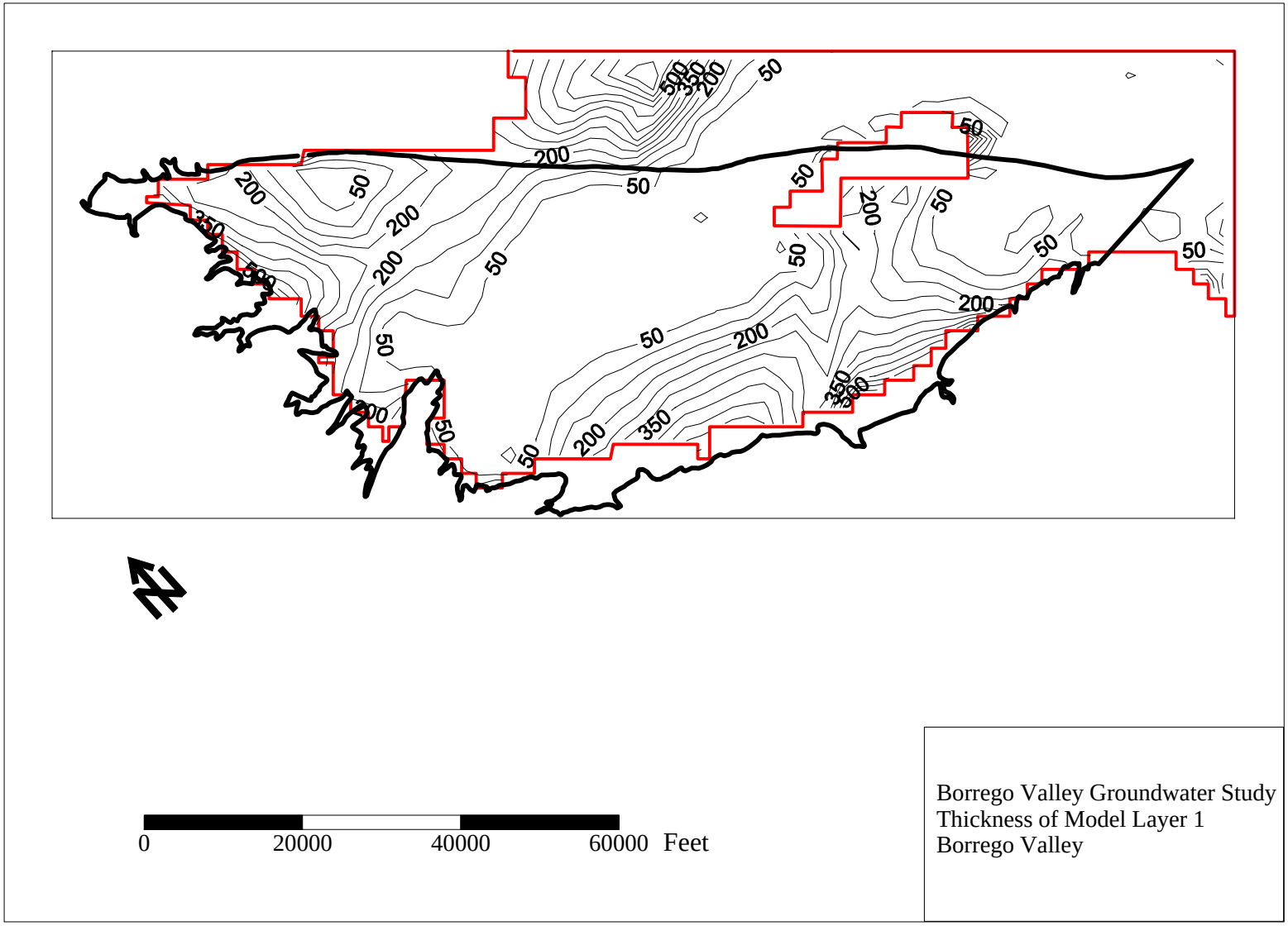


Figure 26. Thickness (feet) of model layer 1.

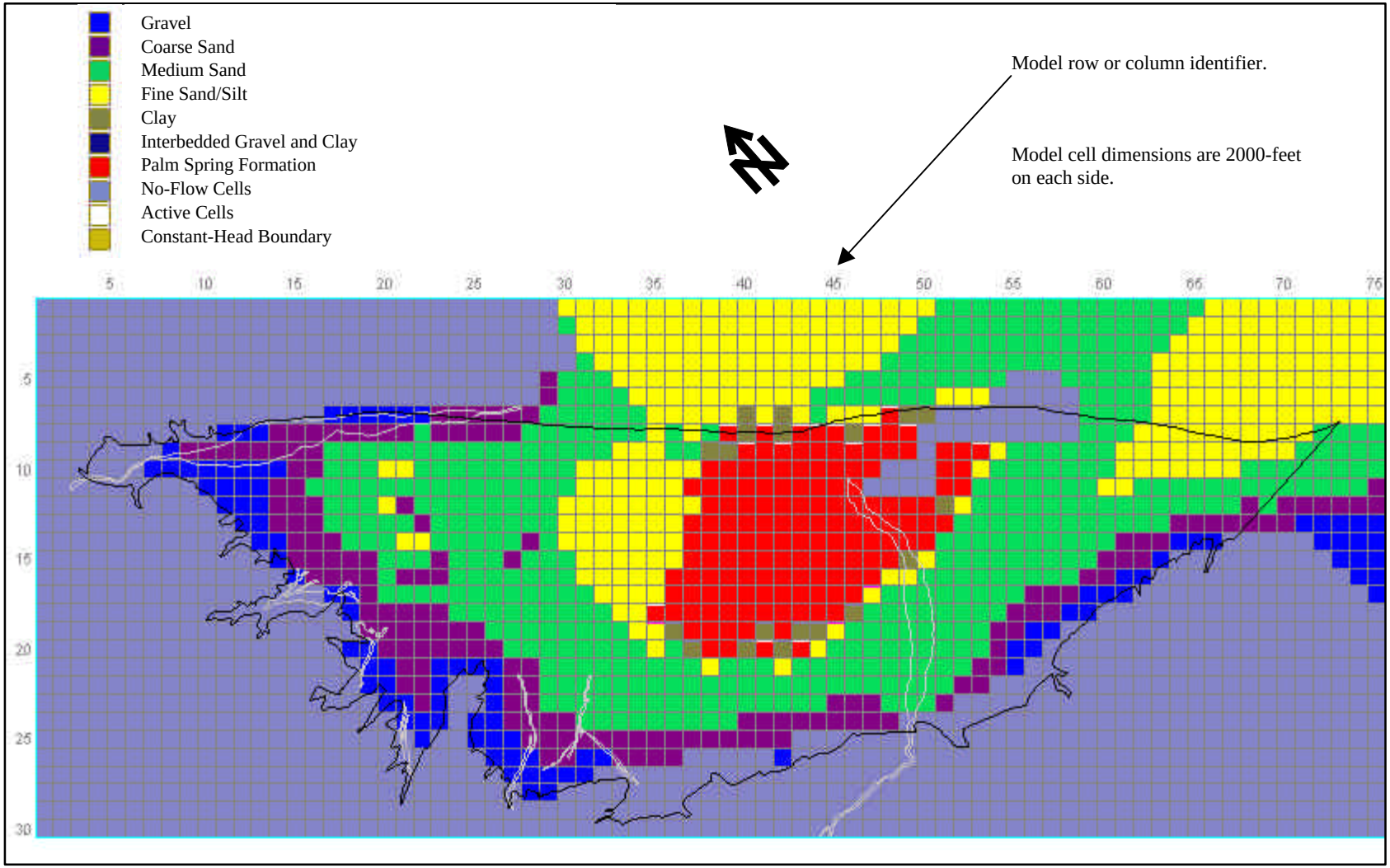


Figure 27. Distribution of soil textures in model layer 1.

as they are deposited between the high-energy depositional environment along the margins of the basin to the lower energy depositional environment of the central portion of the basin.

Model Layer 2

Model layer 2 represents the intermediate-age alluvium hydrogeologic unit and calculates groundwater flow using 1,042 active, and 17 constant-head cells (Figure 28). The surface of model layer 2 generally slopes east-southeast, but is relatively flat through much of the middle portion of the aquifer system (Figure 29). Model layer 2 ranges in thickness from less than 50 feet, up to approximately 550 feet thick, with the area of greatest thickness occurring near the central part of the upper portion of Borrego Valley (Figure 30). The dominant soil textures in model layer 2 are silt and fine to medium sand. However, a significant number of model cells are used to represent the low permeability Palm Spring Formation in the south-central portion of the basin as well as alluvial clays interpreted to be a lacustrine facies of the intermediate-age alluvium (Figure 31).

Model Layer 3

Model layer 3 represents the older alluvium hydrogeologic unit and calculates groundwater flow using 923 active, and 17 constant-head model cells (Figure 32). The thickness of each cell is calculated based on the top of model layer 3 (Figure 33) and the top of model layer 4. Model layer 3 is thickest in the northern portion of the basin and thins gradually to less than 50 feet near the southern part of the central portion of Borrego Valley, where the Palm Spring Formation is at or near land surface (Figure 34). Soil textures in model layer 3 range from clay to gravel, and includes alluvium and formational materials of the Palm Spring Formation (Figure 35). One unique feature of the older alluvium that this model layer represents is an area of interbedded clays and gravels. This zone has been widely used for groundwater production in the vicinity of the City of Borrego Springs. The interbedded nature of this zone reflects the convergence of high-energy alluvial deposits (e.g., gravels) with more quiescent deposits associated with shallow playa lakes (e.g., clays and silts).

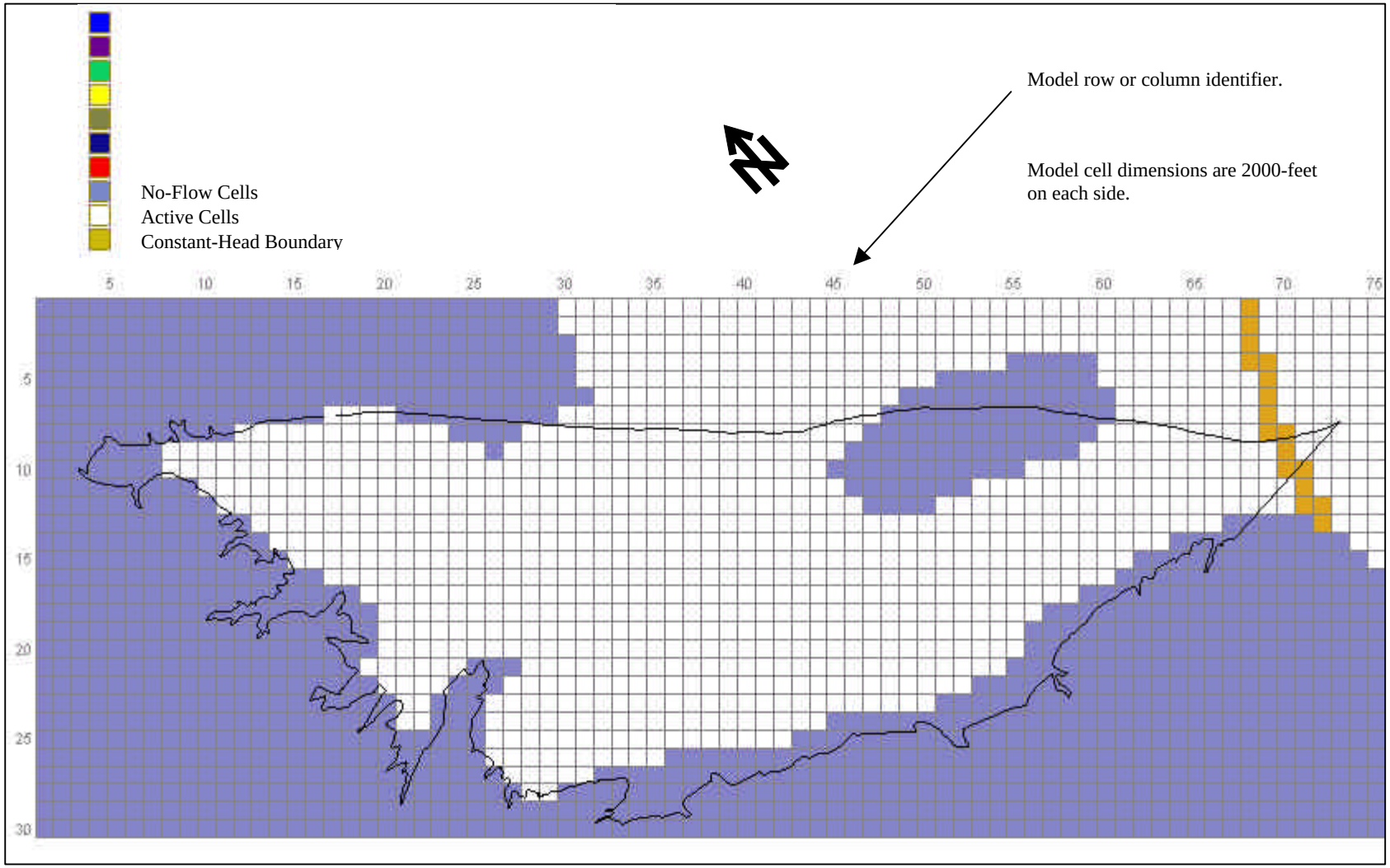


Figure 28. Model layer 2 no-flow, active, and constant-head cells.

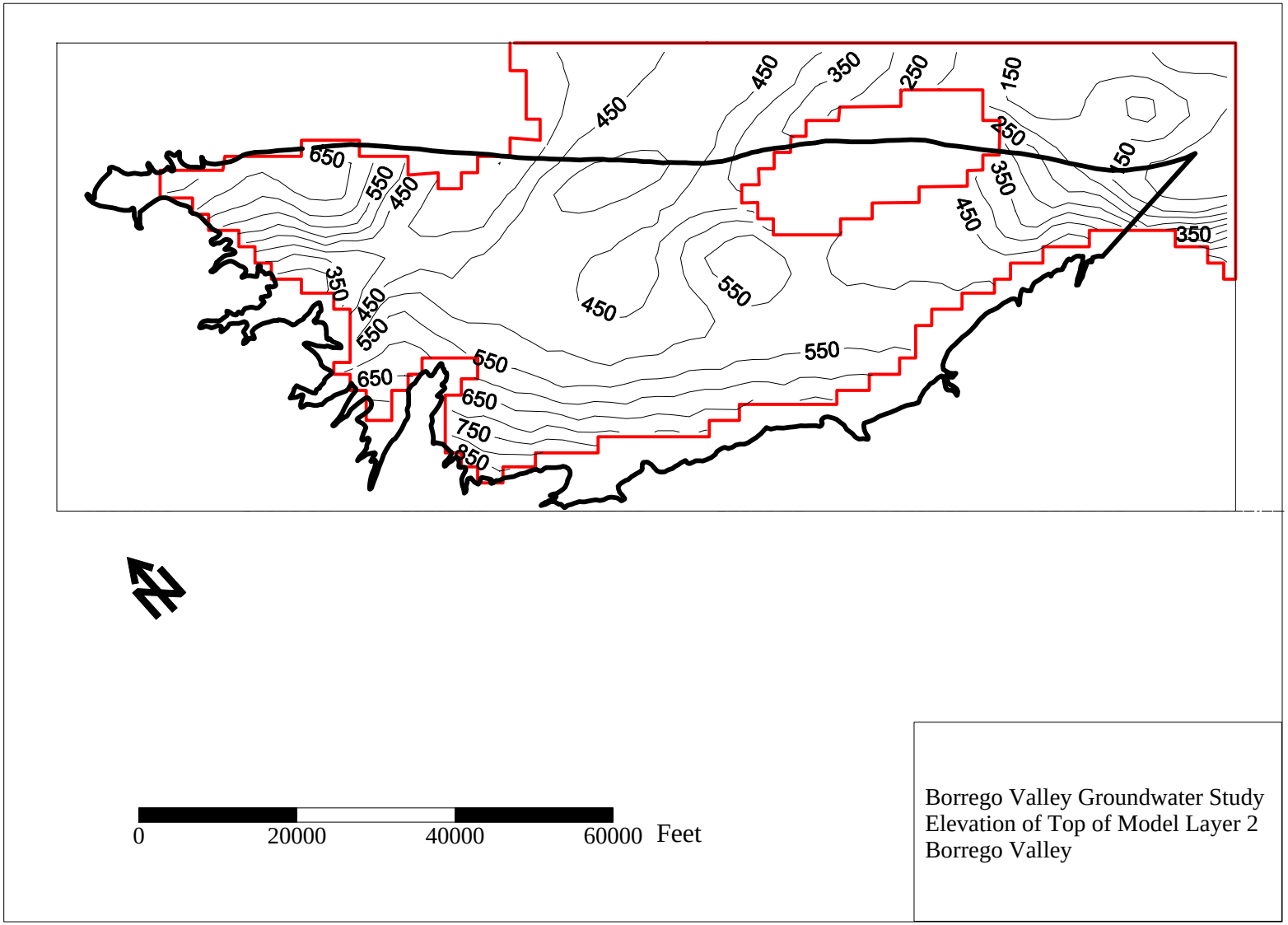


Figure 29. Elevation (feet m.s.l.) of top of model layer 2.

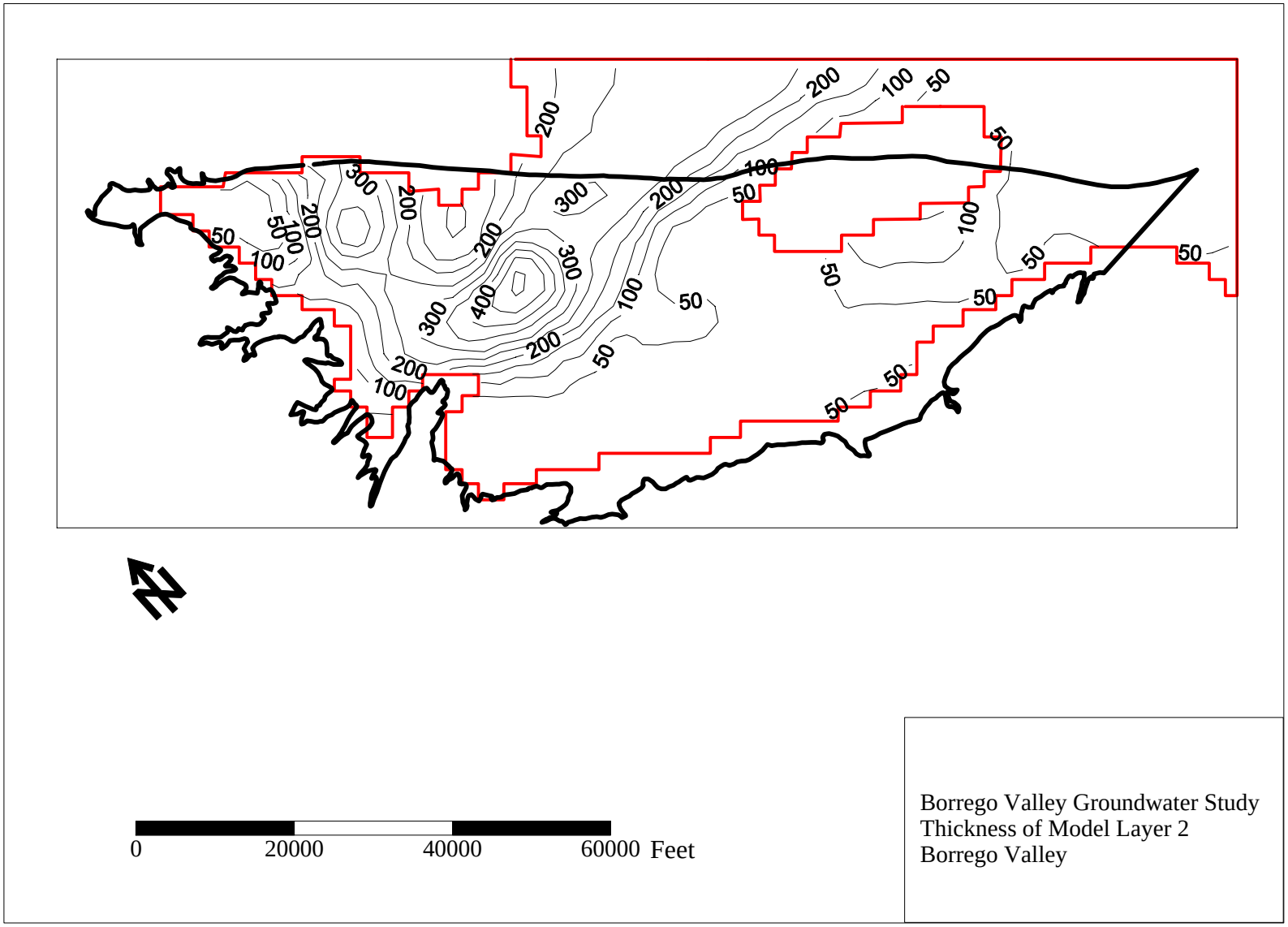


Figure 30. Thickness (feet) of model layer 2.

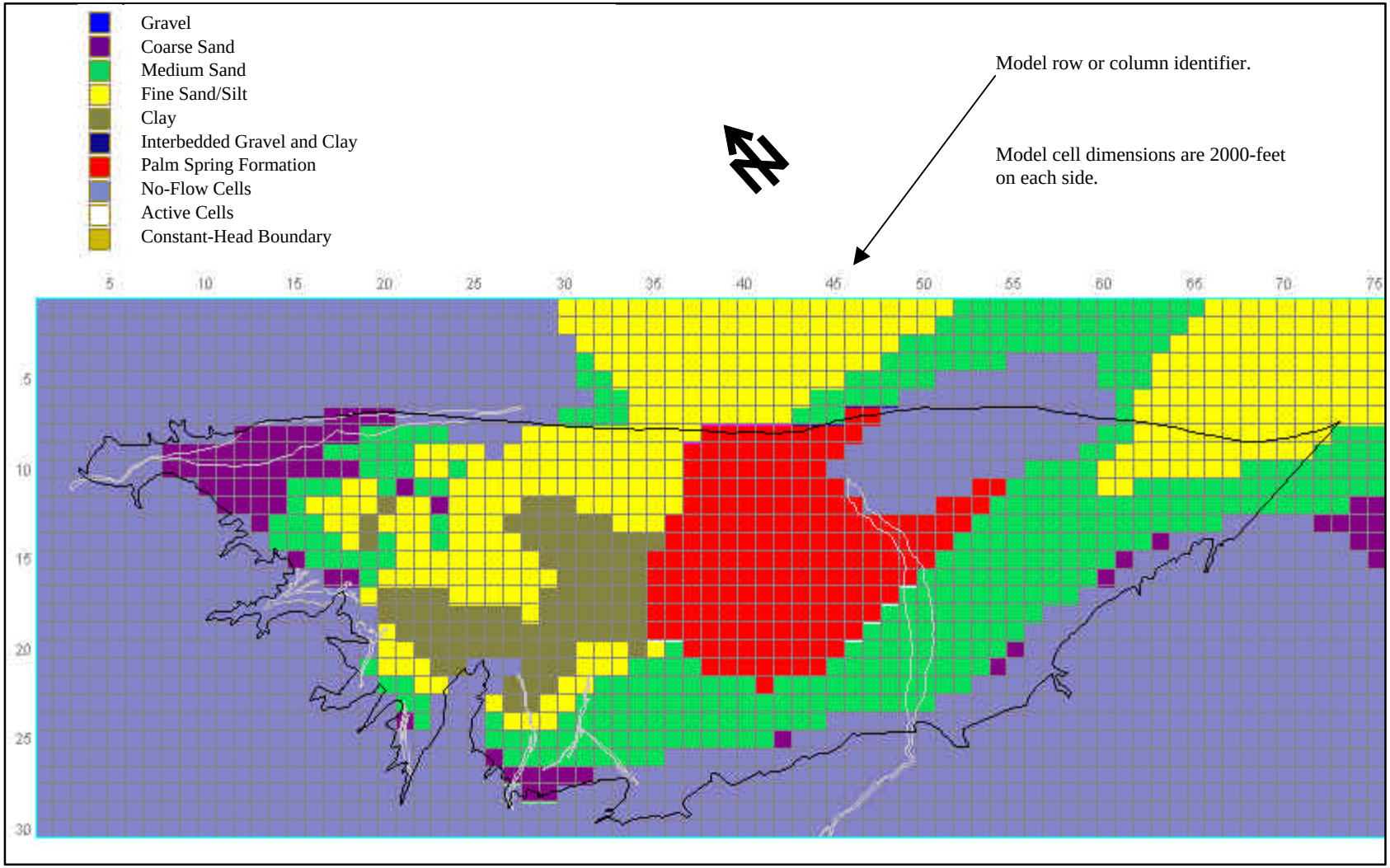


Figure 31. Distribution of soil textures in model layer 2.

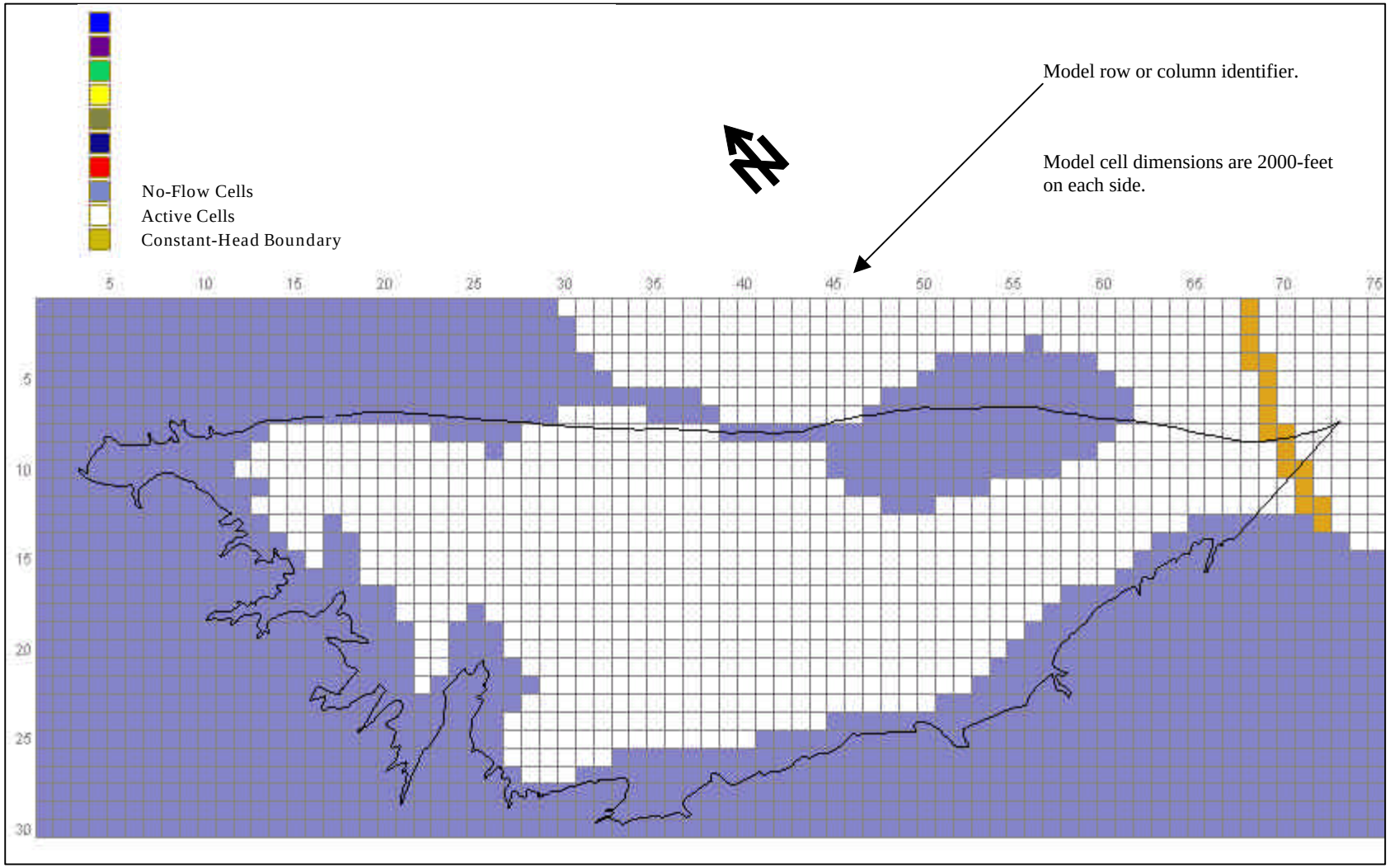


Figure 32. Model layer 3 no-flow, active, and constant-head cells.

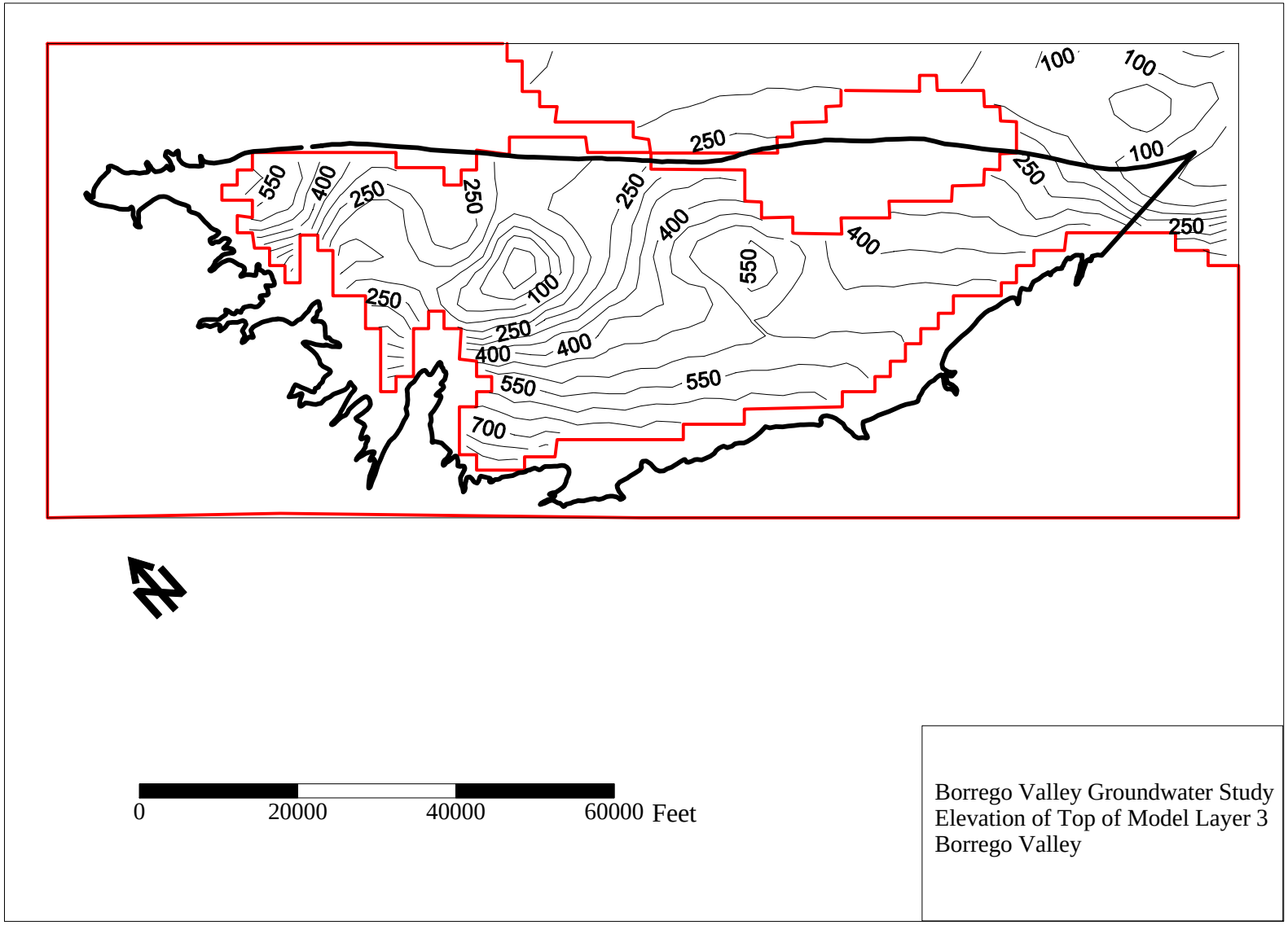


Figure 33. Elevation (feet m.s.l.) of top of model layer 3.

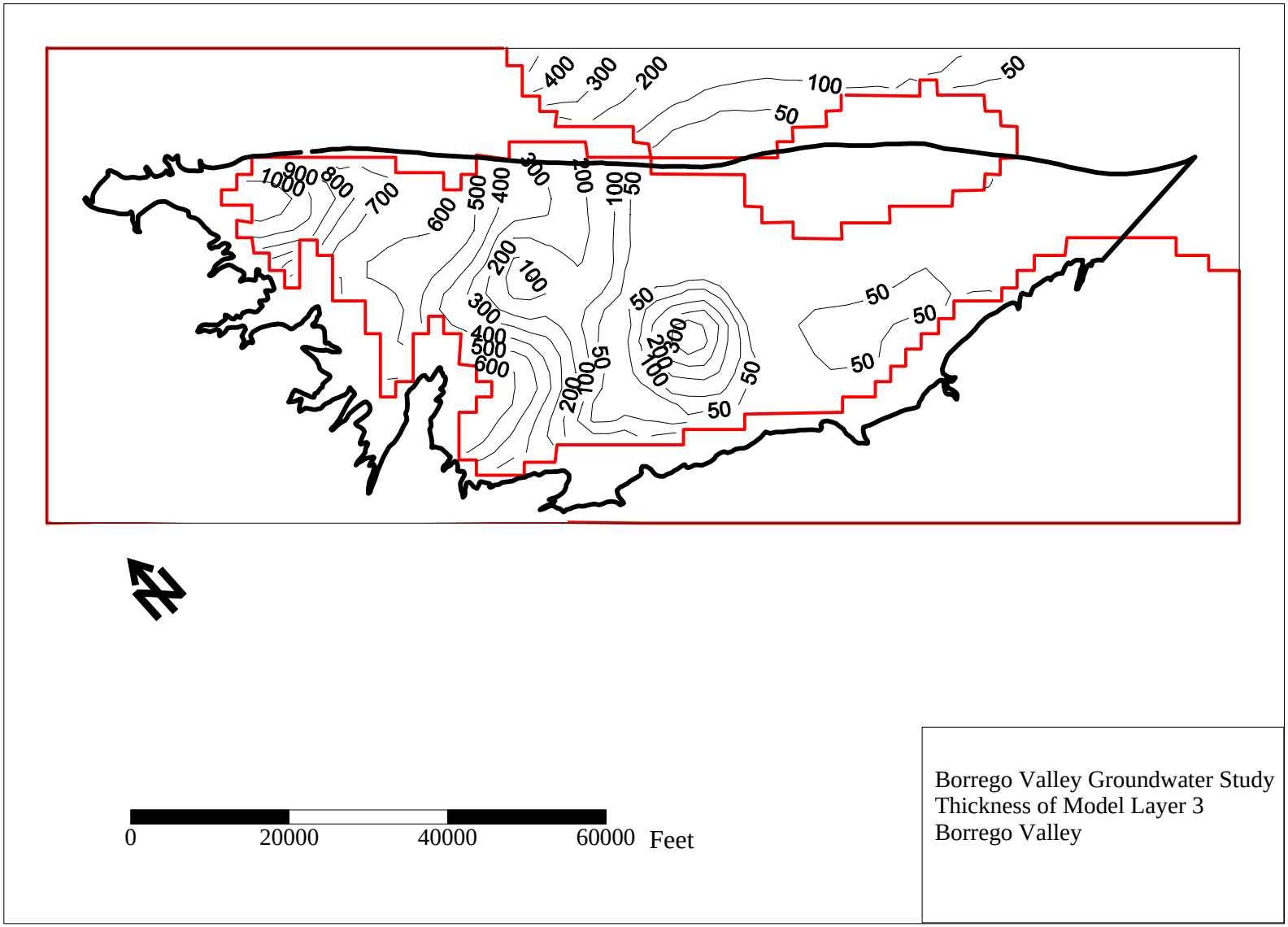


Figure 34. Thickness (feet) of model layer 3.

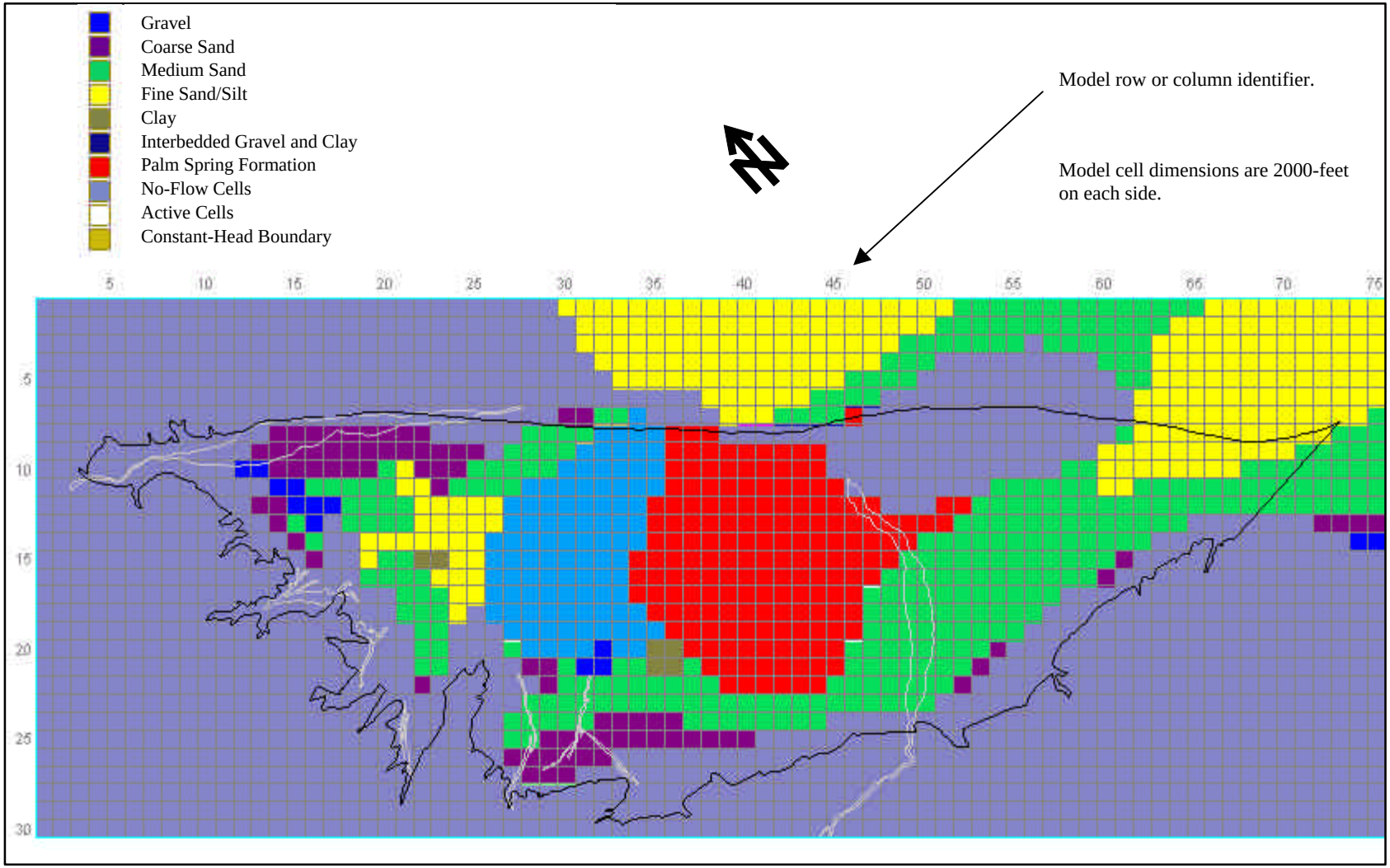


Figure 35. Distribution of soil textures in model layer 3.

Model Layers 4, 5, and 6

The Palm Spring Formation is represented in the model with 3 layers due to its significantly larger thickness (approximately 4,000 feet), relative to the other three hydrogeologic units represented by model layers 1, 2, and 3. Model layer 4 represents the upper portion of the Palm Spring Formation. It uses 650 active and 15 constant-head model cells to represent flow in the portion of the formation (Figure 36). Model layer 5 represents the middle portion of the formation and uses 275 active and eight constant-head cells (Figure 37). Model layer 6 represents the deepest portion of the formation, using only 25 active cells (Figure 38).

The surface of the Palm Spring Formation is at land surface near the central portion of Borrego Valley, south of Desert Lodge (Figure 5). The surface of the formation dips northwest under the central and north-central portion of Borrego Valley (Figure 39). The thickness of model layer 4 ranges from 0 to 1,200 feet, with the thickest portions southwest of the City of Borrego springs and near the Sleepy Hollow Folds (Figure 40). Model layers 5 and 6 represent the middle and deepest portions of the Palm Spring Formation with constant thickness cells (1,700 feet thick).

The soil texture of the Palm Spring Formation is a lumped parameter, as described in Chapter III. The hydraulic conductivity and storage coefficient in layers 4, 5, and 6 are the same of those used to represent the Palm Spring Formation in layers 1, 2, and 3.

Model Input

Input to the numerical model for the steady-state and transient periods included the fluxes calculated for the period 1945 through 2000, as described in Chapter III. Integration of these fluxes into the numerical model is described below.

General

Flux was represented throughout the model system using the evapotranspiration package of MODFLOW and specified-flux cells for both pumping discharge and groundwater recharge. Evapotranspiration of groundwater via native phreatophytes was modeled using 69 cells in model layer 1 (Figure 41 and Table 12, Appendix C).

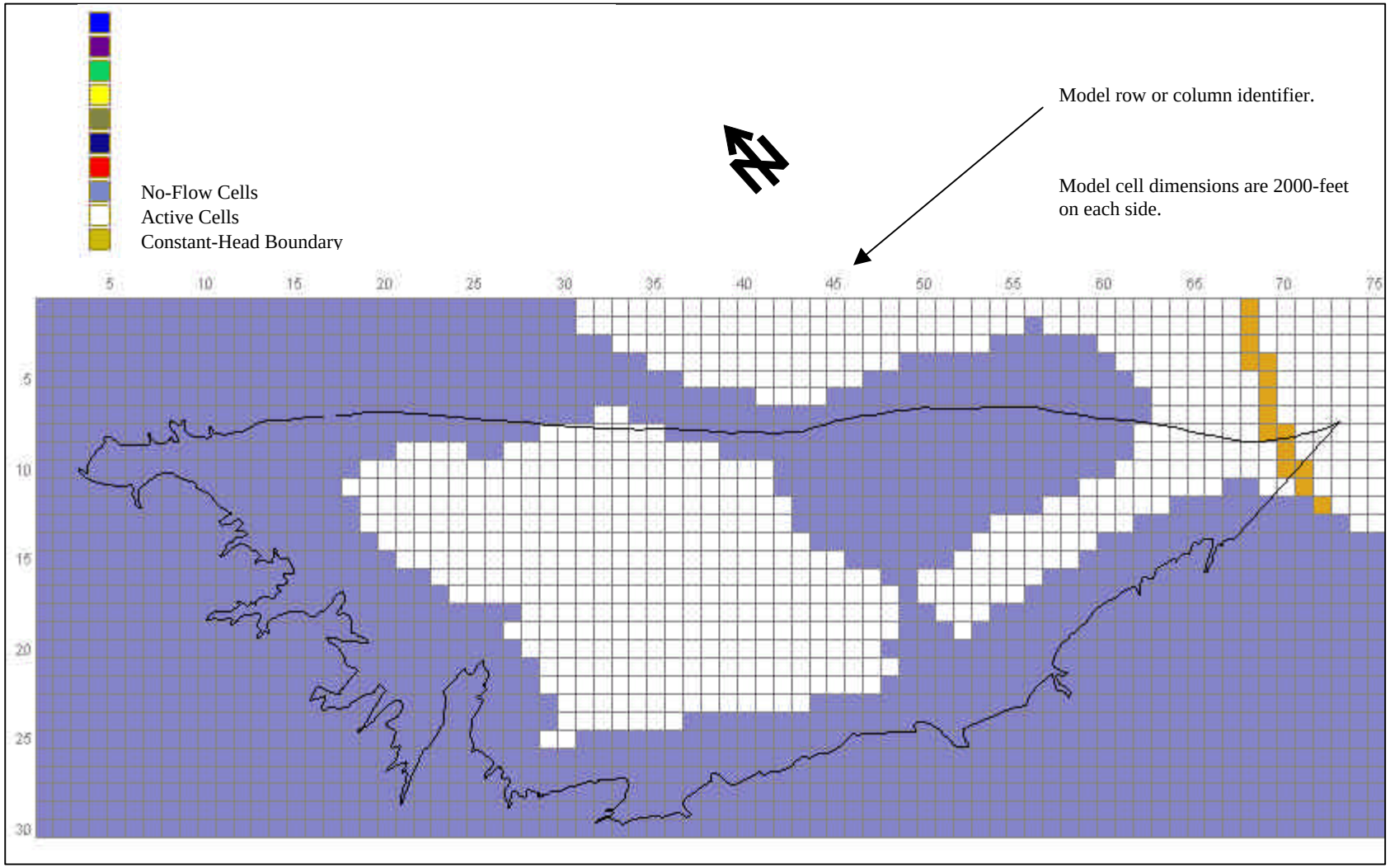


Figure 36. Model layer 4 no-flow, active, and constant-head cells.

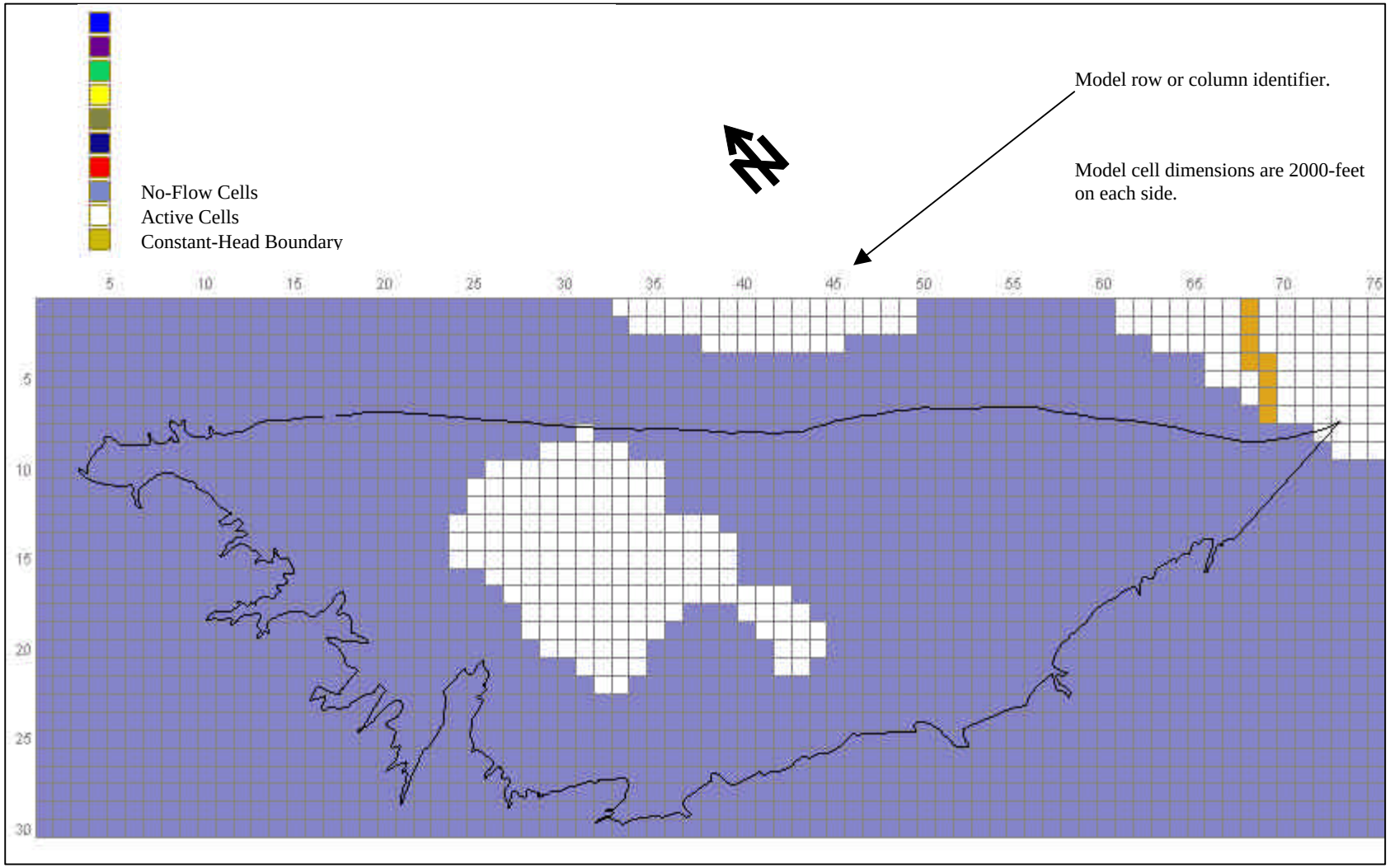


Figure 37. Model layer 5 no-flow, active, and constant-head cells.

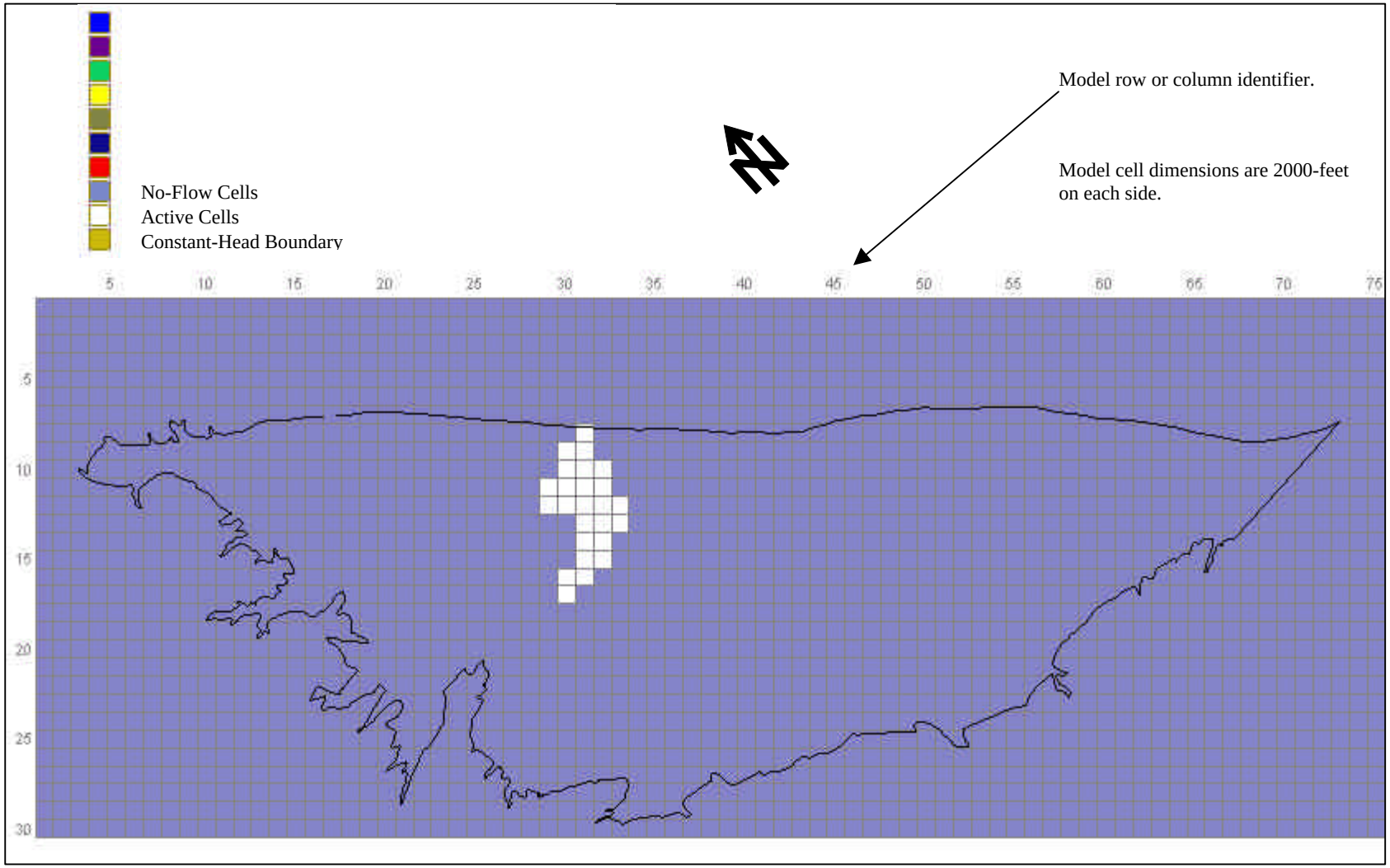


Figure 38. Model layer 6 no-flow, active, and constant-head cells.

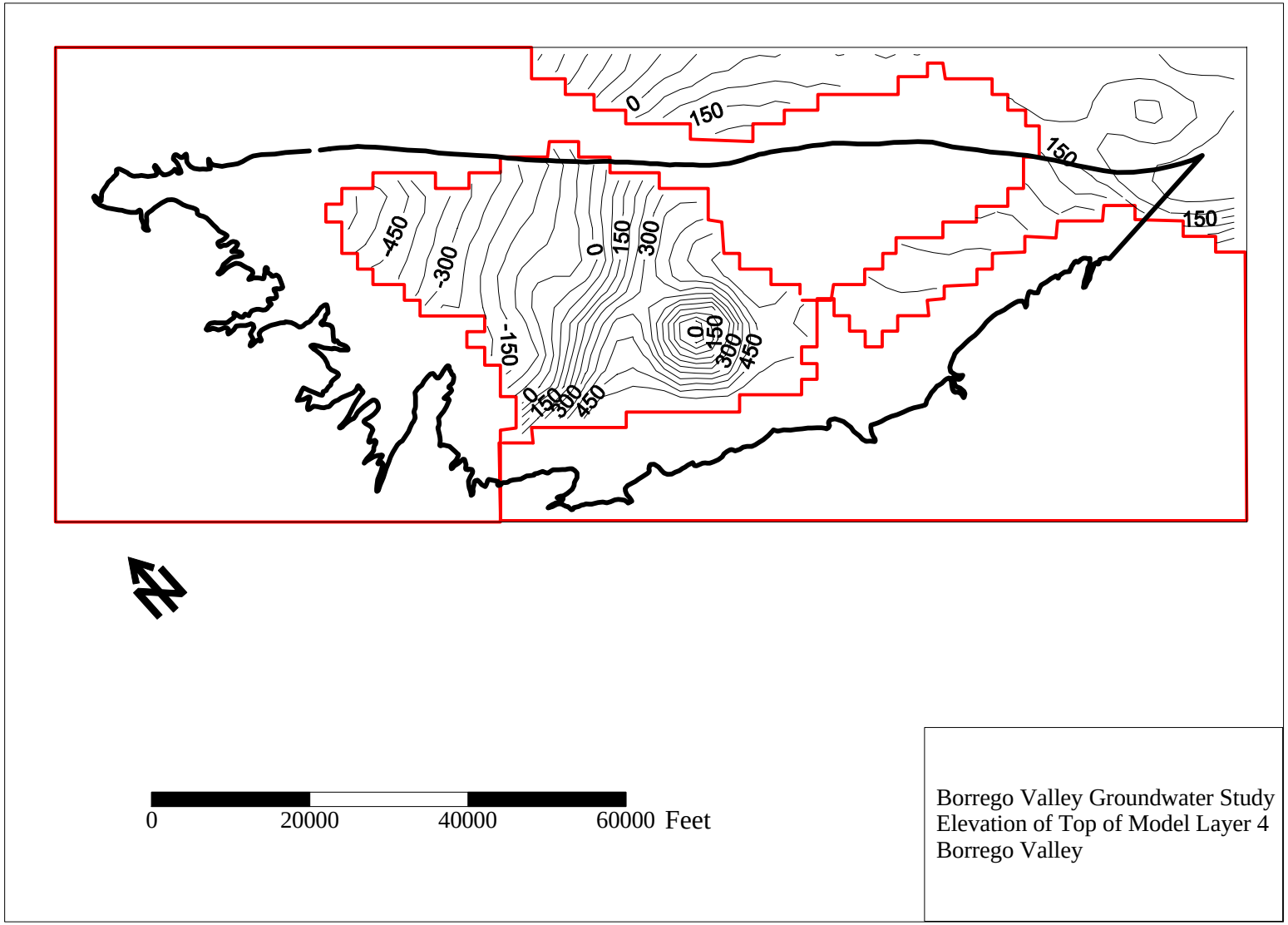


Figure 39. Elevation (feet m.s.l.) of top of model layer 4.

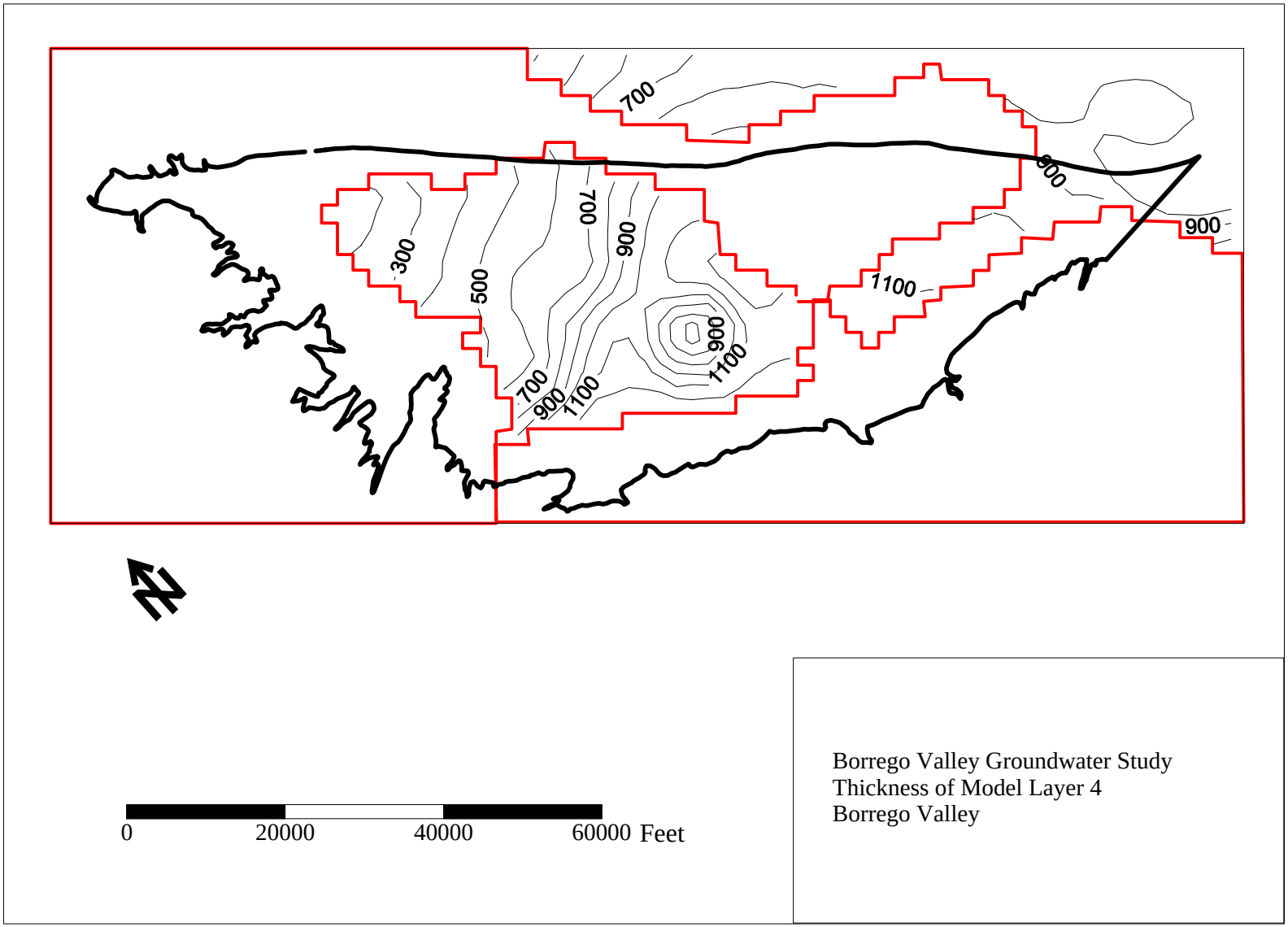


Figure 40. Thickness (feet) of model layer 4.

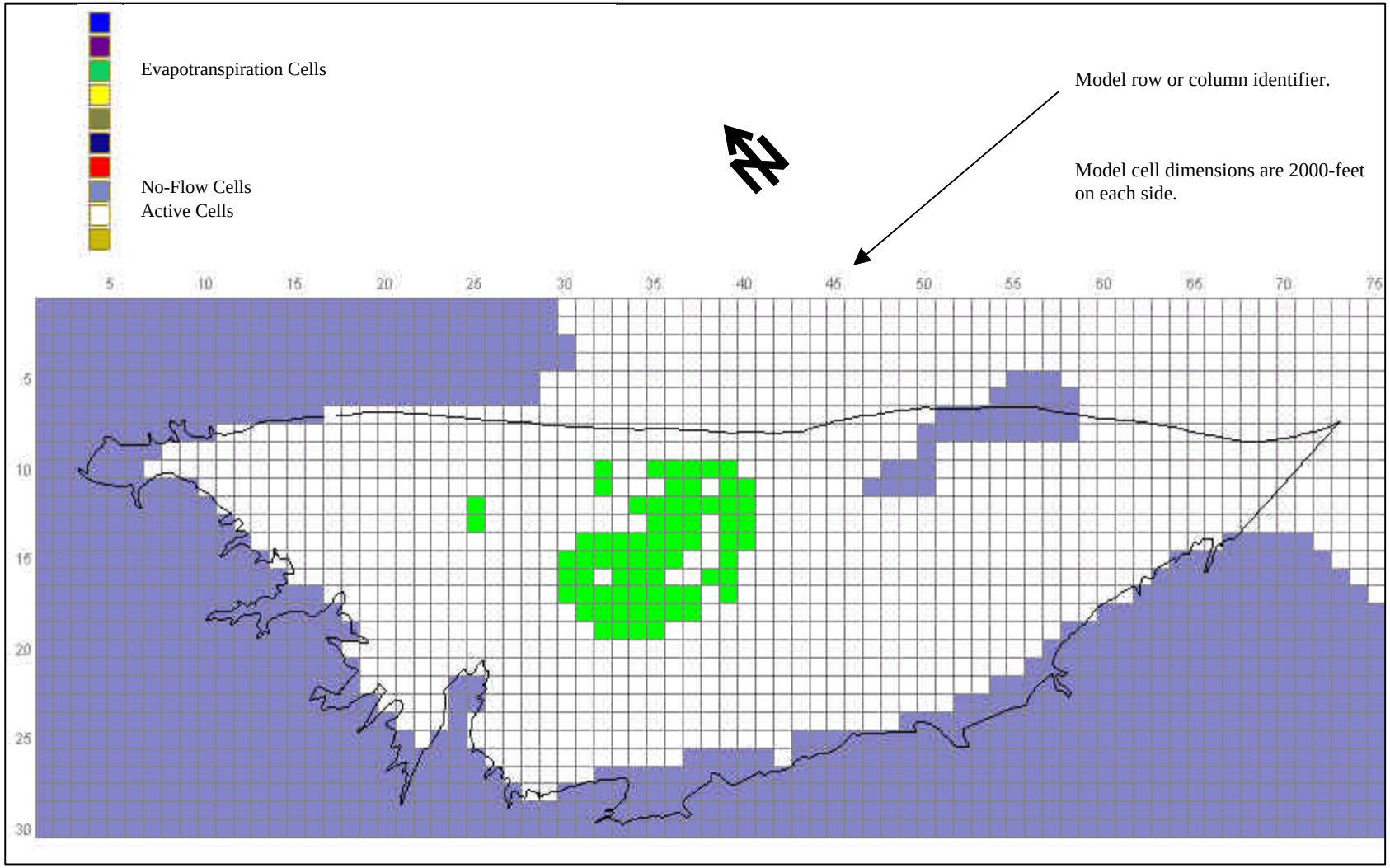


Figure 41. Steady-state, transient, and predictive models – location of evapotranspiration cells (layer 1).

Evapotranspiration was modeled using a unit maximum rate of 4 feet per year. This rate was modeled to decline linearly to zero at an evapotranspiration extinction depth of 20 feet below ground surface.

Recharge to Borrego Valley from various sources was represented using 37 cells around the margins of model layers 3 and 4 (Figures 42 and 43). These cells were used for the steady-state and transient calibration modeling and predictive modeling scenarios, described further in Chapters V and VI.

Discharge from Borrego Valley by pumping was accomplished using a distribution of cells in model layers 3 and 4 (Figures 44 and 45). These cells were used for the transient calibration modeling and predictive modeling scenarios, described in Chapters V and VI.

Steady-State Modeling

As previously described, 37 active cells (Table 13, Appendix C) were utilized to represent recharge during steady-state modeling calibration.

Additional sources of discharge from Borrego Valley during the steady-state period include both evapotranspiration and underflow out of the Valley. The discharge fluxes for each of these sources of discharge is calculated by the numerical model during simulation. The model calculated values are summarized in Chapter III.

Transient-Period Modeling

Sources of recharge to Borrego Valley during the period 1945 through 2000 are those discussed in Chapter III, and are represented by the 37 active cells (Table 13, Appendix C) described above. A summary of total recharge (surface water and bedrock) for the period 1945 through 2000 is provided in Table 14 (Appendix C).

Sources of discharge from Borrego Valley during the period 1945 through 2000 are described in Chapter III, and are represented by 99 active cells, distributed in model layers 3 and 4 (Figures 44 and 45). These 99 cells represent all of the locations of discharge during the period 1945 through 2000. Not all of the cells discharge simultaneously. During each model stress period a subset of the 99 cells have a non-zero discharge, while the rest are inactive for that period. The cell indices (row, column, and layer) for groundwater discharge, as well as the name of the sink they represent are provided in Table 15 (Appendix C). A summary of total discharge due to various sources of groundwater extraction for the period

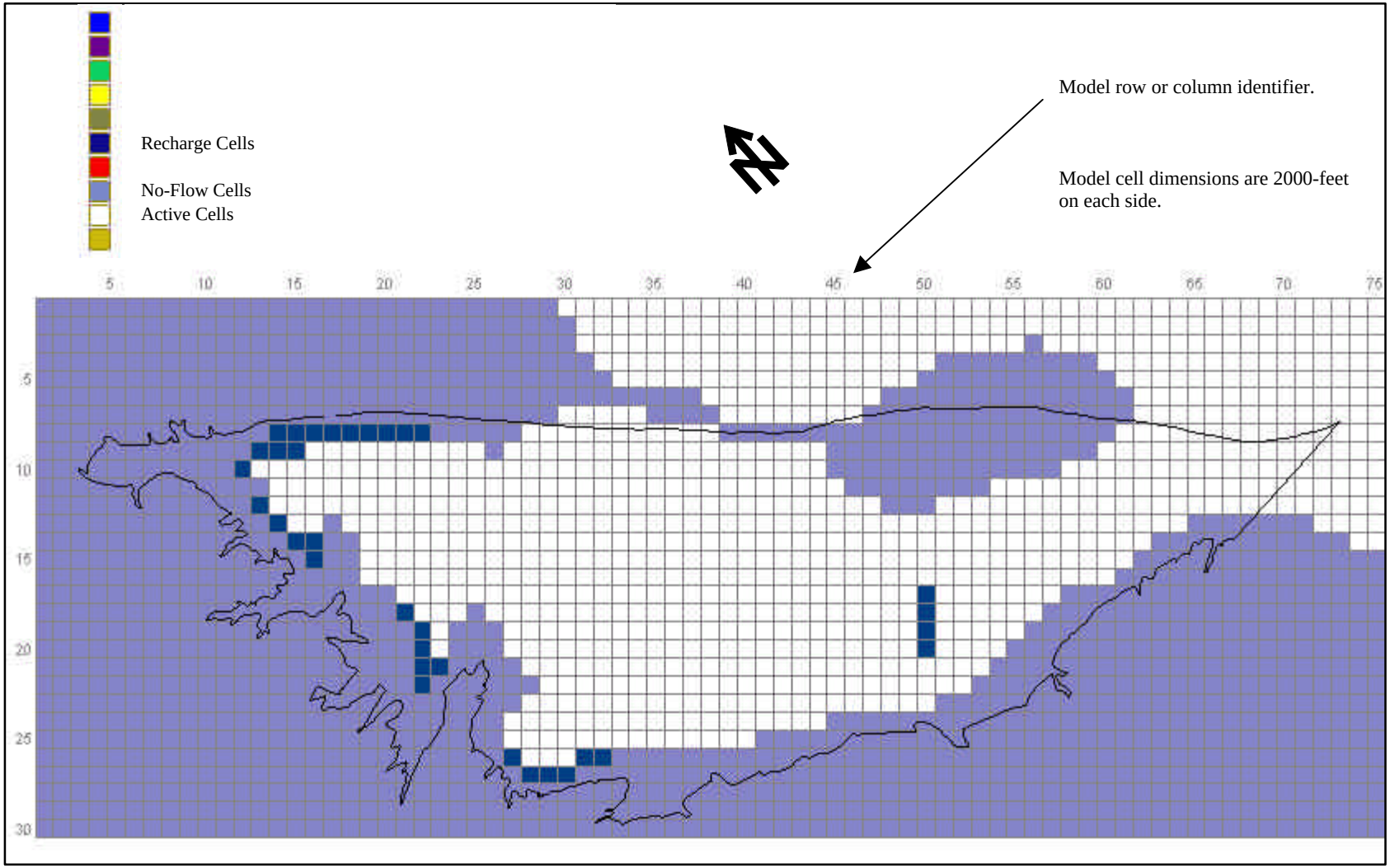


Figure 42. Steady-state, transient, and predictive models – location of recharge cells (layer 3).

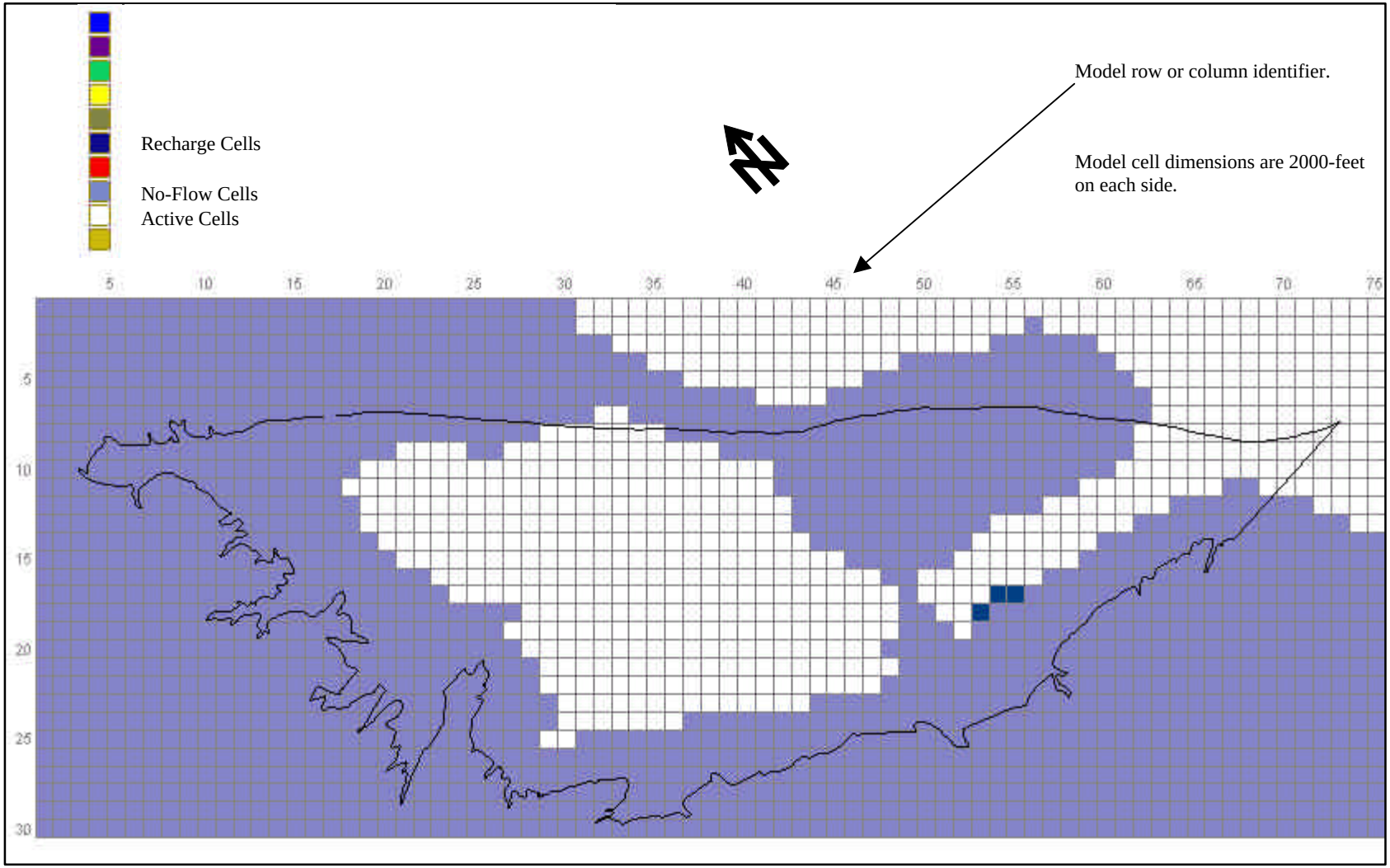


Figure 43. Steady-state, transient, and predictive models – location of recharge cells (layer 4).

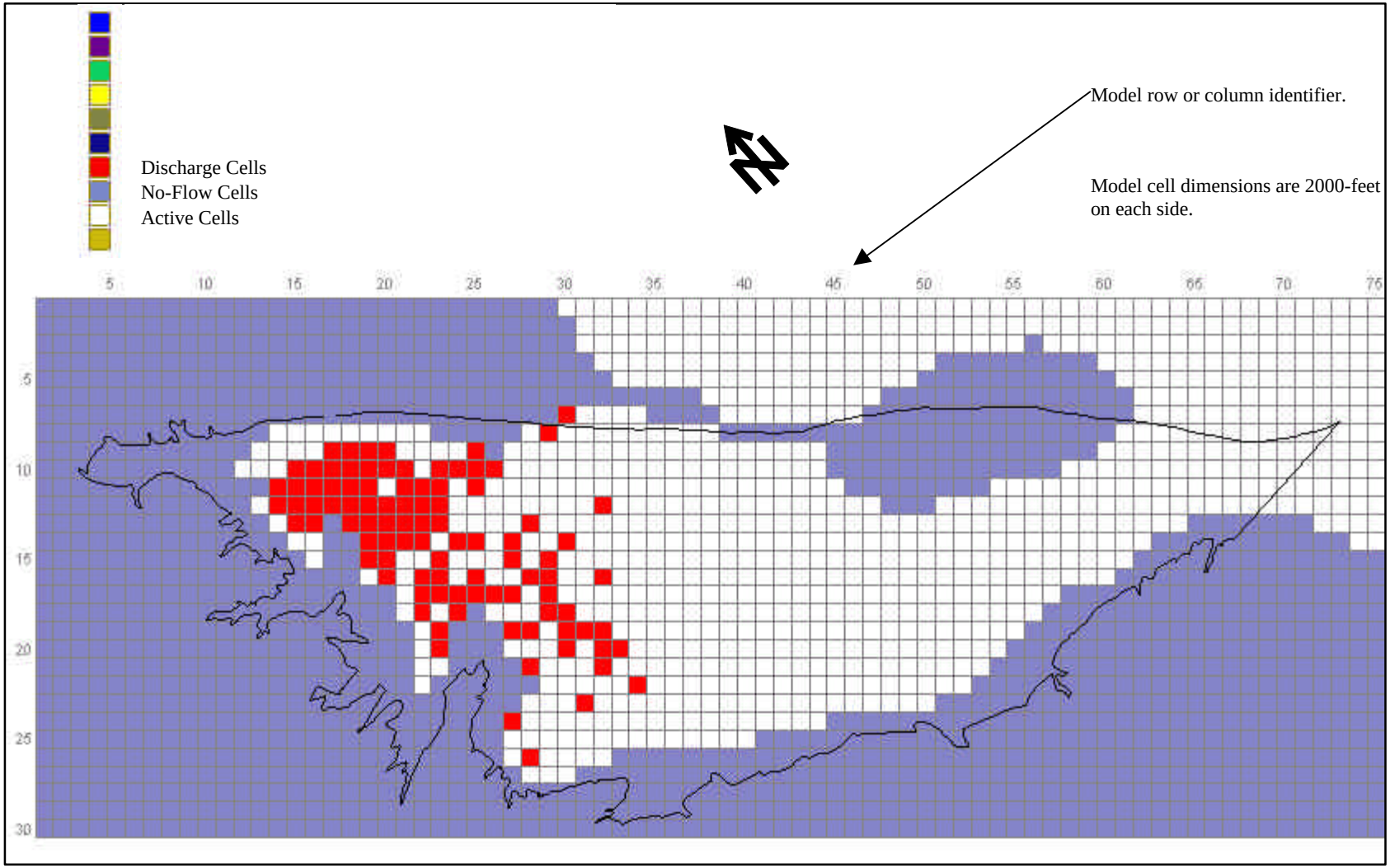


Figure 44. Transient and predictive models – location of discharge cells (layer 3).

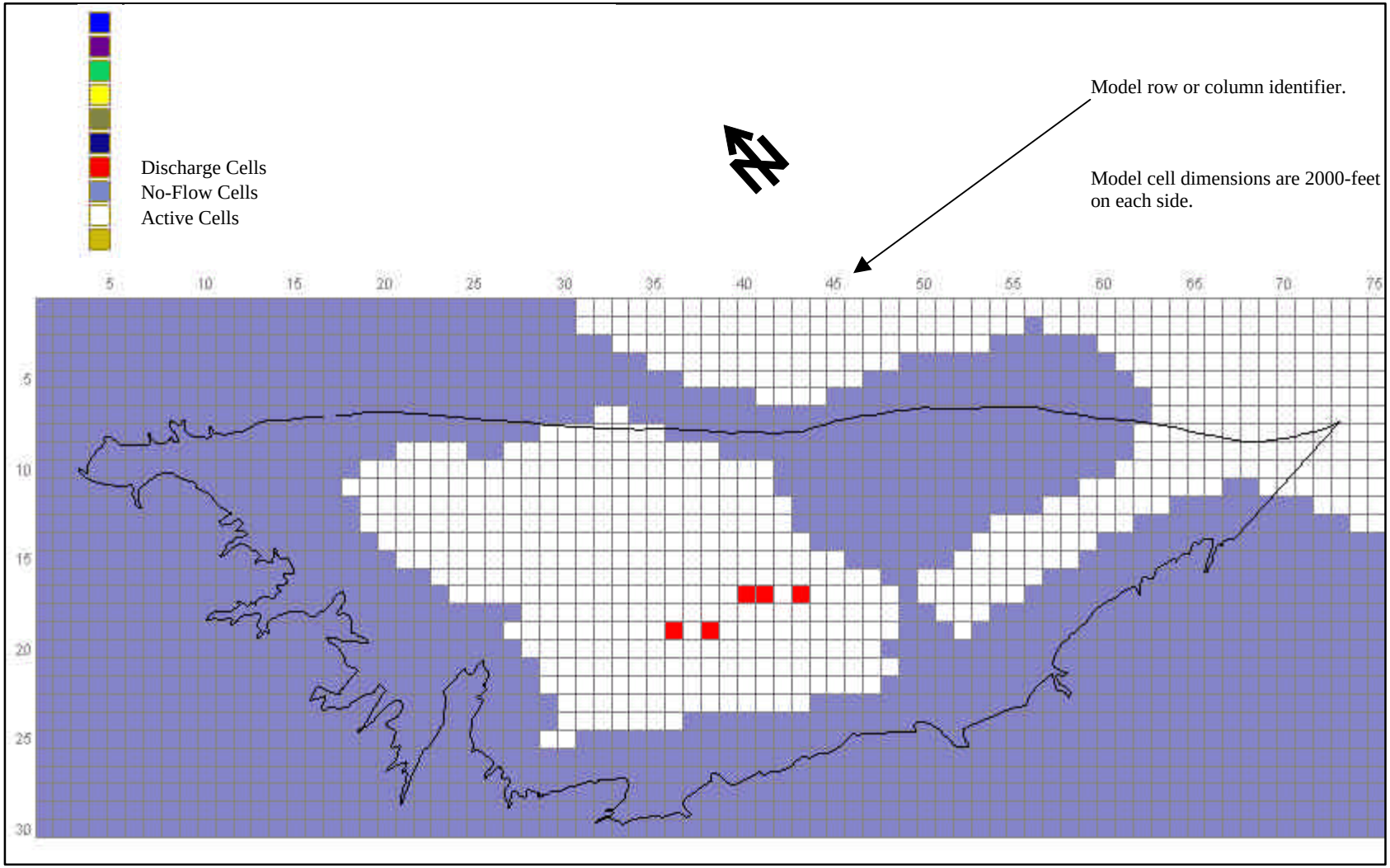


Figure 45. Transient and predictive models – location of discharge cells (layer 4).

1945 through 2000 is provided in Table 16 (Appendix C). In addition to specified-flux cells, groundwater is lost through evapotranspiration and underflow out of the valley, as summarized in Table 11.

CHAPTER V

MODEL CALIBRATION

Calibration of the numerical model was undertaken to adjust the physical system represented by the model, such that the predicted distribution of hydraulic head matched the observed distribution of hydraulic head for both the steady-state and transient modeling.

Steady-State Calibration

Steady-state modeling was undertaken to represent conditions prior to significant development of Borrego Valley (pre-1945). It was used to calibrate the distribution and magnitude of hydraulic conductivity for the soil textures represented in the model.

Steady-State Fluxes

Recharge quantities calculated for 1945 (Chapter III) were assumed to represent steady-state recharge conditions, as recharge calculated for 1945 was about the same as long-term annual recharge. Total recharge in 1945 due to surface water infiltration and bedrock recharge was calculated to be approximately 6,360 acre-feet. The distribution of this flux among cells in the model is described in Chapter IV.

Quantities of discharge for 1945 were calculated internally by the model. Evapotranspiration occurred at a rate ranging from 0 to 4 feet per year in 69 model cells, as described in Chapter IV. Evapotranspiration totaled approximately 3,960 acre-feet during the steady-state period, as calculated by the model. Underflow out of Borrego Valley occurred in the southeast portion of the model domain, and totaled approximately 2,400 Acre-Feet during the steady-state period. Groundwater extraction due to pumping in 1945 was assumed absent and was not modeled.

Calibration Targets

Calibration targets of hydraulic head were required to provide a basis for adjustments to physical properties (and the resulting change in model-predicted hydraulic head). The 1982 and 1988 USGS phase I and II reports utilized “observed” hydraulic head

measurements in Borrego Valley in 1945 for development of contour maps and steady-state modeling. The location of "observed" hydraulic head measurements, interpreted from Plate 9 of the 1982 USGS report, were utilized as calibration targets for steady-state modeling (Figure 46). Plate 9 of the 1982 USGS report provides water level elevation contours for the 1945 period (Figure 17). These contours are based on multiple black dots, interpreted to represent measurement locations, although they are not referenced in the plate, or text. Review of their referenced literature did not yield any observed values of hydraulic head for the period up to 1945. According to the USGS, the original author of the report is now deceased, and they have no record of the basis of these water levels (P. Martin, personal communication, June 12, 2001). In addition, review of topographic maps at 1:24,000 scale indicates that several of the water level elevation targets shown on Plate 9 of the USGS report are above ground surface. In light of these issues, use of these calibration targets was guarded, and the quality of calibration (described later) should consider these problems.

In addition to the issues listed above, modeled steady-state hydraulic head in the vicinity of Desert Lodge and the south end of Borrego Valley near San Felipe Creek did not match the target hydraulic heads well. This may be a function of an incomplete or overly generalized conceptual model, or the targets themselves may be questionable, as previously discussed.

Calibration Quality

The steady-state distribution of the water table in model layer 1 as calculated by the steady-state model accurately represents the expected groundwater flow directions, sources of recharge, discharge from areas with evapotranspiration, and discharge as underflow out of Borrego Valley near the southeast end of the aquifer system (Figure 47).

Evaluation of the results of the steady-state model show that the model does not achieve a good fit between modeled and "observed" values of hydraulic head (Figure 48). Significant effort was made to adjust the physical properties of the model such that modeled values of hydraulic head were within 10% of the range of water levels (100 feet), relative to the observed values of hydraulic head, reported by Moyle (1982). These efforts resulted in moderate success, with several of the targets still exceeding that goal. Most modeled targets were within 20 feet (20% of the range) and all were within 30 feet (30% of the range) of

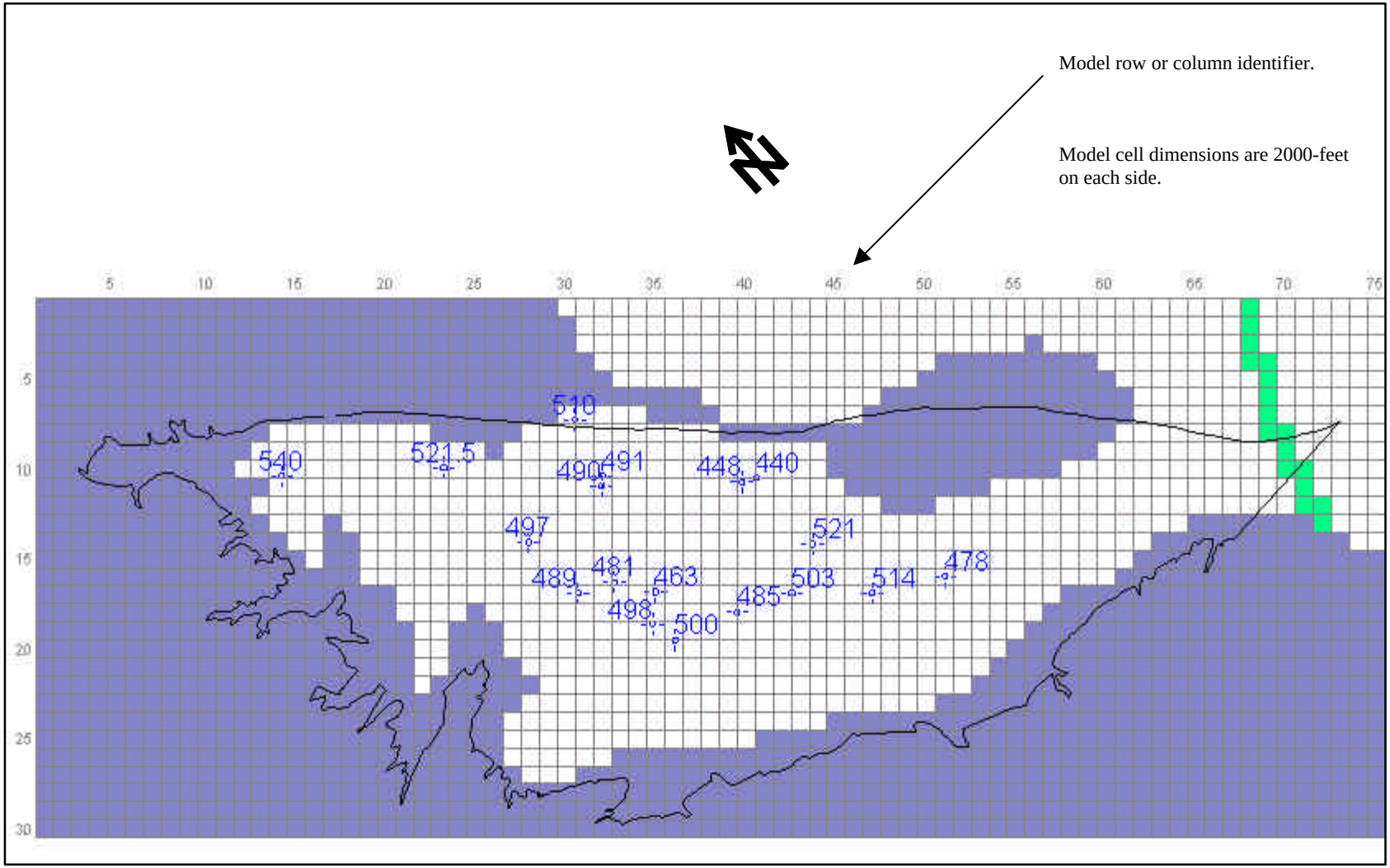


Figure 46. Steady-state water level elevation targets (based on Moyle's interpreted water table contour map).

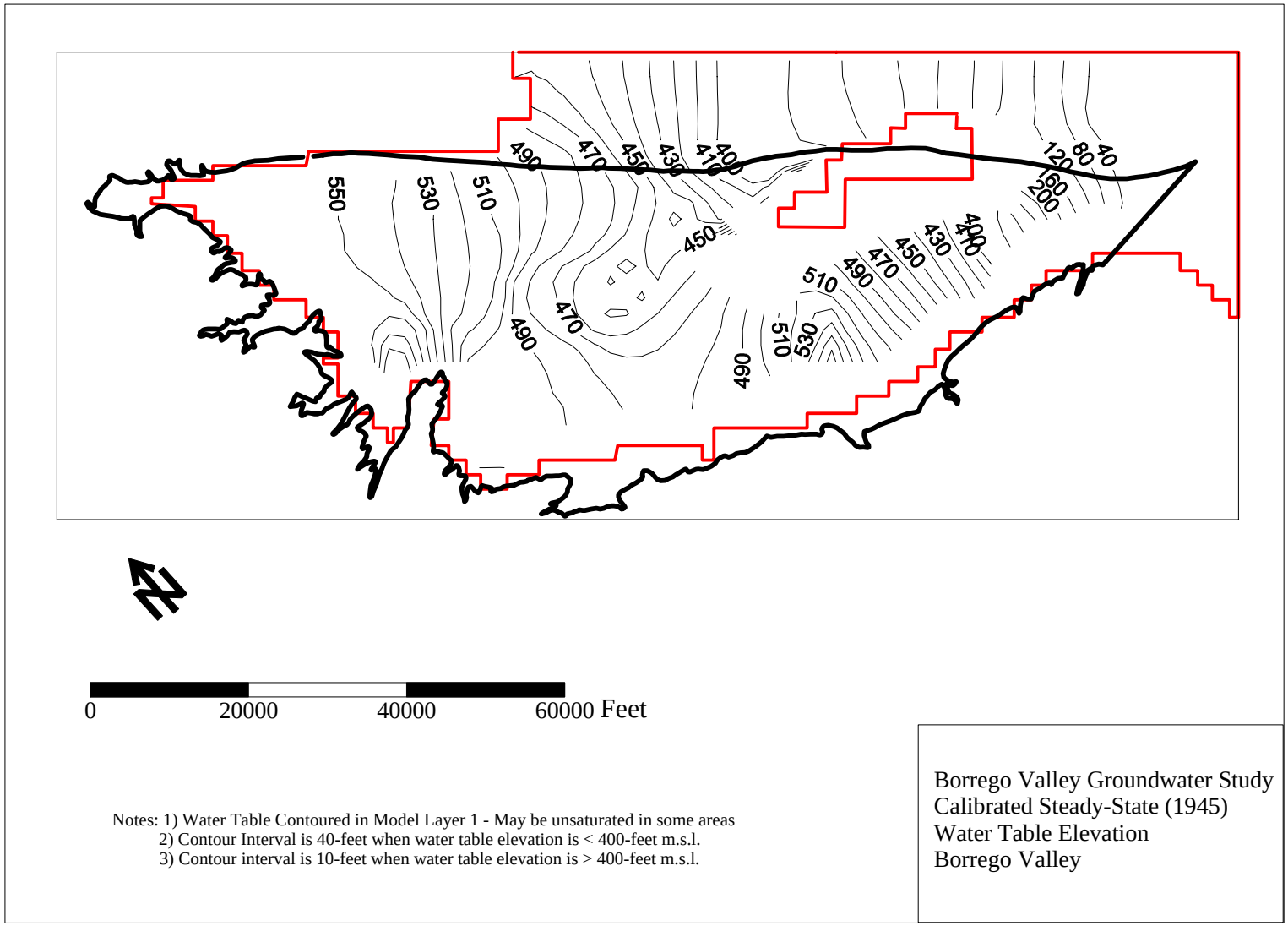


Figure 47. Calibrated steady-state water table elevation.

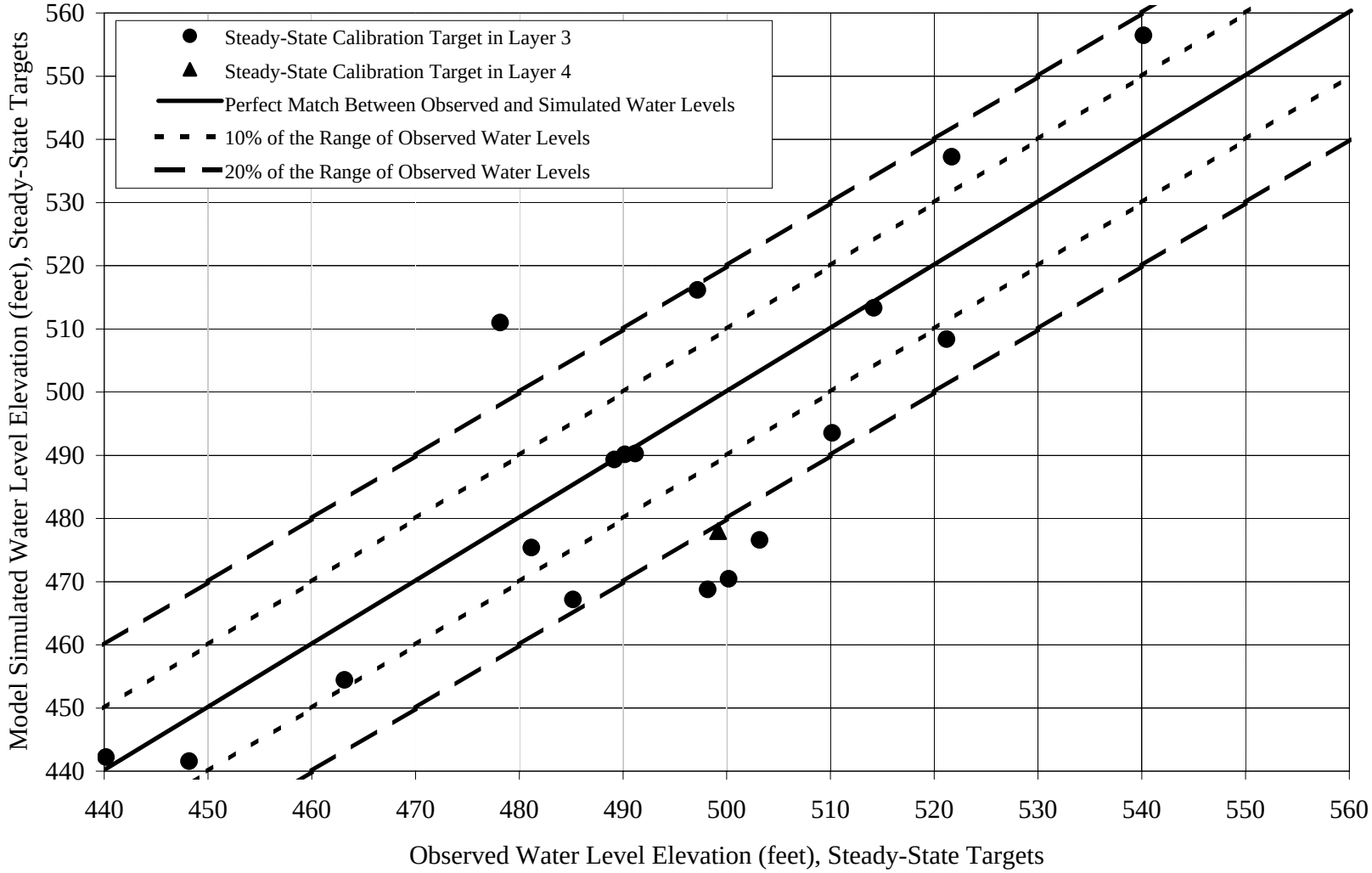


Figure 48. Steady-state modeling, observed vs. simulated water level elevations (feet m.s.l.).

observed values. Failure to reach the goal of within 10% of the range of observed water levels is attributed to uncertainties in the conceptual model as well as the "observed" targets.

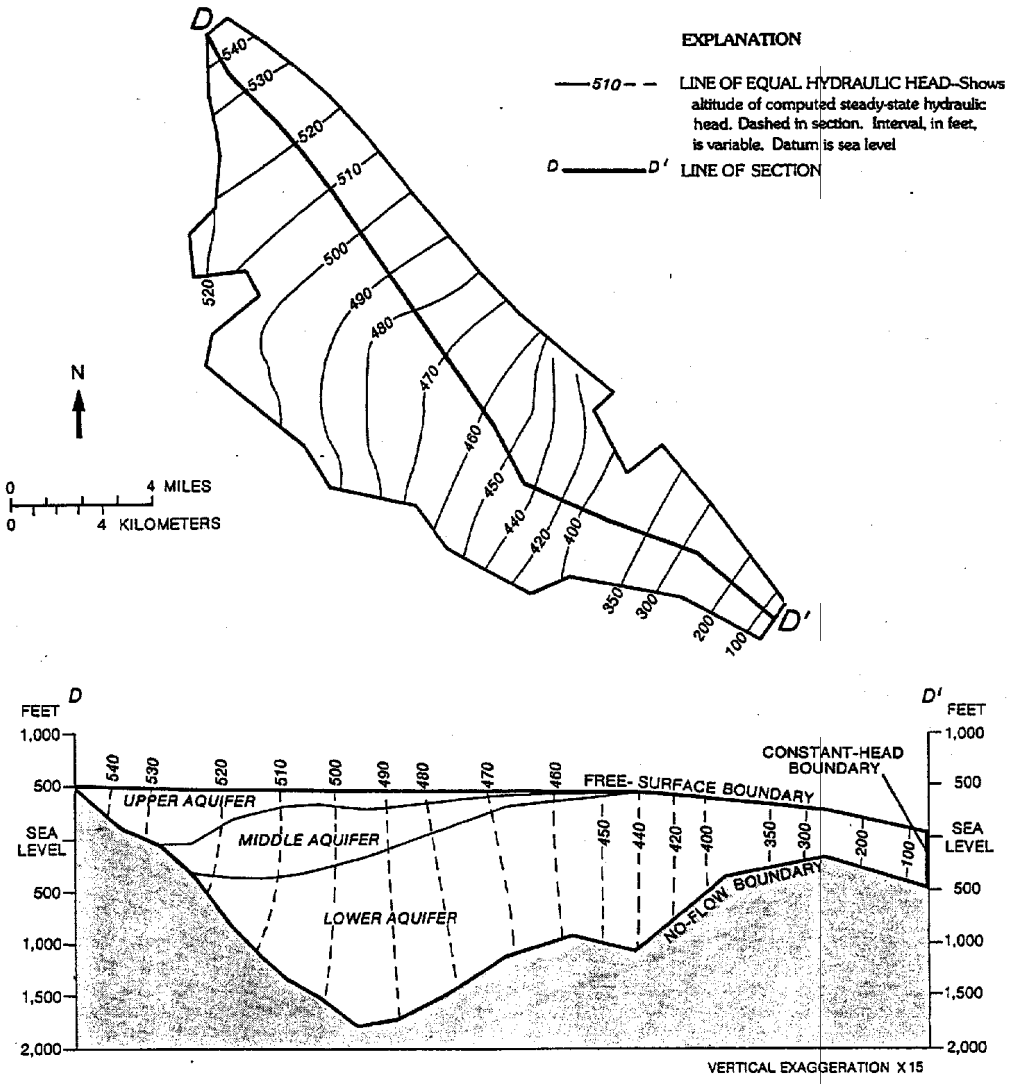
Calibration Difficulties

In addition to the uncertainties listed above, two other issues related to implementation of the conceptual model using MODFLOW required resolution. MODFLOW would not converge (provide a stable solution within identified thresholds) in the steady-state calculation mode with this model. As an alternative, a 1000-year transient simulation, utilizing constant recharge fluxes was run as a surrogate to the steady-state simulation. Mass balance output from the transient simulation was reviewed to ensure that the transient model was in a steady-state condition (e.g., no change in groundwater storage) by the end of the simulation (typically by year 600). In addition, the cell re-wetting capability of the MODFLOW BCF2 package (Hill, 1990) had to be turned off due to excessive oscillations which caused the program to crash. Turning off the re-wetting capability precludes a desaturated cell from becoming resaturated with groundwater. Review of the steady-state distribution of water levels indicates that this limitation is not significant for either the steady-state or transient simulations. This limitation had a small impact on an isolated area of the aquifer system during predictive modeling, as described in Chapter VI.

Comparison with the USGS Conceptual and Numerical Models

The water level distribution and groundwater flow field predicted by the steady-state model agrees with Moyle's conceptual model in a gross sense. Groundwater is modeled to flow from the primary recharge areas along the margins of the basin to the primary discharge areas in the vicinity of Borrego Sink and Lower Borrego Valley. The steady-state model accurately predicts that groundwater recharge originating in the vicinity of San Felipe Creek discharges both north toward Upper Borrego Valley and south toward Lower Borrego Valley, consistent with Moyle's conceptualization.

In contrast, the USGS model predicts a more generalized groundwater flow field for the 1945 steady-state condition (Figure 49). Discharge in the vicinity of Borrego Sink, and recharge in the vicinity of San Felipe Creek are not well represented. The basis for steady-state calibration of the USGS model was the distribution of 1945 water levels reported by



After Mittenthal (1988)

FIGURE 81.—Computed steady-state (1945) hydraulic head.

Figure 49. USGS modeled water level elevations (feet m.s.l.) – 1945.

Moyle. The USGS steady-state model appears to represent the steady-state flow field conceptualized by Moyle in only a coarse and general sense. The distribution of hydraulic conductivity and resulting transmissivities estimated based on the USGS steady-state model may not be accurate, and are discussed later.

Transient State Calibration

Transient modeling was undertaken to represent 1945 through 2000 conditions, and was used to calibrate the distribution and magnitude of specific yield for the soil textures represented in the model.

Transient State Fluxes

Transient state fluxes included recharge due to surface water and bedrock recharge, as described in Chapter IV. Transient state fluxes also included discharge due to agriculture, recreational, and municipal groundwater use, along with evapotranspiration and underflow out of Borrego Valley (Chapter IV).

Calibration Targets

Transient state calibration targets were selected from data available from the USGS, and SD Co. DPLU. The criterion for target selection included location in the aquifer system, as well as the period of available data. Calibration targets were located in model layers 1, 2, and 3 to represent conditions throughout as much of the aquifer system as possible (Figures 50, 51, and 52). Targets were selected to provide information for the modeled period (1945 through 2000), and to provide information throughout the basin, at discrete depth intervals. Due to a lack of development in Borrego Valley prior to 1945, the earliest available water level elevation measurements were made in the late 1940's and early 1950's. Well screen intervals for most of the target wells were not available, but based on lithology reported in driller's logs, most target wells are expected to be screened in model layer 3.

Calibration Quality

Calibration quality was evaluated by comparing observed water levels to modeled water levels for each of the 20 target wells. Hydrographs for seven of the 20 target wells are discussed below. These seven hydrographs provide a spatial distribution throughout the

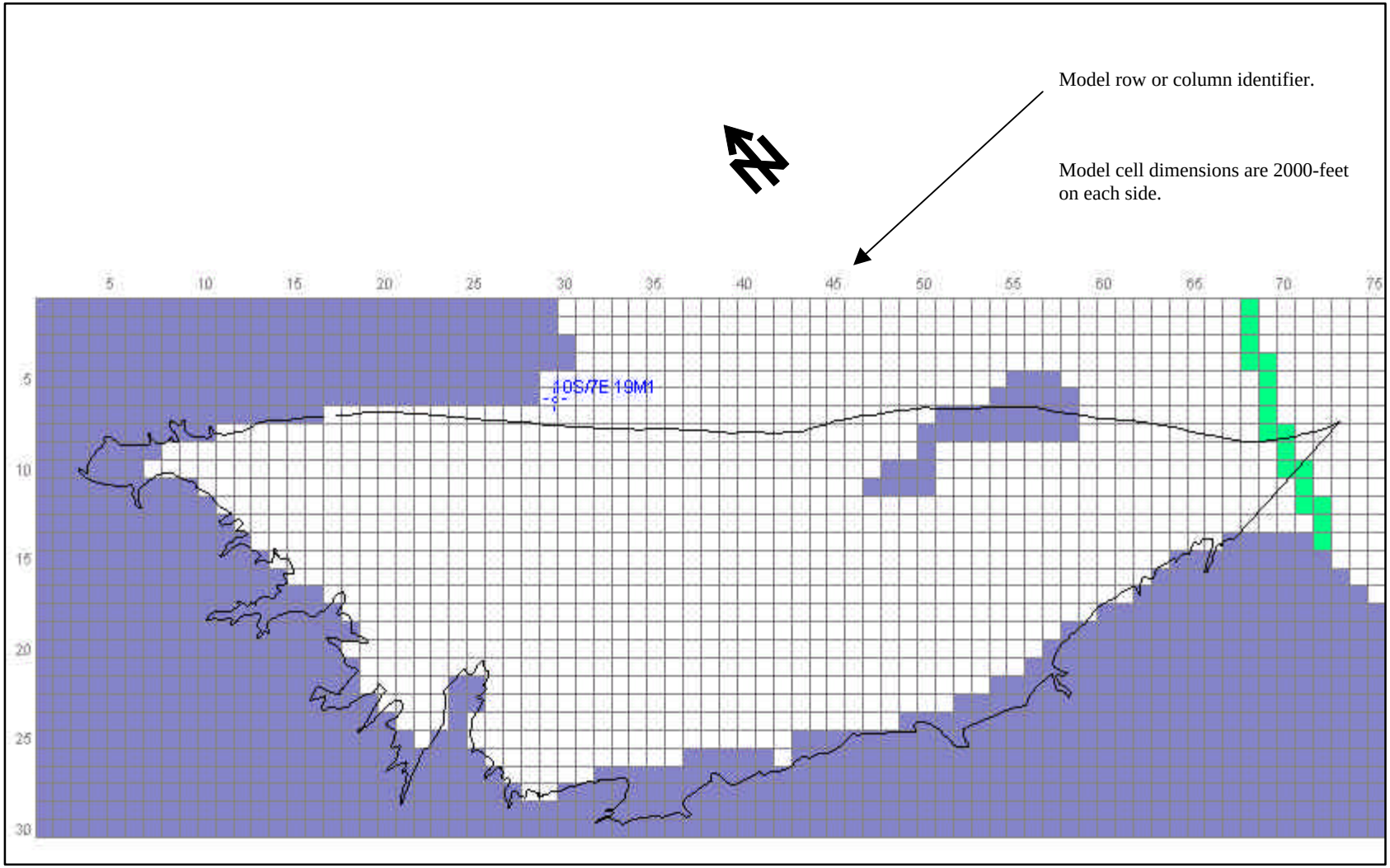


Figure 50. Transient water level targets in model layer 1.

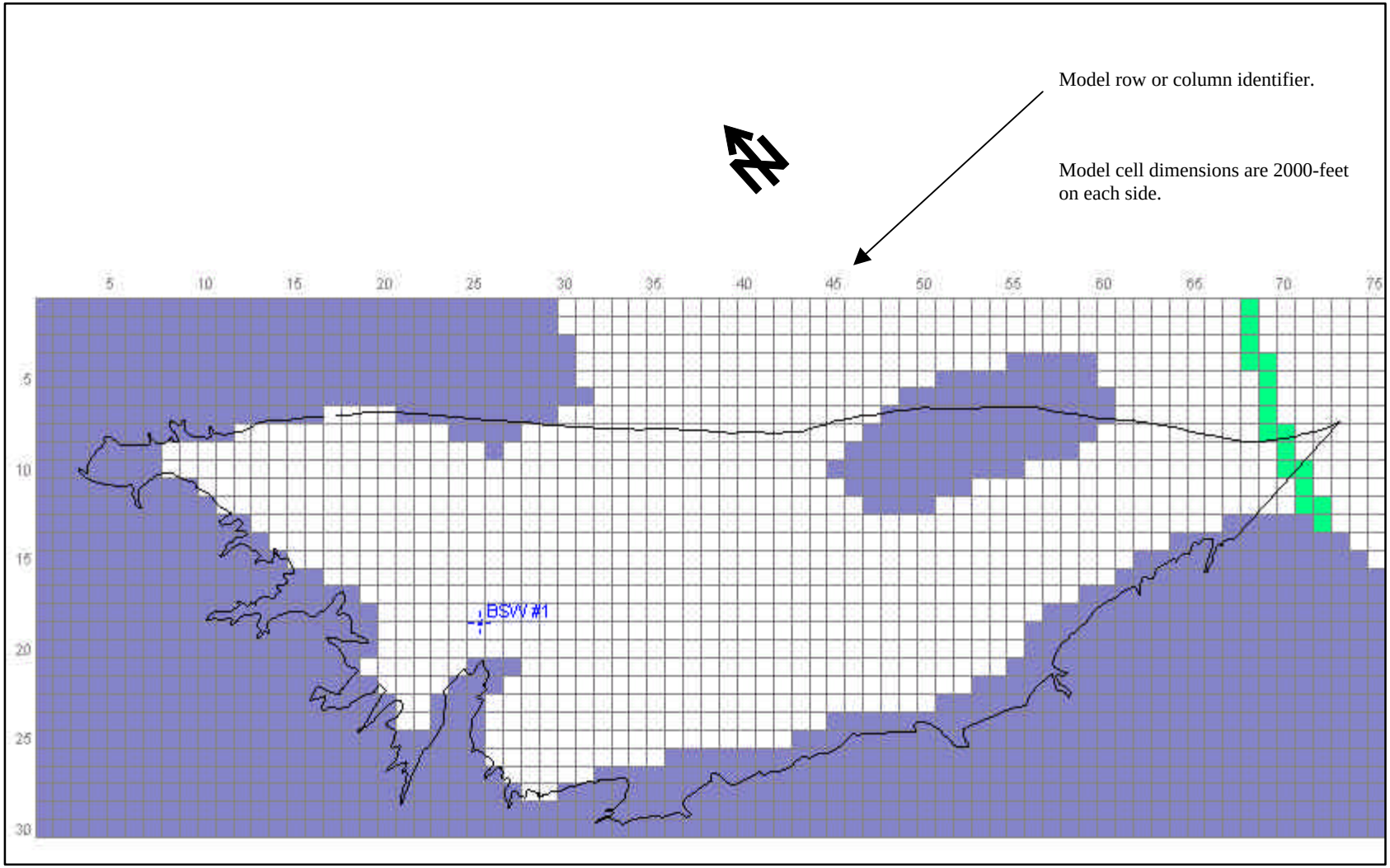


Figure 51. Transient water level targets in model layer 2.

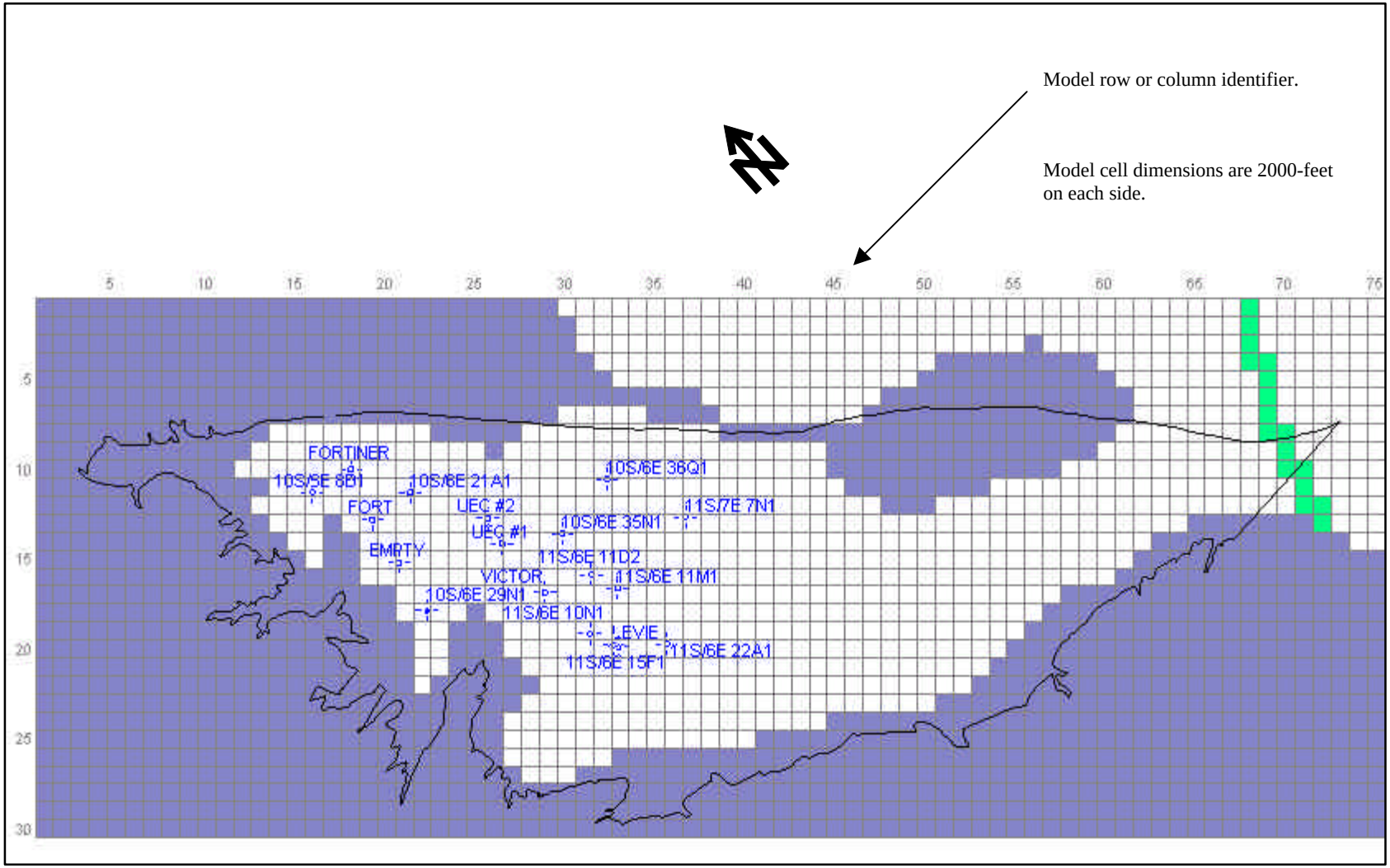


Figure 52. Transient water level targets in model layer 3.

primary (north and north-central) portion of the aquifer system. Water level elevation measurements and well hydrographs are generally sparse in the middle and south portions of the aquifer system. This is most likely due to the shallow presence of the Palm Spring Formation, which has limited water-bearing properties relative to those soils in the north and north-central portion of Borrego Valley.

Fortiner. The Fortiner well is located in the northwest end of the aquifer system (Figure 52), near the northern extent of agriculture in Borrego Valley. The period of water level measurements recorded for this well range from May, 1983 to December, 2000, and includes 68 observations (Figure 53). Model calculated water levels for this cell range from approximately 570-feet a.m.s.l. (late 1940s) to approximately 430-feet a.m.s.l. in 2000, a 140 foot water level decline (Figure 53). In general, the quality of calibration at this well is good.

10S/6E 21A1. The well 10S/6E 21A1 is located in the middle of the northern portion of the aquifer system (Figure 52), in the middle of the primary agricultural production area. The period of water level measurements recorded for the well range from June, 1952 to April 1994, and includes 307 observations (Figure 54). Model calculated water levels for this cell range from approximately 552-feet a.m.s.l. (late 1940s) to approximately 432-feet a.m.s.l. in 2000, representing a decline of approximately 120 feet (Figure 54). The quality of calibration at this well is good.

10S/6E 29N1. The well 10S/6E 29N1 is located near the western edge of the aquifer system (Figure 52), in the vicinity of the Borrego Palm Creek recharge area. The period of water level measurements recorded for the well range from November, 1952 to March, 1971, and includes 38 observations (Figure 55). Due to its proximity to the Borrego Palm Creek recharge area, the model predicts water levels which fluctuate dramatically in response to different yearly recharge fluxes. This is not well represented in the observed data. Model calculated water levels for this cell range from approximately 640-feet a.m.s.l. (1981) to approximately 440-feet a.m.s.l. in 2000 (Figure 55). For the period 1945 through 2000, water levels have declined from approximately 555-feet a.m.s.l. to approximately 440-feet a.m.s.l., representing an overall decline of 115 feet for that period. The quality of calibration at this well is fair.

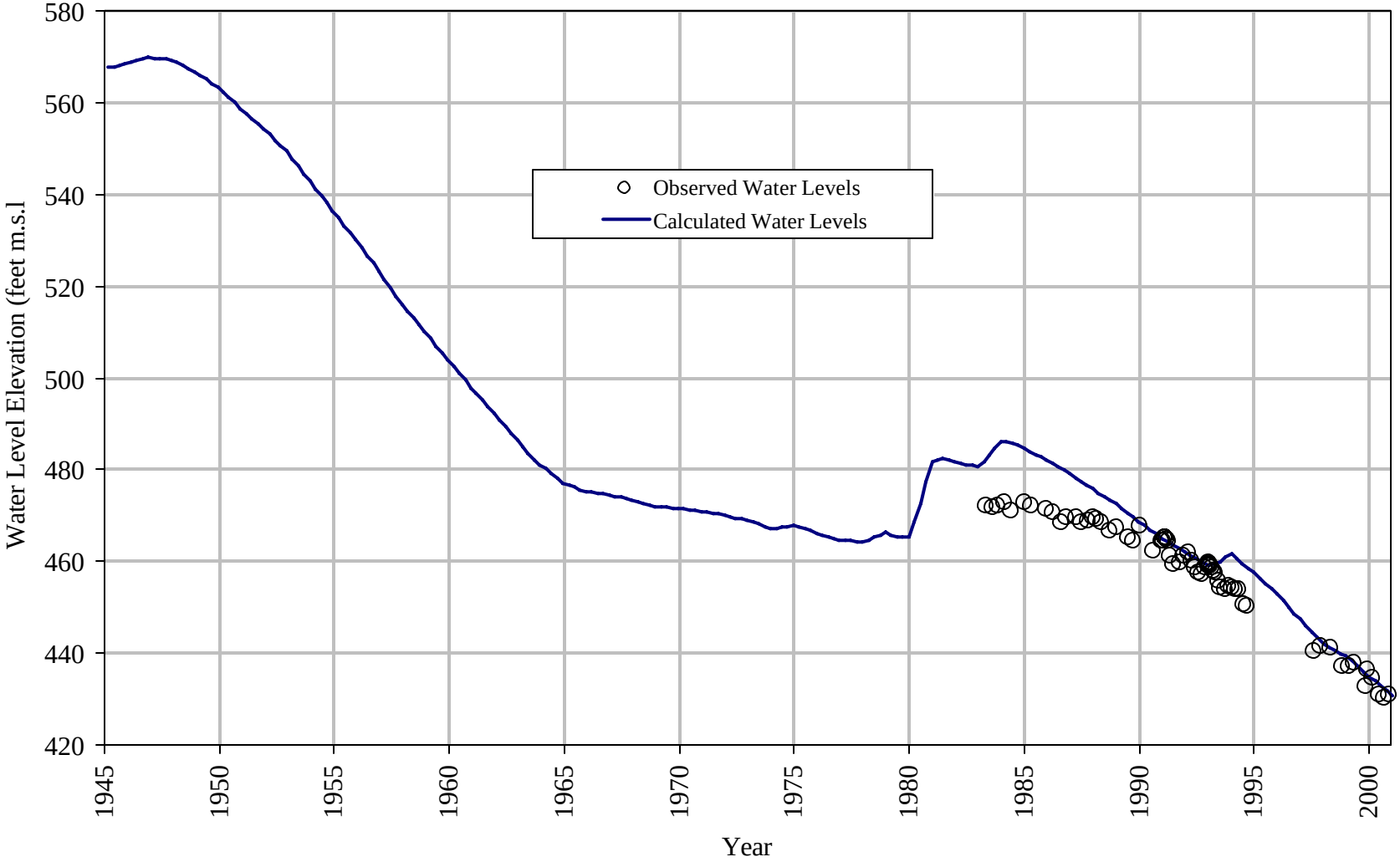


Figure 53. Water level elevation hydrograph well - Fortiner (transient model).

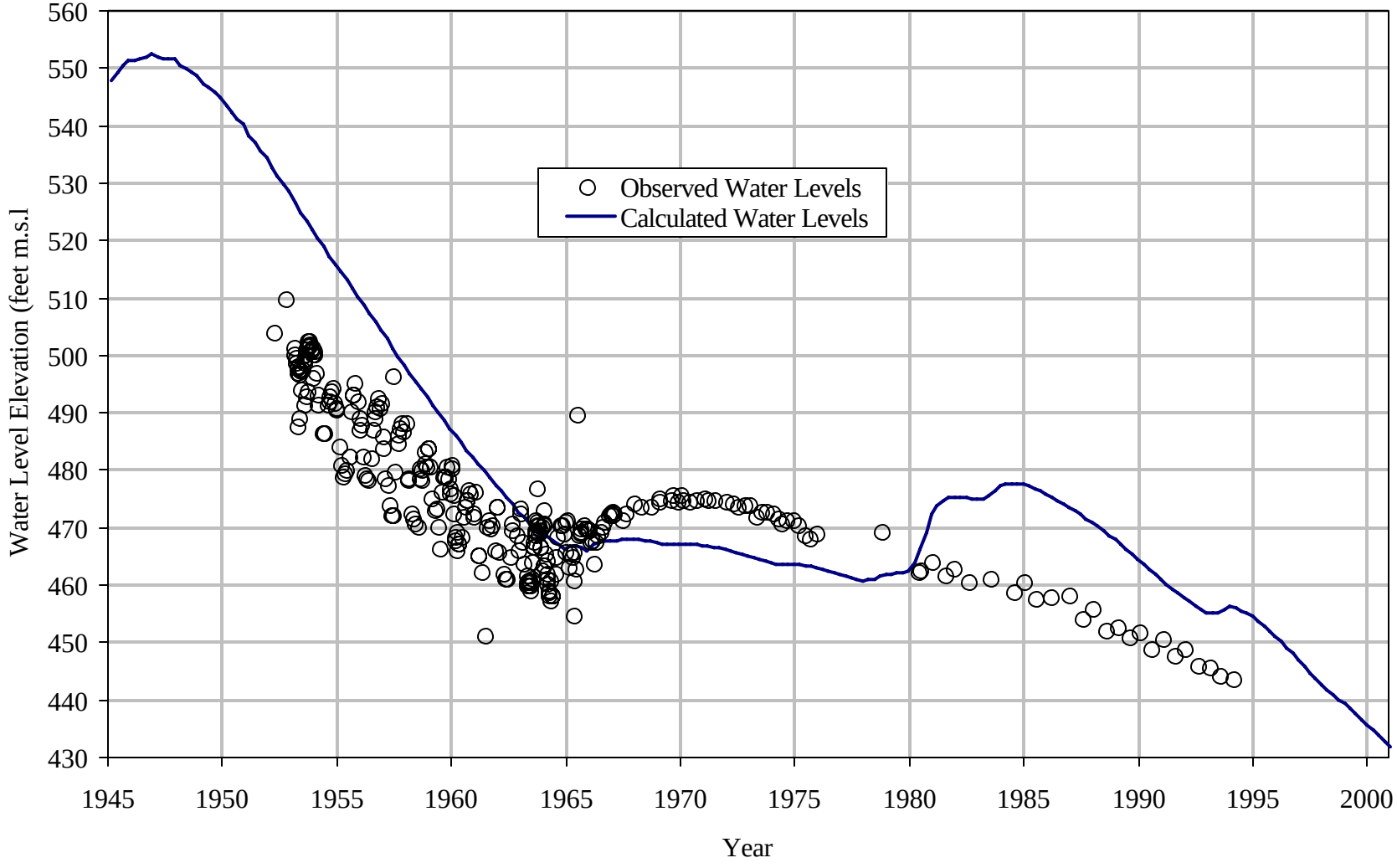


Figure 54. Water level elevation hydrograph well - 10S/6E 21A1 (transient model).

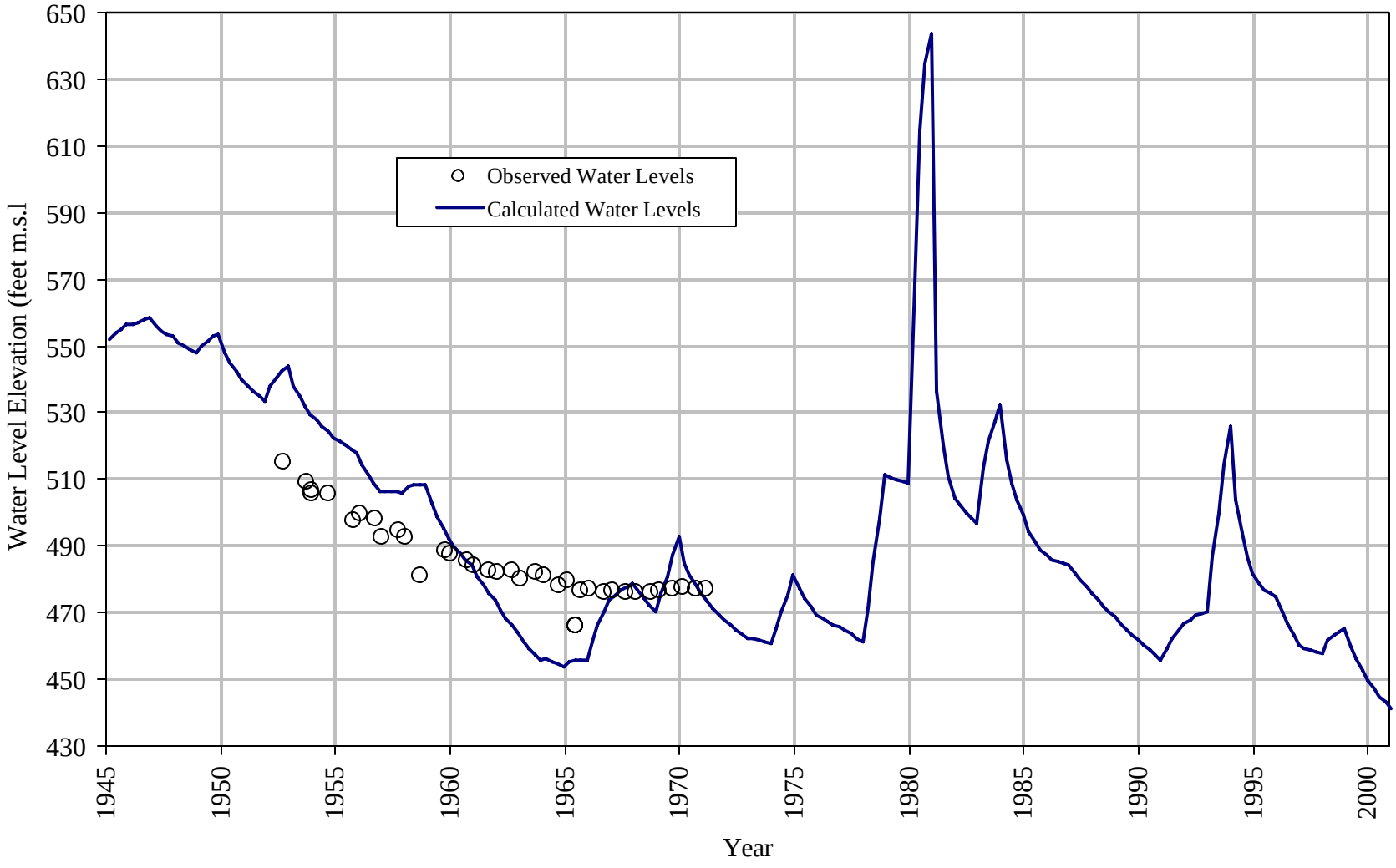


Figure 55. Water level elevation hydrograph well - 10S/6E 29N1 (transient model).

10S/6E 36Q1. The well 10S/6E 36Q1 is located near the middle of the aquifer system (Figure 52), south of the area with intensive agriculture. The period of water level measurements recorded for the well range from April, 1951 to August, 1980, and includes 97 observations (Figure 56). Water level observations for this well may include both pumping and non-pumping measurements. Model calculated water levels for the cell which represents this well in the model range from approximately 488-feet a.m.s.l. (late 1940s) to 438-feet a.m.s.l. in 2000, representing an overall decline of 50 feet at this location in the aquifer system (Figure 56). The quality of calibration at this well is fair to good.

11S/6E 11M1. The well 11S/6E 11M1 is located near the middle of the aquifer system (Figure 52), on the edge of the historic discharge area, in the vicinity of native phreatophytes. The period of water level measurements recorded for the well range from February 1953 to August, 1981, and includes 40 observations (Figure 57). Water level observations for this well indicate that the conceptual water budget and determination of fluxes may not represent this localized area well during the period between 1950 and 1960. Model calculated water levels for the cell which represents this well in the model range from approximately 472-feet a.m.s.l. (late 1940s) to 435-feet a.m.s.l. in 2000, representing an overall decline of approximately 37 feet (Figure 57). The quality of calibration at this well is fair to good.

11S/6E 15F1. The well 11S/6E 15F1 is located in the west side of the aquifer system (Figure 52), south of the City of Borrego Springs, in the vicinity of water level depressions interpreted by Moyle (1982) in 1965 and 1980. The period of water level measurements recorded for the well range from January, 1950 to August 1965, and includes 13 observations (Figure 58). Model calculated water levels for the cell which represents this well in the model range from approximately 486-feet a.m.s.l. (late 1940's) to 429-feet a.m.s.l. in 2000, representing an overall decline of approximately 57 feet (Figure 58). The quality of calibration at this well is good.

11S/7E 7N1. The well 11S/7E 7N1 is located in the south end of the main portion of the aquifer system (north of where the Palm Spring Formation crops out), in an historic groundwater discharge area, currently occupied by native phreatophytes (Figure 52). The

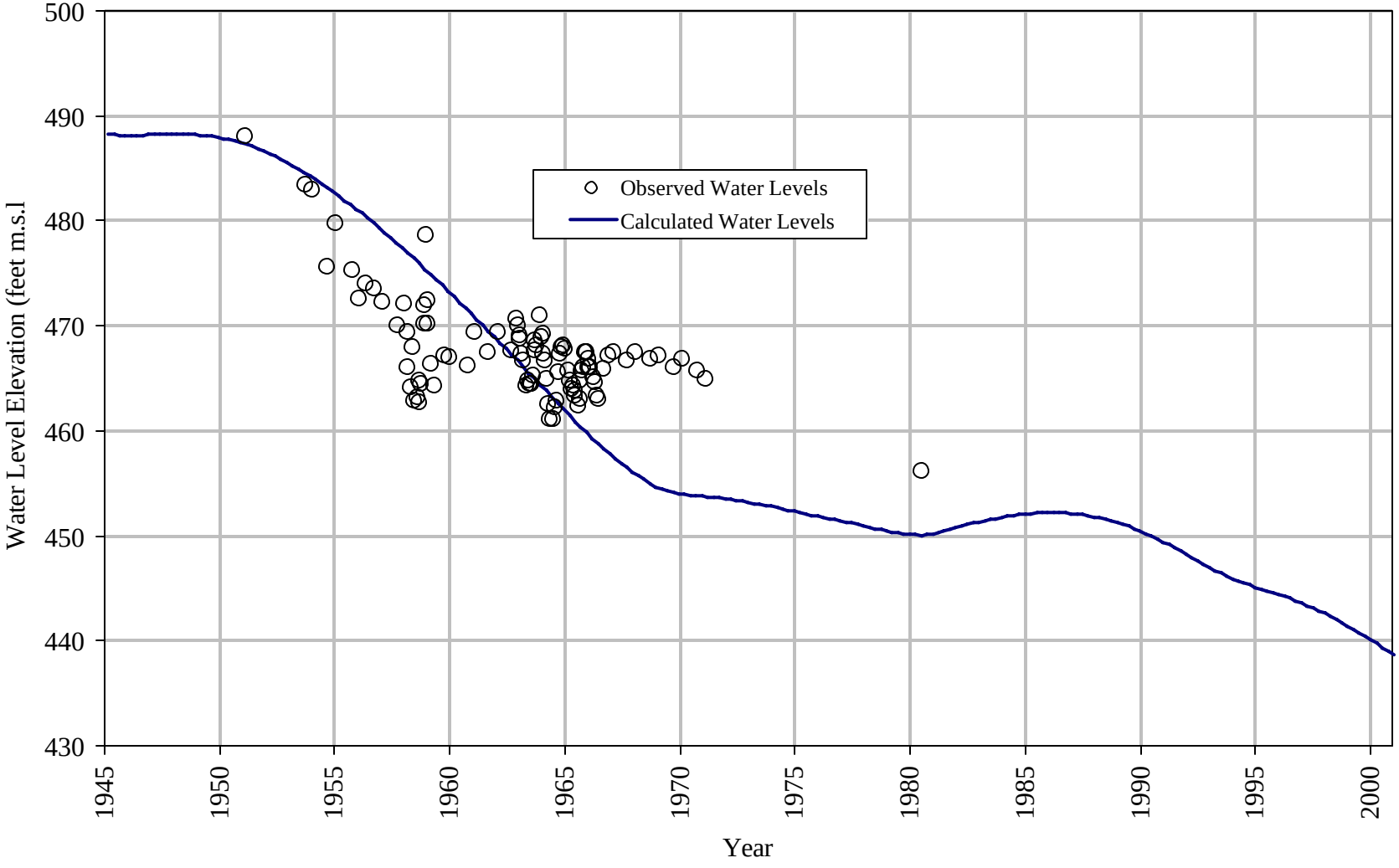


Figure 56. Water level elevation hydrograph well - 10S/6E 36Q1 (transient model).

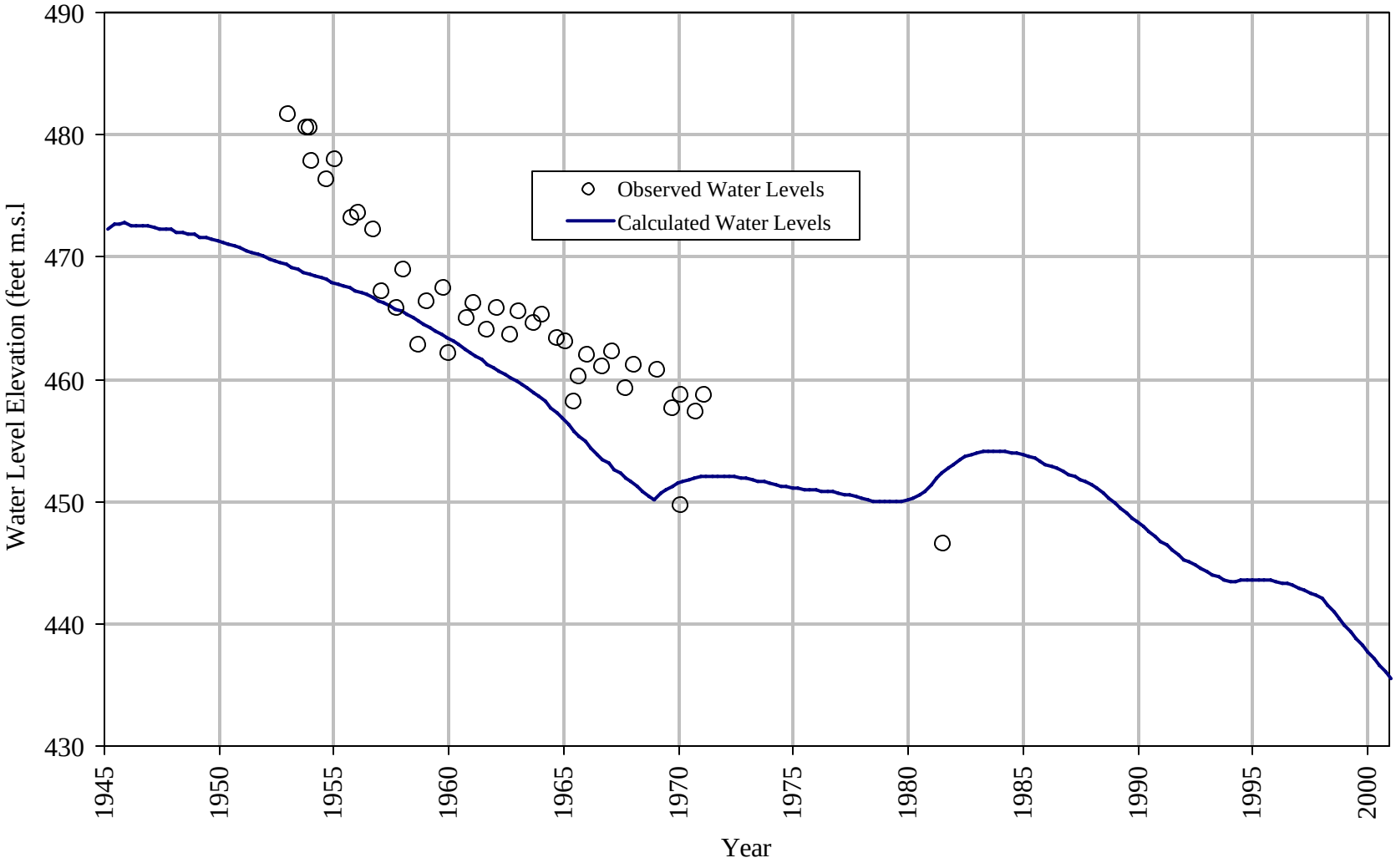


Figure 57. Water level elevation hydrograph well - 11S/6E 11M1 (transient model).

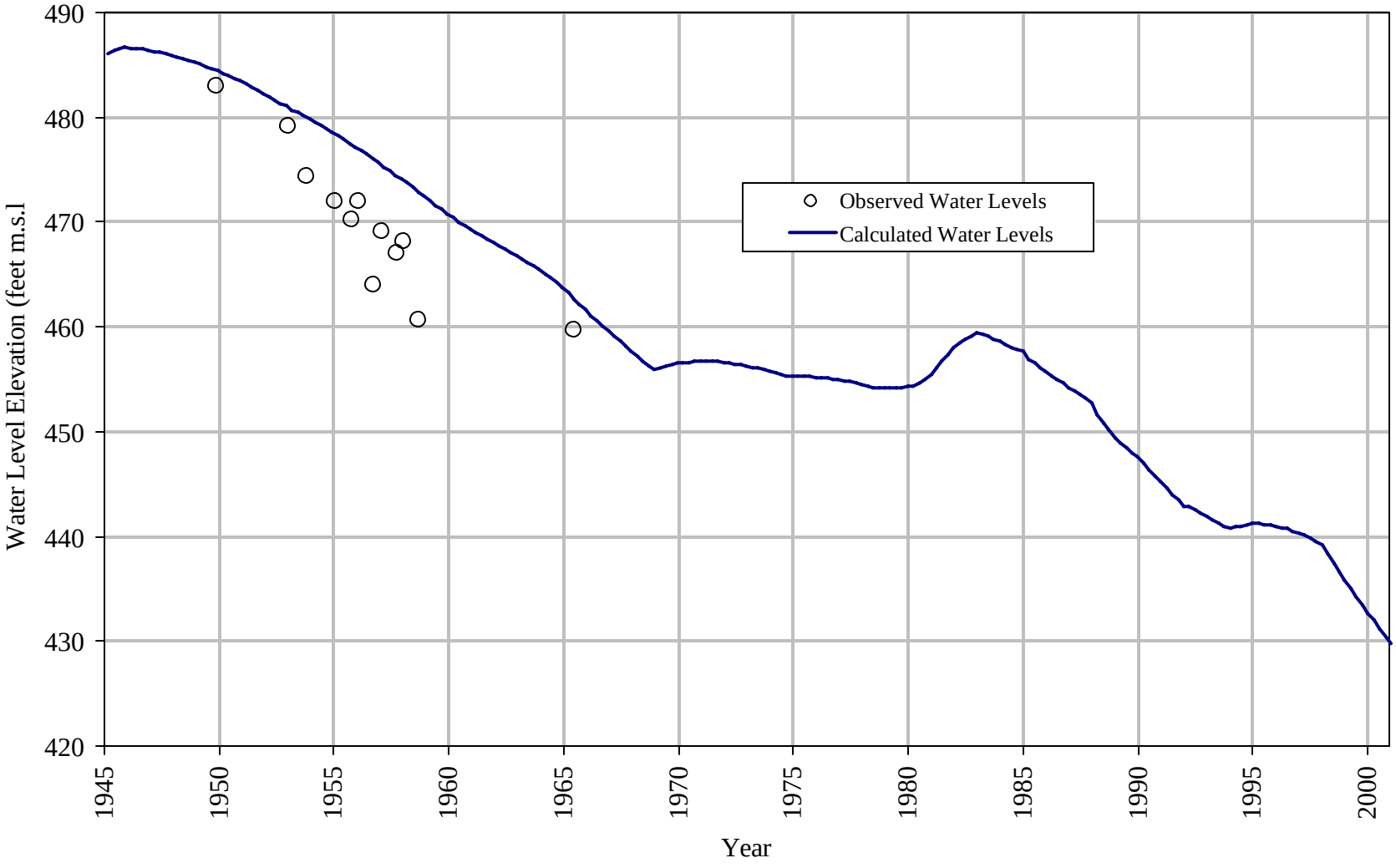


Figure 58. Water level elevation hydrograph well - 11S/6E 15F1 (transient model).

period of water level measurements recorded for this well range from November, 1953 to October, 1965, and includes 24 observations (Figure 59). Observed water levels in this well appear to include both pumping and non-pumping measurements. Because water levels calculated by the model represent water levels throughout the cell, the non-pumping observations (higher elevations) should be used as a basis for quantitative comparison with the model. The pumping observations should be used to qualitatively compare the observed (pumping) water level trends with those predicted by the model. Model calculated water levels for the cell which represents this well in the model range from approximately 457-feet a.m.s.l. (late 1940s) to 440-feet a.m.s.l. in 2000, representing an overall decline of approximately 17 feet (Figure 59).

Other Calibration Targets. Calibration quality at the other 13 targets ranged from poor to good. Poor or fair quality calibration with the other 13 targets is expected to be a function of (1) conceptual model uncertainty, (2) localized water budget inaccuracies, or (3) uncertainties with the target well including potentially dormant conditions (e.g., subject to biofouling or chemical precipitation), or uncertainties regarding the construction details or physical condition of the well (e.g., deteriorated or collapsed well screens).

Hydrographs of observed and model calculated water level elevations for all 20 of the transient target wells are provided in Figures 115 through 134 (Appendix D).

Distribution of Hydraulic Head

Previous authors have provided contour maps of water level elevation in Borrego Valley for several periods of time (Moyle, 1982). These maps are based on human interpretation of water level distributions. Their interpretations of the groundwater flow system are similar, in a gross sense, to the conceptual model used for this study, and no attempts were made to reproduce that work. The numerical model calculated distribution of water levels is presented below for the periods with “known flux” data (aerial photo years), as well as for the year 2000. In addition, the model predicted distribution of hydraulic head for periods coincident with, or close to those periods utilized by Moyle to construct his water level contour maps are discussed

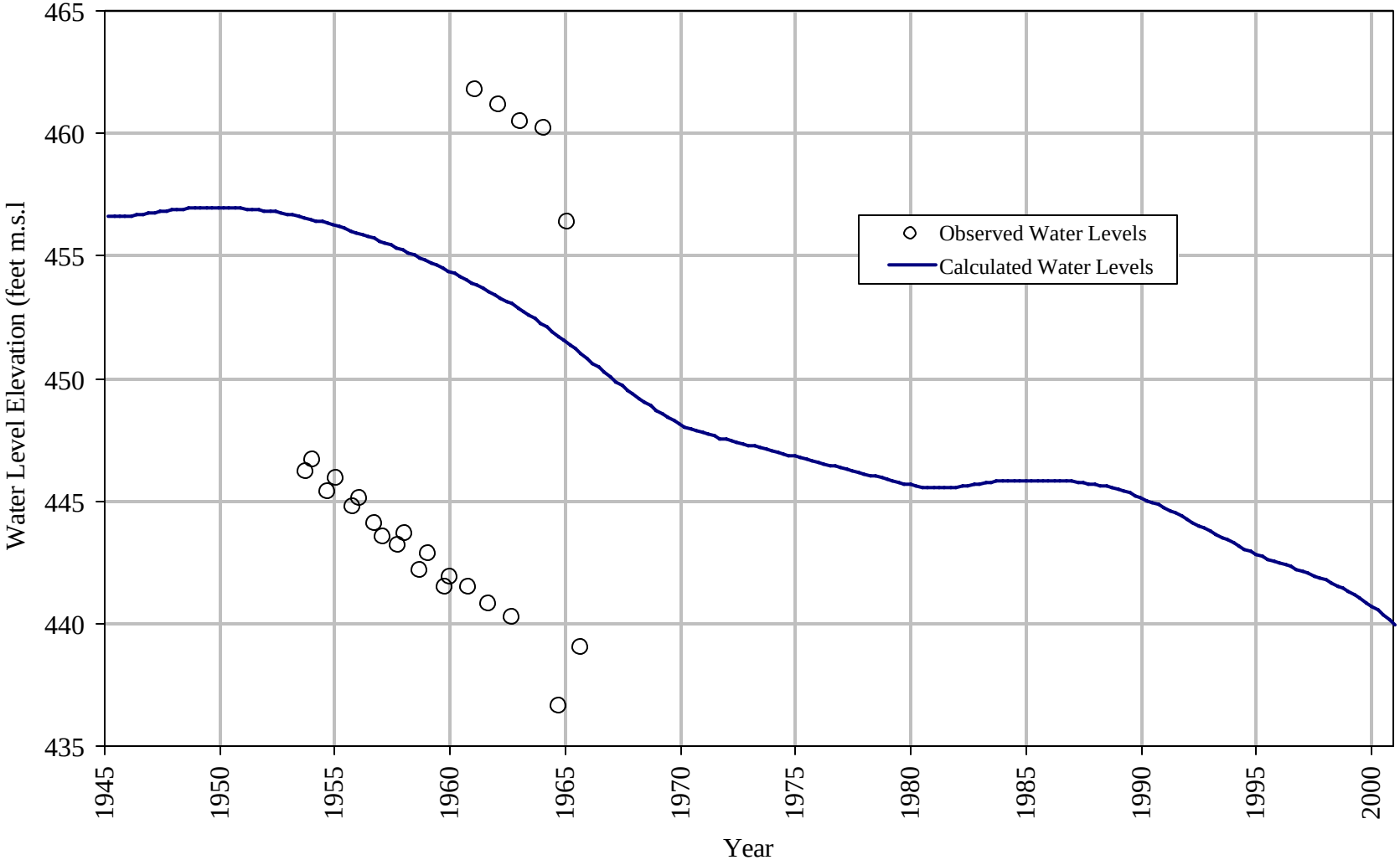


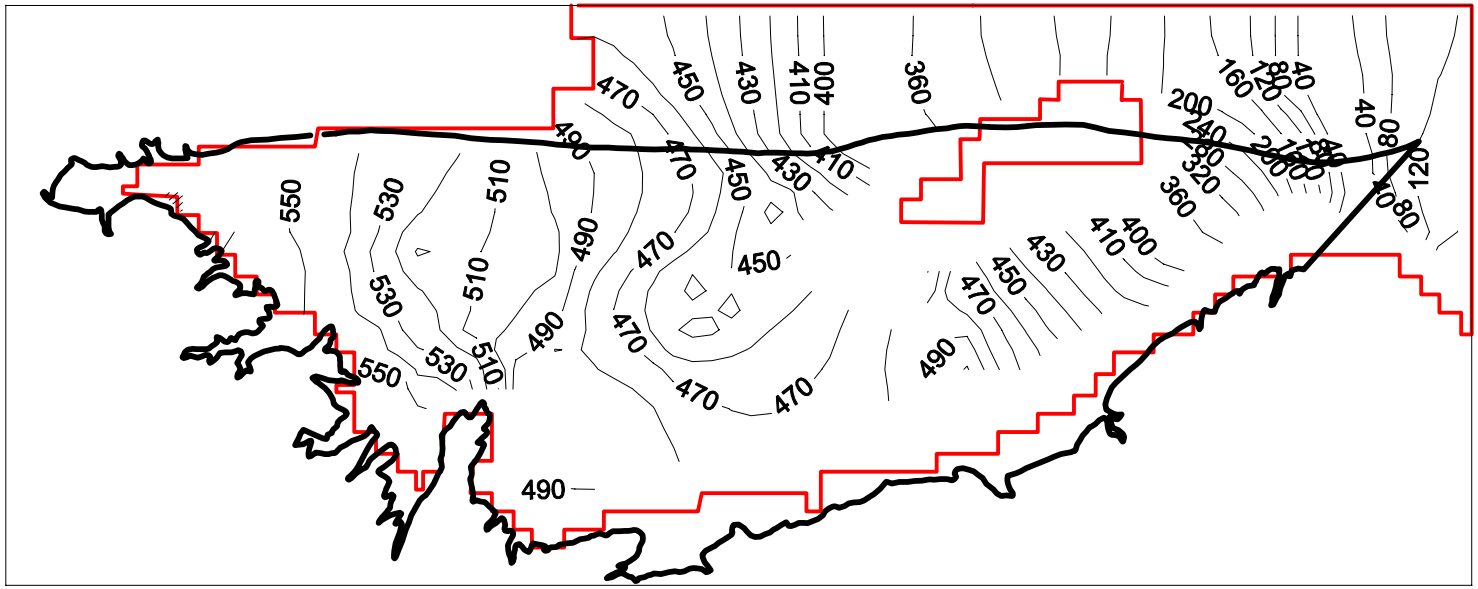
Figure 59. Water level elevation hydrograph well - 11S/7E 7N1 (transient model).

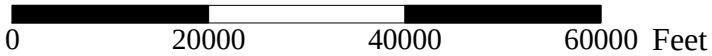
1953 conditions. The model indicates groundwater elevations range from approximately 552 - feet a.m.s.l. in the northern portion of the basin (4 foot decline since 1945), to approximately 450-feet a.m.s.l. in the vicinity of Borrego Sink in 1953 (Figure 60). Water level elevations in the vicinity of San Felipe Creek are approximately 472-feet a.m.s.l., and decline to 0 at the groundwater discharge area near Ocotillo Wells. The model indicates that groundwater flows from the primary recharge areas located at the margins of the basin toward the central portion of the basin in the vicinity of Borrego Sink (an historic groundwater discharge area). Some groundwater flows northeast of the sink, paralleling Coyote Creek Fault and the Borrego Badlands. In addition, groundwater from the vicinity of San Felipe Creek occurs in both the northern direction (toward the main portion of the aquifer system, and in the east-southeast direction toward Lower Borrego Valley.

The model predicted distribution of hydraulic head in 1953 is similar to that predicted by Moyle for the same period (Figure 20). A notable exception is that the model does not predict the discrete cones of water level depression in several areas, as interpreted by Moyle. This may be a function of hand-contouring inaccuracies (Moyle's map does not show the data points utilized), or may be a function of the coarse nature of the grid system utilized by the model (e.g., 2000 foot long by 2000 foot wide cells).

1959 conditions. The model indicates groundwater elevations range from approximately 512-feet a.m.s.l. in the northern portion of the basin (40 foot decline since 1953), to approximately 440-feet a.m.s.l. in the vicinity of Borrego Sink (10 foot decline since 1953) in 1959 (Figure 61). Groundwater flow directions are as those described for 1953, with the exception of a cone of water level depression in the north-central portion of the basin (area of intense agriculture) in 1959. Previous authors did not present contour maps for this period.

1963 conditions. The model indicate groundwater elevations range from approximately 488-feet a.m.s.l. in the northern portion of the basin (24 foot decline since 1959), to approximately 440-feet a.m.s.l. in the vicinity of Borrego Sink (stabilized water levels) in 1963 (Figure 62). Water level elevations in the vicinity of San Felipe Creek are approximately 468-feet a.m.s.l., and decline to zero in Lower Borrego Valley. The overall groundwater flow directions are as previously described. Water level elevations have

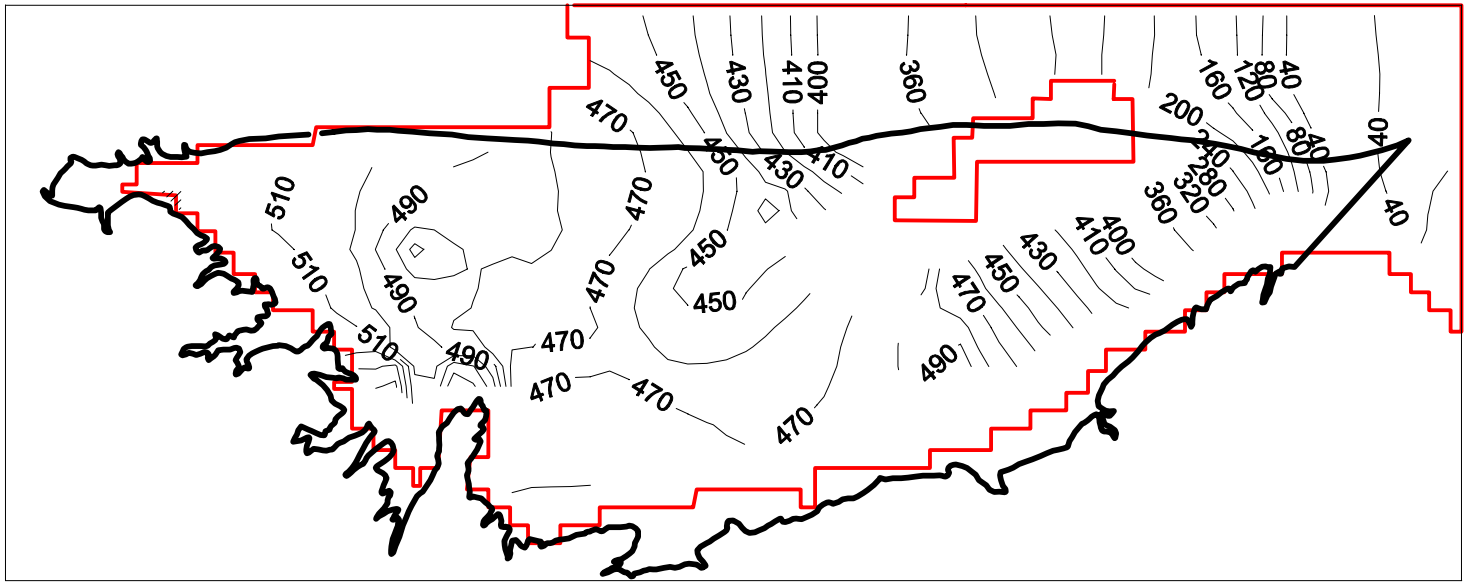




Notes: 1) Water Table Contoured in Model Layer 1 - May be unsaturated in some areas
2) Contour Interval is 40-feet when water table elevation is < 400-feet m.s.l.
3) Contour interval is 10-feet when water table elevation is > 400-feet m.s.l.

Borrego Valley Groundwater Study
1953 Water Table Elevation
Borrego Valley

Figure 60. 1953 water table elevation.

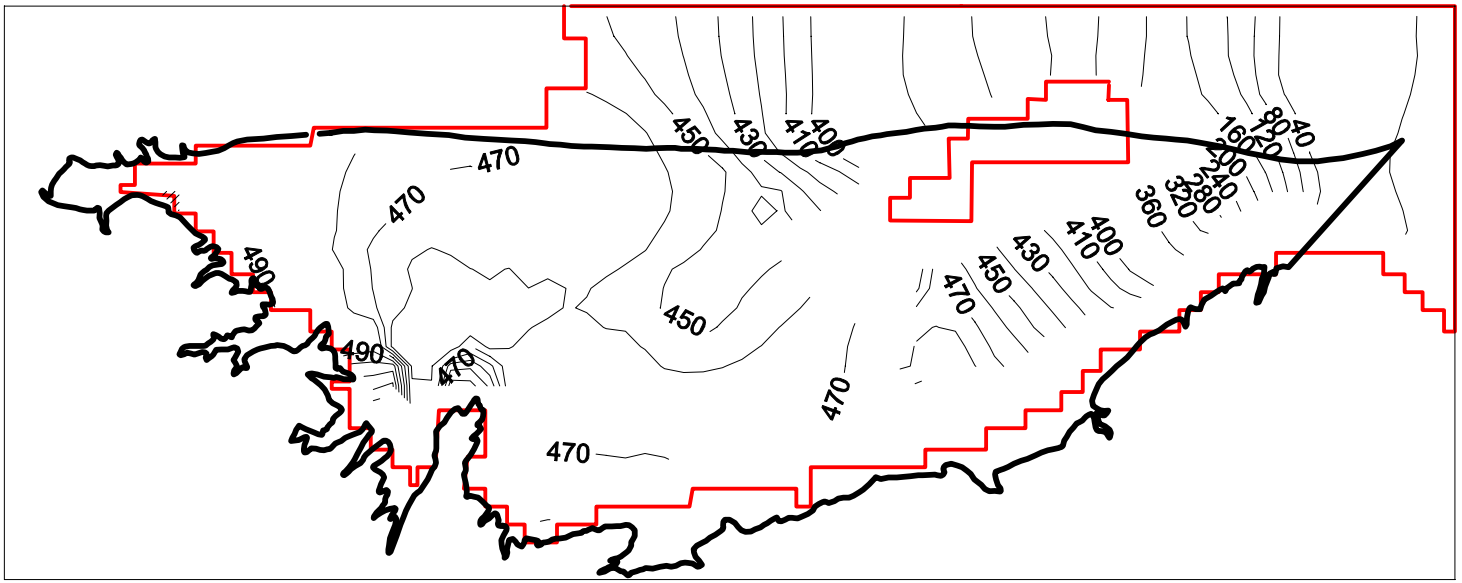


0 20000 40000 60000 Feet

Notes: 1) Water Table Contoured in Model Layer 1 - May be unsaturated in some areas
2) Contour Interval is 40-feet when water table elevation is < 400-feet m.s.l.
3) Contour interval is 10-feet when water table elevation is > 400-feet m.s.l.

Borrego Valley Groundwater Study
1959 Water Table Elevation
Borrego Valley

Figure 61. 1959 water table elevation.



0 20000 40000 60000 Feet

Notes: 1) Water Table Contoured in Model Layer 1 - May be unsaturated in some areas
2) Contour Interval is 40-feet when water table elevation is < 400-feet m.s.l.
3) Contour interval is 10-feet when water table elevation is > 400-feet m.s.l.

Borrego Valley Groundwater Study
1963 Water Table Elevation
Borrego Valley

Figure 62. 1963 water table elevation.

substantially declined relative to 1945 conditions, due to the imbalance between groundwater discharge and recharge.

Model predicted water level conditions in 1963 are grossly similar to those interpreted by Moyle for 1965 (Figure 21). The model accurately represents the area of extreme water level declines in the north-central portion of the basin, attributable to extensive groundwater pumping in support of table grape production during this period. The model does not predict the focused cones of water level depression indicated by Moyle, but rather more widespread water level declines. This may be due to contouring inaccuracies, or the structure of the model as previously described.

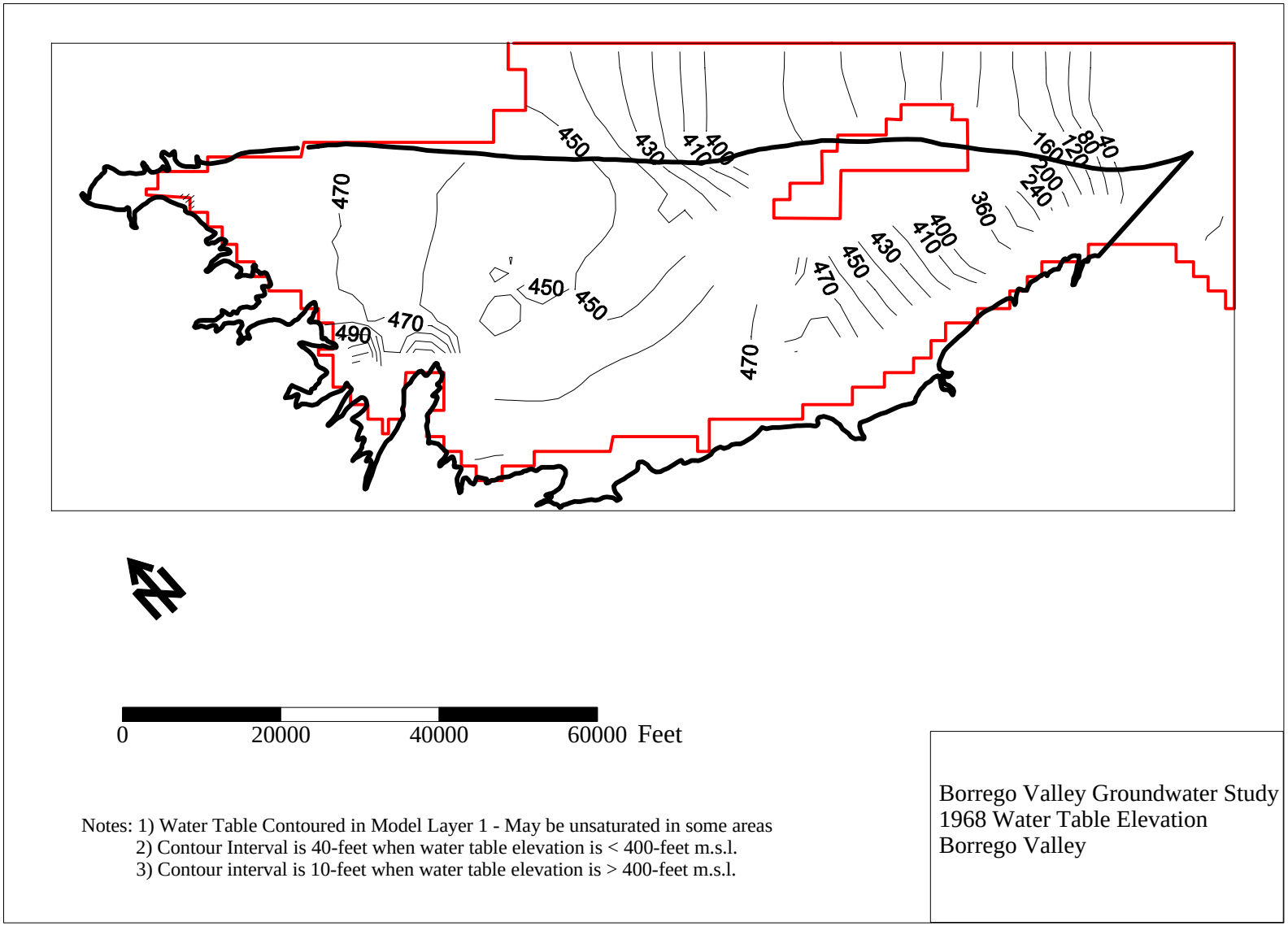
The distribution of water levels predicted by the USGS model during this period was not reported by Mitten et al. (1988).

1968 conditions. The model indicates groundwater elevations and flow directions are closely similar to those described for 1963 (Figure 63). This similarity indicates a stabilization of drawdown, and less net groundwater loss from the aquifer system. This stabilization is also represented in hydrographs from wells in the valley with data from this period (Figures 115 through 134, Appendix D).

1979 conditions. The model indicates that widespread drawdown of water levels in the aquifer system has resumed between 1968 and 1979 (Figure 64). Resumption of drawdown in the aquifer system during this period is also seen in several of the target hydrographs (Figures 115 through 134). Water level elevations range from 470-feet a.m.s.l. in the northern portion of the basin (18 foot decline since 1968), to approximately 440-feet a.m.s.l. in the vicinity of Borrego Sink (Figure 64). Water level elevations in the vicinity of San Felipe Creek are approximately 458-feet a.m.s.l. and decline to zero in Lower Borrego Valley.

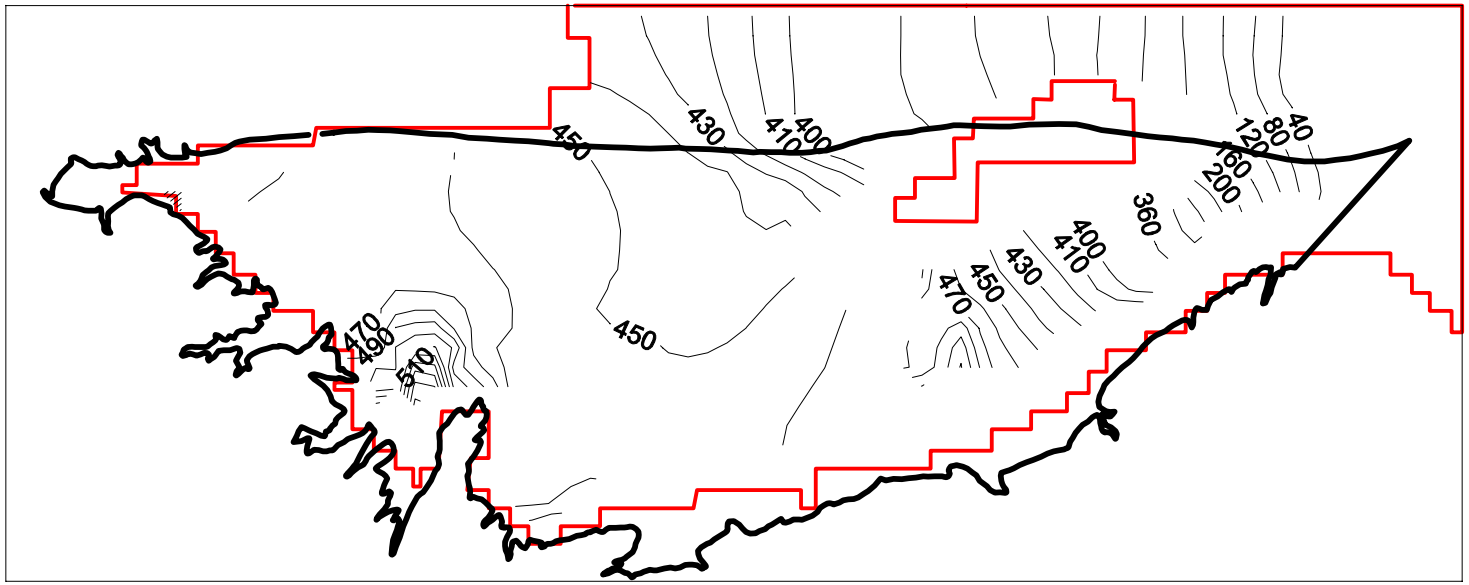
Model predicted water level conditions in 1979 are again, grossly similar to those predicted by Moyle for 1980 (Figure 22). As with previous comparisons, the model predicts widespread water level declines, whereas Moyle's contour maps show localized cones of depression.

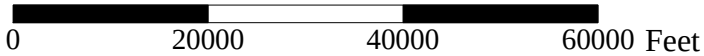
The distribution of water levels predicted by the USGS transient-state model only grossly resembles that conceptualized by Moyle and predicted by the current model (Figure



Notes: 1) Water Table Contoured in Model Layer 1 - May be unsaturated in some areas
2) Contour Interval is 40-feet when water table elevation is < 400-feet m.s.l.
3) Contour interval is 10-feet when water table elevation is > 400-feet m.s.l.

Figure 63. 1968 water table elevation.





Notes: 1) Water Table Contoured in Model Layer 1 - May be unsaturated in some areas
2) Contour Interval is 40-feet when water table elevation is < 400-feet m.s.l.
3) Contour interval is 10-feet when water table elevation is > 400-feet m.s.l.

Borrego Valley Groundwater Study
1979 Water Table Elevation
Borrego Valley

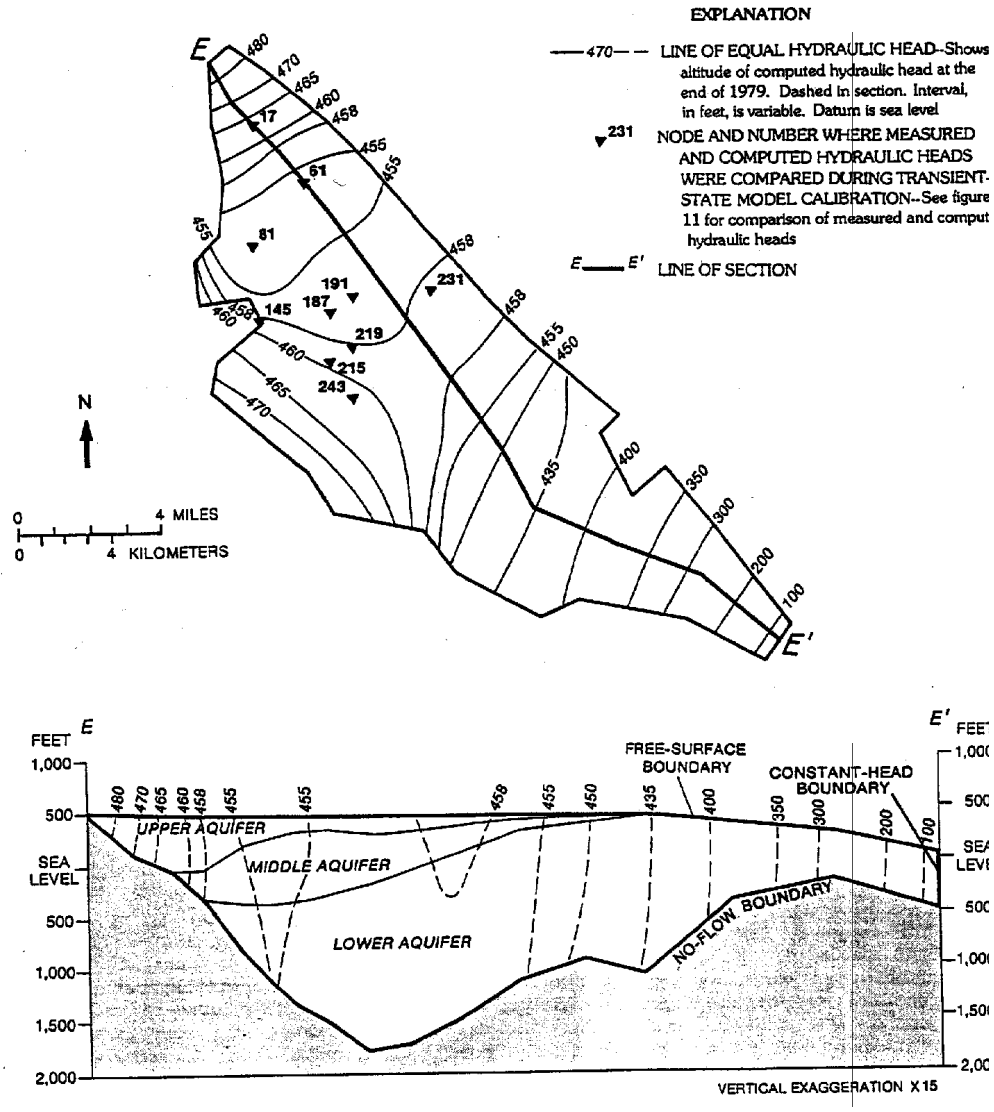
Figure 64. 1979 water table elevation.

65). Groundwater recharge in the vicinity of San Felipe Creek is not well represented. Shortcomings in the USGS transient-state model are probably attributable to the coarse nature of the model, translation of the conceptual model to the numerical model, and poor quantification of the basin-wide water-balance. Deficiencies in the basin-wide water balance directly impact the accuracy of storativity for each hydrogeologic unit estimated by the USGS based on their transient-state model.

1992 conditions. The model indicates an aquifer-system wide decline in water levels of approximately 10 feet, between 1979 and 1993 (Figure 66). The water table ranges in elevation from 464-feet a.m.s.l., in the northern portion of the basin, to approximately 435-feet a.m.s.l. in the vicinity of Borrego Sink. Water level elevations in the vicinity of San Felipe Creek are approximately 444-feet a.m.s.l., and decline to 0 in Lower Borrego Valley. The model predicted groundwater flow system is grossly similar to that of previously described years. One significant difference is that groundwater consumption by phreatophytes in the vicinity of Borrego Sink is no longer a major source of discharge from the groundwater system. Groundwater elevation contours are no longer influenced by evapotranspiration. Existing phreatophytes may be subsisting on surface water or recharge water in the vadose zone. The rate of water level declines appear to increase after about 1987, as indicated in several target hydrographs (Figures 115 through 134, Appendix D), and is related to imbalances between groundwater discharge and recharge, as well as the geometry of the aquifer system.

1995 conditions. The model indicates that groundwater elevations at the end of 1995 are similar to those of 1992 (Figure 67). This indicates a decrease or stabilization in the rate of drawdown, and less net groundwater loss from the basin.

2000 conditions. The model indicates that the rate of water level decline has increased relative to 1995 conditions, with widespread drawdown occurring throughout most of the central and northern portions of the basin (Figure 68). The water table ranges in elevation from 434-feet a.m.s.l. in the northern portion of the basin, to approximately 435-feet a.m.s.l. in the vicinity of Borrego Sink. Water level elevations in the vicinity of San Felipe Creek are approximately 486-feet a.m.s.l., and decline to 0 in Lower Borrego Valley.

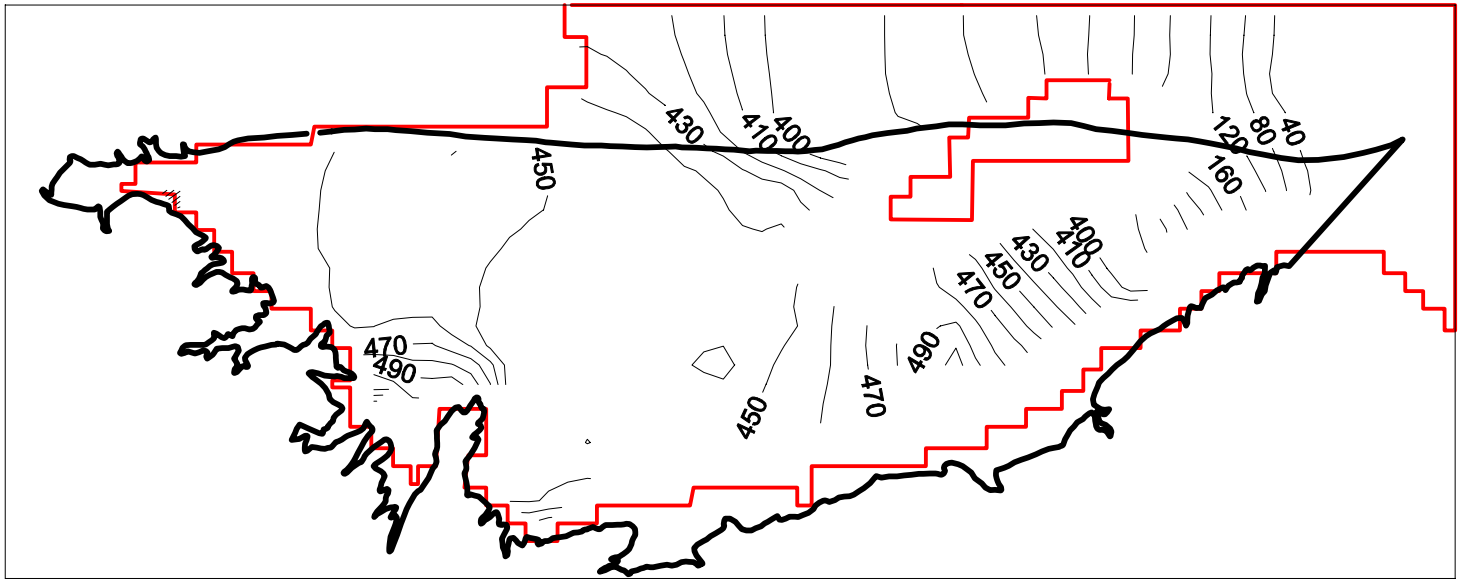


After Miller et al. (1988)

FIGURE 10. Computed hydraulic head at the end of 1979 and location c s where measured water levels were used for the transient-state model calibration.

20

Figure 65. USGS modeled water level elevations (feet m.s.l.) – 1979.

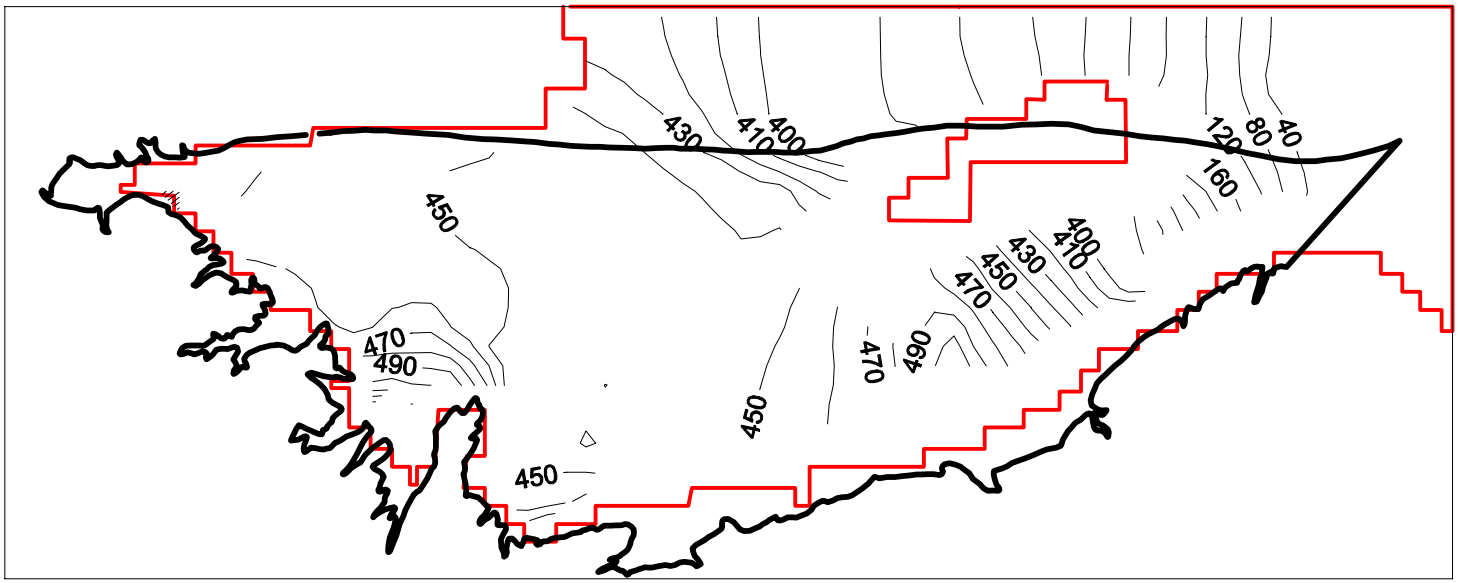


0 20000 40000 60000 Feet

Notes: 1) Water Table Contoured in Model Layer 1 - May be unsaturated in some areas
2) Contour Interval is 40-feet when water table elevation is < 400-feet m.s.l.
3) Contour interval is 10-feet when water table elevation is > 400-feet m.s.l.

Borrego Valley Groundwater Study
1992 Water Table Elevation
Borrego Valley

Figure 66. 1992 water table elevation.

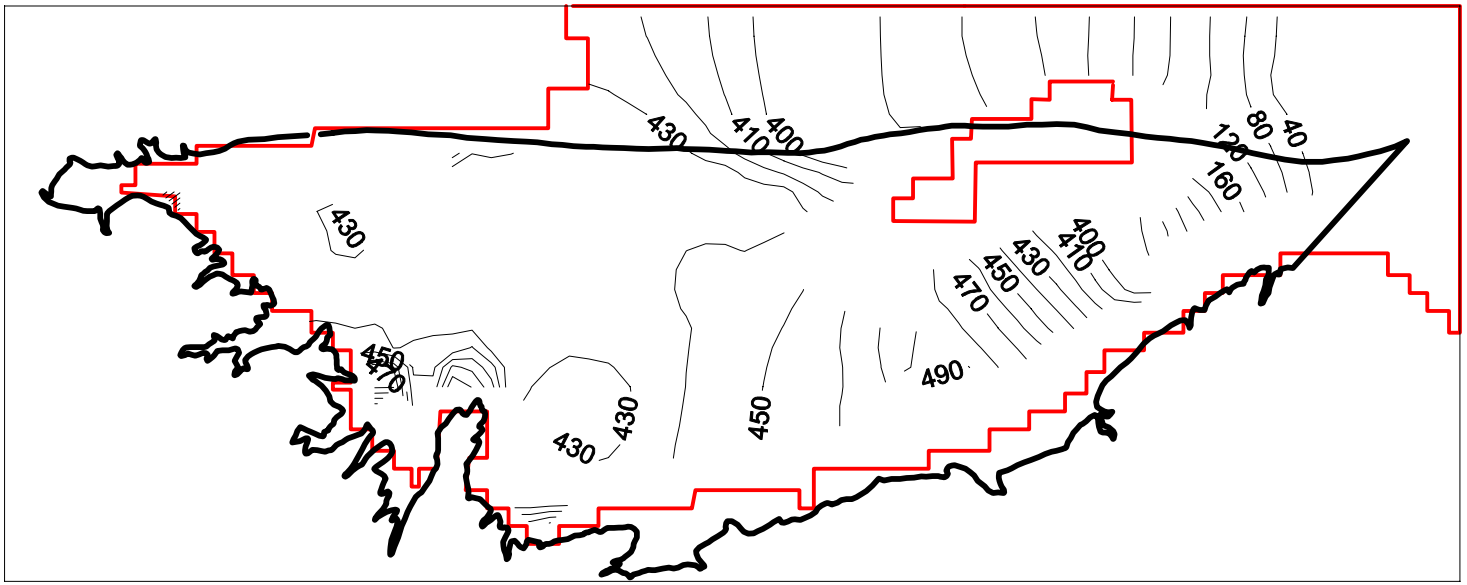


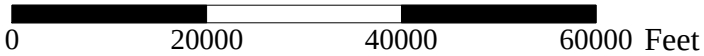
0 20000 40000 60000 Feet

Notes: 1) Water Table Contoured in Model Layer 1 - May be unsaturated in some areas
2) Contour Interval is 40-feet when water table elevation is < 400-feet m.s.l.
3) Contour interval is 10-feet when water table elevation is > 400-feet m.s.l.

Borrego Valley Groundwater Study
1995 Water Table Elevation
Borrego Valley

Figure 67. 1995 water table elevation.





Notes: 1) Water Table Contoured in Model Layer 1 - May be unsaturated in some areas
2) Contour Interval is 40-feet when water table elevation is < 400-feet m.s.l.
3) Contour interval is 10-feet when water table elevation is > 400-feet m.s.l.

Borrego Valley Groundwater Study
2000 Water Table Elevation
Borrego Valley

Figure 68. 2000 water table elevation.

Distribution of Hydraulic Conductivity and Transmissivity

Steady-state calibration of the current model was used to refine estimates of hydraulic conductivity for soil textures in the model (Table 6). The transmissivity of soil textures in each model layer is the product of hydraulic conductivity and layer thickness. The resulting distribution of transmissivity for model layers 1 through 4 are provided in Figures 69, 70, 71, and 72, respectively. The transmissivity of model layers 5 and 6 are both 1700 ft^2 per day (constant hydraulic conductivity and thickness).

Transmissivity was estimated at four wells from aquifer testing, as part of a related study (Netto, 2001). The locations of the four wells tested in Borrego Valley are provided in Figure 73. The following is a brief description of the transmissivity calculated by the model for each of the four wells relative to the estimated transmissivity, based on aquifer testing:

Stan Bauer Well #1

Stan Bauer's Well #1 is located in the northern portion of the basin (Figure 73). The well is perforated from 370 to 390, 410 to 530, 550 to 690, and 710 to 730 feet below land surface, which correspond to layer 3 of the numerical model. Calculated transmissivity based on aquifer testing at this well was approximately 102,000 ft^2 per day (Netto, 2001). This is consistent with layer 3 transmissivity in this area of approximately 100,000 ft^2 per day (Figure 71).

Borrego Springs Water Company Well #5

Borrego Springs Water Company Well #5 is near the middle of the basin (Figure 73), in the vicinity of the Roadrunner Golf Course. The well is perforated from 520 to 570 and 590 to 640 feet below land surface, which correspond to layer 3 of the numerical model. Calculated transmissivity based on aquifer testing at this well was approximately 1,700 ft^2 per day (Netto, 2001). This is consistent with layer 3 transmissivity in this area of between 1,000 and 2,000 ft^2 per day (Figure 71).

Borrego Water District Well #1

Borrego Water District Well #1 is in the vicinity of Desert Lodge (Figure 73), just north of where the Palm Spring Formation crops out. The well is perforated from 180 to 230, 240 to 456, and 465 to 580 feet below land surface, and is completed almost entirely in the

Table 6

Summary of Steady-State Model Calibration Estimates of Hydraulic Conductivity

Model Layer (Hydrogeologic Unit)	Horizontal Hydraulic Conductivity (feet/day)	Vertical Hydraulic Conductivity (feet/day)
Model Layer 1 (Younger Alluvium)		
Gravel	178	18
Coarse Sand	32	3
Medium Sand	20	2
Fine Sand/Silt	7.5	0.75
Clay	0.1	0.1
Model Layer 2 (Intermediate-Age Alluvium)		
Gravel	178	18
Coarse Sand	32	3
Medium Sand	20	2
Fine Sand/Silt	7.5	0.75
Clay	0.1	0.1
Model Layer 3 (Older Alluvium)		
Gravel	178	18
Coarse Sand	32	3
Medium Sand	20	2
Fine Sand/Silt	7.5	0.75
Clay	0.1	0.1
Interbedded Clay and Gravel	9.5	0.95
Model Layers 4, 5, & 6 (Palm Spring Formation)		
All	1	1

Note: As estimated by model calibration

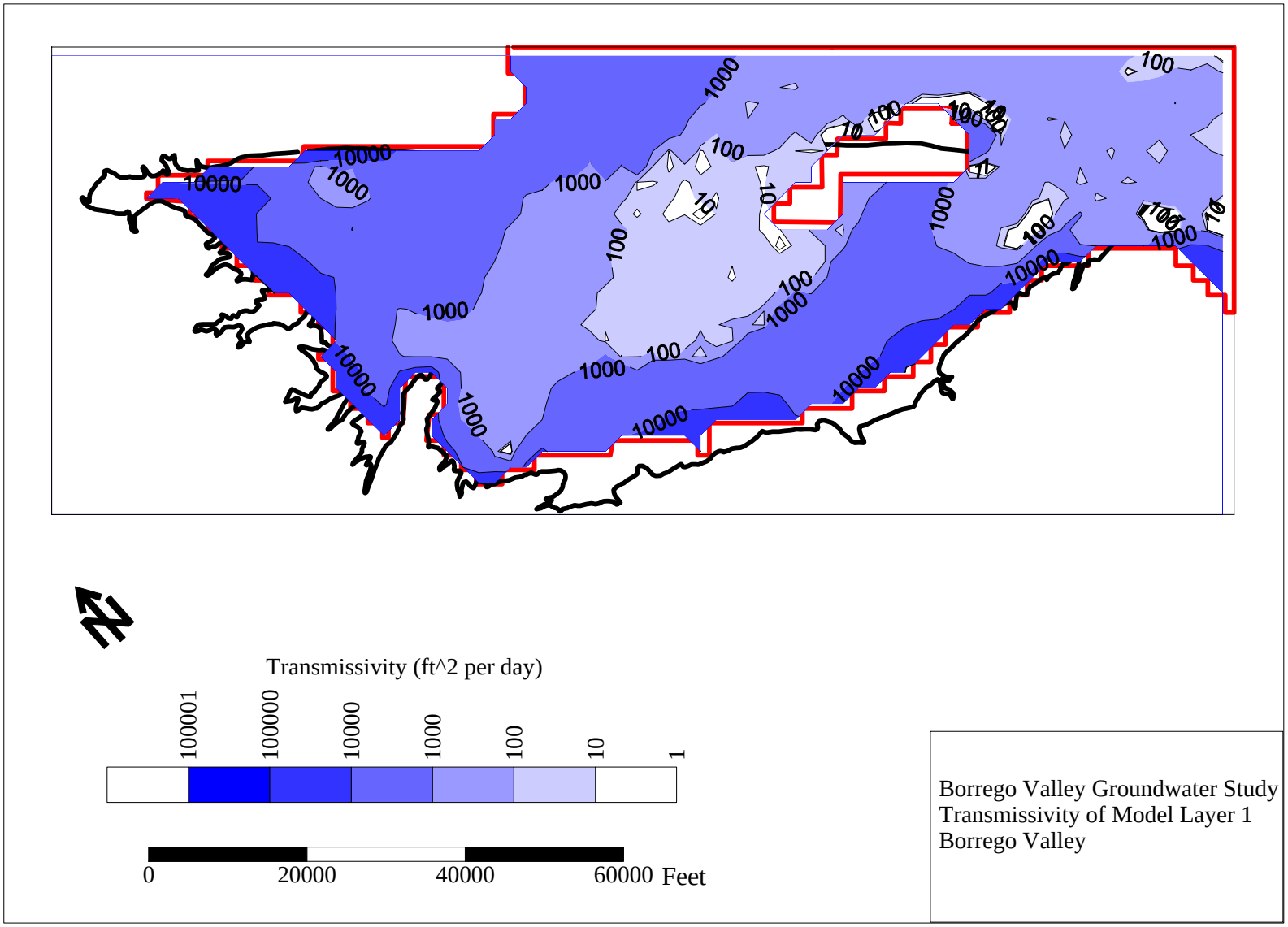


Figure 69. Transmissivity of model layer 1.

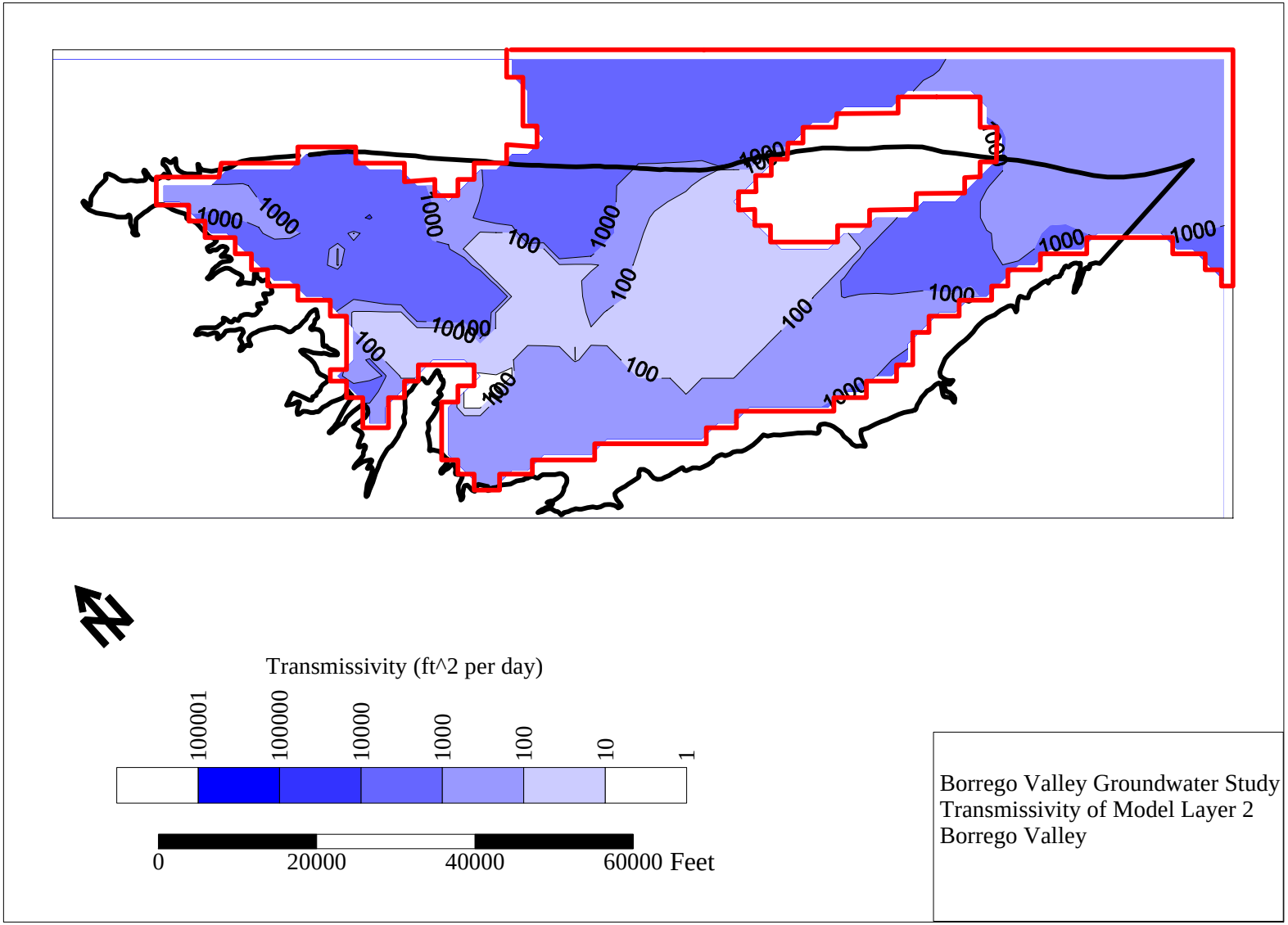


Figure 70. Transmissivity of model layer 2.

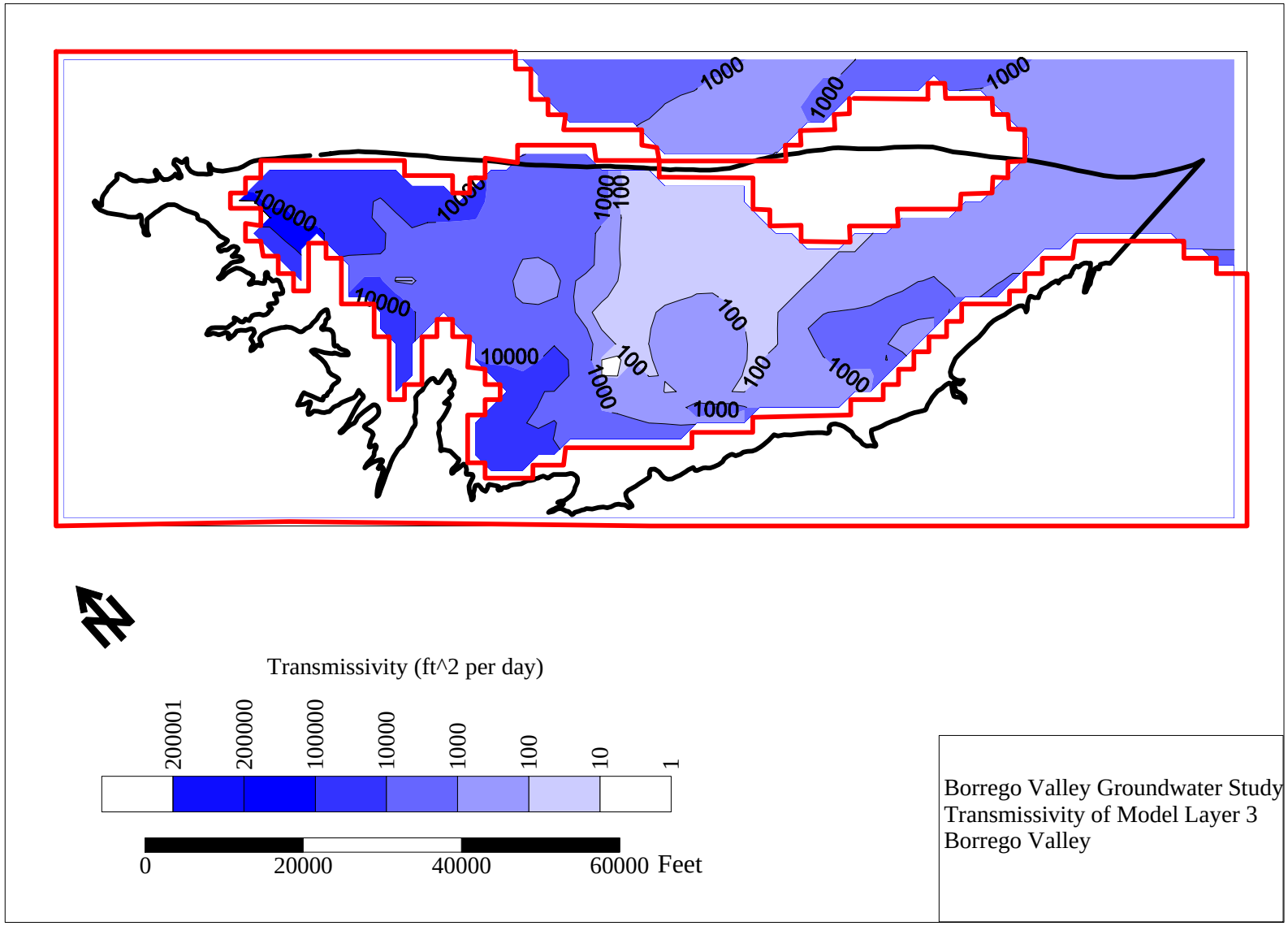


Figure 71. Transmissivity of model layer 3.

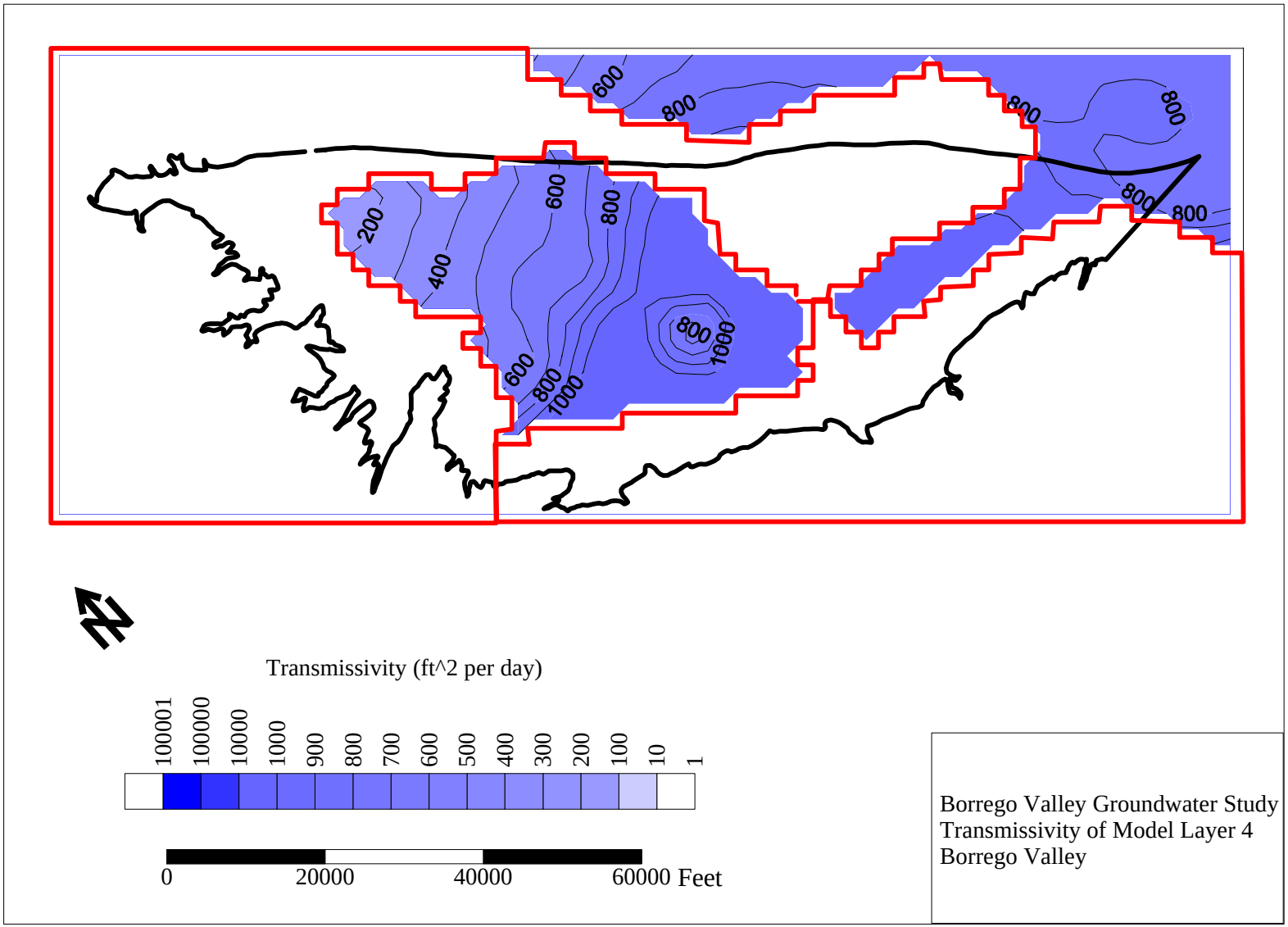


Figure 72. Transmissivity of model layer 4.

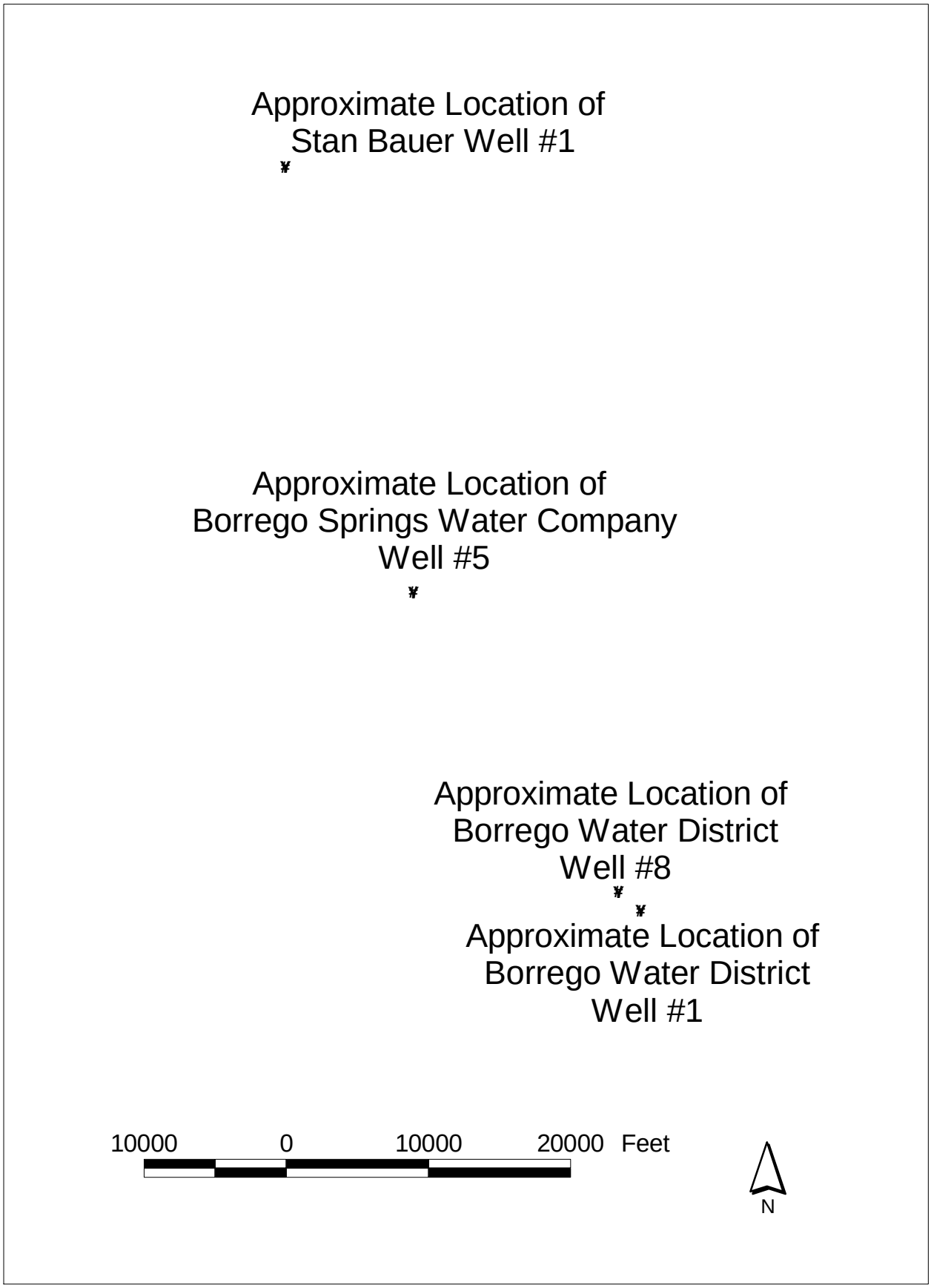


Figure 73. Location of aquifer testing wells.

Palm Spring Formation, with the upper screen intervals in model layer 2, and the lower interval in model layer 3. Calculated transmissivity based on aquifer testing at this well was approximately 735 ft^2 per day (Netto, 2001). This is consistent with layer 2 transmissivity in this area of between 100 and 1,000 ft^2 per day (Figure 70), and layer 3 transmissivity in this area of approximately 1,000 ft^2 per day (Figure 71).

Borrego Water District Well #8

Borrego Water District Well #8 is also in the vicinity of Desert Lodge (Figure 73), just north of where the Palm Spring Formation crops out. The well is perforated from 72 to 240, 260 to 312, and 312 to 830 feet below land surface, and is completed partially in reworked sediments within the trough of a localized syncline (the Sleepy Hollow Folds), but primarily in the Palm Spring Formation. A portion of the upper perforation interval is in model layers 1 and 2 (to 100-feet below ground surface). The balance of the first perforation interval, and the entire second perforation interval is in model layer 3. All of the third perforation interval is in model layer 4. Calculated transmissivity based on aquifer testing at this well was approximately 7,300 ft^2 per day, which is considerably higher than the modeled transmissivities of 100, 100, 250, and 800 ft^2 per day for layers 1, 2, 3, and 4, respectively (Figures 69 through 72). The measured higher transmissivity is interpreted to be related to the expected higher transmissivity of reworked alluvial fill in the trough of the syncline, described earlier. The aquifer tested transmissivity could be higher based on preferential groundwater production from that zone. The model is not sensitive to localized variations in geology or transmissivity, and does not represent them well.

In general, the model matches measured tranmissivities well. However, four aquifer tests are not a sufficient data base with which to compare the numerical model. Further aquifer testing and refinement of the conceptual and numerical models is warranted.

Comparison with USGS Estimates of Hydraulic Conductivity

Moyle's 1982 conceptual model of Borrego Valley estimated hydraulic conductivity for a three layer system. Layer 1, representing Moyle's younger alluvium was estimated to have a bulk horizontal hydraulic conductivity of 50 feet per day. Layer 2 (Moyle's older alluvium, and layer 3 (Moyle's continental deposits) were assigned horizontal hydraulic

conductivities of 5 and 1 feet per day, respectively. The 1988 USGS numerical model, based on Moyle's conceptual model, estimated horizontal hydraulic conductivities of 43 to 81 feet per day (layer 1), 5.8 feet per day (layer 2), and 1.4 feet per day (layer 3) (Mitten et al., 1988). Both Moyle's conceptual model and Mitten et al.'s numerical model assumed a vertical hydraulic conductivity of 1/100th of the horizontal hydraulic conductivity for each of the layers.

Based on the currently model, horizontal hydraulic conductivity estimates range from 0.1 feet per day (clay) to 178 feet per day (gravel), and are a function of soil texture (e.g., grain size). Vertical hydraulic conductivities estimated with the current model range from equal to and down to approximately 1/10th of the corresponding horizontal hydraulic conductivity for each of the soil textures. While the USGS estimates of bulk horizontal hydraulic conductivity for their three layers fall within the range estimated by the current model for various soil textures, model sensitivity analysis indicates that groundwater flow in Borrego Valley is relatively insensitive to variations in estimated horizontal hydraulic conductivity. Further, both the USGS model and the current model show very little sensitivity to variations in vertical hydraulic conductivity (Mitten et al., 1988). As described later, differences between the current model's estimate of specific yield and the USGS's estimate of specific yield are much more important than the noted differences in horizontal and vertical hydraulic conductivity.

Comparison with USGS Estimates of Transmissivity

Moyle (1982) applied his estimates of horizontal hydraulic conductivities to the thicknesses of each of his three conceptual layers to define the distribution of transmissivity in Borrego Valley. He estimated that transmissivity ranged from 0 ft^2 per day (bedrock) to approximately 34,000 ft^2 per day. Mitten et al. (1988) reported the transmissivity of layer 1 of their numerical model as ranging from 0 to 24,000 ft^2 per day, based on model calibration. Mitten et al. Considered layer 1 the principal water-bearing unit in Borrego Valley, and did not report transmissivity values for their layers 2 or 3.

The current model estimates transmissivity values ranging from approximately 1 to 100,000 ft^2 per day. In general, transmissivity estimated by the current model ranged from 1 to 2,000 ft^2 per day for finer soil textures (e.g., Palm Spring Formation and silts/clays), and

from 1,000 to 100,000 ft^2 per day for coarser soil textures (e.g., sands and gravels). Differences between the USGS estimates of transmissivity and the current estimates are attributable to two factors:

1. The USGS use of "bulk" aquifer properties for their conceptual and model layers versus the current model's use of discrete soil textures based on lithologies reported in driller's logs.
2. Differences in estimated aquifer geometry between the USGS models and the current model (e.g., definition of layers and defined layer thicknesses).

The estimates of hydraulic conductivity and transmissivity utilized by the current model are expected to be more reliable than previous estimates because they are based on actual aquifer tests (rather than specific capacity), and are distributed based on observed lithologies rather than as bulk parameters. However, as previously stated, predicted groundwater conditions in Borrego Valley are expected to be relatively insensitive to errors in estimated hydraulic conductivity (and resulting calculated transmissivity).

Distribution of Storativity

Based on transient-state modeling, new values of specific yield for different soil textures were estimated. Specific storage was not adjusted from the initial estimate because, relative to specific yield, the model is insensitive to it. A summary of storativity estimates for different soil textures, in each conceptual hydrogeologic unit was provided in Table 1 (Chapter III). Those storativity values were initial estimates, based on common text-book values. Although several aquifer tests were conducted in Borrego Valley, none of the wells tested had a suitable monitoring well close enough for monitoring and subsequent calculation of an aquifer storativity at that location. Storativity for each of the soil textures was estimated during transient-state modeling (Table 7). Further refinement of storativity values for each soil texture should be achieved with additional aquifer testing.

Comparison with USGS Estimates of Specific Yield and Specific Storage

Moyle (1982) utilized generalized average values of specific yield for his conceptual model of Borrego Valley. Moyle's estimates were 14%, 7%, and 3% for his conceptual layers 1, 2, and 3, respectively. Mitten et al. (1988) utilized Moyle's values of specific yield and an estimated specific storage of 1E-06 for both layers 2 and 3. Mitten et al. reported that

Table 7

Summary of Transient-State Model Calibration Estimates of Storativity

Model Layer (Hydrogeologic Unit)	Specific Yield (Percent)	Specific Storage (per foot of aquifer)
Model Layer 1 (Younger Alluvium)		
Gravel	20	0.000002
Coarse Sand	17	0.000002
Medium Sand	14	0.000002
Fine Sand/Silt	9	0.000002
Clay	2	0.000002
Model Layer 2 (Intermediate-Age Alluvium)		
Gravel	20	0.000002
Coarse Sand	17	0.000002
Medium Sand	14	0.000002
Fine Sand/Silt	9	0.000002
Clay	2	0.000002
Model Layer 3 (Older Alluvium)		
Gravel	20	0.000002
Coarse Sand	17	0.000002
Medium Sand	14	0.000002
Fine Sand/Silt	9	0.000002
Clay	2	0.000002
Interbedded Clay and Gravel	16.2	0.000002
Model Layers 4, 5, & 6 (Palm Spring Formation)		
All	7.5	0.000002

Note. As estimated by transient-state model calibration.

these values provided the best match between observed and modeled water levels for the period 1945 through 1980.

Observed water level conditions for the period 1945 through 2000 were used to estimate specific yield for each of the soil textures in the model (Table 7). Estimated values of specific yield ranged from 2% (clay) to 20% (gravel). The USGS bulk estimates of specific yield are lower than those predicted by calibration of the current model. These differences are attributable to one or both of two factors, as described below.

Aquifer Geometry and Conceptualization

As previously descirbed, the USGS utilized three homogeneous aquifer layers to translate the conceptual model by Moyle into the USGS numerical model. The current model implements a new conceptual geometry (e.g., deeper basin), four hydrogeologic units as opposed to three, and uses heterogeneous model layers to represent horizontally and vertically varying soil textures, based on driller's logs.

Aquifer Water Budget

The water budget calculated for the current model is significantly different from that utilized by the USGS in their model. The most important difference, which explains the relatively higher specific yields in the current model is the calculated cumulative net change in groundwater storage (Figure 74). Between 1945 and 1980, the USGS predicted a net depletion of groundwater in storage of approximately 238,000 acre-feet, while the current model predicts a depletion of over 380,000 acre-feet for the same period (Figure 74). The differences in net groundwater depletion between the current model and the USGS model are attributable to differences in calculated groundwater recharge, calculated underflow out of the aquifer at Lower Borrego Valley, and estimated net groundwater pumpage. The two models use similar values of groundwater discharge due to evapotranspiration of groundwater by native phreatophytes in the vicinity of Borrego Sink (Figure 75). The USGS used a constant value of 4,800 acre-feet per year to represent recharge to groundwater for their entire transient-state simulation period (1946 – 1980).

Simulated groundwater recharge in the current model ranged from approximately 700 to 51,000 acre-feet per year, and averaged 6,174 acre-feet per year. It represents surface water, bedrock, and underflow recharge to Borrego Valley (Figure 76). Simulated

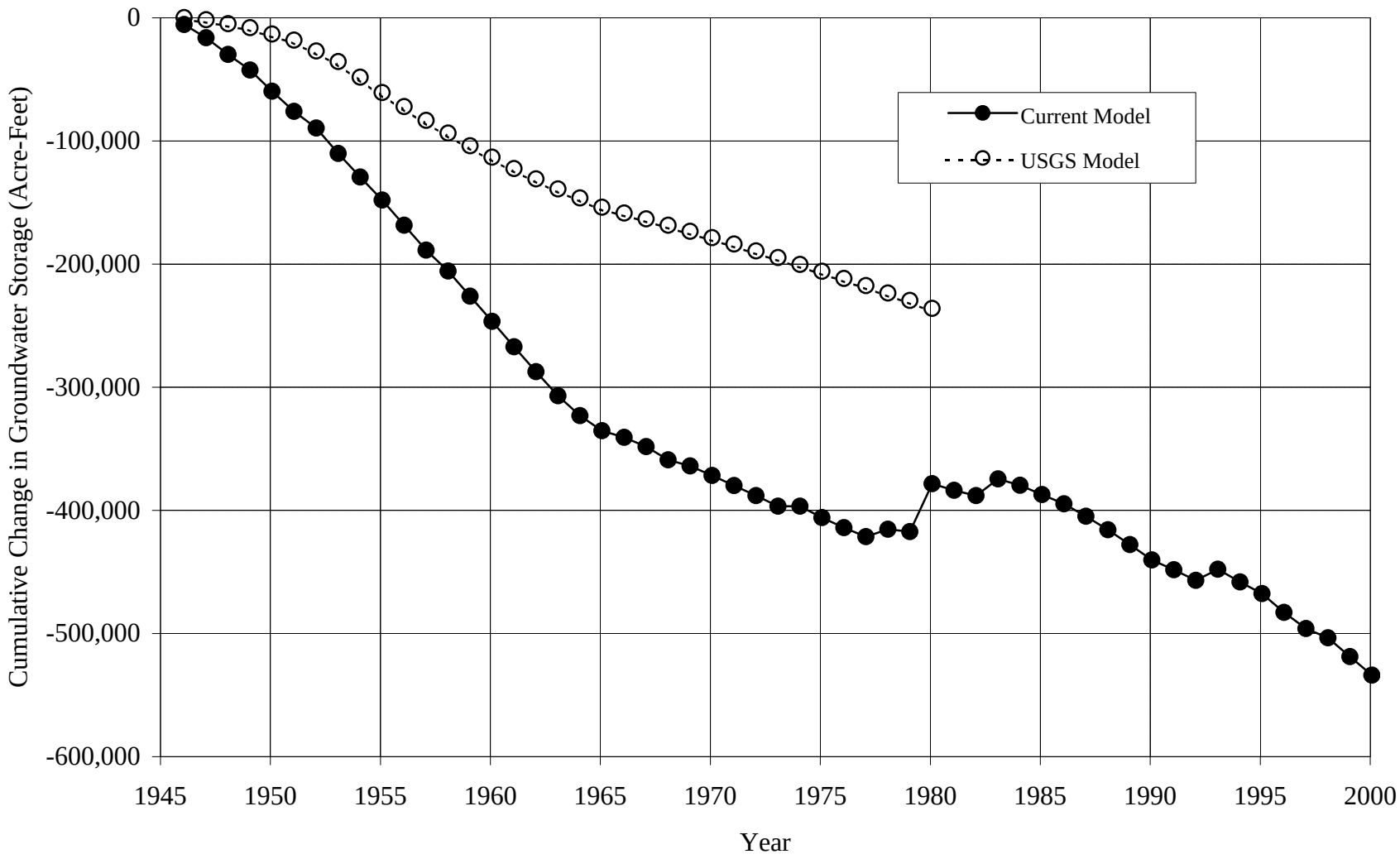


Figure 74. Comparison of calculated cumulative change in storage - current model and USGS model.

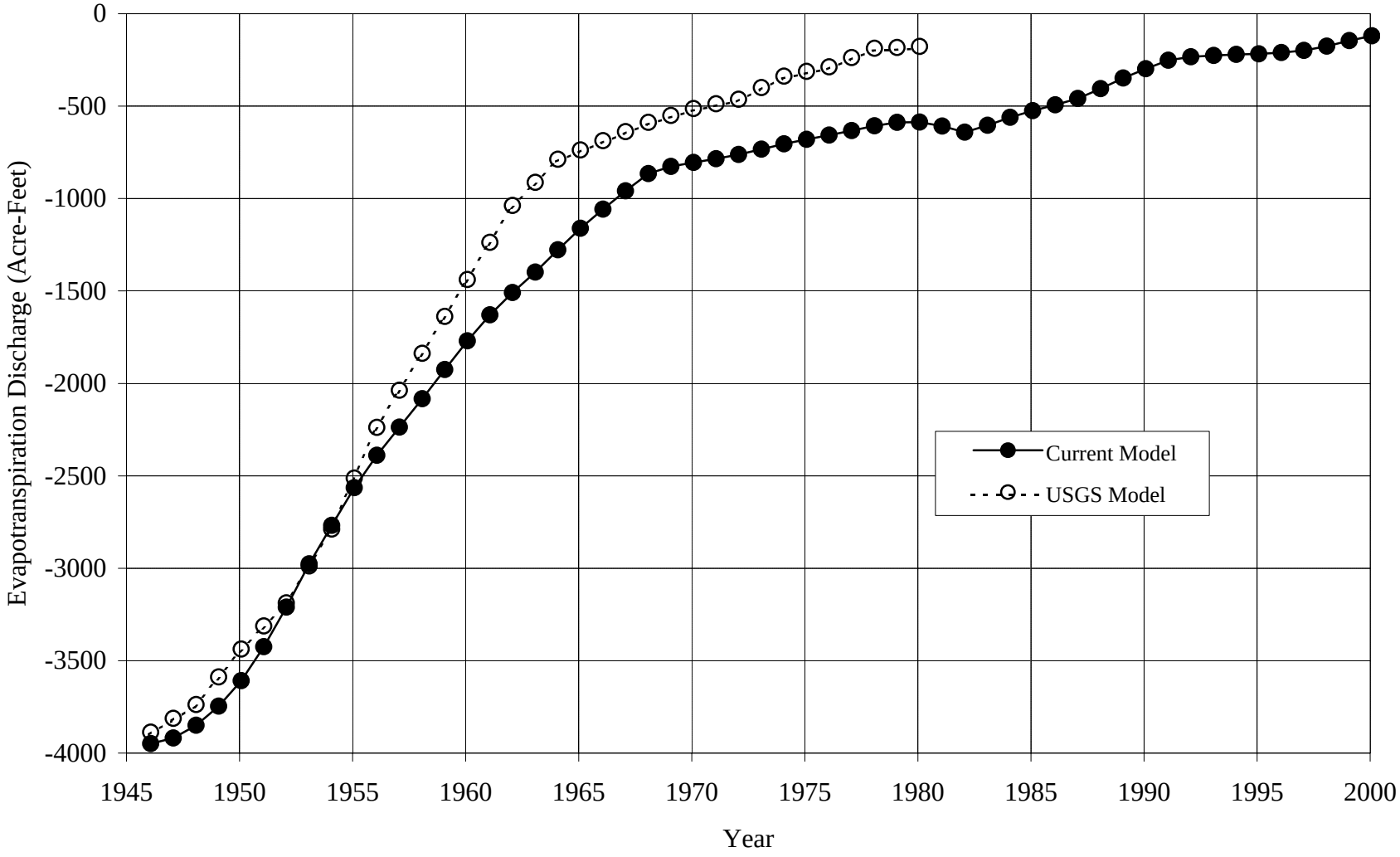


Figure 75. Comparison of calculated evapotranspiration discharge - current model and USGS model.

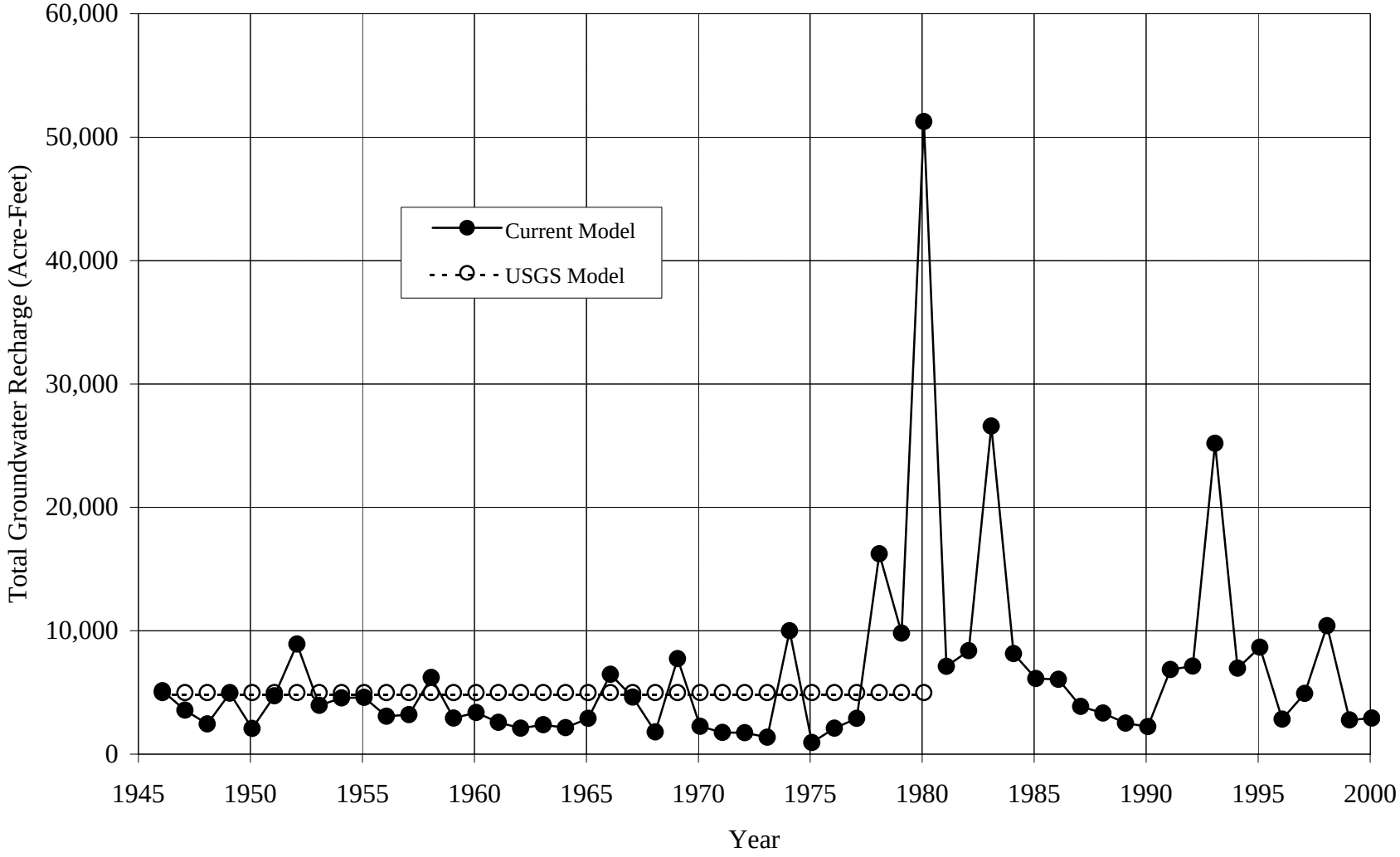


Figure 76. Comparison of simulated total groundwater recharge - current model and USGS model.

groundwater recharge for the entire transient period (1946 – 2000) varied as a function of precipitation in the mountains of the surrounding watershed, as described by Netto (2001). This allowed groundwater to be accurately represented on a yearly (stress-period) basis, as opposed to being averaged over the period of record.

Groundwater discharge from the aquifer system at Lower Borrego Valley was simulated by the USGS at an apparent fixed rate of 930 acre-feet per year. In their description of their numerical model, the USGS described the southeastern boundary of their model as a constant-head boundary. In contrast, the current model estimates underflow discharge at Lower Borrego Valley to range from approximately 2,800 to 6,000 acre-feet per year (Figure 77). The model indicates that underflow discharge out of Borrego Valley decreases during the transient period. This is due to greater consumption of groundwater in the north portion of the basin as groundwater recharge is intercepted by groundwater users in that area. In addition, as water levels in the north and north-central portions of the basin were drawndown during the transient period, a greater quantity of recharge from San Felipe Creek flowed north, with a resulting smaller quantity of recharge flowing south toward Lower Borrego Valley.

Differences in estimated net groundwater pumpage between the current model and the USGS model also contribute to difference in calculated cumulative change in storage between the two models. The USGS estimated and simulated pumpage ranging from 1,700 acre-feet per year to 13,700 acre-feet per year, with peak pumpage occurring in 1960 (Figure 78). The USGS estimates are lower than the estimates used by the current model prior to 1965, and higher than the estimates used by the current model between 1965 and 1980. The average groundwater pumpage estimated for the current model is approximately 15% higher than the average estimated by the USGS for the period 1946 through 1980.

Differences between the USGS estimates of specific yield for their three model layers, and the specific yield estimates for different soil textures in the current model are believed to be a function of (1) differences in calculated net change in groundwater storage, due to differences in recharge and discharge components, and (2) differences in aquifer geometry and conceptualization. The current model evaluated recharge and discharge to groundwater and conceptualization of the aquifer system more rigorously, and in greater

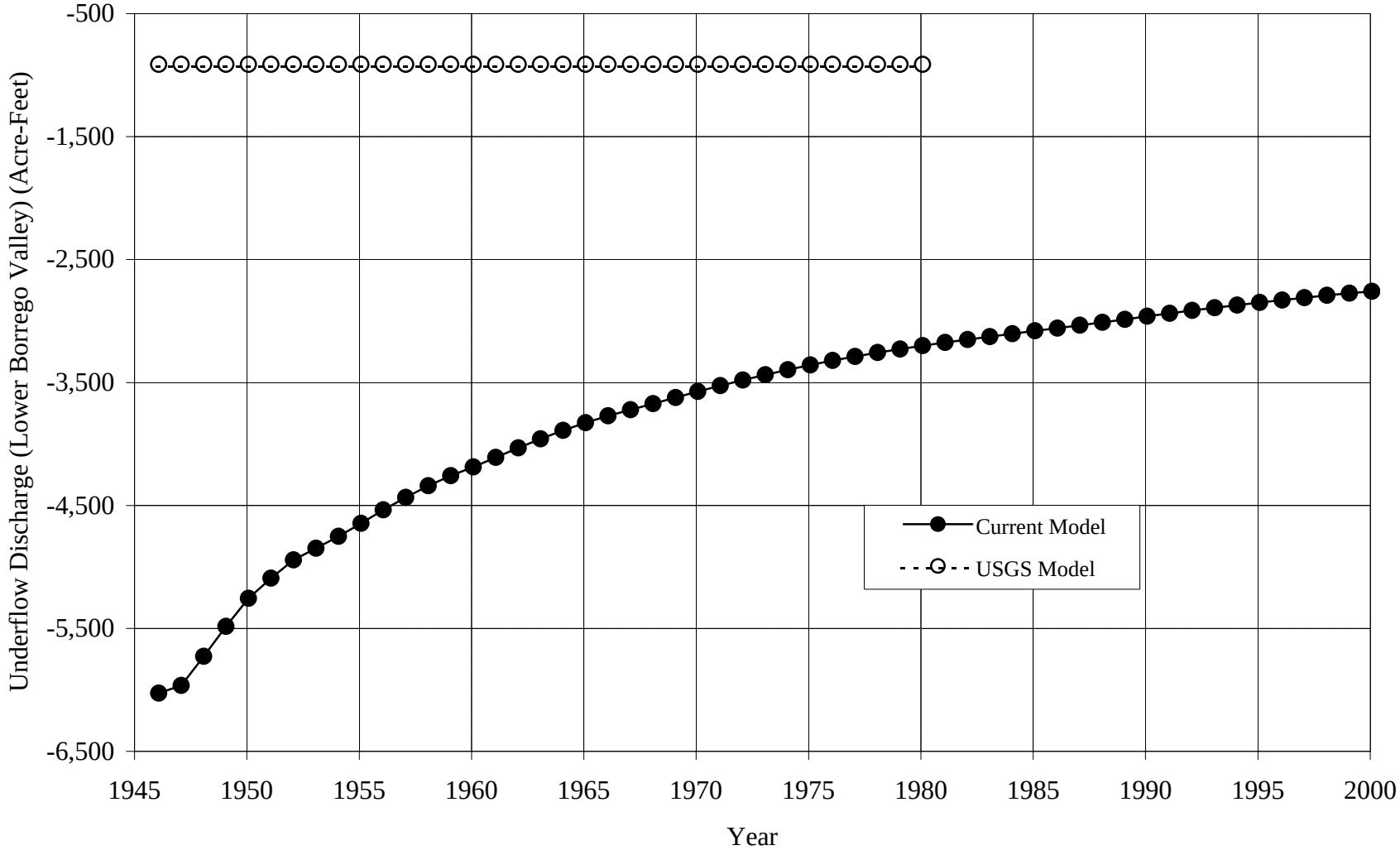


Figure 77. Comparison of simulated underflow out of Lower Borrego Valley - current model and USGS model.

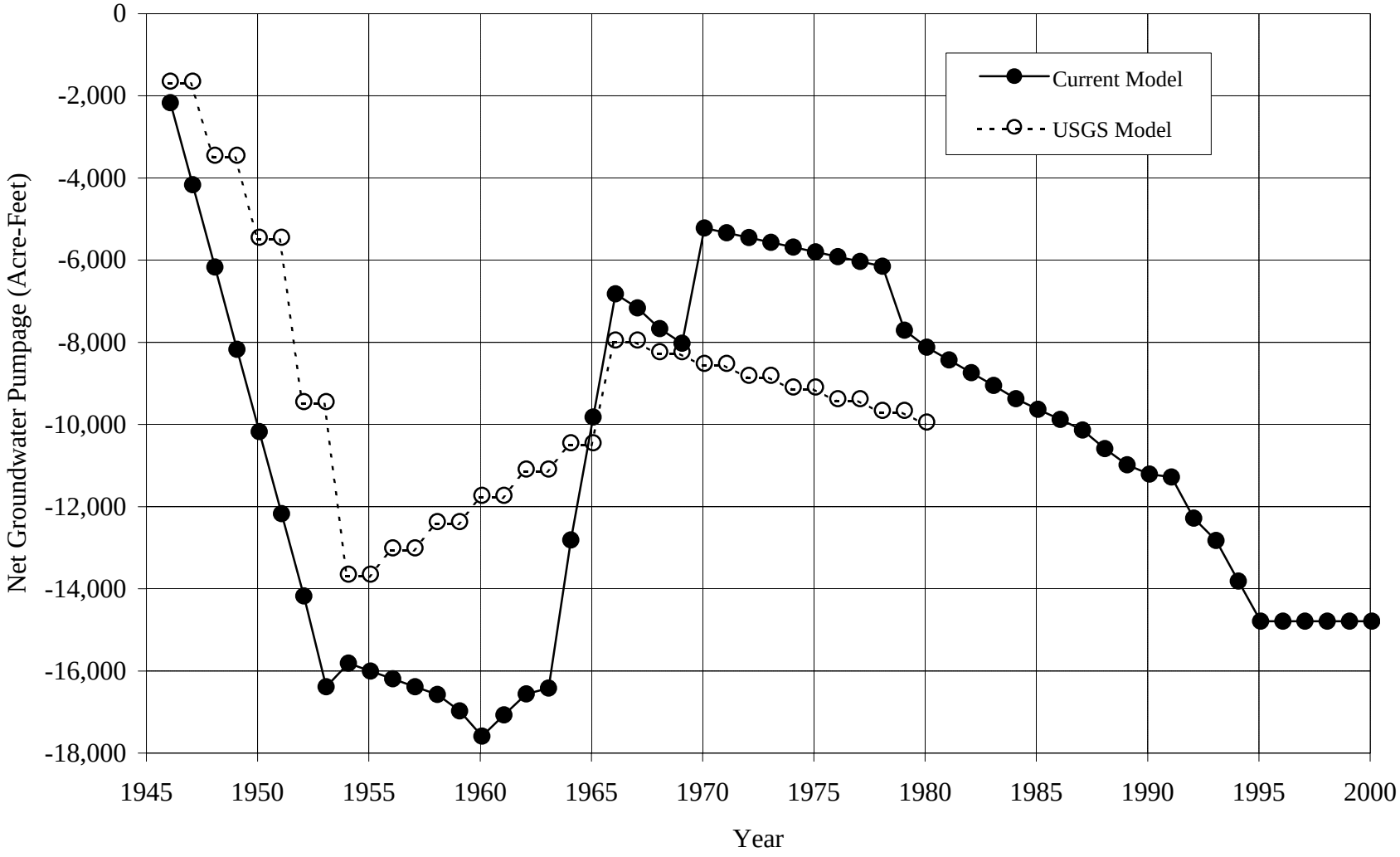


Figure 78. Comparison of simulated net groundwater pumpage - current model and USGS model.

detail, than the USGS model. As such, the current model is expected to be a better representation of historic conditions and a better predictor of future conditions.

Calibration Summary

Steady-state and transient-state calibration modeling was conducted to estimate a unique combination of physical properties of the aquifer system. Calibration of the steady-state and transient-state models was successful. This distribution of hydraulic head at the end of the transient-state model was utilized as the starting condition for the predictive modeling, as described in Chapter VI.

CHAPTER VI

PREDICTIVE MODELING

The primary purpose of building and calibrating the numerical model (described in Chapters IV and V) was for use as a tool to estimate the impacts of future groundwater use scenarios for Borrego Valley. Future groundwater use scenarios were defined by SD Co. DPLU staff in consultation with representatives of some of the water municipalities in Borrego Valley. Two future groundwater use scenarios were developed, one which represents expected future conditions and a second, which represents worst-case future conditions. Both of these scenarios are described in further detail below.

Groundwater Recharge – 2001 through 2030

It is not possible to predict future climatic conditions for the 30 year period selected for predictive modeling. Trends in climatic data indicate that both short and long-term cycles exist, but our ability to predict these trends is limited. However, it is expected that the cyclic nature of climatic patterns will be captured if a long-term period of record is utilized. Based on this, the 30 year period from 1971 through 2000 was used as the basis for recharge during the period 2001 through 2030. Yearly totals of recharge and discharge for the predictive modeling period for each use scenario are provided in Tables 17 and 18 (Appendix E).

Expected Use Scenario – 2001 through 2030

As previously described, SD Co. DPLU staff provided estimates of expected water use during the period 2001 through 2030. In general, this scenario assumes reasonable levels of growth in municipal use of groundwater (based on historic population growth patterns), recreational use of groundwater (based on approved and pending permits for golf courses), and assumes no-growth in agriculture – it is maintained at year 2000 levels. The following sections describe in detail groundwater use for municipal, agricultural, and recreational uses, for the expected use scenario.

Municipal Use

According to SD Co. DPLU staff, historic population growth in Borrego Valley was approximately 3% per year. SD Co. DPLU staff expect this trend to continue, and also expect groundwater consumption to be directly proportional to population growth. Yearly quantities of groundwater extraction were modeled by increasing production at wells in operation during the year 2000 at a rate of 3% per year. Total municipal production was estimated and modeled to range from 2,930 acre-feet per year to 6,900 acre-feet per year, and average 4,640 acre-feet per year during the period 2001 through 2030. A summary of total municipal production for the period 2001 through 2030 is provided in Table 17 (Appendix E).

Agricultural Use

SD Co. DPLU staff have assumed that agricultural growth will not occur relative to 2000 levels for the expected use scenario. As such, year 2000 groundwater extraction for agriculture was used as a basis for agricultural production during the period 2001 through 2030. Agriculture is in a condition of steady-state, with no net gain or loss of acreage, or groundwater extraction. Groundwater extraction in support of agriculture in 2000 is approximately equal to 1995 values, with minor variations (J. Peterson, personal communication, June 18, 2001). The locations of various parcels of land under agricultural production during 1995 are provided in Figure 113 (Appendix B). The rate of net groundwater extraction associated with this agricultural production is 9,280 acre-feet per year, and is held constant at that rate.

Recreational Use

Groundwater extraction in support of recreational use was defined for the period 2001 through 2030 by SD Co. DPLU staff. Recreational use in Borrego Valley is almost exclusively in support of several golf courses in the Valley. For this scenario, use of groundwater at existing golf courses was expected to continue at year 2000 rates. In addition, an analysis of approved and pending permits for additional golf courses was conducted. Based on these permits, expected levels of use were defined, which include the following additions to year 2000 groundwater extraction:

- A nine-hole regulation play golf course is added at the Roadrunner country club in 2005.

- A nine-hole regulation play golf course is added at the Borrego Springs Park and Community Service District (BSPCSD) in 2005.

These additional golf courses are expected to consume (net) approximately 500 acre-feet per year, each. This additional extraction (above what is extracted during 2000) is modeled as an increase in groundwater extraction at the cells which represent each of these golf courses. Total recreational production of groundwater was estimated and modeled to range from 3,110 acre-feet per year to 4,110 acre-feet per year, and average 3,970 acre-feet per year during the period 2001 through 2030 (Table 17, Appendix E).

Expected Use Scenario Analysis

Numerical modeling of the expected use scenario shows that the increasing imbalance between groundwater discharge and groundwater recharge, even over a period that includes representative wet and dry periods, is depleting groundwater in storage at increasing rates. Model simulated conditions in Borrego Valley during the expected use scenario are described using the seven transient calibration wells (Chapter V) and using water table contour maps for 2010, 2020, and 2030.

Predicted water levels in calibration wells. Predicted groundwater levels for this scenario at calibration wells in the north and north-central portions of the aquifer (Fortiner and 10S/6E 21A1) continue to decline despite stabilized groundwater extraction rates in this part of Borrego Valley (Figures 79 and 80). The long-term rates of decline for these wells is predicted to increase as much as 170%, relative to historic trends (Table 8). An increasing rate of water level decline is due, in part, to the increased basin-wide imbalance between groundwater recharge and discharge, caused by increased recreational and municipal pumping in the central and south-central portion of the groundwater basin. The increasing rate of groundwater level decline can also be partially attributed to the geometry of the aquifer system. As described in Chapter IV, the aquifer system's total groundwater storage capacity decreases non-linearly as saturated thickness decreases. Thus, even a stable imbalance between groundwater recharge and discharge would lead to increased rates of decline.

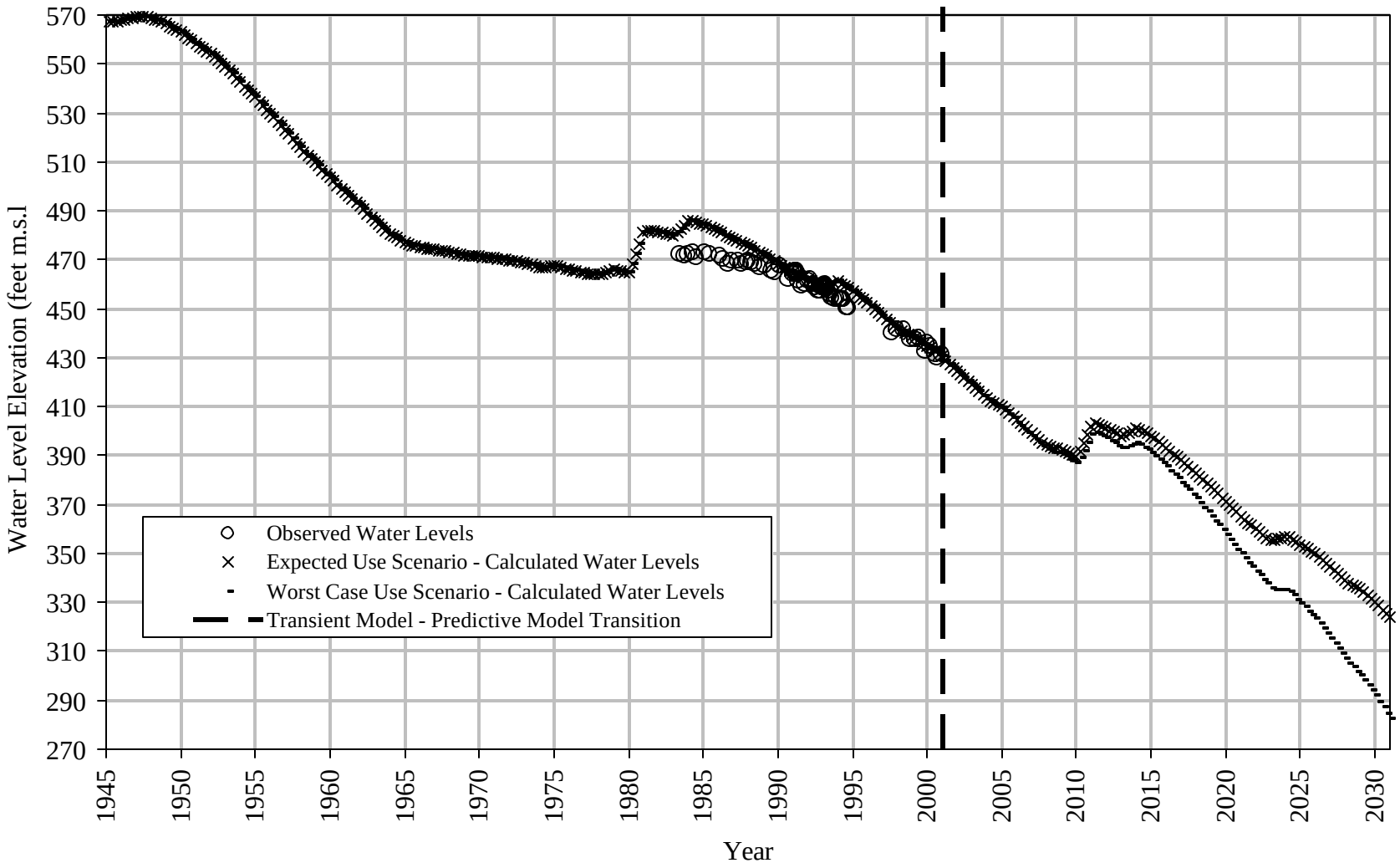


Figure 79. Water level elevation hydrograph well - Fortiner (transient and predictive models).

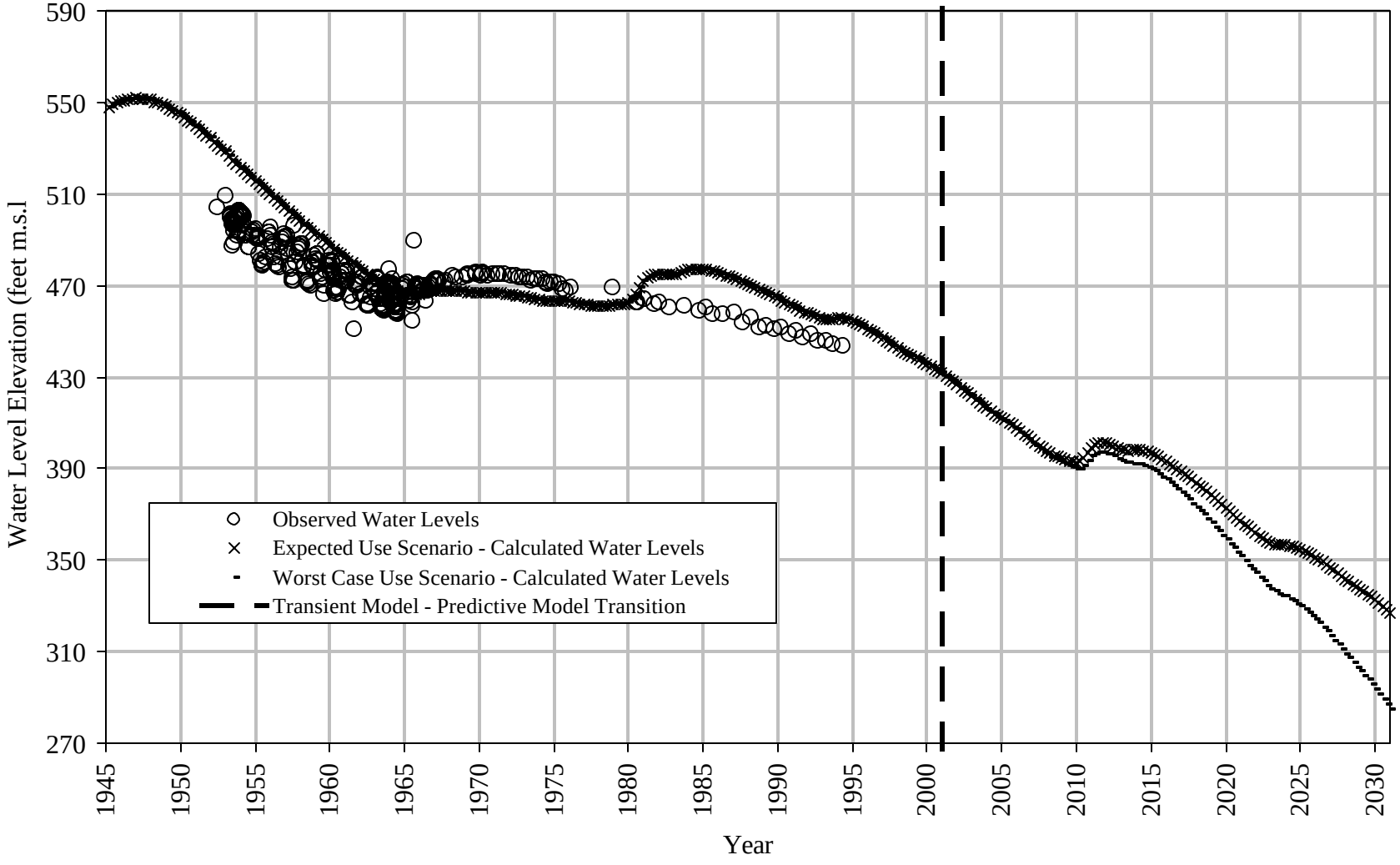


Figure 80. Water level elevation hydrograph well - 10S/6E 21A1 (transient and predictive models).

Table 8

Summary of Water Level Declines for 1945 Through 2000, 2001 Through 2030 (Expected Use Scenario), and 2001 Through 2030 (Worst Case Use Scenario)

Transient Calibration Period					
Select Target Well	1945 W.L.E. (ft a.m.s.l.)	2000 W.L.E. (ft a.m.s.l.)	Period (Years)	Total Decline (ft)	Avg. Decline (ft/yr)
Fortiner	570	430	56	140	2.50
10S/6E 21A1	550	432	56	118	2.11
10S/6E 29N1	555	440	56	115	2.05
10S/6E 36Q1	488	438	56	50	0.89
11S/6E 11M1	474	436	56	38	0.68
11S/6E 15F1	488	430	56	58	1.04
11S/7E 7N1	456	440	56	16	0.11
Expected Use Scenario					
Select Target Well	2000 W.L.E. (ft a.m.s.l.)	2030 W.L.E. (ft a.m.s.l.)	Period (Years)	Total Decline (ft)	Avg. Decline (ft/yr)
Fortiner	430	325	30	105	3.50
10S/6E 21A1	432	325	30	107	3.56
10S/6E 29N1	440	335	30	105	3.50
10S/6E 36Q1	438	370	30	68	2.27
11S/6E 11M1	436	359	30	79	2.63
11S/6E 15F1	430	342	30	88	2.93
11S/7E 7N1	440	389	30	51	1.70
Worst-Case Use Scenario					
Select Target Well	2000 W.L.E. (ft a.m.s.l.)	2030 W.L.E. (ft a.m.s.l.)	Period (Years)	Total Decline (ft)	Avg. Decline (ft/yr)
Fortiner	430	282	30	148	4.93
10S/6E 21A1	432	285	30	147	3.90
10S/6E 29N1	440	272	30	168	5.60
10S/6E 36Q1	438	348	30	90	3.00
11S/6E 11M1	436	316	30	120	4.00
11S/6E 15F1	430	280	30	150	5.00
11S/7E 7N1	440	372	30	68	2.27

Predicted water levels in well 10S/6E 29N1 (located near Borrego Palm Creek – a focused recharge area) indicate increased rates of water level decline are likely, despite stabilized extraction rates in this area (Figure 81, Table 8).

Future increases in groundwater pumpage in Borrego Valley for the expected use scenario are focused in the central and south-central portions of the aquifer system. Groundwater extraction in these areas is predicted to be substantially higher than past extraction. Simulated water levels at wells in these areas decline substantially over the 30-year simulation period (Figures 82 through 85, and Table 8). These wells (10S/6E 36Q1, 11S/6E 11M1, 11S/6E 15F1, and 11S/7E 7N1) are located near the central portion of the basin – near the historic groundwater discharge area, and/or adjacent to the Palm Spring Formation. Soil textures in these areas are simulated to yield less water from storage for a given extraction quantity. Thus, groundwater extraction in these areas will have a greater effect locally than in areas with more coarse soil textures.

Model predicted water levels for this use scenario at the 20 target wells are shown in Figures 135 through 154 (Appendix E).

Distribution of predicted water levels – 2010, 2020, and 2030. The model predicts basin-wide drawdown of groundwater levels during the period 2000 through 2030 for the expected use scenario (Figures 86, 87, and 88). Simulated water levels decline approximately 106 feet in the northern portion of the basin, 48 feet near Borrego Sink, and 210 feet near San Felipe Creek during the period 2000 through 2030. Water levels near San Felipe Creek are influenced by varying yearly quantities of recharge from that source, and water level declines in that area may represent short-term transient processes. Predicted water levels in the other two areas are not influenced by yearly variations in recharge, and represent expected long-term levels.

Worst Case Use Scenario – 2001 through 2030

As previously described SD Co. DPLU staff provided estimates of worst case water use during the period 2001 through 2030. In general, this scenario assumes aggressive levels of growth in municipal use of groundwater, modeled as twice the amount of historic population growth patterns. This scenario also assumes aggressive levels of growth in

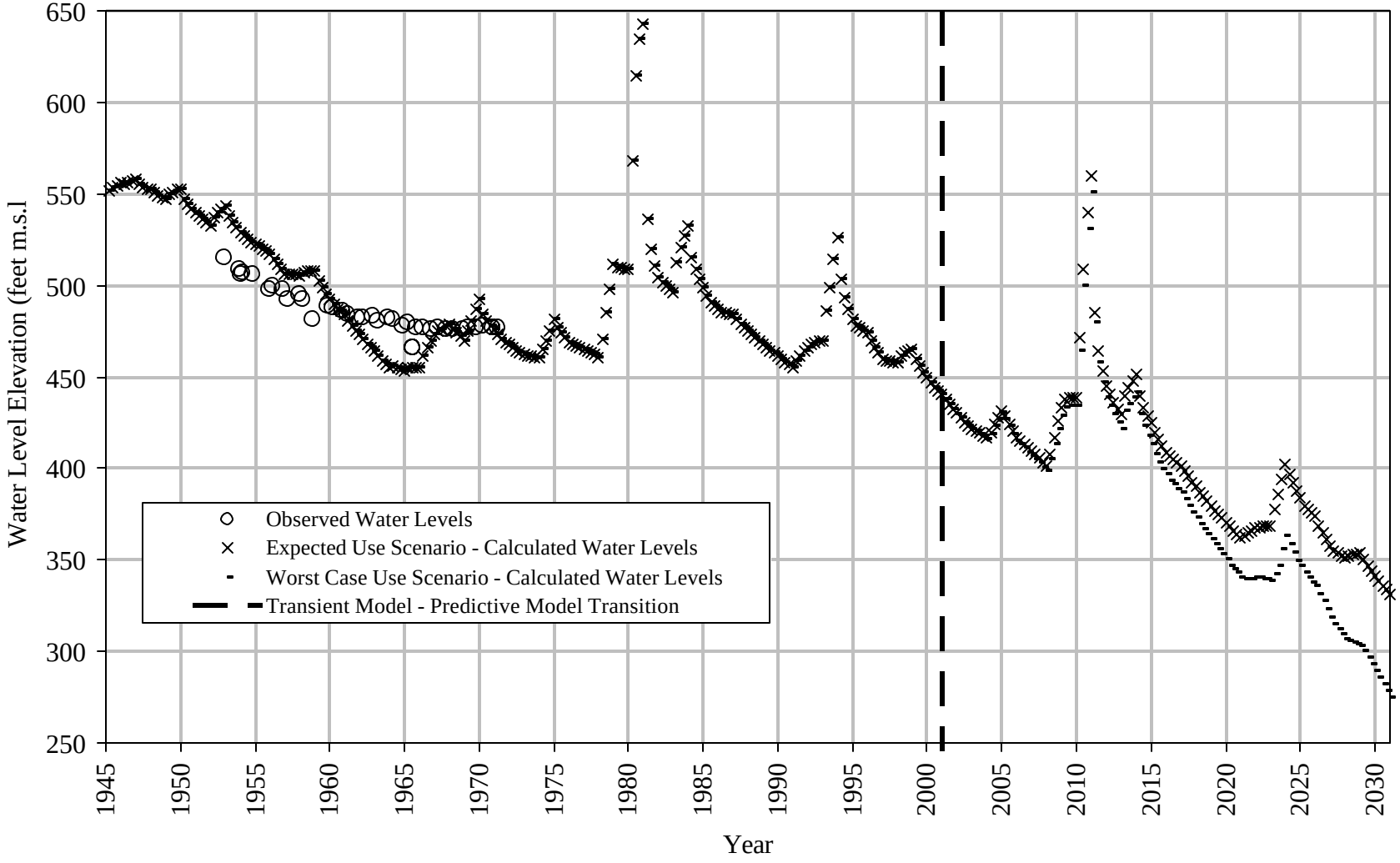


Figure 81. Water level elevation hydrograph well - 10S/6E 29N1 (transient and predictive models).

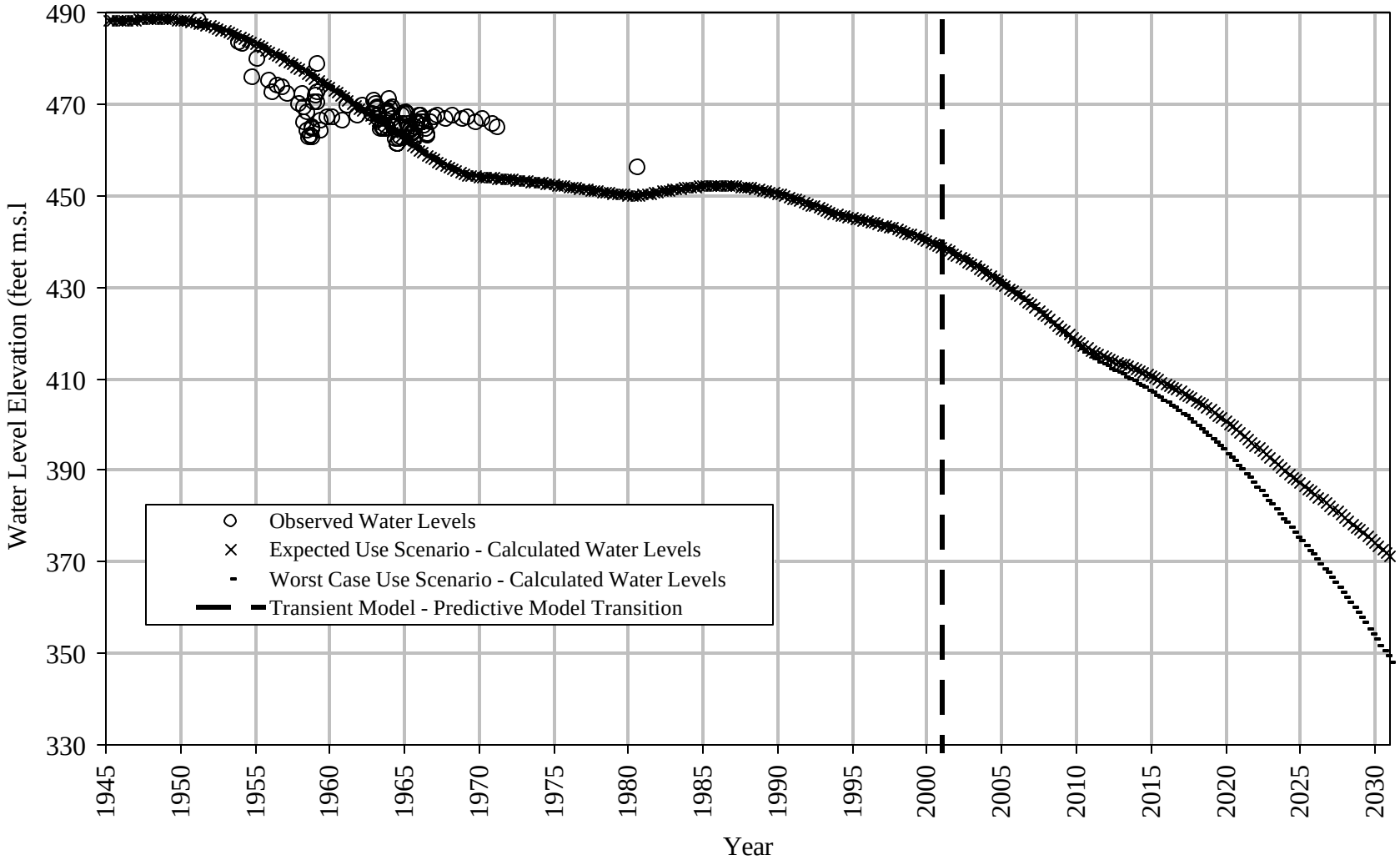


Figure 82. Water level elevation hydrograph well - 10S/6E 36Q1 (transient and predictive models).

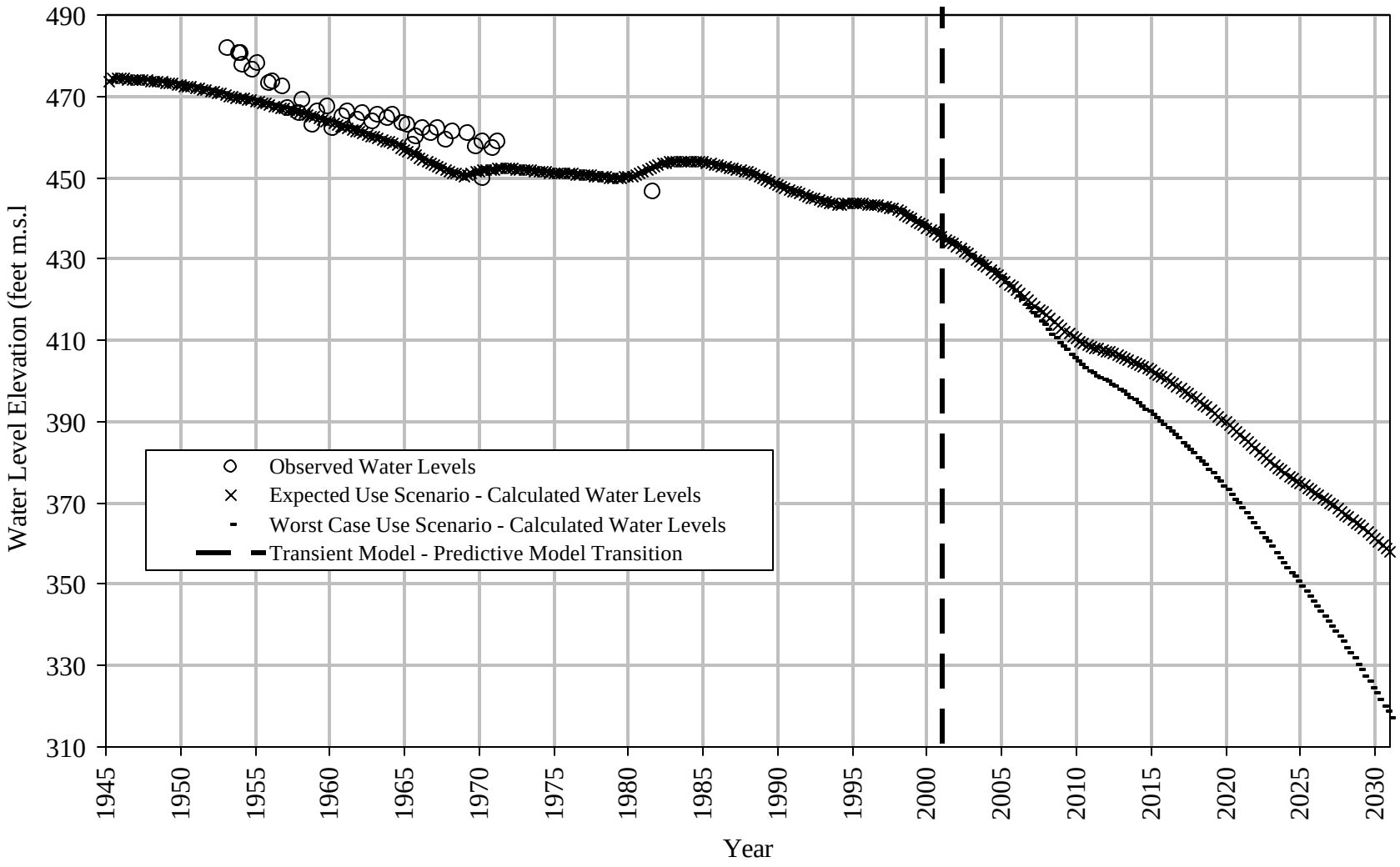


Figure 83. Water level elevation hydrograph well - 11S/6E 11M1 (transient and predictive models).

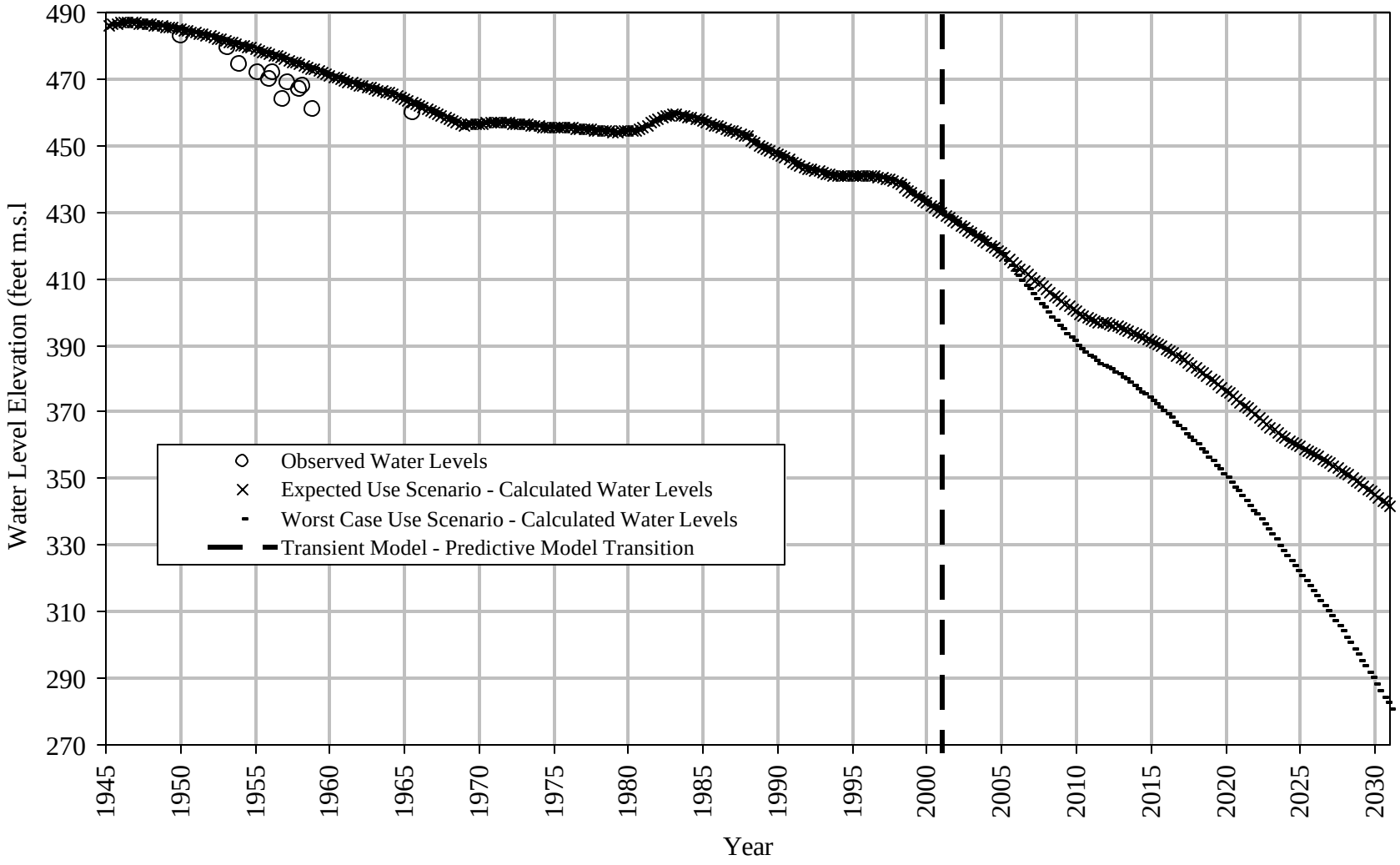


Figure 84. Water level elevation hydrograph well - 11S/6E 15F1 (transient and predictive models).

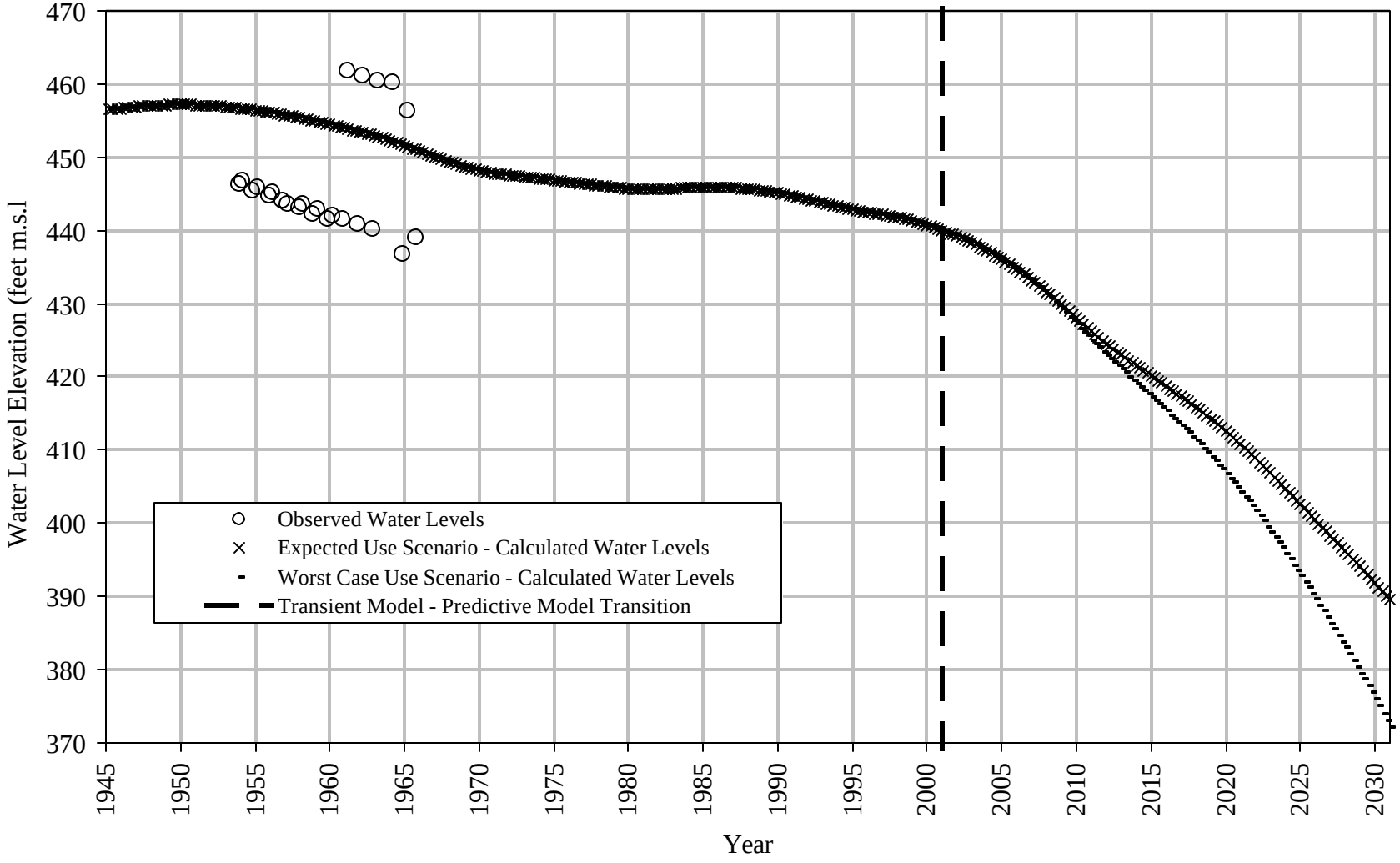
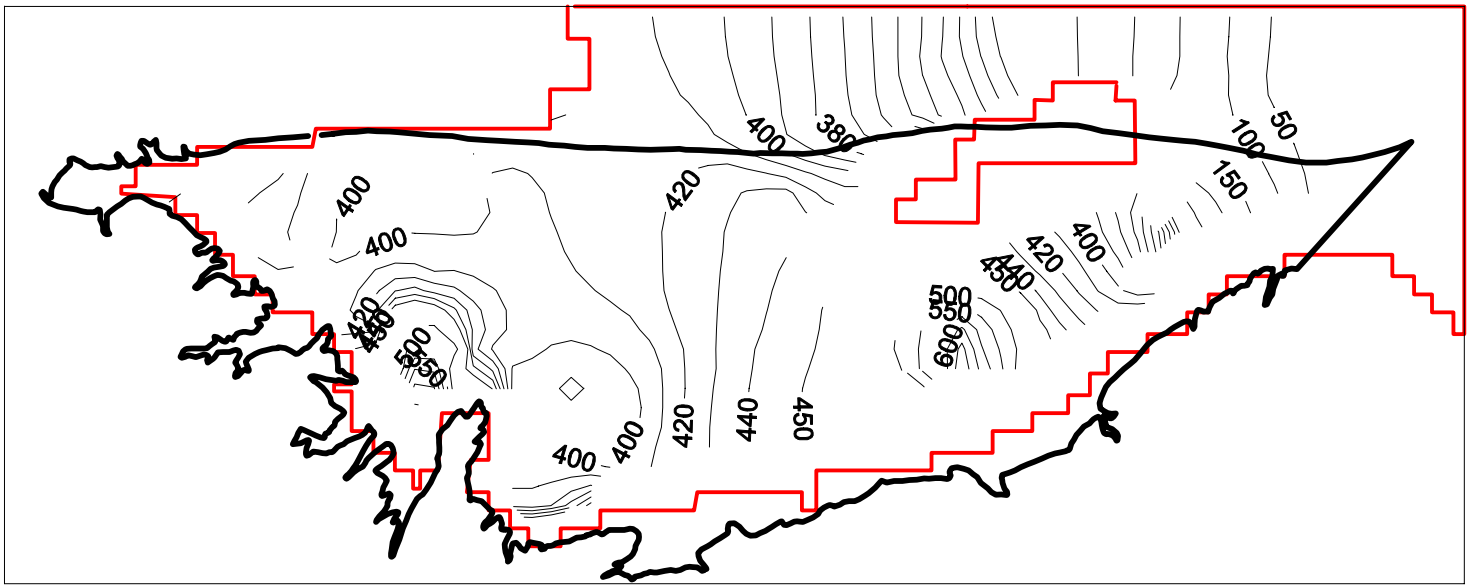


Figure 85. Water level elevation hydrograph well - 11S/7E 7N1 (transient and predictive models).

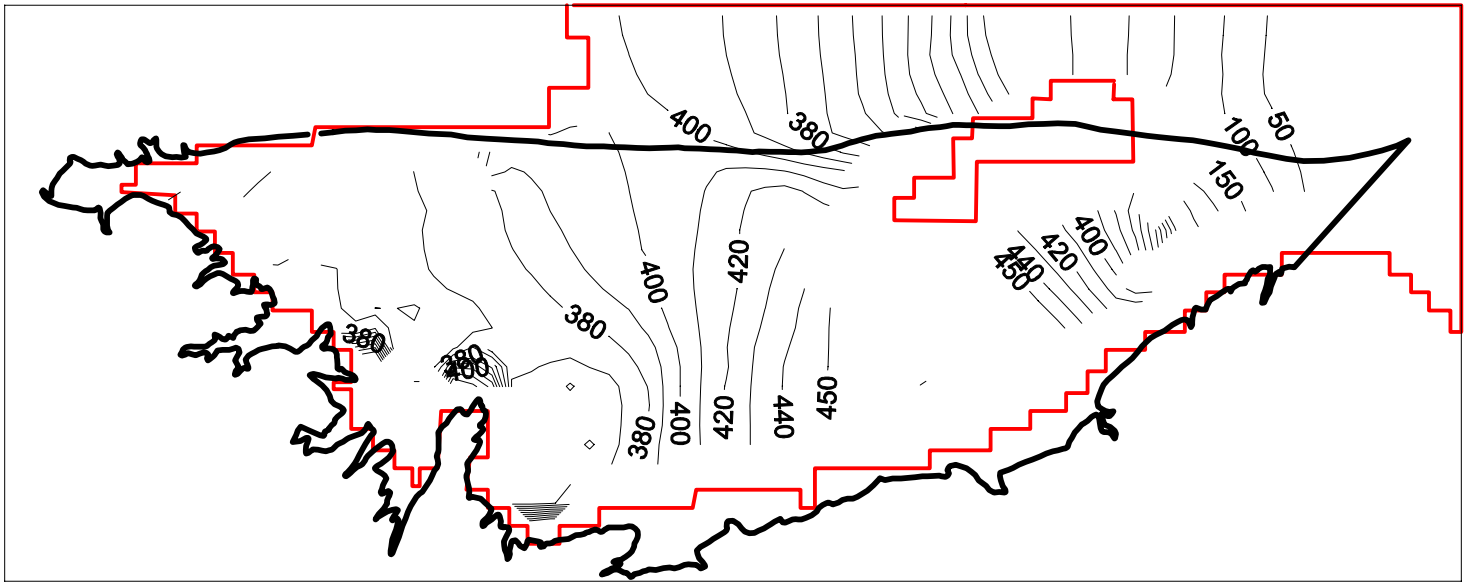


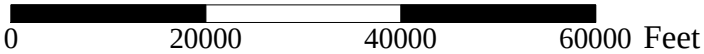
0 20000 40000 60000 Feet

Notes: 1) Water Table Contoured in Model Layer 1 - May be unsaturated in some areas
2) Contour Interval is 50-feet when water table elevation is between 0- and 300-feet m.s.l.
3) Contour interval is 10-feet when water table elevation is between 300- and 450-feet m.s.l.
4) Contour interval is 50-feet when water table elevation is > 450-feet m.s.l.

Borrego Valley Groundwater Study
Predictive Modeling - Expected Use Scenario
2010 Water Table Elevation
Borrego Valley

Figure 86. Predictive modeling (expected use scenario) 2010 water table elevation.





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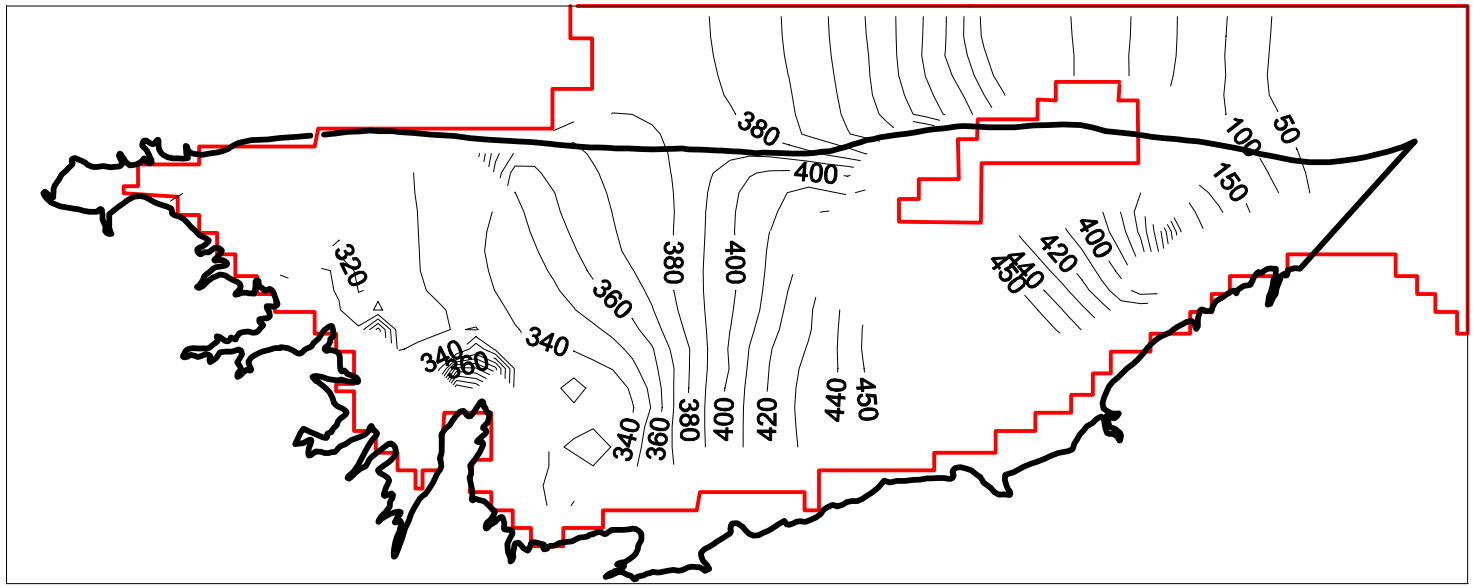
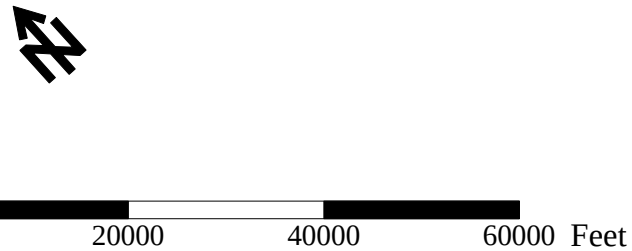
4) Contour interval is 50-feet when water table elevation is > 450-feet m.s.l.

Borrego Valley Groundwater Study
Predictive Modeling - Expected Use Scenario
2020 Water Table Elevation
Borrego Valley

Figure 87. Predictive modeling (expected use scenario) 2020 water table elevation.





Notes: 1) Water Table Contoured in Model Layer 1 - May be unsaturated in some areas
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3) Contour interval is 10-feet when water table elevation is between 300- and 450-feet m.s.l.
4) Contour interval is 50-feet when water table elevation is > 450-feet m.s.l.

Borrego Valley Groundwater Study
Predictive Modeling - Expected Use Scenario
2030 Water Table Elevation
Borrego Valley

Figure 88. Predictive modeling (expected use scenario) 2030 water table elevation.

recreational use of groundwater - based on the assumption that most approved and pending permits are implemented as real projects. Finally, this scenario assumes moderate growth of agriculture to 110% of its current use by the year 2020. The following sections describe groundwater use for municipal, agricultural, and recreational uses, for the worst case scenario.

Municipal Use

According to SD Co. DPLU staff, historic population growth in Borrego Valley was on the order of 3% per year. For this scenario, SD Co. DPLU staff estimated a growth rate twice the historic, and expected groundwater consumption to be directly proportional to that population growth. Yearly quantities of groundwater extraction were modeled by increasing production at wells in operation during the year 2000 at a rate of 6% per year. Total municipal production was estimated and modeled to range from 3,010 acre-feet per year to 16,320 acre-feet per year, and average 7,940 acre-feet per year during the period 2001 through 2030 for this scenario. A summary of total municipal production for the period 2001 through 2030 for this scenario is provided in Table 18 (Appendix E).

Agricultural Use

For the worst case scenario, SD Co. DPLU staff assumed that extraction of groundwater in support of agriculture would grow to 110% of 2000 levels by the year 2020. This increase was assumed to be linear, and was projected beyond 2020 to 2030, based on the linear trend. Growth in groundwater production due to agriculture was modeled as increases to the quantity of water taken from cells in the model which represent year 2000 groundwater production. Agricultural growth under this scenario is expected to occur in close proximity to parcels modeled for 2000 and, as such, this assumption is reasonable. Total agricultural production was estimated and modeled to range from 9,320 acre-feet per year to 10,670 acre-feet per year, and average 10,000 acre-feet per year during the period 2001 through 2030 for this scenario. A summary of agricultural production for the period 2001 through 2030 for this scenario is provided in Table 18 (Appendix E).

Recreational Use

Groundwater extraction in support of recreational use was estimated for the period 2001 through 2030 by SD Co. DPLU staff. For this scenario, existing recreational use was expected to continue at year 2000 rates. In addition, an analysis of approved and pending permits for additional golf courses was conducted. Based on these permits, worst case levels of use were defined, which include the following additions to year 2000 groundwater extraction:

- A nine-hole regulation play golf course is added at the Roadrunner country club in 2005.
- A nine-hole regulation play golf course is added at the Borrego Springs Park and Community Service District (BSPCSD) in 2005.
- A nine-hole par-3 golf course is added at the BSPCSD in 2005.
- An 18-hole regulation play golf course is added at the Ram's Hill Development in 2005.

Nine-hole regulation play golf courses are expected to consume (net) approximately 500 acre-feet per year, each. Nine-hole par-3 golf courses are expected to consume (net) approximately 375 acre-feet per year, each. Finally 18-hole regulation play golf courses consume approximately 1,000 acre-feet per year (net) , each. These additional extractions (above what is extracted during 2000) are modeled as increases in groundwater extraction at the cells which represent each of these golf courses. Total recreational production of groundwater was estimated and modeled to range from 3,110 acre-feet per year to 5,490 acre-feet per year, and average 5,160 during the period 2001 through 2030 (Table 18, Appendix E).

Worst Case Use Scenario Analysis

Numerical modeling of the worst case use scenario shows that an increasing imbalance between groundwater discharge and groundwater recharge, even over a long-term climatic period, would deplete the quantity of groundwater in storage at increasing rates.

Predicted water levels in calibration wells. Predicted groundwater levels at calibration wells in all portions of the basin are lower than those predicted for the expected use scenario (Figures 79 through 85). These lower water levels are due to increased pumping in the central and south-central portions of the basin. These increased extractions, coupled with the geometry of the aquifer system lead to basin-wide increasing rates of water level

decline (Table 8) basin-wide. Simulated water levels in these wells show that both short-term and long-term adverse impacts to the groundwater basin and local residents will occur under the expected use scenario. Adverse impacts under the worst case use scenario are expected to be more numerous and more severe.

Model predicted water levels for the worst-case use scenario at the 20 target wells are shown in Figures 135 through 154 in Appendix E.

Distribution of predicted water levels – 2010, 2020, and 2030. The model predicts severe basin-wide drawdown of groundwater levels during the period 2000 through 2030 (Figures 89, 90, and 91). Simulated water levels decline approximately 146 feet in the northern portion of the basin and 78 feet near Borrego sink (eliminating evapotranspiration of groundwater by native phreatophytes in that area). Water levels near San Felipe Creek are predicted to decline 210 feet, but are probably largely influenced by yearly recharge variability, as previously described.

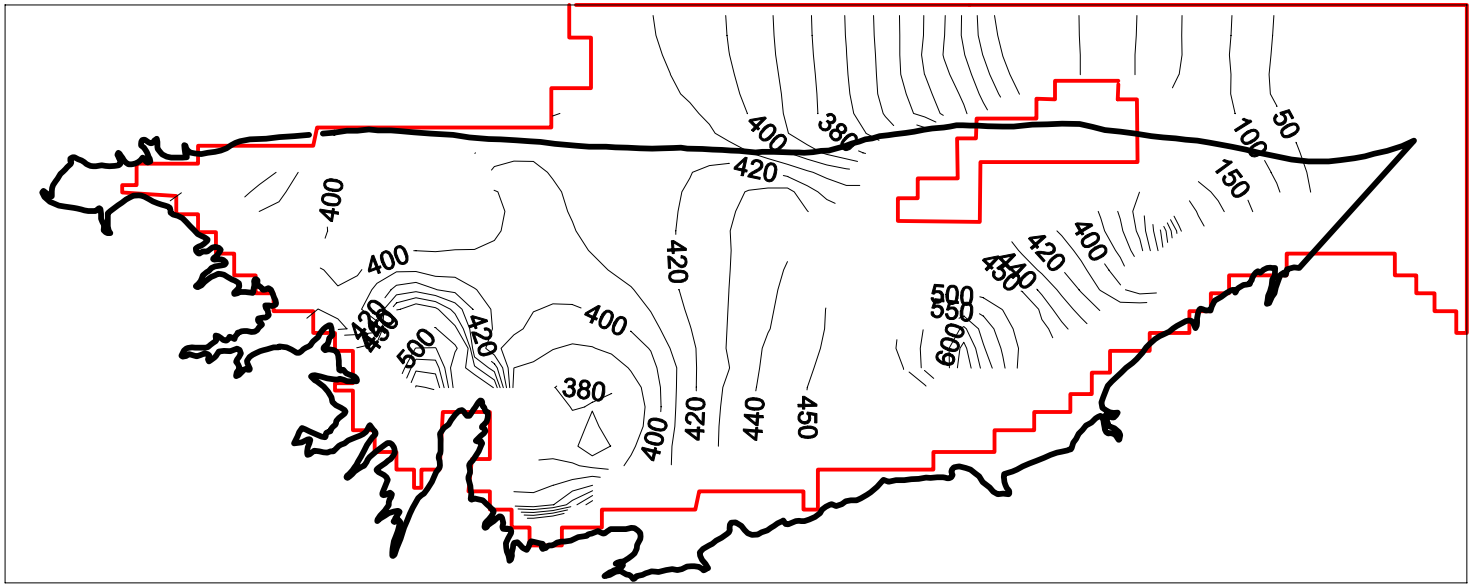
Predictive Modeling Summary

Predictive modeling of future expected and worst-case conditions for Borrego Valley show that the long-term imbalance between groundwater recharge and groundwater discharge, coupled with the geometry of the aquifer system is leading to depletion of groundwater in storage at an ever-increasing rate.

For the expected use predictive modeling scenario, predicted water levels at select well locations distributed throughout the central and north portions of the basin, decline between approximately 50 and 110 feet during the period 2001 through 2030. These declines equate to between 1.70 and 3.56 feet per year.

For the worst case use predictive modeling scenario, predicted water levels at select well locations distributed throughout the central and north portions of the basin, decline between approximately 70 and 170 feet during the period 2001 through 2030. These declines equate to between 2.27 and 5.60 feet per year.

Groundwater extraction in excess of recharge, for an extended period of time equates to groundwater mining, and is termed overdraft. Overdraft of the Borrego Valley aquifer

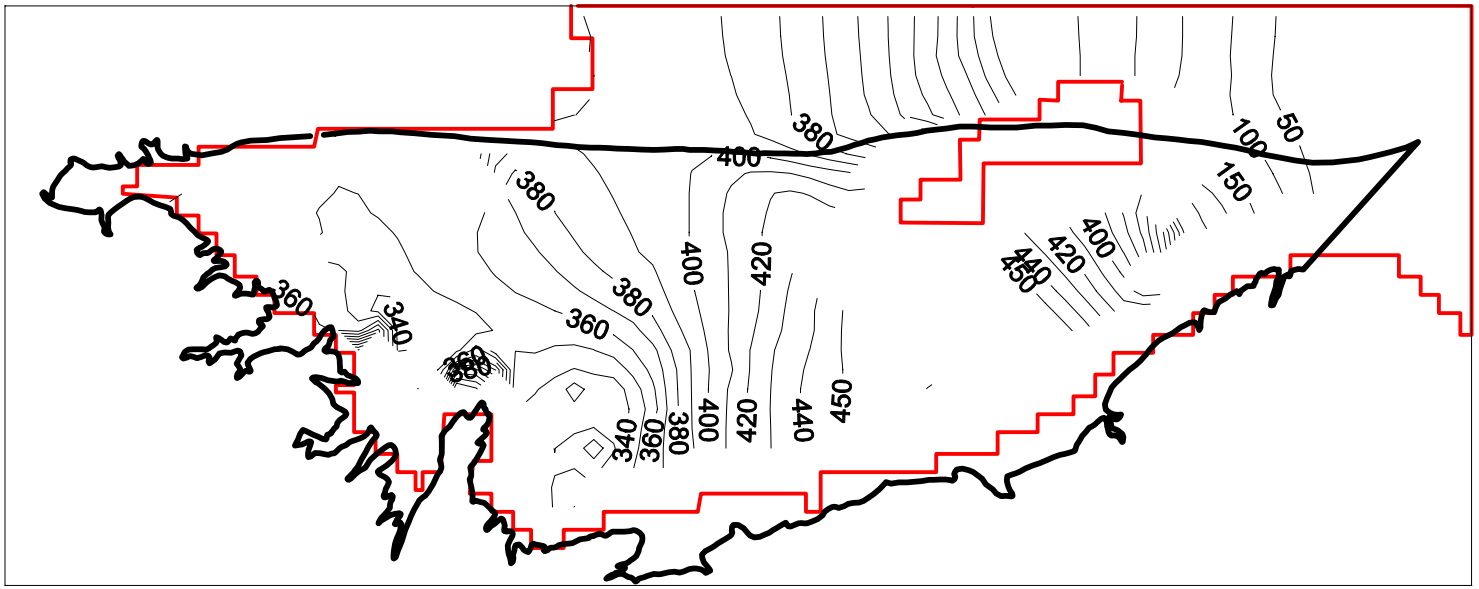


0 20000 40000 60000 Feet

Notes: 1) Water Table Contoured in Model Layer 1 - May be unsaturated in some areas
2) Contour Interval is 50-feet when water table elevation is between 0- and 300-feet m.s.l.
3) Contour interval is 10-feet when water table elevation is between 300- and 450-feet m.s.l.
4) Contour interval is 50-feet when water table elevation is > 450-feet m.s.l.

Borrego Valley Groundwater Study
Predictive Modeling - Worst Case Use Scenario
2010 Water Table Elevation
Borrego Valley

Figure 89. Predictive modeling (worst case use scenario) 2010 water table elevation.

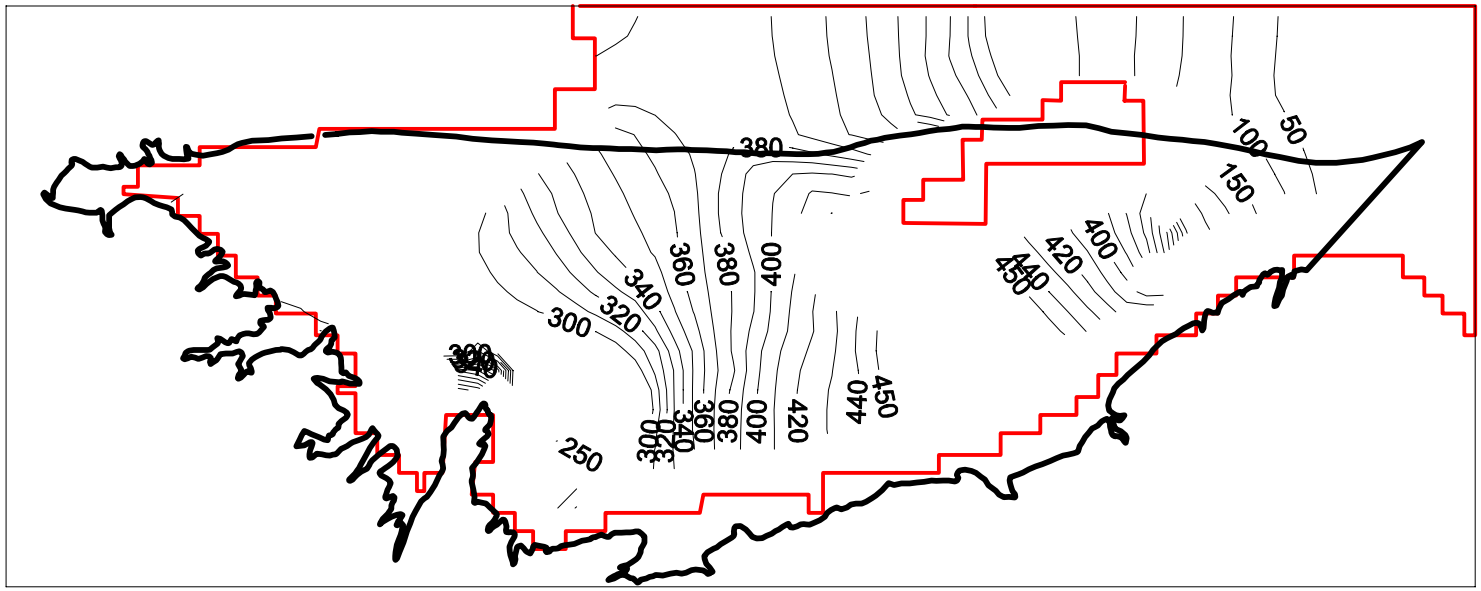


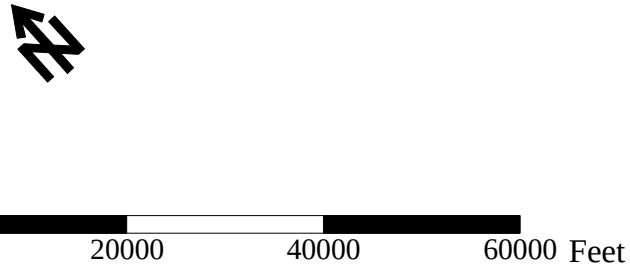
0 20000 40000 60000 Feet

Notes: 1) Water Table Contoured in Model Layer 1 - May be unsaturated in some areas
2) Contour Interval is 50-feet when water table elevation is between 0- and 300-feet m.s.l.
3) Contour interval is 10-feet when water table elevation is between 300- and 450-feet m.s.l.
4) Contour interval is 50-feet when water table elevation is > 450-feet m.s.l.

Borrego Valley Groundwater Study
Predictive Modeling - Worst Case Use Scenario
2020 Water Table Elevation
Borrego Valley

Figure 90. Predictive modeling (worst case use scenario) 2020 water table elevation.





Notes: 1) Water Table Contoured in Model Layer 1 - May be unsaturated in some areas
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4) Contour interval is 50-feet when water table elevation is > 450-feet m.s.l.

Borrego Valley Groundwater Study
Predictive Modeling - Worst Case Use Scenario
2030 Water Table Elevation
Borrego Valley

Figure 91. Predictive modeling (worst case use scenario) 2030 water table elevation.

system could have substantial impacts, and would present a difficult situation for the citizens of Borrego Valley. Some of the most notable probable and possible impacts of overdraft are:

- Aquifer System Desaturation: Producing zones in the aquifer system could become partially or fully desaturated, leading to decreased production capacity at individual wells.
- Partial Desaturation of Wells: Increased drawdown increases pumping lift (a component of total dynamic head, used to calculate and size pumps to ensure adequate performance). Increased pumping lift would lead to less than optimum performance of the pump, or require replacement of the pump. This could lead to economic impacts, especially for private well owners.
- Full Desaturation of Wells: Wells currently perforated in producing zones could go dry, as water levels drop below perforation intervals. Production capacity would have to be restored with a new well. This could lead to substantial economic impacts, especially for private well owners.
- Water Quality Changes: Increased drawdown in Quaternary sediments (Hydrogeologic Units and Model Layers 1, 2, and 3) could create water quality impacts for the central and north portion of the aquifer system. Decreased water levels in the north and central portion of the aquifer system could induce the flow of potentially poor-quality connate water in the Palm Spring Formation and other undefined Tertiary hydrogeologic units underlying the Quaternary alluvium in the north portion of the aquifer system, and adjacent to the Quaternary alluvium in the central portion of the aquifer system.

It is clear that the Borrego Valley aquifer system cannot sustain the current imbalance between groundwater discharge and groundwater recharge.

CHAPTER VII

MODEL SENSITIVITY

The transient calibrated numerical model was used to determine the sensitivity of the model to changes in the hydraulic properties of the aquifer system as well as changes to the parameters which define evapotranspiration rates. The sensitivity analysis was accomplished in multiple runs, during which only one parameter was changed, while the others were held constant. The parameter evaluated was varied over a range of values (as a multiplier of the calibrated value), and the effects of the change were determined by computing the sum of squared residuals. The sum of squared residuals was based on differences between observed and computed water levels for the seven select transient targets, previously described. The residual is the arithmetic difference between observed and computed water levels for the same time period. The residuals are squared to remove negative numbers, and then summed to represent all seven targets simultaneously. Sensitivity analyses were conducted to evaluate model sensitivity to (1) horizontal hydraulic conductivity, (2) vertical hydraulic conductivity, (3) specific yield, and (4) evapotranspiration variables (rate and extinction depth). The following summaries present the results of each.

Sensitivity to Hydraulic Conductivity

The horizontal hydraulic conductivity of all seven soil textures in the numerical model were independently varied using multipliers of 0.1, 0.5, 1.0, 5.0, and 10.0 times the calibrated value. The medium sand and fine sand/silt were the most sensitive of the soil textures (Figure 92). The vertical hydraulic conductivity of the soil textures were varied using the same multiplier of the calibrated value, described above. The coarse sand and clay soil textures were the most sensitive (Figure 93). Relative to the sensitivity of several soil textures to horizontal hydraulic conductivity, however, they are insensitive to changes. The sensitivity of medium sand and fine sand/silt to changes is due to the distribution of these soil textures near the central portion of the basin (groundwater discharge area). Soil textures

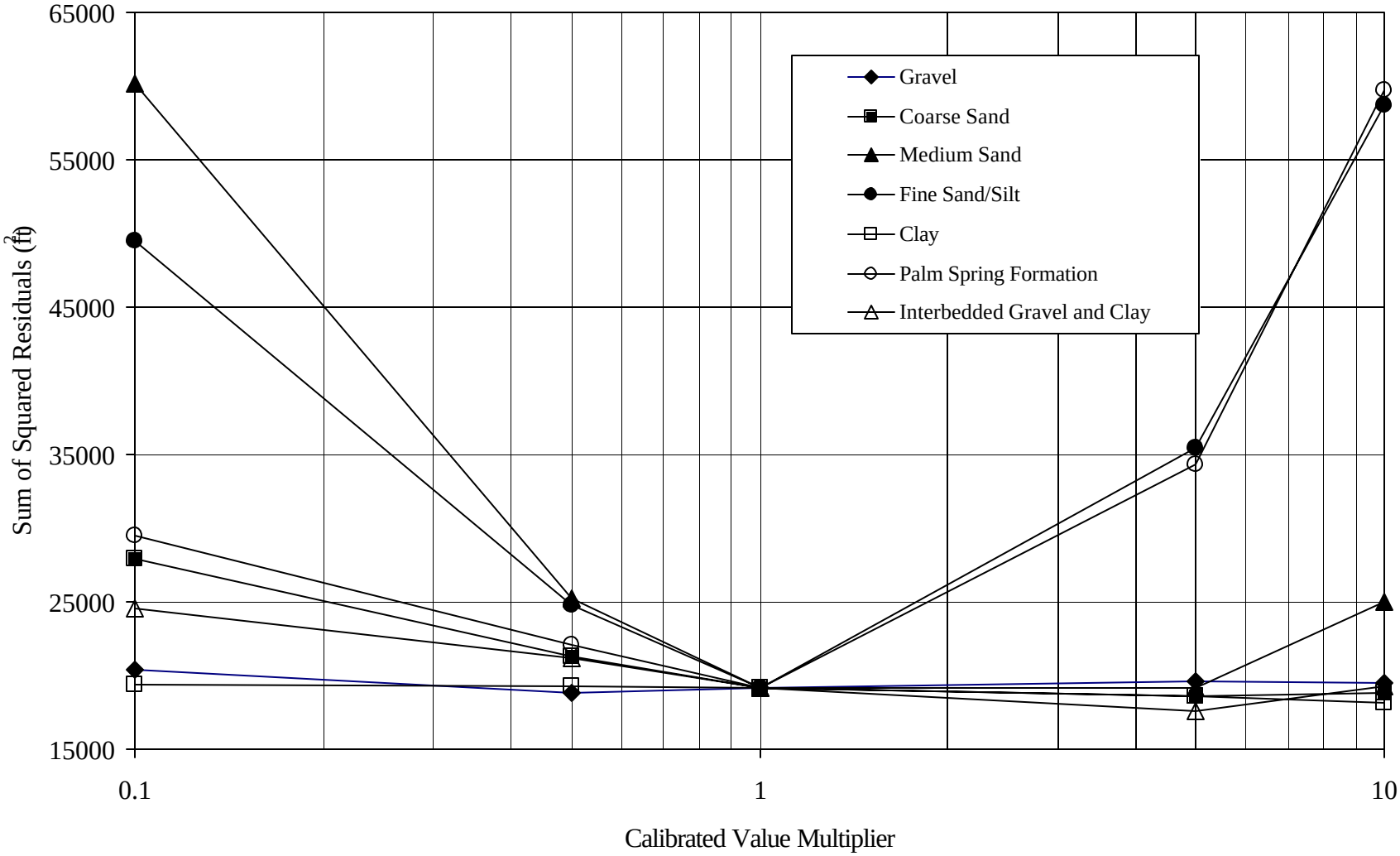

Figure 92. Summary of soil texture sensitivity to horizontal hydraulic conductivity.

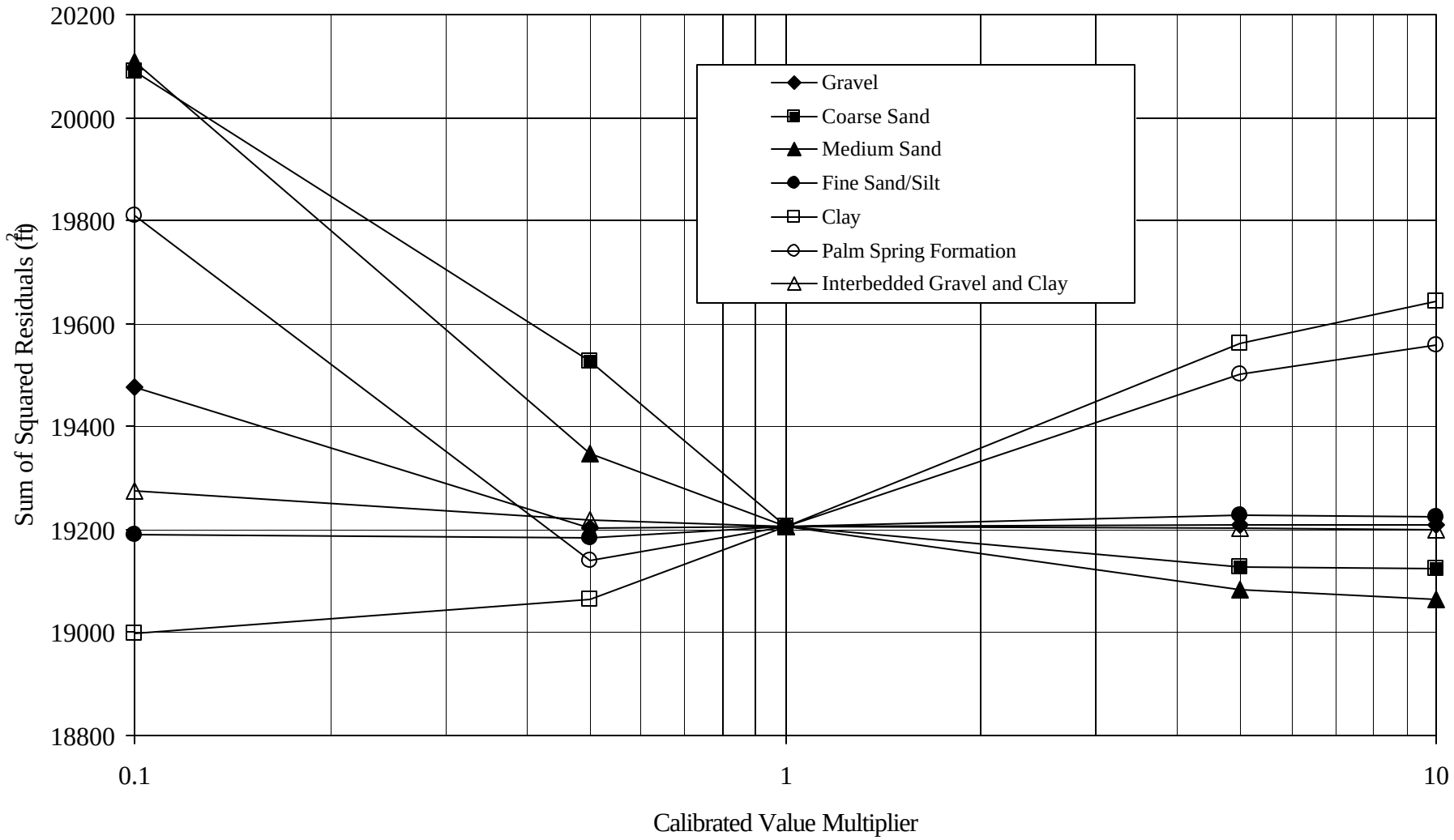

Figure 93. Summary of soil texture sensitivity to vertical hydraulic conductivity.

around the margins of the basin tend to be coarse-grained due to their depositional environment, and are more capable of transmitting recharge than finer grained soil textures.

Sensitivity to Specific Yield

The specific yield of all seven soil textures in the numerical model were varied using multipliers of 0.1, 0.5, 1.0, 1.5 and 2.0 times the calibrated value. The model is most sensitive to the specific yield of the coarse and medium sand soil textures (Figure 94), and in particular, decreased specific yield in those textures. Hydrographs and maps presented previously show that the greatest fluctuations in water levels occur around the margins of the basin. Water levels in the central portion of the basin fluctuate much less than in other areas. The distribution of coarse and medium sand is generally between those two areas, and coincident with areas of groundwater pumpage. The aquifer's ability to yield and store water in response to these fluxes is controlled largely by these two soil textures. Relative to the other physical properties of each soil texture, the aquifer system is most sensitive to specific yield.

Sensitivity to Evapotranspiration Variables

Evapotranspiration rate was varied using 0.5, 0.75, 1.0, 1.5, and 2.0 times the estimated value. Evapotranspiration extinction depth was varied using 0.25, 0.5, and 0.75 times the estimated value. The model is more sensitive to evapotranspiration depth than to evapotranspiration rate (Figure 95). The model is relatively insensitive to both variables, as described next.

Model Sensitivity Discussion

The four parameters to which the model is most sensitive were combined for overall evaluation (Figure 96). The model is most sensitive to specific yield (Figure 96), particularly for the coarse and medium sand and fine sand/silt soil textures (see also Figure 94). Because the aquifer system is most sensitive to specific yield, efforts should be made to measure specific yield of different aquifer units in the field. Calibrated values of specific yield in the numerical model are based on limited calibration points and are subject to error.

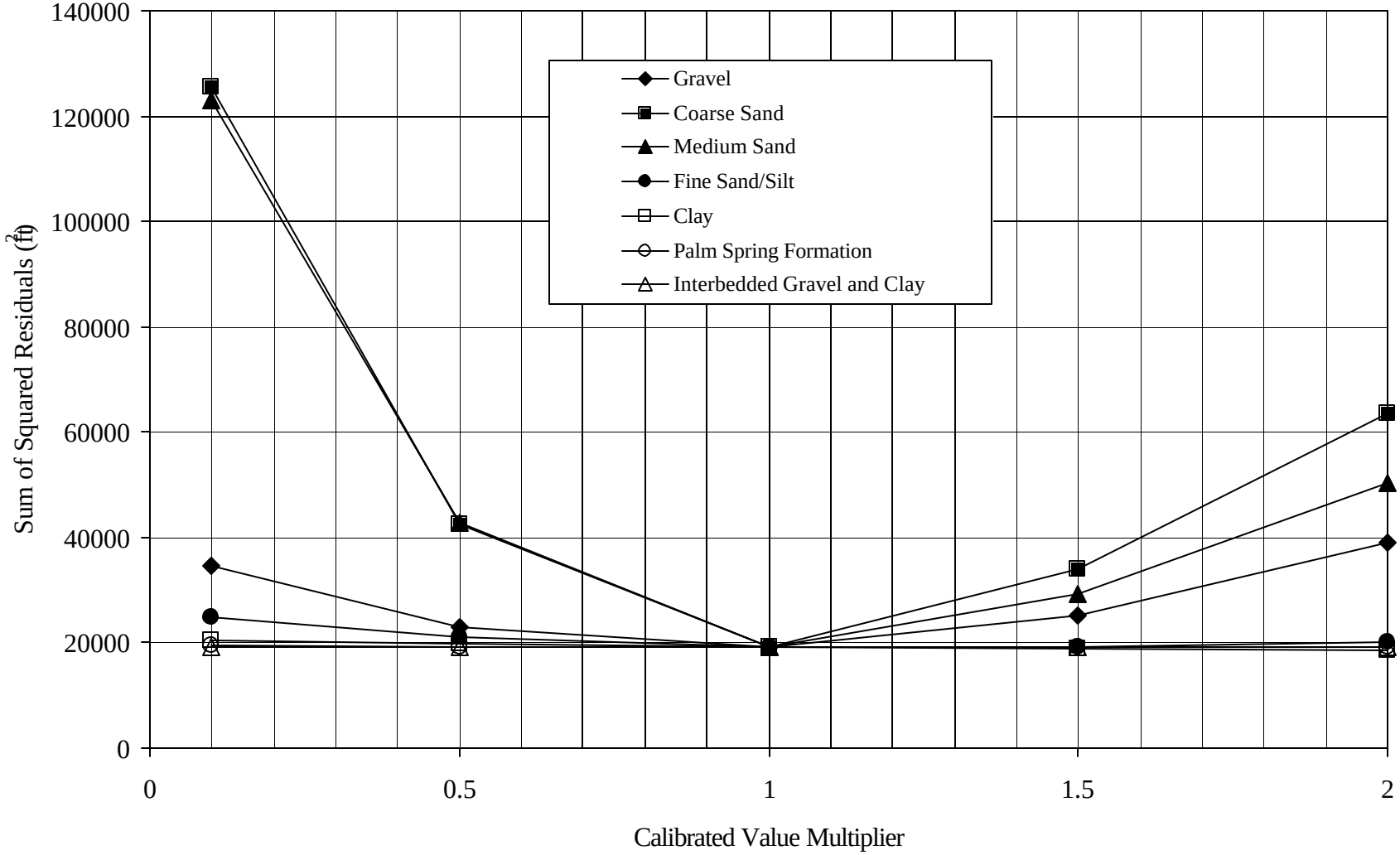

Figure 94. Summary of soil texture sensitivity to specific yield.

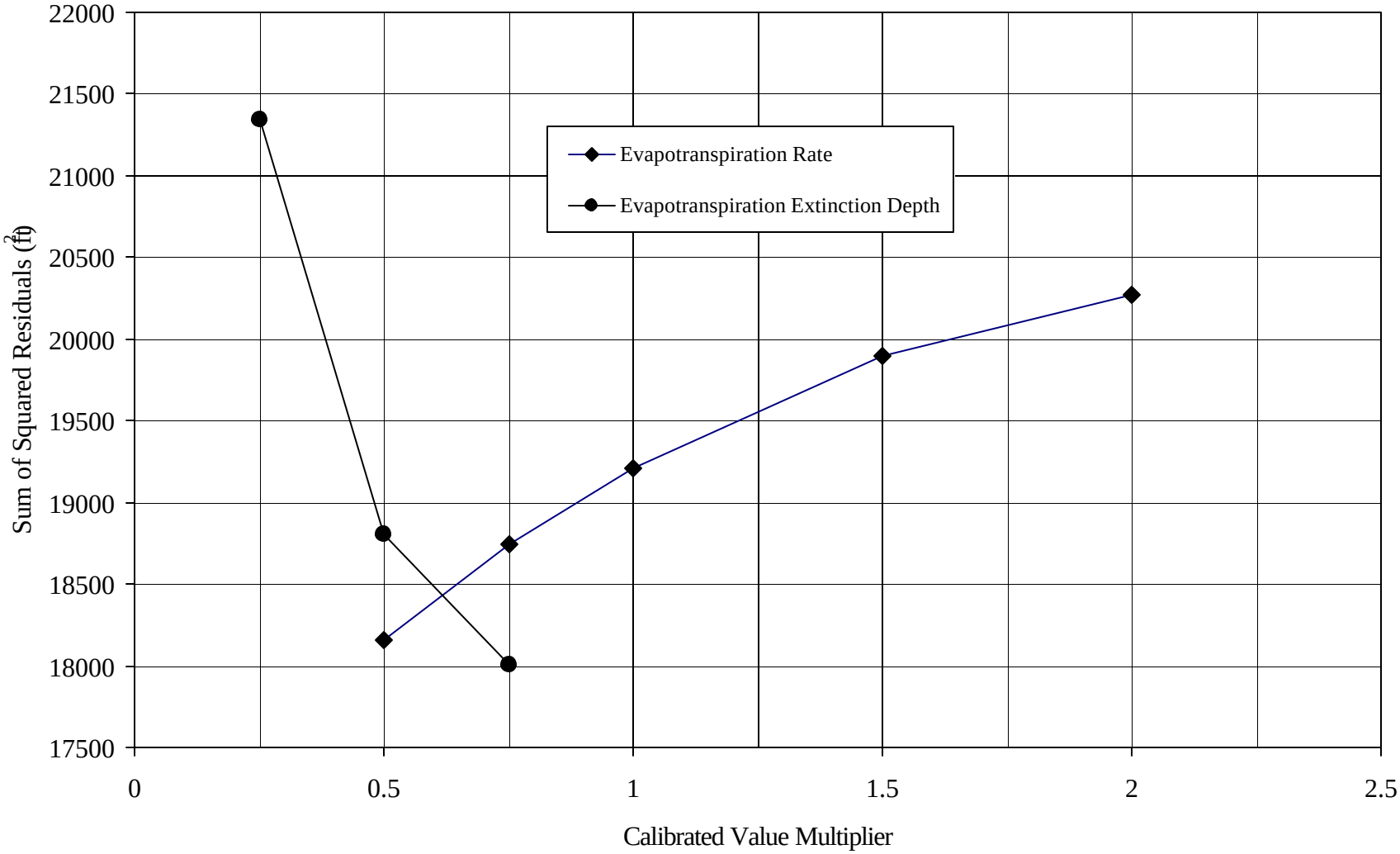

Figure 95. Summary of model sensitivity to evapotranspiration parameters.

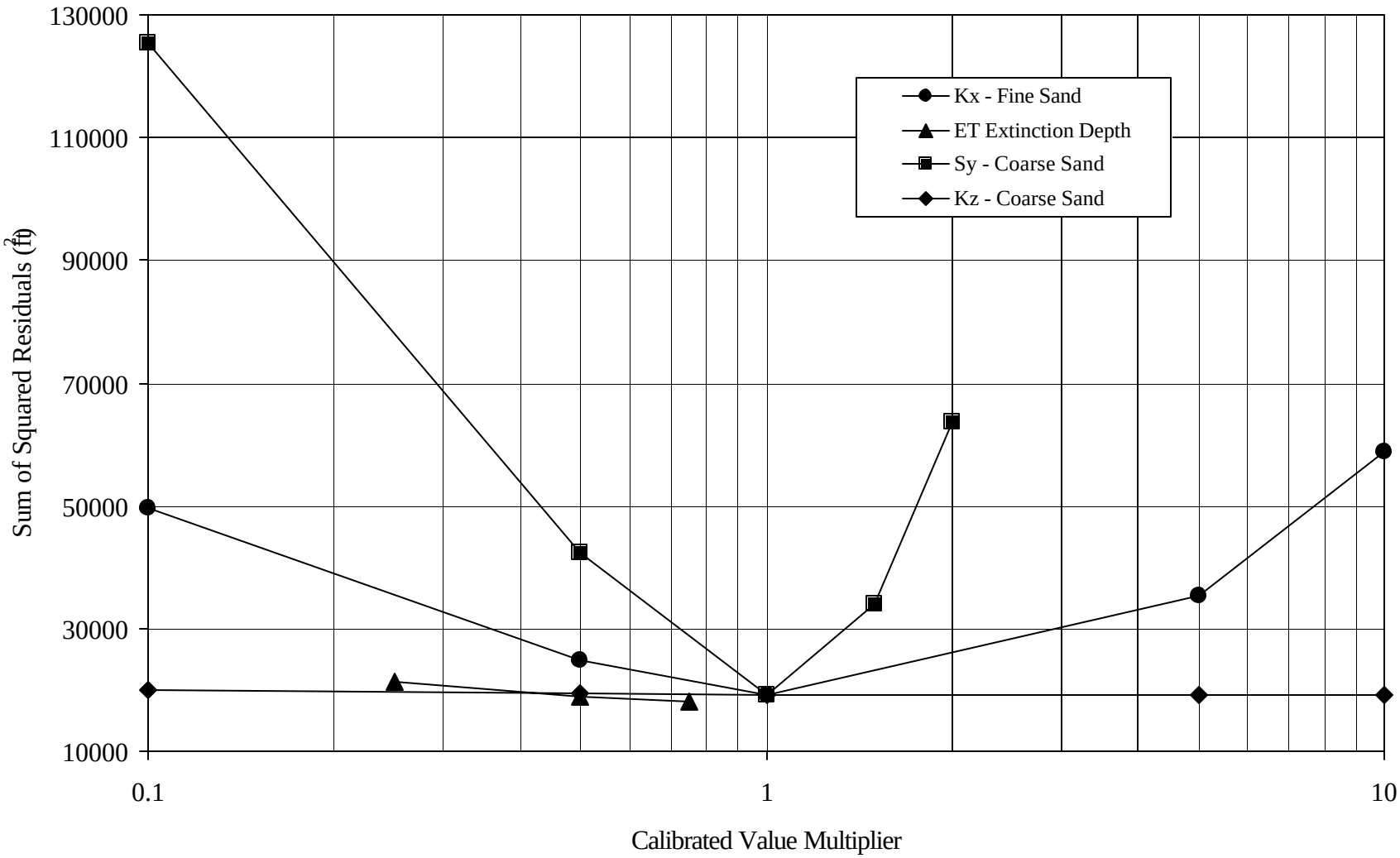

Figure 96. Summary of most sensitive modeling variables.

Sensitivity to estimated values of recharge was not checked. Changes in groundwater storage (water levels) are dependent on both recharge and specific yield. For an equivalent change in groundwater storage, increased specific yield requires decreased recharge. For the same change, decreased specific yield requires more recharge. The calibrated values of specific yield in the current model are dependent on the changes in storage predicted by the water budget described in Chapter IV.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

This purpose of this study was to (1) develop a conceptual model of the aquifer system, (2) develop a numerical model to represent the aquifer system, (3) utilize the numerical model to evaluate historic groundwater trends, and (4) utilize the numerical model to predict future conditions for two groundwater use scenarios. Completion of these objectives lead to development of the conclusions and recommendations listed below.

Conclusions

Completion of this study allowed for the development of many conclusions. These conclusions relate to the geology and hydrogeology of Borrego Valley, development and calibration of the numerical model, and the results of predictive modeling, all described below.

Geology and Hydrogeology

Evaluation of the geology and hydrogeology of the Borrego Valley aquifer system revealed the following:

- The aquifer system in Borrego Valley is comprised of four hydrologeologic units of Quaternary and Tertiary Age. The units are the Quaternary younger alluvium, intermediate-age alluvium, older alluvium, and the Tertiary Palm Spring Formation (inclusive of any older Tertiary sediments not identified). The three Quaternary alluvium units have the ability to yield water to wells, and are important sources or groundwater to Borrego Valley.
- The Quaternary older alluvium is the primary water-bearing hydrogeologic unit in Borrego Valley. This is due in part to the coarse grained nature of this unit, and its thickness in the north portion of Borrego Valley, in the principal agricultural production area.
- The Tertiary Palm Spring formation, is the thickest unit in Borrego Valley. This unit has, by far, the largest volume of sediments in Borrego Valley. This unit is not an important source of groundwater to Borrego Valley. In fact, groundwater contributed to the primary aquifer system (Quaternary alluvial units) in response to overdraft has the potential to be low-quality and may cause degradation of the primary aquifer system.

- The Cretaceous granitic rocks which form the basement complex of the aquifer system are deeper than previously reported. This results in a thicker sequence of Tertiary sediments below Quaternary alluvium.
- The four hydrogeologic units described above are well differentiated near the middle of the aquifer system. The three Quaternary hydrogeologic units are poorly differentiated around the margins of the aquifer system.
- Based on the new conceptual model and numerical modeling, much of the north portion of Borrego Valley appears isolated from the south portion. Isolation occurs due to the geometry of the basement complex, particularly in the vicinity of San Felipe Creek, as well as the thick sequence of Palm Spring Formation which crops out at ground surface in the vicinity of Desert Lodge and the Sleepy Hollow Folds.
- The water budget calculated for the period 1945 through 2000 (as fully reported by Netto, 2001) is significantly different from those calculated by previous authors.
- Bedrock recharge contributes a significant quantity of recharge to the aquifer system in select years, as fully reported by Netto (2001).
- The water budget calculated for this study indicates a long-term imbalance between groundwater recharge and discharge (Netto, 2001).

Numerical Model Calibration

Construction and calibration of a numerical model was completed to represent the Borrego Valley aquifer system. This model was calibrated to steady-state (1945) and transient-state (1945 through 2000) conditions. The following information summarizes key details of the model, or provides conclusions based on model calibration:

- A numerical model comprised of six layers, with 2000-foot by 2000-foot cells was constructed to represent the aquifer system. Layers 1 through 3 of the model represent the Quaternary alluvium hydrogeologic units. Layers 4 through 6 represent different portions of the Tertiary Palm Spring Formation.
- The numerical model was calibrated to steady-state conditions (pre-1945). However, many uncertainties relative to the water level targets utilized for this calibration exist. The results of steady-state calibration should be used cautiously. Calibrated values of hydraulic conductivity for different soil textures among the hydrogeologic units yield transmissivities which are generally consistent with those calculated from aquifer testing at select wells (Netto, 2001). More aquifer tests and further basin characterization will provide more information for confirmation of model calibrated values, or the basis for model updates.
- The numerical model was calibrated to transient-state conditions (1945 through 2000). Calibration is based on twenty target wells distributed spatially throughout the central and north-central portion of the aquifer system. The quality of calibration at these target wells ranges from poor to good. Calibration as a whole is considered good, and the model is expected to accurately represent conditions in the aquifer system, as currently understood. Calibrated values of specific yield for different soil textures among the

hydrogeologic units are reasonable. No measured (from aquifer tests) values of specific yield, were found that would provide a basis for comparison with model calibration estimates. Aquifer tests with suitably located and constructed observation wells could provide specific yield information to either confirm model calibrated values or provide the basis for model updates.

- Numerical modeling of the aquifer system for the period 1945 through 2000 show that imbalances between groundwater recharge and groundwater discharge have had a marked effect on groundwater levels throughout the central and north portion of Borrego Valley. Water level declines in those areas range from 17 to 140-feet for that period.

Predictive Modeling

The calibrated numerical model was used to evaluate future groundwater use scenarios. Conclusions based on that modeling are provided below:

- The expected use scenario developed by SD Co. DPLU staff results in an increasing imbalance between groundwater recharge and discharge for the period 2001 through 2030. When simulated with the numerical model, water levels decline throughout the central and north portions of the basin, at non-linear (increasing) rates. Increasing rates of decline are due to increasing groundwater extraction as well as the geometry of the aquifer system. Water levels are predicted to drop throughout the central and north portion of Borrego Valley for the period 2001 through 2030. Water level declines in those areas range from 50 to 110 feet for that period.
- Relative to the expected use scenario, the worst-case use scenario developed by SD Co. DPLU staff results in an even greater imbalance between groundwater recharge and discharge for 2001 through 2030. Rates of water level decline also increase with time. Water levels are predicted to decline throughout the central and north portion of Borrego Valley, with predicted declines ranging from 90 to 170 feet.

Summary

Based on the work conducted as part of this study, conceptual and numerical models of the aquifer system were developed. The numerical model was utilized to evaluate historic and estimated future conditions. Numerical modeling results indicate that the basin has been, and continues to be in overdraft. The long-term imbalance between groundwater discharge and recharge is expected to increase. The potential for significant adverse impacts is high. Adverse impacts under the worst case predictive use scenario would occur sooner than under the expected use scenario. However adverse impacts will occur at some point in either case. The consequences of groundwater mining are significant from an ecological and economic perspective.

Recommendations

Management of the groundwater resource in Borrego Valley is an important issue that must be addressed. However, this study is not intended to provide any policy guidance, and recommendations for institutional management of the resource are not provided. Recommendations provided herein are focused on work which would supplement information presented in this study. These recommendations deal primarily with the physical, specifically hydrogeologic, aspects of the aquifer system.

1. More aquifer testing is recommended. More aquifer tests can provide information about the water-bearing characteristics of the aquifer system and individual hydrogeologic units. Aquifer testing should be conducted in a controlled-manner, such that the quality of data generated would satisfy the objectives of testing.
2. Observation well drilling is recommended. Observation wells located in close proximity to production wells that can be tested would yield valuable information about the groundwater storativity (e.g. specific yield) of the aquifer system and individual hydrogeologic units. There are no known (measured) values of storativity for Borrego Valley hydrogeologic units. Observation well drilling also provides an additional benefit of verification of the depth and physical nature of hydrogeologic units. Observation well drilling should be conducted in a controlled-manner, such that the quality of data generated would satisfy the objectives of testing.
3. An inventory of all wells in Borrego Valley should be completed. This inventory would provide the basis for a monitoring program (see below). The inventory should include a review of available data for each of the known wells.
4. Based on the results of the well inventory, and comparison with the conceptual model, a monitoring program should be established for monitoring water levels and water quality throughout the aquifer system. The frequency and density of periodic monitoring would be determined based on available data. Monitoring should be conducted until such a time that the basin is no longer in overdraft (when long-term discharge no longer exceeds long-term recharge).
5. The numerical model should be updated and re-calibrated as new data become available. The numerical model should be utilized to predict and monitor future conditions, as well as to evaluate different groundwater management scenarios.

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APPENDIX A

MAGIXPLUS PROFILES AND DATA FROM AGBABIAN ASSOCIATES

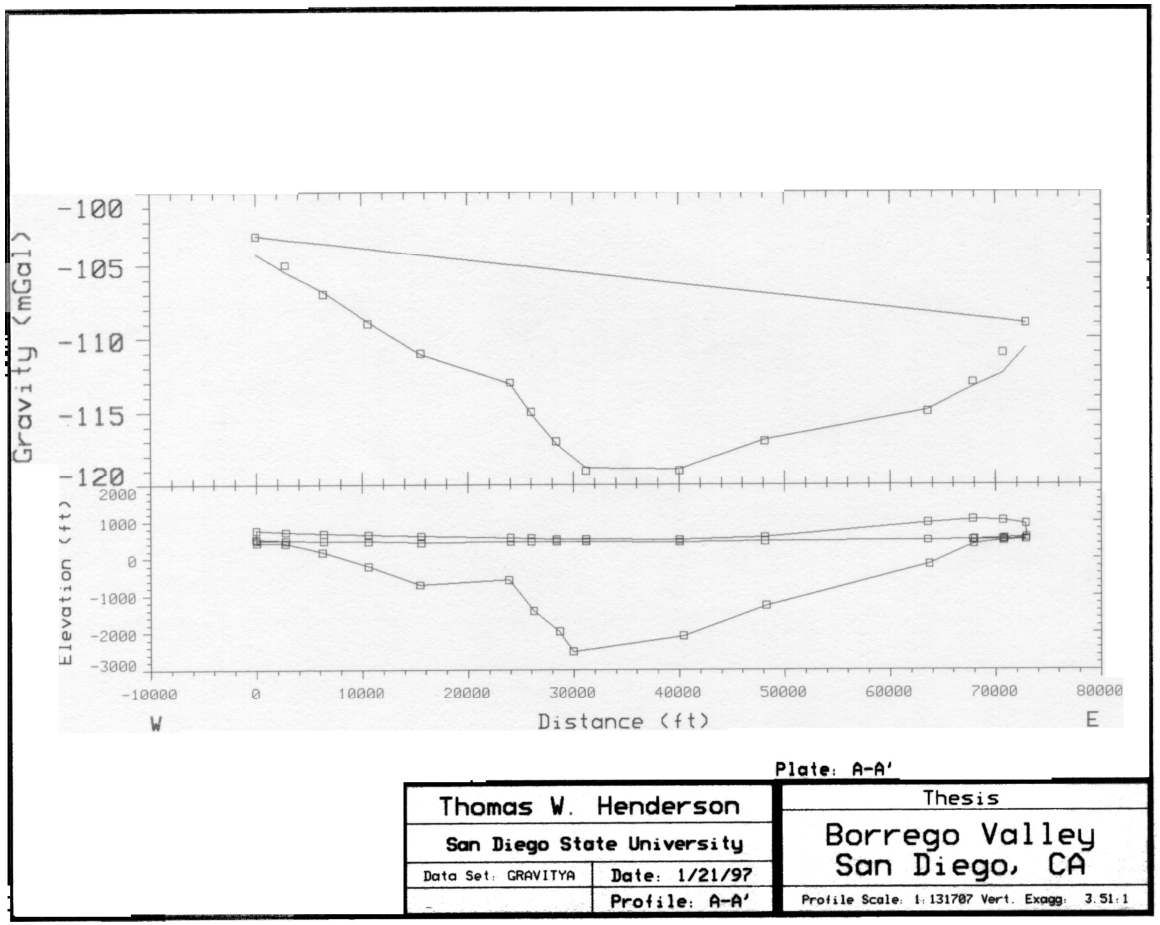


Figure 97. MagixPlus residual gravity anomaly and calculated basement depth (profile A-A')

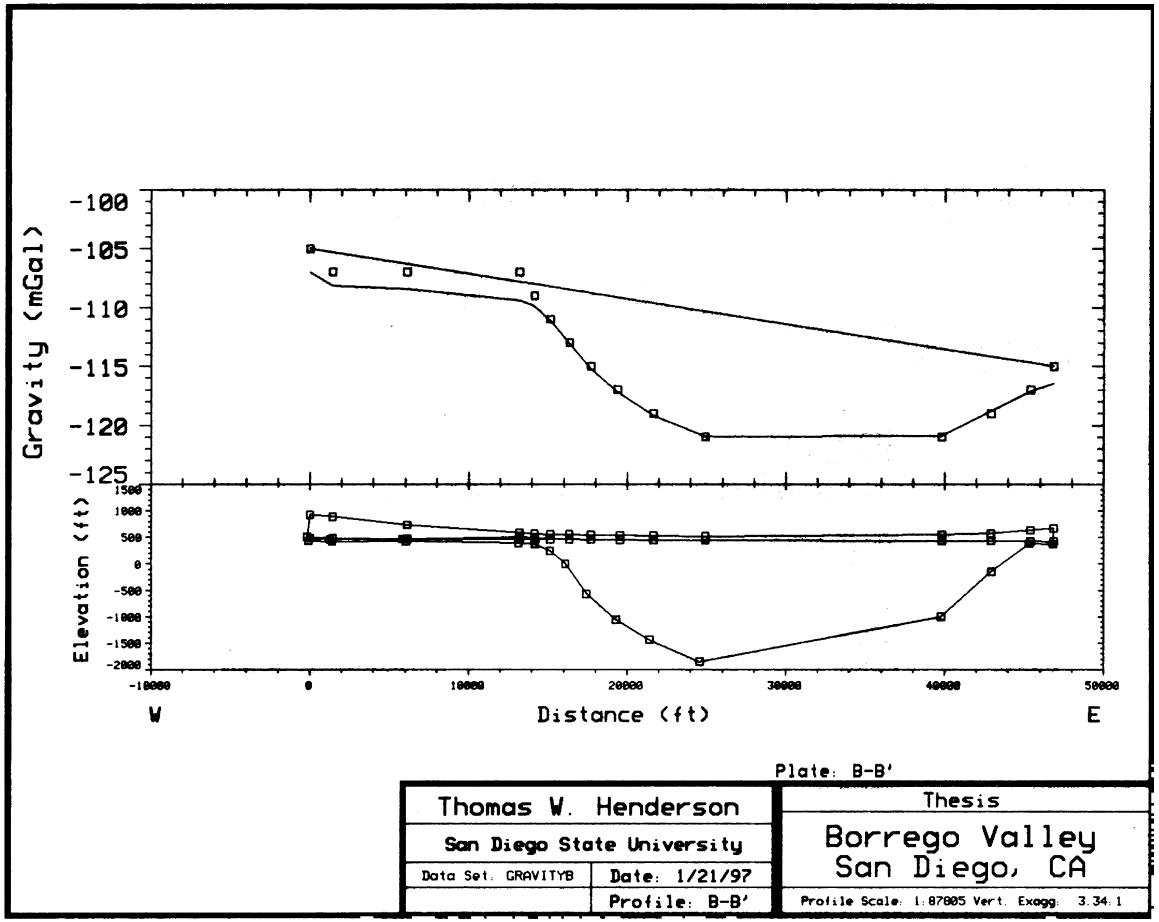


Figure 98. MagixPlus residual gravity anomaly and calculated basement depth (profile B-B').

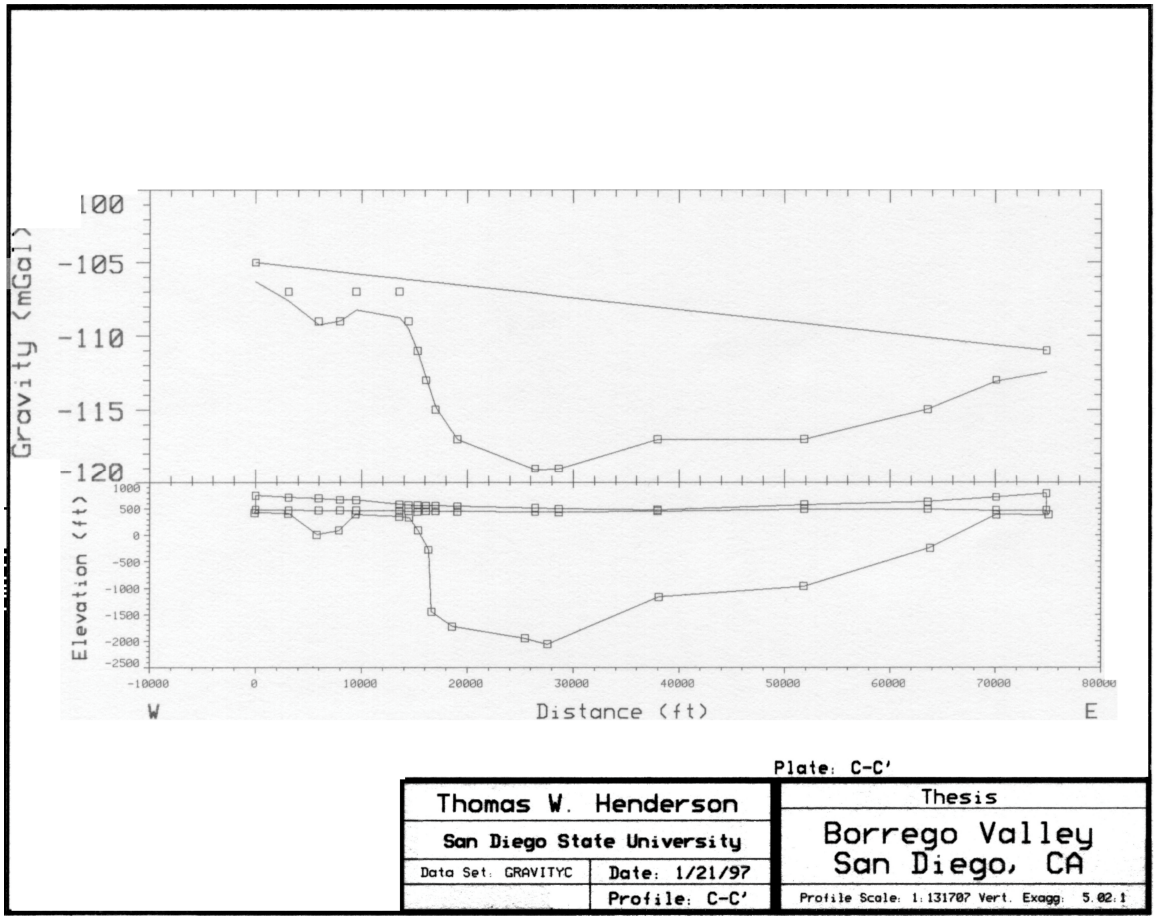


Figure 99. MagixPlus residual gravity anomaly and calculated basement depth (profile C-C').

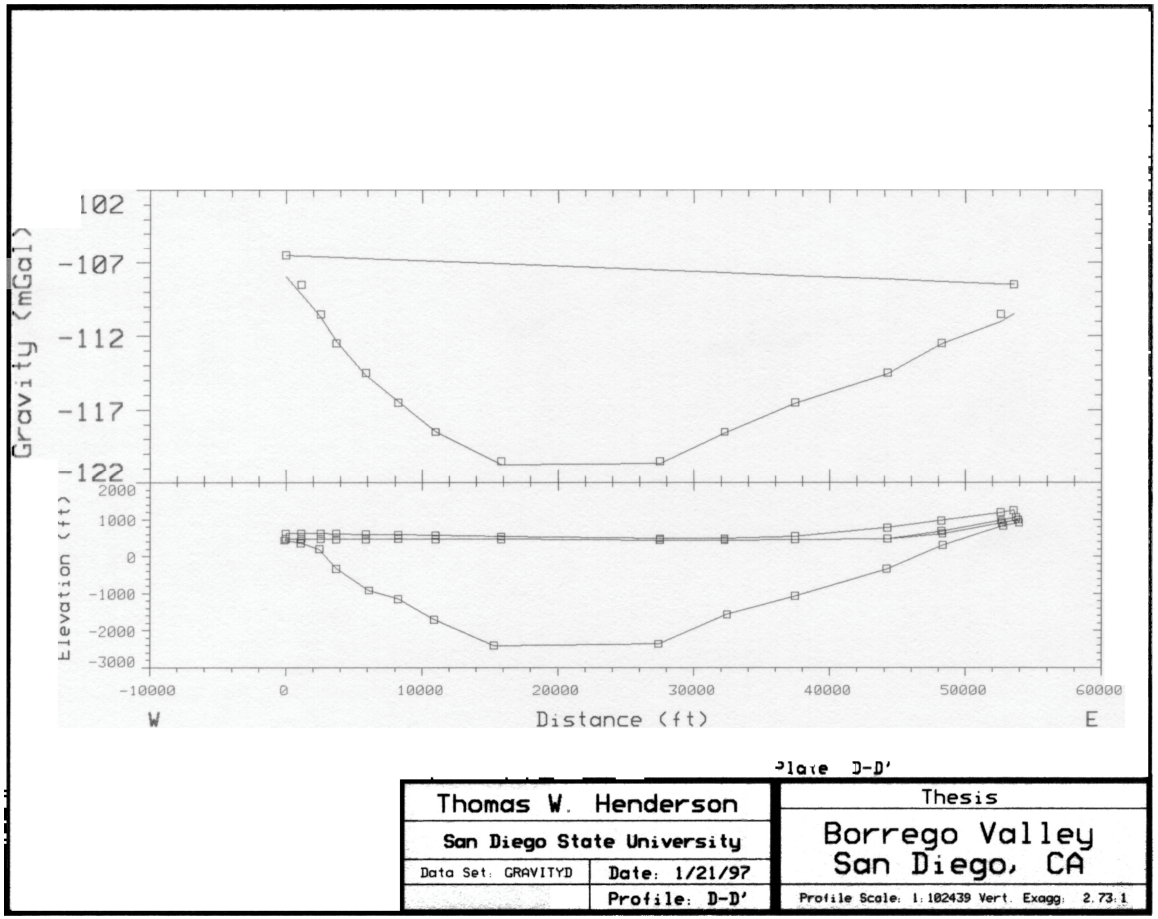


Figure 100. MagixPlus residual gravity anomaly and calculated basement depth (profile D-D').

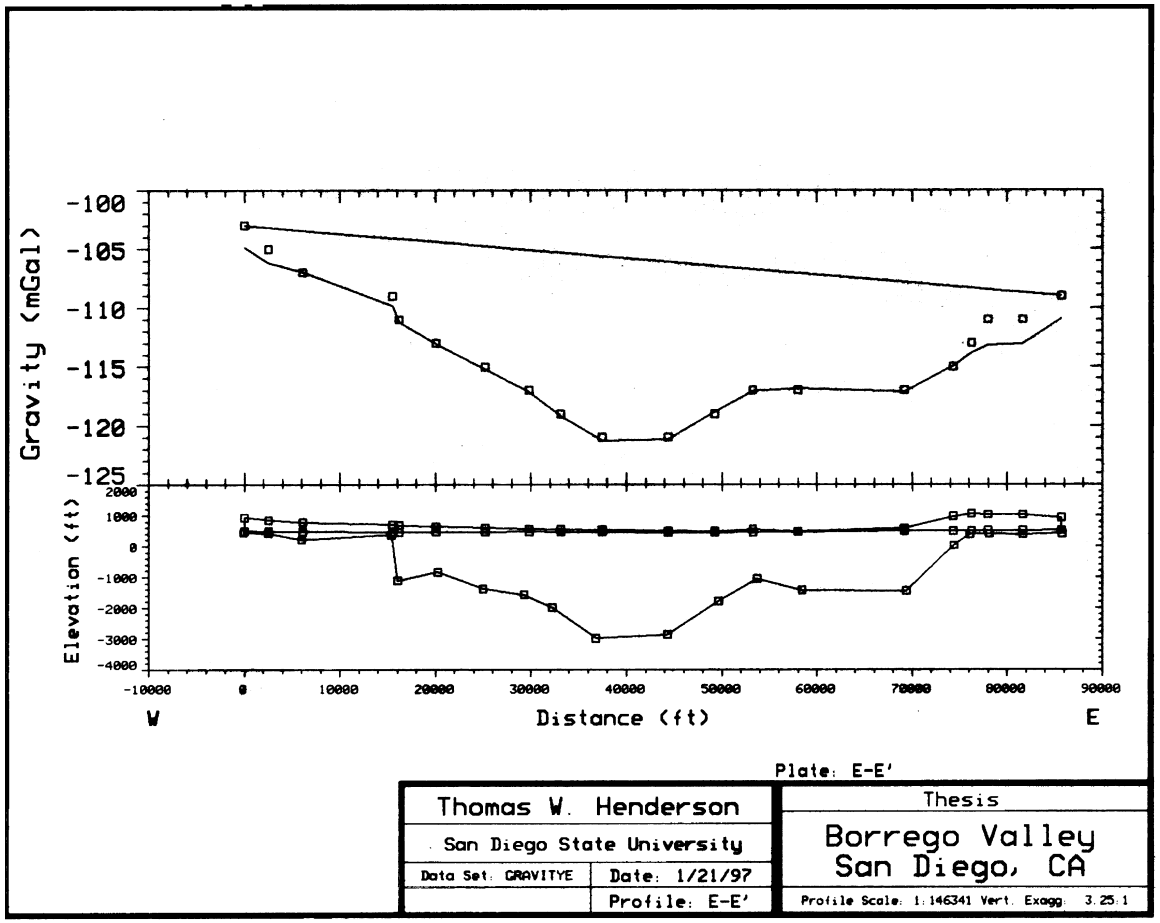


Figure 101. MagixPlus residual gravity anomaly and calculated basement depth (profile E-E').

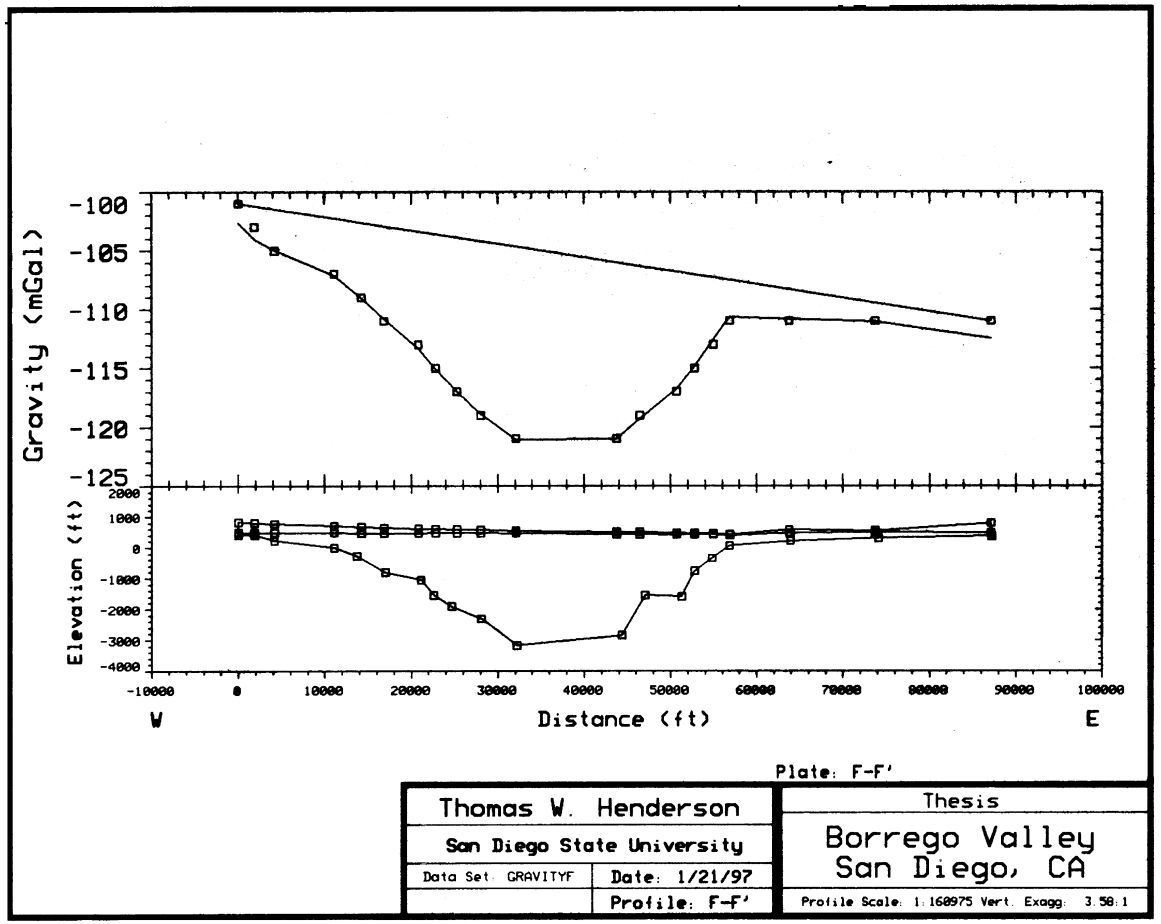


Figure 102. MagixPlus residual gravity anomaly and calculated basement depth (profile F-F').

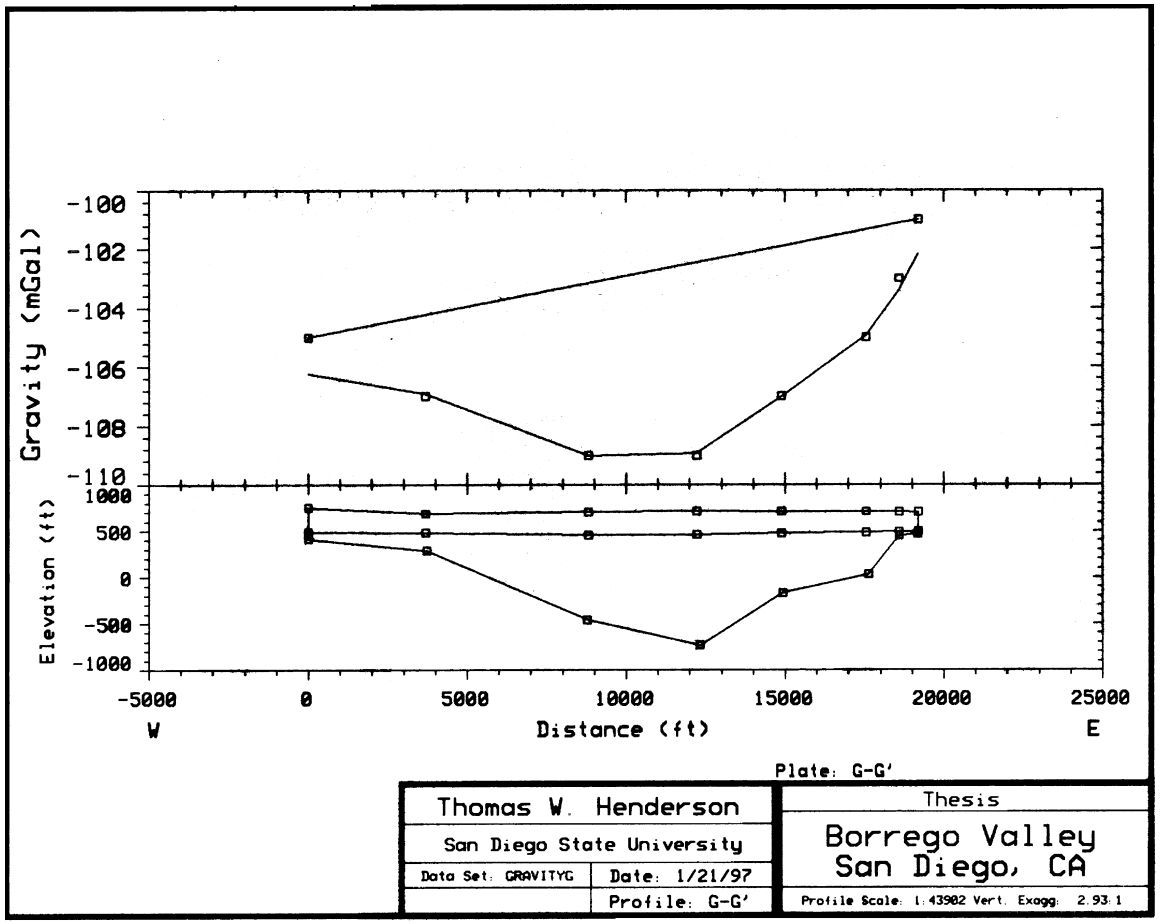


Figure 103. MagixPlus residual gravity anomaly and calculated basement depth (profile G-G').

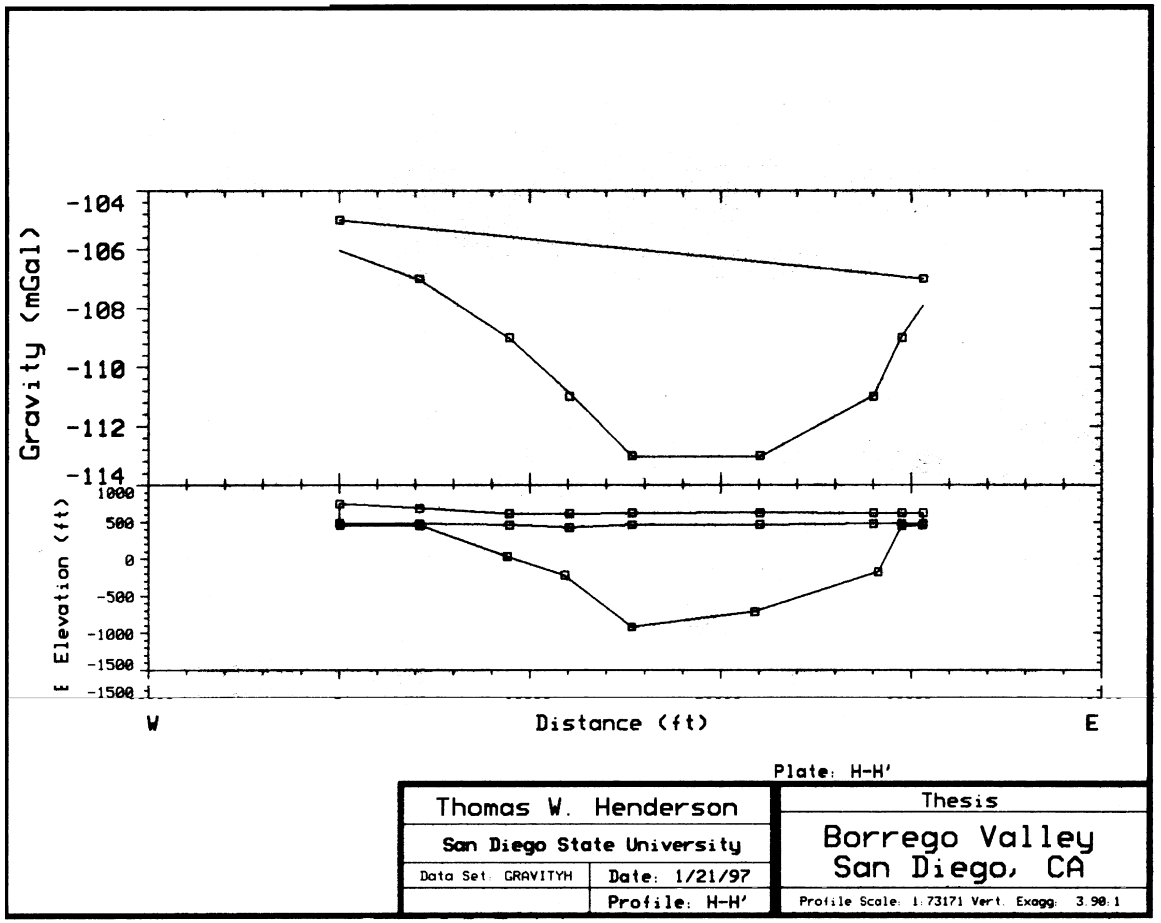


Figure 104. MagixPlus residual gravity anomaly and calculated basement depth (profile H-H').

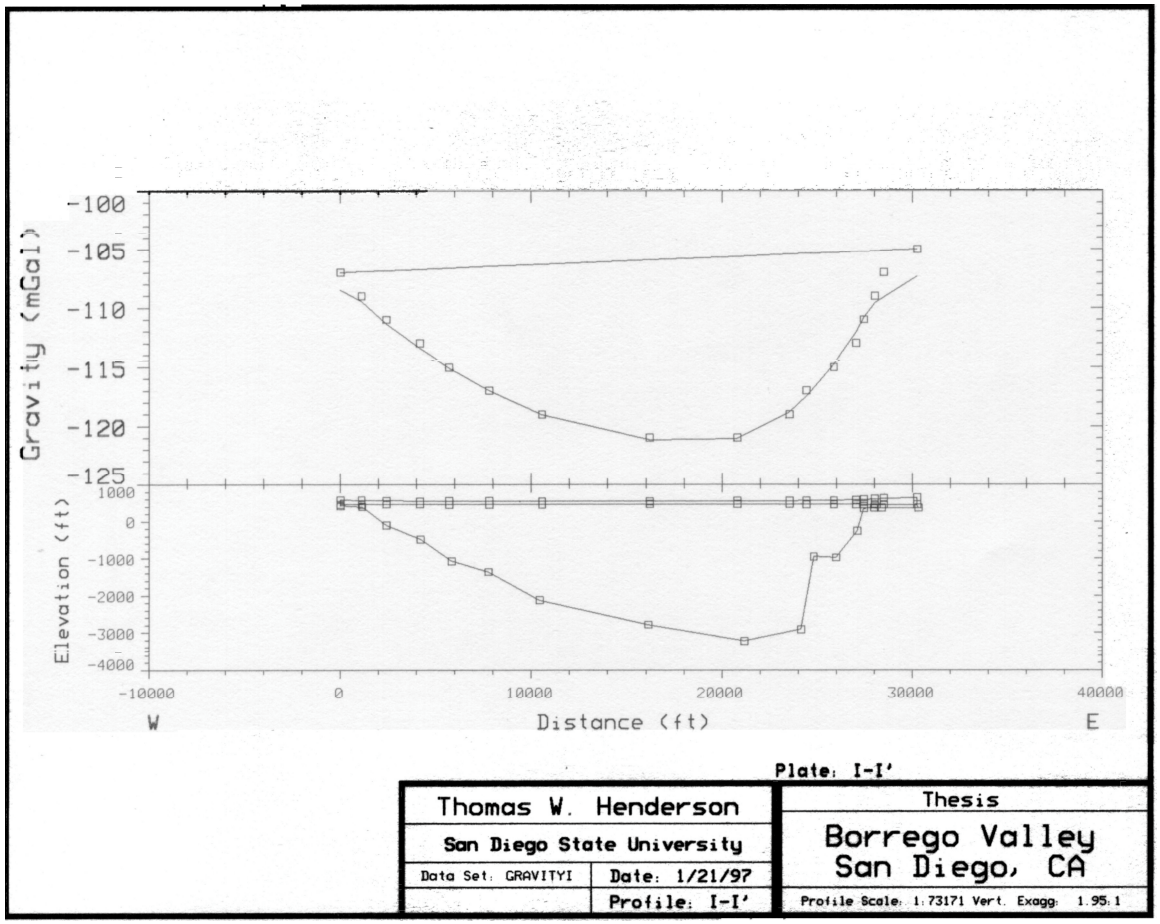


Figure 105. MagixPlus residual gravity anomaly and calculated basement depth (profile I-I').

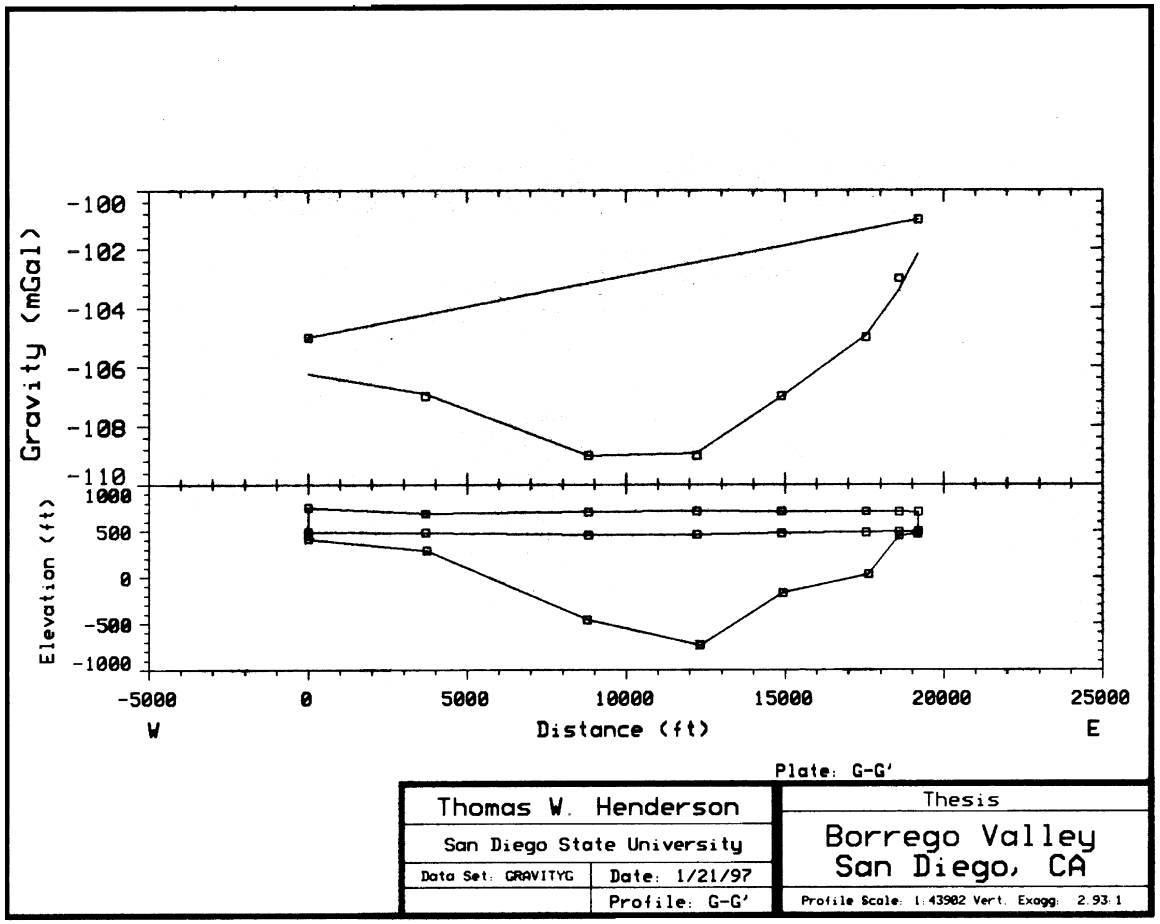


Figure 106. MagixPlus residual gravity anomaly and calculated basement depth (profile J-J').

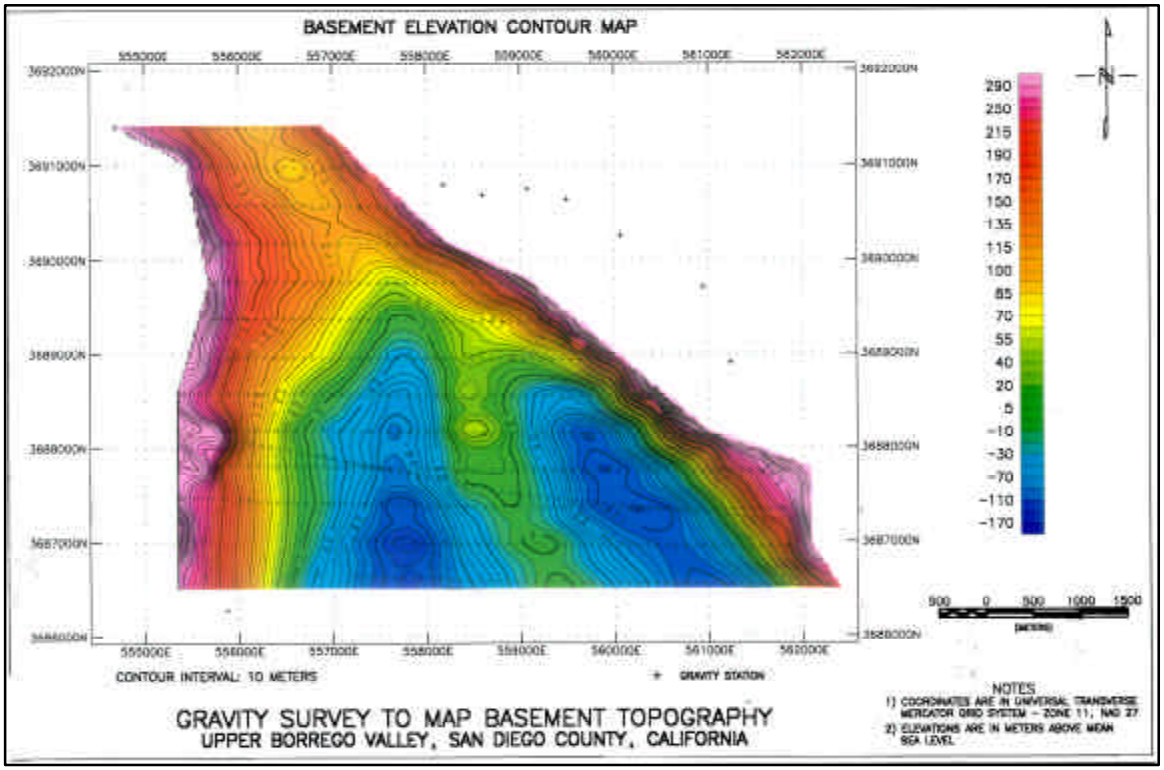


Figure 107. Basement elevation contour map of upper Borrego Valley (as interpreted by Agbabian Associates).

APPENDIX B

WATER BUDGET SUMMARY DATA AND HISTORIC LAND USE MAPS

Table 9

Observed and Calculated Surface Water Recharge - 1946 Through 2000

Year	Borrego Palm Creek (acre-feet)	Coyote Creek (acre-feet)	Upper San Felipe Creek (acre-feet)	Coyote Mountain (acre-feet)	South Coyote Canyon (acre-feet)	Northwest Slopes (acre-feet)	Henderson Canyon (acre-feet)	Indian Head (acre-feet)	South Borrego Palm Canyon (acre-feet)	Hellhole Canyon (acre-feet)	Dry Canyon (acre-feet)	Culp/Tubb Canyon (acre-feet)	Pinyon Ridge (acre-feet)	Lower San Felipe Creek (acre-feet)	East San Felipe Creek (acre-feet)	Totals (acre-feet)
1946	1,040	1,720	280	50	40	30	60	10	9	130	20	130	90	730	20	4,359
1947	590	1,530	220	40	30	20	40	10	7	100	20	100	70	560	10	3,346
1948	470	1,090	0	30	20	20	30	6	4	70	10	70	40	370	8	2,239
1949	800	1,380	170	40	30	20	40	10	7	100	20	100	70	560	10	3,356
1950	13	1,230	50	20	20	10	20	5	4	60	9	60	40	310	7	1,858
1951	270	2,410	460	60	40	30	60	10	9	140	20	140	90	750	20	4,509
1952	980	2,330	690	70	50	40	70	20	10	180	30	170	110	960	20	5,730
1953	240	1,650	280	40	30	20	40	9	6	100	20	90	60	520	10	3,115
1954	300	1,820	340	40	30	30	50	10	7	110	20	110	70	590	10	3,537
1955	360	1,730	340	40	30	20	50	10	7	110	20	110	70	580	10	3,486
1956	230	1,520	240	30	20	20	40	8	6	90	10	90	60	480	10	2,854
1957	150	420	50	10	7	6	10	3	2	30	4	30	20	150	3	895
1958	720	1,860	490	50	40	30	60	10	9	140	20	130	90	730	20	4,399
1959	140	1,500	240	30	20	20	40	8	5	80	10	80	50	450	10	2,682
1960	150	1,490	220	30	20	20	30	8	5	80	10	80	50	440	9	2,643
1961	40	1,440	160	30	20	20	30	7	5	70	10	70	50	390	8	2,350
1962	130	1,020	170	20	20	10	20	5	4	60	9	60	40	310	7	1,885
1963	60	1,320	140	30	20	20	30	6	4	70	10	70	40	360	8	2,189
1964	110	1,100	130	20	20	10	30	5	4	60	9	60	40	320	7	1,925
1965	170	1,580	120	30	20	20	40	8	5	80	10	80	50	450	9	2,672
1966	270	1,190	290	30	20	20	30	7	5	80	10	80	50	420	9	2,511
1967	110	1,140	410	30	20	20	30	7	5	70	10	70	50	400	8	2,380
1968	120	890	90	20	10	10	20	4	3	50	8	50	30	260	6	1,571
1969	720	960	250	30	20	20	40	8	5	90	10	80	60	460	10	2,763
1970	130	1,110	180	20	20	10	30	6	4	60	10	60	40	340	7	2,027
1971	60	910	110	20	10	10	20	4	3	50	7	50	30	260	5	1,550
1972	9	980	70	20	10	10	20	4	3	50	7	50	30	250	5	1,519
1973	260	410	90	10	9	8	10	3	2	30	5	30	20	180	4	1,071
1974	50	1,110	100	20	10	10	20	5	4	60	9	60	40	300	6	1,804

Table 9 (continued)

Year	Borrego Palm Creek (acre-feet)	Coyote Creek (acre-feet)	Upper San Felipe Creek (acre-feet)	Coyote Mountain (acre-feet)	South Coyote Canyon (acre-feet)	Northwest Slopes (acre-feet)	Henderson Canyon (acre-feet)	Indian Head (acre-feet)	South Borrego Palm Canyon (acre-feet)	Hellhole Canyon (acre-feet)	Dry Canyon (acre-feet)	Culp/Tubb Canyon (acre-feet)	Pinyon Ridge (acre-feet)	Lower San Felipe Creek (acre-feet)	East San Felipe Creek (acre-feet)	Totals (acre-feet)
1975	70	350	90	10	6	5	9	2	1	20	3	20	10	120	3	720
1976	100	450	150	10	8	7	10	3	2	30	5	30	20	170	4	998
1977	310	1,450	110	30	20	20	40	8	5	80	10	80	50	450	9	2,672
1978	770	1,810	760	60	40	30	60	10	9	150	20	150	100	800	20	4,789
1979	2,460	2,390	430	90	60	50	100	20	20	230	40	230	150	1,260	30	7,560
1980	5,700	11,260	4,820	390	250	220	400	90	60	960	150	940	620	5,210	110	31,180
1981	1,120	3,360	320	90	60	50	90	20	10	210	30	210	140	1,150	20	6,880
1982	1,560	2,960	860	100	60	60	100	20	20	240	40	230	150	1,290	30	7,720
1983	4,990	8,980	3,590	310	200	180	320	70	50	770	120	760	500	4,200	90	25,130
1984	1,410	3,130	1,000	100	60	60	100	20	20	240	40	240	160	1,330	30	7,940
1985	970	2,410	690	70	50	40	80	20	10	180	30	180	120	970	20	5,840
1986	790	2,130	560	60	40	40	60	10	10	150	20	150	100	830	20	4,970
1987	510	1,680	360	50	30	30	50	10	7	110	20	110	70	610	10	3,658
1988	400	1,490	280	40	30	20	40	9	6	100	20	90	60	520	10	3,115
1989	230	1,210	160	30	20	20	30	6	5	70	10	70	50	380	8	2,299
1990	170	1,120	110	30	20	10	30	6	4	60	10	60	40	340	7	2,016
1991	600	1,820	420	50	30	30	50	10	8	130	20	120	80	680	10	4,058
1992	480	1,610	330	40	30	30	50	10	7	110	20	100	70	580	10	3,477
1993	1,050	2,440	860	80	50	40	80	20	10	190	30	190	120	1,040	20	6,220
1994	1,310	2,570	820	80	50	50	90	20	10	210	30	200	130	1,130	20	6,720
1995	550	1,740	390	50	30	30	50	10	8	120	20	120	80	640	10	3,847
1996	300	1,320	200	30	20	20	30	7	5	80	10	80	50	440	9	2,602
1997	300	1,320	210	30	20	20	30	7	5	80	10	80	50	440	9	2,612
1998	1,540	3,350	1,100	110	70	60	110	20	20	260	40	260	170	1,430	30	8,570
1999	280	1,300	200	30	20	20	30	7	5	80	10	80	50	430	9	2,552
2000	210	1,180	140	30	20	20	30	6	4	70	10	70	40	370	8	2,208

Table 10
Summary of Calculated Bedrock Recharge - 1946 Through 2000

Year	Coyote Mountain (acre-feet)	Dry Canyon (acre-feet)	Hellhole Canyon (acre-feet)	Henderson Canyon (acre-feet)	Indian Head (acre-feet)	Northwest Slopes (acre-feet)	Pinyon Ridge (acre-feet)	South Borrego Palm Canyon (acre-feet)	South Coyote Canyon (acre-feet)	Totals (acre-feet)
1946	0	0	580	0	0	0	0	0	0	580
1947	0	0	0	0	0	0	0	0	0	0
1948	0	0	0	0	0	0	0	0	0	0
1949	0	0	1,350	0	0	0	0	0	0	1,350
1950	0	0	0	0	0	0	0	0	0	0
1951	0	0	0	0	0	0	0	0	0	0
1952	0	0	2,170	360	0	0	390	60	0	2,980
1953	0	0	630	0	0	0	0	0	0	630
1954	0	0	800	0	0	0	0	0	0	800
1955	0	0	910	0	0	0	0	0	0	910
1956	0	0	0	0	0	0	0	0	0	0
1957	0	0	1,460	270	0	0	310	40	0	2,080
1958	0	0	1,600	0	0	0	0	0	0	1,600
1959	0	0	0	0	0	0	0	0	0	0
1960	0	0	500	0	0	0	0	0	0	500
1961	0	0	0	0	0	0	0	0	0	0
1962	0	0	0	0	0	0	0	0	0	0
1963	0	0	0	0	0	0	0	0	0	0
1964	0	0	0	0	0	0	0	0	0	0
1965	0	0	0	0	0	0	0	0	0	0
1966	0	0	2,720	460	0	0	500	70	0	3,750
1967	0	0	1,990	20	0	0	0	5	0	2,015
1968	0	0	0	0	0	0	0	0	0	0
1969	0	0	3,700	520	0	0	460	80	0	4,760
1970	0	0	0	0	0	0	0	0	0	0
1971	0	0	0	0	0	0	0	0	0	0

Table 10 (continued)

Year	Coyote Mountain (acre-feet)	Dry Canyon (acre-feet)	Hellhole Canyon (acre-feet)	Henderson Canyon (acre-feet)	Indian Head (acre-feet)	Northwest Slopes (acre-feet)	Pinyon Ridge (acre-feet)	South Borrego Palm Canyon (acre-feet)	South Coyote Canyon (acre-feet)	Totals (acre-feet)
1972	0	0	0	0	0	0	0	0	0	0
1973	0	0	70	0	0	0	0	0	0	70
1974	290	210	4,100	1,070	90	250	1,450	170	340	7,970
1975	0	0	0	0	0	0	0	0	0	0
1976	0	0	700	90	0	0	70	10	0	870
1977	0	0	0	0	0	0	0	0	0	0
1978	210	240	6,780	1,240	130	330	1,430	200	390	10,950
1979	0	0	1,880	100	0	0	30	20	0	2,030
1980	1,690	630	8,900	2,430	390	980	3,430	380	1,040	19,870
1981	0	0	0	0	0	0	0	0	0	0
1982	0	0	470	0	0	0	0	0	0	470
1983	0	0	1,230	0	0	0	0	0	0	1,230
1984	0	0	0	0	0	0	0	0	0	0
1985	0	0	70	0	0	0	0	0	0	70
1986	0	0	860	0	0	0	0	0	0	860
1987	0	0	0	0	0	0	0	0	0	0
1988	0	0	0	0	0	0	0	0	0	0
1989	0	0	0	0	0	0	0	0	0	0
1990	0	0	0	0	0	0	0	0	0	0
1991	0	0	2,360	180	0	0	5	30	0	2,575
1992	0	70	2,090	470	6	20	610	70	110	3,446
1993	1,990	780	6,720	2,400	450	1,140	3,590	380	1,290	18,740
1994	0	0	0	0	0	0	0	0	0	0
1995	260	200	1,790	640	90	240	950	100	330	4,600
1996	0	0	0	0	0	0	0	0	0	0
1997	0	0	1,460	270	0	0	310	40	0	2,080
1998	0	0	1,600	0	0	0	0	0	0	1,600
1999	0	0	0	0	0	0	0	0	0	0
2000	0	0	500	0	0	0	0	0	0	500

Table 11
Summary of Groundwater Discharge - 1946 Through 2000

	Natural Discharge		Agricultural Discharge				Recreational Discharge			Municipal Discharge			Total Discharge
Year	ET (acre-feet)	Underflow (acre-feet)	Row (acre-feet)	Citrus (acre-feet)	Grape (acre-feet)	Other (acre-feet)	De Anza Country Club (acre-feet)	BSPCSD (acre-feet)	Roadrunner Golf Course (acre-feet)	Borrego Water Company (acre-feet)	BSPCSD (acre-feet)	Borrego Air Ranch (acre-feet)	Total (acre-feet)
1946	-3,960	-6,050	-510	-20	-1,390	0	0	0	0	-140	0	-10	-12,080
1947	-3,930	-5,980	-1,030	-40	-2,780	0	0	0	0	-180	0	-10	-13,950
1948	-3,860	-5,750	-1,540	-60	-4,170	0	0	0	0	-220	0	-10	-15,610
1949	-3,760	-5,500	-2,060	-70	-5,550	0	0	0	0	-260	0	-10	-17,210
1950	-3,620	-5,280	-2,570	-90	-6,940	0	0	0	0	-300	0	-10	-18,810
1951	-3,440	-5,110	-3,090	-110	-8,330	0	0	0	0	-340	0	-10	-20,430
1952	-3,220	-4,960	-3,600	-130	-9,720	0	0	0	0	-380	0	-10	-22,020
1953	-2,990	-4,870	-4,110	-150	-11,110	0	-210	0	0	-420	0	-10	-23,870
1954	-2,780	-4,770	-3,430	-170	-11,120	0	-210	0	0	-460	0	-10	-22,950
1955	-2,580	-4,670	-3,500	-190	-11,130	0	-210	0	0	-500	0	-10	-22,790
1956	-2,400	-4,560	-3,580	-210	-11,150	0	-210	0	0	-540	0	-10	-22,660
1957	-2,250	-4,450	-3,660	-230	-11,160	0	-210	0	0	-580	0	-10	-22,550
1958	-2,100	-4,360	-3,730	-250	-11,170	0	-210	0	0	-620	0	-10	-22,450
1959	-1,940	-4,280	-3,810	-270	-11,190	0	-420	0	0	-660	0	-10	-22,580
1960	-1,780	-4,200	-4,570	-330	-10,900	-3	-420	0	0	-700	0	-10	-22,913
1961	-1,640	-4,130	-4,210	-390	-10,610	-5	-420	0	0	-740	0	-10	-22,155
1962	-1,520	-4,050	-3,840	-450	-10,320	-8	-420	0	0	-780	0	-10	-21,398
1963	-1,410	-3,980	-3,480	-510	-10,030	-10	-420	-170	0	-820	-100	-10	-20,940
1964	-1,290	-3,910	-3,120	-510	-6,690	-9	-440	-170	0	-860	-100	-10	-17,109
1965	-1,170	-3,850	-3,360	-520	-3,340	-7	-450	-170	0	-900	-100	-10	-13,877
1966	-1,070	-3,790	-3,600	-530	0	-4	-470	-170	0	-940	-100	-10	-10,684
1967	-970	-3,740	-3,840	-540	0	-2	-490	-170	0	-980	-100	-10	-10,842
1968	-880	-3,690	-4,080	-550	0	0	-510	-170	-160	-1,020	-100	-10	-11,170
1969	-840	-3,640	-4,320	-550	0	-4	-520	-170	-170	-1,060	-100	-10	-11,384

Table 11 (continued)

	Natural Discharge		Agricultural Discharge				Recreational Discharge			Municipal Discharge			Total Discharge
	ET	Underflow	Row	Citrus	Grape	Other	De Anza Country Club	BSPCSD	Roadrunner Golf Course	Borrego Water Company	BSPCSD	Borrego Air Ranch	Total
Year	(acre-feet)	(acre-feet)	(acre-feet)	(acre-feet)	(acre-feet)	(acre-feet)	(acre-feet)	(acre-feet)	(acre-feet)	(acre-feet)	(acre-feet)	(acre-feet)	(acre-feet)
1970	-820	-3,590	-1,390	-550	0	-9	-540	-170	-190	-1,110	-100	-10	-8,479
1971	-800	-3,540	-1,390	-550	0	-10	-560	-170	-200	-1,150	-100	-10	-8,480
1972	-770	-3,500	-1,390	-550	0	-20	-580	-170	-210	-1,190	-100	-10	-8,490
1973	-750	-3,460	-1,390	-550	0	-20	-590	-170	-230	-1,230	-100	-10	-8,500
1974	-720	-3,420	-1,390	-550	0	-30	-610	-170	-240	-1,270	-100	-10	-8,510
1975	-690	-3,380	-1,390	-550	0	-30	-630	-170	-260	-1,310	-100	-10	-8,520
1976	-670	-3,340	-1,390	-550	0	-40	-650	-170	-270	-1,350	-100	-10	-8,540
1977	-640	-3,310	-1,390	-550	0	-40	-660	-170	-290	-1,390	-100	-10	-8,550
1978	-620	-3,280	-1,390	-550	0	-40	-680	-170	-300	-1,430	-100	-10	-8,570
1979	-600	-3,250	-1,390	-1,990	0	-50	-700	-170	-310	-1,470	-100	-10	-10,040
1980	-600	-3,220	-1,390	-2,130	0	-240	-700	-170	-310	-1,510	-100	-10	-10,380
1981	-620	-3,190	-1,290	-2,270	0	-440	-700	-170	-310	-1,550	-100	-10	-10,650
1982	-650	-3,170	-1,180	-2,410	0	-640	-700	-170	-310	-1,590	-100	-10	-10,930
1983	-620	-3,150	-1,080	-2,550	0	-830	-700	-170	-310	-1,630	-100	-10	-11,150
1984	-570	-3,120	-960	-2,680	0	-1,030	-700	-170	-310	-1,680	-100	-10	-11,330
1985	-540	-3,100	-860	-2,820	0	-1,230	-700	-170	-310	-1,690	-100	-10	-11,530
1986	-510	-3,080	-750	-2,960	0	-1,420	-700	-170	-310	-1,700	-100	-10	-11,710
1987	-470	-3,050	-640	-3,100	0	-1,620	-700	-170	-310	-1,710	-100	-10	-11,880
1988	-420	-3,030	-540	-3,240	0	-1,820	-700	-170	-310	-1,830	-100	-10	-12,170
1989	-360	-3,000	-430	-3,380	0	-2,010	-700	-170	-310	-1,910	-100	-10	-12,380
1990	-310	-2,980	-320	-3,520	0	-2,210	-700	-170	-310	-1,910	-100	-10	-12,540
1991	-260	-2,960	-210	-3,660	0	-2,400	-700	-170	-310	-1,830	-100	-10	-12,610
1992	-250	-2,930	-110	-3,800	0	-2,600	-700	-170	-310	-2,220	-100	-10	-13,200
1993	-240	-2,910	0	-4,630	0	-2,730	-700	-170	-310	-2,060	-100	-10	-13,860
1994	-230	-2,890	0	-5,450	0	-2,870	-700	-170	-310	-2,080	-100	-10	-14,810
1995	-230	-2,870	0	-6,280	0	-3,000	-700	-170	-310	-2,080	-100	-10	-15,750
1996	-220	-2,850	0	-6,280	0	-3,000	-700	-170	-310	-2,080	-100	-10	-15,720
1997	-210	-2,830	0	-6,280	0	-3,000	-700	-170	-310	-2,080	-100	-10	-15,690
1998	-190	-2,810	0	-6,280	0	-3,000	-700	-170	-310	-2,080	-100	-10	-15,650
1999	-160	-2,790	0	-6,280	0	-3,000	-700	-170	-310	-2,080	-100	-10	-15,600
2000	-130	-2,780	0	-6,280	0	-3,000	-700	-170	-310	-2,080	-100	-10	-15,560

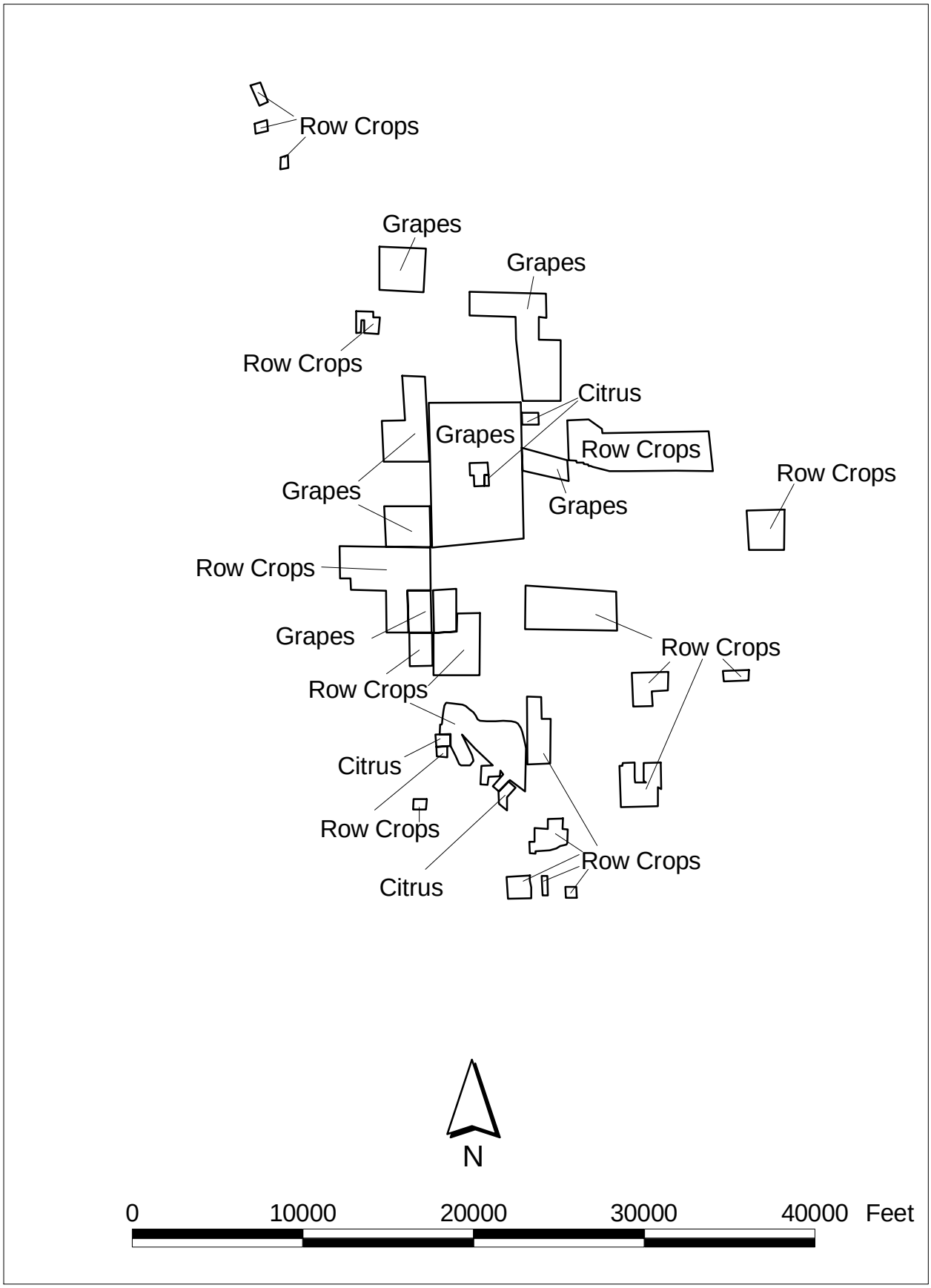


Figure 108. Land use map for 1953.

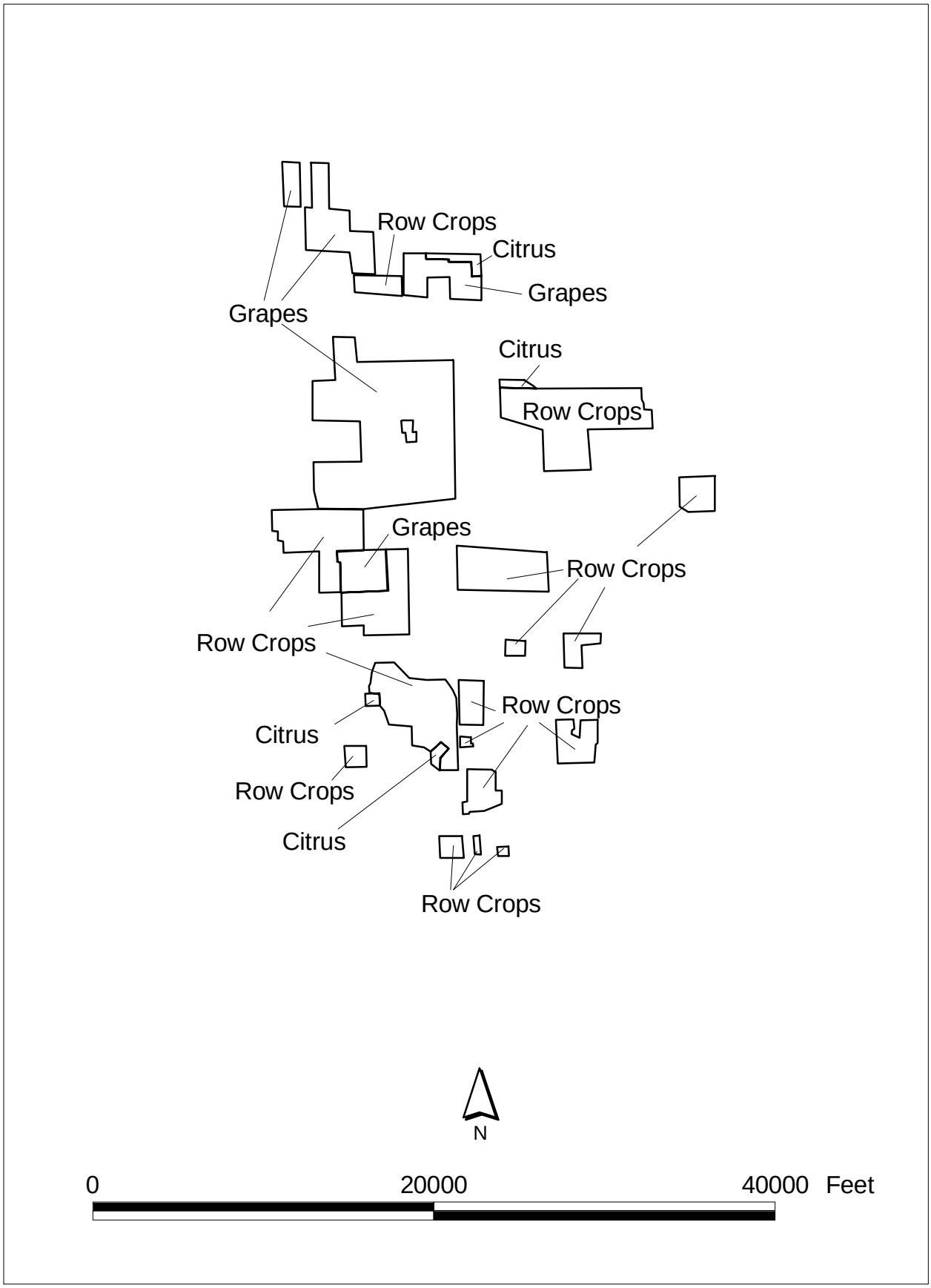
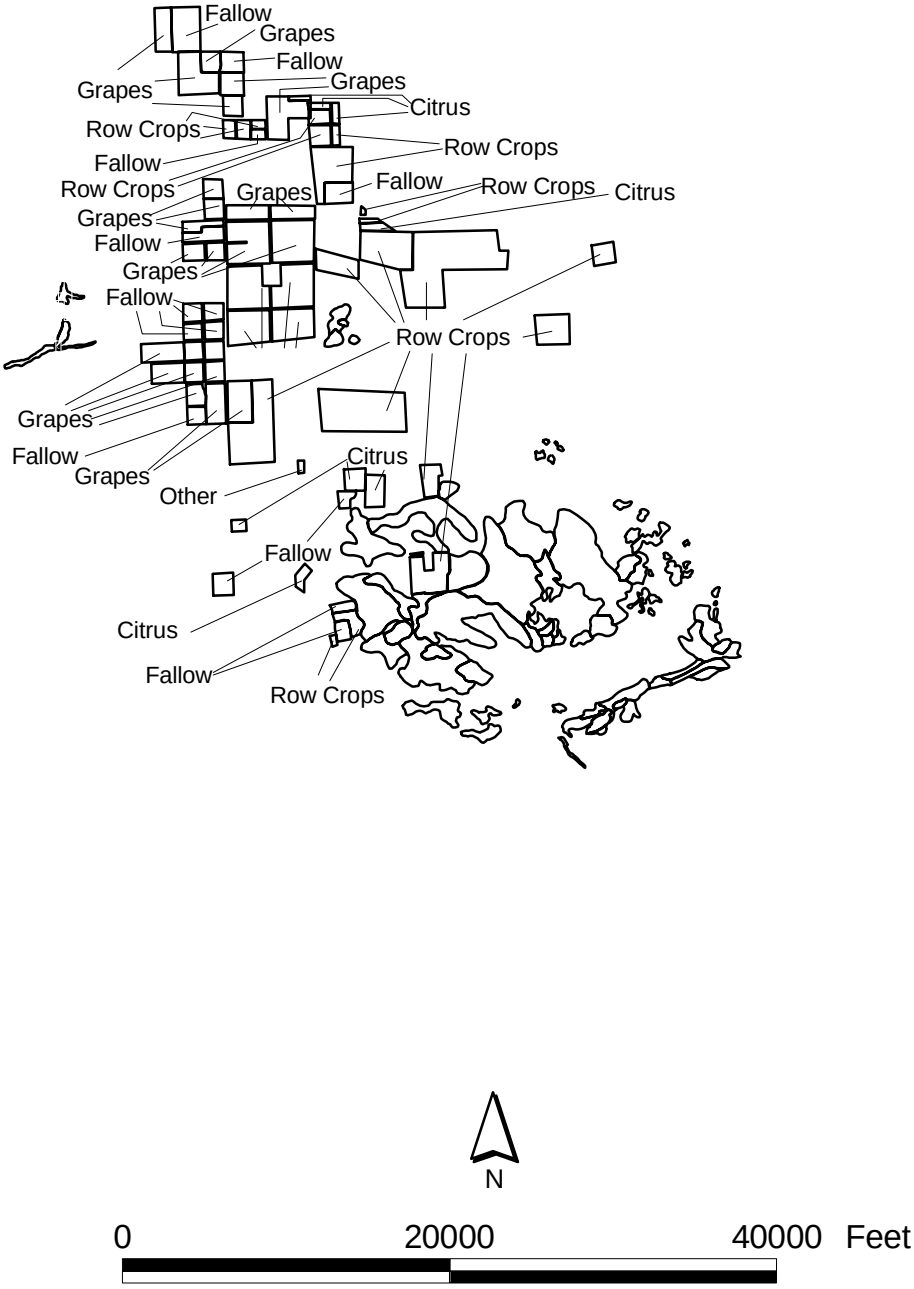


Figure 109. Land use map for 1959.



Note: Defined areas without a label are native phreatophytes

Figure 110. Land use map for 1963.

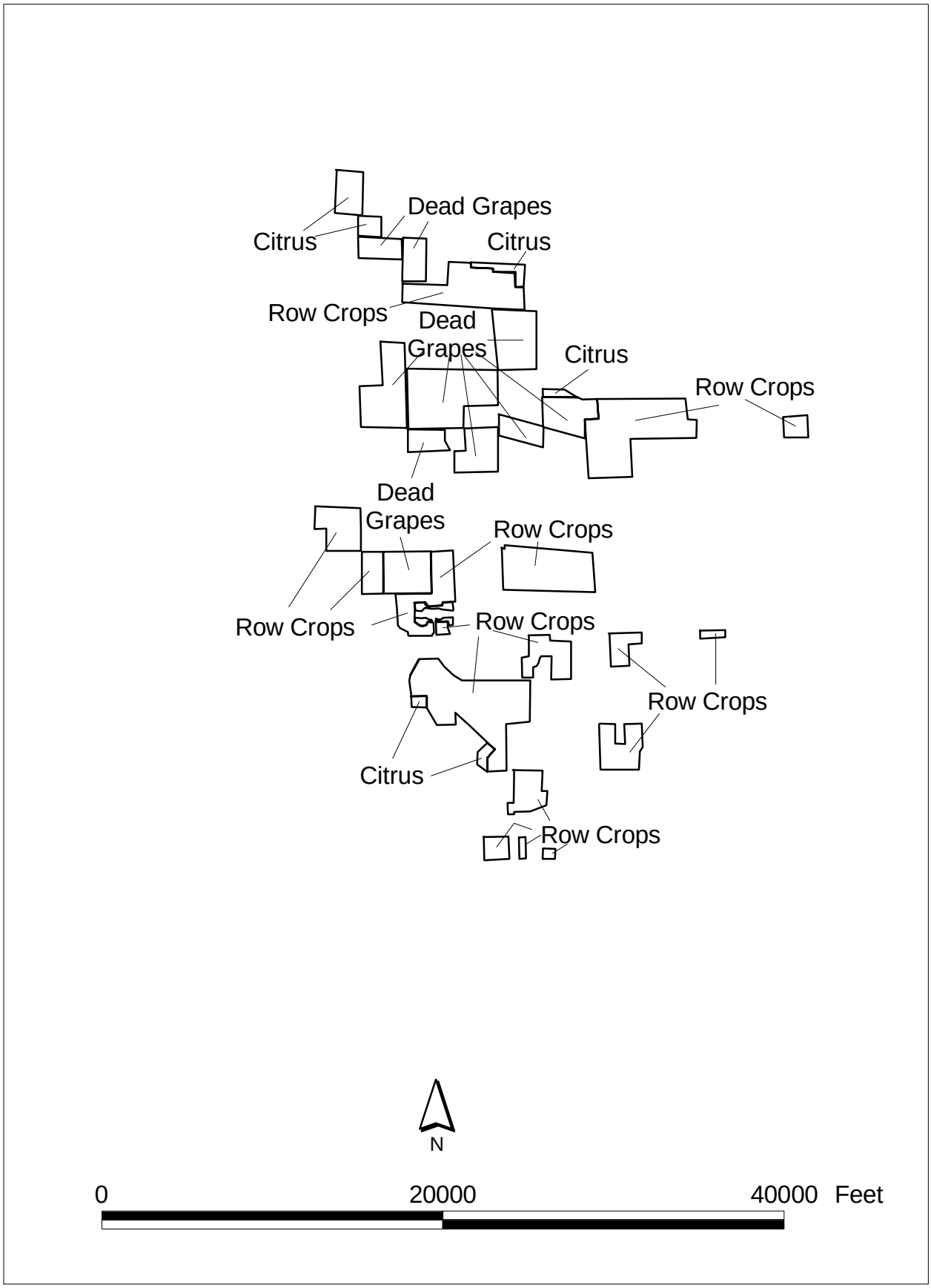


Figure 111. Land use map for 1968.

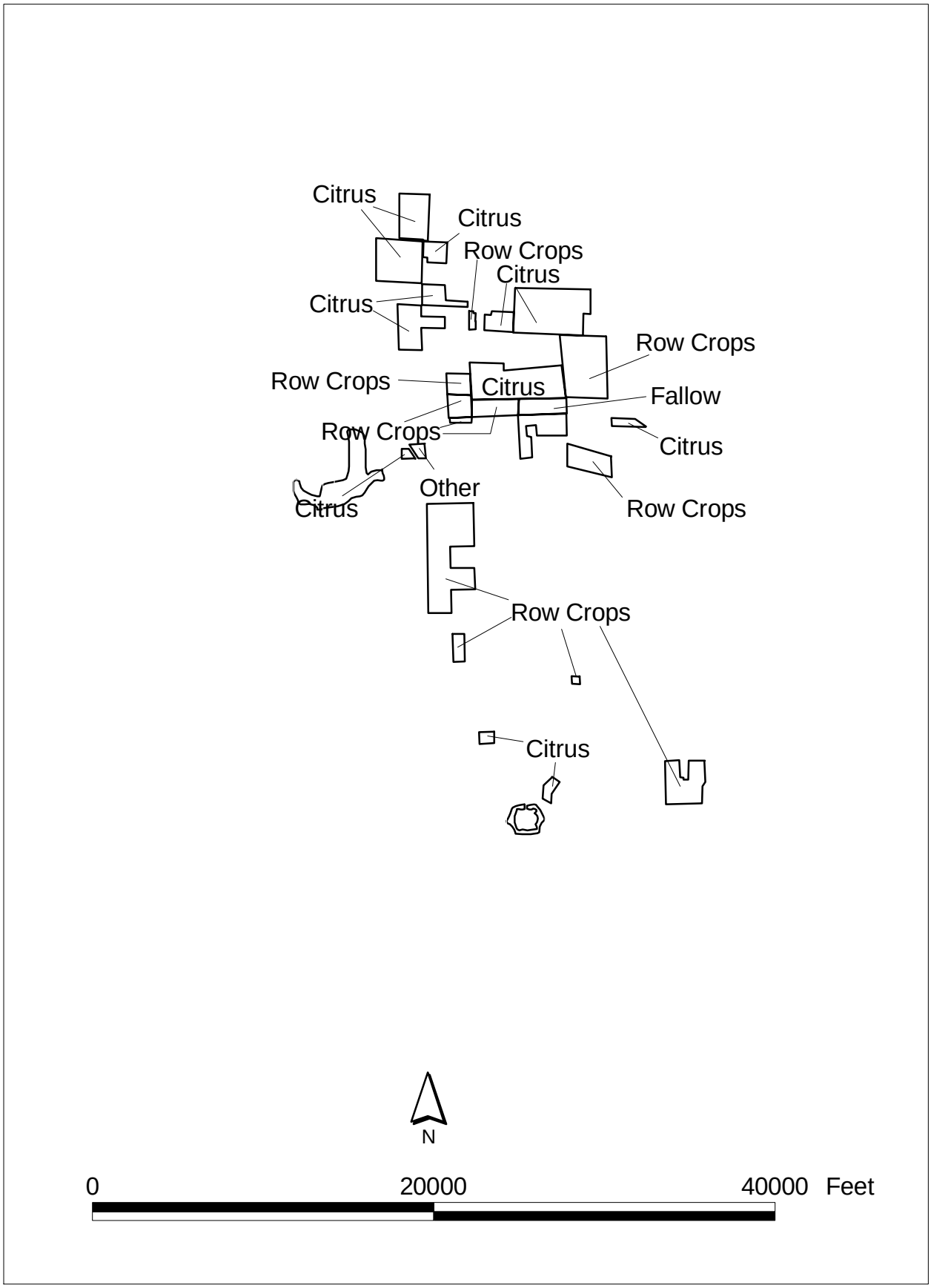
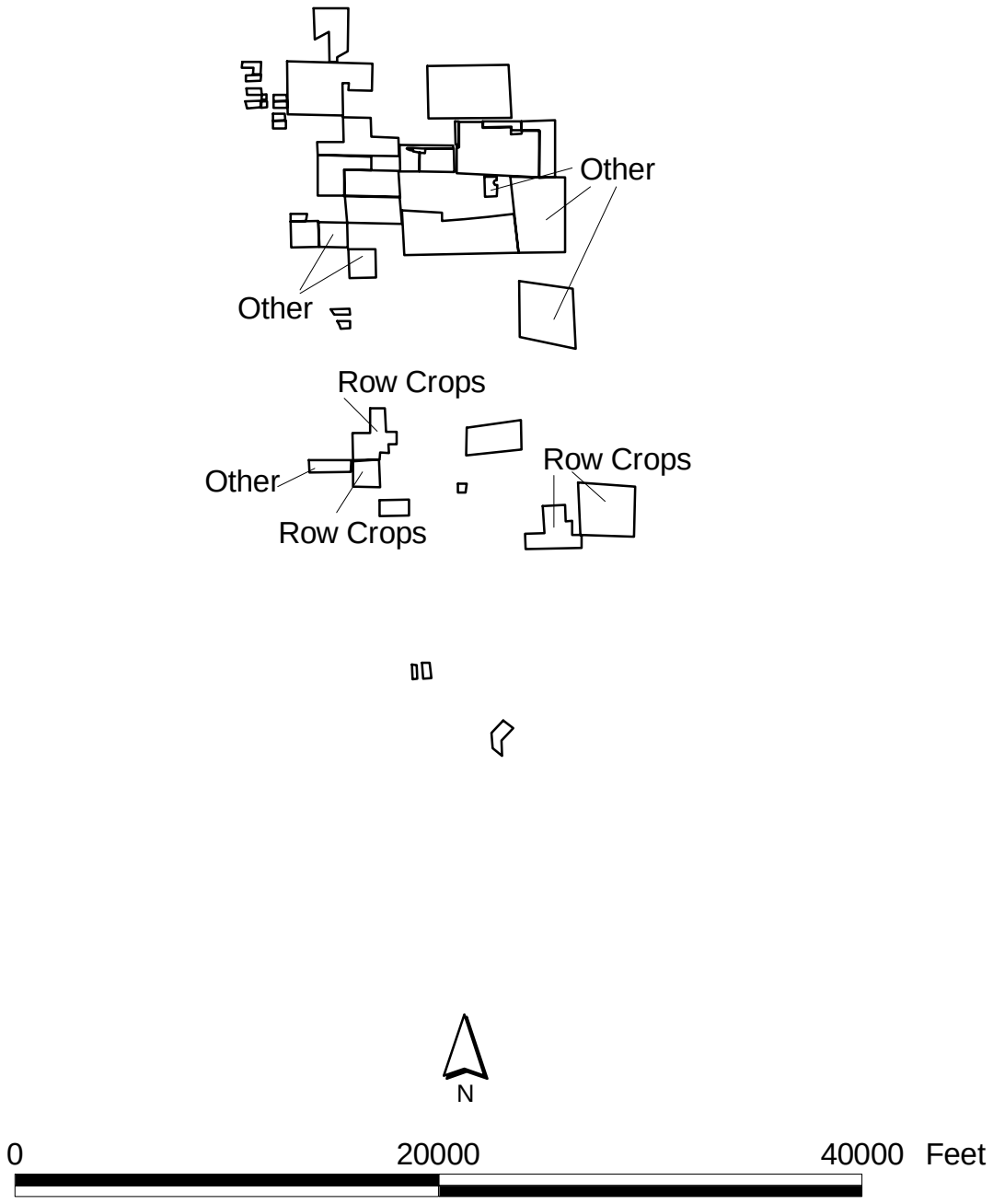
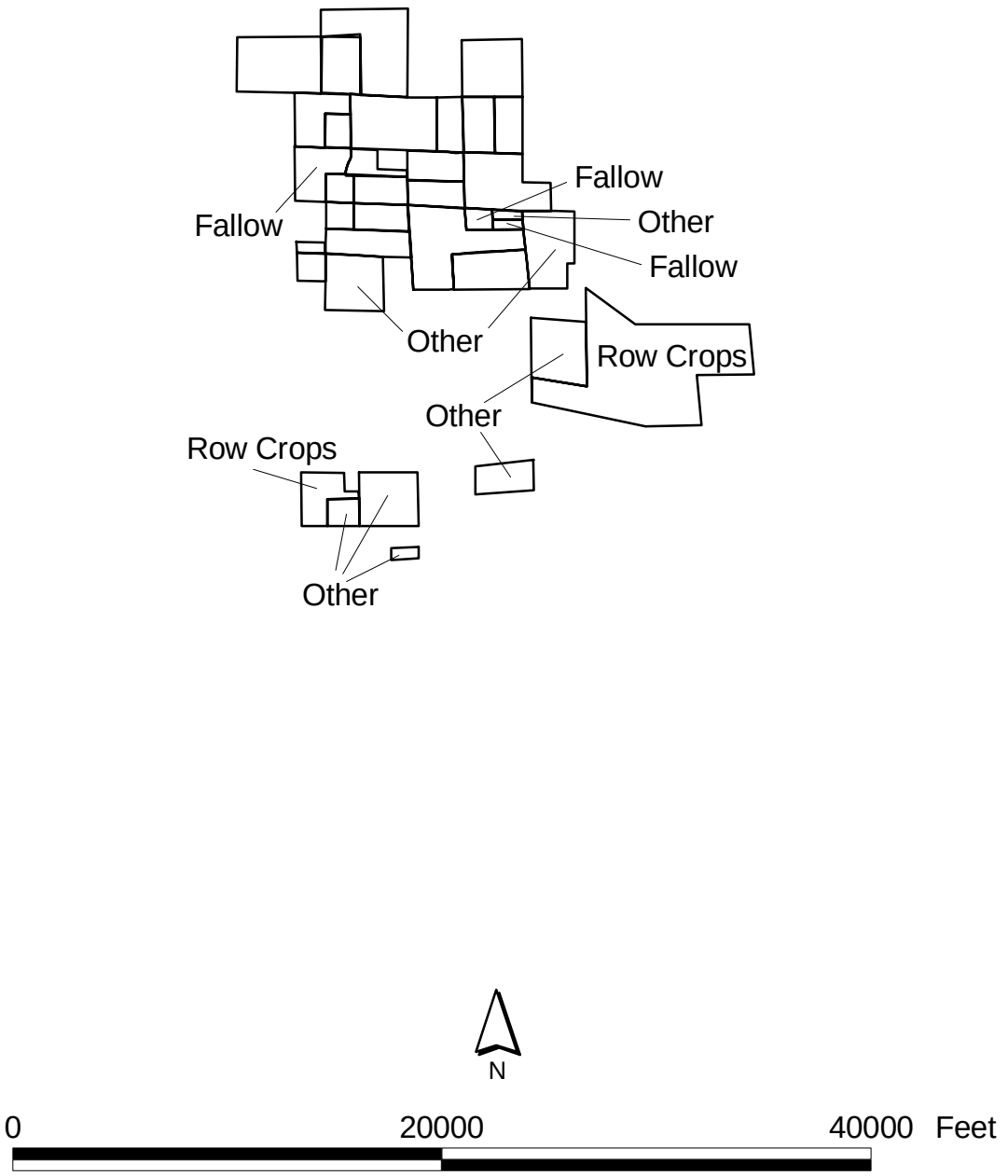


Figure 112. Land use map for 1979.



Note: Defined areas without a label are Citrus

Figure 113. Land use map for 1992.



Note: Defined areas without a label are Citrus

Figure 114. Land use map for 1995.

APPENDIX C

TRANSIENT MODELING FLUX QUANTITIES AND LOCATIONS

Table 12

Summary of Model Evapotranspiration Cell Indices

Row	Column	Layer	Row	Column	Layer
10	32	1	15	30	1
10	35	1	15	31	1
10	36	1	15	32	1
10	37	1	15	33	1
10	38	1	15	34	1
10	39	1	15	35	1
11	32	1	15	36	1
11	36	1	15	39	1
11	37	1	16	30	1
11	39	1	16	31	1
11	40	1	16	33	1
12	25	1	16	34	1
12	34	1	16	35	1
12	35	1	16	38	1
12	36	1	16	39	1
12	37	1	17	30	1
12	38	1	17	31	1
12	39	1	17	32	1
12	40	1	17	33	1
13	25	1	17	34	1
13	35	1	17	35	1
13	36	1	17	36	1
13	37	1	17	37	1
13	39	1	18	31	1
13	40	1	18	32	1
14	31	1	18	33	1
14	32	1	18	34	1
14	33	1	18	35	1
14	34	1	18	36	1
14	35	1	18	37	1
14	36	1	19	32	1
14	37	1	19	33	1
14	39	1	19	34	1
14	40	1	19	35	1

Table 13

Steady-State Period Recharge Cell Indices and Flux Summary

Row	Column	Layer	Surface Water Recharge	Bedrock Recharge	Steady-State Recharge (AF/Yr)	Surface Water and/or Bedrock Recharge Source
8	14	3	X	X	9	Coyote Mountain
8	15	3	X	X	9	Coyote Mountain
8	16	3	X	X	9	Coyote Mountain
8	17	3	X	X	9	Coyote Mountain
8	18	3	X	X	9	Coyote Mountain
8	19	3	X	X	9	Coyote Mountain
8	20	3	X	X	9	Coyote Mountain
8	21	3	X	X	9	Coyote Mountain
8	22	3	X	X	9	Coyote Mountain
9	13	3	X		736	Coyote Creek
9	14	3	X		736	Coyote Creek
9	15	3	X		736	Coyote Creek
10	12	3	X	X	50	South Coyote Canyon
12	13	3	X	X	22	Northwest Slopes
13	14	3	X	X	22	Northwest Slopes
14	15	3	X	X	27	Henderson Canyon
14	16	3	X	X	27	Henderson Canyon
15	16	3	X	X	27	Henderson Canyon
18	21	3	X	X	18	Indian Head Mountain
19	22	3	X		711	Borrego Palm Canyon
20	22	3	X		711	Borrego Palm Canyon
21	22	3	X	X	12	South Borrego Palm Canyon
22	22	3	X	X	161	Hellhole Canyon
21	23	3	X	X	161	Hellhole Canyon
26	27	3	X	X	30	Dry Canyon
27	28	3	X		94	Culp and Tubb Canyons
27	29	3	X		94	Culp and Tubb Canyons
27	30	3	X	X	41	Pinyon Ridge
26	31	3	X	X	41	Pinyon Ridge
26	32	3	X	X	41	Pinyon Ridge
17	50	3	X		441	Upper and Lower San Felipe Creeks
18	50	3	X		441	Upper and Lower San Felipe Creeks
19	50	3	X		441	Upper and Lower San Felipe Creeks
20	50	3	X		441	Upper and Lower San Felipe Creeks
18	53	4	X		7	East San Felipe Creek
17	54	4	X		7	East San Felipe Creek
17	55	4	X		7	East San Felipe Creek

Table 14

Transient Period Recharge Cell Indices and Flux Summary

Year	Stress Period	Total Surface Water and Bedrock Recharge (AFY)	Year	Stress Period	Total Surface Water and Bedrock Recharge (AFY)
1945	SP1	6,360	1973	SP29	1,180
1946	SP2	4,950	1974	SP30	9,800
1947	SP3	3,380	1975	SP31	750
1948	SP4	2,250	1976	SP32	1,900
1949	SP5	4,750	1977	SP33	2,710
1950	SP6	1,890	1978	SP34	16,060
1951	SP7	4,530	1979	SP35	9,610
1952	SP8	8,730	1980	SP36	51,060
1953	SP9	3,760	1981	SP37	6,920
1954	SP10	4,360	1982	SP38	8,200
1955	SP11	4,410	1983	SP39	26,390
1956	SP12	2,880	1984	SP40	7,960
1957	SP13	3,010	1985	SP41	5,930
1958	SP14	6,030	1986	SP42	5,860
1959	SP15	2,720	1987	SP43	3,680
1960	SP16	3,190	1988	SP44	3,140
1961	SP17	2,380	1989	SP45	2,310
1962	SP18	1,910	1990	SP46	2,040
1963	SP19	2,200	1991	SP47	6,670
1964	SP20	1,950	1992	SP48	6,940
1965	SP21	2,720	1993	SP49	25,010
1966	SP22	6,280	1994	SP50	6,760
1967	SP23	4,420	1995	SP51	8,470
1968	SP24	1,610	1996	SP52	2,640
1969	SP25	7,540	1997	SP53	4,730
1970	SP26	2,060	1998	SP54	10,220
1971	SP27	1,570	1999	SP55	2,580
1972	SP28	1,540	2000	SP56	2,370

Table 15

Summary of Groundwater Discharge Cell Indices for Various Sinks

Row	Column	Layer	Groundwater Discharge Source
7	30	3	1963 Row Crop
7	30	3	1968 Row Crop
8	20	3	1959 Citrus Crop
8	29	3	1953 Row Crop
8	29	3	1959 Row Crop
8	29	3	1963 Row Crop
9	17	3	1995 Citrus Crop
9	18	3	1992 Citrus Crop
9	18	3	1995 Citrus Crop
9	18	3	1995 Citrus Crop
9	19	3	1963 Citrus Crop
9	19	3	1963 Citrus Crop
9	19	3	1992 Citrus Crop
9	20	3	1963 Citrus Crop
9	20	3	1963 Row Crop
9	20	3	1963 Row Crop
9	20	3	1963 Row Crop
9	20	3	1968 Citrus Crop
9	20	3	1992 Citrus Crop
9	25	3	1953 Row Crop
9	25	3	1963 Row Crop
10	15	3	1992 Citrus Crop
10	15	3	1995 Citrus Crop
10	16	3	1963 Table Grapes
10	17	3	1963 Table Grapes
10	18	3	1995 Citrus Crop
10	19	3	1959 Table Grapes
10	19	3	1963 Table Grapes
10	19	3	1979 Citrus Crop
10	19	3	1992 Citrus Crop
10	19	3	1992 Citrus Crop
10	19	3	1995 Citrus Crop
10	20	3	1968 Row Crop
10	20	3	1992 Other Crop
10	20	3	1995 Other Crop
10	21	3	1953 Table Grapes

Table 15 (continued)

Row	Column	Layer	Groundwater Discharge Source
10	21	3	1963 Row Crop
10	21	3	1979 Row Crop
10	21	3	1992 Other Crop
10	21	3	1995 Other Crop
10	23	3	1963 Citrus Crop
10	23	3	1963 Row Crop
10	23	3	1963 Row Crop
10	23	3	1968 Citrus Crop
10	23	3	1979 Citrus Crop
10	24	3	1963 Row Crop
10	25	3	1959 Row Crop
10	26	3	1968 Row Crop
11	14	3	1953 Row Crop
11	14	3	1953 Row Crop
11	14	3	1953 Row Crop
11	14	3	1995 Citrus Crop
11	15	3	1959 Table Grapes
11	15	3	1963 Table Grapes
11	15	3	1968 Citrus Crop
11	15	3	1979 Citrus Crop
11	15	3	1995 Citrus Crop
11	16	3	1953 Table Grapes
11	16	3	1959 Table Grapes
11	16	3	1963 Table Grapes
11	16	3	1968 Citrus Crop
11	16	3	1979 Citrus Crop
11	17	3	1995 Citrus Crop
11	18	3	1959 Row Crop
11	18	3	1963 Table Grapes
11	18	3	1963 Row Crop
11	18	3	1963 Row Crop
11	18	3	1979 Row Crop
11	18	3	1992 Citrus Crop
11	18	3	1995 Citrus Crop
11	18	3	1995 Citrus Crop
11	19	3	1963 Row Crop
11	19	3	1979 Citrus Crop

Table 15 (continued)

Row	Column	Layer	Groundwater Discharge Source
11	19	3	1992 Citrus Crop
11	21	3	1995 Citrus Crop
11	22	3	1953 Citrus Crop
11	23	3	1992 Other Crop
11	23	3	1995 Other Crop
11	25	3	1995 Other Crop
12	14	3	1992 Citrus Crop
12	15	3	1979 Citrus Crop
12	15	3	1995 Citrus Crop
12	16	3	1992 Citrus Crop
12	16	3	1995 Citrus Crop
12	17	3	1953 Row Crop
12	17	3	1979 Citrus Crop
12	17	3	1979 Citrus Crop
12	17	3	1992 Citrus Crop
12	17	3	1992 Citrus Crop
12	17	3	1995 Citrus Crop
12	17	3	1995 Citrus Crop
12	18	3	1992 Citrus Crop
12	18	3	1995 Citrus Crop
12	18	3	1995 Citrus Crop
12	19	3	1995 Citrus Crop
12	20	3	1979 Citrus Crop
12	20	3	1992 Citrus Crop
12	21	3	1963 Table Grapes
12	22	3	1963 Table Grapes
12	23	3	1953 Table Grapes
12	23	3	1963 Row Crop
12	23	3	1979 Row Crop
12	32	3	1953 Row Crop
12	32	3	1968 Row Crop
13	15	3	1992 Citrus Crop
13	15	3	1992 Citrus Crop
13	15	3	1992 Citrus Crop
13	15	3	1992 Citrus Crop
13	15	3	1992 Citrus Crop
13	15	3	1992 Citrus Crop

Table 15 (continued)

Row	Column	Layer	Groundwater Discharge Source
13	15	3	1992 Citrus Crop
13	16	3	1992 Citrus Crop
13	18	3	1995 Citrus Crop
13	18	3	1995 Citrus Crop
13	18	3	1995 Citrus Crop
13	18	3	1995 Citrus Crop
13	18	3	Borrego Water Company, Well #18
13	19	3	1963 Table Grapes
13	19	3	1979 Row Crop
13	19	3	1992 Citrus Crop
13	20	3	1963 Table Grapes
13	20	3	1963 Table Grapes
13	21	3	1963 Table Grapes
13	22	3	1953 Table Grapes
13	22	3	1959 Table Grapes
13	23	3	1953 Citrus Crop
13	23	3	1963 Table Grapes
13	28	3	1992 Other Crop
14	19	3	1992 Citrus Crop
14	19	3	1992 Citrus Crop
14	19	3	1992 Other Crop
14	19	3	1992 Other Crop
14	19	3	1995 Other Crop
14	20	3	1953 Table Grapes
14	20	3	1963 Table Grapes
14	21	3	1963 Table Grapes
14	22	3	1963 Table Grapes
14	24	3	1963 Table Grapes
14	24	3	1992 Citrus Crop
14	25	3	1995 Other Crop
14	27	3	1953 Row Crop
14	27	3	1959 Row Crop
14	27	3	1963 Row Crop
14	27	3	1968 Row Crop
14	30	3	1953 Row Crop
14	30	3	1959 Row Crop
14	30	3	1963 Row Crop

Table 15 (continued)

Row	Column	Layer	Groundwater Discharge Source
14	30	3	1968 Row Crop
15	19	3	Borrego Water Company, Well #3
15	20	3	1963 Table Grapes
15	20	3	1979 Citrus Crop
15	20	3	1979 Other Crop
15	20	3	1992 Citrus Crop
15	20	3	1992 Citrus Crop
15	23	3	1963 Table Grapes
15	27	3	1992 Other Crop
15	29	3	1959 Row Crop
15	29	3	1963 Citrus Crop
15	29	3	1968 Row Crop
16	20	3	De Anza Country Club Use
16	22	3	1953 Table Grapes
16	22	3	1979 Row Crop
16	22	3	1992 Other Crop
16	22	3	Borrego Water Company, Well #4
16	23	3	1963 Table Grapes
16	25	3	1992 Citrus Crop
16	28	3	1979 Other Crop
16	29	3	1963 Citrus Crop
16	32	3	1953 Row Crop
16	32	3	1959 Row Crop
16	32	3	1963 Row Crop
16	32	3	1963 Row Crop
16	32	3	1968 Row Crop
16	32	3	1979 Row Crop
17	22	3	1963 Table Grapes
17	22	3	1963 Table Grapes
17	23	3	1953 Row Crop
17	23	3	1959 Row Crop
17	23	3	1963 Table Grapes
17	23	3	1963 Table Grapes
17	23	3	1992 Other Crop
17	23	3	1995 Other Crop
17	24	3	1953 Table Grapes
17	24	3	1959 Table Grapes

Table 15 (continued)

Row	Column	Layer	Groundwater Discharge Source
17	24	3	1963 Table Grapes
17	24	3	1992 Citrus Crop
17	24	3	1995 Other Crop
17	25	3	1953 Table Grapes
17	25	3	1963 Table Grapes
17	25	3	1968 Row Crop
17	25	3	Roadrunner Country Club Use
17	26	3	1953 Row Crop
17	26	3	1959 Row Crop
17	26	3	1963 Row Crop
17	26	3	1968 Row Crop
17	27	3	1963 Other Crop
17	27	3	Borrego Water Company, Well #5
17	29	3	1953 Row Crop
17	29	3	1959 Row Crop
17	40	4	Borrego Water District, Well #2
17	41	4	Borrego Water District, Well #1
17	43	4	Borrego Air Ranch
18	22	3	1963 Table Grapes
18	22	3	1968 Row Crop
18	22	3	1992 Other Crop
18	22	3	1995 Other Crop
18	22	3	1995 Other Crop
18	24	3	1953 Row Crop
18	24	3	1963 Table Grapes
18	24	3	1968 Row Crop
18	24	3	1979 Row Crop
18	29	3	1953 Row Crop
18	29	3	1968 Row Crop
18	30	3	1959 Row Crop
19	23	3	Borrego Water Company, Well #11
19	27	3	1953 Citrus Crop
19	27	3	1959 Citrus Crop
19	27	3	1963 Citrus Crop
19	27	3	1968 Citrus Crop
19	27	3	1979 Citrus Crop
19	27	3	1992 Citrus Crop

Table 15 (continued)

Row	Column	Layer	Groundwater Discharge Source
19	27	3	1992 Citrus Crop
19	28	3	1953 Row Crop
19	28	3	1959 Row Crop
19	30	3	1953 Citrus Crop
19	30	3	1959 Citrus Crop
19	30	3	1963 Citrus Crop
19	30	3	1968 Citrus Crop
19	30	3	1979 Citrus Crop
19	30	3	1992 Citrus Crop
19	31	3	1959 Row Crop
19	31	3	1968 Row Crop
19	32	3	1953 Row Crop
19	32	3	1963 Row Crop
19	32	3	1963 Row Crop
19	36	4	Irrigation District #3 Wells
19	38	4	Borrego Water District, Well #8
20	23	3	1959 Citrus Crop
20	30	3	Borrego Springs Park and Community Service District Use
20	32	3	1953 Row Crop
20	32	3	1959 Row Crop
20	32	3	Borrego Water District, Well #12
20	33	3	1953 Row Crop
20	33	3	1959 Row Crop
20	33	3	1968 Row Crop
20	33	3	1968 Row Crop
21	28	3	1953 Row Crop
21	28	3	1959 Row Crop
21	32	3	1953 Row Crop
21	32	3	1959 Row Crop
21	32	3	1968 Row Crop
22	34	3	Borrego Water District, Well #10
23	31	3	Borrego Water District, Well #16
24	27	3	Borrego Water Company, Well #2
26	28	3	Borrego Water Company, Well #10

Table 16

Summary of Groundwater Discharge From Wells - 1945 Through 2000

Year	Stress Period	Recreational and Municipal Extractions (AF/Yr)	Agricultural Extractions (AF/Yr)
1945	SP1	110	0
1946	SP2	150	1,920
1947	SP3	190	3,840
1948	SP4	230	5,760
1949	SP5	270	7,690
1950	SP6	310	9,610
1951	SP7	350	11,530
1952	SP8	390	13,450
1953	SP9	640	15,370
1954	SP10	680	15,480
1955	SP11	720	15,590
1956	SP12	760	15,700
1957	SP13	800	15,810
1958	SP14	840	15,920
1959	SP15	1,090	16,030
1960	SP16	1,130	15,430
1961	SP17	1,170	14,840
1962	SP18	1,210	14,250
1963	SP19	1,350	13,660
1964	SP20	1,410	10,560
1965	SP21	1,470	7,400
1966	SP22	1,520	4,370
1967	SP23	1,580	4,620
1968	SP24	1,800	4,870
1969	SP25	1,870	1,950
1970	SP26	1,940	1,950
1971	SP27	2,010	1,960
1972	SP28	2,090	1,960
1973	SP29	2160	1960
1974	SP30	2230	1970
1975	SP31	2300	1970
1976	SP32	2370	1980
1977	SP33	2450	1980
1978	SP34	2520	1990
1979	SP35	2590	3430
1980	SP36	2630	3660

Table 16 (continued)

Year	Stress Period	Recreational and Municipal Extractions (AF/Yr)	Agricultural Extractions (AF/Yr)
1981	SP37	2670	3890
1982	SP38	2710	4110
1983	SP39	4110	4340
1984	SP40	4160	4570
1985	SP41	4320	4800
1986	SP42	4300	5030
1987	SP43	4470	5260
1988	SP44	5260	5490
1989	SP45	4960	5710
1990	SP46	5020	5940
1991	SP47	5110	6170
1992	SP48	5300	6400
1993	SP49	5140	7360
1994	SP50	4930	8320
1995	SP51	4950	9280
1996	SP52	4440	9680
1997	SP53	4440	9680
1998	SP54	4440	9680
1999	SP55	4440	9680
2000	SP56	4440	9680

APPENDIX D

TRANSIENT MODELING HYDROGRAPHS

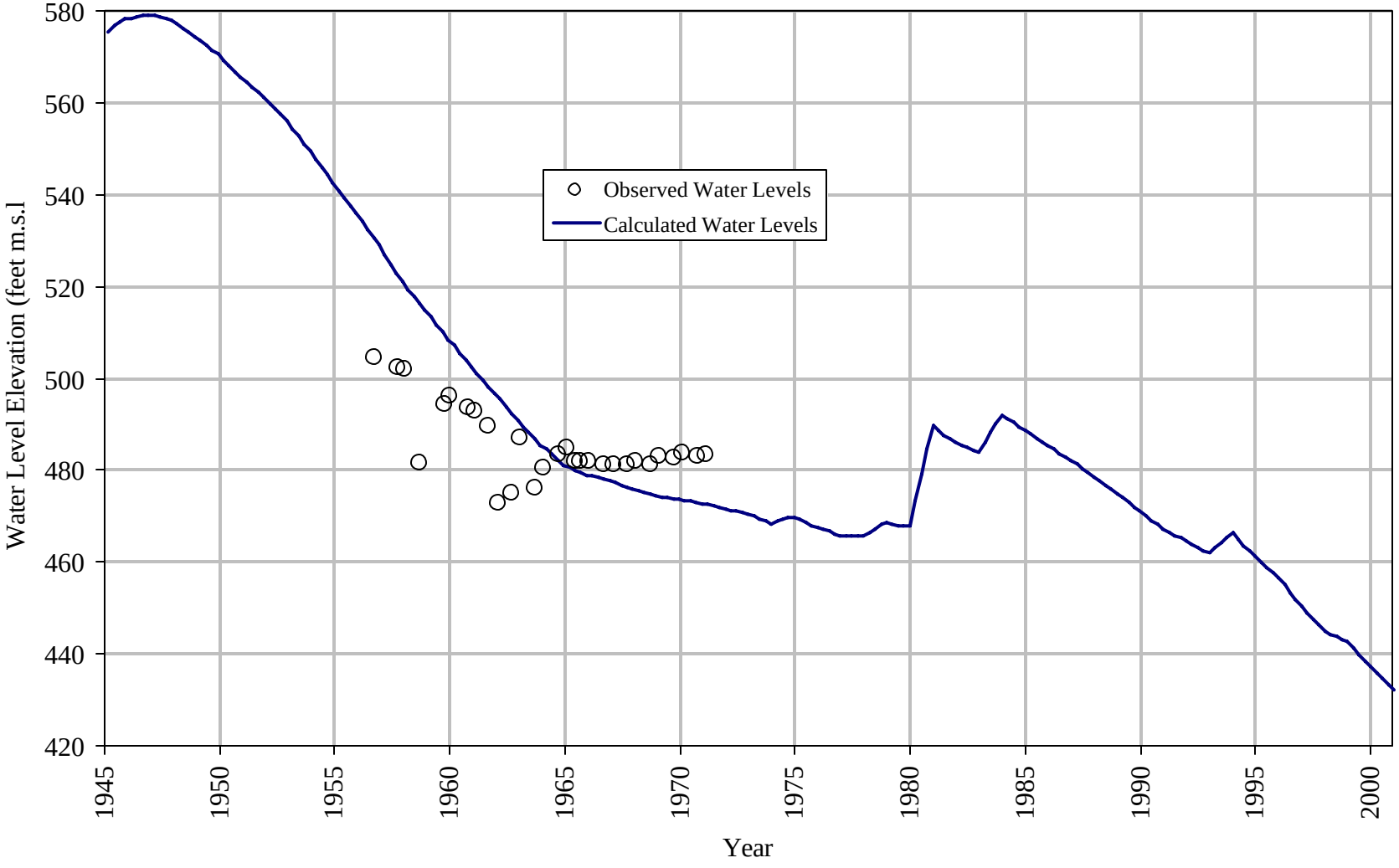


Figure 115. Water level elevation hydrograph well - 10S/6E 8B1 (transient model).

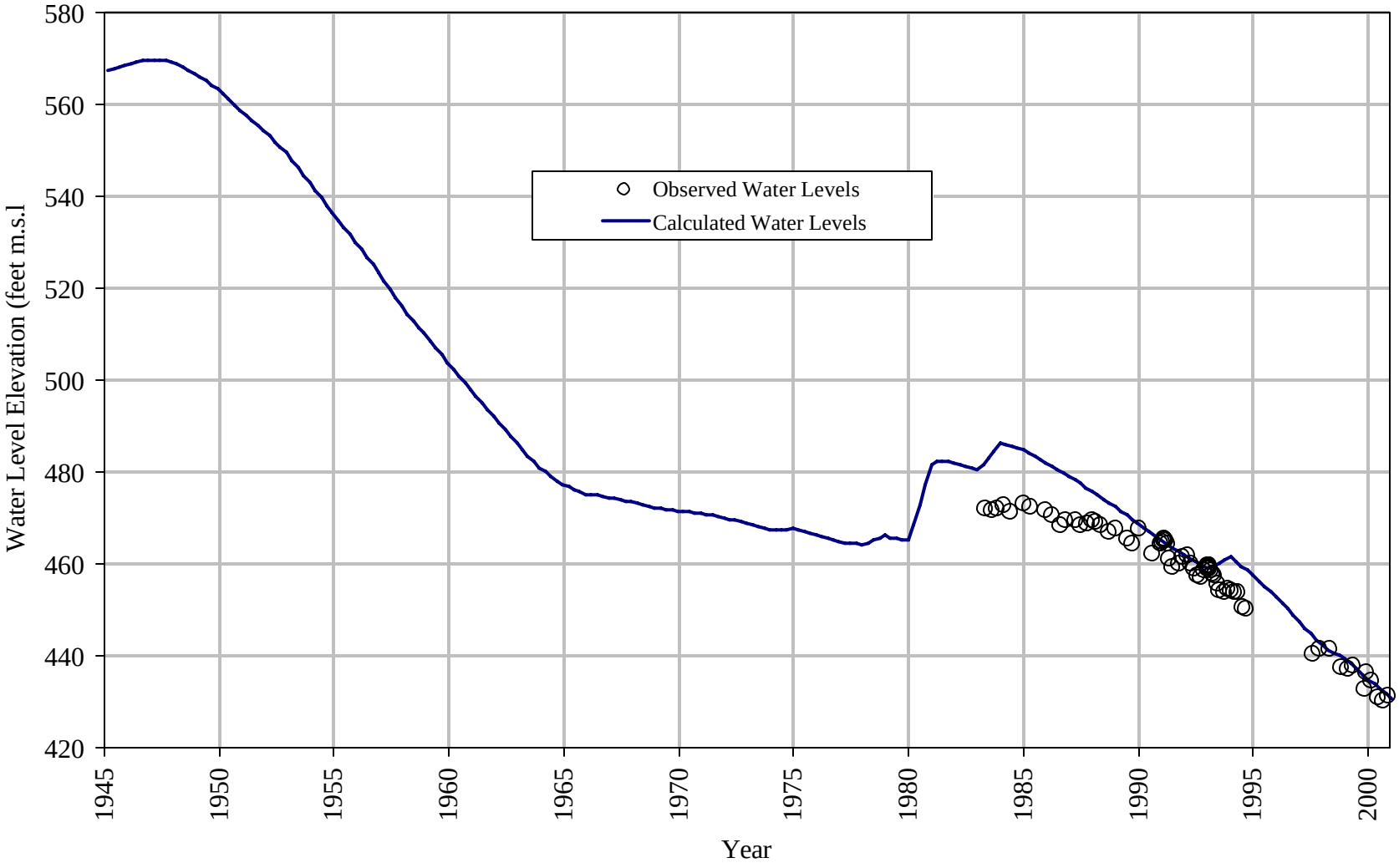


Figure 116. Water level elevation hydrograph well - Fortiner (transient model).

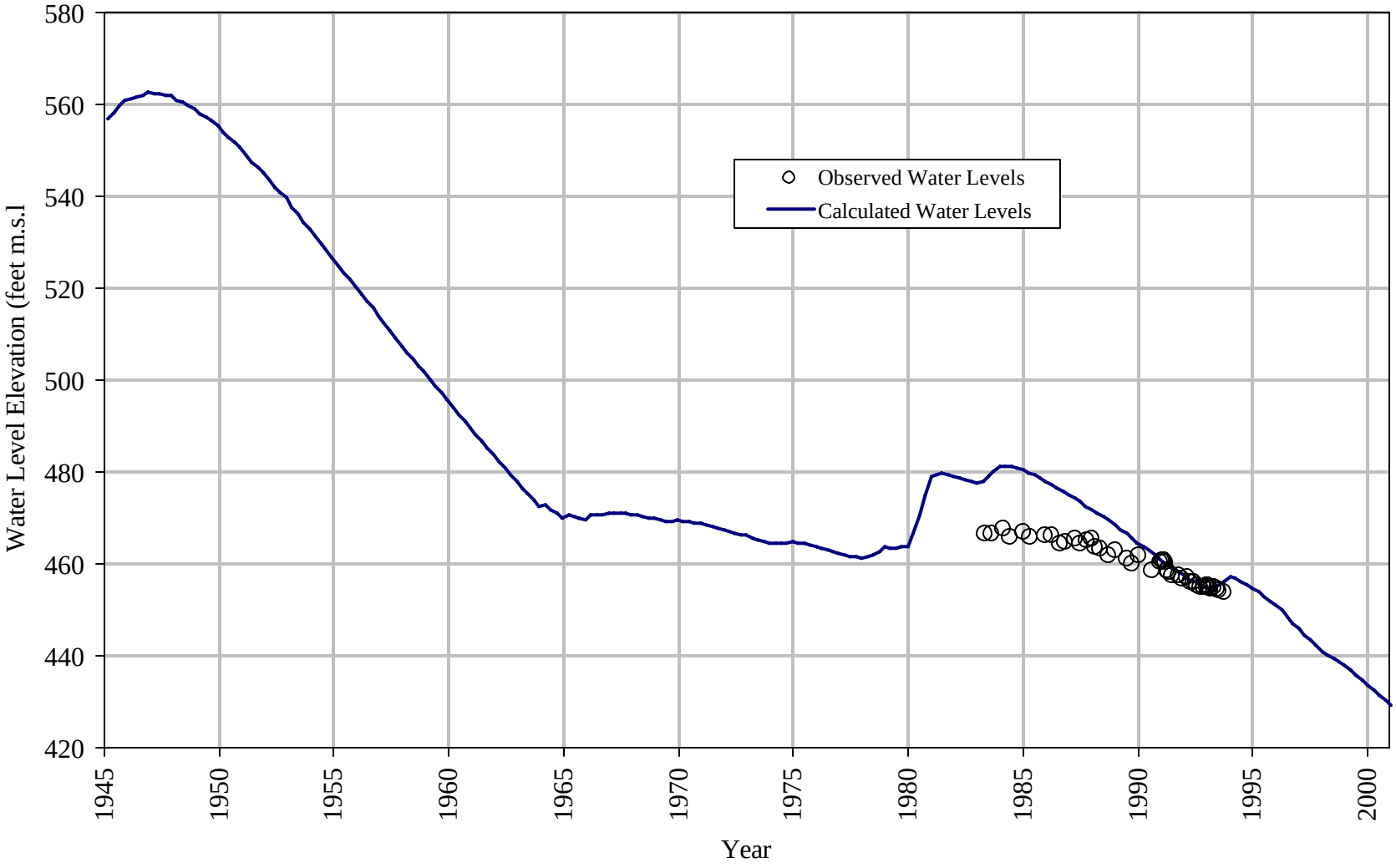


Figure 117. Water level elevation hydrograph well - Fort (transient model).

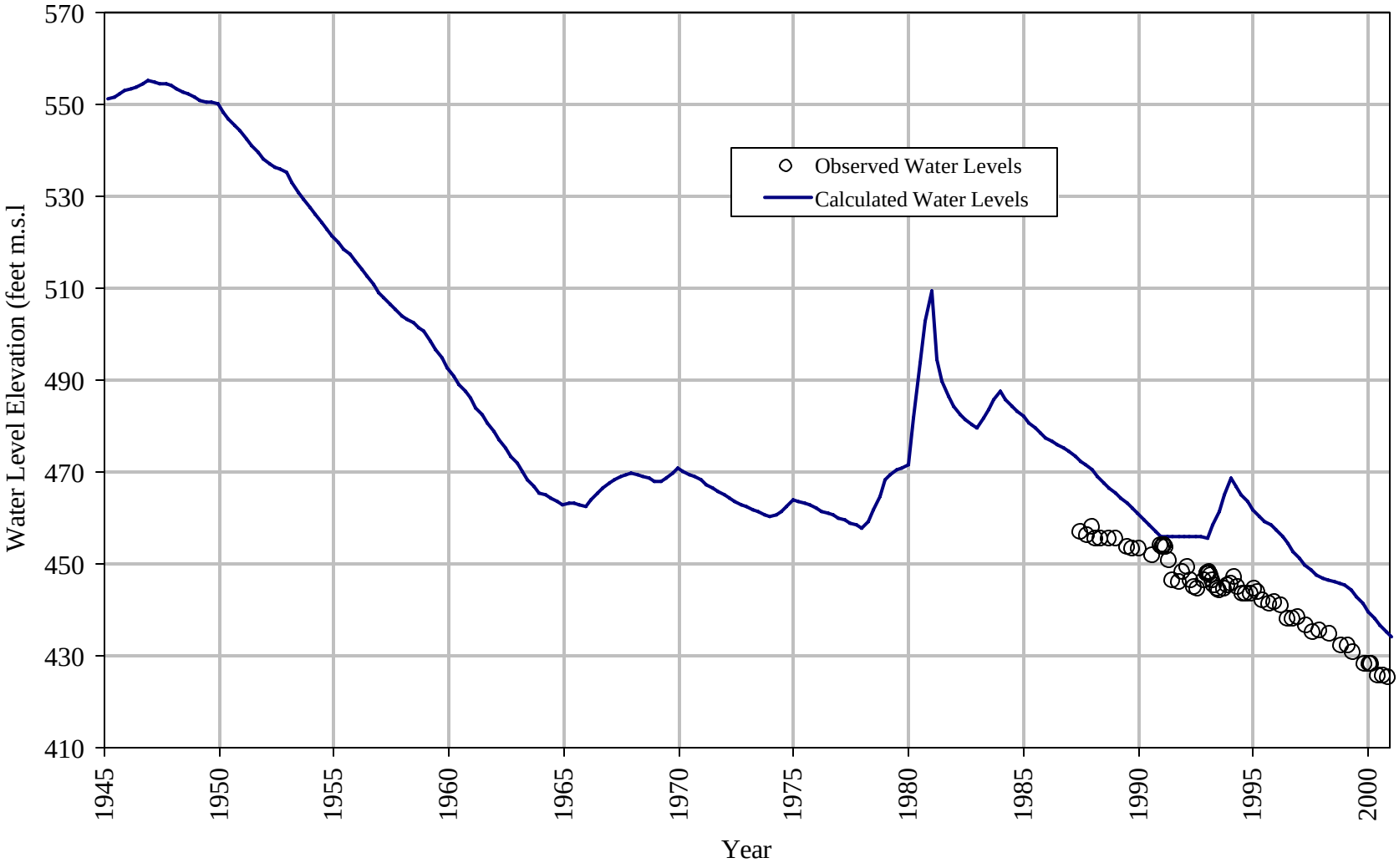


Figure 118. Water level elevation hydrograph well - Empty (transient model).

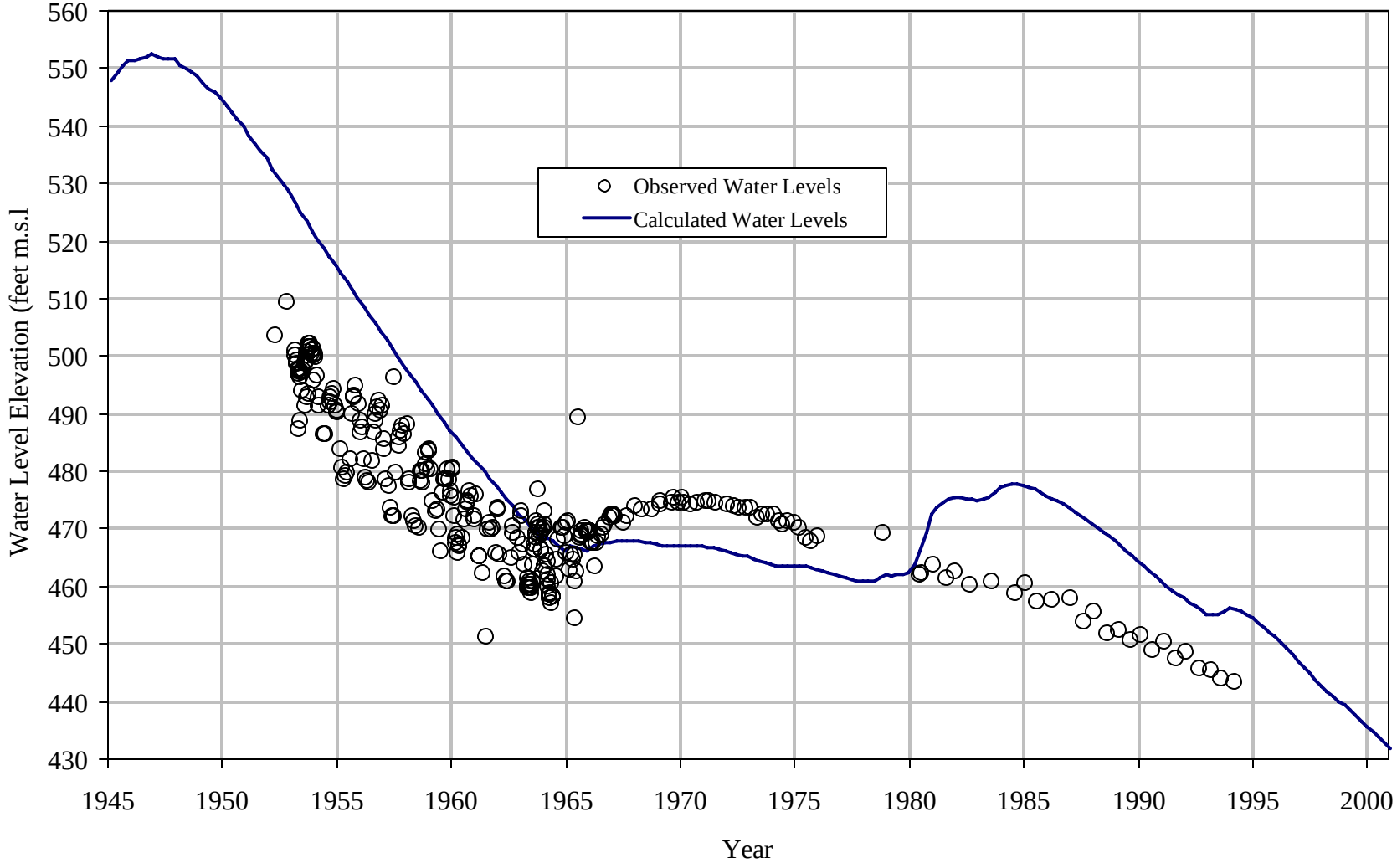


Figure 119. Water level elevation hydrograph well - 10S/6E 21A1 (transient model).

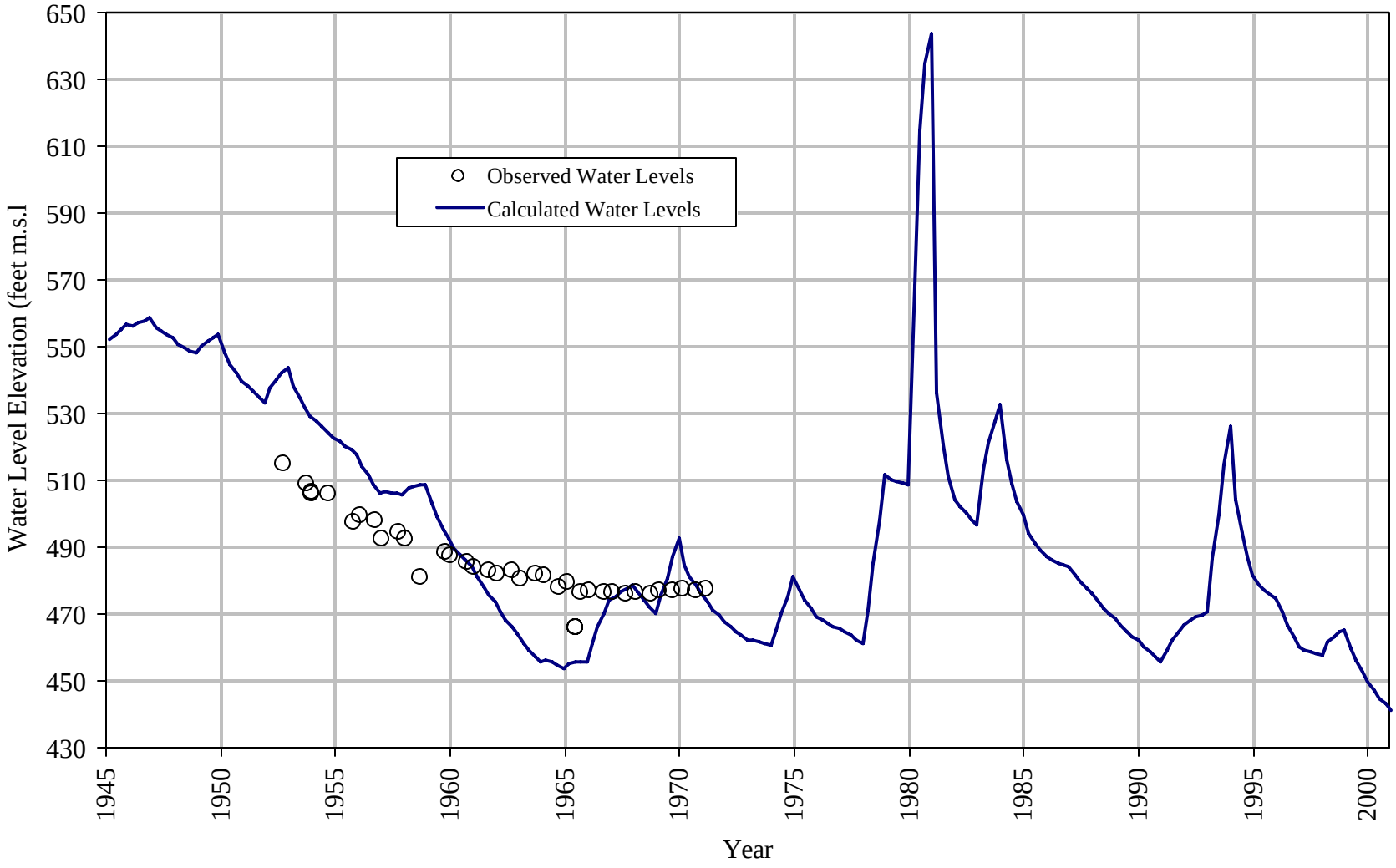


Figure 120. Water level elevation hydrograph well - 10S/6E 29N1 (transient model).

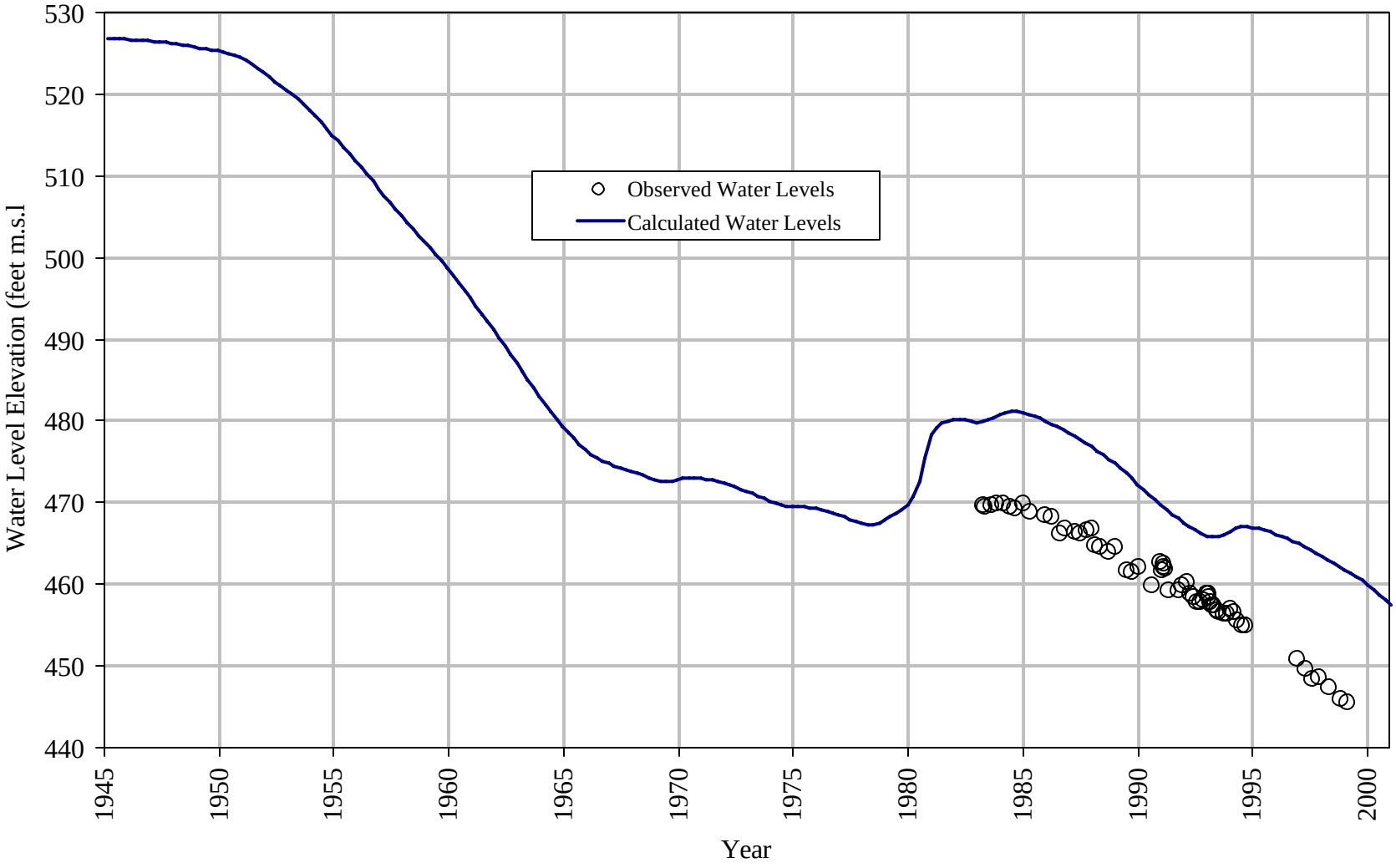


Figure 121. Water level elevation hydrograph well - BSW #1 (transient model).

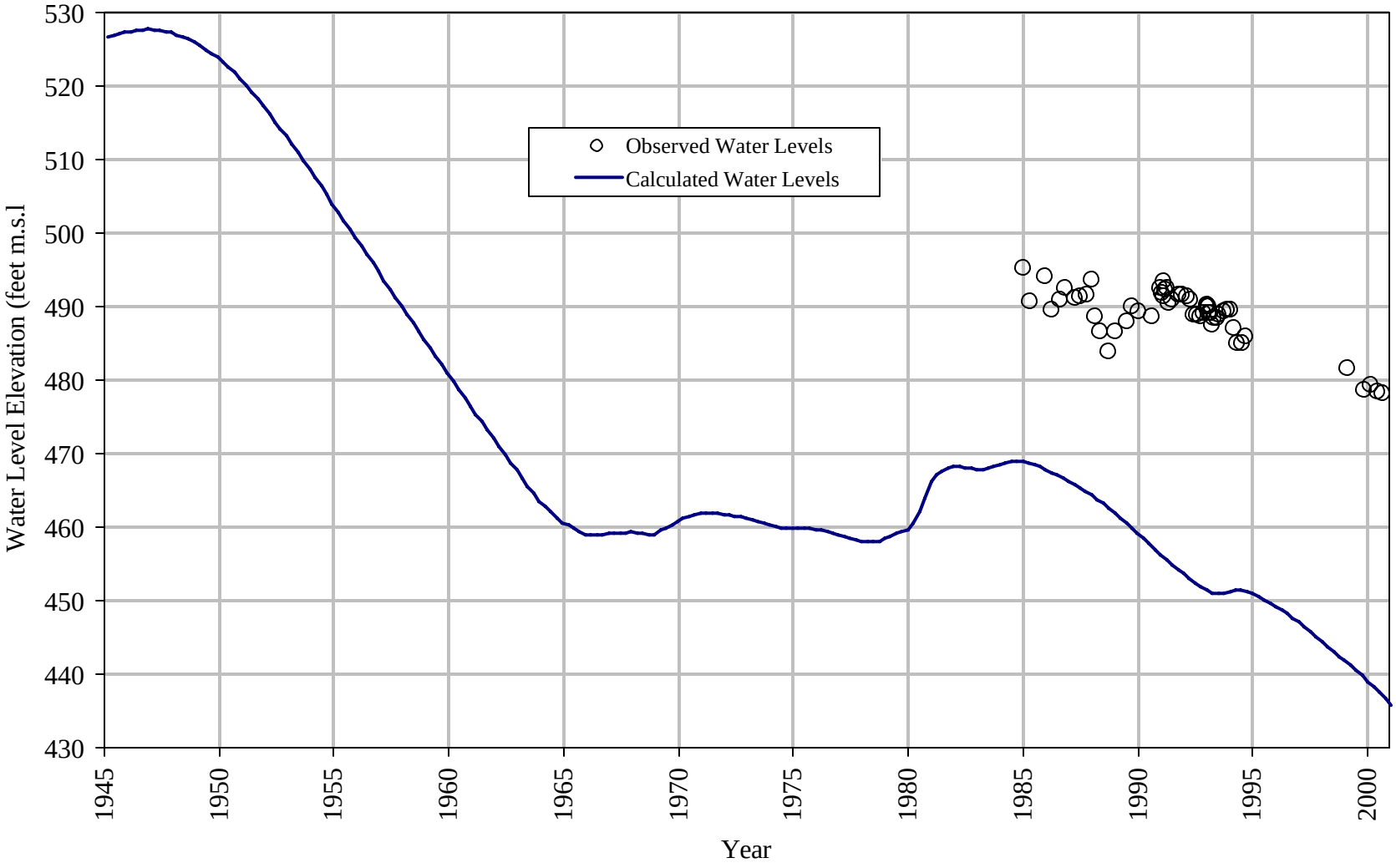


Figure 122. Water level elevation hydrograph well - UEC #2 (transient model).

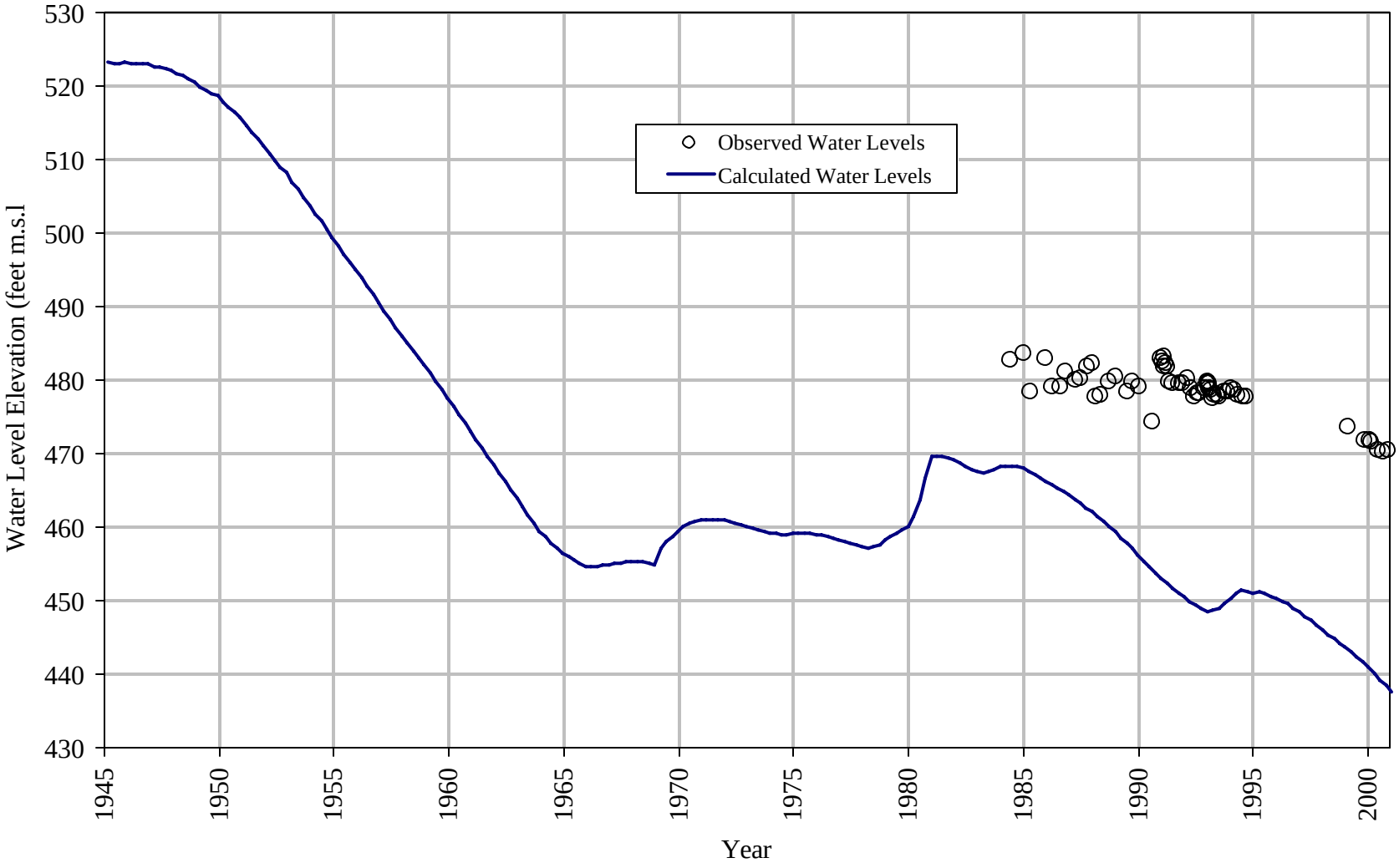


Figure 123. Water level elevation hydrograph well - UEC #1 (transient model).

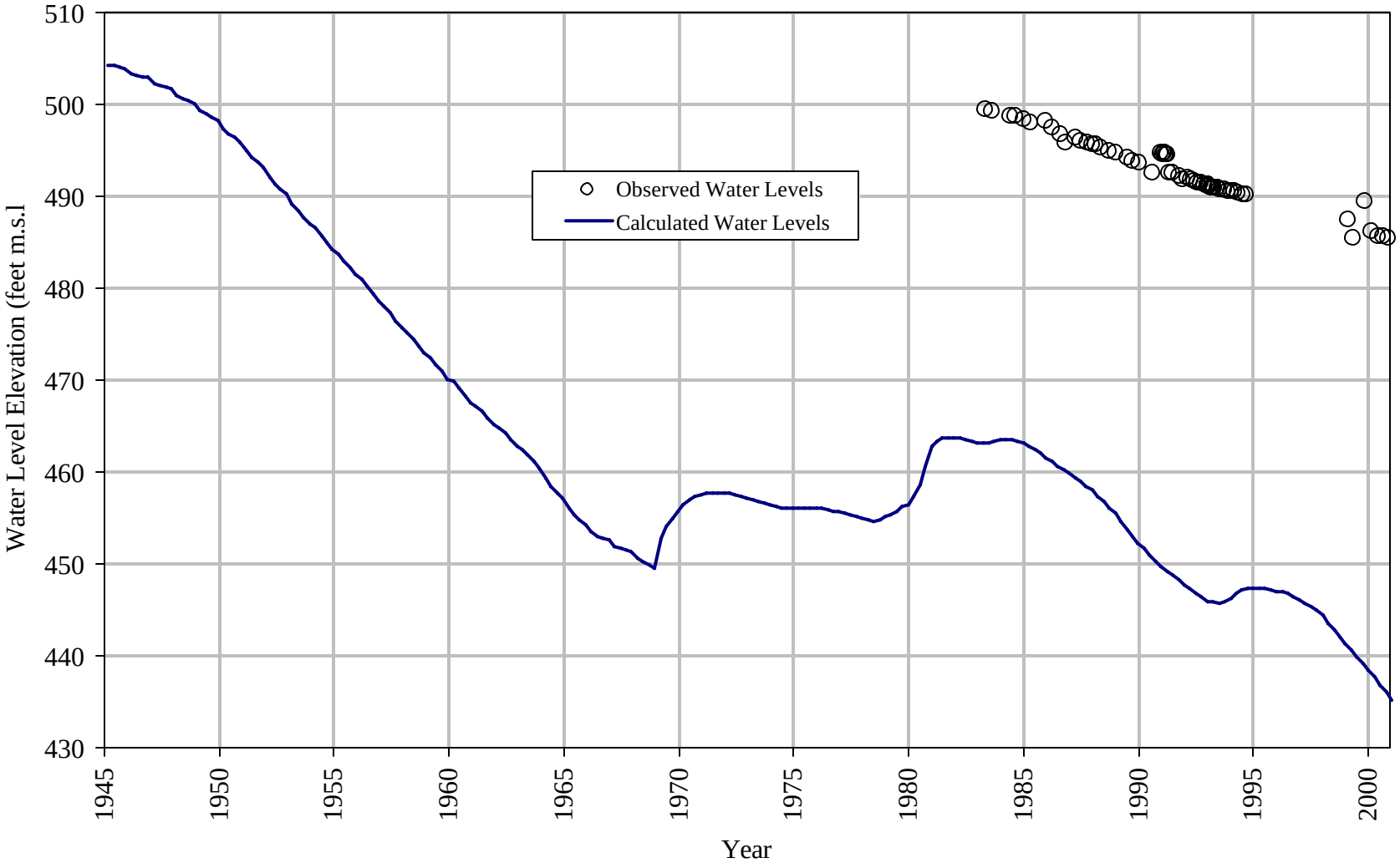


Figure 124. Water level elevation hydrograph well - Victor (transient model).

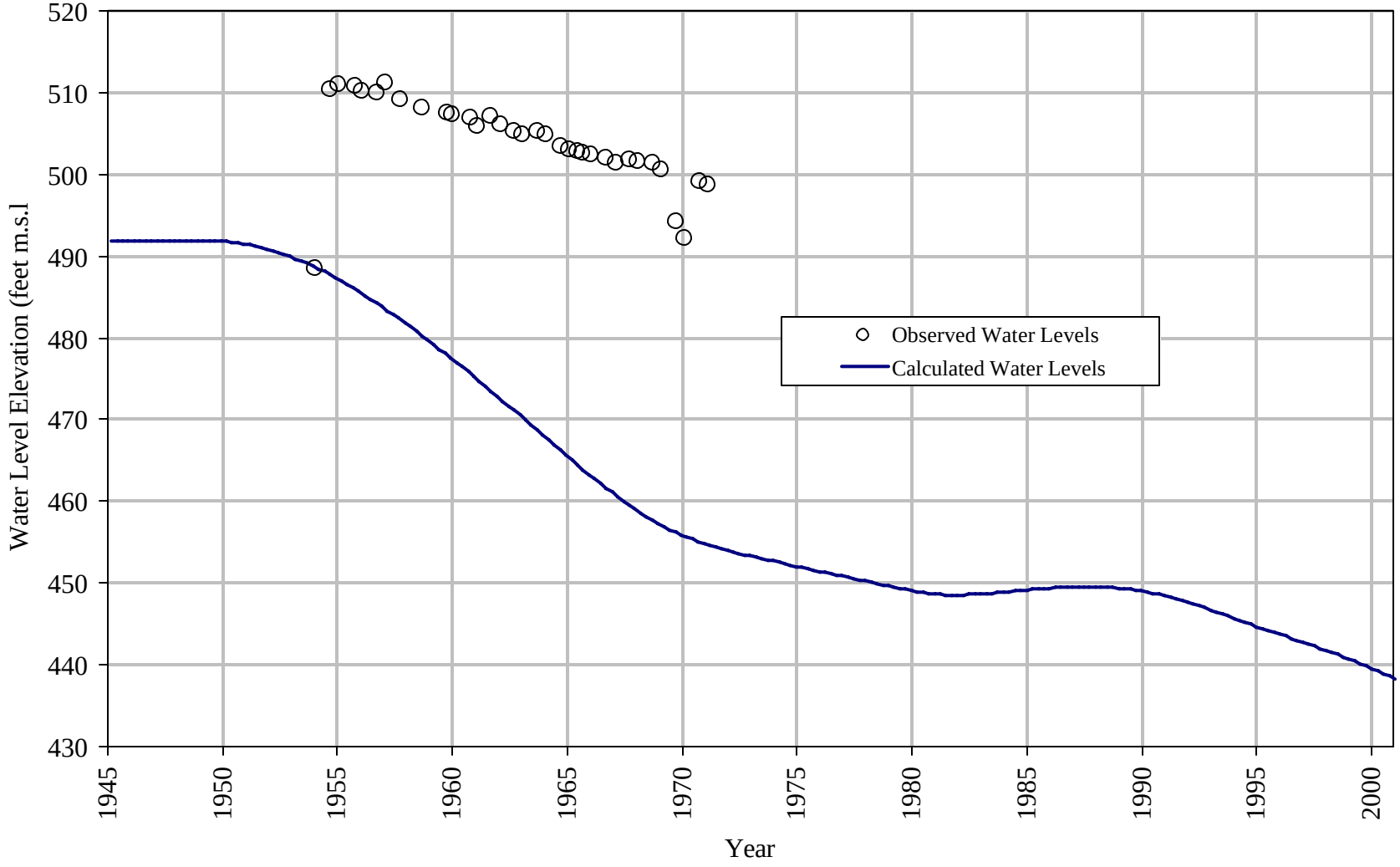


Figure 125. Water level elevation hydrograph well - 10S/7E 19M1 (transient model).

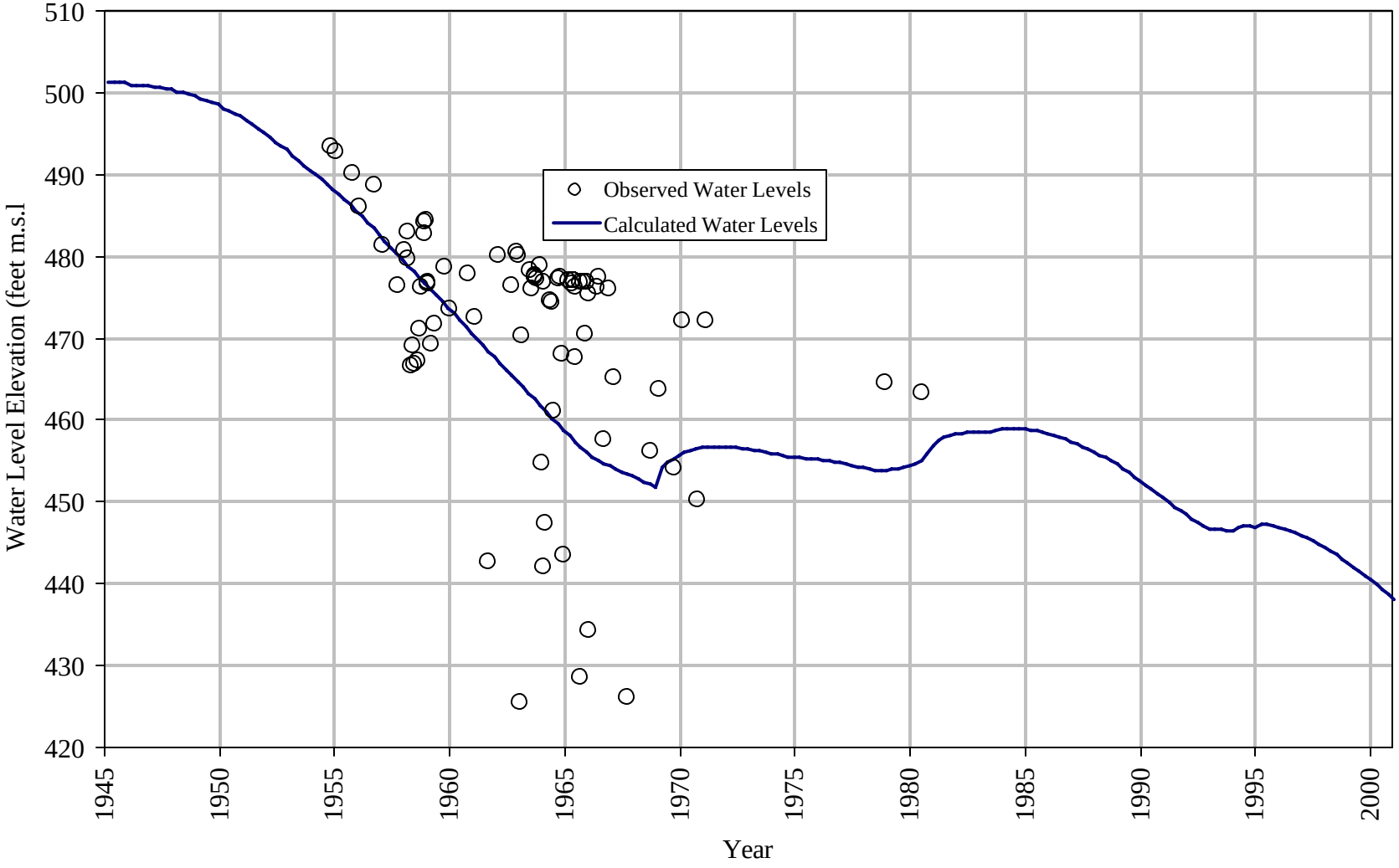


Figure 126. Water level elevation hydrograph well - 10S/6E 35N1 (transient model).

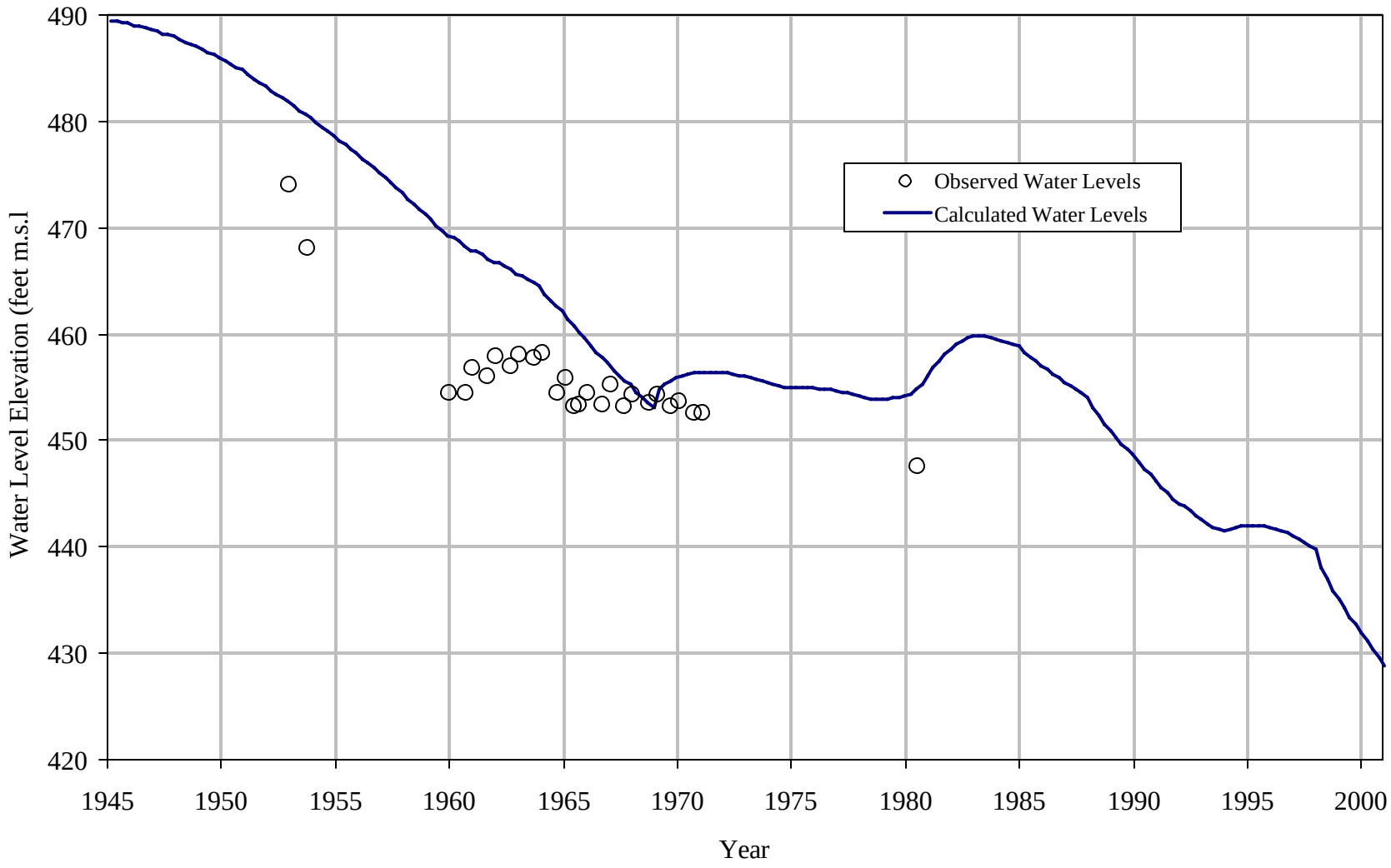


Figure 127. Water level elevation hydrograph well - 11S/6E 10N1 (transient model).

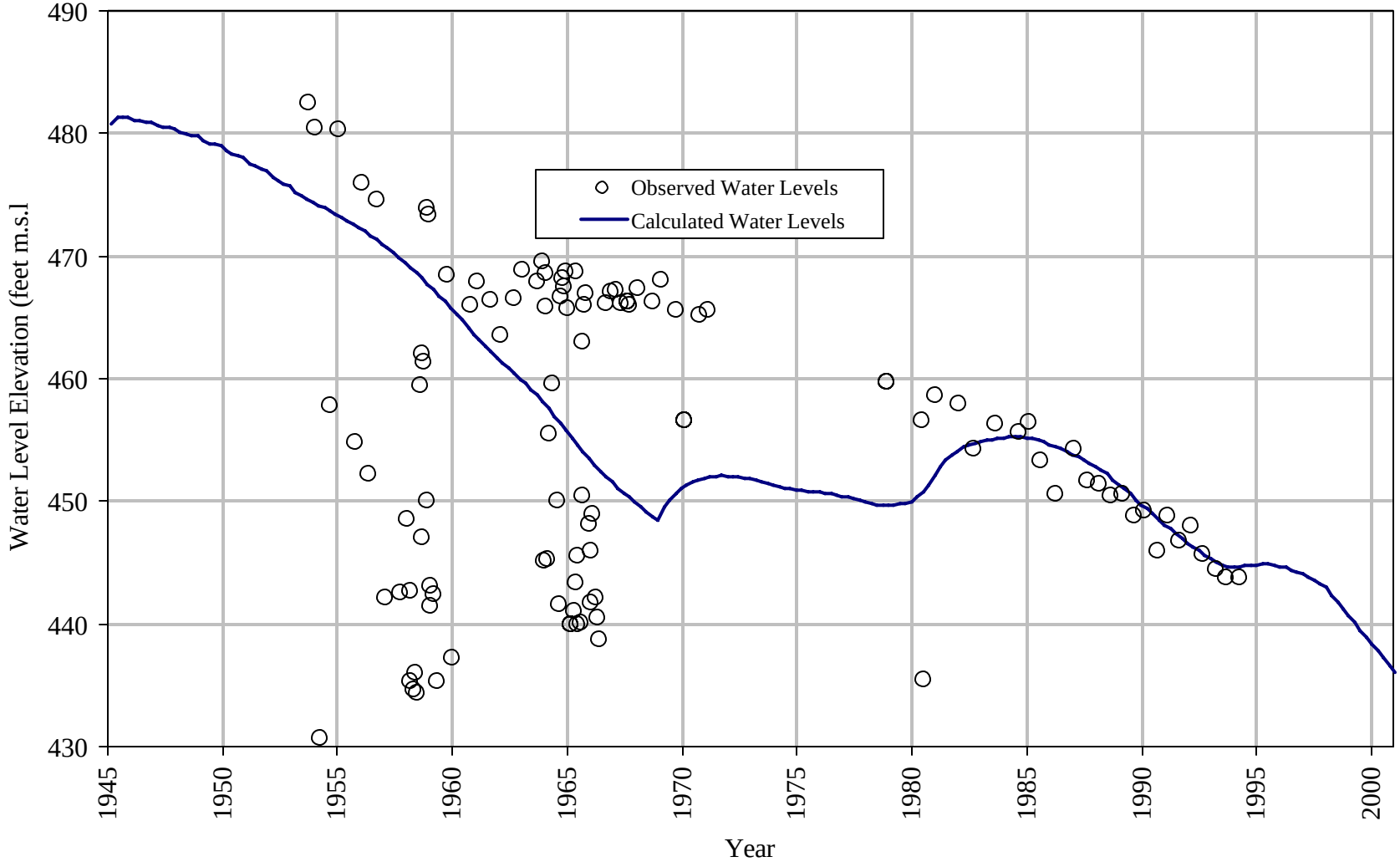


Figure 128. Water level elevation hydrograph well - 11S/6E 11D2 (transient model).

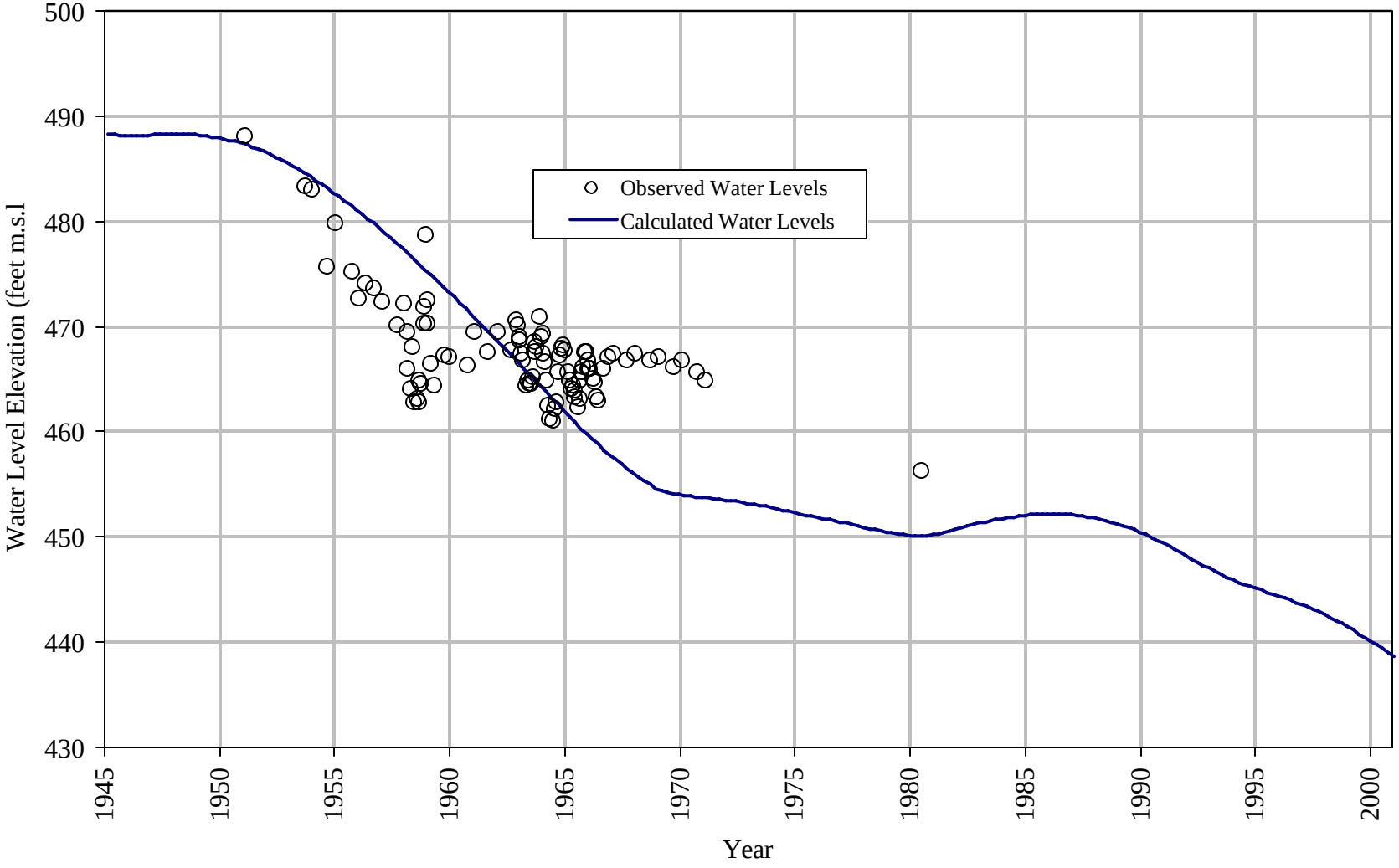


Figure 129. Water level elevation hydrograph well - 10S/6E 36Q1 (transient model).

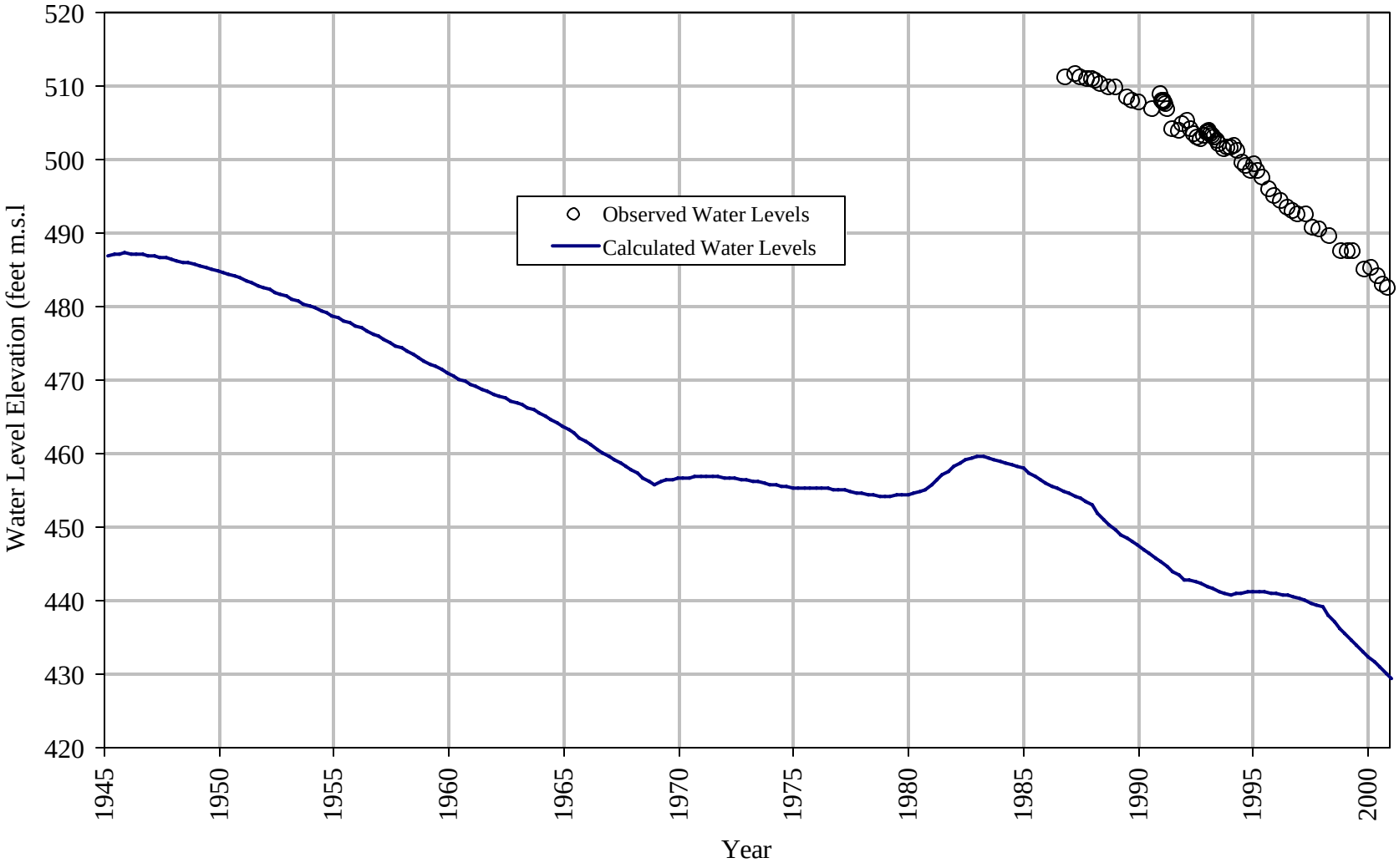


Figure 130. Water level elevation hydrograph well - Levie (transient model).

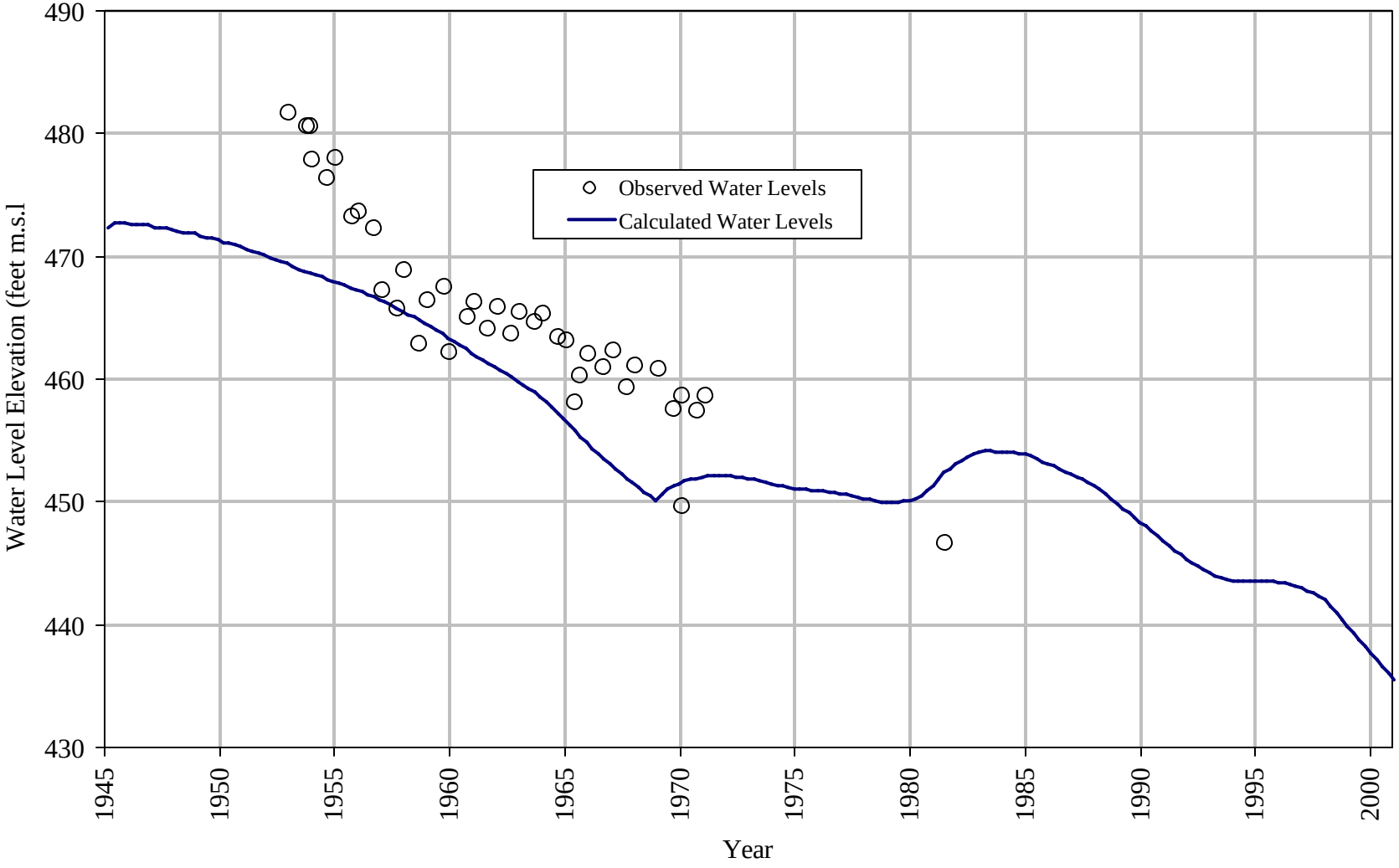


Figure 131. Water level elevation hydrograph well - 11S/6E 11M1 (transient model).

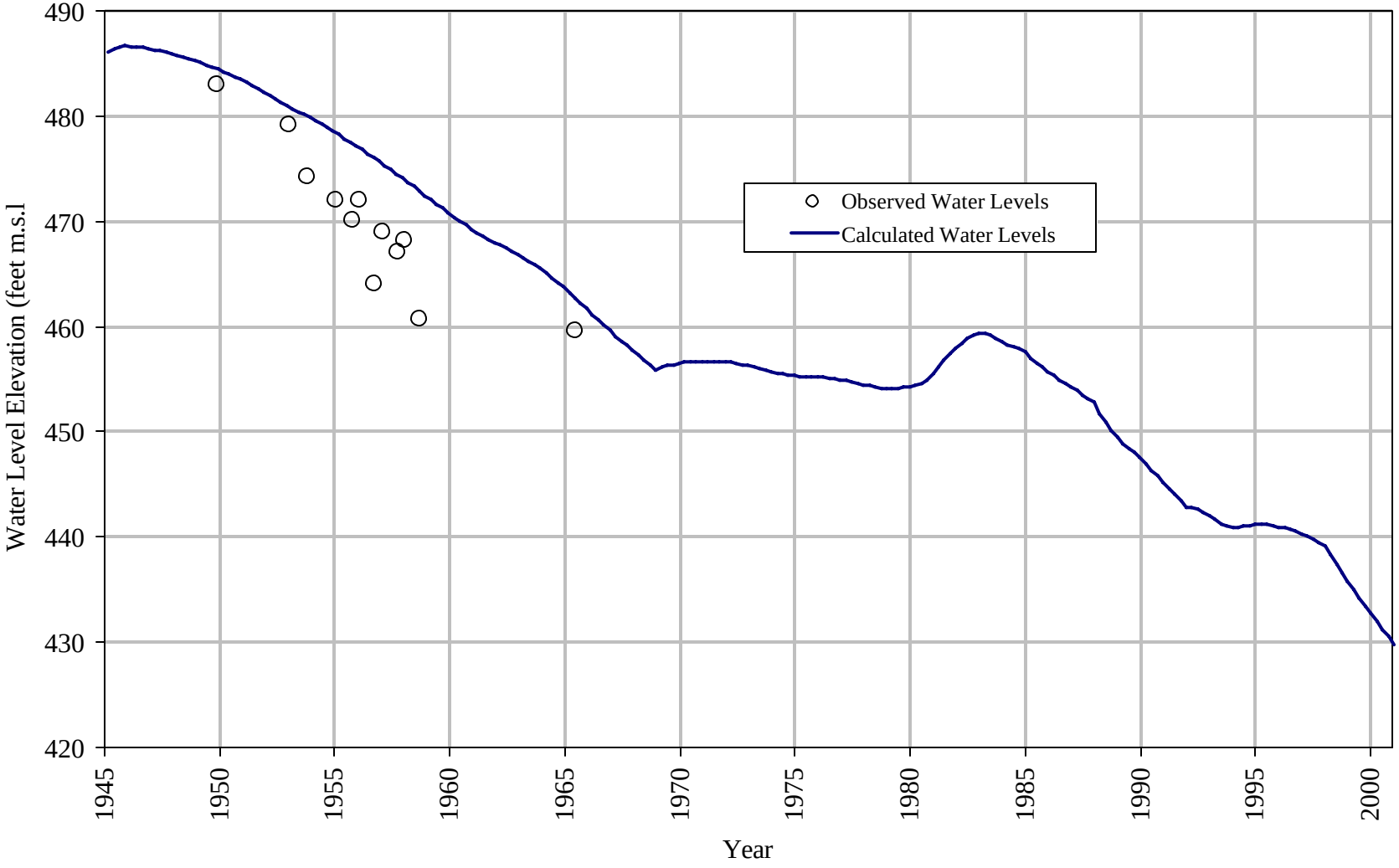


Figure 132. Water level elevation hydrograph well - 11S/6E 15F1 (transient model).

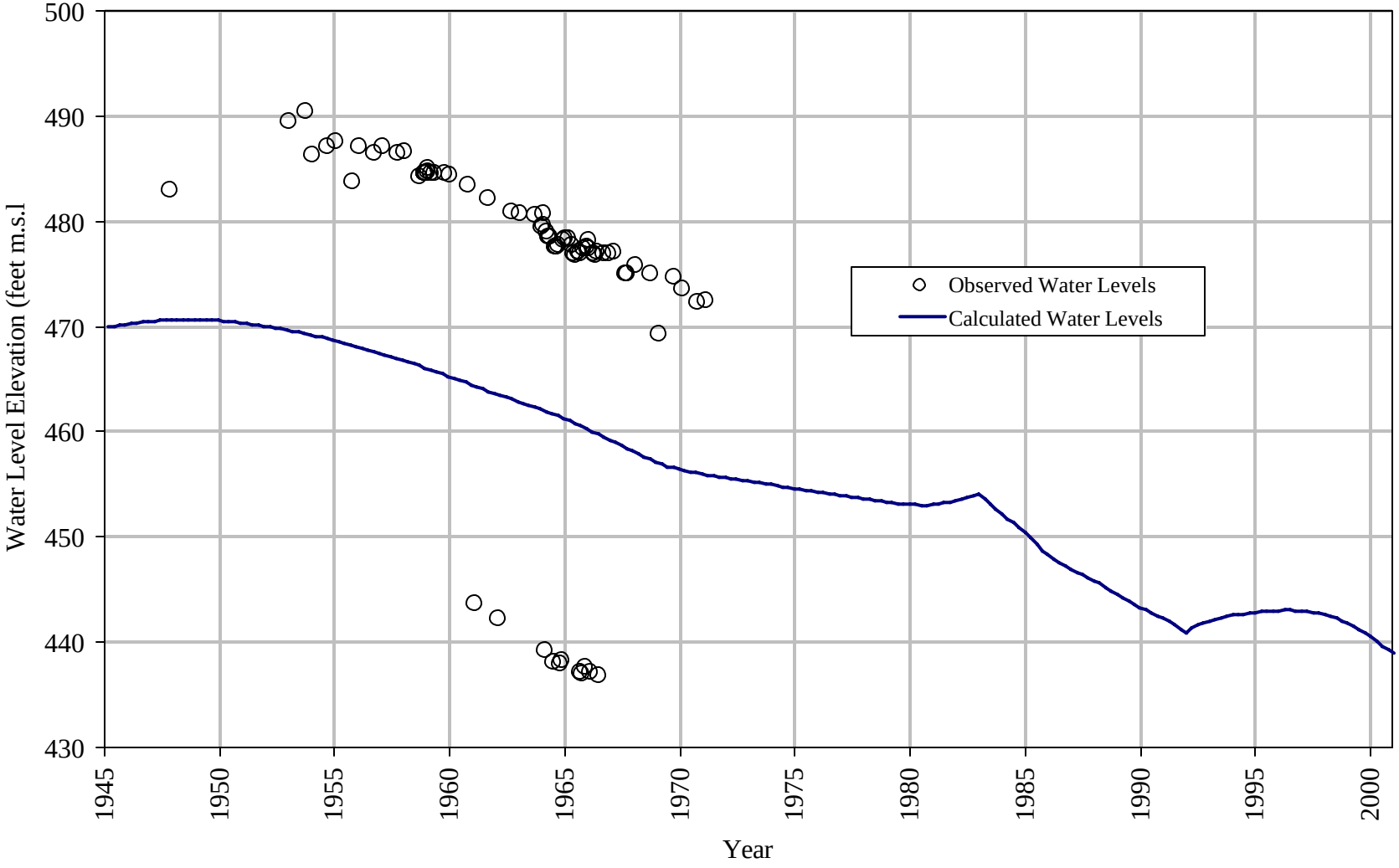


Figure 133. Water level elevation hydrograph well - 11S/6E 22A1 (transient model).

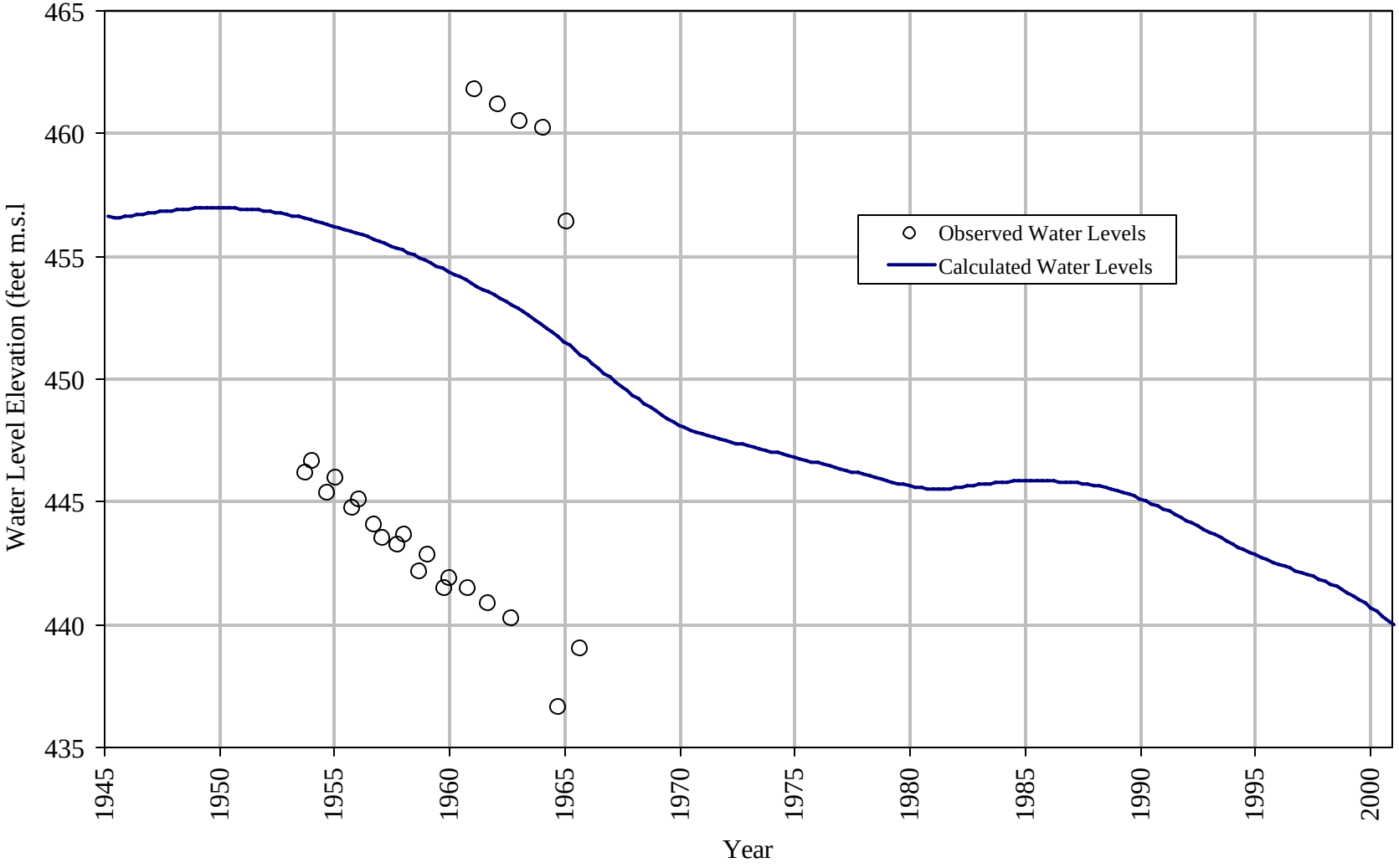


Figure 134. Water level elevation hydrograph well - 11S/7E 7N1 (transient model).

APPENDIX E

PREDICTIVE MODELING FLUX SUMMARIES AND HYDROGRAPHS

Table 17

Summary of Groundwater Fluxes (Predictive Modeling - Expected Use Scenario)

Year	Surface Water Recharge (AF/Yr)	Bedrock Recharge (AF/Yr)	Underflow Recharge (S.F.C.) (AF/Yr)	Municipal Extraction (AF/Yr)	Agricultural Extraction (AF/Yr)	Recreational Extraction (AF/Yr)	Balance (Net) (AF/Yr)
2001	1,540	0	30	-2,930	-9,280	-3,110	-13,750
2002	1,510	0	30	-3,010	-9,280	-3,110	-13,860
2003	1,090	70	30	-3,110	-9,280	-3,110	-14,310
2004	1,800	7,970	30	-3,200	-9,280	-3,110	-5,790
2005	720	0	30	-3,290	-9,280	-4,110	-15,930
2006	990	880	30	-3,390	-9,280	-4,110	-14,880
2007	2,680	0	30	-3,490	-9,280	-4,110	-14,170
2008	4,790	11,240	30	-3,600	-9,280	-4,110	-930
2009	7,550	2,030	30	-3,710	-9,280	-4,110	-7,490
2010	31,180	19,860	30	-3,820	-9,280	-4,110	33,860
2011	6,890	0	30	-3,930	-9,280	-4,110	-10,400
2012	7,700	470	30	-4,050	-9,280	-4,110	-9,240
2013	25,140	1,230	30	-4,170	-9,280	-4,110	8,840
2014	7,930	0	30	-4,300	-9,280	-4,110	-9,730
2015	5,830	70	30	-4,430	-9,280	-4,110	-11,890
2016	4,980	860	30	-4,560	-9,280	-4,110	-12,080
2017	3,650	0	30	-4,700	-9,280	-4,110	-14,410
2018	3,110	0	30	-4,840	-9,280	-4,110	-15,090
2019	2,280	0	30	-4,980	-9,280	-4,110	-16,060
2020	2,010	0	30	-5,130	-9,280	-4,110	-16,480
2021	4,070	2,570	30	-5,290	-9,280	-4,110	-12,010
2022	3,470	3,450	30	-5,440	-9,280	-4,110	-11,880
2023	6,240	18,730	30	-5,610	-9,280	-4,110	6,000
2024	6,730	0	30	-5,780	-9,280	-4,110	-12,410
2025	3,850	4,590	30	-5,950	-9,280	-4,110	-10,870
2026	2,610	0	30	-6,130	-9,280	-4,110	-16,880
2027	2,610	2,090	30	-6,310	-9,280	-4,110	-14,970
2028	8,590	1,600	30	-6,500	-9,280	-4,110	-9,670
2029	2,550	0	30	-6,700	-9,280	-4,110	-17,510
2030	2,200	500	30	-6,900	-9,280	-4,110	-17,560

Table 18

Summary of Groundwater Fluxes (Predictive Modeling - Worst Case Use Scenario

Year	Surface Water Recharge (AF/Yr)	Bedrock Recharge (AF/Yr)	Underflow Recharge (S.F.C.) (AF/Yr)	Municipal Extraction (AF/Yr)	Agricultural Extraction (AF/Yr)	Recreational Extraction (AF/Yr)	Balance (Net) (AF/Yr)
2001	1,540	0	30	-3,010	-9,320	-3,110	-13,870
2002	1,510	0	30	-3,190	-9,370	-3,110	-14,130
2003	1,090	70	30	-3,380	-9,420	-3,110	-14,720
2004	1,800	7,970	30	-3,590	-9,460	-3,110	-6,360
2005	720	0	30	-3,800	-9,510	-5,480	-18,040
2006	990	880	30	-4,030	-9,560	-5,480	-17,170
2007	2,680	0	30	-4,270	-9,600	-5,480	-16,640
2008	4,790	11,240	30	-4,530	-9,650	-5,480	-3,600
2009	7,550	2,030	30	-4,800	-9,690	-5,480	-10,360
2010	31,180	19,860	30	-5,090	-9,740	-5,480	30,760
2011	6,890	0	30	-5,390	-9,790	-5,480	-13,740
2012	7,700	470	30	-5,720	-9,830	-5,480	-12,830
2013	25,140	1,230	30	-6,060	-9,880	-5,480	4,980
2014	7,930	0	30	-6,420	-9,930	-5,480	-13,870
2015	5,830	70	30	-6,810	-9,970	-5,480	-16,330
2016	4,980	860	30	-7,220	-10,020	-5,480	-16,850
2017	3,650	0	30	-7,650	-10,070	-5,480	-19,520
2018	3,110	0	30	-8,110	-10,110	-5,480	-20,560
2019	2,280	0	30	-8,600	-10,160	-5,480	-21,930
2020	2,010	0	30	-9,110	-10,200	-5,480	-22,750
2021	4,070	2,570	30	-9,660	-10,250	-5,480	-18,720
2022	3,470	3,450	30	-10,240	-10,300	-5,480	-19,070
2023	6,240	18,730	30	-10,850	-10,340	-5,480	-1,670
2024	6,730	0	30	-11,500	-10,390	-5,480	-20,610
2025	3,850	4,590	30	-12,200	-10,440	-5,480	-19,650
2026	2,610	0	30	-12,930	-10,480	-5,480	-26,250
2027	2,610	2,090	30	-13,700	-10,530	-5,480	-24,980
2028	8,590	1,600	30	-14,520	-10,580	-5,480	-20,360
2029	2,550	0	30	-15,400	-10,620	-5,480	-28,920
2030	2,200	500	30	-16,320	-10,670	-5,480	-29,740

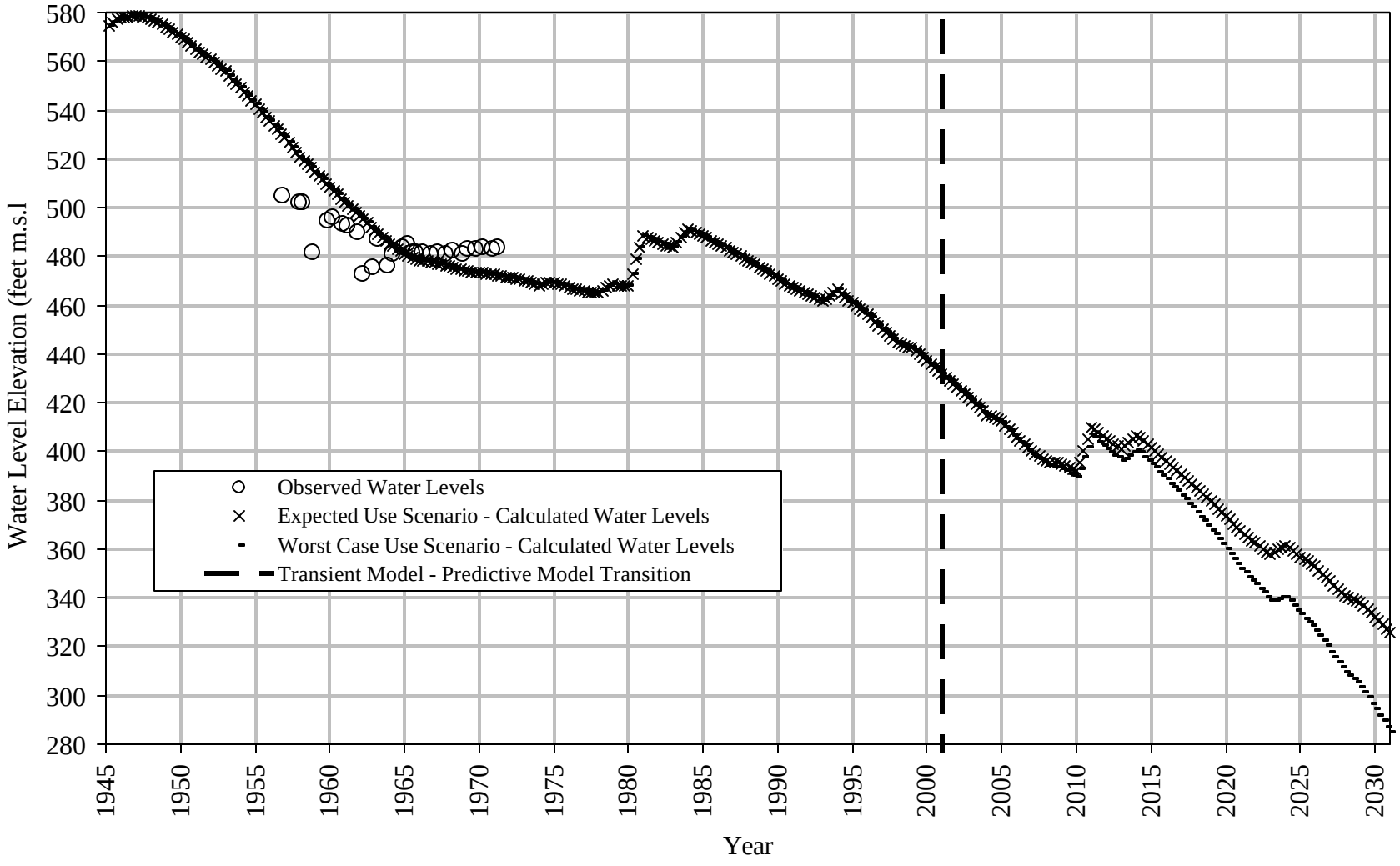


Figure 135. Water level elevation hydrograph well - 10S/6E 8B1 (transient and predictive models).

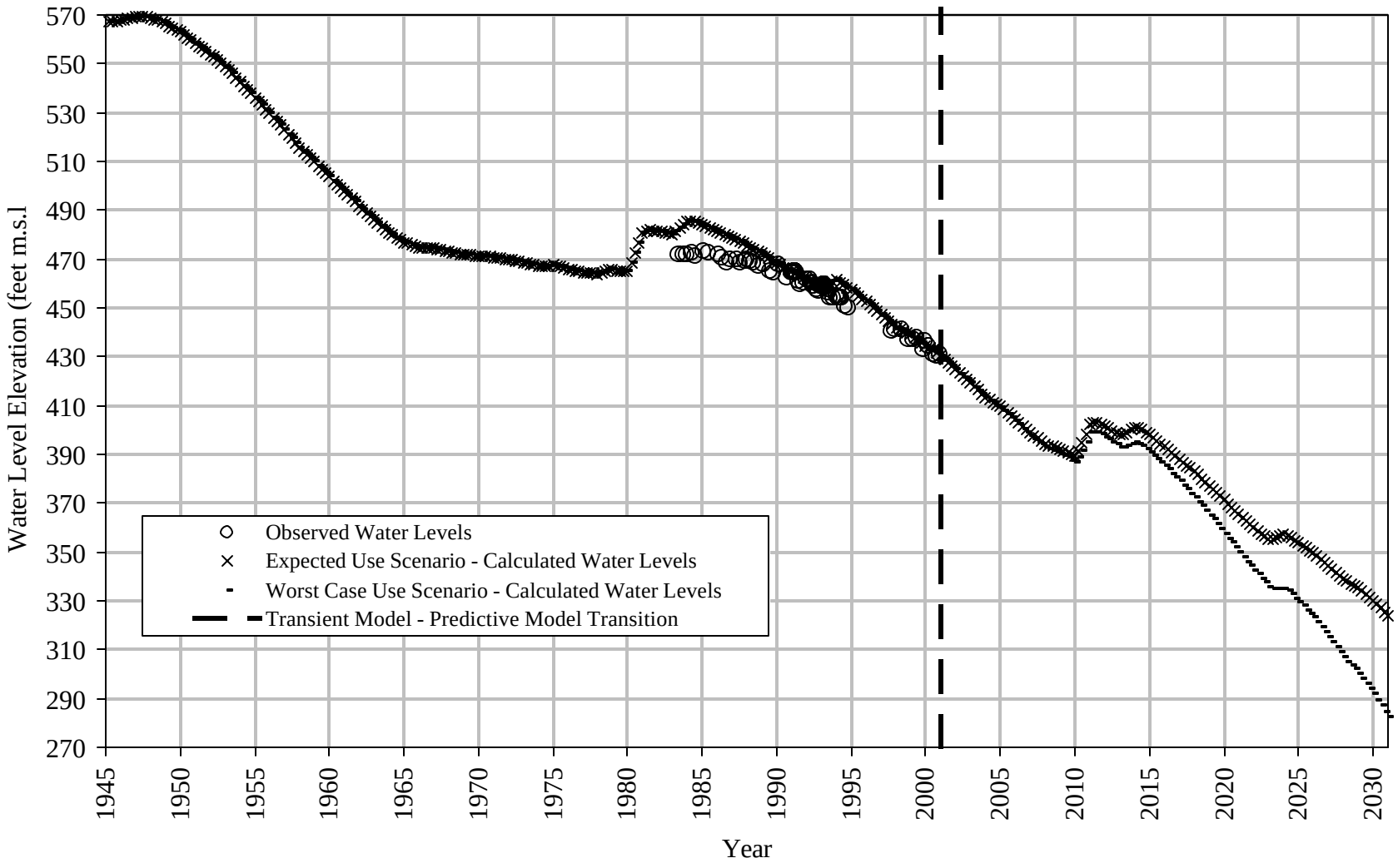


Figure 136. Water level elevation hydrograph well - Fortiner (transient and predictive models).

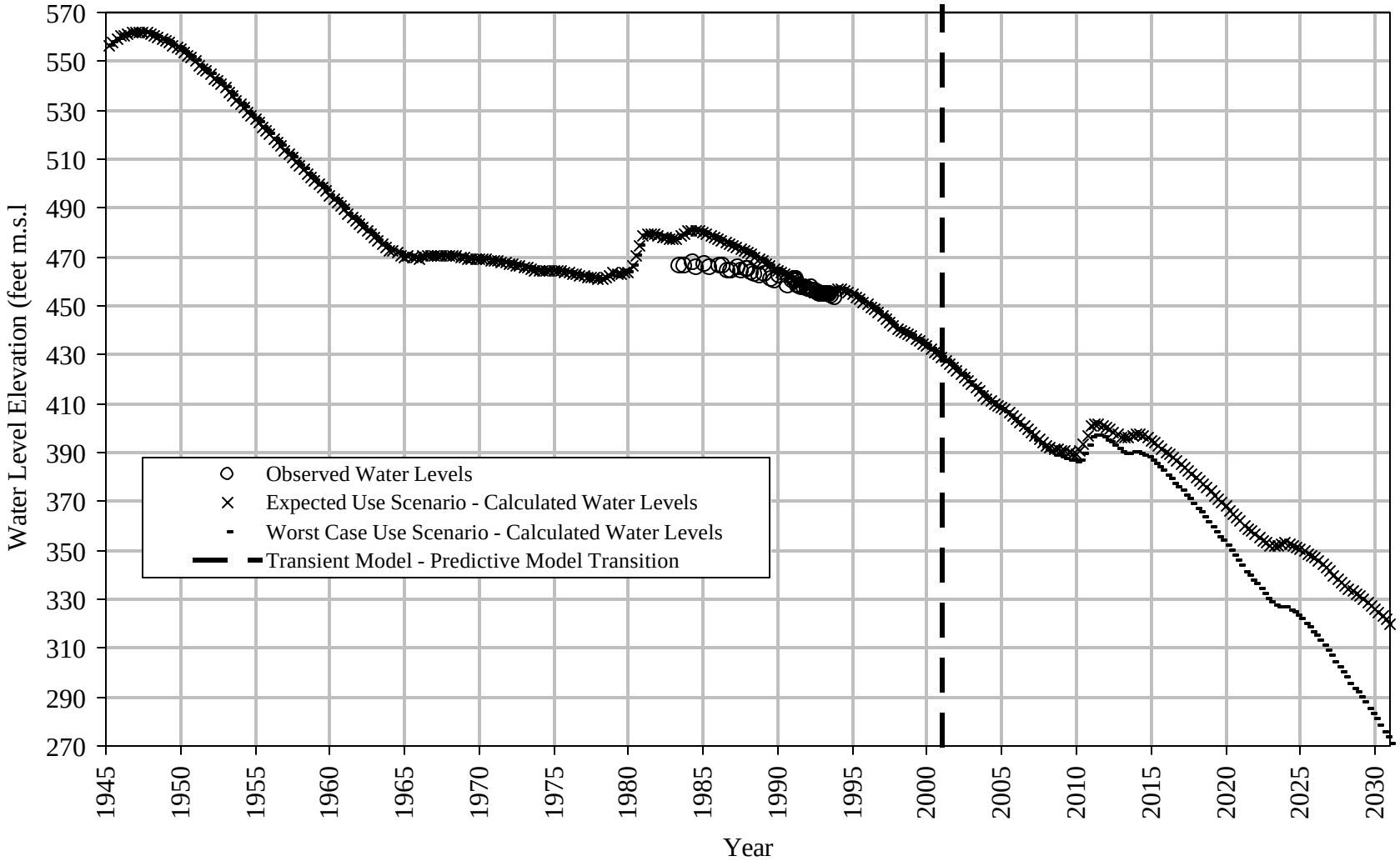


Figure 137. Water level elevation hydrograph well - Fort (transient and predictive models).

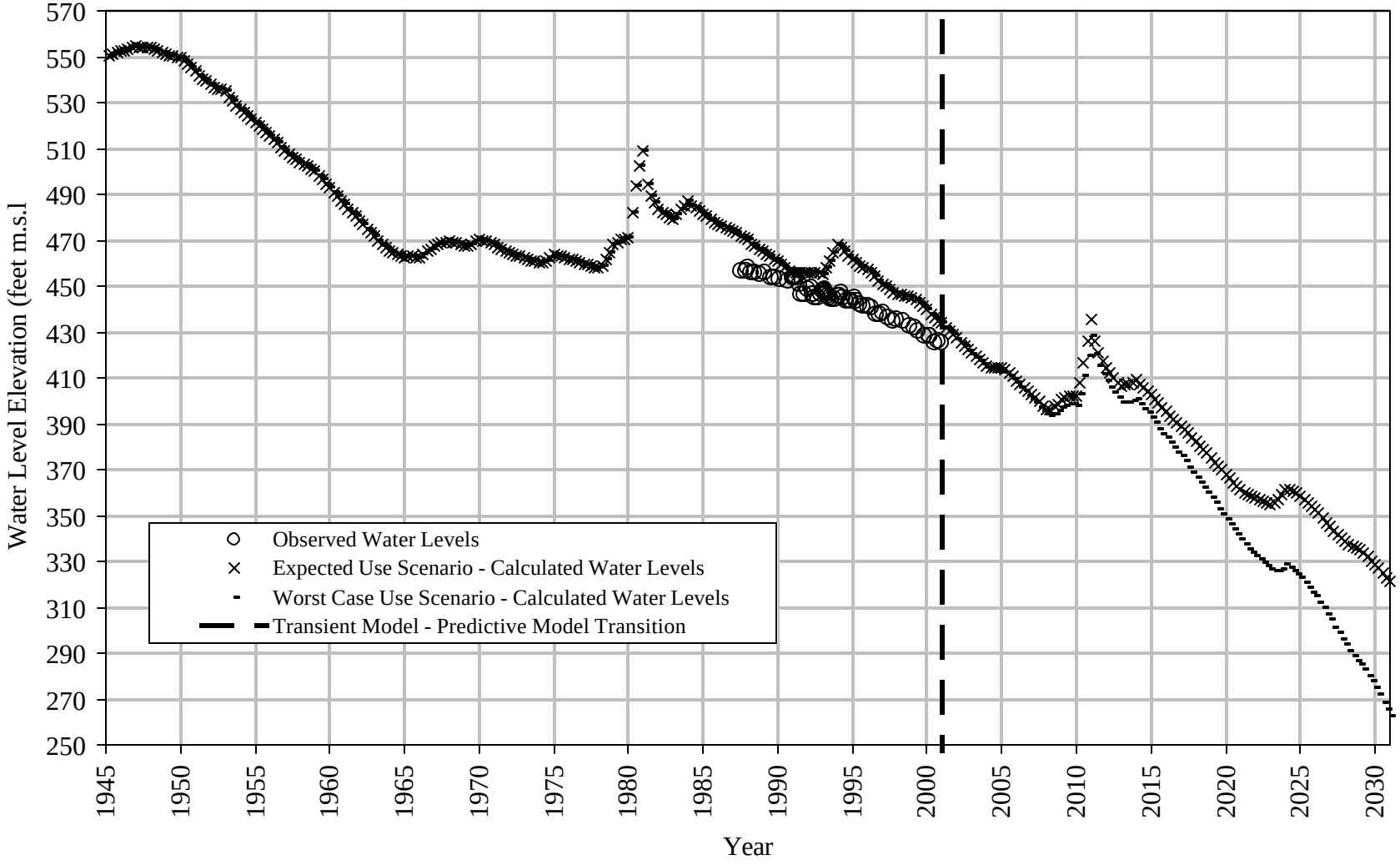


Figure 138. Water level elevation hydrograph well - Empty (transient and predictive models).

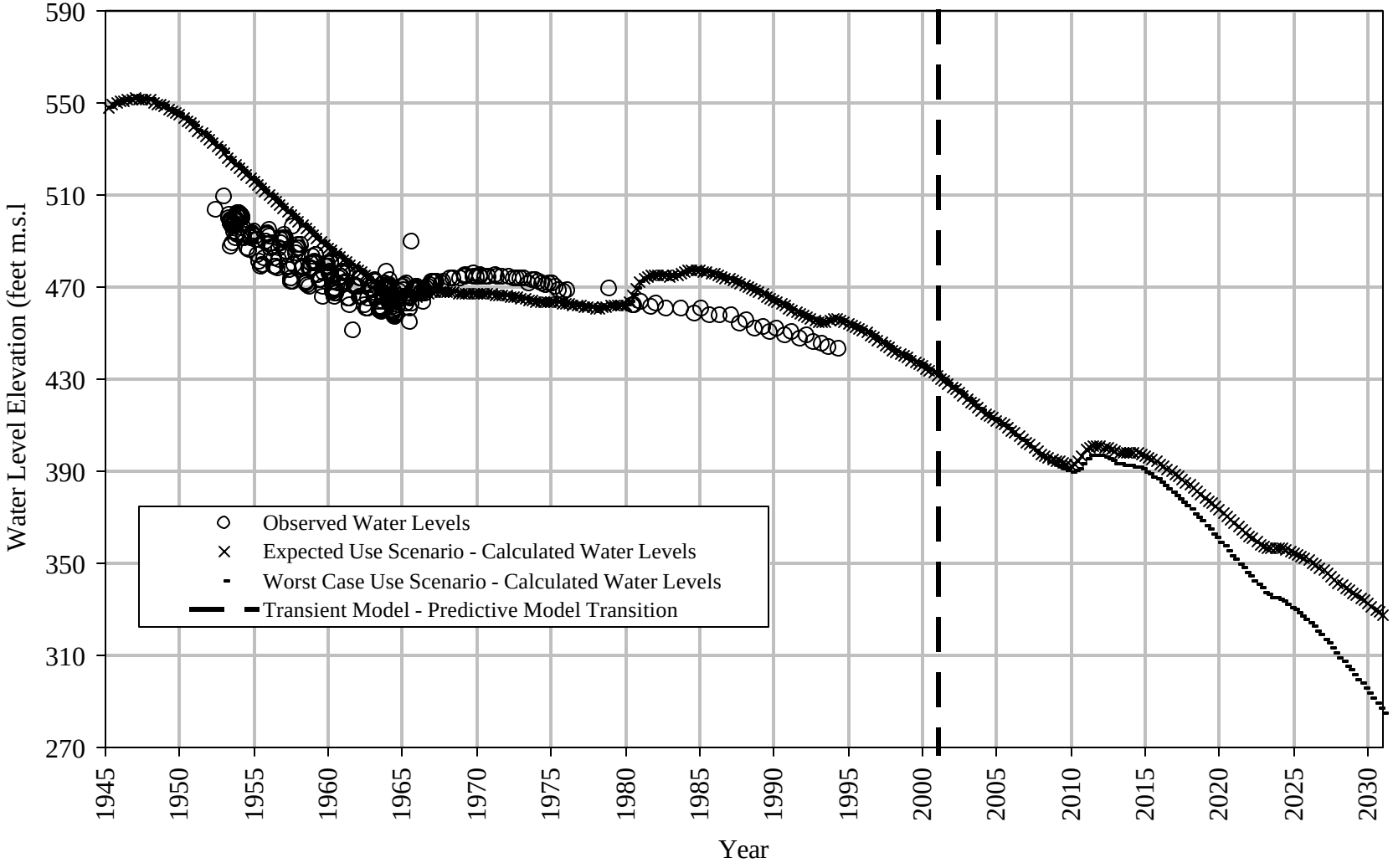


Figure 139. Water level elevation hydrograph well - 10S/6E 21A1 (transient and predictive models).

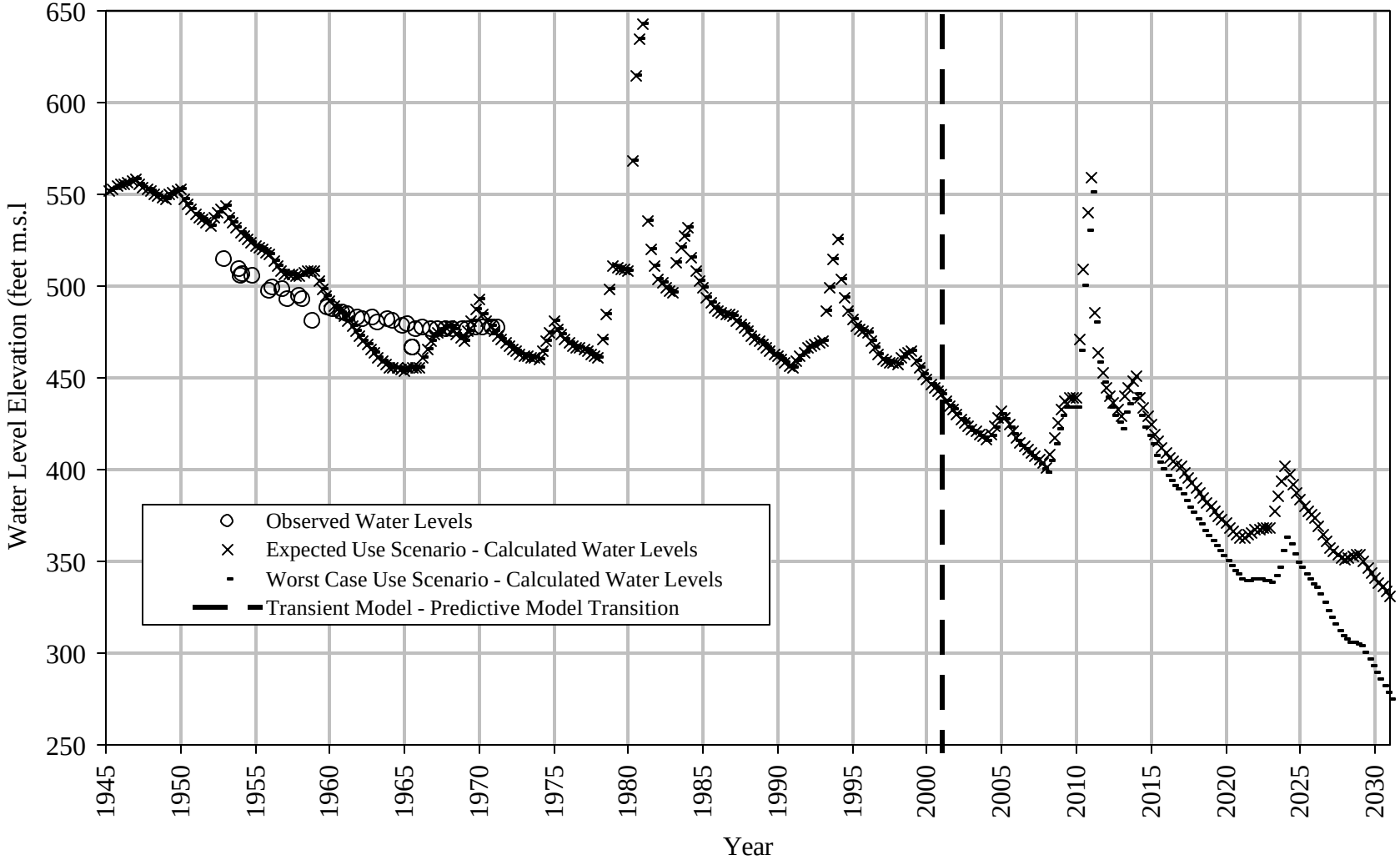


Figure 140. Water level elevation hydrograph well - 10S/6E 29N1 (transient and predictive models).

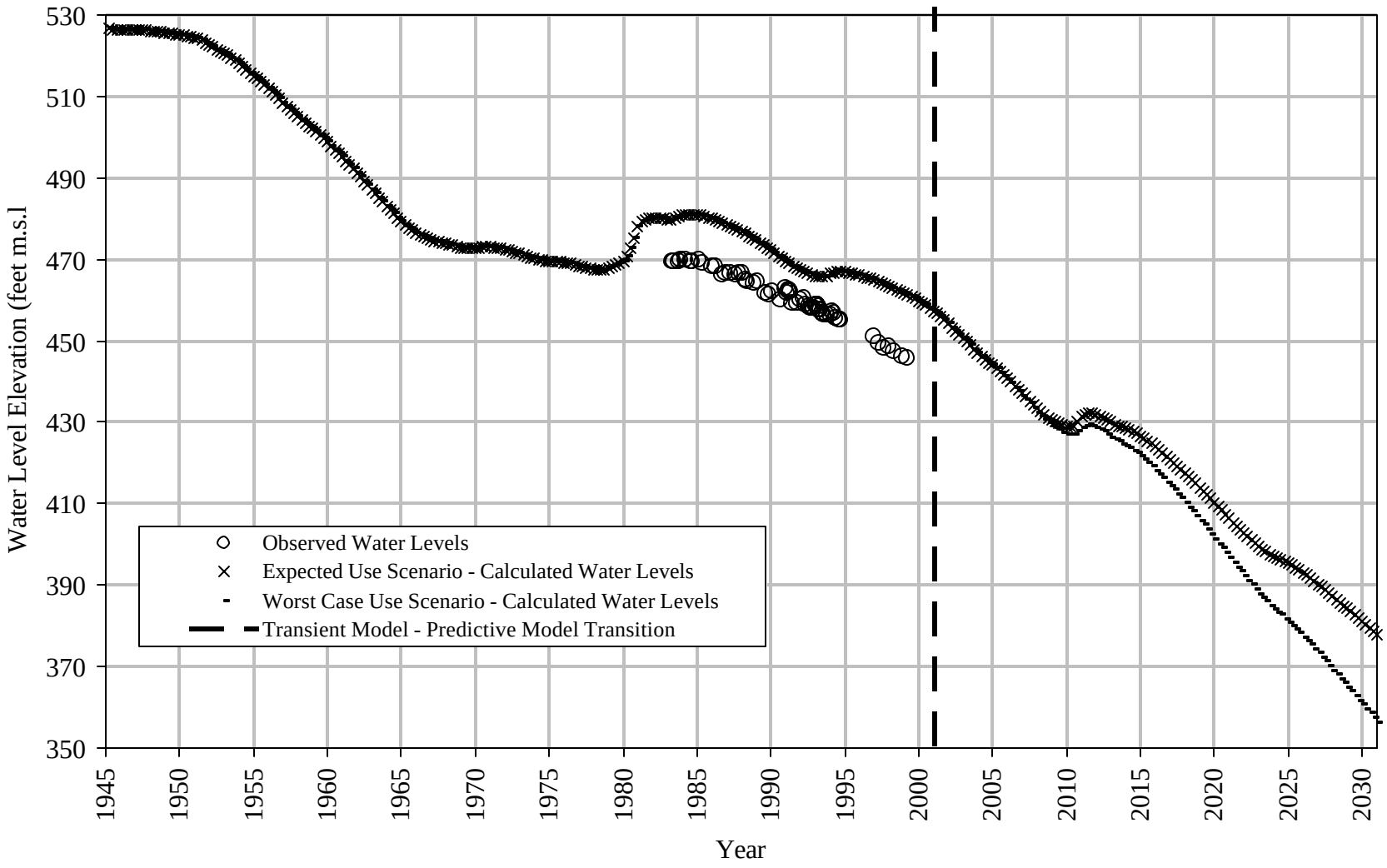


Figure 141. Water level elevation hydrograph well - BSW #1 (transient and predictive models).

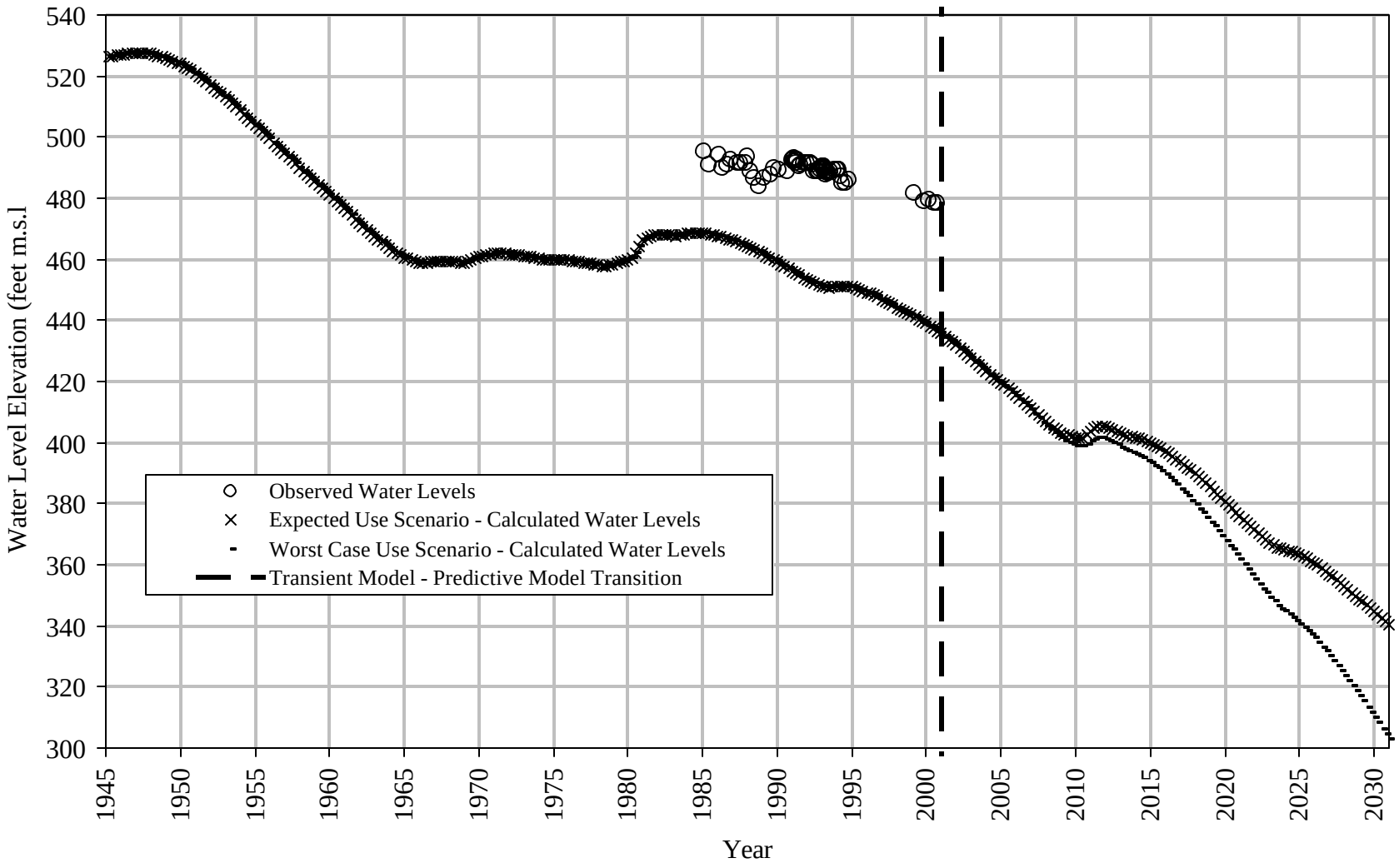


Figure 142. Water level elevation hydrograph well - UEC #2 (transient and predictive models).

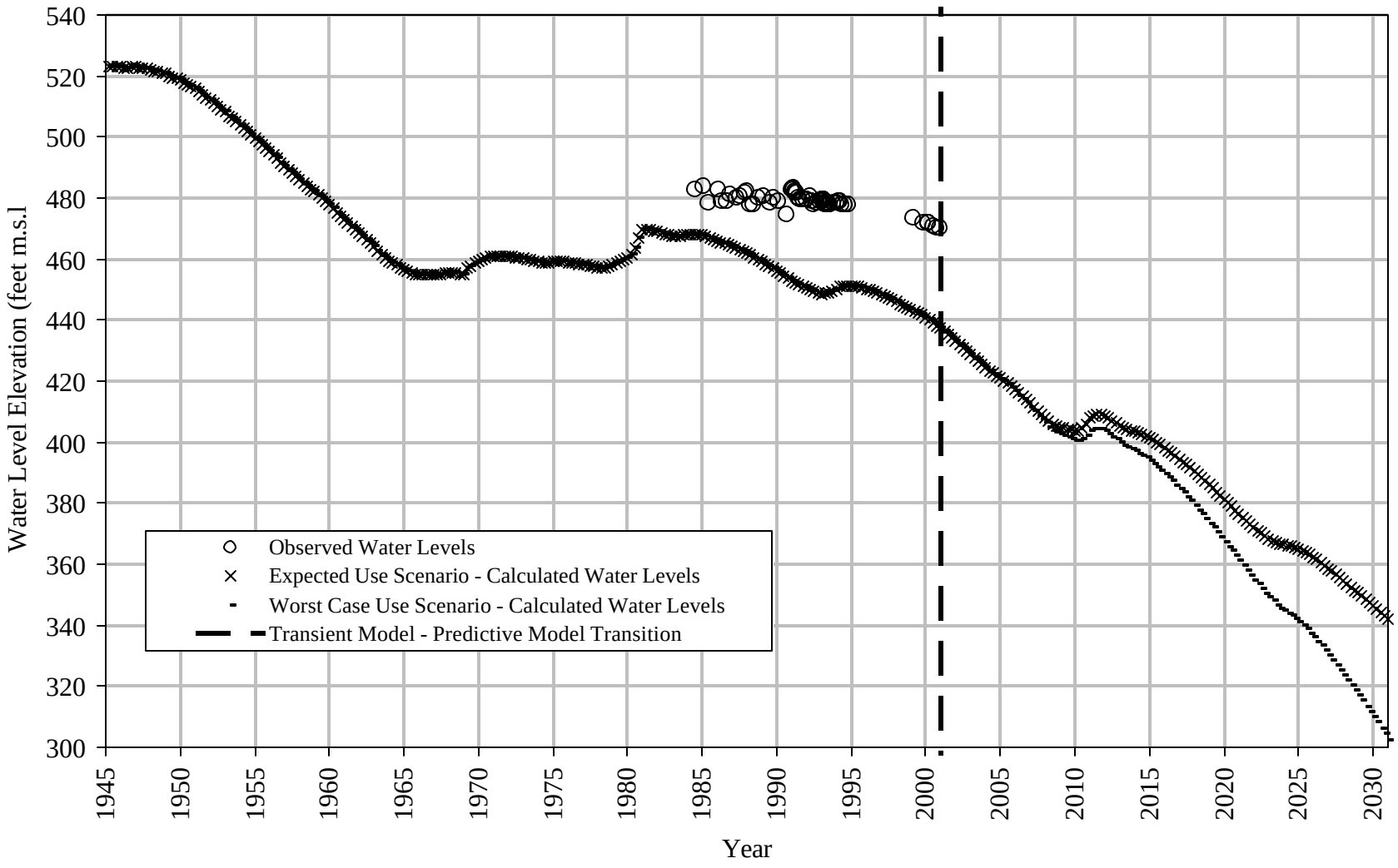


Figure 143. Water level elevation hydrograph well - UEC #1 (transient and predictive models).

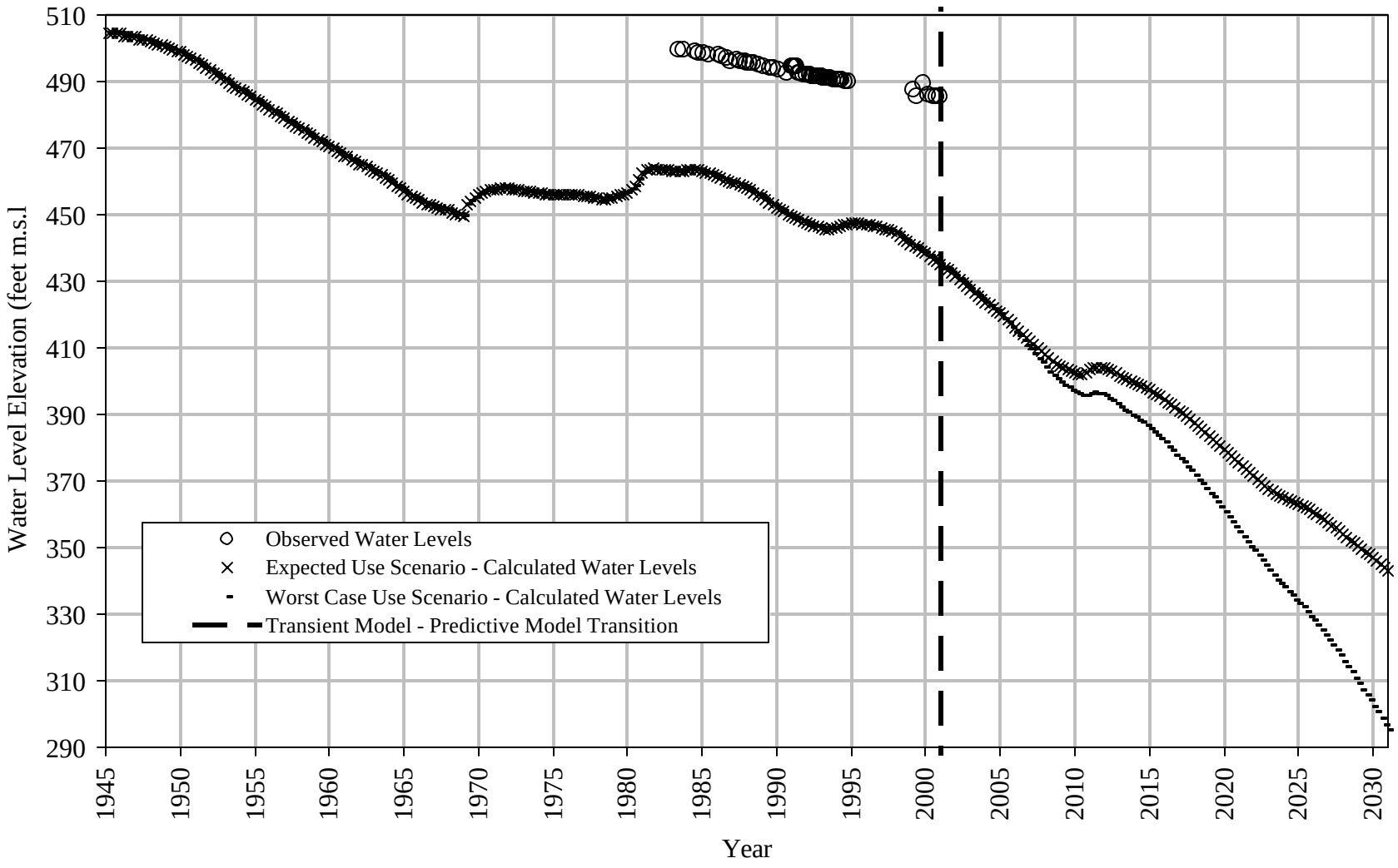


Figure 144. Water level elevation hydrograph well - Victor (transient and predictive models).

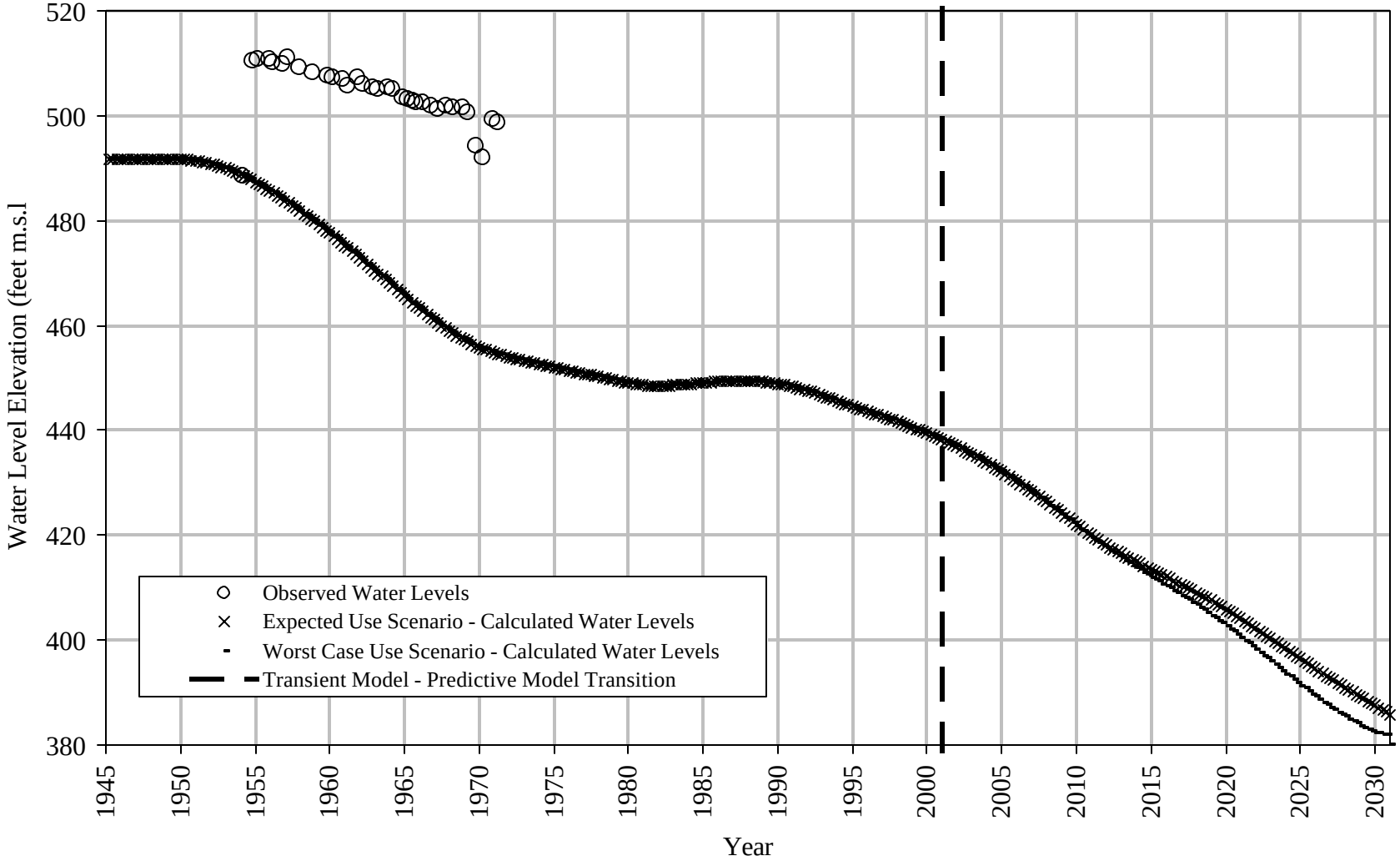


Figure 145. Water level elevation hydrograph well - 10S/7E 19M1 (transient and predictive models).

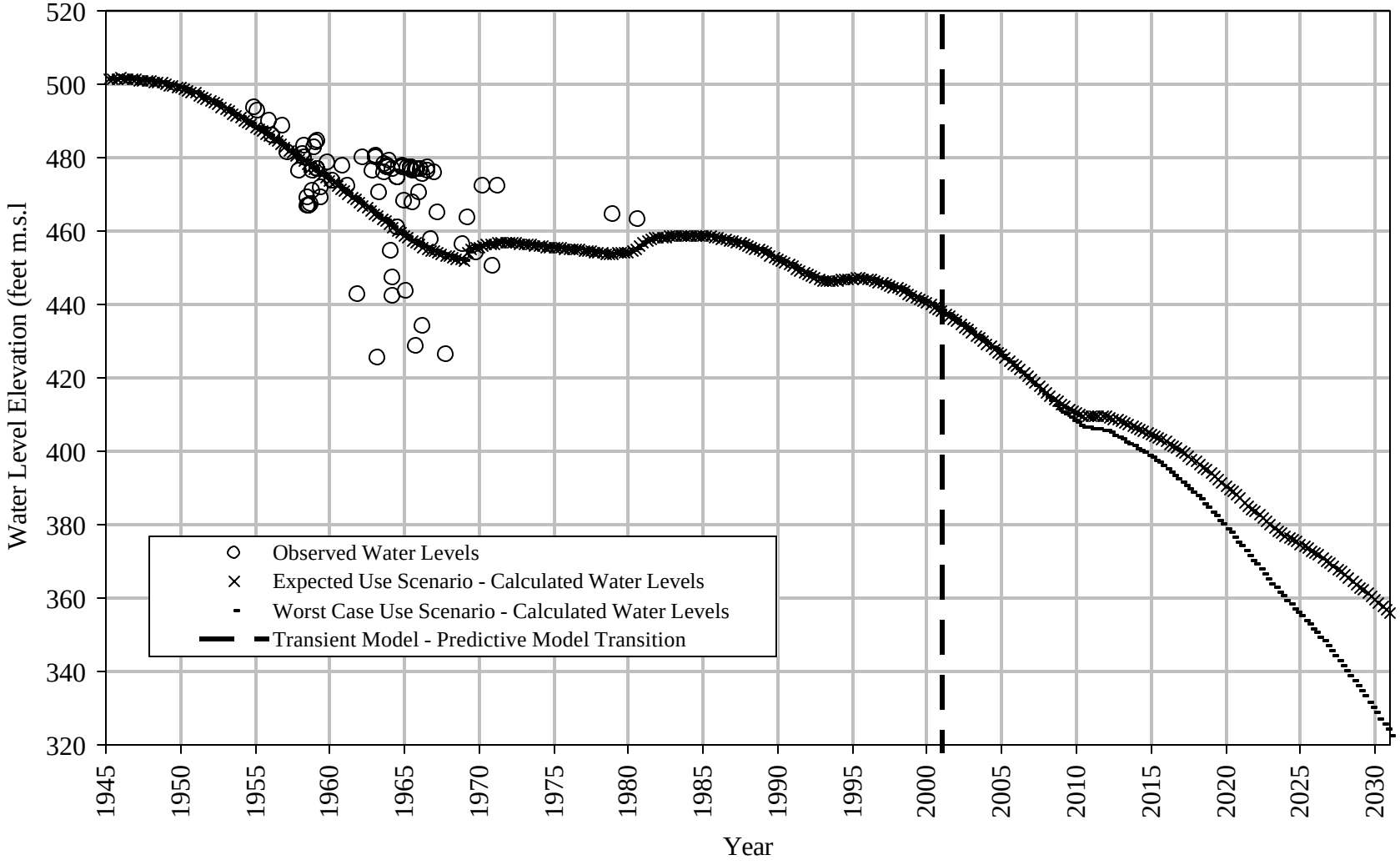


Figure 146. Water level elevation hydrograph well - 10S/6E 35N1 (transient and predictive models).

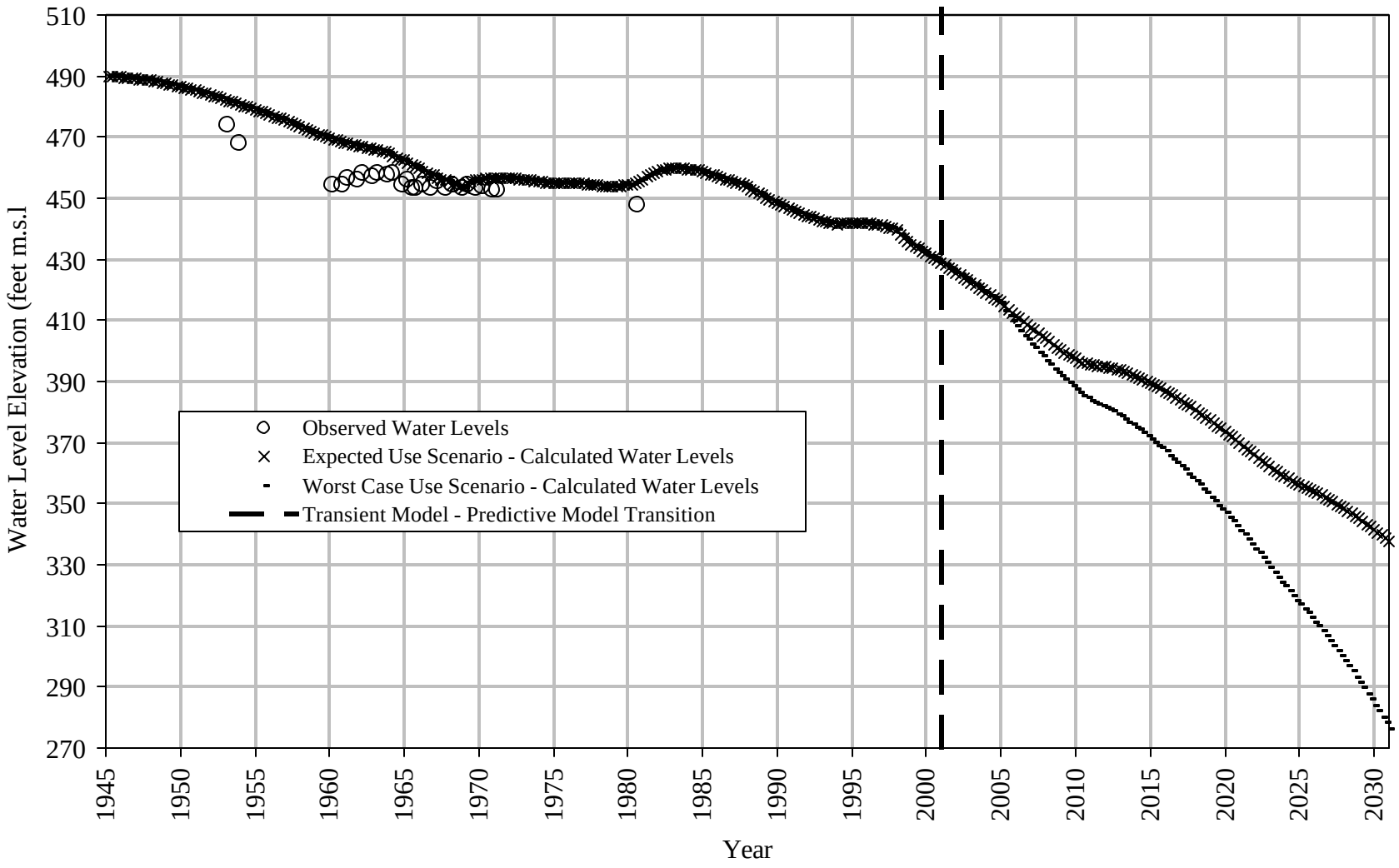


Figure 147. Water level elevation hydrograph well - 11S/6E 10N1 (transient and predictive models).

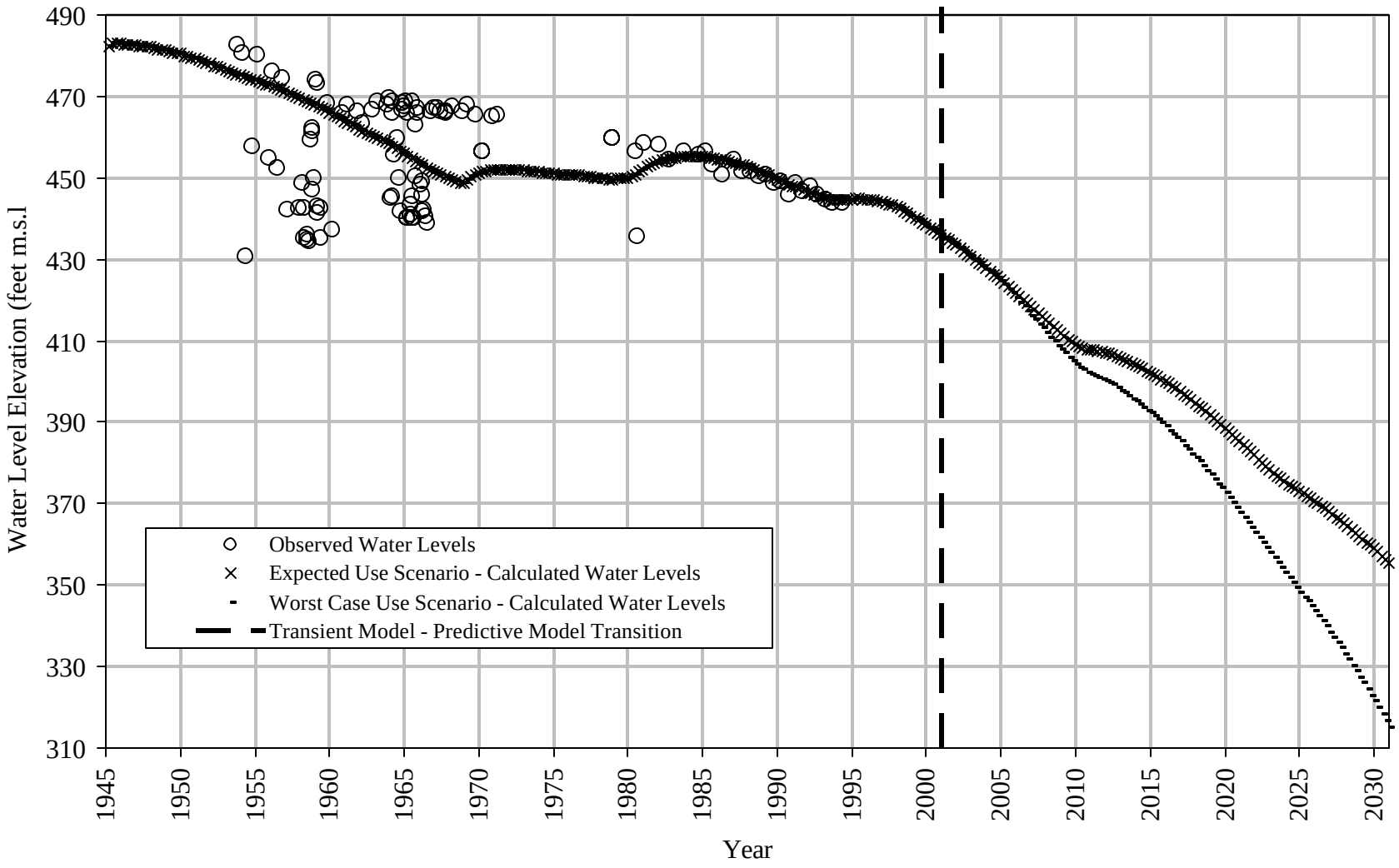


Figure 148. Water level elevation hydrograph well - 11S/6E 11D2 (transient and predictive models).

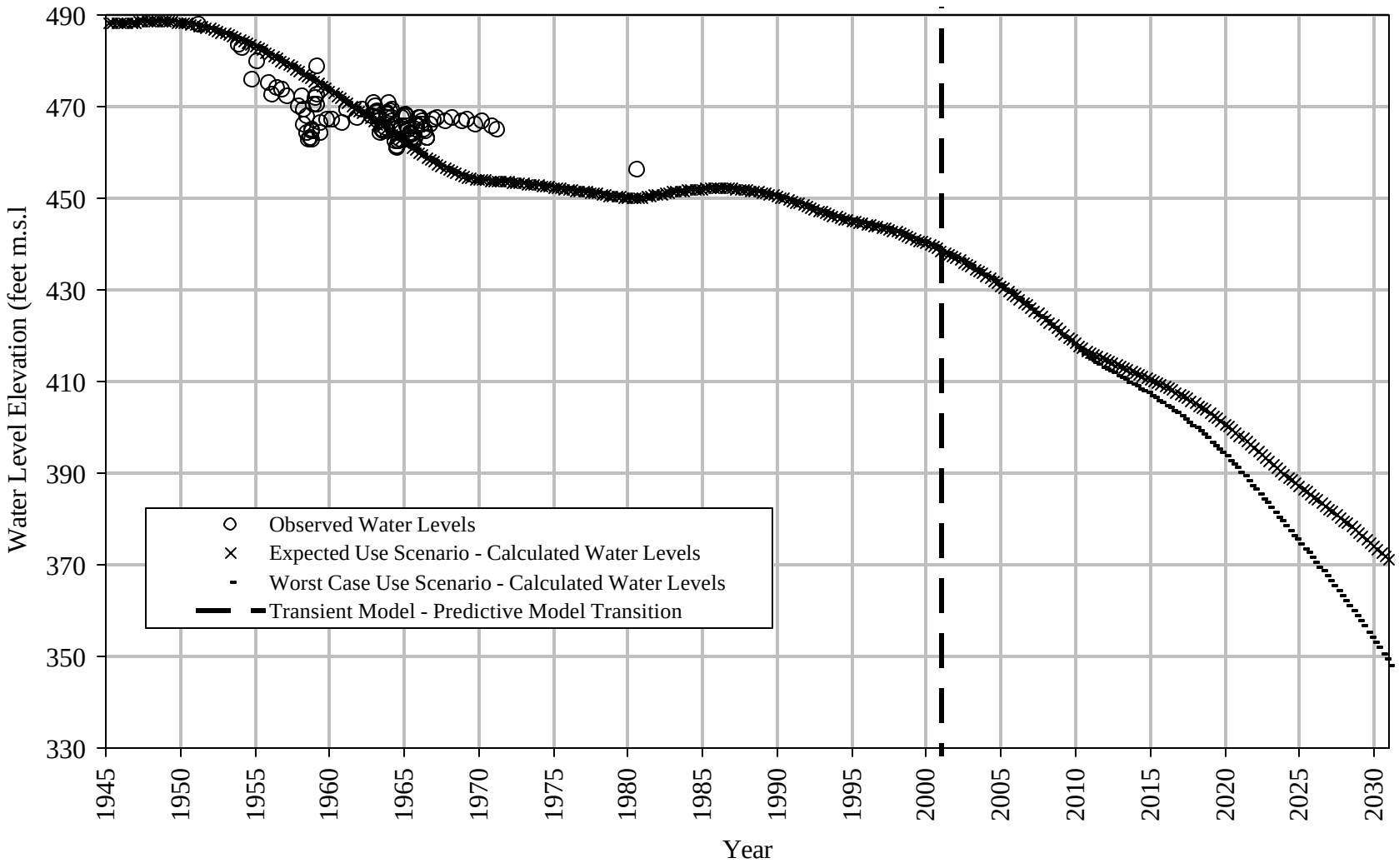


Figure 149. Water level elevation hydrograph well - 10S/6E 36Q1 (transient and predictive models).

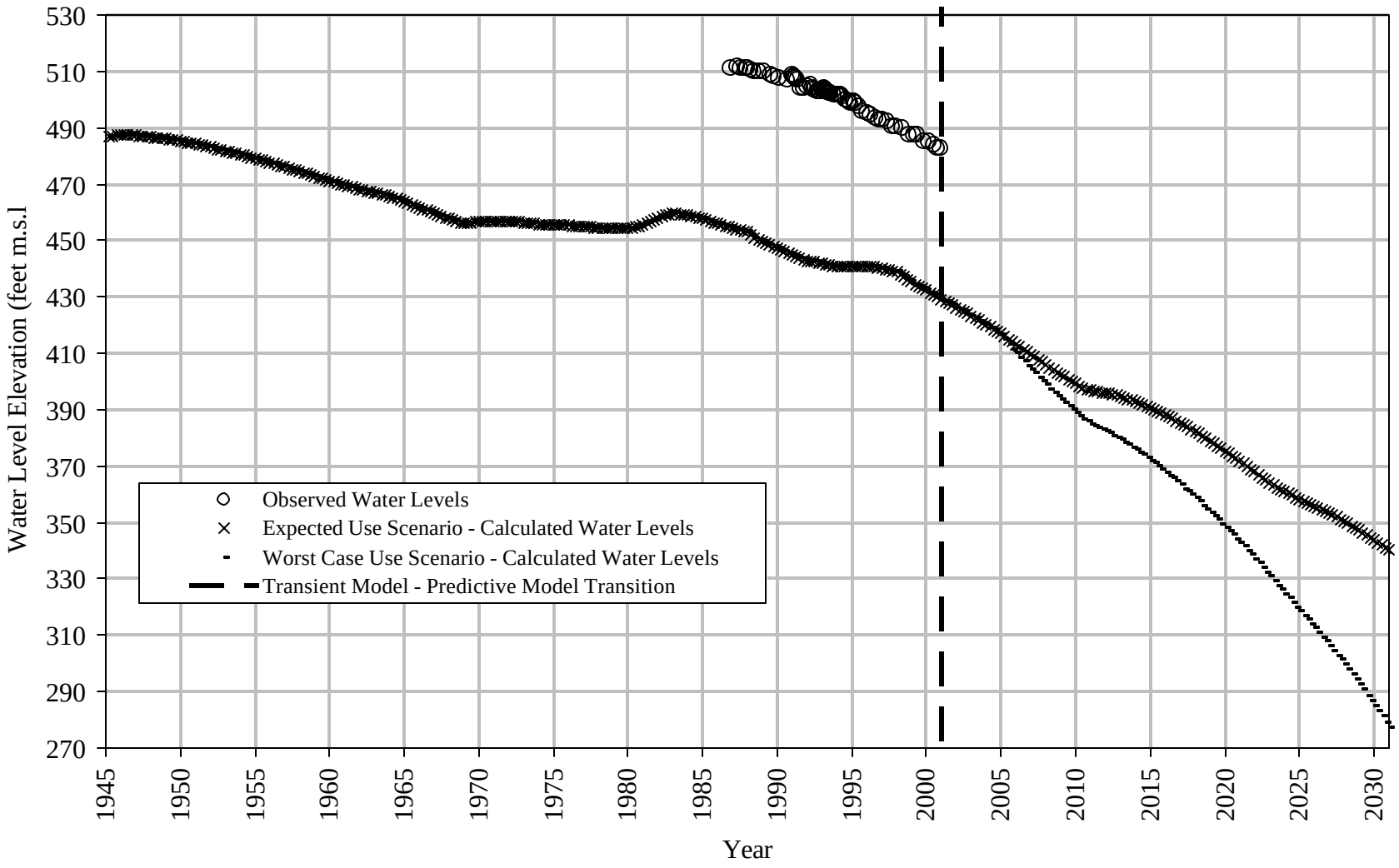


Figure 150. Water level elevation hydrograph well - Levie (transient and predictive models).

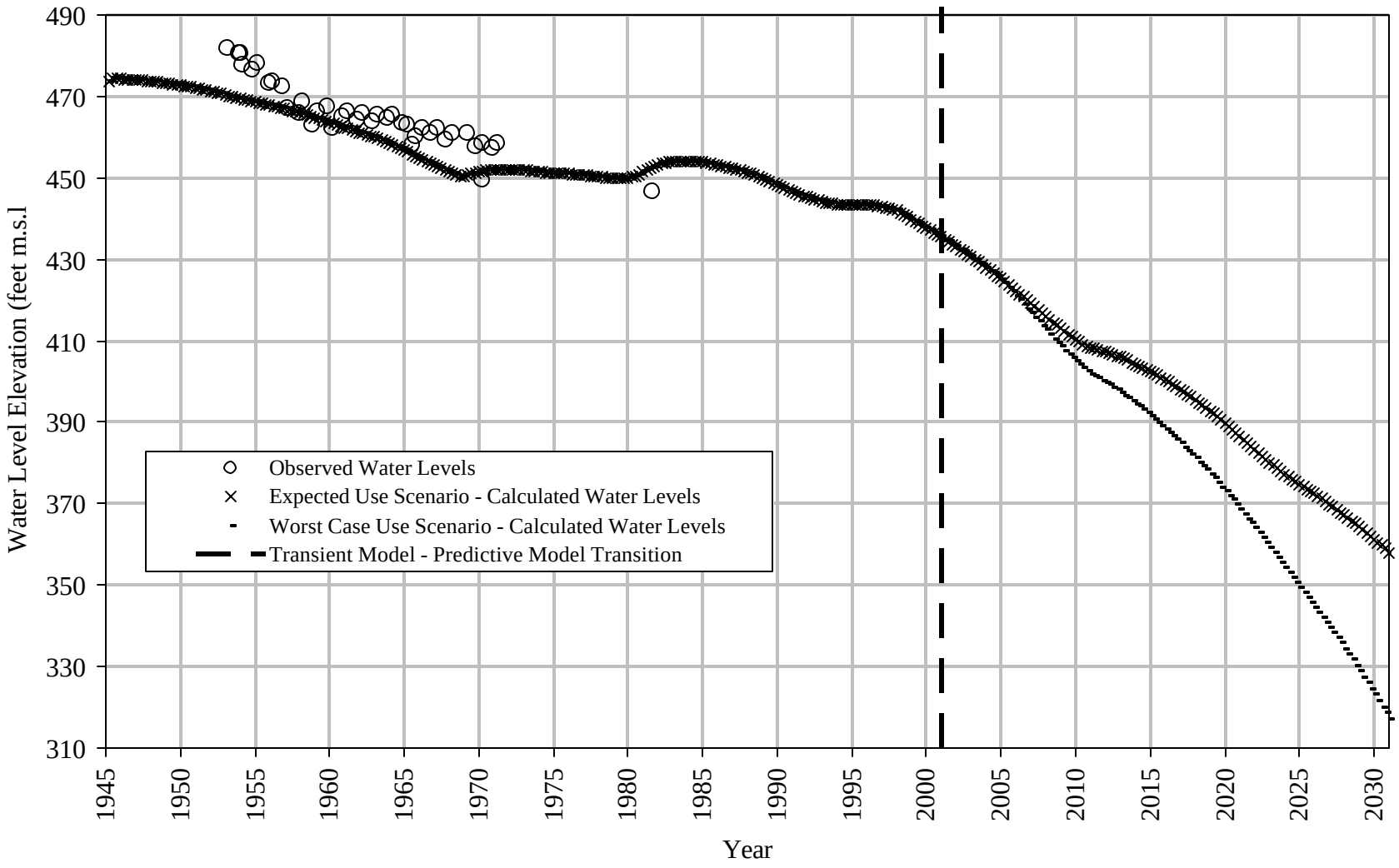


Figure 151. Water level elevation hydrograph well - 11S/6E 11M1 (transient and predictive models).

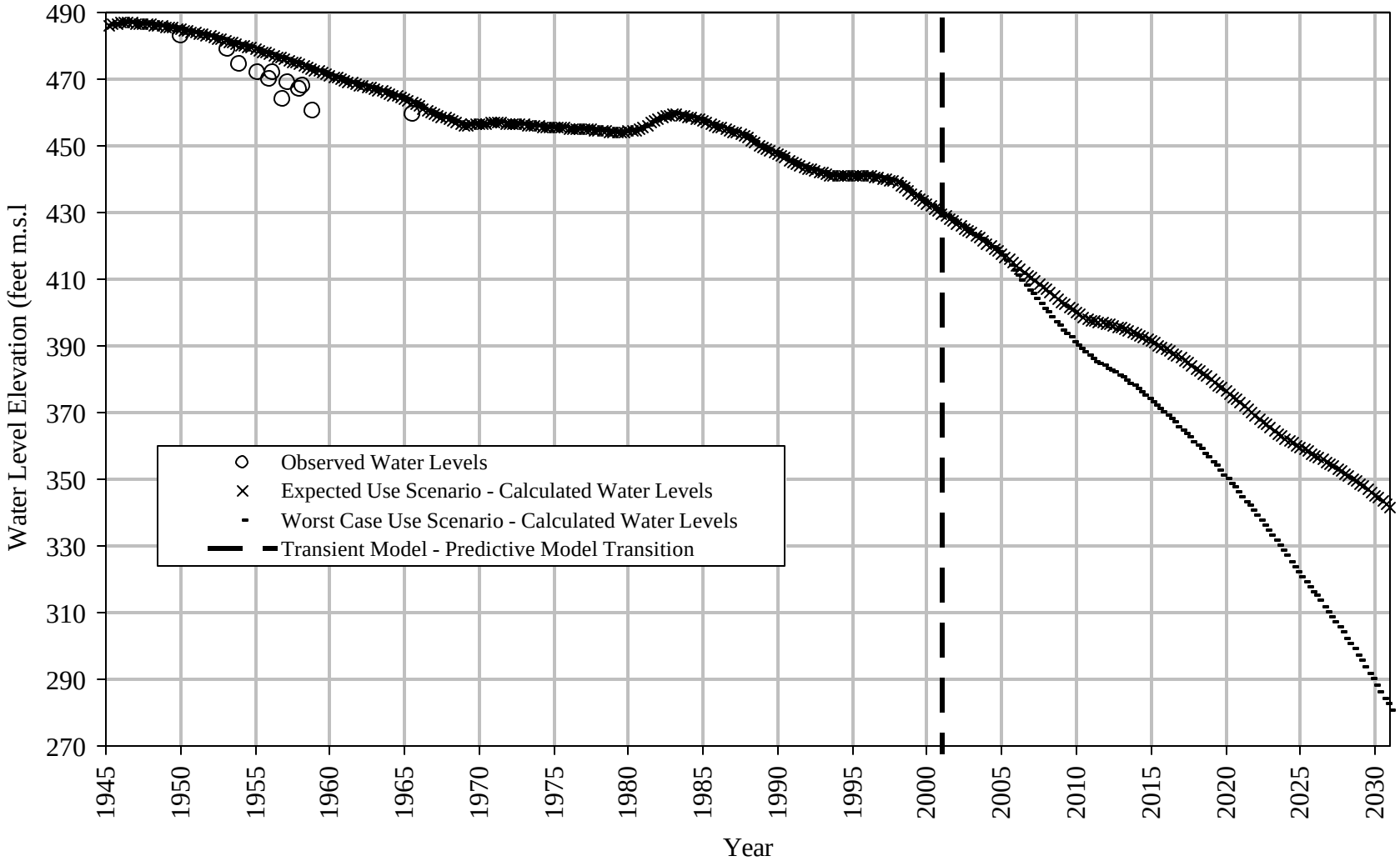


Figure 152. Water level elevation hydrograph well - 11S/6E 15F1 (transient and predictive models).

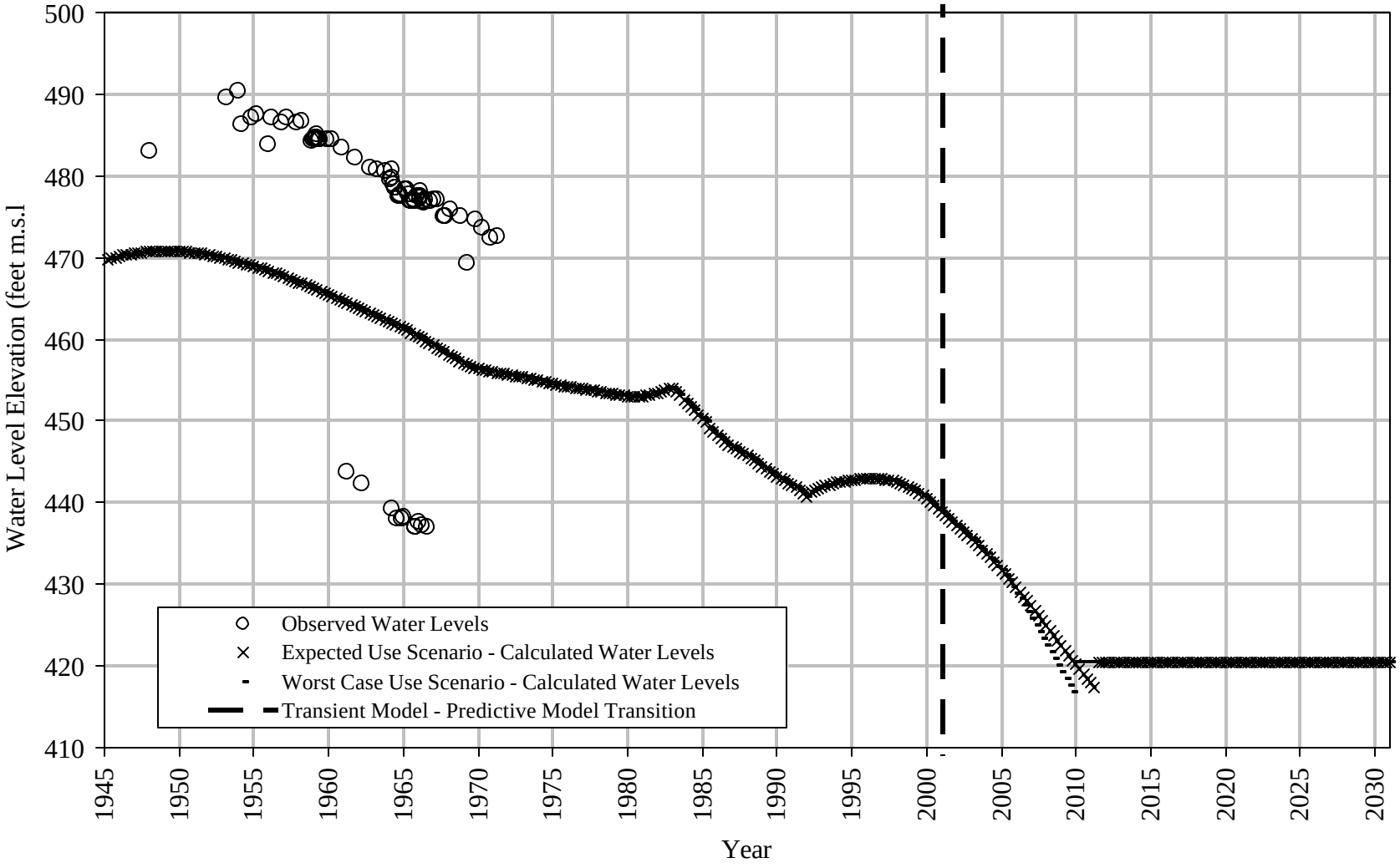


Figure 153. Water level elevation hydrograph well - 11S/6E 22A1 (transient and predictive models).

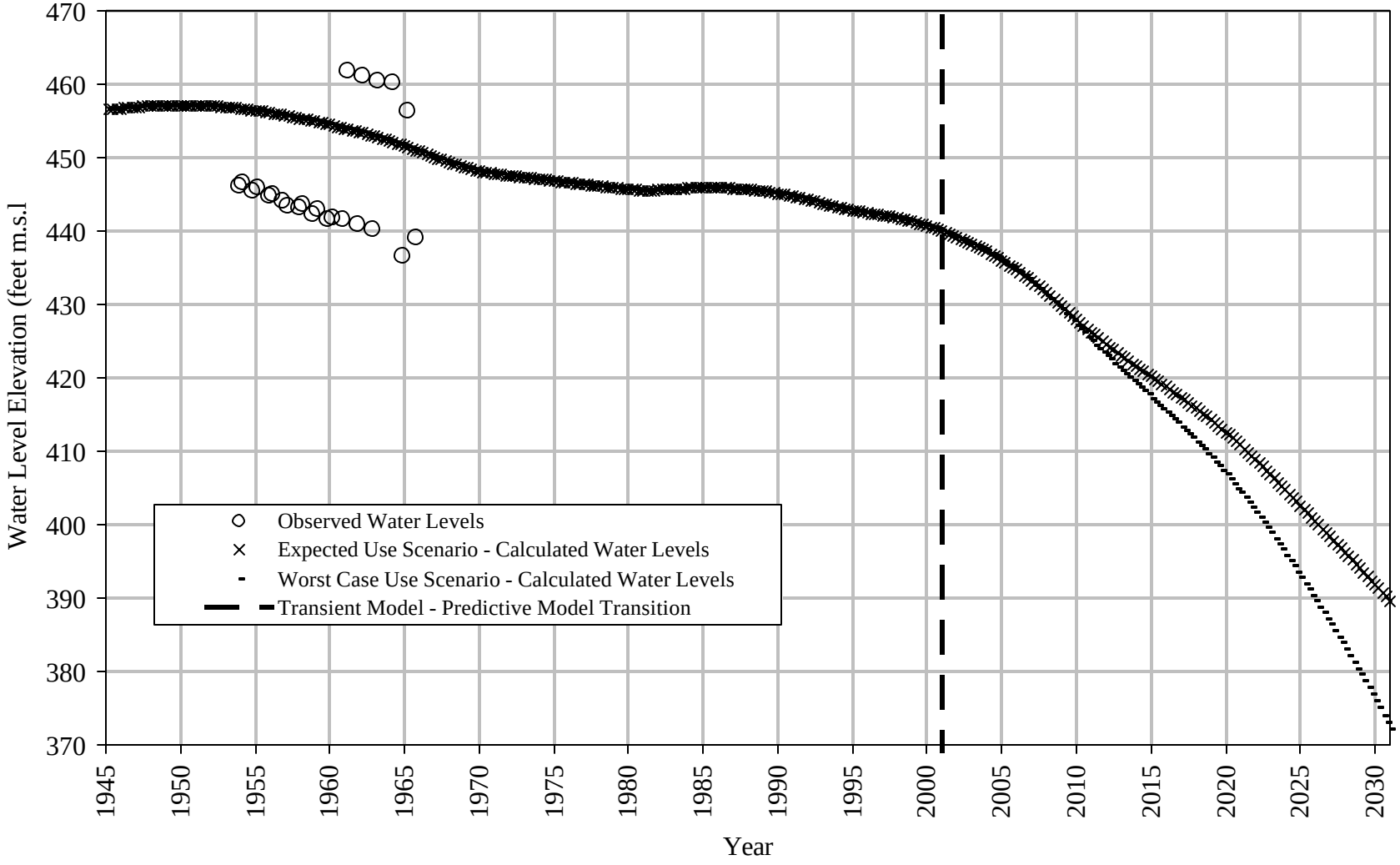


Figure 154. Water level elevation hydrograph well - 11S/7E 7N1 (transient and predictive models).

ABSTRACT

ABSTRACT

Borrego Valley is located in Northeast San Diego County, California, near the western border of Imperial County, California. This area is within the Colorado Desert geomorphic province of California. The study area includes the alluvium and sedimentary-rock filled valley floor, and the crystalline-rock mountains of the surrounding watersheds. Development of Borrego Valley began in the early part of the 20th century, and increased in the period following World War 2. Groundwater has been used extensively to support agricultural, municipal, and recreational water demand. Extensive use of groundwater has led to overdraft of the aquifer system. Groundwater levels in the basin decreased as much as 140 feet during the period 1945 through 2000. The cumulative depletion of groundwater from the aquifer system for that period was over 500,000 acre-feet. The overuse of groundwater has led to adverse impacts including wells going dry, increased operational costs, and deterioration of water quality. Previous studies understated the impacts of historic and future groundwater use in excess of recharge. The objectives of this study were to describe the hydrogeology of the Borrego Valley aquifer system, develop and calibrate a groundwater flow model, and use the model to predict future conditions based on anticipated use scenarios.

The Borrego Valley aquifer system is comprised of four hydrostratigraphic units, including young, intermediate, and old Quaternary alluvium, and the Tertiary Palm Spring Formation. Groundwater is contained in, and flows through each of these units. The alluvial hydrostratigraphic units are comprised of alluvial fan, intermittent-stream, and lacustrine sediments. The Palm Spring Formation includes sediments deposited in a shallow-lake or delta. Groundwater flow is from the recharge areas around the margin of the aquifer system to both the local and regional topographic lows. Groundwater flow is generally horizontal with an absence of vertical hydraulic gradients.

A three-dimensional finite-difference model, MODFLOW, was used to simulate and evaluate groundwater flow in the aquifer system for the period 1945 through 2000. The aquifer system was simulated as six-layers. Calibration of the model was completed to provide estimates of the physical properties of soil textures in each model layer. The quality

of calibration of the numerical model was evaluated by comparison with observed water level data from twenty wells in Borrego Valley.

The calibrated model was utilized to quantify the impacts of future groundwater utilization in the aquifer system. A thirty-year hydrologic cycle was used to represent climatic conditions during the predictive modeling. Future groundwater utilization was estimated based on two scenarios. Both scenarios considered agricultural, recreational, and municipal groundwater demand for the period 2001 through 2030. Maximum future declines in groundwater levels for the scenarios range from 105 to 170 feet for the predictive modeling period.

Observed groundwater levels in the Borrego Valley aquifer system indicate a condition of overdraft. Numerical modeling of the aquifer system predicts continued overdraft of the system under two use scenarios. Overdraft to the aquifer system is expected to exacerbate existing adverse impacts, and led to new adverse impacts such as intrusion of poor-quality connate water from formational deposits.